Multiple zeta values:
from numbers to motives

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With contributions by Ulf Kühn

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Multiple zeta values (MZVs for short) are real numbers of the form
\begin{equation}
\zeta(s_1, s_2, \ldots, s_{\ell}) = \sum_{n_1 > n_2 > \cdots > n_{\ell} \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2} \cdots n_{\ell}^{s_{\ell}}},
\end{equation}
where all the exponents $s_i$ are integers greater than or equal to 1, and we make the assumption $s_1 \geq 2$ to ensure that the series converges. For $\ell = 1$, these are nothing but the values at integers $s \geq 2$ of the Riemann zeta function
\[ \zeta(s) = \sum_{n \geq 1} \frac{1}{n^s}. \]
Euler proved in 1735 that, when $s$ is even, $\zeta(s)$ is a rational multiple of $\pi^s$. Thanks to Lindemann’s proof of the transcendence of $\pi$ a century and a half later, it follows that all the numbers $\zeta(2), \zeta(4), \ldots$ are transcendental. For example,
\[ \zeta(2) = \frac{\pi^2}{6}, \quad \zeta(4) = \frac{\pi^4}{90}, \quad \zeta(6) = \frac{\pi^6}{945}, \]
etc.
The values of the Riemann zeta function at odd integers are much more mysterious. Indeed, a folklore conjecture asserts that they are all “new” transcendental numbers:

**Transcendence conjecture.** The numbers $\pi, \zeta(3), \zeta(5), \zeta(7), \ldots$ are algebraically independent over $\mathbb{Q}$.

Being algebraically independent means that, for each integer $k \geq 0$, there exists no non-zero polynomial $P \in \mathbb{Q}[x_0, \ldots, x_k]$ such that
\[ P(\pi, \zeta(3), \ldots, \zeta(2k + 1)) = 0, \]
and in particular that the numbers $\zeta(3), \zeta(5), \ldots$ are transcendental. This conjecture seems completely out of reach: at the time of writing, the best we know is that $\zeta(3)$ is irrational (Apéry, 1978) and that there are infinitely many irrational numbers among the remaining odd zeta values (Ball and Rivoal, 2001). Neither the transcendence of $\zeta(3)$, let alone its algebraic independence with $\pi$, nor the irrationality of $\zeta(5)$ are known!

The case $\ell = 2$ was also considered by Euler, back in his 1776 article *Meditationes circa singulare serierum genus* (“Meditations about a singular type of series”) [Eul76]. In an attempt to find a closed formula for $\zeta(3)$, he looked for linear relations with integer coefficients among the numbers $\pi^3, \pi^2 \log 2$, and $(\log 2)^3$. This led him to the discovery of remarkable identities involving double zeta values, the simplest being $\zeta(3) = \zeta(2, 1)$.

After more than two centuries of oblivion, multiple zeta values were independently rediscovered in the 1990s by Hoffman and Zagier. It was soon realized that these numbers appear in a wealth of different contexts, including Witten’s zeta functions, Kontsevich’s deformation quantization, Vassiliev knot invariants, and the theory of mixed Tate motives. Most of these topics share a physics flavour and, roughly at the same time, the physicists Broadhurst and Kreimer found that a lot of Feynman amplitudes in quantum field theory can be expressed as linear combinations of multiple zeta values. The next two decades saw extensive work by a host of mathematicians, including Brown, Cartier, Deligne, Drinfeld, Écalle, Goncharov, Hain, Hoffman, Kontsevich, Terasoma, Zagier, and many others. Major progress
was made, but fundamental questions remain open and multiple zeta values are
still nowadays an active and rapidly moving field of research.

The product of two multiple zeta values is a linear combination, with integral
coefficients, of multiple zeta values. For instance,
\[ \zeta(s_1)\zeta(s_2) = \zeta(s_1, s_2) + \zeta(s_2, s_1) + \zeta(s_1 + s_2), \]
an identity already known to Euler. The \( \mathbb{Q} \)-subvector space \( \mathcal{Z} \subseteq \mathbb{R} \) spanned by
all multiple zeta values has thus an algebra structure. Contrary to the algebra
generated by Riemann zeta values, which according to the transcendence conjecture
should simply be a polynomial algebra in \( \zeta(2), \zeta(3), \zeta(5), \ldots \), multiple zeta values
satisfy a plethora of relations that endow \( \mathcal{Z} \) with a rich combinatorial structure.

One can argue that the main goal of the theory is to understand all linear relations
among these numbers.

To make this more precise, we attach to each multiple zeta value
\( \zeta(s_1, \ldots, s_\ell) \) the integer \( s_1 + \cdots + s_\ell \), which is called the weight. Let \( \mathcal{Z}_k \subseteq \mathcal{Z} \) be the vector
subspace generated by multiple zeta values of weight \( k \), with the convention
that \( \mathcal{Z}_0 = \mathbb{Q} \) and \( \mathcal{Z}_1 = \{0\} \). Based on a mix of numerical evidence and pure
thought, Zagier conjectured “after many discussions with Drinfeld, Kontsevich,
and Goncharov” that there is a direct sum decomposition
\[ \mathcal{Z} = \bigoplus_{k \geq 0} \mathcal{Z}_k, \]
and that the dimension of each graded piece is given by a Fibonacci-like sequence
\begin{align*}
\dim_{\mathbb{Q}} \mathcal{Z}_k & = d_k. \\
\end{align*}
Precisely, \( (d_k)_{k \geq 0} \) is defined by the initial terms \( d_0 = d_2 = 1 \) and \( d_1 = 0 \), and the recurrence relation
\( d_k = d_{k-2} + d_{k-3} \) for all \( k \geq 3 \), so that the generating series is
\begin{align*}
\sum_{k \geq 0} d_k t^k & = \frac{1}{1 - t^2 - t^3}. \\
\end{align*}
This conjecture would imply that the dimension of \( \mathcal{Z}_k \) grows like a constant multiple
of \( r^k \), where \( r = 1.3247 \ldots \) is the real root of \( x^3 - x - 1 \), which is much smaller
than the number \( 2^{k-2} \) of multi-indices \( (s_1, \ldots, s_\ell) \) of weight \( k \).

**Plan.** The goal of these notes is to give a reasonably self-contained proof of
the following results towards Zagier’s conjecture:

**Theorem A** (Deligne-Goncharov [DG05], Terasoma [Ter02]). The integers \( d_k \)
are upper bounds for the dimensions of \( \mathcal{Z}_k \):
\[ \dim_{\mathbb{Q}} \mathcal{Z}_k \leq d_k. \]
**Theorem B** (Brown, [Bro12]). Each multiple zeta value can be written as
a \( \mathbb{Q} \)-linear combination of multiple zeta values with only \( 2 \)s and \( 3 \)s as exponents.
That is, the following family generates the \( \mathbb{Q} \)-vector space \( \mathcal{Z} \):
\begin{align*}
\{ \zeta(s_1, \ldots, s_\ell) \mid s_1 \in \{2, 3\} \}. \\
\end{align*}
In fact, Hoffman conjectured that \( (0.4) \) forms a basis of \( \mathcal{Z} \). By a simple counting
argument, equality \( (0.2) \) would follow from this. Theorem B addresses the
“algebraic” part of this conjecture, which suffices to deduce Theorem A. It is also
worth mentioning that, taking these results for granted, the algebraic independence
of the numbers \( \pi, \zeta(3), \zeta(5), \ldots \) is a consequence of Zagier’s conjecture. In a sense,
we have “linearized” the transcendence conjecture. On the negative side, let us emphasize that, despite the progress made thus far, we still do not know a single $k$ for which the dimension of $Z_k$ is bigger than one!

Surprisingly enough, the proofs of these easy-to-state theorems use the machinery of motives. Kontsevich noticed that multiple zeta values of weight $k$ admit a representation as iterated integrals

\[(0.5) \quad \zeta(s_1, \ldots, s_t) = \int_{\Delta^k} \omega_0(t_1) \cdots \omega_0(t_{s_1-1}) \omega_1(t_{s_1}) \omega_0(t_{s_1+1}) \cdots \omega_1(t_k),\]

where $\omega_0(t) = dt/t$ and $\omega_1(t) = dt/(1-t)$ are differential forms on $\mathbb{P}^1 \setminus \{0, 1, \infty\}$, and the integration domain is the simplex

$$\Delta^k = \{(t_1, \ldots, t_k) \in [0,1]^k \mid 1 \geq t_1 \geq t_2 \geq \cdots \geq t_k \geq 0\}.$$  

This integral representation exhibits multiple zeta values as periods of algebraic varieties. In the words of Deligne, “whereas the notion of infinite sum is unfamiliar (étrangère) to algebraic geometry, the study of integrals of algebraic quantities is one of its sources.” Thanks to the identity $(0.5)$, “algebraic geometry, and more precisely the theory of mixed Tate motives, is useful for the study of multiple zeta values” [Del13, p.3].

Usually, the philosophy of motives represents a powerful tool to predict all algebraic relations between periods. However, when it comes to proving them, one is confronted with the problem that even the first step in this program—getting a category of motives with all the desired properties—remains conjectural. In contrast, for mixed Tate motives over a number field, there is an unconditional theory that relies ultimately on Borel’s deep results about the $K$-theory of number fields. This gives good control over the group governing the symmetries of multiple zeta values. Using this group, one can construct a pro-algebraic variety, together with an action of $\mathbb{G}_m$, in such a way that the Hilbert–Poincaré series of its graded algebra of functions $H$ coincides with $(0.3)$. The raison d’être of this construction is the existence of a surjective map $H \to Z$ compatible with the weight; we shall refer to elements of $H$ as “motivic multiple zeta values”. This immediately implies Theorem A. To prove Theorem B, one exploits the motivic coaction, a new structure of $H$, invisible at the level of numbers, that allows one to get relations among motivic multiple zeta values in a systematic way. A variant of the Grothendieck period conjecture asserts that the algebras $H$ and $Z$ are isomorphic, from which Zagier’s conjecture would follow.

Outline. Let us now give a more detailed description of the contents of each chapter. The word cloud on the next page should also give a quick idea of the main concepts involved.

Chapter 1 lays out what could be called the “minimal theory” of multiple zeta values. We first define them as infinite series and prove that the product of two multiple zeta values is a linear combination of multiple zeta values by decomposing the indexation domain. This so-called stuffle product makes $Z$ into a $\mathbb{Q}$-algebra, conjecturally graded by the weight. We discuss Zagier’s conjecture for the dimension of the graded pieces, as well as refinements due to Hoffmann, and Broadhurst and Kreimer. That progress has been made towards these conjectures relies very much on the existence of the integral representation $(0.5)$. We prove that the decomposition of the product of two simplices yields a new algebra structure on $Z$, the shuffle product. Comparing the stuffle and the shuffle product, one gets many
relations among multiple zeta values but not all of them. As we explain in the last section of the chapter, to conjecturally describe the full algebraic structure, one needs to introduce a regularization process that assigns a finite value to the divergent series \( \zeta(1, s_2, \ldots, s_\ell) \).

The goal of Chapter 2 is to show that multiple zeta values are periods of algebraic varieties. To begin with, we briefly recall the definition of singular cohomology of a differential manifold and de Rham’s theorem, which says that it can be computed using analytic differential forms. Grothendieck’s breakthrough was to realize that, if we are dealing with algebraic varieties, then algebraic differential forms suffice; this gives rise to algebraic de Rham cohomology and the period isomorphism. After introducing these concepts, we give a first interpretation of multiple zeta values as periods of the moduli spaces \( M_{0,n} \) of stable genus zero curves due to Goncharov and Manin. We then move to mixed Hodge structures (a first approximation to the notion of motive), discuss a number of examples, and compute the extension groups of \( \mathbb{Q}(0) \) by \( \mathbb{Q}(n) \). We end the chapter with a discussion of the problem of finding a geometric construction of these extensions, as well as a potential application to irrationality proofs following Brown.

Chapter 3 introduces iterated integrals, a second way to interpret multiple zeta values as periods. We first present the basic definitions and tackle the question of which iterated integrals are homotopy invariant. We then recall the notions of affine group scheme and Hopf and Lie algebras, which will be extensively used in the sequel. We define the pro-unipotent completion of a group and we construct it, under some finiteness assumptions, following work of Quillen. One of the main results of the chapter is Chen’s \( \pi_1 \)-de Rham theorem, which roughly says that functions on the pro-unipotent completion of the fundamental group of a differential manifold \( M \) are given by homotopy invariant iterated integrals. A consequence, due to Hain, is that when \( M \) underlies an algebraic variety, this pro-unipotent completion carries a mixed Hodge structure. The general formalism being settled,
we specialize everything to \( \mathbb{P}^1 \setminus \{0, 1, \infty\} \). Multiple zeta values are iterated integrals along the straight path from 0 to 1. Since the endpoints do not belong to the space, this forces us to work with tangential base points. The last section contains a detailed analysis of all the structures carried by the pro-unipotent completion of the fundamental group of \( \mathbb{P}^1 \setminus \{0, 1, \infty\} \), including Goncharov’s coproduct.

In Chapter 4, we study the category of mixed Tate motives over \( \mathbb{Z} \). The first two sections contain reminders of the tannakian formalism, triangulated categories, and \( t \)-structures. We then sketch a construction of Voevodsky’s triangulated category of mixed motives over a field \( k \). It is unknown how to extract an abelian category with good properties from it. However, it was observed by Levine that, when \( k \) is a number field, Borel’s results on \( K \)-theory enable one to extract an abelian category of mixed Tate motives over \( k \), which is moreover tannakian. Even for \( k = \mathbb{Q} \), this category is too large for the purposes of studying multiple zeta values. To remedy this, one defines the subcategory of mixed Tate motives over \( \mathbb{Z} \).

Finally, in Chapter 5 we pull everything together to prove the main results. In the first section, we construct the graded algebra \( \mathcal{H} \) of motivic multiple zeta values and a surjective map \( \mathcal{H} \to \mathcal{Z} \) compatible with the grading. Using the structure of the Tannaka group of the category of mixed Tate motives over \( \mathbb{Z} \), we show that the graded piece \( \mathcal{H}_k \) is of dimension \( d_k \). The existence of the above map then implies the upper bound for the dimensions of \( \mathcal{Z}_k \) in Theorem A. We then present the proof of Theorem B, following closely Brown’s original paper, and a few consequences. Namely, we explain how to deduce the fact that all periods of mixed Tate motives over \( \mathbb{Z} \) are polynomials expressions in \( 1/2\pi i \) and multiple zeta values, as well as the fact that Zagier’s conjecture implies the algebraic independence of \( \pi, \zeta(3), \zeta(5), \ldots \).

The notes are supplemented by an appendix where we give an introduction to some of the notions and techniques from homological algebra (abelian categories, triangulated categories and \( t \)-structures, derived functors, filtrations and spectral sequences, sheaf cohomology...) that are used in the main body.

**Warning.** Before continuing, we should warn the reader that there are two competing conventions for multiple zeta values in the literature, sometimes in the same paper! Other authors, including Brown, define \( \zeta(s_1, \ldots, s_\ell) \), for integers \( s_i \geq 1 \) and \( s_\ell \geq 2 \), as the sum

\[
\sum_{1 \leq n_1 < n_2 < \cdots < n_\ell} \frac{1}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}}.
\]

In fact, one needs to fix conventions for the order of composition of paths, the definition of iterated integrals, and the expression of multiple zeta values as iterated integrals. Things get simpler if they are compatible. We have chosen those conventions for which the monodromy of a local system is a group morphism.

**Prerequisites.** The difficulty of the exposition increases as the notes progress. In Chapter 1, besides a couple of digressions, the emphasis is mainly on combinatorial aspects and very little background is required. From Chapter 2 on, we assume some familiarity with algebraic varieties, the language of schemes and cohomology of sheaves, at the level of any introductory book, for instance Hartshorne’s [Har77].
Chapter 3 contains a crash course on algebraic groups and Lie and Hopf algebras, with an emphasis on unipotent groups and nilpotent Lie algebras, which will play an important role in the sequel. Finally, in Chapter 4 we freely use basic notions from category theory and homological algebra, for example abelian categories (most of them are gathered in the appendix for the convenience of the reader). We have done our best to present all the materials in the most clear and accessible way, but occasionally we were unable to prevent the text from being sketchy. Unfortunately, Borel’s theorem about the \( K \)-theory of number fields is used as a black box.

**Notation and conventions.**

- By an *algebraic variety* over some field \( k \), we mean a reduced separated scheme of finite type over \( k \).
- Given a set \( S \) and functions \( f : S \to \mathbb{C} \) and \( g : S \to \mathbb{R}_{\geq 0} \), the notation \( f = O(g) \) means that there exists a real number \( C \geq 0 \) such that the inequality \( |f(x)| \leq Cg(x) \) holds for all \( x \in S \).
- The word *positive* means strictly bigger than 0 and the word *non-negative* bigger than or equal to 0.
- We denote by \( \lfloor x \rfloor \) the *floor* of a real number \( x \). That is, \( \lfloor x \rfloor \) is the largest integer smaller than or equal to \( x \). Similarly, \( \lceil x \rceil \) denotes the *ceiling* of \( x \), that is, the smallest integer greater than or equal to \( x \).
- If \( R \) is a ring and \( S \) is a set, then \( \langle S \rangle_R \) denotes the \( R \)-module generated by \( S \). If \( S \) is an abstract set, then \( \langle S \rangle_R \) is a free \( R \)-module, while if \( M \) is an \( R \)-module and \( S \subset M \), then \( \langle S \rangle_R \) means the submodule of \( M \) generated by \( S \). For instance, \( \langle x, y \rangle_{\mathbb{Q}} \) is a \( \mathbb{Q} \)-vector space of dimension 2. If the ring \( R \) is understood, then the subindex is omitted.
- If \( R \) is a commutative ring and \( S \) is a set, we will denote by \( R[S] \) the commutative associative \( R \)-algebra generated by \( S \) and by \( R\langle S \rangle \) the associative \( R \)-algebra generated by \( S \). As before, this may have two different meanings depending on whether \( S \) is already a subset of an \( R \)-algebra or an abstract set.
- If \( R \) is a commutative ring and \( S \) is a set, we will denote by \( R[[S]] \) the completion of \( R[S] \) with respect to the ideal generated by \( S \) and by \( R\langle S \rangle \) the completion of \( R\langle S \rangle \), again with respect to the ideal generated by \( S \).

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1. Classical theory of multiple zeta values
(by J. I. Burgos Gil, J. Fresán, and U. Kühn)

In this chapter, we introduce multiple zeta values and begin to study their basic properties. These are the real numbers
\[ \zeta(s_1, \ldots, s_\ell) = \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}} \]
associated with tuples of integers \( s = (s_1, \ldots, s_\ell) \) satisfying \( s_i \geq 1 \) and \( s_1 \geq 2 \). The sum of the exponents \( w = s_1 + \cdots + s_\ell \) is called the weight and \( \ell \) is referred to as the length. Of great importance is that multiple zeta values cannot only be written as infinite series as above, but also as integrals
\[ \zeta(s_1, \ldots, s_\ell) = \int_{1 \geq t_1 \geq \cdots \geq t_w \geq 0} dt_1 \cdots dt_w \frac{1}{t_1 \cdots t_{s_1-1}(1-t_{s_1})t_{s_1+1} \cdots (1-t_w)}. \]
This gives two different ways of writing the product of \( \zeta(s) \) and \( \zeta(s') \) as a linear combination with integral coefficients of multiple zeta values or, in more algebraic terms, of showing that the \( \mathbb{Q} \)-vector space \( \mathbb{Z} \subseteq \mathbb{R} \) generated by multiple zeta values has an algebra structure. From the series representation one obtains the stuffle product, whereas the integral representation gives the shuffle product. Comparing these two products yields many relations among multiple zeta values. Not all of them, however, can be obtained by this method: since the product of any two multiple zeta values has weight at least 4, for example Euler’s identity \( \zeta(3) = \zeta(2, 1) \) does not arise in this manner. A way to accommodate this and other relations is to introduce a regularization process that assigns a finite value to the divergent series corresponding to multi-indices with \( s_1 = 1 \). There will be, in fact, two kinds of regularizations, modelled on the stuffle and the shuffle product. Conjecturally, all relations among multiple zeta values come from comparing them. A few good references for the material of this chapter are the survey articles [Car02], [Wal12], and [Zud03], as well as Chapter 3 of the book [Zha16].

1.1. Riemann zeta values. The Riemann zeta function is one of the most famous objects in mathematics. One often hears that it encodes all arithmetic properties of prime numbers: our task is to extract them!

**Definition 1.1.** The **Riemann zeta function** is defined, on the half-plane of complex numbers \( s \) with \( \text{Re}(s) > 1 \), by the absolutely convergent series
\[ \zeta(s) = \sum_{n \geq 1} \frac{1}{n^s}. \]

It admits a meromorphic continuation to the whole complex plane with a single pole at \( s = 1 \) (see, for example, [Tit86, Chap. II], where no less than seven different methods to obtain this continuation are explained). The Riemann zeta function still keeps many mysteries. The most impenetrable of them is undoubtedly the Riemann hypothesis (the conjecture that all the non-trivial zeros of \( \zeta(s) \) lie in the line \( \text{Re}(s) = 1/2 \)), which has many far-reaching consequences for the study of the distribution of prime numbers in analytic number theory. The aim of this book is to glimpse at other aspects of this function, namely the question:

*which numbers do we get when evaluating \( \zeta(s) \) at integer \( s \)?*
1.1.1. **Even zeta values.** The story in fact began 120 years before Riemann’s article [Rie59], with Euler’s solution to the so-called *Basel problem*, which asked for the computation of the special value

\[ \zeta(2) = \sum_{n \geq 1} \frac{1}{n^2} = \frac{\pi^2}{6}. \]

For the prehistory of the Riemann zeta function, we refer the reader to Weil’s beautiful account [Wei89]. In fact, Euler proved much more than this:

**Theorem 1.3 (Euler, 1735).** The values of the zeta function at even positive integers are given by the formula

\[ \zeta(2k) = (-1)^{k-1} \frac{(2\pi)^{2k}}{2(2k)!} B_{2k} \quad (k \geq 1). \]

Here \( B_{2k} \) are rational numbers, called *Bernoulli numbers* and defined by the power series identity

\[ \frac{t}{e^t - 1} = 1 + \sum_{k \geq 1} B_k \frac{t^k}{k!}. \]  

**Remark 1.6.** Note that the function

\[ f(t) = \frac{t}{e^t - 1} + \frac{1}{2} t = \frac{t(1 + e^t)}{2(e^t - 1)} \]

is even, *i.e.* satisfies \( f(t) = f(-t) \). Hence, the Bernoulli numbers satisfy \( B_1 = -1/2 \) and \( B_k = 0 \) for all odd integers \( k \geq 3 \). The first few are easily computed:

<table>
<thead>
<tr>
<th>(k)</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B_k)</td>
<td>(\frac{1}{6})</td>
<td>(-\frac{1}{30})</td>
<td>(\frac{1}{42})</td>
<td>(-\frac{1}{30})</td>
<td>(\frac{5}{66})</td>
<td>(-\frac{691}{2730})</td>
</tr>
</tbody>
</table>

**Proof of Theorem 1.3.** The key ingredient is an identity for the cotangent function, also due to Euler (see Exercise 1.18): for \( x \in \mathbb{C} \setminus \mathbb{Z} \), the equality

\[ \pi \cot(\pi x) = \frac{1}{x} + \sum_{n \geq 1} \frac{2x}{x^2 - n^2} \]

holds. For \( 0 < |x| < 1 \), we can expand the quotient inside the summation sign as a geometric series. Since the resulting double series is absolutely convergent, we can then interchange the order of summation to obtain

\[ \pi \cot(\pi x) = \frac{1}{x} - 2 \sum_{k \geq 1} \zeta(2k)x^{2k-1}. \]

Besides, the identities

\[ \frac{1}{e^t - 1} = \frac{e^{-t/2}}{e^{t/2} - e^{-t/2}} \quad \text{and} \quad \frac{1}{e^{-t} - 1} = \frac{e^{t/2}}{e^{t/2} - e^{-t/2}}, \]

along with the definition (1.5) of Bernoulli numbers and the fact that they vanish for odd \( k \geq 3 \), imply the equality

\[ \frac{e^{t/2} + e^{-t/2}}{e^{t/2} - e^{-t/2}} = \frac{2}{t} + 2 \sum_{k \geq 1} \frac{B_{2k} t^{2k-1}}{(2k)!}. \]
Therefore, formula (1.7) can be rewritten as

\[
\pi \cot(\pi x) = \pi i \frac{e^{2\pi i x} + e^{-2\pi i x}}{e^{2\pi i x} - e^{-2\pi i x}} = \frac{1}{x} + \sum_{k \geq 1} \frac{(2\pi i)^{2k} B_{2k}}{(2k)!} x^{2k-1},
\]

and we conclude by identifying the coefficients in (1.8) and (1.9) term by term. □

**Remark 1.10.**

i) Euler’s formula (1.4) implies the equality

\[ Q[\zeta(2), \zeta(4), \ldots] = Q[\pi^2] \]

of subrings of the ring of real numbers.

ii) The Riemann zeta function satisfies the functional equation

\[
\pi^{-s} \Gamma\left(\frac{s}{2}\right) \zeta(s) = \pi^{1-s} \Gamma\left(\frac{1-s}{2}\right) \zeta(1-s),
\]

where \( \Gamma \) is the gamma function, see [Tit86, (2.1.13)]. Using that \( \Gamma(s) \) has a simple pole of residue \((-1)^k k! / k!\) at all non-positive integers \( s = -k \) and this functional equation, we derive from Euler’s formula the values of the Riemann zeta function at negative integers:

\[ \zeta(-k) = (-1)^k \frac{B_{k+1}}{k+1} \quad (k \geq 1). \]

In particular, \( \zeta(s) \) vanishes at \( s = -2k \) for all \( k \geq 1 \); these are the “trivial zeros”. One can also compute the value \( \zeta(0) = -1/2 \) on noting that \( \zeta(s) \) has a simple pole of residue 1 at \( s = 1 \).

1.1.2. Odd zeta values. By contrast, despite the many efforts of the mathematical community, nobody has been able to give closed-form expressions for the values of the Riemann zeta function at odd positive integers \( s = 3, 5, \ldots \) in terms of previously known numbers like \( \pi \). This led to the following conjecture:

**Conjecture 1.12 (Transcendence conjecture).** The numbers

\[ \pi, \zeta(3), \zeta(5), \ldots \]

are algebraically independent over \( \mathbb{Q} \). That is, for each integer \( k \geq 0 \) and each non-zero polynomial \( P \in \mathbb{Z}[x_0, \ldots, x_k] \), one has \( P(\pi, \zeta(3), \ldots, \zeta(2k+1)) \neq 0 \).

This conjecture seems completely out of reach of the current techniques in transcendence theory. The transcendence of \( \pi \) was proved by Lindemann in his 1882 paper [Lin82]. Combined with Euler’s formula (1.4), it implies that the numbers \( \zeta(2k) \) are transcendental for all \( k \geq 1 \). But, when it comes to odd zeta values, we do not even know whether \( \zeta(3) \) is transcendental, not to speak of its algebraic independence with \( \pi \), or if \( \zeta(5) \) is irrational. The few known results, at the moment of writing, are summarized below. The Bourbaki seminar [Fis04] contains an excellent survey of the developments prior to 2004.

- Apéry proved the irrationality of \( \zeta(3) \) in 1978, see [Apé79] for a short announcement and [vdP79] for a more detailed account. Different proofs by Beukers [Beu79, Beu87], Nesterenko [Nes96], Sorokin [Sor98], and Prévost [Pré96], among others, are now available, but none of them seems to generalize in any way to other odd zeta values such as \( \zeta(5) \).
Rivoal [Riv00] and Ball and Rivoal [BR01] proved the inequality
\[
\dim_{\mathbb{Q}} \langle 1, \zeta(3), \zeta(5), \ldots, \zeta(n) \rangle \geq \frac{1}{3} \log(n)
\]
for all odd integers \( n \geq 3 \), see also the exposition in [Col03]. In particular, infinitely many odd zeta values \( \zeta(2k+1) \) are irrational. A proof “by elementary means” of this corollary was recently given by Sprang [Spr18] building on ideas of Zudilin [Zud18], see also [FSZ19].

Zudilin [Zud01] proved that out of the four numbers \( \zeta(5), \zeta(7), \zeta(9), \zeta(11) \) at least one is irrational. Brown has suggested in [Bro16] a common geometric framework for these irrationality proofs. The approach is based on the study of periods of the moduli spaces \( M_{0,n} \) of curves of genus zero with \( n \) marked points (see Section 2.9.3).

**Digression 1.13.** Despite their “simplicity”, special values of the Riemann zeta function are linked to much interesting mathematics. For instance, \( K \)-groups and regulators provide an explanation of why the values at even integers are easier to understand than those at odd integers. The material on the Dedekind zeta function and the class number formula is covered for example in [Neu99, Chap. VII, §5].

Let \( F \) be a number field and \( \mathcal{O}_F \) its ring of integers. The Dedekind zeta function of \( F \) is defined, for \( \text{Re}(s) > 1 \), by the absolutely convergent series
\[
\zeta_F(s) = \sum_{a} \frac{1}{N(a)^s},
\]
where \( a \) runs through all non-zero ideals of \( \mathcal{O}_F \) and \( N(a) \) denotes the cardinal of the finite field \( \mathcal{O}_F/a \). In particular, \( \zeta_{\mathbb{Q}} \) agrees with the Riemann zeta function (1.2).

The Dedekind zeta function extends to a meromorphic function on the complex plane, with a simple pole at \( s = 1 \). Its residue is given by the celebrated **class number formula**
\[
\lim_{s \to 1} (s - 1) \zeta_F(s) = \frac{2^{r_1}(2\pi)^2 h_F R_F}{w_F \sqrt{|d_F|}},
\]
where \( r_1 \) (resp. \( r_2 \)) denotes the number of real (resp. pairs of conjugate complex) embeddings of \( F \), \( h_F \) is the class number, \( w_F \) is the number of roots of unity contained in \( F \), and \( d_F \) stands for the discriminant.

The remaining term \( R_F \) is defined using the **Dirichlet regulator** map
\[
\rho: \mathcal{O}_F^\times \to \mathbb{R}^{r_1+r_2}
\]
\[
u \mapsto (\log \|u\|_v)_v.
\]
Here \( v \) runs over all archimedean places of \( F \), and we write
\[
\|u\|_v = \begin{cases} 
|\sigma(u)|, & \text{if } v = \sigma \text{ is a real place}, \\
|\sigma(u)|^2, & \text{if } v = \{\sigma, \overline{\sigma}\} \text{ is a complex place}.
\end{cases}
\]
The product formula \( \prod_v \|u\|_v = 1 \) implies that \( \rho \) lands in the hyperplane of points whose coordinates sum to zero. In fact, Dirichlet showed that the image of \( \rho \) is a lattice in \( \mathbb{R}^{r_1+r_2-1} \), that is, a subgroup of the form \( \mathbb{Z}v_1 \oplus \cdots \oplus \mathbb{Z}v_{r_1+r_2-1} \) for linearly independent vectors \( v_1, \ldots, v_{r_1+r_2-1} \) (**Dirichlet’s unit theorem**). By definition, the **covolume** of such a lattice is the Lebesgue measure of the set
\[
\{x_1 v_1 + \cdots + x_{r_1+r_2-1} v_{r_1+r_2-1} \mid x_i \in \mathbb{R}, \ 0 \leq x_i < 1 \}.
\]
The covolume of the lattice \( \rho(\mathcal{O}_F^*) \) is a real number \( R_F \), abusively called Dirichlet regulator as well.

Borel generalized this picture to other values of the Dedekind zeta function. The role of the units \( \mathcal{O}_F^* \) is played by the higher \( K \)-groups \( K_n(\mathcal{O}_F) \), certain finitely generated abelian groups that carry a lot of information about the “hidden” arithmetic of \( F \). Borel computed the rank of these groups and defined, for each \( n \geq 2 \), the Borel regulator map

\[
\rho_n : K_{2n-1}(\mathcal{O}_F) \longrightarrow \mathbb{R}^{d_n}, \quad d_n = \begin{cases} 
  r_1 + r_2, & \text{if } n \text{ is odd}, \\
  r_2, & \text{if } n \text{ is even}.
\end{cases}
\]

Its image is again a lattice, whose covolume is a real number \( R_n \) also called Borel regulator. Letting \( \zeta^*_F(1 - n) \) denote the first non-vanishing coefficient in the Taylor expansion of the Dedekind zeta function at \( s = 1 - n \), he proved that there exists a rational number \( q_n \) such that

\[
\zeta^*_F(1 - n) = q_n R_n.
\]

The Dedekind zeta function satisfies a functional equation similar to (1.11), from which it follows that \( \zeta_F(n) \) is, up to some easy factor involving the square root of the discriminant of \( F \) and powers of \( \pi \), a rational multiple of \( R_n \):

\[
\zeta_F(n) \sim_{\mathbb{Q}^*} \frac{\pi^{n(r_1 + 2r_2 - d_n)}}{\sqrt{|d_F|}} R_n.
\]

(The notation \( \sim_{\mathbb{Q}^*} \) means that the left-hand side and the right-hand side agree up to a nonzero rational number.)

When \( F = \mathbb{Q} \) is the field of rational numbers, the \( K \)-group \( K_{2n-1}(\mathbb{Z}) \) has rank 1 if \( n \geq 3 \) is odd, and 0 otherwise (see Section 4.3). Therefore, \( R_n = 1 \) holds for even \( n \). Thus, \( \zeta(n) \) is a rational multiple of a power of \( \pi \) for even \( n \), while it involves the “mysterious” Borel regulator for odd \( n \). This result will play a pivotal role in the motivic approach to multiple zeta values. For more details, we refer the reader to the original papers by Borel [Bor74] and [Bor77], the monograph [BG02] or the short survey [Sou10].

1.1.3. Double zeta values. In order to investigate possible relations among zeta values, Euler looked at the algebraic structure of these numbers. The product of two Riemann zeta values gives rise to a new kind of interesting sum:

\[
\zeta(s_1) \cdot \zeta(s_2) = \left( \sum_{n_1 \geq 1} \frac{1}{n_1^{s_1}} \right) \cdot \left( \sum_{n_2 \geq 1} \frac{1}{n_2^{s_2}} \right) = \sum_{n_1, n_2 \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2}} = \sum_{n_1 > n_2 \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2}} + \sum_{n_2 > n_1 \geq 1} \frac{1}{n_2^{s_1} n_1^{s_2}} + \sum_{n=n_1=n_2 \geq 1} \frac{1}{n^{s_1+s_2}}.
\]
The first two terms in the last line are called *double zeta values* and admit the various representations

$$
\zeta(s_1, s_2) = \sum_{n_1 > n_2 \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2}}
$$

$$
= \sum_{n \geq 2} \frac{1}{n^{s_1}} \left( 1 + \frac{1}{2^{s_2}} + \cdots + \frac{1}{(n-1)^{s_2}} \right)
$$

$$
= \sum_{m, n \geq 1} \frac{1}{(n+m)^{s_1} n^{s_2}}.
$$

With this notation, equation (1.14) can be rewritten as

$$
(\zeta(s_1) \cdot \zeta(s_2)) = \zeta(s_1, s_2) + \zeta(s_2, s_1) + \zeta(s_1 + s_2).
$$

This identity already appears in Euler’s work [Eul76, p. 144] under the name of “prima methodus”.

**Example 1.17.** Taking $s_1 = s_2 = 2$ we get $\zeta(2)^2 = 2\zeta(2, 2) + \zeta(4)$, and hence

$$
\zeta(2, 2) = \frac{\pi^4}{120}
$$

by Euler’s formula (1.4). Similarly, one finds that the double zeta value $\zeta(2k, 2k)$ is a rational multiple of $\pi^{4k}$ for all $k \geq 1$.

As we have seen, products of two Riemann zeta values are linear combinations of zeta and double zeta values. To handle products of more factors, multiple zeta values of higher length are needed. These new numbers satisfy many linear relations, and one can argue that the main goal of the theory is to fully understand them.

***

**Exercise 1.18.** Prove that the logarithmic derivative of Euler’s product expansion for the sine function

$$
\frac{\sin \pi z}{\pi z} = \prod_{n \geq 1} \left( 1 - \frac{x^2}{n^2} \right)
$$

yields the identity

$$
\pi \cot(\pi x) = \frac{1}{x} + \sum_{n \geq 1} \frac{2x}{x^2 - n^2} \quad (x \in \mathbb{C}\setminus\mathbb{Z}),
$$

and deduce formula (1.8) in the proof of Theorem 1.3.

**Exercise 1.19.** Prove that the Taylor expansion of the logarithm of the gamma function at $z = 0$ is given by

$$
\log \Gamma(1 - z) = \gamma z + \sum_{n \geq 2} \zeta(n) \frac{z^n}{n},
$$

where $\gamma$ is the Euler-Mascheroni constant

$$
\gamma = \lim_{n \to \infty} \left( \sum_{k=1}^{n} \frac{1}{k} - \log(n) \right).
$$
MULTIPLE ZETA VALUES: FROM NUMBERS TO MOTIVES

Exercise 1.20 (Tornheim sums). Given integers \(a, b, c \geq 0\), the series

\[
S(a, b, c) = \sum_{m, n \geq 1} \frac{1}{m^a n^b (m+n)^c},
\]

is called a Tornheim sum, in reference to the article [Tor50].

i) Prove that \(S(a, b, c)\) converges if and only if the following inequalities hold:

\[
a + c > 1, \quad b + c > 1, \quad a + b + c > 2.
\]

ii) Show that the following Pascal triangle-like recurrence holds:

\[
S(a, b, c) = S(a-1, b, c+1) + S(a, b-1, c+1).
\]

iii) Deduce that \(S(a, b, c)\) is a linear combination with integral coefficients of double zeta values. For example, the identity \(S(1, 1, 1) = 2\zeta(2, 1)\) holds.

iv) Prove by direct computation the equality

\[
S(1, 1, 1) = \zeta(2, 1) + \zeta(3)
\]

and deduce Euler’s identity \(\zeta(3) = \zeta(2, 1)\). [Hint: use the equality

\[
\frac{1}{mn(m+n)} = \frac{1}{m^2} \left( \frac{1}{n} - \frac{1}{m+n} \right)
\]

to transform the sum over \(n\) into a telescoping series.]

1.2. Definition of multiple zeta values. It is now time to introduce the main character of this book. We start with some terminology.

1.2.1. Multi-indices and multiple zeta values.

Definition 1.21. A multi-index

\[
s = (s_1, \ldots, s_\ell) \in \mathbb{Z}^\ell
\]
is called positive if \(s_i \geq 1\) for all \(i = 1, \ldots, \ell\) and admissible if it is positive and, in addition, satisfies \(s_1 \geq 2\). The weight of \(s\) is the sum \(s_1 + \cdots + s_\ell\), and \(\ell\) is called its length (it is also called depth in the literature). By convention, the empty multi-index (\(\ell = 0\)) will also be considered to be admissible of weight and length both equal to 0. We will call \(s_i\) an entry of the multi-index \(s\).

Lemma 1.22. Let \(s = (s_1, s_2, \ldots, s_\ell)\) be a non-empty admissible multi-index. Then the following series converges:

\[
\zeta(s) = \zeta(s_1, s_2, \ldots, s_\ell) = \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}}.
\]

Proof. In view of the inequality

\[
\zeta(s) \leq \zeta(2, 1, \ldots, 1),
\]
it suffices to show that \(\zeta(2, 1, \ldots, 1)\) converges. Using the estimate

\[
\sum_{k=1}^{n} \frac{1}{k} \leq 1 + \log(n),
\]
which is obtained by comparison with the integral \( \int_1^n \frac{dx}{x} \), one gets:

\[
\zeta(2, 1, \ldots, 1) = \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}} \]

(1.23)

The last series converges, as can be seen as follows: from the limit

\[
\lim_{n \to +\infty} \frac{\log(1 + \log(n))}{\log(n)} = 0,
\]

it follows that there is an integer \( n_0 \) such that the inequality \((1 + \log(n))^{\ell-1} < \sqrt{n}\) holds for all \( n \geq n_0 \). The tail of the last series in (1.23) is thus bounded by the convergent series \(\sum_{n \geq n_0} n^{-3/2} \), so it is itself convergent. □

**Definition 1.24.** The *multiple zeta value* associated with an admissible multi-index \( s = (s_1, \ldots, s_\ell) \) is the real number

\[
\zeta(s) = \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}}.
\]

We shall adopt the convention \( \zeta(\emptyset) = 1 \).

**Remark 1.25.** Abusing notation, we will sometimes write

(1.26) \[ \text{wt}(\zeta(s)) = \text{wt}(s) = s_1 + \cdots + s_\ell, \]

(1.27) \[ \ell(\zeta(s)) = \ell(s) = \ell. \]

In particular, \( \text{wt}(1) = \ell(1) = 0 \) for the empty multi-index. Strictly speaking, only the weight and the length of \( s \) are well defined, since there are equalities \( \zeta(s) = \zeta(s') \) for different multi-indices. Conjecturally, when such an equality holds \( s \) and \( s' \) have the same weight, and hence (1.26) makes sense. By contrast, the length is only well defined for multi-indices, as Euler’s relation \( \zeta(2, 1) = \zeta(3) \) already shows that the same value can be represented by multi-indices of different lengths (see Exercise 1.20 or Corollary 1.56 below).

**Example 1.28.** Let \( 2^{(n)} = (2, \ldots, 2) \) denote the admissible multi-index of length \( n \) whose entries are all equal to 2. We compute the value of \( \zeta(2^{(n)}) \) using the method of generating series and Euler’s product expansion for the sine function

(1.29) \[ \frac{\sin \pi x}{\pi x} = \prod_{n \geq 1} \left(1 - \frac{x^2}{n^2}\right). \]
Plugging the definition of $\zeta(2^n)$ into the power series below we get:

$$\sum_{n \geq 0} \zeta(2^n)(-x^2)^n = \sum_{n \geq 0} \sum_{m_1 > \cdots > m_n \geq 1} \left( -\frac{x^2}{m_1^2} \right) \cdots \left( -\frac{x^2}{m_n^2} \right)$$

$$= \prod_{m \geq 1} \left( 1 - \frac{x^2}{m^2} \right)$$

$$= \sum_{n \geq 0} (-1)^n \frac{\pi^{2n}}{(2n + 1)!} x^{2n}.$$

The second equality above comes from the elementary observation that, in the power series expansion of the infinite product, the terms of degree $2n$ correspond bijectively to choices of $n$ integers satisfying $m_1 > m_2 > \cdots > m_n \geq 1$. The third equality is the combination of (1.29) and the power series expansion of the sine function. Now, identification of the coefficients yields

$$\zeta(2^n) = \frac{\pi^{2n}}{(2n + 1)!}.$$

Note the particular case $\zeta(2, 2) = \pi^4/120$ from Example 1.17.

### 1.2.2. The algebra of multiple zeta values.

**Definition 1.31.** We will write $\mathcal{Z}$ for the $\mathbb{Q}$-subvector space of $\mathbb{R}$ generated by all multiple zeta values:

$$\mathcal{Z} = \langle 1, \zeta(2), \zeta(3), \zeta(2, 1), \zeta(4), \ldots \rangle_{\mathbb{Q}}.$$  

Given integers $k, \ell \geq 0$, we also consider the following subvector spaces of $\mathcal{Z}$:

$$\mathcal{Z}_k = \langle \zeta(s) \mid \text{wt}(s) = k \rangle_{\mathbb{Q}},$$

$$F_\ell \mathcal{Z} = \langle \zeta(s) \mid \ell(s) \leq \ell \rangle_{\mathbb{Q}},$$

$$F_\ell \mathcal{Z}_k = \langle \zeta(s) \mid \text{wt}(s) = k, \ell(s) \leq \ell \rangle_{\mathbb{Q}}.$$  

In particular, the equalities $\mathcal{Z}_0 = \mathbb{Q}$ and $\mathcal{Z}_1 = \{0\}$ hold.

**Remark 1.32.** The subspaces $F_\ell \mathcal{Z}$ define an increasing filtration of $\mathcal{Z}$:

$$\mathcal{Q} = F_0 \mathcal{Z} \subseteq F_1 \mathcal{Z} \subseteq F_2 \mathcal{Z} \subseteq \cdots.$$  

There is an obvious inclusion

$$F_\ell \mathcal{Z}_k \subseteq F_\ell \mathcal{Z} \cap \mathcal{Z}_k$$

that is expected to be an equality (Exercise 1.100), but this is not yet known.

The identity (1.16) is the first indication that the $\mathbb{Q}$-vector space $\mathcal{Z}$ has the richer structure of an algebra. Recall that this simply means that $\mathcal{Z}$ is equipped with a bilinear multiplication map $\mathcal{Z} \times \mathcal{Z} \to \mathcal{Z}$.

**Theorem 1.33.** The multiplication of real numbers induces an associative commutative algebra structure on $\mathcal{Z}$ that is compatible with the weight and the length filtration in that there is an inclusion

$$F_{\ell_1} \mathcal{Z}_{k_1} \cdot F_{\ell_2} \mathcal{Z}_{k_2} \subseteq F_{\ell_1 + \ell_2} \mathcal{Z}_{k_1 + k_2}$$

for all non-negative integers $\ell_1, \ell_2, k_1, k_2$.  

The theorem says, in particular, that every product of multiple zeta values can be written as a linear combination of multiple zeta values, hence the following

**Corollary 1.34.** Every polynomial relation between Riemann zeta values \( \zeta(k) \) gives rise to a linear relation between multiple zeta values.

Thus, finding algebraic relations among zeta values amounts to finding linear relations among multiple zeta values; this is a first interpretation of what we meant by “linearizing the transcendence conjecture” in the preface.

1.2.3. **Proof of Theorem 1.33.** The result will directly follow from Lemmas 1.39 and 1.40 below. Before stating them, we need to introduce the notion of **stuffle multiplicities** of multi-indices.

**Construction 1.35.** Given positive multi-indices \( s = (s_1, s_2, \ldots, s_\ell) \), \( s' = (s'_1, s'_2, \ldots, s'_{\ell'}) \), consider the set of all \( 2 \times \ell'' \)-matrices, for integers \( \ell'' \) from \( \max(\ell, \ell') \) to \( \ell + \ell' \), satisfying the following properties:

i) the entries of the first row are the numbers \( s_i \), for \( 1 \leq i \leq \ell \), in this order, plus some interlaced zeros;

ii) the entries of the second row are the numbers \( s'_i \), for \( 1 \leq i \leq \ell' \), in this order, plus some interlaced zeros;

iii) no column has two zeros.

Each such matrix defines a new positive multi-index \( s'' = (s''_1, \ldots, s''_{\ell''}) \) by adding the two entries of each column.

An equivalent construction will be given in Exercise 1.46.

**Example 1.36.** For the multi-indices \( s = (2, 1, 1) \) and \( s' = (2, 3) \), two possible choices of such a matrix are

\[
\begin{pmatrix}
0 & 2 & 1 & 1 \\
2 & 0 & 3 & 0
\end{pmatrix},
\]

from which we get the multi-index \( s'' = (2, 2, 4, 1) \), and

\[
\begin{pmatrix}
2 & 1 & 1 \\
2 & 0 & 3
\end{pmatrix},
\]

which gives \( s'' = (4, 1, 4) \). Observe that the length of \( s'' \) varies.

**Definition 1.37.** Let \( s, s', \) and \( s'' \) be positive multi-indices. The **stuffle multiplicity** \( \text{st}(s, s'; s'') \) is the number of times that the multi-index \( s'' \) appears as an outcome of the previous construction.

By definition, the stuffle multiplicity is a non-negative integer.

**Example 1.38.** In the easy case \( s = (2) \) and \( s' = (2) \), all possible matrices are

\[
\begin{pmatrix}
2 \\
2
\end{pmatrix},
\begin{pmatrix}
2 & 0 \\
0 & 2
\end{pmatrix},
\begin{pmatrix}
2 \\
0
\end{pmatrix}.
\]
from which one gets multi-indices \((4), (2, 2)\) and \((2, 2)\). Hence, in this example the stuffle multiplicity is equal to

\[
\text{st}(s, s'; s'') = \begin{cases} 
1, & \text{if } s'' = (4), \\
2, & \text{if } s'' = (2, 2), \\
0, & \text{otherwise.}
\end{cases}
\]

From conditions i), ii), and iii) in Construction 1.35, we immediately deduce the following properties of the stuffle multiplicity:

**Lemma 1.39.** Let \(s, s'\) and \(s''\) be positive multi-indices satisfying the condition \(\text{st}(s, s'; s'') > 0\). Then the following holds:

i) \(\text{wt}(s'') = \text{wt}(s) + \text{wt}(s')\);

ii) \(\ell(s'') \leq \ell(s) + \ell(s')\);

iii) if \(s\) and \(s'\) are admissible, then so is \(s''\).

The main reason to introduce the stuffle multiplicity is the following result, which together with the previous lemma implies Theorem 1.33.

**Lemma 1.40.** Let \(s = (s_1, s_2, \ldots, s_\ell)\) and \(s' = (s'_1, s'_2, \ldots, s'_{\ell'})\) be admissible multi-indices. The following equality holds:

\[
\zeta(s) \cdot \zeta(s') = \sum_{s''} \text{st}(s, s'; s'') \zeta(s'').
\]

**Proof.** Multiplying the series

\[
\zeta(s) = \sum_{n_1 > \cdots > n_\ell \geq 1} \frac{1}{n_1^{s_1} \cdots n_\ell^{s_\ell}} \quad \text{and} \quad \zeta(s') = \sum_{m_1 > \cdots > m_{\ell'} \geq 1} \frac{1}{m_1^{s'_1} \cdots m_{\ell'}^{s'_{\ell'}}},
\]

one gets

\[
\zeta(s) \zeta(s') = \sum_{n_1 > \cdots > n_\ell \geq 1} \frac{1}{n_1^{s_1} \cdots n_\ell^{s_\ell} m_1^{s'_1} \cdots m_{\ell'}^{s'_{\ell'}}}.
\]

We now decompose the sum (1.41) according to the possible orderings of the terms of the sequence \(n_1, \ldots, n_\ell, m_1, \ldots, m_{\ell'}\). For instance, if \(\ell = \ell' = 1\), we distinguish the three cases \(n_1 > m_1, n_1 = m_1\) and \(n_1 < m_1\), which results in the decomposition

\[
\sum_{n_1 \geq m_1 \geq 1} \frac{1}{n_1^{s_1} m_1^{s'_1}} = \sum_{n_1 > m_1 \geq 1} \frac{1}{n_1^{s_1} m_1^{s'_1}} + \sum_{n_1 \geq m_1 \geq 1} \frac{1}{n_1^{s_1} m_1^{s'_1}} + \sum_{m_1 > n_1 \geq 1} \frac{1}{n_1^{s_1} m_1^{s'_1}},
\]

which was already obtained in formula (1.16). By construction, the number of times that a given sum

\[
\zeta(s'') = \sum_{k_1 > \cdots > k_{\ell''} \geq 1} \frac{1}{k_1^{s'_{k_1}} \cdots k_{\ell''}^{s'_{\ell''}}}
\]

appears in this process is precisely the stuffle multiplicity \(\text{st}(s, s'; s'')\).
Example 1.42. Let \( a, b, c \) be integers satisfying \( a, c \geq 2 \) and \( b \geq 1 \). We decompose the product \( \zeta(a, b) \zeta(c) \) as:

\[
\zeta(a, b) \zeta(c) = \sum_{n_1 > n_2 \geq 1} \frac{1}{n_1^n n_2^m} + \sum_{m=n_1 > n_2 \geq 1} \frac{1}{n_1^{a+m} n_2^n} + \sum_{n_i > m > n_2 \geq 1} \frac{1}{n_1^{a+m} n_2^b} \\
+ \sum_{n_1 > m = n_2 \geq 1} \frac{1}{n_1^a n_2^b} + \sum_{n_1 > n_2 > m \geq 1} \frac{1}{n_1^a n_2^b m^n} = \zeta(a, c, b) + \zeta(a + c, b) + \zeta(a, c, b) + \zeta(a, b + c) + \zeta(a, b, c).
\]

More examples will be presented in the next sections.

Exercise 1.43. It would have been possible, as Euler did in length two (see Figure 1 below), to define multiple zeta values as

\[
\zeta^*(s_1, s_2, \ldots, s_\ell) = \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{1}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}}.
\]

Find the relation between \( \zeta(s_1, s_2, \ldots, s_\ell) \) and \( \zeta^*(s_1, s_2, \ldots, s_\ell) \).

Exercise 1.44. Given an integer \( s \geq 2 \), we let \( s^{(n)} = (s, \ldots, s) \) denote the admissible multi-index of length \( n \) with all entries equal to \( s \).

i) Adapt the argument from Example 1.28 to prove the equality

\[
\sum_{n \geq 0} \zeta(s^{(n)}) x^n = \exp \left( \sum_{k \geq 1} (-1)^{k-1} \zeta(sk) \frac{x^k}{k} \right).
\]

ii) Deduce that \( \zeta(s^{(n)}) \) belongs to the ring \( \mathbb{Q}[\zeta(s), \zeta(2s), \zeta(3s), \ldots] \). More precisely, consider an infinite collection of weighted variables \( (x_k)_{k \geq 1} \), where \( x_k \) is given weight \( sk \). Then, for each \( n \geq 1 \), there exists a polynomial with rational coefficients \( P_n(x_1, \ldots, x_n) \), homogeneous of weight \( sn \), such that the equality

\[
\zeta(s^{(n)}) = P_n(\zeta(s), \zeta(2s), \ldots, \zeta(ns))
\]

holds. Combined with this, Euler’s formula (1.4) implies that, for even \( s \), the multiple zeta value \( \zeta(s^{(n)}) \) is a rational multiple of \( \pi^{ns} \).
iii) Some explicit formulas:

\[
\zeta(4^{[n]}) = \frac{(2\pi)^{4n}}{2^{2n-1}(4n+2)!}, \quad \zeta(6^{[n]}) = \frac{6(2\pi)^{6n}}{(6n+3)!}, \\
\zeta(8^{[n]}) = \frac{(2\pi)^{8n}}{2^{2n-2}(8n+4)!} \left[ (\sqrt{2} + 1)^{4n+2} + (\sqrt{2} - 1)^{4n+2} \right].
\]

Despite its appearance, the last factor is rational since it is invariant under the substitution \(\sqrt{2} \mapsto -\sqrt{2}\).

**Exercise 1.45.** Use the stuffle multiplicities to prove the equality

\[
\zeta(2k+1)\zeta(2^{[n-k]}) = \sum_{i=0}^{n-k} \zeta(2^{[i]}, 2k+1, 2^{[n-k-i]}) \\
+ \sum_{i=0}^{n-k-1} \zeta(2^{[i]}, 2k+3, 2^{[n-k-1-i]})
\]

for all integers \(n, k \geq 1\).

**Exercise 1.46.** Let \(\text{st}(\ell, \ell'; r)\) denote the set of surjective maps

\[\sigma: \{1, 2, \ldots, \ell + \ell'\} \rightarrow \{1, 2, \ldots, \ell + \ell' - r\}\]

satisfying \(\sigma(1) < \sigma(2) < \cdots < \sigma(\ell)\) and \(\sigma(\ell + 1) < \cdots < \sigma(\ell + \ell')\).

i) Determine the cardinality of \(\text{st}(\ell, \ell'; r)\) and show how to get from \(\sigma\) a matrix like the ones in Construction 1.35.

ii) Prove the identity

\[
\sum_{s''} \text{st}(s, s'; s'')\zeta(s'') = \min(\ell, \ell') \sum_{\sigma \in \text{st}(\ell, \ell'; r)} \zeta(s''(\sigma)_1, \ldots, s''(\sigma)_{\ell + \ell' - r}),
\]

where \(\ell = \ell(s), \ell' = \ell(s')\) and \(s''(\sigma)\) is the multi-index with

\[
s''(\sigma)_k =\begin{cases} 
s_i, & \text{if } \sigma^{-1}(k) = \{i\} \text{ for } i \leq \ell, \\
s_j', & \text{if } \sigma^{-1}(k) = \{\ell + j\}, \\
s_i + s_j', & \text{if } \sigma^{-1}(k) = \{i, \ell + j\}.
\end{cases}
\]

(By definition of \(\text{st}(\ell, \ell'; r)\), all possibilities for \(\sigma^{-1}(k)\) are covered.)

1.3. Relations among double zeta values. We now undertake the task of finding linear relations among multiple zeta values by elementary methods. Historically, one of the first techniques consisted of reordering multiple sums by means of a partial fraction decomposition. In what follows, we show how this yields linear relations among double zeta values.

1.3.1. Partial fraction decompositions. For integers \(a, b\) with \(b \geq 0\), we shall use the standard convention for binomial numbers:

\[
\binom{a}{b} = \frac{a(a-1) \cdots (a-b+1)}{b!}.
\]

In particular, \(\binom{0}{0} = 1\) holds for all \(a\) and, if \(b > a \geq 0\), then \(\binom{a}{b} = 0\) holds.
Lemma 1.48. Let \( i, j \geq 1 \) be integers. The following equality of rational functions holds:

\[
\frac{1}{x^iy^j} = \sum_{r=1}^{i+j-1} \left[ \frac{\binom{r-1}{i-1}}{(x+y)^{r+i+j-r}} + \frac{\binom{r-1}{j-1}}{(x+y)^{r+i+j-r}} \right].
\]

Proof. We proceed by induction on \( i \) and \( j \). The proof in the case \( i = j = 1 \) reduces to a simple checking. Assume that (1.49) holds for a given pair \((i, j)\). Differentiating with respect to \( x \), we find that \(1/x^{i+1}y^j\) is equal to

\[
\frac{1}{i} \sum_{r=1}^{i+j-1} \left[ \frac{\binom{r-1}{i-1}}{(x+y)^{r+i+j-r}} + \frac{\binom{r-1}{j-1}}{(x+y)^{r+i+j-r}} \right] =
\]

\[
\frac{1}{i} \sum_{r=2}^{i+j} \left[ \frac{(r-1)\binom{r-2}{i-1}}{(x+y)^{r+i+j-r}} + \frac{(r-1)\binom{r-2}{j-1}}{(x+y)^{r+i+j-r}} \right] + \frac{1}{i} \sum_{r=1}^{i+j-1} \frac{(i+j-r)\binom{r-1}{j-1}}{(x+y)^{r+i+j+1-r}}.
\]

Thanks to the identities

\[
(r-1)\binom{r-2}{i-1} = i\binom{r-1}{i-1} \quad \text{and} \quad (r-1)\binom{r-2}{j-1} = (r-j)\binom{r-1}{j-1},
\]

and taking the convention (1.47) into account, the previous expression becomes

\[
\sum_{r=1}^{i+j} \left[ \frac{\binom{r-1}{i}}{(x+y)^{r+i+j-r}} + \frac{\binom{r-1}{j-1}}{(x+y)^{r+i+j-r}} \right],
\]

which agrees with the right-hand side of (1.49) for \((i, j)\). The induction step from \((i, j)\) to \((i, j+1)\) is completely symmetric. \(\square\)

Corollary 1.50. Let \( p, q \geq 1 \) be integers. For any non-zero complex number \( a \), the following equality of rational functions holds:

\[
\frac{1}{u^p(u-a)^q} = (-1)^q \sum_{k=0}^{p-1} \frac{(q+k-1)}{u^{p-k}a^q+k} + \sum_{k=0}^{q-1} (-1)^k \frac{(p+k-1)}{a^{p+k}(u-a)^{q-k}}.
\]

Proof. Take \( y = u \) and \( x = a - u \) in equation (1.49). To transform the resulting expression into (1.51), observe that the binomial number \(\binom{p-1}{q-1}\) vanishes unless \( q \leq r \leq p+q-1 \), and hence the indexes \( r \) that contribute can be all written as \( r = q+k \) for \( k = 0, \ldots, p-1 \). The same holds for the binomial number \( \binom{r-1}{p-1} \). \(\square\)

1.3.2. Applications. A straightforward consequence of the partial fraction decomposition of Lemma 1.48 is the shuffle relation

\[
\zeta(j)\zeta(k-j) = \sum_{r=2}^{k-1} \left[ \binom{r-1}{j-1} + \binom{r-1}{k-j-1} \right] \zeta(r, k-r)
\]

for any \( k \geq 4 \) and \( 2 \leq j \leq k-2 \). Replacing the product in the left-hand side of (1.52) with the stuffle formula (1.16) we get the linear identity

\[
\zeta(j, k-j) + \zeta(k-j, j) + \zeta(k) = \sum_{r=2}^{k-1} \left[ \binom{r-1}{j-1} + \binom{r-1}{k-j-1} \right] \zeta(r, k-r),
\]

which is called a double shuffle relation. The reason for these names will become apparent in Section 1.5.
A more sophisticated application of partial fraction decompositions gives the following result, essentially what Euler calls “tertia methodus” in [Eul76]. We refer the reader to [Har18] for a nice exposition of his techniques.

**THEOREM 1.54** (Euler, 1776). Given integers \( p \geq 2 \) and \( q \geq 1 \), the following equality holds:

\[
\zeta(p, q) = \sum_{k=0}^{q-2} (-1)^k \binom{p+k-1}{p-1} \zeta(q-k) \zeta(p+k) + (-1)^q \sum_{k=0}^{p-2} \binom{q+k-1}{q-1} \zeta(p-k, q+k) + (-1)^q \binom{p+q-k-2}{2} [\zeta(p+q) + \zeta(p+q-1, 1)].
\]

**Remark 1.55.** The assumptions \( p \geq 2 \) and \( q \geq 1 \) ensure that all the terms in the above formula are convergent series. Euler also allowed the case \( p = 1 \). Then the sum contains divergent terms such as \( \zeta(1) \) or \( \zeta(1, 1) \) that need to be regularized, see [Har18] for a rigorous treatment of Euler’s method.

Making \( q = 1 \) we immediately get:

**COROLLARY 1.56** (Euler’s sum formula). If \( s \geq 3 \), then

\[
\zeta(s) = \sum_{j=1}^{s-2} \zeta(s-j, j).
\]

In particular, the equality \( \zeta(3) = \zeta(2, 1) \) holds.

**Proof of Theorem 1.54.** We borrow the argument from Nielsen’s book, see [Nie65, Chap. III, §18, p. 48]. Recall the equality

\[
\zeta(p, q) = \sum_{n>m \geq 1} \frac{1}{n^p m^q} = \sum_{n \geq 2} \left( \sum_{a=1}^{n-1} \frac{1}{n^p (n-a)^q} \right)
\]

from (1.15). Applying the partial fraction decomposition of Corollary 1.50 to each summand in the right-hand side and separating the terms coming from \( k = p-1 \) and \( k = q-1 \) yields the equality

\[
\sum_{a=1}^{n-1} \frac{1}{n^p (n-a)^q} = (-1)^q \sum_{k=0}^{p-2} \sum_{a=1}^{n-1} \frac{\binom{q+k-1}{q-1}}{np^k a^q+k} + \sum_{k=0}^{q-2} \sum_{a=1}^{n-1} (-1)^k \frac{\binom{p+k-1}{p-1}}{np^k (n-a)^q-k} + (-1)^q \binom{p+q-k-2}{2} \sum_{a=1}^{n-1} \left[ \frac{1}{n^p a^q+1} - \frac{1}{a^p+q-1(n-a)} \right].
\]

The sum over \( n \) of the first two terms in the above expression converges, whereas the sum of each individual summand of the third term diverges. We will show below that the sum over \( n \) of the third term is also convergent.

Using identity (1.58), the sum over \( n \) of the first term can be written as

\[
\sum_{n \geq 2} (-1)^q \sum_{k=0}^{p-2} \sum_{a=1}^{n-1} \frac{\binom{q+k-1}{q-1}}{np^k a^q+k} = (-1)^q \sum_{k=0}^{p-2} \frac{\binom{q+k-1}{q-1}}{q-1} \zeta(p-k, q+k).
\]
We next observe the equality
\[ \zeta(p)\zeta(q) = \sum_{n \geq 2} \sum_{a=1}^{n-1} \frac{1}{(n-a)p^aq^a}, \]
which implies that the sum over \( n \) of the second term is equal to
\[ \sum_{n \geq 2} \sum_{k=0}^{q-2} \frac{(-1)^k (p^k - 1)}{p^{k+1}(n-a)^{q-k}} \sum_{k=0}^{q-2} (-1)^k (p^k - 1) \zeta(q-k)\zeta(p+k). \]

For the last term, we use the identity
\[ \sum_{a=1}^{n-1} \frac{1}{a^{p+q-1}(n-a)} = \sum_{a<n/2}^{a<n/2} \frac{1}{(n-a)a^{p+q-1}} + \sum_{a>n/2}^{a>n/2} \frac{1}{a^{p+q-1}(n-a)} + \begin{cases} \frac{1}{2^{p+q}}, & \text{if } n \text{ is even}, \\ 0, & \text{if } n \text{ is odd}. \end{cases} \]

We note the equalities
\[ \sum_{n \geq 2}^{n \text{ even}} \frac{1}{(n/2)^{p+q}} = \zeta(p+q) \quad \text{and} \quad \sum_{n \geq 2}^{n \text{ odd}} \frac{1}{(n-a)a^{p+q-1}} = \zeta(p+q-1, 1). \]

We finally estimate the remaining term. For \( N \geq 3 \), one has:
\[ \sum_{n=2}^{N} \left( \sum_{a=1}^{n-1} \frac{1}{n(n-a)^{p+q-1}} - \sum_{a=n/2}^{a=n/2} \frac{1}{(n-a)a^{p+q-1}} \right) = \sum_{n=2}^{N} \sum_{a=n/2}^{n/2} \frac{1}{na^{p+q-1}}. \]

Using the assumption \( p + q - 1 \geq 2 \), one sees that the last term converges to zero as \( N \) goes to \( \infty \). The theorem results from summing up all the computations.

**Corollary 1.59 (Nielsen).** For each \( n \geq 2 \), the following equalities hold:
\[ \sum_{r=1}^{n-1} \zeta(2r, 2n-2r) = \frac{3}{4} \zeta(2n), \]
\[ \sum_{r=1}^{n-1} \zeta(2r+1, 2n-2r-1) = \frac{1}{4} \zeta(2n). \]

**Proof.** Following [Nie65, Chap. III, § 19, p. 49], we shall use the identity
\[ \sum_{r=2}^{p-1} \zeta(r)\zeta(p-r+1) = p\zeta(p+1) - 2\zeta(p, 1), \]
which results from the decomposition (1.16) of the product of two zeta values and Euler’s sum formula (1.57). This will be combined with the equality
\[ (2n-2) \left[ \zeta(2n) + \zeta(2n-1, 1) \right] = \sum_{k=0}^{2n-4} (-1)^k \zeta(k+1)\zeta(k+2)\zeta(2n-k-2), \]
which is obtained by applying Theorem 1.54 to \( p = 2 \) and \( q = 2n - 2 \). Note that the term \( \zeta(k + 2)\zeta(2n - k - 2) \) on the right-hand side is invariant under the substitution \( k \mapsto 2n - k - 4 \) and that it appears with multiplicity \((-1)^k(2n - 2)\). Therefore,

\[
2 [\zeta(2n) + \zeta(2n - 1, 1)] = \sum_{k=0}^{2n-4} (-1)^k \zeta(k + 2)\zeta(2n - k - 2)
\]

\[
= \sum_{r=1}^{n-1} \zeta(2r)\zeta(2n - 2r) - \sum_{r=1}^{n-2} \zeta(2r + 1)\zeta(2n - 2r - 1).
\]

(1.61)

Summing and subtracting equations (1.61) and (1.60) for \( p = 2n - 1 \) yields the recursion formulas

\[
\sum_{r=1}^{n-1} \zeta(2r)\zeta(2n - 2r) = \frac{2n + 1}{2} \zeta(2n) \quad (n \geq 2),
\]

\[
\sum_{r=1}^{n-2} \zeta(2r + 1)\zeta(2n - 2r - 1) = \frac{2n - 3}{2} \zeta(2n) - 2\zeta(2n - 1, 1) \quad (n \geq 3).
\]

The statement is proved by replacing the products of zeta values in the left-hand sides with their expression (1.16) as sums of double zeta values. \( \square \)

**Remark 1.62.** The previous corollary was rediscovered by Gangl, Kaneko, and Zagier, see [GKZ06, Thm. 1] and Exercise 1.66.

1.3.3. **Relations in low weight.** We now show how to use the above results to get linear relations among multiple zeta values of low weight.

**Corollary 1.63.** The following relations hold in \( \mathbb{Z} \):

i) in weight 3:

\[
\zeta(3) = \zeta(2, 1).
\]

ii) in weight 4:

\[
\zeta(4) = 4\zeta(3, 1),
\]

\[
\zeta(2, 2) = 3\zeta(3, 1).
\]

iii) in weight 5:

\[
\zeta(5) = -4\zeta(4, 1) + 2\zeta(2, 3),
\]

\[
\zeta(3, 2) = -5\zeta(4, 1) + \zeta(2, 3).
\]

iv) in weight 6:

\[
\zeta(6) = 4\zeta(5, 1) + 4\zeta(3, 3),
\]

\[
\zeta(2, 4) = \frac{13}{3} \zeta(5, 1) + \frac{7}{3} \zeta(3, 3),
\]

\[
\zeta(4, 2) = -\frac{4}{3} \zeta(5, 1) + \frac{2}{3} \zeta(3, 3).
\]

**Proof.** All the relations follow from Theorem 1.54 together with the decomposition (1.16). We have already seen that the equality \( \zeta(3) = \zeta(2, 1) \) is the first instance of Euler’s sum formula.
Let us now derive the two relations in weight 4. On the one hand, Theorem 1.54 applied to \( p = q = 2 \) gives 
\[
\zeta(2)^2 = 2\zeta(4) + 2\zeta(3, 1).
\]
Combining this with the identity \( \zeta(2)^2 = 2\zeta(2, 2) + \zeta(4) \) from Example 1.17, we obtain 
\[
\zeta(4) + 2\zeta(3, 1) = 2\zeta(2, 2).
\]
On the other hand, by Euler’s sum formula, \( \zeta(4) = \zeta(3, 1) + \zeta(2, 2) \), hence the equalities \( \zeta(4) = 4\zeta(3, 1) \) and \( \zeta(2, 2) = 3\zeta(3, 1) \).

The remaining identities are left as an exercise. \( \square \)

1.3.4. An upper bound for the dimension of \( F_2 \mathbb{Z}_k \). Putting all the identities of this section together, one gets upper bounds for the dimension of the \( \mathbb{Q} \)-vector space generated by zeta and double zeta values of a given weight. However, as we will see in the next section, these bounds are not expected to be optimal in general (see Remark 1.96).

**Proposition 1.64.** For each \( k \geq 4 \), the \( \mathbb{Q} \)-vector space spanned by zeta and double zeta values of weight \( k \) satisfies 
\[
\dim_{\mathbb{Q}} F_2 \mathbb{Z}_k \leq \left\lfloor \frac{k - 2}{2} \right\rfloor.
\]

**Proof.** The space \( F_2 \mathbb{Z}_k \) is generated by the \( k - 1 \) elements \( \zeta(k) \) and \( \zeta(j, k-j) \) for \( j = 2, \ldots, k-1 \). Recall from Corollary 1.56 that they satisfy Euler’s sum formula 
\[
\zeta(2, k - 2) + \cdots + \zeta(k - 1, 1) - \zeta(k) = 0,
\]
as well as the double shuffle relations (1.53) 
\[
\zeta(j, k-j) + \zeta(k-j, j) + \zeta(k) = \sum_{r=2}^{k-1} \binom{r-1}{j-1} + \binom{r-1}{k-j-1} \zeta(r, k-r) \quad (j = 2, \ldots, k-2).
\]
Since the latter are invariant under the substitution \( j \mapsto k-j \), it suffices to consider the equations for \( j \leq k-j \), that is \( j \leq \left\lfloor \frac{k}{2} \right\rfloor \).

One gets one equation from Euler’s sum formula and \( \left\lfloor \frac{k}{2} \right\rfloor - 1 \) equations from the double shuffle relations. We claim that these \( \left\lfloor \frac{k}{2} \right\rfloor \) equations are linearly independent. As \( k-1 - \left\lfloor \frac{k}{2} \right\rfloor = \left\lceil \frac{k-2}{2} \right\rceil \), this implies the statement. Indeed, by the convention (1.47), the double shuffle relations take the form 
\[
\sum_{r=j+1}^{k-1} a_r \zeta(r, k-r) - \zeta(k) = 0 \quad (j = 2, \ldots, k-2),
\]
with \( a_r \) positive integers. The matrix of relations is thus upper triangular with non-zero entries in the diagonal, and hence invertible. \( \square \)

***

**Exercise 1.65.** Derive the remaining relations of Corollary 1.63.

**Exercise 1.66 (Gangl-Kaneko-Zagier).** Define the generating function of double zeta values of weight \( k \) as the formal power series 
\[
T_k(X, Y) = \sum_{r+s=k \atop r, s \geq 1} \zeta(r, s) X^{r-1} Y^{s-1}.
\]
i) Use the double shuffle relation (1.53) to prove the functional equation
\[ T_k(X + Y, Y) + T_k(X + Y, X) = T_k(X, Y) + T_k(Y, X) + \zeta(k) \frac{X^{k-1} - Y^{k-1}}{X - Y} \]
for all integers \( k \geq 3 \).

ii) Give an alternative proof of Corollary 1.59 using the above functional equation for \((X, Y) = (1, 0)\) and \((1, -1)\).

1.4. The Zagier and the Broadhurst–Kreimer conjectures. As we saw in the previous section, there are many linear relations between multiple zeta values. To get an intuition of what the structure of the algebra \( \mathcal{Z} \) might be, one can start by performing numerical experiments.

1.4.1. Numerical experiments. The first step is to use clever techniques to accelerate the convergence of the infinite series defining multiple zeta values. With these techniques, one can compute them with very high precision (for instance 800 significant digits) in a reasonable amount of time; see [Bro96, §4] for a description of such techniques, as well as [BBV10] for the state of the art some years ago. Then we can apply lattice algorithms such as the LLL algorithm or, more efficiently, the PSLQ algorithm to find linear relations with integer coefficients among the computed multiple zeta values. At a given precision, we will find many spurious relations (as we are only working with rational approximations), but we can easily distinguish between true relations and spurious ones. The true relations should have small coefficients compared to the inverse of the precision that was used. Moreover, the true relations will survive after doubling the precision, say from 100 to 200 significant digits.

After extensive experimentation by many mathematicians, no non-trivial linear relations among multiple zeta values of different weight have been found: all known relations are homogeneous. Moreover, we can write a table with the “experimental” dimension of each vector space \( \mathcal{Z}_k \). Below, \( k \) is the weight, \( d_k^{\exp} \) is the apparent dimension of \( \mathcal{Z}_k \) given by the experiments and \( 2^{k-2} \) is the number of admissible multi-indices of weight \( k \), that is, the dimension \( \mathcal{Z}_k \) would have had if there were no \( \mathbb{Q} \)-linear relations at all.

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<tr>
<th>( k )</th>
<th>2</th>
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</tr>
<tr>
<td>( d_k^{\exp} )</td>
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<td>2</td>
<td>2</td>
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<td>5</td>
<td>7</td>
<td>9</td>
<td>12</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 1.1. Experimental dimension

Of course, the experiments are not conclusive. There may exist linear relations with “big” coefficients that we have not yet found; then the dimension of \( \mathcal{Z}_k \) would be smaller than \( d_k^{\exp} \). In fact, there is not even a single value of \( k \) for which the dimension of \( \mathcal{Z}_k \) is known to be bigger than 1.

Many of the relations obtained experimentally can be proved theoretically. For instance, Euler’s sum formula (1.57) gives
\[ \zeta(3) = \zeta(2, 1), \]
the expected relation in weight 3. In weight 4, there are four admissible multi-
indices but \( d^4_{\text{exp}} = 1 \); we thus need to find three independent relations. Indeed,
from Corollary 1.63 and Example 1.139 below, we get
\[
\zeta(3, 1) = \frac{1}{4} \zeta(4), \quad \zeta(2, 2) = \frac{3}{4} \zeta(4), \quad \zeta(2, 1, 1) = \zeta(4).
\]

In weight 5, we expect six relations. In fact, by Corollary 1.63 and Exercise 1.145
below, there are linear relations
\[
\zeta(5) = \frac{4}{5} \zeta(3, 2) + \frac{6}{5} \zeta(2, 3), \quad \zeta(4, 1) = -\frac{1}{5} \zeta(3, 2) + \frac{1}{5} \zeta(2, 3),
\]
\[
\zeta(2, 1, 2) = \zeta(2, 3), \quad \zeta(2, 1, 1) = \zeta(2, 1), \quad \zeta(2, 1, 1) = \zeta(3, 1).
\]

However, given the lack of a theoretical proof, it is conceivable that experimen-
tal relations survive up to the number of significant digits that we have used but
fail with higher precision.

1.4.2. Does the weight define a grading? The fact that all known relations be-
tween multiple zeta values are homogeneous led to the following:

**CONJECTURE 1.68.** The subspaces \( \mathcal{Z}_k \subseteq \mathcal{Z} \) are in direct sum:
\[
\mathcal{Z} = \bigoplus_{k \geq 0} \mathcal{Z}_k.
\]

As we already know the inclusion \( \mathcal{Z}_{k_1} \cdot \mathcal{Z}_{k_2} \subseteq \mathcal{Z}_{k_1+k_2} \) from Theorem 1.33, this
conjecture will be reformulated below as the statement that the weight defines a
grading on the \( \mathbb{Q} \)-algebra \( \mathcal{Z} \).

**REMARK 1.69.** Assuming Conjecture 1.68, we immediately deduce that all
multiple zeta values of positive weight are transcendental numbers. Indeed, let \( s \)
be an admissible multi-index of weight \( w > 0 \). If \( \zeta(s) \) were algebraic, it would
satisfy a polynomial equation of the form \( \sum_{k=0}^d a_k \zeta(s)^k = 0 \), where the \( a_k \)
are rational numbers. But then one would have
\[
a_d \zeta(s)^d \in \mathcal{Z}_{wd} \cap \bigoplus_{d' < d} \mathcal{Z}_{wd'},
\]
and hence \( a_d = 0 \) since subspaces of different weights intersect only at 0.

1.4.3. Zagier’s conjecture. The conjectural dimension of the \( \mathbb{Q} \)-vector spaces \( \mathcal{Z}_k \)
is given by a Fibonacci-like sequence of integers, namely the sequence \( \{d_k\}_{k \geq 0} \n\)
recursively defined by the conditions
\[
d_0 = 1, \quad d_1 = 0, \quad d_2 = 1,
\]
\[
d_k = d_{k-2} + d_{k-3}.
\]

These numbers fit together into the generating series
\[
\sum_{k \geq 0} d_k t^k = \frac{1}{1 - t^2 - t^3}.
\]

Indeed, \( 1 - t^2 - t^3 \) is invertible in \( \mathbb{Q}[t] \) and the coefficients \( a_k \) of the inverse power
series must satisfy the relations (1.70) for the equality \( (1 - t^2 - t^3) \sum a_k t^k = 1 \) to
hold; they are thus equal to \( d_k \).
There is an overwhelming amount of numerical evidence for the following conjecture, stated by Zagier in [Zag94, p. 509] “after many discussions with Drinfel’d, Kontsevich and Goncharov”.

**Conjecture 1.71 (Zagier).** The equality \( \dim \mathbb{Q} \mathcal{Z}_k = d_k \) holds.

Hoffman [Hof97, Conj. C, p. 493] proposed a refinement of Zagier’s conjecture, in which not only the dimension of \( \mathcal{Z}_k \) but also a particular \( \mathbb{Q} \)-basis is postulated. This conjecture is based on the observation that the equality
\[
d_k = \# \{ \text{multi-indices of weight } k \text{ with entries } 2 \text{ and } 3 \}
\]
holds because the numbers on the right-hand side also verify conditions (1.70).

**Conjecture 1.73 (Hoffman).** For each integer \( k \geq 2 \), the multiple zeta values \( \zeta(s_1, \ldots, s_\ell) \) of weight \( k \) with \( s_i \in \{2, 3\} \) form a \( \mathbb{Q} \)-basis of \( \mathcal{Z}_k \).

This would imply the following representations of the spaces \( \mathcal{Z}_k \):
\[
\begin{align*}
\mathcal{Z}_2 &= \mathbb{Q} \zeta(2) \\
\mathcal{Z}_3 &= \mathbb{Q} \zeta(3) \\
\mathcal{Z}_4 &= \mathbb{Q} \zeta(2, 2) \\
\mathcal{Z}_5 &= \mathbb{Q} \zeta(2, 3) \oplus \mathbb{Q} \zeta(3, 2) \\
\mathcal{Z}_6 &= \mathbb{Q} \zeta(2, 2, 2) \oplus \mathbb{Q} \zeta(3, 3) \\
\mathcal{Z}_7 &= \mathbb{Q} \zeta(2, 2, 3) \oplus \mathbb{Q} \zeta(2, 3, 2) \oplus \mathbb{Q} \zeta(3, 2, 2)
\end{align*}
\]

**Remark 1.74.**

i) By the relations (1.67), we see that \( \mathcal{Z}_5 \) is generated by \( \zeta(2, 3) \) and \( \zeta(3, 2) \). Thus, the first step towards the conjecture would be to prove that these numbers are \( \mathbb{Q} \)-linearly independent.

ii) Having the right number of elements does not mean finding a basis. For instance, one could have thought that the elements
\[
\zeta(2n_1 + 1, \ldots, 2n_r + 1) \zeta(2)^k,
\]
for \( r \geq 0, k \geq 0, \) and \( n_i \geq 1 \), form a basis of \( \mathcal{Z} \), since their number in a given weight agrees with the conjectural dimension (Exercise 1.102). But Gangl, Kaneko, and Zagier [GKZ06, p. 74] discovered the relation
\[
28\zeta(9, 3) + 150\zeta(7, 5) + 168\zeta(5, 7) = \frac{5197}{691}\zeta(12),
\]
which disproves such an expectation.

**1.4.4. Algebra generators of multiple zeta values.** In the remainder of this section, the word \( \mathbb{Q} \)-algebra (without any further qualifier) is tacitly understood to mean an associative commutative algebra with unit, i.e. a \( \mathbb{Q} \)-vector space \( A \) endowed with a bilinear multiplication \( A \times A \to A \) that is associative, commutative, and has a neutral element 1. A morphism of \( \mathbb{Q} \)-algebras is a linear map \( f : A \to B \) that sends 1 to 1 and preserves multiplication.

**Definition 1.75.** A graded \( \mathbb{Q} \)-algebra is a \( \mathbb{Q} \)-algebra \( A \), together with a direct sum decomposition (called grading)
\[
A = \bigoplus_{k \in \mathbb{Z}} A_k
\]
into \( \mathbb{Q} \)-vector subspaces \( A_k \) satisfying \( A_k \cdot A_{k'} \subseteq A_{k+k'} \). Note that the unit of the algebra then belongs necessarily to \( A_0 \), hence a map \( \eta : \mathbb{Q} \to A_0 \).

A graded \( \mathbb{Q} \)-algebra is said to be \textit{connected} if \( A_k = 0 \) for all \( k < 0 \) and \( \eta \) is an isomorphism. Moreover, \( A \) is said to be \textit{free} if it is isomorphic to a polynomial algebra \( \mathbb{Q}[X_1, \ldots, X_n, \ldots] \) with \( X_i \) homogeneous of some degree; the \( X_i \) are then called \textit{free algebra generators} of \( A \).

**Definition 1.76.** Let \( A = \bigoplus_{k \in \mathbb{Z}} A_k \) be a graded \( \mathbb{Q} \)-algebra such that all \( A_k \) are finite-dimensional. The \textit{Hilbert–Poincaré series} of \( A \) is defined as

\[
H_A(t) = \sum_{k \in \mathbb{Z}} \dim \mathbb{Q}(A_k) t^k.
\]

If \( A \) is connected, then its Hilbert–Poincaré series has only positive degrees and the constant coefficient is equal to 1.

**Lemma 1.77.** Let \( A \) be a connected graded free \( \mathbb{Q} \)-algebra such that all \( A_k \) are finite-dimensional, and let \( D_k \) denote the number of free algebra generators in degree \( k \). Then the Hilbert–Poincaré series of \( A \) is equal to

\[
H_A(t) = \prod_{k \geq 1} (1 - t^k)^{-D_k}.
\]

**Proof.** Let \( X_{1,1}, \ldots, X_{1,D_1}, \ldots, X_{\ell,1}, \ldots, X_{\ell,D_\ell}, \ldots \) be a set of homogeneous free algebra generators of \( A \), with \( X_{i,j} \) of degree \( i \geq 1 \). It suffices to observe that the coefficient of \( t^k \) in the power series expansion of the product (1.78) agrees with the number of monomials of degree \( k \) in the variables \( X_{i,j} \), and hence with the dimension of \( A_k \) since we are dealing with a free algebra. \( \square \)

We now explain how to compute the number of algebra generators in terms of the logarithm of the Hilbert–Poincaré series. Let us keep the assumptions on \( A \) from Lemma 1.77, and write

\[
\log H_A(t) = \sum_{n \geq 1} c_n t^n.
\]

Recall that the Möbius function \( \mu \) takes the value 1 (resp. \(-1\)) on square-free integers with an even (resp. odd) number of prime factors, and 0 on non-square-free integers. In particular, \( \mu(1) = 1 \). The \textit{Möbius inversion formula} is the statement that, if two sequences of complex numbers \((a_n)_{n \geq 1}\) and \((b_n)_{n \geq 1}\) are related by the equality \( a_n = \sum_{d|n} b_d \) for all \( n \geq 1 \), then

\[
b_n = \sum_{d|n} \mu(d) a_{n/d}.
\]

**Lemma 1.80.** Let \( A \) be as in Lemma 1.77, let \( D_k \) denote the number of free algebra generators in degree \( k \) and let \( c_n \) be the coefficient of \( t^n \) in \( \log H_A(t) \) as in (1.79). Then the following equality holds:

\[
D_k = \sum_{d|k} \frac{\mu(d)}{d} c_{k/d}.
\]
Proof. Taking the logarithm of the identity (1.78) and using the formal power series expansion
\[ -\log(1 - x) = \sum_{n \geq 1} \frac{x^n}{n}, \]
one gets
\[ \log H_A(t) = -\sum_{k \geq 1} D_k \log(1 - t^k) = \sum_{k \geq 1} D_k \sum_{d \geq 1} \frac{t^{kd}}{d} = \sum_{n \geq 1} \left( \sum_{d \mid n} \frac{D_{n/d}}{d} \right) t^n. \]
Comparison of coefficients then yields
\[ c_n = \sum_{d \mid n} \frac{D_{n/d}}{d} = \frac{1}{n} \sum_{d \mid n} dD_d, \]
and the equality (1.81) follows from the Möbius inversion formula applied to the sequences \( a_n = nc_n \) and \( b_n = nD_n \). \( \square \)

Let us specialize the above discussion to the algebra \( \mathbb{Z} \) of multiple zeta values. According to Zagier’s conjecture, its Hilbert–Poincaré series is given by
\[ H_{\mathbb{Z}}(t) = \frac{1}{1 - t^2 - t^3}. \]

Conjecture 1.82. \( \mathbb{Z} \) is a connected graded free \( \mathbb{Q} \)-algebra.

Assuming this and Zagier’s conjecture, we would like to compute the number \( D_k \) of free algebra generators in weight \( k \). For this, we define a sequence of integers \( (P_d)_{d \geq 1} \) by the equality
\[ \sum_{d \geq 1} P_d t^d = \sum_{d \geq 1} dc_d t^d = \frac{d}{dt} \log H_{\mathbb{Z}}(t) = \frac{2t^2 + 3t^3}{1 - t^2 - t^3}. \]
Equivalently, it is the sequence uniquely determined by the conditions
\[ P_1 = 0, \ P_2 = 2, \ P_3 = 3, \ P_d = P_{d-2} + P_{d-3} \text{ for all } d \geq 4. \]
Therefore, Lemma 1.80 gives
\[ D_k = \frac{1}{k} \sum_{d \mid k} \mu(k/d)P_d. \]
The first values of \( P_k \) and \( D_k \) are given in Table 1.2 below.

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<thead>
<tr>
<th>( k )</th>
<th>1</th>
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<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
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</thead>
<tbody>
<tr>
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<td>3</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>10</td>
<td>12</td>
<td>17</td>
<td>22</td>
<td>29</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>( D_k )</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.2. Conjectural values of \( D_k \) for the algebra \( \mathbb{Z} \)

Recall that Hoffman’s conjecture 1.73 predicts that the set of multiple zeta values \( \zeta(s_1, \ldots, s_\ell) \) with all \( s_i \) equal to 2 and 3 is a graded \( \mathbb{Q} \)-basis of \( \mathbb{Z} \). It is then only natural to try to extract from these elements a set of algebra generators; this is done through the theory of Lyndon words.

Definition 1.83. Let \( X \) be the alphabet \( \{a, b\} \) and \( X^* \) the set of words in \( X \). We endow \( X^* \) with the lexicographic order for which \( a < b \). A Lyndon word is a non-empty word \( w \in X^* \) such that, for each non-trivial decomposition \( w = uv \), the inequality \( w < v \) holds.
For example, \(ab\) is a Lyndon word because \(ab < b\), but none of the words \(aa, ba, bb\) is Lyndon.

Every word in the alphabet \(\{2, 3\}\) can be seen as an admissible multi-index with entries \(s_i \in \{2, 3\}\), and hence defines a multiple zeta value.

**Conjecture 1.84.** The free \(\mathbb{Q}\)-algebra generated by Lyndon words on the alphabet \(\{2, 3\}\) with the order \(2 < 3\) is isomorphic to \(\mathbb{Z}\). The isomorphism is given by sending a Lyndon word to the corresponding multiple zeta value.

Assuming that the conjecture holds, the algebra generators in weights up to 13 are listed in Table 1.3 below.

<table>
<thead>
<tr>
<th>weight</th>
<th>generators</th>
<th>weight</th>
<th>generators</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>(\zeta(2))</td>
<td>8</td>
<td>(\zeta(2, 3, 3))</td>
</tr>
<tr>
<td>3</td>
<td>(\zeta(3))</td>
<td>9</td>
<td>(\zeta(2, 2, 2, 3))</td>
</tr>
<tr>
<td>4</td>
<td>(\emptyset)</td>
<td>10</td>
<td>(\zeta(2, 2, 3, 3))</td>
</tr>
<tr>
<td>5</td>
<td>(\zeta(2, 3))</td>
<td>11</td>
<td>(\zeta(2, 2, 2, 3, 3), \zeta(2, 3, 3, 3))</td>
</tr>
<tr>
<td>6</td>
<td>(\emptyset)</td>
<td>12</td>
<td>(\zeta(2, 2, 2, 3, 3), \zeta(2, 2, 3, 2, 2, 3))</td>
</tr>
<tr>
<td>7</td>
<td>(\zeta(2, 2, 3))</td>
<td>13</td>
<td>(\zeta(2, 2, 2, 2, 3, 3), \zeta(2, 3, 2, 2, 3, 3)), (\zeta(2, 3, 2, 3, 3))</td>
</tr>
</tbody>
</table>

**Table 1.3.** First Lyndon words on the alphabet \(\{2, 3\}\)

For example, the other conjectural basis element in weight 5 can be written as

\[\zeta(3, 2) = \frac{5}{9} \zeta(2) \zeta(3) - \frac{11}{9} \zeta(2, 3)\]

See Exercise 1.103 for weight 6.

**1.4.5. The Broadhurst–Kreimer conjecture.** So far, we have only taken the weight of multiple zeta values into account. A difficulty to add the length to the picture is that it is only expected to induce a filtration and not a grading, as it is already evident from the existence of relations among multiple zeta values associated with multi-indices of different length such as \(\zeta(3) = \zeta(2, 1)\).

**Definition 1.85.**

i) A **filtration** on a \(\mathbb{Q}\)-algebra \(A\) is an increasing sequence of vector subspaces

\[\cdots \subseteq F_{\ell-1} A \subseteq F_\ell A \subseteq F_{\ell+1} A \subseteq \cdots\]

indexed by \(\ell \in \mathbb{Z}\) and satisfying

\[F_\ell A \cdot F_\ell A \subseteq F_{\ell+\ell} A.\]

We say that the filtration is **separated** if \(\bigcap_\ell F_\ell A = 0\), and **exhaustive** if \(\bigcup_\ell F_\ell A = A\). A **filtered** \(\mathbb{Q}\)-algebra is a \(\mathbb{Q}\)-algebra endowed with a filtration.

ii) The **graded algebra** associated with a filtered algebra \((A, F_\bullet)\) is defined as

\[\text{Gr}^F A = \bigoplus_{\ell \in \mathbb{Z}} F_\ell A / F_{\ell-1} A.\]

Note that the compatibility of the product and the filtration guarantees that \(\text{Gr}^F A\) has indeed an induced graded algebra structure.
iii) A filtered graded $\mathbb{Q}$-algebra is a $\mathbb{Q}$-algebra $A$ with a filtration $F^\bullet A$ and a grading $A = \bigoplus_{k \in \mathbb{Z}} A_k$ which are compatible in the sense that

$$F_\ell A = \bigoplus_{k \in \mathbb{Z}} F_\ell A_k.$$

Given such an algebra, we set

$$A_{k,\ell} = \text{Gr}^F_{\ell} A_k = F_\ell A_k / F_{\ell-1} A_k$$

and form the associated bigraded algebra $\bigoplus_{k,\ell \in \mathbb{Z}} A_{k,\ell}$.

Remark 1.86. Let $A$ be a $\mathbb{Q}$-algebra endowed with an exhaustive filtration $F^\bullet$ satisfying $F_{-1} = \{0\}$. If $\text{Gr}^F A$ is a free graded algebra, then $A$ is a free algebra. Indeed, let $X_i$ be homogeneous free algebra generators of $\text{Gr}^F A$, and pick liftings $Y_i$ of $X_i$ lying in the step of the filtration corresponding to the degree of $X_i$. The free algebra $\mathbb{Q}[Y_i]$ is then endowed with the filtration corresponding to the degree and the natural map $\mathbb{Q}[Y_i] \to A$ is a morphism of algebras compatible with the filtrations. It induces an isomorphism on $F_{-1}$ since both $F_{-1} \mathbb{Q}[Y_i]$ and $F_{-1} A$ vanish. Assume that $F_{-1} \mathbb{Q}[Y_i] \to F_{-1} A$ is an isomorphism. Then the leftmost and rightmost arrows in the commutative diagram

$$
\begin{array}{cccccc}
0 & \longrightarrow & F_{\ell-1} \mathbb{Q}[Y_i] & \longrightarrow & F_\ell \mathbb{Q}[Y_i] & \longrightarrow & \text{Gr}^F_\ell \mathbb{Q}[Y_i] & \longrightarrow & 0 \\
& & \downarrow & & \downarrow & & \downarrow & & \\
0 & \longrightarrow & F_{\ell-1} A & \longrightarrow & F_\ell A & \longrightarrow & \text{Gr}^F_\ell A & \longrightarrow & 0
\end{array}
$$

are isomorphisms, and hence so is $F_\ell \mathbb{Q}[Y_i] \to \text{Gr}^F_\ell A$ by an elementary diagram chase. Since the filtration is exhaustive, $A$ isomorphic to the free algebra $\mathbb{Q}[Y_i]$.

Returning to the algebra of multiple zeta values, we see that the length defines a separated and exhaustive filtration

$$F_\ell \mathcal{Z} = \langle \zeta(s) \mid \ell(s) \leq \ell \rangle_\mathbb{Q}.$$

Assuming Conjecture 1.68, $\mathcal{Z}$ is hence a filtered graded algebra and

$$\mathcal{Z}_{k,\ell} = F_\ell \mathcal{Z}_k / F_{\ell-1} \mathcal{Z}_k$$

is the space of multiple zeta values of weight $k$ and length $\ell$ that cannot be written as linear combinations of multiple zeta values of smaller length.

The associated bigraded algebra is not free, since the relation $\zeta(2) \cdot \zeta(2) = \frac{5}{2} \zeta(4)$ implies that $\zeta(2)^2$ vanishes in $\mathcal{Z}_{4,2}$. To remedy this, we consider the quotient by the ideal generated by $\zeta(2)$:

$$\mathcal{Z}^\circ = \mathcal{Z} / \zeta(2) \cdot \mathcal{Z}.$$

It is a graded filtered algebra as well. Moreover, we equip $\mathbb{Q}[\zeta(2)]$ with the filtration

$$F_0 = \mathbb{Q} \subset F_1 = \mathbb{Q}[\zeta(2)],$$

and the grading that gives $\zeta(2)$ weight 2.

The following is a refinement of Conjecture 1.82.

Conjecture 1.87.

i) $\text{Gr}^F \mathcal{Z}^\circ$ is a free bigraded algebra.

ii) There is an isomorphism of filtered graded algebras $\mathcal{Z}^\circ \otimes_\mathbb{Q} \mathbb{Q}[\zeta(2)] \to \mathcal{Z}$. 
Definition 1.76 and Lemmas 1.77 and 1.80 extend to bigraded algebras. In particular, if \( A = \bigoplus_{k,\ell} A_{k,\ell} \) is a connected free bigraded algebra, then

\[
H_A(x, y) = \sum_{k,\ell \geq 0} (\dim_Q A_{k,\ell}) x^k y^\ell = \prod_{k,\ell \geq 1} (1 - x^k y^\ell)^{-D_{k,\ell}},
\]

where \( D_{k,\ell} \) is the number of free algebra generators in bidegree \((k, \ell)\).

Extensive numerical experiments support the following refinement of Zagier’s conjecture, due to Broadhurst and Kreimer [BK97, §2]:

**Conjecture 1.88 (Broadhurst–Kreimer).** Define integers \((D_{k,\ell})_{k \geq 3, \ell \geq 1}\) by the product expansion formula

\[
\prod_{k \geq 1} \prod_{\ell \geq 1} (1 - x^k y^\ell)^{-D_{k,\ell}} = \frac{1}{1 - O(x)y + S(x)y^2 - S(x)y^4},
\]

where \(O(x)\) and \(S(x)\) are the formal power series

\[
O(x) = \frac{x^3}{1 - x^2} = x^3 + x^5 + x^7 + x^9 + \cdots,
\]

\[
S(x) = \frac{x^{12}}{(1 - x^4)(1 - x^6)} = x^{12} + x^{16} + x^{18} + x^{20} + x^{22} + 2x^{24} + \cdots.
\]

Then \(D_{k,\ell}\) agrees with the number of free algebra generators of \(Gr^F Z^0\) of weight \(k\) and length \(\ell\).

For shorthand, write \(BK^0(x, y)\) for the power series expansion of

\[
\frac{1}{1 - O(x)y + S(x)y^2 - S(x)y^4}.
\]

Arguing as in Lemma 1.80, the numbers \(D_{k,\ell}\) are given by the formula

\[
D_{k,\ell} = \sum_{d \mid (k,\ell)} \frac{\mu(d)}{d} \cdot \text{coefficient of } x^{k} y^{\ell} \text{ in } \log BK^0(x, y),
\]

where \((k,\ell)\) denotes the greatest common divisor of \(k\) and \(\ell\).

Taking Conjecture 1.87 for granted, the multiplicative formula (1.89) becomes equivalent to the following additive version, which is the one that is usually found in the literature:

**Conjecture 1.91 (Broadhurst–Kreimer).** Let \((d_{k,\ell})_{k,\ell \geq 0}\) be the sequence of non-negative integers defined by the generating series

\[
\sum_{k,\ell \geq 0} d_{k,\ell} x^k y^\ell = \frac{1 + E(x)y}{1 - O(x)y + S(x)y^2 - S(x)y^4},
\]

where

\[
E(x) = \frac{x^2}{1 - x^2} = x^2 + x^4 + x^6 + x^8 + \cdots.
\]

Then \(d_{k,\ell}\) agrees with the dimension of the space of multiple zeta values of (precisely) weight \(k\) and length \(\ell\), that is

\[
d_{k,\ell} = \dim_Q Z_{k,\ell}.
\]
Remark 1.92. The power series $E(x)$ "counts" even zeta values, while $O(x)$ counts odd zeta values. More interestingly, Zagier realized that $S(x)$ agrees with the generating series

$$S(x) = \sum_{k \geq 1} (\dim Q S_k) x^k,$$

where $S_k$ stands for the vector space of cusp modular forms of weight $k$ for the full modular group $SL_2(\mathbb{Z})$. It is a classical result that

$$\dim Q S_k = \begin{cases} \left\lfloor \frac{k}{12} \right\rfloor, & \text{if } k \text{ is even and } k \not\equiv 2 \pmod{12}, \\ \left\lfloor \frac{k}{12} \right\rfloor - 1, & \text{if } k \equiv 2 \pmod{12}, \\ 0, & \text{otherwise.} \end{cases}$$

(see e.g. §1.3 and §2.1 of [Zag08] for an elementary proof).

Let us denote by $BK(x, y)$ the power series expansion of

$$1 + E(x) y + O(x) y^2 - S(x) y^4.$$

Expanding the fraction as a geometric series and collecting the terms with lower powers of $y$, we obtain

$$BK(x, y) = 1 + [E(x) + O(x)] y + [(E(x) + O(x)) O(x) - S(x)] y^2 + [(O(x)^2 - 2 S(x)) O(x) + (O(x)^2 - S(x)) E(x)] y^3 + \cdots.$$

Remark 1.93. Observe that $d_{k,1} = 1$ for all $k \geq 2$. Since $F_0 \mathbb{Z} = \mathbb{Q}$, the Broadhurst–Kreimer conjecture holds in this case if and only if $\zeta(k)$ is irrational, which is only known for even $k$ and $k = 3$.

The first values of $d_{k,2}$ and $d_{k,3}$ are given in Table 1.4.

<table>
<thead>
<tr>
<th>$k$</th>
<th>1</th>
<th>2</th>
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<th>4</th>
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<td>4</td>
<td>5</td>
<td>5</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>$d_{k,3}$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>6</td>
<td>9</td>
<td>8</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 1.4. First values of $d_{k,2}$ and $d_{k,3}$

Similarly, we derive

$$\log BK^0(x, y) = - \log(1 - O(x) y + S(x) y^2 - S(x) y^4)$$

$$= O(x) y + \left( \frac{1}{2} O(x)^2 - S(x) \right) y^2 + \left( \frac{1}{3} O(x)^3 - O(x) S(x) \right) y^3 + \cdots.$$

Remark 1.94. Note that $D_{k,\ell} = 0$ if $k$ and $\ell$ have different parity. Indeed, in this case the integers $d$ contributing to formula (1.90) are all odd, so $k/d$ and $\ell/d$ have again different parity. However, it is clear from the above expression for the series $\log BK^0(x, y)$ that only monomials in which the degree of $x$ and the degree of $y$ have the same parity appear.

Lemma 1.95.

i) If $k$ is even, then $D_{k,2} = \left\lfloor \frac{k-2}{6} \right\rfloor$.

ii) If $k$ is odd, then $D_{k,3} = \left\lfloor \frac{(k-3)^2 - 1}{48} \right\rfloor$. 
Proof. Specializing (1.90) to the case $\ell = 2$, we get

$$D_{k,2} = \text{coeff. of } x^k y^2 - \frac{1}{2} \text{ coeff. of } x^\frac{3}{2} y \text{ in } \log BK^0(x, y)$$

$$= \text{coeff. of } x^k \text{ in } \left( \frac{1}{2} O(x)^2 - S(x) \right) - \frac{1}{2} \text{ coeff. of } x^\frac{3}{2} \text{ in } O(x).$$

Taking the equality $O(x)^2 = \sum_{k \geq 6} \frac{k-4}{2} x^k$ into account, we find the formula

$$D_{k,2} = \begin{cases} \frac{k-4}{4} - \left\lfloor \frac{k}{12} \right\rfloor, & \text{if } k \equiv 0 \mod 4, \\ \frac{k-6}{4} - \left\lfloor \frac{k}{12} \right\rfloor, & \text{if } k \equiv 2 \mod 4 \text{ and } k \neq 2 \mod 12, \\ \frac{k-2}{4} - \left\lfloor \frac{k}{12} \right\rfloor, & \text{if } k \equiv 2 \mod 12. \end{cases}$$

It is then a simple matter to check that this quantity agrees with $\left\lfloor \frac{k-2}{6} \right\rfloor$. The proof of the second assertion follows the same pattern (Exercise 1.106). $\square$

Remark 1.96.

i) The numbers $D_{k,2}$ and $D_{k,3}$ are known to be upper bounds for the number of generators of length 2 and 3. It is proved in [Zag93, §3] for $\ell = 2$ and in [Gon98, Thm. 1.5] for $\ell = 3$. From this we get the inequality

$$\dim_{\mathbb{Q}} (F_\ell \mathbb{Z}_k / F_{\ell-1} \mathbb{Z}_k) \leq d_{k,\ell}$$

in lengths $\ell = 1, 2, 3$.

ii) In particular, for double zeta values we get

$$\dim_{\mathbb{Q}} F_2 \mathbb{Z}_k - 1 \leq d_{k,2}.$$

By contrast, Proposition 1.64 yields the upper bound

$$\dim_{\mathbb{Q}} F_2 \mathbb{Z}_k - 1 \leq \left\lfloor \frac{k-4}{2} \right\rfloor.$$

The right-hand side of this last inequality agrees with the coefficient of degree $k$ of the power series $(E(x) + O(x))O(x)$, while $d_{k,2}$ is, by definition, the coefficient of degree $k$ in $(E(x) + O(x))O(x) - S(x)$. Therefore, the bound of Proposition 1.64 is not optimal for those integers $k$ such that there exists a non-zero cusp form of weight $k$.

iii) Brown reformulated the Broadhurst–Kreimer conjecture in terms of the homology of a certain Lie algebra [Bro21].

1.4.6. Known results. Not much is known about these conjectures, especially the one by Broadhurst and Kreimer. The goal of these notes is to explain in detail the following two results towards Zagier’s and Hoffman’s conjectures. In spite of their elementary formulation, this will carry us far away since the only known proofs are based on the theory of motives.

Theorem 1.97 (Terasoma [Ter02], Deligne–Goncharov [DG05]). The number $d_k$ is an upper bound for the dimension of the $\mathbb{Q}$-vector space of multiple zeta values of weight $k$, that is

$$\dim_{\mathbb{Q}} \mathbb{Z}_k \leq d_k.$$

Theorem 1.98 (Brown, [Bro12]). Every multiple zeta value can be written as a $\mathbb{Q}$-linear combination of $\zeta(s_1, \ldots, s_l)$ with $s_i \in \{2, 3\}$. 


Remark 1.99. As we will see at the very end of the text (Section 5.5.1), a corollary of these two theorems is that Zagier’s conjecture implies the algebraic independence of odd zeta values (Conjecture 1.12).

⋆ ⋆ ⋆

Exercise 1.100. Prove that, if the weight defines a grading on the algebra of multiple zeta values (Conjecture 1.68), then the inclusion

\[ F_\ell Z_k \subseteq F_\ell Z \cap Z_k \]

from Remark 1.32 is an equality.

Exercise 1.101. Prove that the sequence \((d_k)_{k \geq 0}\) satisfies

\[
\lim_{k \to \infty} (d_k - \kappa r^k) = 0
\]

where \(\kappa = \frac{r+1}{2r+3}\) and \(r\) is the real root of \(x^3 - x - 1\).

Exercise 1.102. Let \(\delta_k\) denote the number of ordered sequences of integers \((s, n_1, \ldots, n_r)\) such that \(r \geq 0, s \geq 0, n_i \geq 1,\) and

\[ k = 2s + 2n_1 + 1 + \cdots + 2n_r + 1. \]

Show that \(\delta_0 = 1, \delta_1 = 0, \delta_2 = 1\) and \(\delta_k = \delta_{k-2} + \delta_{k-3}\) for all \(k \geq 3.\) Therefore, the equality \(\delta_k = d_k\) holds.

Exercise 1.103. Express the conjectural basis elements \(\zeta(2,2,2)\) and \(\zeta(3,3)\) of \(Z_6\) as polynomial expressions in \(\zeta(2), \zeta(3), \zeta(2,3)\).

Exercise 1.104. Assume that the numbers \(\zeta(2), \zeta(3), \zeta(5), \ldots\) are algebraically independent, so that \(\mathbb{Q}[\zeta(2), \zeta(3), \ldots] \) is a free graded algebra. Apply Lemma 1.80 to compute the dimensions of the graded pieces, and compare them to the conjectural dimensions of multiple zeta values. Then find an example of a multiple zeta value which is not expected to be in the algebra generated by Riemann zeta values.

Exercise 1.105. Show that either Hoffman’s or the Broadhurst–Kreimer conjecture implies Zagier’s conjecture.

Exercise 1.106. Prove the equality \(D_{k,3} = \lfloor (k-3)^2/48 \rfloor \).

Exercise 1.107. Let \(A = \bigoplus A_k\) be a connected graded free \(\mathbb{Q}\)-algebra with finite-dimensional graded pieces and \(I = \bigoplus_{k>0} A_k\). Prove that the number of free algebra generators in degree \(k\) of \(A\) is the dimension of the \(k\)-th graded piece of the quotient \(I/I^2\).

Exercise 1.108. Consider the \(\mathbb{Q}\)-algebra of formal power series \(A = \mathbb{Q}[\ell]\) endowed with the exhaustive filtration given by

\[
F_\ell A = t^{-\ell} \mathbb{Q}[\ell] \quad \text{for } \ell \leq 0 \quad \text{and} \quad F_\ell A = A \quad \text{for } \ell \geq 0.
\]

Prove that the associated graded algebra \(\text{Gr}_F A\) is free, but that \(A\) is not. This shows that the assumption \(F_{-1} A\) from Remark 1.86 is necessary.
1.5. Integral representation of multiple zeta values. We defined multiple zeta values as sums of infinite series. Using this representation, we proved that the product of two multiple zeta values is a linear combination of multiple zeta values with coefficients given by the stuffle multiplicities. We also derived some linear relations among multiple zeta values by means of partial fraction decompositions. Kontsevich found a different representation in terms of integrals. This way of writing multiple zeta values is central to the theory. From a combinatorial point of view, it yields the shuffle product, a new structure from which many other linear relations are obtained in a systematic way. More importantly, from a conceptual point of view, the integral representation shows that multiple zeta values are periods of algebraic varieties and allow us to use algebro-geometric tools to study them.

1.5.1. Two examples.

Example 1.109. The following identity holds:

\[
\zeta(2) = \int_{1 \geq t_1, t_2 \geq 0} \frac{dt_1}{t_1} \frac{dt_2}{1 - t_2} = \int_0^1 \left( \frac{1}{t_1} \frac{dt_2}{1 - t_2} \right) dt_1.
\]

Indeed, from the geometric series expansion

\[
\frac{1}{1 - t_2} = \sum_{n \geq 1} t_2^{n-1},
\]

valid for \(0 \leq t_2 < 1\), we get the equality

\[
\int_0^{t_1} \frac{dt_2}{1 - t_2} = \sum_{n \geq 1} \int_0^{t_1} t_2^{n-1} dt_2 = \sum_{n \geq 1} \frac{t_1^n}{n}.
\]

Plugging it into the integrand gives

\[
\int_0^1 \left( \frac{1}{t_1} \frac{dt_2}{1 - t_2} \right) dt_1 = \int_0^1 \sum_{n \geq 1} \frac{t_1^n}{n} \frac{dt_1}{t_1} = \sum_{n \geq 1} \frac{1}{n} \int_0^1 t_1^{n-1} dt_1 = \sum_{n \geq 1} \frac{1}{n^2}.
\]

Example 1.111. The identity

\[
\zeta(2, 1) = \int_{1 \geq t_1, t_2, t_3 \geq 0} \frac{dt_1}{t_1} \frac{dt_2}{1 - t_2} \frac{dt_3}{1 - t_3}
\]

holds. Indeed, this follows from the transformations

\[
\int_{1 \geq t_1, t_2, t_3 \geq 0} \frac{dt_1}{t_1} \frac{dt_2}{1 - t_2} \frac{dt_3}{1 - t_3} = \int_{1 \geq t_1, t_2 \geq 0} \frac{1}{t_1} \sum_{n \geq 1} \frac{t_1^n}{n} \frac{dt_1}{1 - t_2} \frac{dt_2}{1 - t_3}
\]

\[
= \int_{1 \geq t_1, t_2 \geq 0} \frac{1}{t_1} \sum_{n, m \geq 1} \frac{t_1^{n+m}}{n} dt_1 dt_2
\]

\[
= \int_{1 \geq t_1 \geq 0} \sum_{n, m \geq 1} \frac{t_1^{n+m}}{(n+m)n} dt_1
\]

\[
= \sum_{n, m \geq 1} \frac{1}{(n+m)^2 n} = \zeta(2, 1).
\]
Solve Exercise 1.140 to convince yourself that the exchange of the order of integration and summation is justified in these two examples.

**Remark 1.112.** As we will see in Section 3.8, the above integrals are instances of the notion of *iterated* integral, but for the moment we will think of them just as ordinary integrals over a simplex.

1.5.2. *The integral representation.* A piece of notation is needed to describe the general integral representation of multiple zeta values.

**Notation 1.113.** Given a real number $0 \leq t \leq 1$, we define

$$\Delta^p(t) = \{(t_1, \ldots, t_p) \in \mathbb{R}^p | t \geq t_1 \geq t_2 \geq \cdots \geq t_p \geq 0\}.$$  

Note that $\Delta^0(t)$ is a singleton for all $t$. We endow $\Delta^p(t)$ with the standard orientation given by the order of the variables. We will simply write $\Delta^p = \Delta^p(1)$ for $t = 1$.

Furthermore, consider the measures

$$\omega_0(t) = \frac{dt}{t}, \quad \omega_1(t) = \frac{dt}{1-t}.$$  

on the open interval $(0, 1)$.

If $s = (s_1, \ldots, s_l) \in \mathbb{Z}^l$ is a positive multi-index (recall that this means $s_i \geq 1$ for all $i$), we write $r_i = s_1 + \cdots + s_i$ for each $i = 1, \ldots, l$. In particular, $r_1 = s_1$ and $r_l$ is the weight of $s$. For convenience, we also set $r_0 = 0$. Let $\omega_s$ be the measure on the interior of the simplex $\Delta^{wt(s)}$ given by

$$(1.114) \quad \omega_s = \prod_{i=1}^l \omega_0(t_{r_{i-1}+1}) \cdots \omega_0(t_{r_i-1}) \omega_1(t_{r_i}).$$

For example, one has:

$$\omega_{(2)} = \frac{dt_1 \ dt_2}{t_1 \ (1-t_2)}, \quad \omega_{(2,2)} = \frac{dt_1 \ dt_2 \ dt_3 \ dt_4}{t_1 \ (1-t_2 \ t_3 \ (1-t_4))},$$  

$$\omega_{(2,1)} = \frac{dt_1 \ dt_2 \ dt_3}{t_1 \ (1-t_2 \ (1-t_3))}, \quad \omega_{(1,3)} = \frac{dt_1 \ dt_2 \ dt_3 \ dt_4}{1-t_1 \ t_2 \ t_3 \ (1-t_4)}.$$  

The following result is attributed to Kontsevich:

**Theorem 1.115.** *Let $s = (s_1, \ldots, s_l)$ be an admissible multi-index. The multiple zeta value $\zeta(s)$ is equal to the value of the absolutely convergent integral*

$$(1.116) \quad \zeta(s) = \zeta(s_1, \ldots, s_l) = \int_{\Delta^{wt(s)}} \omega_s.$$  

In order to easily prove this theorem, we introduce the polylogarithm functions, which will also be of use later in Chapter 3.

**Definition 1.117.** Let $s = (s_1, \ldots, s_l)$ be a positive multi-index and $t$ a complex number with $|t| < 1$. We define

$$\operatorname{Li}_s(t) = \sum_{n_1 > n_2 > \cdots > n_l \geq 1} \frac{t^{n_1}}{n_1^{s_1} n_2^{s_2} \cdots n_l^{s_l}}.$$
We call \( \text{Li}_s \) the (multiple) polylogarithm function (of one variable).

**Remark 1.118.** Similarly, one can define multiple polylogarithms of several variables by the absolutely convergent series

\[
\text{Li}_s(t_1, \ldots, t_\ell) = \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{t_1^{n_1} \cdots t_\ell^{n_\ell}}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}}
\]

whenever the complex numbers \( t_i \) satisfy \( |t_1| < 1 \) and \( |t_i| \leq 1 \) for \( i = 2, \ldots, \ell \).

The following proposition is a straightforward consequence of basic results in complex analysis:

**Proposition 1.119.** If \( s \) is a positive multi-index, then the function \( \text{Li}_s \) is holomorphic on the open unit disc \( |t| < 1 \). Moreover, if \( s \) is admissible, then \( \text{Li}_s \) can be extended continuously to the closed disc \( |t| \leq 1 \) and

\[
\text{Li}_s(1) = \zeta(s).
\]

For instance,

\[
\text{Li}_1(t) = \sum_{n \geq 1} \frac{t^n}{n} = -\log(1 - t) = \int_0^t \frac{dt_1}{1 - t_1}.
\]

An important property of polylogarithms is that they satisfy many functional equations, the easiest being:

**Proposition 1.121.** The following identities hold for all \( |t| < 1 \):

\[
\begin{align*}
\int_0^t \text{Li}_{s_1, \ldots, s_\ell}(t_1) \frac{dt_1}{t_1} &= \text{Li}_{s_1+1, s_2, \ldots, s_\ell}(t), \\
\int_0^t \text{Li}_{s_1, \ldots, s_\ell}(t_1) \frac{dt_1}{1 - t_1} &= \text{Li}_{s_1, s_2, \ldots, s_\ell}(t).
\end{align*}
\]

**Proof.** We first prove equation (1.122):

\[
\begin{align*}
\int_0^t \text{Li}_{s_1, \ldots, s_\ell}(t_1) \frac{dt_1}{t_1} &= \int_0^t \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{t_1^{n_1} \cdots t_\ell^{n_\ell}}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell} t_1} \frac{dt_1}{t_1} \\
&= \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{t_1^{n_1} \cdots t_\ell^{n_\ell}}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell} t_1} \\
&= \text{Li}_{s_1+1, s_2, \ldots, s_\ell}(t).
\end{align*}
\]

Similarly, equation (1.123) follows from the manipulations

\[
\begin{align*}
\int_0^t \text{Li}_{s_1, \ldots, s_\ell}(t_1) \frac{dt_1}{1 - t_1} &= \int_0^t \sum_{n_1 > n_2 > \cdots > n_\ell \geq 1} \frac{t_1^{n_1} \cdots t_\ell^{n_\ell}}{n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}} \sum_{m \geq 0} \frac{t_1^m}{1 - t_1} \\
&= \sum_{n_0 > n_1 > \cdots > n_\ell \geq 1} \frac{n_0^{n_1} \cdots n_\ell^{n_\ell}}{n_0 n_1^{s_1} n_2^{s_2} \cdots n_\ell^{s_\ell}} \\
&= \text{Li}_{s_1, s_2, \ldots, s_\ell}(t),
\end{align*}
\]

where we have written \( n_0 = n_1 + m + 1 > n_1 \). \( \square \)

Now Theorem 1.115 is a particular case of the next result.
Theorem 1.124. If \( s \) is a positive multi-index and \( 0 < t < 1 \) a real number, then the following identity holds:

\[
\text{Li}_s(t) = \int_{\Delta^\text{wt}(s)(t)} \omega_s.
\]

Proof. The proof is by induction on the weight of \( s \). If \( \text{wt}(s) = 1 \), then \( s = (1) \) and the statement is just formula (1.120). The inductive step follows from the functional equations in Proposition 1.121. Indeed, let \( s = (s_1, \ldots, s_\ell) \) be a positive multi-index and assume that the result is true for all multi-indices of lower weight. If \( s_1 > 1 \), we write \( s' = (s_1 - 1, \ldots, s_\ell) \). Then, by the identity (1.122) and induction,

\[
\text{Li}_s(t) = \int_0^t \text{Li}_{s'}(t_1) \frac{dt_1}{t_1} = \int_0^t \int_{\Delta^\text{wt}(s')(t_1)} \omega_{s'} \frac{dt_1}{t_1} = \int_{\Delta^\text{wt}(s)(t)} \omega_s.
\]

The case \( s_1 = 1 \) is similar, using equation (1.123) instead.

1.5.3. Shuffles. Since multiple zeta values are integrals along simplices, certain combinatorial properties of the latter translate into relations among the former. Let us first illustrate this with an example.

Example 1.125. We have the following equalities:

\[
\zeta(2)^2 = \int_{1 \geq t_1, t_2 \geq 0} \frac{dt_1 dt_2}{t_1(1 - t_2)} \cdot \int_{1 \geq u_1, u_2 \geq 0} \frac{du_1 du_2}{u_1(1 - u_2)}
\]

\[
= \int_{1 \geq t_1, t_2 \geq 0} \frac{dt_1 dt_2 du_1 du_2}{(1 - t_2)u_1(1 - u_2)}
\]

\[
= 6 \sum_{i=1}^6 \int_{U_i} \frac{dt_1 dt_2 du_1 du_2}{(1 - t_2)u_1(1 - u_2)}
\]

\[
= \zeta(3, 1) + \zeta(3, 1) + \zeta(2, 2) + \zeta(3, 1) + \zeta(3, 1) + \zeta(2, 2)
\]

\[
= 4\zeta(3, 1) + 2\zeta(2, 2),
\]

where the sets \( U_i, i = 1, \ldots, 6 \), are defined by

\[
U_1 = \{1 \geq t_1 \geq u_1 \geq t_2 \geq u_2 \geq 0\},
\]

\[
U_2 = \{1 \geq t_1 \geq u_1 \geq t_2 \geq u_2 \geq 0\},
\]

\[
U_3 = \{1 \geq t_1 \geq t_2 \geq u_1 \geq u_2 \geq 0\},
\]

\[
U_4 = \{1 \geq u_1 \geq t_1 \geq u_2 \geq t_2 \geq 0\},
\]

\[
U_5 = \{1 \geq u_1 \geq t_1 \geq t_2 \geq u_2 \geq 0\},
\]

\[
U_6 = \{1 \geq u_1 \geq u_2 \geq t_1 \geq t_2 \geq 0\}.
\]

The third equality comes from the decomposition

\[
\{(t_1, t_2, u_1, u_2) | 1 \geq t_1 \geq t_2 \geq 0, 1 \geq u_1 \geq u_2 \geq 0\} = \bigcup_{i=1}^6 U_i,
\]

and the fourth one from Theorem 1.115.
Remark 1.126. This expression of $\zeta(2)^2$ as linear combination of double zeta values is different from the one obtained by means of the series representation in Example 1.17. Combining both, we recover one of the relations which was proved in Corollary 1.63 using the method of partial fraction expansions, namely:

$$\zeta(4) = 4\zeta(3,1)$$

To generalize the previous example, we consider shuffles:

Definition 1.127. Let $r, s \geq 0$ be integers. A permutation $\sigma$ of the set \{1, 2, $\ldots$, r + s\} is called a shuffle of type $(r, s)$ if the following two conditions are satisfied:

$$\sigma(1) < \sigma(2) < \cdots < \sigma(r) \quad \text{and} \quad \sigma(r + 1) < \sigma(r + 2) < \cdots < \sigma(r + s).$$

We denote the set of all shuffles of type $(r, s)$ by $\mathcal{W}(r, s)$.

Remark 1.128. By definition, a shuffle is a permutation that respects the ordering of two distinguished subsets. The name comes from the way gamblers shuffle a deck of cards in western saloons.

Example 1.129. The set of shuffles of type $(2, 2)$ consists of the permutations $\text{Id}$, (23), (243), (123), (1243), and (13)(24).

Shuffles allow us to decompose a product of two simplices into a union of simplices, and therefore to express a product of integrals over simplices as a linear combination of integrals.

Proposition 1.130. Let $r, s \geq 0$ be integers, $0 < t < 1$ a real number and $\mu_i \in \{\omega_0, \omega_1\}$ for $i = 1, \ldots, r + s$. Then

$$\int_{\Delta^r(t)} \mu_1(t_1) \cdot \mu_r(t_r) \int_{\Delta^s(t)} \mu_{r+1}(t_{r+1}) \cdot \mu_{r+s}(t_{r+s})$$

$$= \sum_{\sigma \in \mathcal{W}(r, s)} \int_{\Delta^{r+s}(t)} \mu_{\sigma^{-1}(1)}(t_1) \cdot \mu_{\sigma^{-1}(r+s)}(t_{r+s}).$$

Proof. Using the decomposition

$$\Delta^r(t) \times \Delta^s(t) = \bigcup_{\sigma \in \mathcal{W}(r, s)} \{(t_1, \ldots, t_{r+s}) \mid t \geq t_{\sigma^{-1}(1)} \geq \cdots \geq t_{\sigma^{-1}(r+s)} \geq 0\},$$

together with the fact that the intersection of two simplices on the right-hand side is a set of measure zero we obtain

$$\int_{\Delta^r(t)} \mu_1(t_1) \cdot \mu_r(t_r) \int_{\Delta^s(t)} \mu_{r+1}(t_{r+1}) \cdot \mu_{r+s}(t_{r+s})$$

$$= \int_{\Delta^r(t) \times \Delta^s(t)} \mu_1(t_1) \cdot \mu_{r+s}(t_{r+s})$$

$$= \sum_{\sigma \in \mathcal{W}(r, s)} \int_{\Delta^{r+s}(t)} \mu_{\sigma^{-1}(1)}(t_1) \cdot \mu_{\sigma^{-1}(r+s)}(t_{r+s}),$$

$$= \sum_{\sigma \in \mathcal{W}(r, s)} \int_{\Delta^{r+s}(t)} \mu_{\sigma^{-1}(1)}(t_1) \cdot \mu_{\sigma^{-1}(r+s)}(t_{r+s}).$$
where, in the last equality we have made the change of variables \( t_i = t_{\sigma - i(1)} \) to put the set \( t \geq t_{\sigma - i(1)} \geq \cdots \geq t_{\sigma - i(r+s)} \geq 0 \) as \( \Delta^{r+s}(t) \).

1.5.4. Multi-indices and binary sequences. To exploit the preceding proposition to derive relations among polylogarithms, and in particular among multiple zeta values, we need a new notation.

Definition 1.131. A binary sequence is an element \( \alpha \in \{0, 1\}^k \). We call \( k \) the weight of \( \alpha \), while its length is defined as the number of ones in the sequence. A sequence is called positive if it ends in one and admissible if it ends in one and starts with zero.

We will use the following notation to go from multi-indices to binary sequences and the other way around.

Notation 1.132. To each positive multi-index \( s = (s_1, \ldots, s_\ell) \) we attach the positive binary sequence \( bs(s) = (0^{s_1-1}, 1, \ldots, 0^{s_\ell-1}, 1) \) where \( 0^{s} \) means that the entry zero is repeated \( s \) times. By convention, the empty binary sequence is admissible of weight and length both equal to zero. Clearly, \( bs \) is a bijection between the set of positive multi-indices and the set of positive binary sequences which respects the weight and the length. Moreover, it restricts to a bijection between the subsets of admissible objects on both sides.

If \( \alpha = (\varepsilon_1, \ldots, \varepsilon_r) \) is a binary sequence we will set \( \omega_\alpha = \omega_{\varepsilon_1} \ldots \omega_{\varepsilon_r} \).

In particular, if \( s \) is a positive multi-index then

\[
\omega_s = \omega_{bs(s)}.
\]

Moreover, if \( \alpha \) is positive we will denote \( \text{Li}_\alpha(t) = \text{Li}_{bs^{-1}(\alpha)}(t) \) and if it is also admissible, we write \( \zeta(\alpha) = \zeta(bs^{-1}(\alpha)) \).

1.5.5. The shuffle multiplicities.

Definition 1.133. Let \( \alpha = (\varepsilon_1, \ldots, \varepsilon_r) \), \( \alpha' = (\varepsilon_{r+1}, \ldots, \varepsilon_{r+s}) \) and \( \alpha'' \) be three binary sequences of lengths \( r \), \( s \) and \( t \) respectively. Then the shuffle multiplicity \( \shuffle(\alpha, \alpha'; \alpha'') \) is the number of shuffles of type \( (r, s) \) which send \( \alpha \alpha' \) to \( \alpha'' \). That is,

\[
\shuffle(\alpha, \alpha'; \alpha'') = \# \{ \sigma \in \shuffle(r, s) \mid \alpha'' = (\varepsilon_{\sigma-1(1)}, \ldots, \varepsilon_{\sigma-1(r+s)}) \}.
\]

Clearly, \( \shuffle(\alpha, \alpha'; \alpha'') = 0 \) unless \( t = r + s \).

The next result is the analogue of Lemma 1.39 for the shuffle multiplicity; it follows directly from the definition as well.

Lemma 1.134. Let \( \alpha, \alpha' \) and \( \alpha'' \) be three binary sequences satisfying the condition \( \shuffle(\alpha, \alpha'; \alpha'') > 0 \). Then

i) \( \text{wt}(\alpha'') = \text{wt}(\alpha) + \text{wt}(\alpha') \);

ii) \( \ell(\alpha'') = \ell(\alpha) + \ell(\alpha') \);

iii) if both \( \alpha \) and \( \alpha' \) are positive (resp. admissible), then so is \( \alpha'' \).

With this notation, Proposition 1.130 translates into the following result, which is the analogue of Lemma 1.40 for shuffles.
Lemma 1.135. Let \( \alpha \) and \( \alpha' \) be positive binary sequences. Then
\[
\Li_\alpha(t) \Li_{\alpha'}(t) = \sum_{\alpha''} \U(\alpha, \alpha'; \alpha'') \Li_{\alpha''}(t).
\]
Moreover, if \( \alpha \) and \( \alpha' \) are admissible, then
\[
\zeta(\alpha) \cdot \zeta(\alpha') = \sum_{\alpha''} \U(\alpha, \alpha'; \alpha'') \zeta(\alpha'').
\]

1.5.6. An involution. Another useful identity comes from exploiting the symmetry \( t \to 1 - t \).

Proposition 1.136. Let \( \alpha = (\varepsilon_1, \ldots, \varepsilon_r) \) be an admissible binary sequence. Then
\[
\int_{1 \geq t_1 \geq \cdots \geq t_r \geq 0} \omega_{\varepsilon_1}(t_1) \cdots \omega_{\varepsilon_r}(t_r) = \int_{1 \geq t_1 \geq \cdots \geq t_r \geq 0} \tilde{\omega}_{\varepsilon_1}(t_1) \cdots \tilde{\omega}_{\varepsilon_r}(t_r),
\]
where \( \tilde{\omega}_0 = \omega_1 \) and \( \tilde{\omega}_1 = \omega_0 \).

Proof. The change of variables \( s_i = 1 - t_i \) transforms the measure \( \omega_0(t_i) \) into \( \omega_1(s_i) = \tilde{\omega}_0(s_i) \), and \( \omega_1(t_i) \) into \( \omega_0(s_i) = \tilde{\omega}_1(s_i) \). Hence,
\[
\int_{1 \geq t_1 \geq \cdots \geq t_r \geq 0} \omega_{\varepsilon_1}(t_1) \cdots \omega_{\varepsilon_r}(t_r) = \int_{0 \leq s_1 \leq \cdots \leq s_r \leq 1} \tilde{\omega}_{\varepsilon_1}(s_1) \cdots \tilde{\omega}_{\varepsilon_r}(s_r).
\]
The sought formula follows after renaming the variables in the right as \( s_i = t_{r-i} \).

Definition 1.137. For a binary sequence \( \alpha = (\varepsilon_1, \ldots, \varepsilon_r) \), we write \( \tau(\alpha) = (1 - \varepsilon_r, \ldots, 1 - \varepsilon_1) \).

If \( \alpha \) is admissible, then so is \( \tau(\alpha) \).

As a consequence of Proposition 1.136 and Theorem 1.115, we deduce

Corollary 1.138. If \( \alpha \) is an admissible binary sequence, then
\[
\zeta(\alpha) = \zeta(\tau(\alpha)).
\]

Example 1.139. We have:
\[
\zeta(4) = \zeta((0, 0, 0, 1)) = \zeta((0, 1, 1, 1)) = \zeta(2, 1, 1).
\]

***

Exercise 1.140. Justify the exchange of the integral and the summation sign in the computations of Examples 1.109 and 1.111.

Exercise 1.141. Show that there are \( \binom{r+s}{r} \) shuffles of type \( (r, s) \).

Exercise 1.142. Manipulating series, show directly that
\[
\zeta(3) = \int_{1 \geq t_1 \geq t_2 \geq t_3 \geq 0} \frac{dt_1}{t_1} \frac{dt_2}{t_2} \frac{dt_3}{1 - t_3}
\]
and, more generally,
\[
\zeta(s) = \int_{1 \geq t_1 \geq t_2 \geq \cdots \geq t_s \geq 0} \frac{dt_1}{t_1} \cdots \frac{dt_{s-1}}{t_{s-1}} \frac{dt_s}{1 - t_s}.
\]
Exercise 1.143. Use Lemma 1.135 to check the shuffle relation (1.52) for the product $\zeta(j)\zeta(k-j)$.

Exercise 1.144. Find a formula for $\zeta(s)\zeta(p,q)$ with shuffles.

Exercise 1.145. Check the identities

$$\zeta(5) = \zeta(2,1,1,1), \quad \zeta(4,1) = \zeta(3,1,1),$$
$$\zeta(2,1,2) = \zeta(2,3), \quad \zeta(2,2,1) = \zeta(3,2)$$

with the help of Proposition 1.136.

1.6. Quasi-shuffle products and the Hoffman algebra. In the previous sections, we saw two methods to express a product of multiple zeta values as a linear combination of MZVs. The first one, using the series representation, gives the product in terms of the stuffle multiplicities. The second one, using the integral representation, gives the product in terms of the shuffle multiplicities. As we saw in Examples 1.17 and 1.125, both methods may give different linear combinations for the same product of multiple zeta values, thus leading to linear relations among them. The stuffle multiplicities are easily expressed in terms of multi-indices as in Lemma 1.40, while the shuffle multiplicities are expressed more conveniently using binary sequences as in Lemma 1.135. We now want to put a little order to make the combinatorial structure of multiple zeta values clearer. To this end, we will define the stuffle product and the shuffle product as products in certain formal algebras that encode the stuffle and the shuffle multiplicities respectively.

1.6.1. Alphabets and the quasi-shuffle product.

Notation 1.146. Let $A = \{a_i\}_{i \in S}$ be a countable (possibly finite) set. The elements of $A$ will be called letters and $A$ is called an alphabet. Let $Q(A)$ be the $Q$-vector space with $A$ as a basis. Let $Q \langle A \rangle$ be the non-commutative polynomial algebra over $A$, that is,

$$Q \langle A \rangle = \langle a_i a_{i_2} \cdots a_{i_n} | n \geq 0, i_j \in S \rangle_Q$$

is the vector space with the set of words in the letters of $A$ as a basis, along with the concatenation product

$$(a_{i_1} \cdots a_{i_n}) \cdot (a_{j_1} \cdots a_{j_m}) = a_{i_1} \cdots a_{i_n} a_{j_1} \cdots a_{j_m}.$$ We say that a word $w = a_1 \cdots a_n$ has length $\ell(w) = n$. We consider $1$ as the empty word and set $\ell(1) = 0$.

Definition 1.147. Let $A$ be an alphabet and let

$$\Diamond: QA \times QA \to QA$$

be a commutative and associative product. We define a new product $\star_{\Diamond}$ on $Q \langle A \rangle$ recursively by setting $1 \star_{\Diamond} w = w \star_{\Diamond} 1 = w$ and

$$aw \star_{\Diamond} bv = a(w \star_{\Diamond} bv) + b(aw \star_{\Diamond} v) + (a \Diamond b)(w \star_{\Diamond} v),$$

for letters $a, b \in A$ and words $w, v \in Q \langle A \rangle$. This product is extended to $Q \langle A \rangle$ by $Q$-linearity and is called the quasi-shuffle product associated with $\Diamond$.

Theorem 1.148 (Hoffman [Hof00]). The vector space $Q \langle A \rangle$ equipped with the product $\star_{\Diamond}$ is a commutative $Q$-algebra.
PROOF. Let us check the commutativity
\[(1.149) \quad u_1 \ast_\Diamond u_2 = u_2 \ast_\Diamond u_1\]
by induction on \(\ell(u_1) + \ell(u_2)\). If either \(u_1\) or \(u_2\) is the empty word, then \((1.149)\) holds trivially. It thus suffices to consider the case \(u_1 = aw\) and \(u_2 = bv\) with letters \(a, b \in A\) and words \(w, v \in \mathbb{Q}(A)\). Then, by definition of the product \(\ast_\Diamond\) and the induction hypothesis, we get
\[u_1 \ast_\Diamond u_2 - u_2 \ast_\Diamond u_1 = (a \Diamond b)(w \ast_\Diamond v) - (b \Diamond a)(v \ast_\Diamond w)\]
Since \(\Diamond\) is assumed to be commutative, \((1.149)\) follows from induction. The proof of the associativity is similar and is left as an exercise. \(\square\)

We will next give two examples of quasi-shuffle products.

1.6.2. Stuffle product. Let \(Y\) be the alphabet with letters \(y_1, y_2, y_3, \ldots\), together with the product
\[(\Diamond_1: \mathbb{Q}Y \times \mathbb{Q}Y \rightarrow \mathbb{Q}Y, \quad y_i \Diamond_1 y_j = y_{i+j}\]
which is commutative and associative. The product \(\ast_{\Diamond_1}\) on \(\mathbb{Q}(Y)\) will be denoted by \(\ast\) and called the stuffle product. By definition, it is given by
\[(1.150) \quad y_i w \ast y_j v = y_i(w \ast y_j v) + y_j(y_i w \ast v) + y_{i+j}(w \ast v)\]

Example 1.151. We have \(y_i \ast y_j = y_i y_j + y_j y_i + y_{i+j}\) and
\[y_2 \ast y_3 y_4 = y_2(y_3 y_4) + y_3(y_2 \ast y_4) + y_5(y_4)\]
\[= y_2 y_3 y_4 + y_3(y_2 y_4 + y_4 y_2 + y_6) + y_5 y_4\]
\[= y_2 y_3 y_4 + y_3 y_2 y_4 + y_3 y_4 y_2 + y_3 y_6 + y_5 y_4\]

Notation 1.152. A positive multi-index \(s = (s_1, \ldots, s_\ell)\) defines a word
\[y_s = y_{s_1} \cdots y_{s_\ell}\]
In fact, the set of positive multi-indices and the set of words in the alphabet \(Y\) are in bijection. We will use this bijection to identify both sets.

Lemma 1.153. The stuffle product is given by
\[y_s \ast y_{s'} = \sum_{s''} \text{st}(s, s'; s'') y_{s''}\]

Proof. The proof is by induction on the length of \(s\) and \(s'\). If one of them has length zero, say \(s\), then both sides of the equality to be proven are \(y_{s'}\), so the equality is true in this case. Assume then that both \(s\) and \(s'\) have length \(\geq 1\), and write \(s = (s_1, \ldots)\) and \(s' = (s'_1, \ldots)\), so that the associated words are of the form \(y_s = y_{s_1} v\) and \(y_{s'} = y_{s'_1} w\). Equation \((1.150)\) gives us
\[y_s \ast y_{s'} = y_{s_1}(v \ast y_{s'}) + y_{s'_1}(y_s \ast v) + y_{s_1 + s'_1}(v \ast w)\]
The matrices that are used to compute the stuffle indices \(\text{st}(s, s'; s'')\) in Definition 1.37 fall into three types, namely
\[
\begin{pmatrix}
s_1 & \cdots \\
0 & \cdots
\end{pmatrix}, \quad \begin{pmatrix}
0 & \cdots \\
s'_1 & \cdots
\end{pmatrix}, \quad \begin{pmatrix}
s_1 & \cdots \\
s'_1 & \cdots
\end{pmatrix}
\]
Using the induction hypothesis, one sees that the matrices of the first type give rise to the term \(y_{s_1}(v \ast y_{s'})\), the matrices of the second type to the term \(y_{s'_1}(y_s \ast v)\) and the matrices of the third type to the term \(y_{s_1 + s'_1}(v \ast w)\). \(\square\)
Since the words of the alphabet $Y$ are related to multi-indices and the product of $Q(Y)$ is the stuffle product, one may expect a morphism of $Q$-algebras
\[
(Q(Y), \ast) \rightarrow (Z, \cdot)
\]
yielding
\[
y_{s_1} \cdots y_{s_\ell} \mapsto \zeta(s_1, \ldots, s_\ell).
\]
However, since multiple zeta values are defined only when $s_1 > 1$, we need to restrict the source of this map. Later, in Section 1.7 we will see how to extend it to the whole $(Q(Y), \ast)$.

**Definition 1.154.** A word $w = y_{s_1} \cdots y_{s_\ell}$ is called admissible if $s_1 > 1$, i.e. if it corresponds to an admissible multi-index. We will denote by $Q(Y)^0$ the vector subspace of $Q(Y)$ generated by admissible words.

**Proposition 1.155.**

i) $(Q(Y)^0, \ast)$ is a subalgebra of $(Q(Y), \ast)$.

ii) There is a morphism of $Q$-algebras
\[
Q(Y)^0 \rightarrow Z
\]
determined by the assignment
\[
y_{s_1} \cdots y_{s_\ell} \mapsto \zeta(s_1, \ldots, s_\ell).
\]

**Proof.** The first statement can be checked directly from the definition of the product $\ast$. Alternatively, it follows from Lemma 1.153 and part (3) of Lemma 1.39. The second statement follows from Lemmas 1.153 and 1.40. \[\square\]

Since we have identified positive multi-indices with words in the alphabet $Y$, we often just write $\zeta(w)$ instead of $\zeta(s_1, \ldots, s_\ell)$ for $w = y_{s_1} \cdots y_{s_\ell}$. With this notation,
\[
(1.156) \quad \zeta(w \ast v) = \zeta(w) \zeta(v)
\]
holds for all words $w, v \in Q(Y)^0$.

1.6.3. **Shuffle product.** Let $X$ be the alphabet in two letters $X = \{x_0, x_1\}$, along with the trivial product $a \triangleleft_0 b = 0$ for all $a, b \in X$. We denote by $\uplus$ the corresponding product $\ast_{\triangleleft_2}$ and call it the shuffle product. By definition, it is given by
\[
x_i w \uplus x_j v = x_i(w \uplus x_j v) + x_j(x_iw \uplus v).
\]

**Definition 1.157.** We call $\mathcal{H} = (Q(X), \uplus)$ the Hoffman algebra.

**Proposition 1.158.** Given words $x_{\varepsilon_1} \cdots x_{\varepsilon_r}$ and $x_{\varepsilon_{r+1}} \cdots x_{\varepsilon_{r+s}}$ on the alphabet $X$, their shuffle product is equal to
\[
x_{\varepsilon_1} \cdots x_{\varepsilon_r} \uplus x_{\varepsilon_{r+1}} \cdots x_{\varepsilon_{r+s}} = \sum_{\sigma \in \Omega(r,s)} x_{\varepsilon_{\sigma^{-1}(1)}} \cdots x_{\varepsilon_{\sigma^{-1}(r+s)}}.
\]

**Proof.** Exercise 1.170. \[\square\]

**Example 1.159.** We have
\[
x_0x_1 \uplus x_0x_1 = 2x_0x_1x_0x_1 + 4x_0^2x_1^2
\]
\[
x_0x_1 \uplus x_0^2x_1 = x_0x_1x_0^2x_1 + 3x_0^2x_1x_0x_1 + 6x_0^3x_1^2.
\]
There is an obvious bijection between binary sequences and words in the alphabet $X$ that with a binary sequence $\alpha = (\varepsilon_1, \ldots, \varepsilon_r)$ associates the word $x_\alpha = x_{\varepsilon_1} \ldots x_{\varepsilon_r}$. Using this bijection, we can transfer the shuffle multiplicity, as introduced in Definition 1.133, to words in the alphabet $X$. The resulting multiplicity will be denoted by $\Psi(u, v; w)$. With this notation, Proposition 1.158 can be rewritten as

\begin{equation}
(1.161) \quad u \uplus v = \sum_w \Psi(u, v; w).
\end{equation}

This equation hints at the existence of an algebra morphism from $\mathcal{H}$ to multiple zeta values. As was the case for the alphabet $Y$, one needs to restrict the source of this map to the subspace that gives rise to convergent series.

Definition 1.162. A word in the alphabet $X$ is said to be positive if it ends in $x_1$ and is said to be admissible if it ends in $x_1$ and starts with $x_0$.

Proposition 1.163. Let $\mathcal{F}^1$ (resp. $\mathcal{F}^0$) be the subspace generated by positive (resp. admissible) words, so that there are inclusions $\mathcal{F} \supset \mathcal{F}^1 \supset \mathcal{F}^0$.

Then the following properties hold:

i) $(\mathcal{F}^0, \uplus)$ and $(\mathcal{F}^1, \uplus)$ are subalgebras of $(\mathcal{F}, \downarrow)$.

ii) There is a morphism of $Q$-algebras

$$
\zeta : \mathcal{F}^0 \longrightarrow \mathbb{Z}
$$

given by the assignment

$$
x_\alpha \longmapsto \zeta(\alpha).
$$

(Recall that the multiple zeta value corresponding to an admissible binary sequence was defined as $\mathcal{F}^1(\bs^{-1}(\alpha))$ in Notation 1.132).

Proof. Exercise 1.171.

Since we are identifying binary sequences and words in the alphabet $X$, we will often write $\zeta(x_\alpha)$ instead of $\zeta(\alpha)$. With this notation, Proposition 1.163 becomes

\begin{equation}
(1.164) \quad \zeta(w \uplus v) = \zeta(w)\zeta(v)
\end{equation}

for all $w, v \in \mathcal{F}^0$.

1.6.4. Double shuffle relations. In the same way that positive multi-indices can be translated into binary sequences, there is a natural map between $Q(Y)$ and $\mathcal{F}$. This map does not transform the the stuffle product on $Q(Y)$ into the shuffle product on $\mathcal{F}$. To remedy this, we define a second product on $\mathcal{F}$.

Definition 1.165. Setting $z_p = x_0^{p-1} x_1$, the stuffle product

$$
* : \mathcal{F} \times \mathcal{F} \longrightarrow \mathcal{F}
$$

is inductively defined as follows:

$$
1 * w = w * 1 = w \quad \text{for } w \in \mathcal{F},
$$

$$
x_p^p * w = w * x_0^p = wx_p^p \quad \text{for } p \geq 1 \text{ and } w \in \mathcal{F},
$$

$$
z_p w * z_q v = z_p (w * z_q v) + z_q (z_p w * v) + z_{p+q} (w * v) \quad \text{for } w, v \in \mathcal{F}.
$$
**Proposition 1.166.**

i) \((\mathcal{H}, \ast)\) is a commutative and associative \(\mathbb{Q}\)-algebra.

ii) The map

\[
\begin{align*}
(Q(Y), \ast) & \longrightarrow (\mathcal{H}, \ast) \\
y_i & \longmapsto z_i = x_0^{i-1}x_1.
\end{align*}
\]

is an injective morphism of algebras with image the subalgebra \(\mathcal{H}^1\).

**Proof.** Exercise 1.172. □

We will use this map to identify \(\mathcal{H}^1\) and \(Q(Y)\).

**Theorem 1.167.** Let \(\zeta: \mathcal{H}^0 \rightarrow \mathbb{Z}\) be the map from Proposition 1.163. Then,

\[
\zeta(w \ast v - w \ast v) = 0.
\]

**Proof.** This follows from equations (1.156) and (1.164). □

This theorem is a source of relations among multiple zeta values that are called double shuffle relations. Nevertheless, it is clear that they are not enough to describe all relations among them. For instance, we do not obtain Euler’s relation in weight 3, and we can only produce one relation in weight 4, while there are at least 3 independent relations. In order to obtain the remaining relations, we will consider products with non-admissible words in the next section.

***

**Exercise 1.168.** Prove the identity

\[
x_0^r \cup x_0^s = x_0 \cdots x_0 \cup x_0 \cdots x_0 = \frac{(r + s)!}{r!s!} x_0^{r+s}.
\]

**Exercise 1.169.** Prove the identity

\[
a \cup wv = (a \cup w)v + w(a \cup v) - wav
\]

for a letter \(a\) and words \(w\) and \(v\) in the alphabet \(X = \{x_0, x_1\}\).

**Exercise 1.170.** Prove Proposition 1.158.

**Exercise 1.171.** Prove Proposition 1.163.

**Exercise 1.172.** Prove Proposition 1.166.

**Exercise 1.173.** Given a multi-index \(s\) and an integer \(M \geq 0\), we set

\[
\zeta_M(s) = \sum_{M > m_1 > m_2 > \cdots > m_r > 0} \frac{1}{m_1^{s_1} \cdots m_r^{s_r}}.
\]

i) Show that, if \(s\) is admissible, then \(\lim_{M \rightarrow \infty} \zeta_M(s) = \zeta(s)\).

ii) Recall that we identified words and multi-indices. Prove that the map

\[
\zeta_M: (\mathcal{H}^1, \ast) \longrightarrow \mathbb{Q}
\]

is a morphism of algebras, i.e. for all \(w, v \in \mathcal{H}^1\)

\[
\zeta_M(w \ast v) = \zeta_M(w) \zeta_M(v).
\]
Exercise 1.174. Using the identification between words in the alphabet $X$ and binary sequences, we obtain a map

$$\text{Li} : \mathcal{H} \rightarrow C^\infty((0,1))$$

that sends $w \in \mathcal{H}$ to the polylogarithm function $\text{Li}_w(t)$ from Definition 1.117. Prove that this map satisfies

$$\text{Li}_{wv}(t) = \text{Li}_w(t) \cdot \text{Li}_v(t)$$

for all $w, v \in \mathcal{H}$, and is hence a morphism of algebras

$$\text{Li} : (\mathcal{H}, \cdot) \rightarrow (C^\infty((0,1)), \cdot).$$

1.7. Regularization and the Ihara-Kaneko-Zagier theorem. In this section, we discuss how to extend multiple zeta values to non-admissible words and use this extension to derive relations among them. Conjecturally, all relations can be obtained in this way. We follow the paper [IKZ06].

1.7.1. The stuffle algebra as a polynomial ring.

Theorem 1.175. The map

$$\varphi : \mathbb{Q}[Y]^0[T] \rightarrow \mathbb{Q}(Y)$$

$$T \mapsto y_1$$

is an isomorphism of $(\mathbb{Q}(Y)^0, \ast)$-algebras.

Proof. We first show that the map $\varphi$ is surjective, which amounts to saying that any element $w \in \mathbb{Q}(Y)$ can be written as a polynomial in $y_1$ with coefficients in $\mathbb{Q}(Y)^0$. The bijection between the sets of multi-indices and words in the alphabet $Y$ induces a grading by the weight $\text{wt}$ and a filtration by the length $\ell$ on the space $\mathbb{Q}(Y)$ given by

$$\text{wt}(y_{s_1} \cdots y_{s_\ell}) = s_1 + \cdots + s_\ell$$

$$\ell(y_{s_1} \cdots y_{s_\ell}) = \ell.$$

If we show that, for a fixed length $\ell$ and a word $w \in F_\ell \mathbb{Q}(Y)$, there are elements $v_1 \in F_\ell \mathbb{Q}(Y)^0$ and $v_2, v_3 \in F_{\ell-1} \mathbb{Q}(Y)$ such that

$$w = v_1 + v_2 \ast y_1 + v_3,$$

then the surjectivity follows by induction on $\ell$.

Any word of length $\ell$ can be written as

$$w = \underbrace{y_1 \cdots y_1}_{m} y_{s_1} \cdots y_{s_{\ell-m}} = \{y_1\}^m y_{s_1} \cdots y_{s_{\ell-m}}$$

with $s_1 \neq 1$ and $m \geq 0$.

We next prove, by induction on $m$, that $w$ can be written as in (1.176). For $m = 0$, we have $w \in \mathbb{Q}(Y)^0$. Thus, we can choose $v_1 = w$, $v_2 = v_3 = 0$. For the induction step we compute

$$\{y_1\}^{m-1} y_{s_1} \cdots y_{s_{\ell-m}} \ast y_1 = m \cdot w + \sum_{i=1}^{\ell-m} \{y_1\}^{m-1} y_{s_1} \cdots y_{s_i} y_{s_{i+1}} \cdots y_{s_{\ell-m}} - v_3$$

with $v_3 \in F_{\ell-1} \mathbb{Q}(Y)$. Applying the induction hypothesis with respect to $m$ we deduce that $w$ can be written as in (1.176). It follows that $\varphi$ is surjective.
To prove the injectivity of $\varphi$, we write each non-zero $P \in \mathbb{Q}(Y)^0[T]$ as

$$P = w_1T^m + w_2$$

with $0 \neq w_1 \in \mathbb{Q}(Y)^0$ and $w_2$ of degree less than $m$ in the variable $T$. Then

$$\varphi(P) = m!y_1^m w_1 + v_2$$

where all the words in $v_2$ have less than $m$ factors $y_1$ in the front. Thus, $\varphi(P) \neq 0$ and $\varphi$ is injective. □

1.7.2. The shuffle algebra as a polynomial ring. Mutatis mutandis, one can prove the analogous result for the shuffle product.

**Theorem 1.177.**

i) The map of $(\mathcal{S}^0, \shuffle)$-algebras

$$\psi_1: \mathcal{S}^0[T] \rightarrow \mathcal{S}^1$$

$$T \mapsto x_1$$

is an isomorphism.

ii) The map of $(\mathcal{S}^1, \shuffle)$-algebras

$$\psi_2: \mathcal{S}^1[U] \rightarrow \mathcal{S}$$

$$U \mapsto x_0$$

is an isomorphism.

Therefore, the map of $(\mathcal{S}^0, \shuffle)$-algebras

$$\psi: \mathcal{S}^0[T, U] \rightarrow \mathcal{S}$$

$$T \mapsto x_1$$

$$U \mapsto x_0$$

is an isomorphism.

**Proof.** Exercise 1.211. □

1.7.3. Regularized zeta values. Using the previous theorems, we define the stuffle and shuffle regularization maps. Recall the identification $\mathcal{S}^1 = \mathbb{Q}(Y)$ from Proposition 1.166.

**Definition 1.178.** The stuffle regularization map

$$\text{reg}_{\mathcal{S}}^T: \mathcal{S}^1 = \mathbb{Q}(Y) \rightarrow \mathcal{S}^0[T] = \mathbb{Q}(Y)^0[T]$$

is defined as $\text{reg}_{\mathcal{S}}^T = \varphi^{-1}$, while the shuffle regularization maps

$$\text{reg}_{\mathcal{S}}^T: \mathcal{S}^1 \rightarrow \mathcal{S}^0[T], \quad \text{and} \quad \text{reg}_{\mathcal{S}}^{T, U}: \mathcal{S} \rightarrow \mathcal{S}^0[T, U]$$

as $\text{reg}_{\mathcal{S}}^T = \psi_1^{-1}$ and $\text{reg}_{\mathcal{S}}^{T, U} = \psi^{-1}$.

Theorems 1.175 and 1.177 allow us to extend the function $\zeta$ in a formal way.

**Definition 1.179.** The stuffle regularized zeta map is the composition

$$\zeta^T: \mathbb{Q}(Y) \xrightarrow{\text{reg}_{\mathcal{S}}^T} \mathbb{Q}(Y)^0[T] \rightarrow \mathbb{Q}[T] \subset \mathbb{R}[T].$$

We denote by $\zeta_*$ the composition of $\zeta^T_*$ with the evaluation at $T = 0$. 
The shuffle regularized zeta map, denoted by $\zeta_T$, is the composition

$$\mathcal{S}_T^1 \xrightarrow{\text{reg}} \mathcal{S}_0[T] \xrightarrow{\zeta} \mathcal{Z}[T] \subset \mathbb{R}[T].$$

Similarly, we write $\zeta_{T,U}$ for the composition

$$\mathcal{S}_T \xrightarrow{\text{reg}_{T,U}} \mathcal{S}_0[T,U] \xrightarrow{\zeta} \mathcal{Z}[T,U] \subset \mathbb{R}[T,U].$$

We denote by $\zeta$ the composition of $\zeta_{T,U}$ with the evaluation at $T = U = 0$. We will also denote by $\zeta$ its restriction to $\mathcal{H}_1$.

By identifying $(\mathbb{Q}(\langle Y \rangle), *)$ with $(\mathcal{H}_1, *)$, we will also consider $\zeta^*_T$ as the linear map from $(\mathcal{H}_1, *)$ to $\mathbb{R}[T]$ characterized by the conditions

$$\zeta^*_T(w) = \zeta(w) \in \mathbb{R}, \quad \text{if } w \in \mathcal{H}_0,$$

$$\zeta^*_T(x_1) = T,$$

$$\zeta^*_T(v * w) = \zeta^*_T(v)\zeta^*_T(w).$$

In the same way, the map $\zeta^*_T$ is characterized by linearity and the identities

$$\zeta^*_{T,U}(w) = \zeta(w) \in \mathbb{R}, \quad \text{if } w \in \mathcal{H}_0,$$

$$\zeta^*_{T,U}(x_1) = T,$$

$$\zeta^*_{T,U}(v \cup w) = \zeta^*_{T,U}(v)\zeta^*_{T,U}(w).$$

The maps $\zeta_*, \zeta_{T,U}$ and $\zeta^*_{T,U}$ are determined by similar conditions. For future reference we single out the properties characterizing $\zeta_{T,U}$.

\textbf{Proposition 1.180.} The map $\zeta_{T,U} : \mathcal{S}_1 \rightarrow \mathbb{R}$ is the only linear map satisfying

\begin{align*}
\zeta_{T,U}(w) &= \zeta(w) \in \mathbb{R}, \quad \text{if } w \in \mathcal{H}_0, \\
\zeta_{T,U}(x_0) &= 0, \quad \zeta_{T,U}(x_1) = 0, \\
\zeta_{T,U}(v \cup w) &= \zeta_{T,U}(v)\zeta_{T,U}(w).
\end{align*}

\textbf{Corollary 1.184.} The image of $\zeta_{T,U}$ agrees with $\mathcal{Z}$.

\textbf{Proof.} By Theorem 1.177, every element $w \in \mathcal{S}_1$ can be written as a finite sum $w = \sum a_{ij} \cup x_0 \cup x_1$ for some $a_{ij} \in \mathcal{S}_0$. By Proposition 1.180, the equality $\zeta_{T,U}(w) = \zeta_{T,U}(a_{00})$ holds, and hence $\zeta_{T,U}(w)$ belongs to $\mathcal{Z}$. \hfill \square

\textbf{Example 1.185.} On the one hand, we have

$$\zeta^*_T(1, 2) = \zeta^*_T(y_1y_2)$$

$$= \zeta^*_T(y_2 * y_1 - y_2y_1 - y_3)$$

$$= \zeta(2)T - \zeta(2, 1) - \zeta(3),$$

which yields $\zeta_*(1, 2) = -\zeta(2, 1) - \zeta(3)$. On the other hand,

$$\zeta^*_{T,U}(1, 2) = \zeta^*_{T,U}(x_1x_0x_1)$$

$$= \zeta^*_{T,U}(x_0x_1 \cup x_1 - 2x_0x_1x_1)$$

$$= \zeta(2)T - 2\zeta(2, 1).$$

Therefore, $\zeta_{T,U}(1, 2) = -2\zeta(2, 1)$. 
Comparing the shuffle and the stuffle regularizations. As we just saw in the previous example, the regularizations \( \zeta^T_{\text{sh}}(w) \) and \( \zeta^T_{\text{st}}(w) \) are in general different from each other. In order to compare them, we introduce the formal power series

\[
A(u) = e^{\gamma_u} \Gamma(1 + u) = \exp \left( \sum_{n \geq 2} \frac{(-1)^n}{n} \zeta(n) u^n \right),
\]

where \( \gamma \) is the Euler-Mascheroni constant, and the second identity follows from Exercise 1.19. We write

\[
A(u) = \sum_{k \geq 0} \gamma_k u^k.
\]

Observe that \( \gamma_k \) is a linear combination, with rational coefficients, of multiple zeta values of weight \( k \).

Here are the first values:

<table>
<thead>
<tr>
<th>( k )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \gamma_k )</td>
<td>1</td>
<td>0</td>
<td>\frac{\zeta(2)}{2}</td>
<td>-\frac{\zeta(3)}{3}</td>
<td>\frac{\zeta(2,2)}{4} + \frac{3\zeta(4)}{8} - \frac{\zeta(2,3)}{6} - \frac{\zeta(3,2)}{6} - \frac{11\zeta(5)}{30}</td>
<td></td>
</tr>
</tbody>
</table>

We define an \( \mathbb{R} \)-linear map \( \varphi : \mathbb{R}[T] \rightarrow \mathbb{R}[T] \) by

\[
(1.186)\quad \varphi(T^n) = \frac{d^n}{du^n} \left( A(u) e^{Tu} \right) \bigg|_{u=0} = n! \sum_{k=0}^{n} \gamma_k \frac{T^{n-k}}{(n-k)!}.
\]

**Theorem 1.187** (Ihara-Kaneko-Zagier, [IKZ06]). The identity

\[
\zeta^T_{\text{sh}}(w) = \varphi(\zeta^T_{\text{st}}(w))
\]

holds for all words \( w \in \mathcal{Y}^1 \).

**Example 1.188.** Since \( \gamma_0 = 1 \) and \( \gamma_1 = 0 \), we have \( \varphi(1) = 1 \) and \( \varphi(T) = T \).

Combining this with Example 1.185 we find

\[
\varphi(\zeta_{\text{sh}}^T(1, 2)) = \varphi(\zeta(2)T - \zeta(2,1) - \zeta(3)) = \zeta(2)T - \zeta(2,1) - \zeta(3).
\]

On the other hand,

\[
\zeta^T_{\text{sh}}(1, 2) = \zeta(2)T - 2\zeta(2,1),
\]

and hence we recover Euler’s relation \( \zeta(2,1) = \zeta(3) \).

**Proof of Theorem 1.187.** The idea is to view \( \zeta^T_{\text{sh}}(w) = \varphi(\zeta^T_{\text{st}}(w)) \) as an identity of functions in \( T \). Let \( M > 0 \) be an integer and \( w = y_{s_1} \cdots y_{s_t} \) a word in the alphabet \( Y \). We write

\[
\zeta_M(w) = \sum_{M > m_1 > m_2 > \cdots > m_t > 0} \frac{1}{m_1^{s_1} \cdots m_t^{s_t}}.
\]

Note that, if \( w \) is admissible, then \( \lim_{M \to \infty} \zeta_M(w) = \zeta(w) \). We extend \( \zeta_M \) to a map \( \mathbb{Q}(Y) \rightarrow \mathbb{R} \) by linearity. Then \( \zeta_M \) satisfies the stuffle relation

\[
\zeta_M(w_1) \zeta_M(w_2) = \zeta_M(w_1 \ast w_2).
\]

by Exercise 1.173. From the approximation of the harmonic series

\[
\zeta_M(y_1) = 1 + \frac{1}{2} + \frac{1}{3} + \cdots + \frac{1}{M-1} = \log M + \gamma + O \left( \frac{1}{M} \right)
\]
and the representation of $\zeta^T(w)$ as a polynomial on $\zeta_\ast(1)$, it follows that there exists $j \geq 0$ such that, for $M$ large enough, one has

$$\zeta_M(w) = \zeta^\log M + \gamma M + O(M^{-1} \log M),$$

(1.189)

where $\zeta^\log M + \gamma M$ means the evaluation at $T = \log M + \gamma$ of $\zeta^T(w)$.

Recall that, with each positive multi-index $s$ we associated a polylogarithm function. Using the identification of positive multi-indices with words in the alphabet $Y$ and linearity, we attach, to each element $w \in \mathcal{S}$ a function $Li_w$ on the segment $(0, 1)$. If $w \in \mathcal{S}^0$, then

$$\lim_{t \to 1^-} Li_w(t) = \zeta(w).$$

Moreover, we have for all $w, w'$ and $t \in (0, 1)$

$$Li_w(t) \cdot Li_{w'}(t) = Li_{w\cdot w'}(t)$$

by Exercise 1.174. Since

$$Li_y(t) = \log \frac{1}{1- t},$$

when $t \to 1^-$

$$Li_w(t) = \zeta^\log \left(\frac{1}{1-t}\right) + O\left((1-t) \log^j \left(\frac{1}{1-t}\right)\right)$$

(1.190)

for some $j \geq 0$ depending on $w$. Here $\zeta^\log \left(\frac{1}{1-t}\right)$ means the evaluation at $T = \log \left(\frac{1}{1-t}\right)$ of $\zeta^T(1/w)$.

By explicit calculations,

$$Li_w(t) = \sum_{m_1 > m_2 > \cdots > m_\ell > 0} \frac{t^{m_1}}{m_1^{m_1} \cdots m_\ell^{m_\ell}}$$

$$= \sum_{m \geq 1} \left(\sum_{m_1 > m_2 > \cdots > m_\ell > 0} \frac{1}{m_1^{m_1} m_2^{m_2} \cdots m_\ell^{m_\ell}}\right) t^m$$

$$= \sum_{m \geq 1} (\zeta_{m+1}(w) - \zeta_m(w)) t^m$$

$$= (1-t) \sum_{m \geq 2} \zeta_m(w) t^{m-1},$$

where the last equality uses the vanishing $\zeta_1(w) = 0$.

To go further, we apply Lemma 1.191 below to the polynomials $P(T) = \zeta^T_\ast(w)$ and $Q(T) = \phi(\zeta^T_\ast(w))$. We derive

$$Li_w(t) = (1-t) \sum_{m \geq 2} \zeta_m(w) t^{m-1}$$

(1.189)

$$= (1-t) \sum_{m \geq 2} \zeta^\log m + \gamma m t^{m-1} + (1-t) \sum_{m \geq 1} O\left(\frac{\log^j m}{m}\right) t^{m-1}$$

(1.192)

$$= Q \left(\log \frac{1}{1-t}\right) + O\left((1-t) \log^j \left(\frac{1}{1-t}\right)\right).$$

Comparing with the asymptotic expansion we get the claimed identity

$$\zeta^T_\ast(s) = \phi(\zeta^T_\ast(s)).$$

□
The next lemma was used in the proof of Theorem 1.187.

**Lemma 1.191.**

i) Let $P(T) \in \mathbb{R}[T]$ and $Q(T) = \varrho(P(T))$. Then

$$
\sum_{m \geq 2} P(\log(m) + \gamma)t^{m-1} = \frac{1}{1-t} Q\left( \log\left(\frac{1}{1-t}\right) \right) + O\left( \log^j \left( \frac{1}{1-t} \right) \right)
$$

for some $j \in \mathbb{N}$, as $t \to 1^-$.

ii) As $t \to 1^-$, we have

$$
\sum_{m \geq 2} \frac{\log^j m}{m} t^{m-1} = O\left( \log^{j+1} \left( \frac{1}{1-t} \right) \right).
$$

**Proof.** Let us prove (1.193) first. Since

$$
\sum_{m \geq 2} \frac{1}{m} t^{m-1} = -1 - \frac{1}{t} \log(1-t),
$$

for $j = 0$ the left hand side of (1.193) is of type $O\left( \log \left( \frac{1}{1-t} \right) \right)$ as $t \to 1^-$, which proves the statement in this case. Now we proceed by induction on $j$. We have

$$
\log^{j+1}(m) \leq c_j \sum_{n=1}^{m} \frac{\log^j n}{n}
$$

for $m \geq 1, j \geq 0$. This follows easily from the integral

$$
\int_{1}^{m} \frac{\log^j(x)}{x} \, dx = \frac{\log^{j+1}(m)}{j+1}.
$$

Hence, for $t < 1$, we obtain

$$
\sum_{m \geq 1} \frac{\log^{j+1}(m)}{m} t^{m-1} \leq c_j \sum_{m \geq 1} \frac{t^{m-1}}{m} \sum_{n=1}^{m} \frac{\log^j(n)}{n}
$$

$$
= c_j \sum_{n \geq 1} \frac{\log^j(n)}{n} t^{n-1} \sum_{r \geq 1} \frac{t^{r-1}}{r + n - 1}
$$

$$
< c_j \left( \sum_{n \geq 1} \frac{\log^j(n)}{n} t^{n-1} \right) \left( \frac{1}{t} \log \left( \frac{1}{1-t} \right) \right).
$$

Now (1.193) follows by induction on $j$ for all $j \geq 0$.

We now establish the identity (1.192). Since $\varrho$ is by construction a linear map on $\mathbb{R}[T]$, it suffices to prove it for $P(T) = (T - \gamma)^n$. Thus, we put $Q(T) = \varrho((T - \gamma)^n)$. Then, by equation (1.186),

$$
Q(T) = \left. \frac{d^n}{du^n} \left( A(u)e^{(T-\gamma)u} \right) \right|_{u=0} = \left. \frac{d^n}{du^n} \left( \Gamma(1+u)e^{Tu} \right) \right|_{u=0}.
$$
Hence,
\[
\frac{1}{1-t}Q \left( \log \left( \frac{1}{1-t} \right) \right) = \frac{d^n}{du^n} \left( \frac{\Gamma(1+u)}{(1-t)^{1+n}} \right) \bigg|_{u=0} = \frac{d^n}{du^n} \left( \sum_{m \geq 1} \frac{\Gamma(m+u)}{\Gamma(m)} t^m \right) \bigg|_{u=0} = \sum_{m \geq 1} \frac{\Gamma(n)(m)}{\Gamma(m)} t^{m-1},
\]
where \( \Gamma^{(n)}(m) \) is the \( n \)-th derivative of the \( \Gamma \) function evaluated at \( m \). Now we use that, for \( m \to \infty \) and all \( n \), we have the estimate
\[
\frac{\Gamma^{(n)}(m)}{\Gamma(m)} = \log \left( \frac{m}{n} \right) + O \left( \frac{\log^{-1}(m)}{m} \right).
\]
Using this and (1.193) we obtain
\[
\sum_{m \geq 1} \frac{\Gamma^{(n)}(m)}{\Gamma(m)} t^{m-1} = \sum_{m \geq 1} \log^n(m) t^{m-1} + O \left( \frac{\log^n \left( \frac{1}{1-t} \right)}{m} \right),
\]
concluding the proof of the lemma. \( \square \)

1.7.5. The extended double shuffle relations. We now introduce extended double shuffle relations. We first recall the two commutative diagrams
\[
\begin{align*}
\begin{array}{ccc}
(\mathcal{H}^0, \sqcup) & \xrightarrow{\text{reg}} & (\mathcal{H}^0, \sqcup[T]) \\
\zeta_T & \downarrow & \zeta_T^T \\
\mathbb{R}[T] & \xrightarrow{w \mapsto \zeta(w)} & \mathbb{R}[T]
\end{array}
\end{align*}
\]

\[
\begin{align*}
\begin{array}{ccc}
(\mathcal{H}^1, *) & \xrightarrow{\text{reg}} & (\mathcal{H}^0, *)[T] \\
\zeta_T & \downarrow & \zeta_T^T \\
\mathbb{R}[T] & \xrightarrow{w \mapsto \zeta(w)} & \mathbb{R}[T]
\end{array}
\end{align*}
\]

Definition 1.196. Let \((R, \cdot)\) be a \( \mathbb{Q} \)-algebra and \( Z_R : \mathcal{H}^0 \to R \) a map. The pair \((R, Z_R)\) is said to satisfy the finite double shuffle relations if \( Z_R \) is a morphism of algebras with respect to both the shuffle and the stuffle product on \( \mathcal{H}^0 \); that is, if the equalities
\[
Z_R(w \sqcup v) = Z_R(w) \cdot Z_R(v) = Z_R(w \ast v)
\]
hold for all \( w, v \in \mathcal{H}^0 \).

By composition with the regularization maps \( \text{reg}_{\sqcup}^T \) and \( \text{reg}^T_* \), the map \( Z_R \) gives rise to maps
\[
Z_{R,\sqcup}^T : (\mathcal{H}^1, \sqcup) \rightarrow R[T],
Z_{R,\ast}^T : (\mathcal{H}^1, \ast) \rightarrow R[T].
\]
Since \( R \) is a \( \mathbb{Q} \)-algebra that receives a map from \( \mathcal{H}^0 \), we can define the formal power series
\[
A_R(u) = \exp \left( \sum_{n \geq 2} \frac{(-1)^n}{n} Z_R(y_n) u^n \right),
\]
and then, by analogy with $\rho$, the linear map $\varrho_R: R[T] \to R[T]$ given by
\begin{equation}
\varrho_R(e^{T_u}) = A_R(u)e^{T_u}.
\end{equation}

**Definition 1.199.** Assume that the pair $(R, Z_R)$ satisfies the finite double shuffle relations. We say that $(R, Z_R)$ satisfies the extended double shuffle relations if, in addition, the equality
\begin{equation}
Z_{R, w}^T = \varrho_R(Z_{R, R*w}^T(w)).
\end{equation}
holds for all $w \in \mathcal{S}^1$.

In light of this definition, Theorems 1.167 and 1.187 can then be reformulated as follows:

**Theorem 1.201.** The pair $(\mathbb{R}, \zeta)$ satisfies the extended double shuffle relations.

This theorem is a source of new relations among multiple zeta values that cannot be obtained by comparing the usual shuffle and stuffle product. For the next result see [IKZ06, Thm. 2].

**Corollary 1.202.** Let $w_1 \in \mathcal{S}^1$ and $w_0 \in \mathcal{S}^0$. Then
\begin{equation}
\zeta_{w_1 \cup w_0 - w_1 * w_0} = 0.
\end{equation}

For example, since $x_1 \cup w - x_1 * w$ belongs to $\mathcal{S}^0$ for every word $w \in \mathcal{S}^0$ (Exercise 1.206), we deduce the so-called **Hoffman relation**
\begin{equation}
\zeta(x_1 \cup w - x_1 * w) = 0,
\end{equation}
which implies Euler’s sum formula (1.57) by Exercise 1.207.

1.7.6. **The universal algebra satisfying the extended double shuffle relations.** By considering the quotient of $\mathcal{S}^0$ by all extended double shuffle relations, we obtain an algebra $R_{EDS}$ and a map $Z_{EDS}: \mathcal{S}^0 \to R_{EDS}$ such that the pair $(R_{EDS}, Z_{EDS})$ satisfies the extended double shuffle relations. It is the universal one in the following sense: for any $(R, Z_R)$ satisfying the extended double shuffle relations, there exists a unique map $\varphi_R: R_{EDS} \to R$ such that the diagram
\begin{equation}
\begin{CD}
\mathcal{S}^0 @>>> R_{EDS} \\
@VVZ_{EDS}V @VV\varphi_RV \\
\mathcal{S}^0 @>>\varphi_R>
\end{CD}
\end{equation}
commutes. The algebra $R_{EDS}$ is the quotient of $\mathcal{S}^0$ by all extended double shuffle relations.

The following conjecture describes the combinatorial structure of the algebra of multiple zeta values.

**Conjecture 1.204.** The map $\varphi_R$ is injective. Equivalently the algebra $Z$ of multiple zeta values is isomorphic to $R_{EDS}$.

**Remark 1.205.** The finite double shuffle relations are linear and homogeneous with respect to the weight. Moreover, the extended double shuffle relations are also homogeneous (Exercise 1.209). Since the coefficients of the power series $A_R$ are polynomials in zeta values, the extended double shuffle relations relations are polynomial in the MZVs. Since products of MZVs can be reduced to linear combinations of MZVs using either the shuffle or the stuffle product, we can reduce the extended
double shuffle relations to linear ones. Hence, all possible relations among MZVs are conjectured to be generated by homogeneous linear relations.

\* \* \*

**Exercise 1.206.** Show that \( x_1 \cup w - x_1 \ast w \) belongs to \( \mathcal{H}^0 \) for all \( w \in \mathcal{H}^0 \).

**Exercise 1.207.** Deduce Euler’s sum formula (1.57) from the Hoffman relation. [Hint: take \( w = x_0^{p-1}x_1 \).]

**Exercise 1.208.** Show that \( \gamma_k \) is a polynomial in \( \zeta(2), \zeta(3), \ldots \), that is homogeneous of weight \( k \).

**Exercise 1.209.** Use Exercise 1.208 to prove that the EDS relations are homogeneous.

**Exercise 1.210.** Which identities do we get from the comparison of the regularized multiple zeta values \( \zeta_s(1, 1, 2) \) and \( \zeta(1, 1, 2) \)?

**Exercise 1.211.** Prove Theorem 1.177.

**Exercise 1.212.** Check the estimates

\[
\zeta_M(s) = \sum_{k=0}^n a_k \left( \log M + \gamma + O \left( \frac{1}{M} \right) \right)^k = \sum_{k=0}^n a_k (\log M + \gamma)^k + O \left( \frac{1}{M} \log^{n-1}(M) \right).
\]

**Exercise 1.213.** Prove the estimate (1.194).

**Exercise 1.214.** Use Corollary 1.202 to prove that the identity

\[
\zeta(1^n \ast w) = 0
\]

holds for all \( w \in \mathcal{H}^0 \) and \( m \geq 1 \).
2. Periods of mixed Hodge structures

In this chapter, we introduce the first tools from algebraic geometry that will be needed for the study of multiple zeta values. Our main goal is to show that all these numbers can be obtained by integrating an algebraic differential form over a topological cycle on an algebraic variety defined over the field of rational numbers. The extra structures carried by cohomology will then give non-trivial information about multiple zeta values. With this in mind, we begin by recalling the definition of singular homology and cohomology of a topological space $M$ in Section 2.1. It is a classical theorem of de Rham that, whenever $M$ is a differentiable manifold, singular cohomology can be computed using differential forms. More precisely, the map that sends a differential form to the integration functional on singular homology induces an isomorphism between de Rham cohomology and singular cohomology. If $M$ underlies a complex algebraic variety $X$, this cohomology can be even computed using differential forms with polynomial coefficients. As we explain in Sections 2.2 and 2.3, it is isomorphic to algebraic de Rham cohomology by a theorem of Grothendieck. A remarkable consequence is that, when $X$ is defined over $\mathbb{Q}$, we get two different rational structures on the same complex vector space that are not compatible. This is not bad news, quite the opposite: the comparison between them produces an interesting class of complex numbers called periods; we define them in various equivalent ways in Section 2.4. Then, in Section 2.5, we explain how to interpret multiple zeta values as periods of a cohomology group built out of the moduli spaces $M_{0,n}$ following Goncharov and Manin. Another important result relying on the comparison isomorphism is that the cohomology of $X$ is equipped with two filtrations the interaction of which gives rise to a mixed Hodge structure, a notion developed by Deligne at the beginning of the 70s. We explain the definition in Section 2.6 and how to compute certain extension groups in the category of mixed Hodge structures in Section 2.7. In Section 2.8, we sketch some of the ideas in the proof that the cohomology of any algebraic variety carries a mixed Hodge structure and we give many examples, in particular of Hodge structures of mixed Tate type. Conjecturally, mixed Hodge structures of algebraic varieties over $\mathbb{Q}$ capture all algebraic relations between periods. As an illustration, in the final Section 2.9 we go back to the interpretation of $\zeta(2)$ as a period of a pair of algebraic varieties, we take a closer look at the mixed Hodge structure on its cohomology, and we indicate how the information we obtain may be used to prove “by pure thought” that $\zeta(2)$ is a rational multiple of $\pi^2$.

2.1. Singular homology and cohomology. We begin by briefly recalling the definition of singular homology and cohomology of a topological space; for more details, we refer the reader to Chapters 2 and 3 of Hatcher’s book [Hat02].

For each integer $n \geq 0$, let

$$\Delta_{st}^n = \left\{(t_0, \ldots, t_n) \in \mathbb{R}^{n+1} \mid \sum_{i=0}^{n} t_i = 1 \text{ and } t_i \geq 0 \text{ for } i = 0, \ldots, n\right\}$$

be the standard $n$-dimensional simplex in $\mathbb{R}^{n+1}$. For each integer $i = 0, \ldots, n+1$, there is a face map $\delta^i: \Delta_{st}^n \to \Delta_{st}^{n+1}$ given by plugging a 0 at the $i$-th coordinate:

$$\delta^i(t_0, \ldots, t_n) = (t_0, \ldots, t_{i-1}, 0, t_i, \ldots, t_n).$$
Remark 2.1. The standard simplex $\Delta^n_{st}$ is homeomorphic to the simplex $\Delta^n$ from Notation 1.113 (Exercise A.180). The representation we use here is more symmetric and enables one to write down the face maps in a uniform way. By contrast, working with $\Delta^n$ is more convenient for decomposing a product of simplices (see Section 1.5.3 and Example A.169).

Let $M$ be a topological space. A continuous map $\sigma: \Delta^n_{st} \to M$ is called a singular $n$-simplex on $M$. For each $n \geq 0$, let

$$C_n(M) = \bigoplus_{\sigma: \Delta^n_{st} \to M} \mathbb{Z}\sigma$$

be the free abelian group generated by singular $n$-simplices on $M$. The elements of $C_n(M)$ are thus finite linear combinations with integral coefficients of continuous maps $\sigma: \Delta^n_{st} \to M$; they are called singular $n$-chains on $M$, or simply singular chains when $n$ is clear from the context. For example, a singular 0-chain is a linear combination of points of $M$ and a singular 1-chain is a linear combination of paths $\gamma: [0, 1] \to M$, up to identifying $[0, 1]$ with the simplex $\Delta^1_{st}$ through the homeomorphism $t \mapsto (t, 1-t)$. That is,

$$C_0(M) = \bigoplus_{p \in M} \mathbb{Z}p, \quad C_1(M) = \bigoplus_{\gamma: [0, 1] \to M} \mathbb{Z}\gamma.$$

To make the notation uniform in what follows, we also set $C_n(M) = 0$ for all $n < 0$.

For each $n \geq 1$, we define a boundary homomorphism

$$\partial_n: C_n(M) \longrightarrow C_{n-1}(M)$$

(2.2)

$$\sigma \mapsto \sum_{i=0}^{n} (-1)^i (\sigma \circ \delta^i).$$

This is well defined, since $\sigma \circ \delta^i: \Delta^{n-1}_{st} \to \Delta^n_{st} \to M$ is a singular $(n-1)$-simplex on $M$, namely the restriction of $\sigma$ to the face of $\Delta^n_{st}$ defined by the equation $t_i = 0$. We also set $\partial_n = 0$ on $C_n(M)$ for all $n \leq 0$. Thanks to the alternating signs in the above formula, the boundary maps satisfy

$$\partial_{n-1} \circ \partial_n = 0$$

for each integer $n$ (Exercise 2.46), thus making

(2.3)  
$$\begin{pmatrix} C_0(M) & \partial_0 & \partial_1 & \partial_2 & \cdots \end{pmatrix}$$

into a chain complex of abelian groups in the sense of Definition A.7 v) from the appendix: the singular chain complex of $M$.

Elements in the kernel of the boundary map $\partial_n$ are called closed singular chains, or more often cycles, and elements in the image of $\partial_{n+1}$ are called boundaries.

Definition 2.4. Let $n$ be an integer. The singular homology in degree $n$ of $M$ is the $n$-th homology group

$$H_n(M, \mathbb{Z}) = \frac{\text{Ker}(\partial_n: C_n(M) \longrightarrow C_{n-1}(M))}{\text{Im}(\partial_{n+1}: C_{n+1}(M) \longrightarrow C_n(M))}$$

of the singular chain complex of $M$. In other words, $H_n(M, \mathbb{Z})$ is the quotient of the abelian group of cycles by the subgroup of boundaries.
Example 2.5. In degree zero, $H_0(M, Z)$ is the direct sum of copies of $Z$ indexed by the set $\pi_0(M)$ of path-connected components of $M$. Indeed, any two points $p$ and $q$ in the same component define the same element of $H_0(M, Z)$ since $q - p$ is the boundary of a path $\gamma : [0, 1] \to M$ satisfying $\gamma(0) = p$ and $\gamma(1) = q$. Therefore, choosing a point on each path-connected component we obtain a set of generators of $H_0(M, Z)$. On the other hand, since $[0, 1]$ is path-connected, the image of a continuous map $\gamma : [0, 1] \to M$ is contained in a path-connected component, and this implies that all elements in the previous set of generators are linearly independent.

The construction of singular homology is functorial. For each continuous map of topological spaces $f : M_1 \to M_2$, sending a singular $n$-simplex $\sigma : \Delta^n \to M_1$ on $M_1$ to the singular $n$-simplex $f \circ \sigma : \Delta^n \to M_2$ on $M_2$ induces homomorphisms (2.6)

$$f_* : C_n(M_1) \to C_n(M_2)$$

that are compatible with the boundary maps $\partial_n$ (Exercise 2.47), and hence homomorphisms of homology groups, still denoted by

$$f : H_n(M_1, Z) \to H_n(M_2, Z).$$

Dualizing the definitions of singular chains and boundary maps, we find the free abelian group of singular $n$-cochains

$$C^n(M) = \text{Hom}_Z(C_n(M), Z),$$

as well as coboundary maps $d^n : C^n(M) \to C^{n+1}(M)$. In particular, $C_n(M)$ and $d^n$ are zero for all $n < 0$. Explicitly, $d^n$ maps a singular $n$-cochain $\eta : C_n(M) \to Z$ to the singular $(n + 1)$-cochain that takes the value (2.7)

$$(d^n \eta)(\sigma) = \eta(\partial_{n+1} \sigma)$$

on an $(n + 1)$-singular chain $\sigma$ on $M$. These coboundary maps satisfy

$$d^{n+1} \circ d^n = 0$$

for each integer $n$ (Exercise 2.46), thus making (2.8)

$$(C^*(M), d^*) = \left[ \cdots \to C^n(M) \xrightarrow{d} C^{n+1}(M) \xrightarrow{d} \cdots \right]$$

into a cochain complex of abelian groups in the sense of Definition A.7) from the appendix: the singular cochain complex of $M$. The elements of the kernel of $d^n$ are called cocycles and the elements of the image coboundaries.

Definition 2.9. Let $n$ be an integer. The singular cohomology in degree $n$ of $M$ is the $n$-th cohomology group

$$H^n(M, Z) = \frac{\ker(d^n : C^n(M) \to C^{n+1}(M))}{\im(d^{n-1} : C^{n-1}(M) \to C^n(M))}$$

of the singular cochain complex of $M$. In other words, $H^n(M, Z)$ is the quotient of the abelian group of cocycles by the subgroup of coboundaries.

Similarly as above, singular cohomology is functorial: from a continuous map of topological spaces $f : M_1 \to M_2$ we get a homomorphism $f^* : C^n(M_2) \to C^n(M_1)$ by sending a singular $n$-cochain $\eta : C_n(M_2) \to Z$ on $M_2$ to the singular $n$-cochain $\eta \circ f_* : C_n(M_1) \to Z$ on $M_1$ obtained by composition with (2.6). The map $f^*$ being compatible with the coboundaries $d^n$ (Exercise 2.47), it induces a homomorphism

$$f^* : H^n(M_2, Z) \to H^n(M_1, Z).$$
of cohomology groups that we still denote by the same symbol.

**Remark 2.10.**

i) We defined singular homology and cohomology with integral coefficients, but the same construction extends to other coefficient rings \( \Lambda \); the resulting objects are then \( \Lambda \)-modules. In fact, for any ring \( \Lambda \) the unique ring morphism \( \mathbb{Z} \to \Lambda \) induces a map of \( \Lambda \)-modules

\[
H^*(M, \mathbb{Z}) \otimes_{\mathbb{Z}} \Lambda \longrightarrow H^*(M, \Lambda).
\]

By the *universal coefficient theorem* (see e.g. [Hat02, §3.A]), this map is an isomorphism if \( \Lambda \) is a field \( k \) of characteristic zero:

\[
H^*(M, k) \cong H^*(M, \mathbb{Z}) \otimes_{\mathbb{Z}} k.
\]

Most of the time, it will be enough for our purposes to work with rational coefficients, that is, to take \( \Lambda = \mathbb{Q} \).

ii) Singular homology and cohomology are defined for any topological space. When \( M \) underlies a differentiable manifold, instead of continuous maps \( \sigma : \Delta^n_{st} \to M \) we may use smooth maps, that is, maps admitting a \( C^\infty \) extension to an open neighborhood of \( \Delta^n_{st} \) in \( \mathbb{R}^{n+1} \). It is a standard result of differential geometry (see [War83, §5.32] or [Lee13, Thm. 18.7]) that the singular homology and cohomology groups remain the same when one considers this restricted set of generators.

iii) Working with rational coefficients, we may identify singular cohomology with the linear dual of singular homology

\[
\text{(2.11)} \quad H^n(M, \mathbb{Q}) \cong \text{Hom}_{\mathbb{Q}}(H_n(M, \mathbb{Q}), \mathbb{Q}),
\]

and think of cohomology classes as linear functionals on homology. This point of view will be useful to discuss periods. However, the isomorphism (2.11) cannot hold integrally since the group \( \text{Hom}(H_n(M, \mathbb{Z}), \mathbb{Z}) \) is always torsion free, while \( H^n(M, \mathbb{Z}) \) may have torsion (see Exercise 2.49 for an example).

In the sequel, we will mainly consider the singular cohomology with rational coefficients of complex algebraic varieties, which deserves the special name of *Betti cohomology*. Namely, given an algebraic variety \( X \) defined over a subfield \( k \) of \( \mathbb{C} \), the set of complex points \( X(\mathbb{C}) \) carries a natural topology coming from the euclidean topology of \( \mathbb{C} \); it is usually called the *classical* or the *analytic*, or yet the *transcendental* topology to distinguish it from the Zariski topology on \( X \).

**Definition 2.12.** Let \( k \) be a subfield of \( \mathbb{C} \) and let \( X \) be an algebraic variety over \( k \). The *Betti cohomology* \( H^*_B(X) \) of \( X \) is the singular cohomology with rational coefficients of the set of complex points \( X(\mathbb{C}) \) equipped with the classical topology:

\[
H^*_B(X) = H^*(X(\mathbb{C}), \mathbb{Q}).
\]

2.1.1. **Properties of singular homology and cohomology.** Singular homology and cohomology have many useful properties such as the following.

- **Homotopy invariance:** If \( f : M_1 \to M_2 \) is a homotopy equivalence, then the maps
  
  \[
  f_* : H_*(M_1, \mathbb{Z}) \longrightarrow H_*(M_2, \mathbb{Z}), \quad f^* : H^*(M_2, \mathbb{Z}) \longrightarrow H^*(M_1, \mathbb{Z})
  \]

  are isomorphisms of abelian groups.
Mayer-Vietoris: for any cover $M = U \cup V$ by open subspaces $U$ and $V$, there is a long exact sequence

$$\cdots \longrightarrow H_n(U \cap V, \mathbb{Z}) \overset{\alpha}{\longrightarrow} H_n(U, \mathbb{Z}) \oplus H_n(V, \mathbb{Z}) \overset{\beta}{\longrightarrow} H_n(M, \mathbb{Z}) \longrightarrow \cdots$$

(2.13)

Letting $\iota_{U \cap V}: U \cap V \to U$ denote the inclusion, and similarly for other pairs of a space and a subspace, the maps $\alpha$ and $\beta$ are given by

$$\alpha = (- (\iota_{U \cap V, U})_*, (\iota_{U \cap V, V})_*), \quad \beta = (\iota_{U, M})_* + (\iota_{V, M})_*.$$  

The morphism connecting two lines is defined as follows: using barycentric subdivision (see, for instance, [Hat02, p.150]), each $n$-cycle $\sigma$ on $M$ can be written as a sum $\sigma = \sigma' + \sigma''$ of $n$-chains $\sigma'$ and $\sigma''$ on $U$ and $V$ respectively. The class $[\sigma]$ is then mapped to the class of $\partial \sigma' = - \partial \sigma''$, which represents a well-defined element of $H_{n-1}(U \cap V, \mathbb{Z})$. Dually, there is a long exact sequence in cohomology

$$\cdots \longleftarrow H^n(U \cap V, \mathbb{Z}) \longleftarrow H^n(U, \mathbb{Z}) \oplus H^n(V, \mathbb{Z}) \longleftarrow H^n(M, \mathbb{Z}) \longleftarrow \cdots$$

(2.14)

K"unneth formula: Singular homology and cohomology are equipped with an external product that induces isomorphisms

$$H_n(M_1 \times M_2, \mathbb{Q}) \simeq \bigoplus_{i+j=n} H_i(M_1, \mathbb{Q}) \otimes_{\mathbb{Q}} H_j(M_2, \mathbb{Q}),$$

(2.15)

$$H^n(M_1 \times M_2, \mathbb{Q}) \simeq \bigoplus_{i+j=n} H^i(M_1, \mathbb{Q}) \otimes_{\mathbb{Q}} H^j(M_2, \mathbb{Q}).$$

(2.16)

Note that for the K"unneth formula to be true as stated we need to consider cohomology with rational coefficients (Exercise 2.51). A more sophisticated formula involving Tor groups is true with integral coefficients, see e.g. [Hat02, Thm. 3B.6].

The combinatorial structure involved in the construction of the external product is very much related to that of multiple zeta values. We focus on the case of the homology, the cohomological picture being obtained by duality.

The tensor product (see Example A.27) of the chain complexes $C_*(M_1)$ and $C_*(M_2)$ is the chain complex $C_*(M_1) \otimes C_*(M_2)$ with degree $n$ term

$$\bigoplus_{k=0}^n C_k(M_1) \otimes C_{n-k}(M_2)$$

and differential $\partial$ given on $\alpha \in C_k(M_1)$ and $\beta \in C_{n-k}(M_2)$ by

$$\partial(\alpha \otimes \beta) = \partial \alpha \otimes \beta + (-1)^k \alpha \otimes \partial \beta.$$  

First, there is a map

$$F: C_*(M_1 \times M_2) \longrightarrow C_*(M_1) \otimes C_*(M_2).$$

To describe it, observe that a simplex in $M_1 \times M_2$ is given by a pair $(\sigma, \tau)$, where $\sigma$ is a simplex in $M_1$ and $\tau$ is a simplex in $M_2$. Then $F$ is defined, for $(\sigma, \tau) \in$
One can check that \( F \) is a morphism of chain complexes, that is, that the equality \( \partial \circ F = F \circ \partial \) holds. Therefore, \( F \) induces a map in homology

\[
H_n(M_1 \times M_2, \mathbb{Z}) \to H_n(C_\ast(M_1) \otimes C_\ast(M_2)).
\]

Second, there is a map

\[
G : C_\ast(M_1) \otimes C_\ast(M_2) \to C_\ast(M_1 \times M_2)
\]

defined using shuffles as in Section 1.5.3. Namely, given simplices \( \alpha \in C_k(M_1) \) and \( \beta \in C_{n-k}(M_2) \), we set

\[
G(\alpha \otimes \beta) = \sum_{\sigma \in \Omega(k,n-k)} (\alpha \otimes \beta)_\sigma,
\]

where, if we see \( \alpha \) and \( \beta \) as maps from the non-standard simplices \( \Delta^k \) and \( \Delta^{n-k} \) respectively (see Remark 2.1), then \((\alpha \otimes \beta)_\sigma\) is the map \( \Delta^n \to M_1 \times M_2 \) given by

\[
(\alpha \otimes \beta)_\sigma(t_1, \ldots, t_n) = (\alpha(t_{\sigma(1)}, \ldots, t_{\sigma(k)}), \beta(t_{\sigma(k+1)}, \ldots, t_{\sigma(n)})).
\]

The map \( G \) is again a morphism of chain complexes. Hence induces maps

\[
H_n(C_\ast(M_1) \otimes C_\ast(M_2)) \to H_n(M_1 \times M_2, \mathbb{Z}), \quad n \geq 0.
\]

The compositions \( F \circ G \) and \( G \circ F \) are both homotopically equivalent to the identity, which implies that the maps (2.18) and (2.20) are isomorphisms inverse to each other. This fact can be proved in a completely abstract way without writing down the explicit homotopies, by using the acyclic models theorem.

An augmented chain complex of abelian groups is the data of a chain complex of abelian groups \( C_\ast \) satisfying \( C_n = 0 \) for \( n < 0 \) and a homomorphism \( \varepsilon : C_0 \to \mathbb{Z} \) satisfying \( \varepsilon \circ \partial = 0 \), which is called an augmentation. The tensor product of augmented complexes \( B_\ast \) and \( C_\ast \) is again an augmented complex, with augmentation

\[
\varepsilon_B \otimes \varepsilon_C : B_0 \otimes C_0 \to \mathbb{Z} \otimes \mathbb{Z} \xrightarrow{\text{mult}} \mathbb{Z}.
\]

For any topological space \( M \), the complex of singular chains \( C_\ast(X) \) is an augmented complex with augmentation

\[
\varepsilon : C_0(M) \to \mathbb{Z}, \quad \sum a_\sigma \sigma \mapsto \sum a_\sigma.
\]

The acyclic models theorem implies the following result:
Theorem 2.21 (Eilenberg-Zilber, [EZ53]). Consider singular chains as a covariant functor $C_*$ from the category of topological spaces to the category of augmented chain complexes of abelian groups.

i) There exists a natural transformation of functors
$$\alpha: C_*(\cdot \times \cdot) \to C_*(\cdot) \otimes C_*(\cdot)$$
that is unique up to a natural homotopy.

ii) There exists a natural transformation of functors
$$\beta: C_*(\cdot) \otimes C_*(\cdot) \to C_*(\cdot \times \cdot)$$
that is unique up to a natural homotopy.

iii) The natural transformations $\alpha$ and $\beta$ are natural homotopy equivalences that are inverse to each other.

In order to see that the maps $F$ and $G$ defined previously are candidates to the natural transformations $\alpha$ and $\beta$ we only need to solve Exercise 2.50, that is a straightforward although cumbersome exercise. Then Theorem 2.21 implies that $F$ and $G$ are homotopy equivalences inverse to each other as claimed.

The last piece of information we need in order to obtain the Künneth isomorphism as stated in (2.15) is that there are natural injective maps
$$\bigoplus_{k=0}^n H_k(C_*(M_1)) \otimes H_{n-k}(C_*(M_2)) \to H_n(C_*(M_1) \otimes C_*(M_2)).$$
that become isomorphisms after tensoring by the field of rational numbers (use [Wei94, Thm. 3.6.3], taking into account that every module over a field is flat). It is only in this last step where it is necessary to have rational coefficients.

Remark 2.22. Note the similarities between the map $F$ and the deconcatenation coproduct that will be introduced later in Example 3.62 and between the map $G$ and the shuffle product in the same example.

Cup-product: One of the advantages of working with cohomology rather than homology is that combining the external product with the contravariant functoriality of cohomology one obtains a product in cohomology called the *cup-product*. Namely, consider the diagonal embedding
$$\text{diag}: M \to M \times M.$$ 
$$x \mapsto (x, x)$$
The cup-product is defined as the composition
$$H^k(M, \mathbb{Z}) \otimes H^{n-k}(M, \mathbb{Z}) \to H^n(M \times M, \mathbb{Z}) \xrightarrow{\text{diag}^*} H^n(M, \mathbb{Z}).$$

Finiteness: Let $X$ be a quasi-projective algebraic variety over a field $k \subset \mathbb{C}$. Then Betti cohomology $H^n_b(X)$ is finite-dimensional. Indeed, let $\overline{X} \subset \mathbb{P}^n$ be a projective compactification of $X$ and write $Z = \overline{X} \setminus X$. By Exercise 2.55, we can embed $\mathbb{P}^n(\mathbb{C})$ as a bounded semi-algebraic subset of $\mathbb{R}^N$ for some big enough $N$. By a theorem of Lojasiewicz [Loj64, Thm. 3], there is a finite triangulation of $\mathbb{P}^n(\mathbb{C})$ that induces a triangulation of $\overline{X}(\mathbb{C})$ and a triangulation of $Z(\mathbb{C})$. The pair $(\overline{X}(\mathbb{C}), Z(\mathbb{C}))$ is hence homeomorphic to a pair $(K, K')$, where $K$ and $K'$ are finite simplicial complexes (see [Hat02, p.107] for the notion of simplicial complex). After, if necessary,
passing to a refinement of $K$, we may assume that the intersection with $K'$ of every simplex $\sigma$ of $K$ is either empty, all of $\sigma$, or one of its faces. In that case, the set

$$K'' = \bigcup_{\sigma \in K} \sigma$$

is a finite simplicial complex homotopically equivalent to $K \setminus K'$. Therefore,

$$X(\mathbb{C}) = \overline{X(\mathbb{C})} \setminus \mathcal{Z}(\mathbb{C})$$

has the homotopy type of a finite CW complex.

**Remark 2.23.** In fact, using Nagata’s compactification theorem [Con07], the fact that every variety can be embedded as a closed subvariety of a smooth one, and Grauert’s embedding theorem [Gra58], the argument carries over to any variety (separated scheme of finite type) over $k$.

**Example 2.24.** Let $M = \mathbb{C} \setminus \{0\}$ be the punctured complex plane. Since $M$ is path-connected, $H_0(M, \mathbb{Z})$ is the free abelian group generated by the singular simplex $\sigma_0: \Delta^0_0 \to M$ that maps $1 \in \Delta^0_0$ to $1 \in M$. Using that $M$ is homotopic to the unit circle $S^1$ and the Mayer–Vietoris long exact sequence for the cover of $S^1$ by two arcs of circle, one can show that the group $H_1(M, \mathbb{Z})$ is also free of rank one, generated by the singular simplex

$$\sigma_1: \Delta^1_1 \to M, \quad (t, 1-t) \mapsto \exp(2\pi it),$$

and that all other homology groups vanish.

**Poincaré duality:** Let $M$ be an oriented compact topological manifold of dimension $n$. For instance, the topological space underlying the analytical space $X(\mathbb{C})$ associated with a smooth proper variety $X$ over the field of complex numbers of dimension $d$ is a topological manifold of dimension $2d$. Then, for each $0 \leq j \leq 2d$, there is a canonical isomorphism

$$(2.25) \quad H^j(M, \mathbb{Z}) \simeq H_{n-j}(M, \mathbb{Z}).$$

If we consider cohomology with rational coefficients, we obtain isomorphisms

$$(2.26) \quad H^j(M, \mathbb{Q}) \simeq \text{Hom}(H^{2d-j}(M, \mathbb{Q}), \mathbb{Q})$$

by the universal coefficients theorem.

**2.1.2. Relative homology and cohomology.** There is also a relative version of singular homology, in which chains are allowed to have a non-zero boundary as long as it lies in a fixed subspace. If $\iota: N \hookrightarrow M$ is a topological subspace, the morphism of chain complexes $\iota_*: C_*(N) \to C_*(M)$ is injective. The relative singular complex $C_*(M, N)$ is defined as the cone of this morphism:

$$C_*(M, N) = \text{cone}(\iota_*),$$

which by Remark A.20 in the appendix is the complex given by

$$C_n(M, N) = C_{n-1}(N) \oplus C_n(M)$$

in degree $n$, together with the differential

$$\partial(a, b) = (-\partial a, \partial b + \iota_*(a)).$$
Definition 2.27. Let \( n \) be an integer. The relative singular homology in degree \( n \) of a pair \((M, N)\) consisting of a topological space \( M \) and a subspace \( N \subseteq M \) is the \( n \)-th homology group of the relative singular complex \( C_*(M, N) \). We write
\[
H_n(M, N; \mathbb{Z}) = H_n(C_*(M, N)).
\]

Exercise 2.53 presents an alternative construction of relative homology in terms of the quotient \( C_*(M)/C_*(N) \).

Remark 2.28. An element of the relative homology \( H_n(M, N; \mathbb{Z}) \) is represented by a pair \((\sigma_N, \sigma_M)\) consisting of singular chains \( \sigma_N \in C_{n-1}(N) \) and \( \sigma_M \in C_n(M) \) satisfying \( \partial_{n-1} \sigma_N = 0 \) and \( \partial_n \sigma_M = -\iota_* \sigma_N \). Since \( \iota_* \) is injective, the singular chain \( \sigma_N \) is determined by the latter condition, which implies the former thanks to the relation \( \partial_n \circ \partial_{n-1} = 0 \). In other words, relative homology classes are represented by singular chains in \( M \) which are not necessarily closed but whose boundary is constrained to lie in the subspace \( N \).

By design, \( C_*(M, N) \) fits into a short exact sequence of complexes
\[
0 \rightarrow C_*(M) \xrightarrow{b} C_*(M, N) \xrightarrow{a} C_*(N)[-1] \rightarrow 0,
\]
where the map \( b \) sends \( b \) to \((0, b)\), and the map \( a \) sends \((a, b)\) to \( a \). Above, the shifted complex \( C_*(N)[-1] \) has \( C_{n-1}(N) \) as degree \( n \) term, with differential \(-\partial_{n-1}\), so that the relation \( H_n(C_*(N)[-1]) = H_{n-1}(N, \mathbb{Z}) \) holds. The associated long exact sequence then reads
\[
\cdots \rightarrow H_n(M, \mathbb{Z}) \xrightarrow{\iota_*} H_n(M, N; \mathbb{Z}) \xrightarrow{\partial} H_{n-1}(N, \mathbb{Z}) \rightarrow H_{n-1}(M, N; \mathbb{Z}) \rightarrow \cdots,
\]
and the connecting morphisms are given by
\[
-\iota_* : H_*(N, \mathbb{Z}) \rightarrow H_*(M, \mathbb{Z}),
\]
the opposite of the maps induced by the inclusion \( \iota : N \hookrightarrow M \).

Remark 2.31. The reason why the negative sign appears in the connecting morphism is explained in Remark A.65. Instead of looking at the short exact sequence (2.29), we may consider the distinguished triangle
\[
C_*(N) \xrightarrow{\iota_*} C_*(M) \rightarrow C_*(M, N) \rightarrow C_*(N)[-1]
\]
(in the language of Section A.3) to obtain the long exact sequence of abelian groups
\[
\cdots \rightarrow H_n(N, \mathbb{Z}) \xrightarrow{\iota_*} H_n(M, \mathbb{Z}) \xrightarrow{\partial} H_{n-1}(N, \mathbb{Z}) \rightarrow H_{n-1}(M, \mathbb{Z}) \rightarrow \cdots
\]
where the maps from \( H_n(N, \mathbb{Z}) \) to \( H_n(M, \mathbb{Z}) \) are not affected by a sign anymore.

Example 2.32. Consider \( M = \mathbb{C} \setminus \{0\} \) and let \( N = \{p, q\} \subseteq M \) be a subspace consisting of two distinct points. Let \( \sigma_2 : \Delta^1 \rightarrow M \) be any continuous map such that \( \sigma_2(0, 1) = p \) and \( \sigma_2(1, 0) = q \). Then
\[
\partial \sigma_2 = p - q \in C_0(N),
\]
so $\sigma_2$ defines a relative chain. It follows from the long exact sequence (2.30) that the only non-trivial relative homology group is $H_1(M, N; \mathbb{Z})$, which has a basis given by the chain $\sigma_1$ from Example 2.24 and $\sigma_2$ (see Figure 2).

In a similar way, one defines relative cohomology groups. Let $\iota: N \hookrightarrow M$ be the inclusion of a topological subspace and $\iota^*: C^*(M) \to C^*(N)$ the induced map on cochain complexes. We consider the total complex $C^*(M, N) = \text{Tot}(\iota^*) = \text{cone}(\iota^*)[-1]$, as explained in Example A.26 from the appendix. Explicitly, this is the complex given in degree $n$ by

$$C^n(M, N) = C^n(M) \oplus C^{n-1}(N)$$

It fits into a distinguished triangle (see Section A.3.2)

$$C^*(M, N) \longrightarrow C^*(M) \overset{\iota^*}{\longrightarrow} C^*(N) \longrightarrow C^*(M, N)[1].$$

DEFINITION 2.33. Let $n$ be an integer. The relative singular cohomology in degree $n$ of the pair $(M, N)$ is the $n$-th cohomology group of the complex $C^*(M, N)$, that is,

$$H^n(M, N; \mathbb{Z}) = H^n(C^*(M, N)).$$

By construction, relative cohomology fits into a long exact sequence of abelian groups

$$\cdots \longrightarrow H^n(M, N; \mathbb{Z}) \longrightarrow H^n(M, \mathbb{Z}) \overset{\iota^*}{\longrightarrow} H^n(N, \mathbb{Z}) \longrightarrow$$

$$\cdots \longrightarrow H^{n+1}(M, N; \mathbb{Z}) \longrightarrow H^{n+1}(M, \mathbb{Z}) \longrightarrow \cdots$$

(2.34)

REMARK 2.35. It is instructive to compare the definitions of relative homology and cohomology. In the first case, we use the cone of the morphism $\iota_*$, whereas in the second case we use the total complex of $\iota^*$. Both points of view are equivalent according to Example A.26 from the appendix. The use of the cone or of the total
complex of a morphism of complexes depends on whether we want the degree of the resulting complex to agree with the degree of the source or the target complex.

2.1.3. **Singular cohomology as sheaf cohomology.** Under mild assumptions on the topological space $M$, the singular cohomology groups $H^*(M, \mathbb{Z})$ can be identified with the sheaf cohomology groups of the constant sheaf. More precisely, let $\mathbb{Z}_M$ be the sheaf associated with the presheaf that assigns to each open subset $V$ of $M$ the abelian group $\mathbb{Z}$, with all restriction maps equal to the identity. Its sections are

$$\mathbb{Z}_M(V) = \{\text{locally constant functions } V \to \mathbb{Z}\},$$

that is, those functions with the property that each point of $V$ has an open neighborhood on which they are constant.

**Theorem 2.36.** Assume that $M$ is locally contractible and that every open subset of $M$ is paracompact. There is a canonical isomorphism

$$(2.37) \quad H^*(M, \mathbb{Z}) \simeq H^*(M, \mathbb{Z}_M),$$

where the left-hand side is the singular cohomology of $M$ and the right-hand side is the sheaf cohomology of $\mathbb{Z}_M$.

The proof of this result is presented in Section A.9.8 of the appendix, see Theorem A.236. The main idea is to introduce the sheaves $\tilde{C}^n$ on $M$ associated with the presheaves $U \mapsto C^n(U)$. As $n$ varies, they form a complex together with the differentials $d^n: \tilde{C}^n \to \tilde{C}^{n+1}$. The proof of (2.37) then relies on the following three properties of this complex:

i) The natural morphism $(C^*(M), d^*) \to (\tilde{C}^*(M), d^*)$ from the singular chain complex to the complex of global sections is a quasi-isomorphism.

ii) All the sheaves $\tilde{C}^n$ are flasque, and hence hypercohomology can be computed using global sections: $H^*(M, \tilde{C}^*) \simeq H^*(M, \tilde{C}^*(M))$.

iii) The map of sheaves $\mathbb{Z}_M \to \tilde{C}^0$ associated with the map of presheaves that sends 1 to the singular 0-cochain $(\sum n_x[x] \to \sum n_x)$ induces a quasi-isomorphism $\mathbb{Z}_M \to \tilde{C}^*$.

Using the universal coefficient theorem and the fact that tensoring by a field is an exact operation, we deduce that the same result holds for the cohomology with coefficients in a field of characteristic zero, for instance $\mathbb{Q}$.

In the same spirit, relative cohomology, as introduced in 2.1.2, can be written as the hypercohomology of a complex of sheaves. Indeed, let $M$ be a topological space and let $\iota: N \to M$ be the inclusion of a closed subspace. Consider the direct image sheaf $\iota_*\mathbb{Z}_N$ on $M$ whose sections on an open subset $V$ are

$$(\iota_*\mathbb{Z}_N)(V) = \mathbb{Z}_N(V \cap N).$$

Note that this definition makes sense since $V \cap N$ is an open subset of $N$. The stalks of this sheaf are

$$(\iota_*\mathbb{Z}_N)_x = \begin{cases} \mathbb{Z}, & \text{if } x \in N, \\ 0, & \text{if } x \notin N. \end{cases}$$

If $N$ is locally contractible as well, then there is an isomorphism

$$H^*(N, \mathbb{Z}) \simeq H^*(M, \iota_*\mathbb{Z}_N).$$
Indeed, the functor \( \iota_* \) is exact (Exercise A.250), so that we have \( \iota_* \mathbb{Z}_N = R\iota_* \mathbb{Z}_N \), and hence \( H^*(M, \iota_* \mathbb{Z}_N) = H^*(N, \mathbb{Z}_N) \) by (A.215). Moreover, there is a canonical map of sheaves \( \mathbb{Z}_M \to \iota_* \mathbb{Z}_N \) which is abstractly given by the adjunction morphism (A.222) on noting that \( \mathbb{Z}_N = \iota^{-1} \mathbb{Z}_M \), or simply by sending a locally constant function on \( V \) to the locally constant function on \( V \cap N \) obtained by restriction.

**Theorem 2.38.** Let \( \iota : N \to M \) be the inclusion of a closed subspace such that, both \( M \) and \( N \) are locally contractible and every open subset of \( M \) is paracompact, then

\[
H^*(M, N; \mathbb{Z}) \cong H^*(M, \mathbb{Z}_M \to \iota_* \mathbb{Z}_N).
\]

**Proof.** Since the functor \( \iota_* \) is exact, it maps the quasi-isomorphism \( \mathbb{Z}_N \to \tilde{C}_N^* \) to a quasi-isomorphism \( \iota_* \mathbb{Z}_N \to \iota_* \tilde{C}_N^* \). Besides, the sheaves \( \iota_* \tilde{C}_N^* \) are flasque, since the restriction maps \( (\iota_* \tilde{C}_N^*)(V) \to (\iota_* \tilde{C}_N^*)(V') \) for open subsets \( V' \subset V \) are by definition the restriction maps \( \tilde{C}_N^*(V \cap N) \to \tilde{C}_N^*(V' \cap N) \), which are surjective as the sheaves \( \tilde{C}_N^* \) are flasque. To compute the hypercohomology group on the right-hand side, we can therefore replace the complex of sheaves \( \mathbb{Z}_M \to \iota_* \mathbb{Z}_N \) with the double complex of global sections \( \tilde{C}_M^*(M) \to (\iota_* \tilde{C}_N^*)(M) = \tilde{C}_N^*(N) \). Since the source and the target are quasi-isomorphic to the singular cochain complexes \( C^*(M) \) and \( C^*(N) \) respectively, we find:

\[
H^*(M, \mathbb{Z}_M \to \iota_* \mathbb{Z}_N) \cong H^*(\text{Tot}(C^*(M) \xrightarrow{\iota^*} C^*(N))),
\]

which is precisely the definition of the relative singular cohomology groups of the pair \( (M, N) \). \( \square \)

**Remark 2.39.** A similar result is true if \( N \) is not closed, but for that we have to replace \( \iota_* \mathbb{Z}_N \) by \( R\iota_* \mathbb{Z}_N \) because, in general, the functor \( \iota_* \) is not exact.

Let \( U = M \setminus N \) be the complementary open subset and let \( j : U \to M \) denote the inclusion. Consider the extension by zero sheaf \( j_! \mathbb{Z}_U \), which is the sheaf on \( M \) associated with the presheaf

\[
V \mapsto \begin{cases} \mathbb{Z}_U(V), & \text{if } V \subset U, \\ 0, & \text{otherwise}. \end{cases}
\]

The stalks of this sheaf are

\[
(j_! \mathbb{Z}_U)_x = \begin{cases} \mathbb{Z}, & \text{if } x \in U, \\ 0, & \text{otherwise}. \end{cases}
\]

Moreover, there is a canonical map of sheaves \( j_! \mathbb{Z}_U \to \mathbb{Z}_M \) given by the adjunction morphism (A.233) on noting that \( \mathbb{Z}_U = j^{-1} \mathbb{Z}_M \) (concretely, it is induced by the map of presheaves from (2.40) to \( \mathbb{Z}_M \) that, for each open subset \( V \subset U \), sends a locally constant function \( V \to \mathbb{Z} \) to itself regarded as a locally constant function on the open subset \( V \subset M \)). This map and the previous one fit into an exact sequence of sheaves of abelian groups

\[
0 \to j_! \mathbb{Z}_U \to \mathbb{Z}_M \to \iota_* \mathbb{Z}_N \to 0,
\]

as is readily checked stalk by stalk.
Remark 2.42. Thanks to the exact sequence (2.41), the complex $\mathbb{Z}_M \to j_* \mathbb{Z}_U$ is quasi-isomorphic to the complex concentrated in degree zero $j! \mathbb{Z}_U$, and hence relative cohomology can also be expressed as the cohomology of a single sheaf rather than the hypercohomology of a complex of sheaves, namely

$$H^*(M, N; \mathbb{Z}) \simeq H^*(M, j! \mathbb{Z}_U).$$

Moreover, combining (2.41) with Theorem 2.36, we recover the long exact sequence (2.34) of relative cohomology.

2.1.4. Cohomology with compact support and Poincaré duality. Once we have interpreted singular cohomology as sheaf cohomology, we can apply Definition A.231 to define cohomology with compact support.

Definition 2.43. Let $M$ be a locally contractible topological space with all open subsets paracompact. Then the (singular) cohomology of $M$ with compact support is the cohomology with compact support of the sheaf $\mathbb{Z}$:

$$H^*_c(M, \mathbb{Z}) = H^*_c(M, \mathbb{Z}).$$

One defines similarly cohomology with compact support for other coefficients like $\mathbb{Q}$.

Remark 2.44. Another way to define cohomology with compact support is to consider the complex $C^*_{BM}(M)$ of locally finite chains on a topological space $M$. This gives rise to Borel–Moore homology. Then the dual complex $C^*_c(M) = \text{Hom}(C^*_{BM}(M), \mathbb{Z})$ gives rise to cohomology with compact support.

The cohomology with compact support allows us to extend Poincaré duality to non-compact topological manifolds.

Theorem 2.45 (Poincaré Duality). Let $M$ be a oriented topological manifold of dimension $n$ with a finite number of connected components. Then, for each $0 \leq j \leq n$ there is a canonical isomorphism

$$H^j(M, \mathbb{Q}) \simeq \text{Hom}(H^{n-j}_c(M, \mathbb{Q}), \mathbb{Q}).$$

***

Exercise 2.46. Prove that the boundary maps (2.2) in the definition of singular homology satisfy $\partial_{n-1} \circ \partial_n = 0$ for all integers $n \geq 1$. Deduce that the coboundary maps (2.7) in the definition of singular cohomology satisfy $d^{n+1} \circ d^n = 0$ for all integers $n \geq 0$.

Exercise 2.47. Prove that the map $f_*$ from (2.6) is compatible with the boundary maps, and hence defines a morphism in homology. Deduce the same result for singular cochains.

Exercise 2.48. Use the Mayer-Vietoris long exact sequences (2.13) and (2.14) and Example 2.24 to compute the homology and the cohomology of the Riemann sphere $\mathbb{P}^1(\mathbb{C})$.

Exercise 2.49. In this exercise, we compute the homology and the cohomology of the real projective plane.
i) Let $M$ be the Möbius band defined as the quotient

$$ M = [0, 1] \times (0,1) / \sim, $$

where $\sim$ is the equivalence relation generated by $(0, x) \sim (1, 1 - x)$. Prove that the first homology group of $M$ is spanned by the singular simplex

$$ \sigma: \Delta^1_{st} \to M, \quad \sigma(t, 1 - t) = (t, 1/2) $$

and that the simplex

$$ \sigma_1(t, 1 - t) = \begin{cases} 
(2t, 3/4), & \text{if } t \leq 1/2, \\
(2t - 1, 1/4), & \text{if } t \geq 1/2,
\end{cases} $$

is closed and represents the same class as $2\sigma$ in $H_1(M, \mathbb{Z})$.

ii) Let $\mathbb{P}^2(\mathbb{R})$ be the real projective plane viewed as the quotient

$$ \mathbb{P}^2(\mathbb{R}) = S^2 / \sim $$

of the two-dimensional sphere $S^2$ by the equivalence relation generated by $x \sim -x$. Show that $\mathbb{P}^2(\mathbb{R})$ can be covered by an open subset homeomorphic to the unit disc in $\mathbb{R}^2$ and an open subset homeomorphic to the Möbius band from i).

iii) Use the Mayer-Vietoris sequences in homology and cohomology to compute

$$ H_i(\mathbb{P}^2(\mathbb{R}), \mathbb{Z}) = \begin{cases} 
\mathbb{Z}, & \text{if } i = 0, \\
\mathbb{Z}/2\mathbb{Z}, & \text{if } i = 1, \\
0, & \text{if } i = 2.
\end{cases} $$

$$ H^i(\mathbb{P}^2(\mathbb{R}), \mathbb{Z}) = \begin{cases} 
\mathbb{Z}, & \text{if } i = 0, \\
0, & \text{if } i = 1, \\
\mathbb{Z}/2\mathbb{Z}, & \text{if } i = 2.
\end{cases} $$

**Exercise 2.50.** Prove that the maps $F$ and $G$ defined in (2.17) and (2.19) satisfy the following properties:

i) They are morphisms of chain complexes.

ii) They are functorial in $M_1$ and $M_2$, and hence define natural transformations of functors $\alpha: C_\ast(\cdot \times \cdot) \to C_\ast(\cdot) \otimes C_\ast(\cdot)$ and $\beta: C_\ast(\cdot) \otimes C_\ast(\cdot) \to C_\ast(\cdot \times \cdot)$.

iii) They are compatible with the augmentations.

**Exercise 2.51.** Compute the homology and the cohomology of $\mathbb{P}^2(\mathbb{R}) \times \mathbb{P}^2(\mathbb{R})$ and deduce that the Künneth formulas (2.15) and (2.16) do not hold with integral coefficients instead of rational coefficients.

**Exercise 2.52.** Prove that there is a natural short exact sequence

$$ 0 \to \text{Ext}(H_{n-1}(M, \mathbb{Z}), \mathbb{Z}) \to H^n(M, \mathbb{Z}) \to \text{Hom}(H_n(M, \mathbb{Z}), \mathbb{Z}) \to 0. $$

Whenever $H_{n-1}(M, \mathbb{Z})$ is torsion-free, the Ext group vanishes and we get an isomorphism between $H^n(M, \mathbb{Z})$ and the linear dual of $H_n(M, \mathbb{Z})$. 


Exercise 2.53 (An alternative definition of relative homology). We keep the notation from Section 2.1.2. Given a topological space $M$ and a subspace $N$, show that the boundary maps $\partial_n$ yield a complex

$$
\cdots \to C_n(M) \xrightarrow{\partial_n} C_{n-1}(M) \to \cdots
$$

which is quasi-isomorphic to the relative singular homology complex $C_*(M, N)$ (see Exercise A.71). Therefore, one can also define the relative homology of the pair $(M, N)$ as the homology of (2.54). Note that the corresponding long exact sequence is (2.30) shifted by one.

Exercise 2.55. Let $n \geq 0$ be an integer and set $N = 2(n+1)^2$. Prove that the map

$$
(x_0: \ldots: x_n) \mapsto \left( \ldots, \frac{\text{Re}(x_i \bar{x}_j)}{\sum_{m=0}^n x_m \bar{x}_m}, \frac{\text{Im}(x_i \bar{x}_j)}{\sum_{m=0}^n x_m \bar{x}_m}, \ldots \right)
$$

induces a homeomorphism from $\mathbb{P}^n(\mathbb{C})$ onto a closed bounded semi-algebraic subset of $\mathbb{R}^N$ (see [HMS17], p. 62).

2.2. Algebraic de Rham cohomology. Inspired by ideas of Atiyah and Hodge, Grothendieck introduced the de Rham cohomology of algebraic varieties over fields of characteristic zero in his paper [Gro66], which was written shortly after Hironaka’s proof of the resolution of singularities. In this section, we explain the definition of algebraic de Rham cohomology and compute it in a few examples.

2.2.1. Motivation: de Rham’s theorem in differential geometry. Before going into Grothendieck’s construction, we shall give a quick review of the more familiar objects in differential geometry. The reader is encouraged to consult the book by Bott and Tu [BT82] for a very nice exposition of the subject.

Let $M$ be a differentiable manifold of dimension $d$. We denote by $TM$ its tangent bundle of $M$ and by $T^*M$ its cotangent bundle, which is by definition the dual of $TM$; they are both vector bundles of rank $d$ over $M$. For each integer $p \geq 0$, consider the $p$-th exterior power of the cotangent bundle and the sheaf $E_p$ of real vector spaces of smooth sections of $\Lambda^p T^* M$. For each open subset $U$ of $M$, the sections of $E_p$ are given by

$$
E_p(U) = \{ \text{smooth maps } f: U \to \Lambda^p T^* M \text{ such that } \pi \circ f \text{ is the inclusion } U \hookrightarrow M \}.
$$

In particular, $E^0_p$ is the sheaf of smooth functions on $M$. Sections of $E^p_p$ are called smooth differential $p$-forms, or simply differential $p$-forms, and can be written in a local chart with coordinates $x_1, \ldots, x_d$ as

$$
\omega = \sum_{1 \leq i_1 < i_2 < \cdots < i_p \leq d} f_{i_1, \ldots, i_p}(x_1, \ldots, x_d) dx_{i_1} \wedge \cdots \wedge dx_{i_p}
$$

for some $C^\infty$-functions $f_{i_1, \ldots, i_p}(x_1, \ldots, x_d)$ on the local chart. Write

$$
E^p(M) = \Gamma(M, E^p_p)
$$

for the real vector space of global sections of $E^p_p$ and set

$$
E^*(M) = \bigoplus_{p=0}^d E^p(M).
$$
Definition 2.57. The exterior derivative

\[ d : \mathcal{E}^*_M \rightarrow \mathcal{E}^*_M \]

is the unique \( \mathbb{R} \)-linear map of sheaves of degree 1 (i.e. that maps \( \mathcal{E}_M^p \) to \( \mathcal{E}_M^{p+1} \)) that satisfies the following two conditions:

i) If \( f \) is a smooth function, then \( df \) is given in local coordinates by

\[ df = \sum_{i=1}^d \frac{\partial f}{\partial x_i} dx_i. \]

ii) If \( \alpha \) is a local section of \( \mathcal{E}_M^p \), then the equality

\[ d(\alpha \wedge \beta) = d\alpha \wedge \beta + (-1)^p \alpha \wedge d\beta \]

holds for every local section \( \beta \) of \( \mathcal{E}^*_M \).

It follows from the definition (Exercise 2.103) that the exterior derivative satisfies \( d^2 = 0 \). Taking global sections, we thus get a complex

\[ 0 \rightarrow E^0(M) \xrightarrow{d} E^1(M) \xrightarrow{d} \cdots \xrightarrow{d} E^d(M) \rightarrow 0, \]

whose cohomology \( H^*_dR(M) \) is called the de Rham cohomology of \( M \). When we want to emphasize that this is a real vector space we write \( H^*_dR(M, \mathbb{R}) \) instead.

A classical theorem of de Rham asserts that singular cohomology with real coefficients \( H^*(M, \mathbb{R}) \) can be computed using differential forms. As was mentioned in Remark 2.10 ii), if one replaces singular chains with smooth singular chains in the definition of singular homology the resulting groups are the same. We denote by \( C^*_\text{sm}(M, \mathbb{R}) \) the complex of smooth singular chains with real coefficients and, as in Remark A.239, we define smooth singular cochains as the linear dual

\[ S^*_n(M, \mathbb{R}) = \text{Hom}_{\mathbb{R}}(C^*_n(M, \mathbb{R}), \mathbb{R}). \]

The vector spaces \( S^*_n(M, \mathbb{R}) \) form a complex that computes the singular cohomology with real coefficients of \( M \). At this point, the advantage of working with smooth chains is that we can integrate differential forms along them: given a smooth simplex \( \sigma : \Delta^n_{st} \rightarrow M \) and a differential form \( \omega \in E^*(M) \), the integral \( \int_\sigma \omega \) is defined as

\[ (2.58) \int_\sigma \omega = \int_{\Delta^n_{st}} \sigma^* \omega, \]

and extended linearly to all smooth singular chains. We thus get a map

\[ (2.59) E^*(M) \rightarrow S^*(M, \mathbb{R}) \]

that associates with each differential form \( \omega \in E^*(M) \) the integration functional

\[ \int_\sigma : S_\sigma(M, \mathbb{R}) \rightarrow \mathbb{R} \quad \sigma \mapsto \int_\sigma \omega. \]

Lemma 2.60. The map (2.59) is a functorial morphism of complexes.

Proof. Functoriality means that, for any morphism \( f : M \rightarrow M' \) of differentiable manifolds, the diagram

\[ \begin{array}{ccc} E^*(M') & \rightarrow & S^*(M', \mathbb{R}) \\ f^* \downarrow \quad \downarrow f^* \\ E^*(M) & \rightarrow & S^*(M, \mathbb{R}) \end{array} \]

is commutative.
commutes. This amounts to the equality
\[ \int_{\sigma} f^* \omega = \int_{f \circ \sigma} \omega, \]
which readily follows from the definition (2.58) of the integral along a chain. Being a morphism of complexes means that the map (2.59) commutes with the differentials on the de Rham and the singular chain complexes. This amounts to the equality
\[ \int_{\sigma} d\omega = \int_{\partial \sigma} \omega, \]
which is the content of the classical Stokes theorem. \qed

In view of the lemma, the morphism (2.59) induces a functorial linear map
\[ \int : H^*_{dR}(M, \mathbb{R}) \to H^*(M, \mathbb{R}), \]
which we still call the integration functional. De Rham’s theorem is the statement that this map is an isomorphism or, equivalently, that the original morphism of complexes (2.59) is a quasi-isomorphism.

**Theorem 2.62 (de Rham).** Let \( M \) be a differentiable manifold of dimension \( d \). For each \( 0 \leq j \leq d \), the map
\[ H^j_{dR}(M, \mathbb{R}) \to H^j(M, \mathbb{R}) \]
that sends the class of a differential form \( \omega \) to the integration functional \( \int \omega \) is an isomorphism. This isomorphism is functorial for maps of differentiable manifolds.

**Proof.** Recall that \( E^p(M) \) is defined, for each \( p \geq 0 \), as the real vector space of global sections of the sheaf \( E^p_M \) of smooth differential \( p \)-forms on \( M \). The existence of partitions of unity implies that all the sheaves \( E^p_M \) are fine, and hence acyclic (see Example A.199 and Lemma A.200 from the appendix). Moreover, by the differentiable Poincaré lemma (see e.g. [Lee13, Thm. 17.14] or Theorem 2.127 below for the holomorphic Poincaré lemma, which is proven in the same way) the inclusion of sheaves \( \mathbb{R}_M \to E^0_M \) that sends a locally constant function to the corresponding \( C^\infty \)-function fits into an exact sequence of sheaves
\[ 0 \to \mathbb{R}_M \to E^0_M \to E^1_M \to \cdots. \]
Let \( \hat{S}^*_M \) be the complex of sheaves of smooth cochains on \( M \), i.e. the sheaves associated with the presheaves \( U \mapsto S^n(U, \mathbb{R}) \), as explained in Remark A.239. The map (2.59) induces a morphism of complexes of sheaves
\[ \int : E^*_M \to \hat{S}^*_M \]
that fits into a commutative diagram
\[
\begin{array}{ccc}
\mathbb{R}_M & \to & E^*_M \\
\downarrow & & \downarrow f \\
\hat{S}^*_M & \to & \\
\end{array}
\]
For each integer $0 \leq j \leq d$, taking the cohomology in degree $j$ of these complexes of sheaves we get a commutative diagram

\[
\begin{array}{c}
\text{H}^j(M, R^j M) \\
\downarrow \\
\text{H}^j(M, \mathbb{R}).
\end{array}
\]

The horizontal arrow is an isomorphism by the exactness of (2.63) and the fact that the sheaves $\mathcal{E}^p_M$ are acyclic, the diagonal arrow is an isomorphism by Theorem A.236 and Remark A.239. Thus, the vertical arrow is an isomorphism as well. The claim about functoriality then follows from the commutativity of diagram (2.61). □

2.2.2. Kähler differentials. Remarkably enough, when $M$ is the differential manifold underlying a smooth affine complex algebraic variety $X$, it suffices to consider differential forms with regular functions on $X$ as coefficients to capture all de Rham cohomology classes. In this way, one obtains a purely algebraic definition of cohomology.

From now on, we will assume that the reader is familiar with the rudiments of the language of schemes, as can be found in the first sections of Chapter II of [Har77]. We first recall the notion of Kähler differentials, the substitute for the differential forms (2.56) that will allow for a purely algebraic definition of de Rham cohomology.

Let $k$ be a field of characteristic zero and let $A$ be a finitely generated reduced $k$-algebra. Being reduced means that there are no non-zero nilpotent elements in $A$; that is, if $x^n = 0$ for some integer $n \geq 1$, then $x = 0$. The spectrum $X = \text{Spec}(A)$ is then an affine algebraic variety over $k$.

**Definition 2.64.** Let $M$ be an $A$-module. A $k$-linear derivation of $A$ into $M$ is a $k$-linear map $D: A \to M$ satisfying the Leibniz rule

\[(2.65) \quad D(ab) = aD(b) + bD(a)\]

for all elements $a, b \in A$.

Using (2.65), the $k$-linearity of $D$ is equivalent to the condition $D(r) = 0$ for all $r \in k$. In particular, elements of $k$ are “constants” for the derivation.

**Definition 2.66.** The $A$-module of Kähler differentials $\Omega^1_{A/k}$ is the quotient of the free $A$-module generated by symbols $da$, for all $a \in A$, by the submodule spanned by the elements

\[(2.67) \quad dr, \quad d(a + b) - da - db, \quad d(ab) - adb - bda.\]

for all $r \in k$ and all $a, b \in A$.

By construction, the map $d: A \to \Omega^1_{A/k}$ that sends an element $a$ to $da$ is a $k$-linear derivation. It is the universal one: for any $k$-linear derivation $D: A \to M$, there is a unique morphism of $A$-modules $\varphi: \Omega^1_{A/k} \to M$ making the following
diagram commute:

\[
\begin{array}{ccc}
A & \overset{d}{\rightarrow} & \Omega_{A/k}^1 \\
\downarrow{D} & & \downarrow{\varphi} \\
M. & & \\
\end{array}
\]

The following example is at the base of many computations in algebraic de Rham cohomology.

**Example 2.69.** Set \(A = k[x_1, \ldots, x_d]\). Then \(\Omega_{A/k}^1\) is the free \(A\)-module generated by \(dx_1, \ldots, dx_d\). Indeed, let \(D: A \rightarrow M\) be any \(k\)-linear derivation. It follows from the Leibniz rule (2.65) that the image of a polynomial \(f \in A\) is equal to

\[
D(f) = \sum_{i=1}^d \frac{\partial f}{\partial x_i} D(x_i),
\]

where \(\frac{\partial f}{\partial x_i} \in A\) stands for the partial derivative of \(f\) with respect to \(x_i\). From this it follows that the free \(A\)-module generated by \(dx_1, \ldots, dx_d\) along with the derivation \(f \mapsto \sum_i \frac{\partial f}{\partial x_i} dx_i\) is the universal derivation.

More generally, if \(A\) is the \(k\)-algebra (2.70) \(A = k[x_1, \ldots, x_n] / (f_1, \ldots, f_m)\) for some polynomials \(f_1, \ldots, f_m\), then the \(A\)-module of Kähler differentials \(\Omega_{A/k}^1\) has generators \(dx_1, \ldots, dx_n\) and relations \(df_j = \sum_{i=1}^n \frac{\partial f_j}{\partial x_i} dx_i = 0\) for \(j = 1, \ldots, m\).

In other words, it is given by the quotient

\[
\Omega_{A/k}^1 = (Adx_1 \oplus \cdots \oplus Adx_n) / (df_1, \ldots, df_m).
\]

2.2.3. **Algebraic de Rham cohomology of smooth affine varieties.** The first part of Example 2.69 can be generalized in the following proposition.

An \(A\)-module \(M\) is said to be **locally free** of some rank \(d\) if, for each maximal ideal \(m\) of \(A\), the localization \(M_m\) is a free module of rank \(d\) over the ring \(A_m\), i.e. isomorphic to \(A_m^{\oplus d}\).

**Proposition 2.71.** If \(X = \text{Spec}(A)\) is smooth of dimension \(d\), then the module of Kähler differentials \(\Omega_{A/k}^1\) is locally free of rank \(d\).

By the **jacobian criterion for smoothness**, an algebra \(A\) of the form (2.70) is smooth of dimension \(d\) if, for every prime ideal \(p\) of \(A\), corresponding to a prime ideal \(q\) of \(k[x_1, \ldots, x_n]\), there exist

- elements \(g_1, \ldots, g_{n-d}\) of the ideal \(I = (f_1, \ldots, f_m)\) whose images in the localization \(k[x_1, \ldots, x_n]_q\) generate \(I \cdot k[x_1, \ldots, x_n]_q\);

- indexes \(i_1, \ldots, i_{n-d}\) such that the jacobian determinant \(\det(\frac{\partial g_i}{\partial x_j})\) does not belong to \(q\).

In the case where \(I\) is locally generated by a single polynomial \(f\), this simply means that at least one partial derivative of \(f\) does not belong to \(q\).

Since we are assuming that \(k\) has characteristic zero, the proposition follows from [Har77, Chap. II, Thm. 8.8]. Exercise 2.111 illustrates why the smoothness condition is necessary for Proposition 2.71 to hold.
In the remainder of this section, \( A \) denotes a \( k \)-algebra such that \( X = \text{Spec}(A) \) is a smooth variety of dimension \( d \). For each integer \( p \geq 0 \), let
\[
\Omega^p_{A/k} = \Lambda^p \Omega^1_{A/k}
\]
be the \( p \)-th exterior power of \( \Omega^1_{A/k} \) over \( A \). In particular, \( \Omega^0_{A/k} = A \) and \( \Omega^p_{A/k} = 0 \) for all \( p > d \). For each \( 1 \leq p \leq d \), the \( A \)-module \( \Omega^p_{A/k} \) is the quotient of the free \( A \)-module generated by the elements \( \omega_1 \wedge \cdots \wedge \omega_p \), with \( \omega_i \in \Omega^1_{A/k} \), by the submodule generated by the elements
\[
a \omega_1 \wedge \cdots \wedge \omega_i \wedge \cdots \wedge \omega_p - b \omega_1 \wedge \cdots \wedge \omega_i' \wedge \cdots \wedge \omega_p
\]
for all \( 1 \leq i \leq p \) and all \( a, b \in A \) and by \( \omega_1 \wedge \cdots \wedge \omega_p \) whenever two of the \( \omega_i \) are equal. From this we get the identity
\[
\omega_{\sigma(1)} \wedge \cdots \wedge \omega_{\sigma(p)} = \text{sign}(\sigma) \omega_1 \wedge \cdots \wedge \omega_p
\]
for each permutation \( \sigma \in \mathfrak{S}_p \). We call algebraic differential forms of degree \( p \) or just \( p \)-forms the elements of \( \Omega^p_{A/k} \). Since \( \Omega^1_{A/k} \) is locally free of rank \( d \), the \( p \)-th exterior power \( \Omega^p_{A/k} \) is locally free of rank \( d^p \).

As in the case of classical de Rham cohomology recalled in Section 2.2.1, the derivation \( d : A \to \Omega^1_{A/k} \) extends in a unique way to \( k \)-linear maps
\[
d^p : \Omega^p_{A/k} \to \Omega^{p+1}_{A/k}
\]
satisfying the following properties:
\begin{itemize}
  \item[i)] \( d^p \circ d^{-1} = 0 \) for all \( p \),
  \item[ii)] \( d^{p+q}(\alpha \wedge \beta) = d\alpha \wedge \beta + (-1)^p \alpha \wedge d\beta \) for all \( p \)-forms \( \alpha \) and \( q \)-forms \( \beta \),
\end{itemize}
with \( d^0 = d \). Explicitly, every 1-form is a \( k \)-linear combination of elements of the form \( adb \), for some \( a, b \in A \), and one defines
\[
d^1(adb) = da \wedge db.
\]
For \( p \)-forms, one sets
\[
d^p(\omega_1 \wedge \cdots \wedge \omega_p) = \sum_{j=1}^{p} (-1)^{j+1} \omega_1 \wedge \cdots \wedge \omega_{j-1} \wedge d^1 \omega_j \wedge \omega_{j+1} \wedge \cdots \wedge \omega_p.
\]
It is straightforward to check that these maps are well defined (\textit{i.e.} vanish on the elements \((2.67)\) defining relations on \( \Omega^1_{A/k} \) and its exterior powers) and satisfy the above conditions i) and ii). This yields the \textit{algebraic de Rham complex}
\[
\Omega^*_{A/k} : \quad A \longrightarrow \Omega^1_{A/k} \longrightarrow \Omega^2_{A/k} \longrightarrow \cdots \longrightarrow \Omega^d_{A/k}.
\]
A \( p \)-form is said to be \textit{closed} if it belongs to the kernel of \( d^p \) and \textit{exact} if it belongs to the image of \( d^{p-1} \).

**Definition 2.72.** The \textit{algebraic de Rham cohomology} of \( X = \text{Spec}(A) \) is the cohomology of the algebraic de Rham complex
\[
H^*_\text{dR}(X) = H^*(\Omega^*_{A/k}).
\]
In other words, \( H^*_\text{dR}(X) \) is the quotient of the vector space of closed \( n \)-forms on \( X \) by the subspace of exact \( n \)-forms.
Both the space of closed forms and the space of exact forms on $X$ have in general infinite dimension. However, we will prove below (Corollary 2.148) that the $k$-vector space $H^*_d(X)$ is finite-dimensional.

Example 2.73 (Punctured affine line). Consider the affine variety
\[ G_m = \mathbb{A}^1_k \setminus \{0\} = \text{Spec} \left( k[t, s]/(ts - 1) \right) = \text{Spec} \left( k[t, t^{-1}] \right), \]
which is the algebraic analogue of the punctured complex plane from Example 2.24. Set $A = k[t, t^{-1}]$. By Example 2.69, the module of Kähler differentials $\Omega^1_{A/k}$ is generated by $dt$ and $ds$, modulo the relation $sdt + tds = 0$ obtained by differentiating the defining equation $ts = 1$. Since this relation amounts to $ds = -t^{-2}dt$, the module $\Omega^1_{A/k} = Adt$ is free of rank one. The algebraic de Rham complex of $X$ is therefore the two-term complex
\[ d: k[t, t^{-1}] \longrightarrow k[t, t^{-1}]/dt. \]

There is non-zero cohomology at most in degrees zero and one, given by
\[ H^0_{dR}(X) = \ker(d), \quad H^1_{dR}(X) = \text{Coker}(d). \]
Since only constant Laurent polynomials have zero derivative, we find that $H^0_{dR}(X)$ is the one-dimensional $k$-vector space generated by $1$. To compute the cokernel of $d$, we note that $t^m dt = d(t^{m+1}/(m+1))$ lies in the image of $d$ except for $m = -1$, in which case the function $1/t$ does not admit a primitive among Laurent polynomials. It follows that $H^1_{dR}(X)$ is the one-dimensional $k$-vector space generated by the class of $dt/t$. Here is the summary of our computation:
\[ H^n_{dR}(G_m) = \begin{cases} k, & \text{if } n = 0, \\ k[dt/t], & \text{if } n = 1, \\ 0, & \text{otherwise}. \end{cases} \]

Example 2.74 (Affine elliptic curves). Let $a, b \in k$ be such that $4a^3 + 27b^2$ is non-zero. Then the polynomial
\[ f(x) = x^3 + ax + b \]
has no double roots, and hence the equation $y^2 = f(x)$ defines a smooth affine plane curve $X \subseteq \mathbb{A}^2_k$. We will call $X$ an affine elliptic curve since its projective closure $\overline{X} \subseteq \mathbb{P}^2_k$ is an elliptic curve, from which $X$ is obtained by removing the point $O = [0: 1: 0]$ at infinity. From the point of view of schemes, the affine elliptic curve $X$ is the spectrum of the $k$-algebra
\[ A = k[x, y]/(y^2 - f(x)) \simeq k[x] \oplus k[x]y. \]
According to Example 2.69, the $A$-module of Kähler differentials is then given by
\[ \Omega^1_{A/k} = (Adx \oplus Ady)/(2ady - f'(x)dx), \]
where $f'$ denotes the derivative of $f$. Since $\Omega^p_{A/k}$ vanishes for $p \geq 2$, the algebraic de Rham complex of $X$ is the two-term complex $A \to \Omega^1_{A/k}$. It has non-zero cohomology at most in degrees zero and one, given by
\[ H^0_{dR}(X) = \ker(d: A \to \Omega^1_{A/k}), \quad H^1_{dR}(X) = \text{Coker}(d: A \to \Omega^1_{A/k}). \]
To compute these spaces, we first give a more manageable presentation of $\Omega^1_{A/k}$. The intuition for the computation below is that, in case $k$ is a subfield of the complex numbers, the complex points $\mathcal{X}(\mathbb{C})$ can be described as the quotient $\mathbb{C}/\Lambda$ of the complex plane by the action by translation of a lattice $\Lambda$. Under the explicit uniformization map that provides such an isomorphism, the differential form $dz$ of the complex plane by the action by translation of a lattice $\Lambda$. Under the explicit complex numbers, the complex points $k$ Thus, the complex points $A/k$ the complex points $U$ hand, since $\omega$, $x \omega$, . . . , $x^n \omega$ of the class of $\Omega^1_{A/k}$ since the function $y$ is not invertible in $A$. To show that $dx$ is indeed divisible by $y$ in $\Omega^1_{A/k}$, we resort to the following trick. Since $f$ has no double roots, the polynomials $f$ and $f'$ are coprime. By Bézout’s identity, there are polynomials $P, Q \in k[x]$ satisfying $Pf + Qf' = 1$. We can then consider the 1-form $\omega = Pydx + 2Qdy \in \Omega^1_{A/k}$.

Using the equalities $y^2 = f(x)$ in $A$ and $2y dy = f'(x) dx$ in $\Omega^1_{A/k}$, we find $y \omega = Pyy^2 dx + 2Qy dy = (Pf + Qf') dx = dx,$ which shows that $\omega$ is the form $dx/y$. Similarly, the relation

$$\frac{f'(x)\omega}{2} = \frac{Pyf'(x)dx}{2} + Qf'(x)dy = (Py^2 + Qf'(x))dy = dy$$

holds in $\Omega^1_{A/k}$. From the expression of the generators $dx$ and $dy$ in terms of $\omega$, we see that every element of $\Omega^1_{A/k}$ can be written uniquely as $(R + Sy)\omega$ for some polynomials $R, S \in k[x]$. In other words, there is an isomorphism $\Omega^1_{A/k} \simeq A\omega$, which shows that $\Omega^1_{A/k}$ is free of rank one in this case.

In terms of this presentation, the differential is given by the formula

$$(2.75) \quad \text{d}(T + Uy) = T' dx + U'y dx + U dy = (U'f + Uf' + T'y)\omega$$

for polynomials $T, U \in k[x]$. Note that the polynomial $U'f + Uf' + 2$ has degree $\geq 2$ for every non-zero $U$. Therefore, the right-hand side of (2.75) vanishes if and only if $U = 0$ and $T' = 0$. It follows that $H^1_{\text{dR}}(X)$ is the one-dimensional $k$-vector space of constant polynomials.

To compute $H^1_{\text{dR}}(X)$, we need to find which of the forms $(R + Sy)\omega$ are exact. This is the case for all $Sy\omega$, as we see by choosing $U = 0$ and a primitive of $S$ for $T$. It remains to check when $R\omega$ is exact. For this, we try to write $x^n\omega$ as a linear combination of forms of the same shape with smaller $n$ modulo the image of the differential. For each $m \geq 0$, it follows from the equality

$$\text{d}(\frac{2x^m y}{3 + 2m}) = (x^m + \text{polynomial of degree } \leq m)\omega$$

that the class of $x^{m+2}\omega$ in the cokernel of $d$ is a $k$-linear combination of the classes of $\omega, x\omega, \ldots, x^m \omega$. Therefore, $H^1_{\text{dR}}(X)$ is spanned by $\omega$ and $x\omega$. On the other hand, since $U'f + Uf' + 2$ is either zero or has degree $\geq 2$, no linear combination of $\omega$ and $x\omega$ lies in the image of $d$. Hence, the classes of $x$ and $x\omega$ form a basis of $H^1_{\text{dR}}(X)$. Here is the summary of our computation:

$$H^1_{\text{dR}}(X) = \begin{cases} k, & \text{if } n = 0, \\
[k\frac{dx}{y}] \oplus k[x\frac{dx}{y}], & \text{if } n = 1, \\
0, & \text{otherwise.} \end{cases}$$
2.2.4. Algebraic de Rham cohomology of smooth varieties. Let us now turn to the case where \( X \) is any variety over \( k \), not necessarily affine. Gluing differential forms on affine open subsets, we get a sheaf for the Zariski topology on \( X \). The following result is explained in [Har77, Chap. II, §8].

**Proposition 2.76.** There exists a unique coherent \( \mathcal{O}_X \)-module \( \Omega^1_{X/k} \) whose restriction to every affine open subset \( U \) of \( X \) is the \( \mathcal{O}_U \)-module associated with the Kähler differentials \( \Omega^1_{\mathcal{O}_X(U)/k} \) and the restriction maps between open affine subsets are given by the restriction of differential forms.

Coherence is a finiteness property that allows for vanishing results, comparison theorems between algebraic and analytic cohomology, and so on. It is briefly discussed in Section A.9.9 of the appendix. Many of the properties we have discussed in the affine case globalize to arbitrary smooth varieties. In particular, if \( X \) is a smooth variety of dimension \( d \), then the sheaf \( \Omega^1_X \) is a locally free sheaf of rank \( d \) and is equipped with the universal \( k \)-derivation \( d: \mathcal{O}_X \to \Omega^1_X \). If \( \Omega^p_X \) denotes the \( p \)-th exterior power of \( \Omega^1_X \), then \( d \) canonically extends to maps \( d^p: \Omega^p_X \to \Omega^{p+1}_X \) satisfying \( d^{p+1} \circ d^p = 0 \). The resulting complex

\[
(\Omega^*_X, d): \quad \mathcal{O}_X \xrightarrow{d} \Omega^1_X \xrightarrow{d} \Omega^2_X \xrightarrow{d} \cdots
\]

is called the algebraic de Rham complex. Observe that every term in this complex is a locally free \( \mathcal{O}_X \)-module but the differential \( d \) is not \( \mathcal{O}_X \)-linear, only \( k \)-linear. The default of \( \mathcal{O}_X \)-linearity is precisely measured by the Leibniz rule.

**Definition 2.78.** Let \( X \) be a smooth variety over a field \( k \) of characteristic zero. The algebraic de Rham cohomology of \( X \) is the hypercohomology of the algebraic de Rham complex. We denote it by

\[
H^*_\text{dR}(X) = H^*(\mathcal{O}_X, \Omega^*_X).
\]

Recall from Section A.9.4 of the appendix that the hypercohomology of \( \Omega^*_X \) is defined as the cohomology of the complex of global sections of an acyclic resolution of \( \Omega^*_X \), for example Godement’s canonical resolution

\[
\text{Gd}(\Omega^*_X) = \text{Tot} \text{Gd}^*(\Omega^*_X)
\]

from Section A.9.3. That is, the algebraic de Rham cohomology of \( X \) can be computed as the cohomology of a complex of \( k \)-vector spaces, namely

\[
H^*_{\text{dR}}(X) = H^*(\Gamma(X, \text{Gd}(\Omega^*_X))).
\]

**Remark 2.79.** When \( X \) is affine, there is no need to use hypercohomology to define algebraic de Rham cohomology. Indeed, as all coherent sheaves on an affine variety are acyclic (Theorem A.241), the complex \( \Omega^*_X \) consists of acyclic sheaves, so it is an acyclic resolution of itself. It follows that its hypercohomology agrees with the cohomology of the complex of global sections \( (\Omega^*_X(X), d) \). This last complex is called the global de Rham complex. In the affine case, the global de Rham complex agrees with the complex of Kähler differentials

\[
\Omega^*_X(X) = \Omega^*_X/k
\]

by Proposition 2.76, and hence Definitions 2.72 and 2.78 agree for affine varieties.

In general, when \( X \) is not affine, the cohomology of the global de Rham complex does not coincide with the algebraic de Rham cohomology. For example, the global sections \( \Omega^p_X(X) \) vanish for \( p > \text{dim} X \), and hence so does the cohomology of the
global de Rham complex, while a variety will in general have non-trivial cohomology
$H^\ast_{dR}(X)$ up to degree $2 \dim X$. Most of the varieties we will deal with in applications
are affine, so we will often be able to use the global de Rham complex.

A tool to compute algebraic de Rham cohomology is to view it, as the hyper-
cohomology of any complex of sheaves, as the abutment of a spectral sequence
\[ E_1^{p,q} = H^q(X, \Omega^p_X) \Rightarrow H^{p+q}_{dR}(X) \]
with differentials $d_1: E_1^{p,q} \to E_1^{p+1,q}$ induced by $d: \Omega^p_X \to \Omega^{p+1}_X$. This is called the
Frölicher or Hodge–de Rham spectral sequence

In practice, to compute the algebraic de Rham cohomology of $X$ and make the
Hodge–de Rham spectral sequence explicit one chooses a cover of $X$ by a finite
collection of affine open subsets $U_1, \ldots, U_n$, and forms the Čech double complex

\[
\begin{array}{c}
\bigoplus_i \Omega^1(U_i) \rightarrow \bigoplus_{i<j} \Omega^1(U_i \cap U_j) \rightarrow \cdots \\
\bigoplus_i \mathcal{O}(U_i) \rightarrow \bigoplus_{i<j} \mathcal{O}(U_i \cap U_j) \rightarrow \cdots
\end{array}
\]

where the vertical differentials are the differentials in the algebraic de Rham com-
plex and the horizontal differentials

\[
\bigoplus_{i_0 < \cdots < i_{q+1}} \Omega^p(U_{i_0} \cap \cdots \cap U_{i_{q+1}}) \rightarrow \bigoplus_{i_0 < \cdots < i_{q+1}} \Omega^p(U_{i_0} \cap \cdots \cap U_{i_{q+1}})
\]

send a section $\alpha \in \Omega^p(U_{i_0} \cap \cdots \cap U_{i_{q+1}})$ to the element $\partial \alpha$ with factors

\[
(\partial \alpha)_{i_0, \ldots, i_{q+1}} = \sum_{r=0}^{q+1} (-1)^{r+1} \alpha_{i_0, \ldots, \hat{i}_r, \ldots, i_{q+1}}|_{U_{i_0} \cap \cdots \cap U_{i_{q+1}}}
\]

Thanks to Remark 2.79, the algebraic de Rham cohomology of $X$ is the coho-
mology of the total complex associated with this double complex (Definition A.25).
Moreover, (2.80) is the spectral sequence associated with it as in Example A.154.

**Example 2.82.** Let $X = \mathbb{P}^1_k$ be the projective line over $k$. We consider the
cover by the two affine open subsets

\[
U_0 = \mathbb{P}^1_k \setminus \{0\} = \text{Spec}(k[t]), \quad U_1 = \mathbb{P}^1_k \setminus \{\infty\} = \text{Spec}(k[s]),
\]

whose coordinates are related by $s = 1/t$ on the intersection $U_0 \cap U_1$. The only
non-zero terms in the double complex (2.81) are then

\[
k[t]dt \oplus k[s]ds \xrightarrow{d \oplus d} k[t, t^{-1}]dt
\]

where

\[
k[t] \oplus k[s] \xrightarrow{d} k[t, t^{-1}]
\]
where the horizontal differentials are given by

\[(f dt, g ds) \mapsto (f(t) + g(1/t)t^{-2}) dt, \quad (f, g) \mapsto f(t) - g(1/t).\]

We leave as Exercise 2.105 to check that the cohomology groups of the associated total complex are

\[(2.83) \quad H^0 = k, \quad H^1 = 0, \quad H^2 = k \frac{dt}{t}.\]

Alternatively, we can compute the algebraic de Rham cohomology of \(\mathbb{P}^1_k\) by means of the spectral sequence (2.80). The sheaf of Kähler differentials \(\Omega^1_{\mathbb{P}^1}\) is the line bundle \(\mathcal{O}_{\mathbb{P}^1}(-2)\). By the standard computation of the cohomology of line bundles on \(\mathbb{P}^1\) \([\text{Har77}, \text{Chap. III, \S 5}]\), \(\mathcal{O}_{\mathbb{P}^1}\) has only non-vanishing cohomology in degree zero and \(\mathcal{O}_{\mathbb{P}^1}(-2)\) has only non-vanishing cohomology in degree one. Therefore, the spectral sequence reads

\[
\begin{array}{c}
0 \rightarrow H^1(\mathbb{P}^1, \Omega^1_{\mathbb{P}^1}) \\
H^0(\mathbb{P}^1, \mathcal{O}_{\mathbb{P}^1}) \\n0
\end{array}
\]

and all differentials vanish already at the first page. This yields isomorphisms

\[
H^n_{\text{dR}}(\mathbb{P}^1) = \begin{cases} 
H^0(\mathbb{P}^1, \mathcal{O}_{\mathbb{P}^1}), & \text{if } n = 0, \\
0, & \text{if } n = 1, \\
H^1(\mathbb{P}^1, \Omega^1_{\mathbb{P}^1}), & \text{if } n = 2.
\end{cases}
\]

**Example 2.84.** Let \(X\) be a smooth connected projective curve over an algebraically closed field \(k\) of characteristic zero. In this example, we will use without proof a few results from the theory of algebraic curves, for which the reader can for instance consult \([\text{Har77}, \text{Chap. IV}]\). Recall that the *genus* of \(X\) is the dimension

\[
g = \dim H^0(X, \Omega^1_X)
\]

of the space of global sections of the sheaf of differential forms. Besides, since \(X\) is projective and connected, the only global sections of \(\mathcal{O}_X\) are the constant functions, that is: \(H^0(X, \mathcal{O}_X) = k\).

Moreover, Serre’s duality implies (see \([\text{Har77}, \text{Cor. 7.13}]\)) that

\[
\dim H^1(X, \mathcal{O}_X) = g, \quad \dim H^1(X, \Omega^1_X) = 1.
\]

The spectral sequence (2.80) computing \(H^*_\text{dR}(X)\) is given by

\[
\begin{array}{c}
H^1(X, \mathcal{O}_X) \rightarrow H^1(X, \Omega^1_X) \\
H^0(X, \mathcal{O}_X) \rightarrow H^0(X, \Omega^1_X)
\end{array}
\]

and the lower horizontal map is zero since the differential of a constant function vanishes. We shall show that the upper horizontal map is zero as well.
Let \( f : X \to \mathbb{P}^1 \) be a non-constant rational function and let us cover \( X \) by the affine open subsets
\[
U_0 = X \setminus f^{-1}(0) \quad U_1 = X \setminus f^{-1}(\infty).
\]

As explained after Remark 2.79, the first page of the spectral sequence (2.80) can be computed using the commutative diagram with exact columns
\[
\begin{array}{ccc}
0 & & 0 \\
\downarrow & & \downarrow \\
H^1(X, \mathcal{O}_X) & \xrightarrow{d_1} & H^1(X, \Omega^1_X) \\
\uparrow & & \uparrow \\
\mathcal{O}_X(U_0 \cap U_1) & \xrightarrow{d} & \Omega^1_X(U_0 \cap U_1) \\
\downarrow & & \downarrow \\
\mathcal{O}_X(U_0) \oplus \mathcal{O}_X(U_1) & \xrightarrow{d} & \Omega^1_X(U_0) \oplus \Omega^1_X(U_1) \\
\downarrow & & \downarrow \\
H^0(X, \mathcal{O}_X) & \xrightarrow{d_1} & H^0(X, \Omega^1_X) \\
\downarrow & & \downarrow \\
0 & & 0
\end{array}
\]

The zeroth cohomology groups are the kernels of the middle vertical arrows and the first cohomology groups are the cokernels of the same maps. The differentials denoted \( d_1 \) are just the induced maps. We have already discussed that the lower \( d_1 \) is zero and our task now is to prove that the upper \( d_1 \) is zero.

To this end we will use the residue map. For any Zariski open subset \( U \) of \( X \) and any \( k \)-point \( P \in X \setminus U \), there is a residue map
\[
\text{res}_P : \Omega^1_X(U) \to k
\]
satisfying the following properties:

i) for each \( \omega \in \Omega^1_X(U) \), the equality \( \sum_{P \in X \setminus U} \text{res}_P(\omega) = 0 \) holds;

ii) for forms \( \omega = dg \), where \( g \in \mathcal{O}_X(U) \) is a regular function, the vanishing \( \text{res}_P(\omega) = 0 \) holds for all \( P \in X \setminus U \).

This is explained for instance in [Ser88, §II.7].

We define the map \( \varphi : \Omega^1_X(U_0 \cap U_1) \to k \) as
\[
\varphi(\omega) = \sum_{P \in X \setminus U_0} \text{res}_P(\omega) = -\sum_{P \in X \setminus U_1} \text{res}_P(\omega),
\]
where the second equality follows from property i) of the residue map applied to the open set \( U_0 \cap U_1 \). Again by property i), but this time applied to the open sets \( U_0 \) and \( U_1 \), the composition \( \varphi \circ \partial = 0 \). Therefore, the map \( \varphi \) factors through
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\[ H^1(X, \Omega^1_X) \text{ giving rise to a commutative diagram} \]

\[
\begin{array}{ccc}
H^1(X, \mathcal{O}_X) & \xrightarrow{d_1} & H^1(X, \Omega^1_X) \\
\uparrow \phi_0 & & \uparrow \phi \\
\mathcal{O}_X(U_0 \cap U_1) & \xrightarrow{d} & \Omega^1_X(U_0 \cap U_1) \\
\uparrow \partial & & \uparrow \\
\Omega^1_X(U_0) \oplus \Omega^1_X(U_1) & & & & & \end{array}
\]

The differential form \( df/f \) has simple poles whenever \( f \) has a zero or a pole. The residue of \( df/f \) at a point is exactly the order of vanishing of \( f \) at the point. In particular, positive if \( f \) has a zero and negative if \( f \) has a pole. Since \( f \) is non-constant, it has at least one zero. Being \( X \setminus U_0 \) the set of zeros of \( f \) we deduce \( \phi_0(d(f/f)) \neq 0 \). Hence the map \( \phi_0 \) is surjective. Since we already know that the dimension of \( H^1(X, \Omega^1_X) \) is one, \( \phi_0 \) is an isomorphism. By property ii) of the residue we deduce that the composition \( \phi \circ d = 0 \). This implies that the upper \( d_1 = 0 \). In conclusion, the spectral sequence (2.80) degenerates at the page \( E_1 \). As a consequence we deduce that

\[ H^0_{\text{dR}}(X) = H^0(X, \mathcal{O}_X), \quad H^2_{\text{dR}}(X) = H^1_{\text{dR}}(X, \Omega^1_X) \]

are both one-dimensional, and that the first de Rham cohomology group sits in the exact sequence

\[ 0 \rightarrow H^0(X, \Omega^1_X) \rightarrow H^1_{\text{dR}}(X) \rightarrow H^1(X, \mathcal{O}_X) \rightarrow 0. \]

In particular, \( \dim H^1_{\text{dR}}(X) = 2g \). Elements of \( H^0(X, \Omega^1_X) \) are called, in the classical literature, \emph{differentials of the first kind}.

In this particular example we have proved by hand that the Hodge–de Rham spectral sequence degenerates at the term \( E_1 \). In fact, the degeneration of the Hodge–de Rham spectral sequence is a general result for smooth proper varieties and is at the heart of the Hodge decomposition.

2.2.5. Some properties of algebraic de Rham cohomology.

\textbf{Base change:} Algebraic de Rham cohomology is compatible with extensions of the field of definition.

\textbf{Lemma 2.85.} Let \( X \) be a smooth variety over a field \( k \) of characteristic zero, let \( K \) be a field extension of \( k \), and let \( X_K = X \times_{\text{Spec}(k)} \text{Spec}(K) \) denote the extension of scalars. There is a canonical isomorphism

\[ H^n_{\text{dR}}(X) \otimes_k K \xrightarrow{\sim} H^n_{\text{dR}}(X_K). \]

\textbf{Functoriality:} Let \( U = \text{Spec}(A) \) and \( V = \text{Spec}(B) \) be smooth affine varieties over \( k \) and let \( f: U \rightarrow V \) be a morphism between them. We still denote by \( f \) the associated morphism of \( k \)-algebras \( B \rightarrow A \). The map \( f \) endows \( \Omega^1_{A/k} \) with a structure of \( B \)-module. Since the composition \( B \rightarrow A \rightarrow \Omega^1_{A/k} \) is a \( k \)-linear derivation, by the universal property of Kähler differentials, there exists a morphism of \( B \)-modules

\[ f^*: \Omega^1_{B/k} \rightarrow \Omega^1_{A/k}. \]
Now let \( f : X \to Y \) be a morphism between any smooth varieties over \( k \). For each Zariski open subset \( U \) of \( Y \), gluing (2.86) on affine open covers of \( U \) and \( f^{-1}(U) \) yields a morphism

\[
\Omega^1_Y(U) \to \Omega^1_X(f^{-1}(U)) = (f_*\Omega^1_X)(U),
\]

and hence morphisms \( \Omega^*_Y(U) \to (f_*\Omega^*_X)(U) \) which are compatible with the differential. From this we get morphisms of complexes of sheaves

\[
\Omega^*_Y(U) \to f_*\Omega^*_X(U) \to Rf_*\Omega^*_X.
\]

Using the analogue of (A.215) for complexes one obtains

\[
H^*(Y, Rf_*\Omega^*_X) = H^*(X, \Omega^*_X).
\]

Hence the above morphism induces a \( k \)-linear map

\[
f^* : H^*_dR(Y) \to H^*_dR(X).
\]

**Cup-product**: The exterior product of differential forms gives rise to a *cup-product*

\[
H^*_dR(X) \otimes H^*_dR(X) \to H^*_dR(X)
\]

in algebraic de Rham cohomology. Indeed, from the morphism of complexes

\[
\text{Tot}(\Omega^*_X \otimes_k \Omega^*_X) \to \Omega^*_X
\]

given by exterior product, we get a morphism of Godement resolutions

\[
\text{Gd}(\Omega^*_X \otimes_k \Omega^*_X) \to \text{Gd}(\Omega^*_X).
\]

Since every module over a field is flat, tensoring by \( \Omega^*_X \) is an exact functor, and hence the natural map

\[
\Omega^*_X \otimes_k \Omega^*_X \to \text{Gd}(\Omega^*_X) \otimes_k \text{Gd}(\Omega^*_X)
\]

is a quasi-isomorphism. Applying the Godement resolution again, we obtain a quasi-isomorphism

\[
\text{Gd}(\Omega^*_X \otimes_k \Omega^*_X) \to \text{Gd}(\text{Gd}(\Omega^*_X)) \to \text{Gd}(\Omega^*_X).
\]

Composing the natural map from a complex to its Godement resolution, the inverse of the quasi-isomorphism (2.88) and the product (2.87), we obtain a morphism in the derived category

\[
\text{Gd}(\Omega^*_X) \otimes_k \text{Gd}(\Omega^*_X) \to \text{Gd}(\text{Gd}(\Omega^*_X)) \to \text{Gd}(\Omega^*_X).
\]

Taking the equality \( H^*_dR(X) = H^*(\Gamma(X, \text{Gd}(\Omega^*_X))) \) into account, this morphism induces the sought-after product after composing with the map

\[
H^*(\Gamma(X, \text{Gd}(\Omega^*_X))) \otimes H^*(\Gamma(X, \text{Gd}(\Omega^*_X))) \to H^*(\Gamma(X, \text{Gd}(\Omega^*_X))) \otimes \Gamma(X, \text{Gd}(\Omega^*_X)) \to H^*(\Gamma(X, \text{Gd}(\Omega^*_X) \otimes_k \text{Gd}(\Omega^*_X)) \to H^*(\Gamma(X, \text{Gd}(\Omega^*_X))).
\]

A variant of the above construction yields an external product

\[
H^*_dR(X) \otimes H^*_dR(Y) \to H^*_dR(X \times Y)\]
for smooth varieties $X$ and $Y$ over $k$.

2.2.6. Relative de Rham cohomology. There is also a relative version of algebraic de Rham cohomology. For simplicity, we explain the construction only in the affine case. Let $X$ be a smooth affine variety over $k$, and consider a smooth closed subvariety $ι: Z \hookrightarrow X$, which is hence affine. There is a restriction morphism of complexes $ι^*: Ω^*(X) \to Ω^*(Z)$. Let $Ω^*(X, Z)$ denote the complex

$$Ω^*(X, Z) = \text{Tot}(ι^*) = \text{cone}(ι^*)[-1]$$

Explicitly it is given by

$Ω^n(X, Z) = Ω^n(X) \oplus Ω^{n-1}(Z)$

with differential

$d(α, β) = (dα, ι^*(α) - dβ)$.

By construction, there is a short exact sequence

$$0 \to Ω^*(Z)[-1] \to Ω^*(X, Z) \to Ω^*(X) \to 0$$

in the category of complexes of $k$-vector spaces, that induces a distinguished triangle in the corresponding derived category (see Section A.3.2)

(2.89) \[\Omega^*(X, Z) \to \Omega^*(X) \xrightarrow{ι^*} \Omega^*(Z) \to \Omega^*(X, Z)[1].\]

DEFINITION 2.90. For $X$ a smooth affine variety and $Z \hookrightarrow X$ a smooth closed subvariety, the relative de Rham cohomology of the pair $(X, Z)$ is the cohomology of the complex $Ω^*(X, Z)$:

$$H^*_\text{dr}(X, Z) = H^*(Ω^*(X, Z)).$$

Again, a relative de Rham class is represented by a pair of differential forms $(α, β)$ such that $α$ is closed and the restriction of $α$ to $Z$ is equal to $dβ$. However, in general, neither $α$ nor $β$ is determined by the other form. Taking the long exact sequence associated with (2.89) one gets

$$\cdots \to H^{n-1}_\text{dr}(Z) \to H^n_\text{dr}(X, Z) \to H^n_\text{dr}(X) \to H^n_\text{dr}(Z) \to \cdots$$

EXAMPLE 2.91. Set $X = \text{Spec}(k[x, x^{-1}])$, and let $Z = \{p, q\}$ be the closed subvariety of $X$ consisting of two distinct $k$-points $p$ and $q$, the zero locus of the polynomial $(x-p)(x-q)$. Then $Ω^*(Z)$ is concentrated in degree zero, $Ω^0(Z) = k \oplus k$, and the map

$$ι^*: Ω^0(X) = k[x, x^{-1}] \to Ω^0(Z) = k \oplus k$$

is given by evaluating functions at $p$ and $q$, that is, $ι^*(f) = (f(p), f(q))$. Therefore, the complex $Ω^*(X, Z)$ reads

(2.92) \[d: k[x, x^{-1}] \to k[x, x^{-1}]dx \oplus k \oplus k \quad f \mapsto (f'(x)dx, f(p), f(q)).\]

The differential $d$ is injective. Indeed, if $f$ lies in its kernel, then $f$ is constant since $f'(x) = 0$, but this constant must be equal to $f(p) = f(q) = 0$. Hence, $H^0_\text{dr}(X, Z) = 0$. Besides, using the equalities $d(1) = (0, 1, 1)$ and

$$d(x^n/(n+1)) = (x^n dx, p^{n+1}/(n+1), q^{n+1}/(n+1)) \quad (n \neq -1),$$

one sees that the cokernel of $d$ is generated by

$$ω_1 = (0, 1, 0), \quad ω_2 = (dx/x, 0, 0).$$
As no linear combination of these two elements lies in the image of d, they form a
basis of Coker(d) and $H^1_{\text{dR}}(X, Z)$ is thus the $k$-vector space $\langle \omega'_1, \omega_2 \rangle_k$. As you will
show in Exercise 2.108, the element $\omega'_1$ is cohomologous to $\omega_1 = (dx/(p-q), 0, 0)$. Therefore, we can represent $H^1_{\text{dR}}(X, Z)$ using the differential forms $\omega_1 = dx/(p-q)$
and $\omega_2 = dx/x$ on $X$ that vanish when restricted to $Z$.

**Remark 2.93.** The de Rham cohomology of affine smooth varieties vanishes
above the dimension. If $n = \dim X$ and $Z \subset X$ is a closed smooth subvariety
of smaller dimension, then a useful part of the long exact sequence of relative
cohomology is

\[
\cdots \rightarrow H^{n-1}_{\text{dR}}(Z) \rightarrow H^n_{\text{dR}}(X, Z) \rightarrow H^n_{\text{dR}}(X) \rightarrow 0.
\]

**2.2.7. The case of normal crossing divisors.** In the sequel, we will also need to
consider relative de Rham cohomology in the case where $Z$ is not a smooth subvariety, but a simple normal crossing divisor. Using standard tools from homological
algebra, we will be able to extend Definition 2.90 to this setting. We first recall the
relevant notions from algebraic geometry.

Let $X$ be a smooth algebraic variety of dimension $d$ over a field $k$. Given a
closed point $p$ of $X$, we denote by $\mathcal{O}_{X,p}$ the local ring of germs of regular functions
at $p$, by $\mathfrak{m}_p$ its maximal ideal, and by $\kappa(p) = \mathcal{O}_{X,p}/\mathfrak{m}_p$ its residue field. Recall
that $\mathcal{O}_{X,p}$ is regular of Krull dimension $d$, which means that a minimal set of
generators of $\mathfrak{m}_p$ contains $d$ elements; any such set is called a regular system of parameters. By Nakayama’s lemma, the elements $x_1, \ldots, x_d \in \mathfrak{m}_p$ form a regular
system of parameters if and only if their residue classes $\bar{x}_1, \ldots, \bar{x}_d$ modulo $\mathfrak{m}_p^2$ form
a $\kappa(p)$-basis of the cotangent space $T_p X = \mathfrak{m}_p/\mathfrak{m}_p^2$.

**Definition 2.95.** A closed subvariety $D \subset X$ of codimension one is called
a simple normal crossing divisor if, for each $p \in D$, there exists a Zariski open
neighborhood $p \subset U_p \subset X$, a regular system of parameters $x_1, \ldots, x_d \in \mathfrak{m}_p$, and an
integer $1 \leq r \leq d$ such that $D \cap U_p$ lies in the zero locus of $x_1 \cdots x_r$.

It follows from the definition that the irreducible components of a simple normal
crossing divisor $D$ are smooth and that the intersection of $m$ distinct irreducible
components is a smooth subvariety of codimension $m$ in $X$.

**Remark 2.96.** Simple normal crossing divisors are also called strict normal
crossing divisors in the literature. Note that this definition is sensitive to the base
field. For example, if $-1$ is not a square in $k$, the subvariety $D = \{x^2 + y^2 = 0\} \subset \mathbb{A}^2_k$
is irreducible and singular at the origin, and hence is not a simple normal crossing
divisors. However, if $k$ contains a square root of $-1$, the factorization

\[
x^2 + y^2 = (x + \sqrt{-1}y)(x - \sqrt{-1}y)
\]

shows that $D$ is the union of two affine lines meeting at the origin, which is the
paradigmatic example of a simple normal crossing divisor.

**Construction 2.97.** Let $X$ be a smooth affine variety over $k$ and let $D$ be a
simple normal crossing divisor, with irreducible components $D_0, \ldots, D_r$. Given a
subset $I \subseteq \{0, \ldots, r\}$, we set

\[
D_I = \bigcap_{i \in I} D_i.
\]
We define $D^0 = X$ and, for $p = 1, \ldots, r + 1$,

$$D^p = \coprod_{|I| = p} D_I.$$ 

Then there is a double complex of $k$-vector spaces

$$K^{p,q} = \Omega^q(D^p),$$

where the vertical differentials $d^{\text{ver}}$ are the differentials $d$ in the de Rham complex, and the horizontal differentials $d^{\text{hor}}$ are alternating sums of restriction maps. More precisely, $d^{\text{hor}}: K^{p,q} \to K^{p+1,q}$ is given by

$$\bigoplus_{|I| = p, |J| = p+1, I \subset J} \varepsilon(I,J) d_{J,I},$$

where $d_{J,I}: \Omega^q(D_I) \to \Omega^q(D_J)$ denotes the restriction map and the sign $\varepsilon(I,J)$ is defined as follows: if $J = \{j_0, \ldots, j_p\}$ with the indexes ordered as $j_0 < \ldots < j_p$, and $I = \{j_0, \ldots, j_\ell, \ldots, j_p\}$, then $\varepsilon(I,J) = (-1)^\ell$.

Let $\Omega^*(X,D)$ denote the total complex associated with $K^{p,q}$, that is,

$$\Omega^*(X,D) = \bigoplus_{p+q = *} K^{p,q}, \quad \partial = d^{\text{hor}} + (-1)^p d^{\text{ver}}.$$ 

Note that, thanks to the sign $(-1)^p$ in front of the vertical differential, the map $\partial$ satisfies $\partial^2 = 0$ and $\Omega^*(X,D)$ is thus a complex. To understand it as a relative complex, we define the double complex

$$\Omega^{p,q}(D) = \Omega^q(D^{p+1})$$

with differentials

$$d^{\text{hor}} = \bigoplus_{|I| = p, |J| = p+1, I \subset J} -\varepsilon(I,J) d_{J,I}, \quad d^{\text{ver}} = d^{\text{dR}}$$

and

$$\Omega^*(D) = \text{Tot}(\Omega^* \circ \mathbb{I}).$$

Then the de Rham cohomology of $D$ is defined as the cohomology of $\Omega^*(D)$, there is a restriction map $\mathbb{I}^*: \Omega^*(X) \to \Omega^*(D)$ and

$$\Omega^*(X,D) = \text{Tot}(\mathbb{I}^*).$$

Observe the parallelism of the complex $\Omega^*(D)$ with the Čech double complex (2.81) so one may think of $\Omega^*(D)$ as a Čech complex associated to a closed cover of $D$.

**Definition 2.100.** The *relative de Rham cohomology* $H^\ast_{\text{dR}}(X,D)$ is the cohomology of the complex $\Omega^*(X,D)$.

As for any total complex associated with a double complex, the cohomology can be computed by means of the spectral sequence

$$E_1^{p,q} = H^q(\Omega^*(D^p)) \Longrightarrow H^{p+q}_{\text{dR}}(X,D).$$
Let $d = \dim X$. By definition, a class in the top degree cohomology $H^d(X, D)$ is represented by a tuple 
\[(\omega_0, \ldots, \omega_d) \in \bigoplus_{p=0}^{d} \Omega^{d-p}(D^p).\]

What is more, one can always choose $\omega_p = 0$ for $p = 1, \ldots, d$, so that all classes in $H^d(X, D)$ are indeed represented by some $\omega \in \Omega^d(X)$. The key point here is that the restriction maps $\Omega^{d-p-1}(D^p) \to \Omega^{d-p-1}(D^{p+1})$ are all surjective [HMS17, Lem. 3.3.20]. We will see in the example below how to use this result to find a representative of the sought shape; the proof of the existence of such representatives in the general case is analogous.

Example 2.102. Let $X = \mathbb{A}^2 = \text{Spec}(k[x, y])$ and let $D \subset X$ be the union of three lines in general position. After an affine transformation, we may assume without loss of generality that $D$ is the union of the lines
\[D_0 = \{y = 0\}, \quad D_1 = \{x = 0\}, \quad D_2 = \{x + y = 1\}.\]

In this case, the double complex (2.98) is equal to
\[\langle \Omega^*(\mathbb{A}^2), d \rangle \longrightarrow \bigoplus_{i=0}^{2} \langle \Omega^*(D_i), d \rangle \longrightarrow \bigoplus_{0 \leq i < j \leq 2} \langle \Omega^*(D_i \cap D_j), d \rangle \longrightarrow 0.\]

To make all the above terms and maps explicit, we write
\[D_0 = \text{Spec}(k[x]), \quad D_1 = \text{Spec}(k[y])\]
and we parametrize \( D_2 = \text{Spec} \left( k[x, y]/(x + y - 1) \right) \) by the coordinate \( z = x \). Then one gets:

\[
\begin{array}{c}
k[x, y]dx \wedge dy \\
d \downarrow \\
k[x, y]dx \oplus k[x, y]dy \\
c \downarrow \\
k[x, y]d^x \oplus k[y]dy \oplus k[z]dz \\
d \downarrow \\
k[x] \oplus k[y] \oplus k[z] \\
b \downarrow \\
k \oplus k \oplus k,
\end{array}
\]

where \( d \) is the exterior derivative, the maps \( a \) and \( b \) are given by

\[
\begin{align*}
a: & \quad f(x, y) \mapsto (f(x, 0), f(0, y), f(z, 1 - z)), \\
b: & \quad (f(x), g(y), h(z)) \mapsto (g(0) - f(0), h(1) - f(1), h(0) - g(1)),
\end{align*}
\]

and \( c \) is induced from \( a \) in the obvious way. The spectral sequence (2.101) thus reads

\[
\begin{array}{c}
0 \\
0 \\
k \rightarrow k \oplus k \oplus k \rightarrow k \oplus k \oplus k
\end{array}
\]

where the first map sends \( a \) to \((a, a, a)\) and the second one is given by

\[
(a, b, c) \mapsto (b - a, c - a, c - b).
\]

Since the cohomology of the bottom complex is concentrated in degree two, where it is generated by the class of the element \((1, 0, 0)\), the second page of the spectral sequence is reduced to \( E_2^{2,0} = k \). It follows that \( \text{H}^i_{\text{dR}}(\mathbb{A}^2, D) \) vanishes for \( i \neq 2 \) and is one-dimensional for \( i = 2 \).

To produce a differential \( \omega \in \Omega^2(\mathbb{A}^2) \) representing the cohomology class, we follow the “zig-zag” method, which consists of

- finding \( \omega_1 \in k[x] \oplus k[y] \oplus k[z] \) such that \( b(\omega_1) = (1, 0, 0) \);
- applying \( d^{\text{ver}} \) to get \( \omega_2 = d\omega_1 \) one row above, hence,

\[
\partial \omega_1 = d^{\text{hor}} \omega_1 - d^{\text{ver}} \omega_1 = b(\omega_1) - d\omega_1 = (1, 0, 0) - \omega_2,
\]

so \((1, 0, 0)\) and \( \omega_2 \) are cohomologous;
- choosing \( \omega_3 \in k[x, y]dx \oplus k[x, y]dy \) such that \( c(\omega_3) = \omega_2 \).

Then, setting \( \omega = -d\omega_3 \), one has

\[
\partial \omega_3 = c(\omega_3) + d\omega_3 = \omega_2 - \omega,
\]

so that \( \omega \) and \( \omega_2 \) are also cohomologous. Summing up \( \omega \) and \((1, 0, 0)\) are cohomologous.

It is straightforward to check that one can take

\[
\omega_1 = (x - 1, 0, 0), \quad \omega_2 = (dx, 0, 0), \quad \omega_3 = (1 - y)dx + xdy.
\]
This yields the differential form $\omega = -2dx \wedge dy$ on $\mathbb{A}^2$, which defines a relative cohomology class since it has top degree. In conclusion:

$$H_{dR}^i(X, D) = \begin{cases} (dx \wedge dy)_k, & \text{if } i = 2, \\ 0, & \text{otherwise.} \end{cases}$$

** Exercise 2.103. Prove that the axioms i) and ii) in Definition 2.57 imply that, in local coordinates $x_1, \ldots, x_d$, the exterior derivative is given by

$$d(fdx_{i_1} \wedge \cdots \wedge dx_{i_p}) = \sum_{i=1}^d \frac{\partial f}{\partial x_i} dx_{i_1} \wedge \cdots \wedge dx_{i_p}.$$ 

Deduce that $d^2 = d \circ d$ vanishes.

** Exercise 2.104. Let $k$ be a field of characteristic zero. Show that $H_{dR}^0(\mathbb{A}^n_k) = k$ and that all the other cohomology groups vanish.

** Exercise 2.105. Check the identities (2.83) in Example 2.82.

** Exercise 2.106. In Example 2.74 we saw that a basis of the de Rham cohomology of an affine elliptic curve $X \subseteq \mathbb{A}^2_k$ is given by the classes of the differential forms $\omega$ and $x\omega$. Let $\overline{X} \subseteq \mathbb{P}^2_k$ be the projective completion of $X$, that is, the smooth projective curve obtained by adjoining to $X$ the point at infinity $O = [0 : 1 : 0]$. Prove that $\omega$ extends to a holomorphic differential on $\overline{X}$, whereas $x\omega$ has a double pole at $O$.

** Exercise 2.107. We have defined de Rham cohomology for varieties over a field of characteristic zero. Show by means of an example that the same definition gives pathological results in positive characteristic (for instance, the cohomology of $\mathbb{A}^1$ has infinite dimension).

** Exercise 2.108. We place ourselves in the situation of Example 2.91.

i) Show that the elements $-\omega_1' = (0, -1, 0)$ and $\omega_1 = (dx/(p-q), 0, 0)$ are cohomologous.

ii) Show that, for every integer $r \neq -1$ the elements

$$(x^r dx, 0, 0), \quad \frac{p^r+1 - q^r+1}{r+1} \omega_1$$

are cohomologous.
EXERCISE 2.109. Let \( D \subset \mathbb{P}^n \) be the union of a finite collection of hyperplanes. Under which condition on the hyperplanes is \( D \) a simple normal crossing divisor?

EXERCISE 2.110. Let \( A \) be a \( k \)-algebra and let \( \mu: A \otimes_k A \to A \) denote the multiplication map which sends an element \( \sum a_i \otimes b_i \) to \( \sum a_i b_i \). Set
\[
I = \ker(\mu: A \otimes_k A \to A).
\]
The goal of the exercise is to prove that \( \Omega^1_{\mathbb{A}_k} \simeq I/I^2 \) as \( A \)-modules.

i) Show that the map \( a \mapsto 1 \otimes a - a \otimes 1 \) induces a \( k \)-linear derivation \( A \to I/I^2 \), and hence a morphism of \( A \)-modules \( \varphi: \Omega^1_{\mathbb{A}_k} \to I/I^2 \) by the universal property (2.68).

ii) Consider the ring \( R = A \oplus \Omega^1_{\mathbb{A}_k} \), where \( A \) acts on \( \Omega^1_{\mathbb{A}_k} \) through the \( A \)-module structure and the product of any two elements of \( \Omega^1_{\mathbb{A}_k} \) is zero. Show that the \( k \)-bilinear map
\[
A \times A \to R \quad (a_1, a_2) \mapsto (a_1 a_2, a_1 da_2).
\]
factors through \( A \otimes_k A \) and sends \( I \) to \( \Omega^1_{\mathbb{A}_k} \) and \( I^2 \) to zero. Therefore, it defines a map \( \psi: I/I^2 \to \Omega^1_{\mathbb{A}_k} \).

iii) Prove that \( \varphi \) and \( \psi \) are inverse of each other.

EXERCISE 2.111 (The module of Kähler differentials is not locally free for singular varieties). Set \( A = k[x, y]/(xy) \) and \( X = \text{Spec}(A) \). By Example 2.69, the module of Kähler differentials \( \Omega^1_X \) has generators \( dx \) and \( dy \), which are subject to the relation \( xdy = -ydx \). Let \( \omega = xdy \).

i) Show that \( \omega \neq 0 \) but \( x\omega = y\omega = 0 \).

ii) Let \( z \in A \). Show that \( xz = yz = 0 \) implies \( z = 0 \). Conclude that \( \Omega^1_X \) is not locally free.

iii) Show that \( k \cdot \omega \) sits in an exact sequence
\[
0 \to k \cdot \omega \to \Omega^1_X \to k[x]dx \oplus k[y]dy \to 0.
\]
and that this exact sequence does not split as a sequence of \( A \)-modules.

iv) Prove that \( \Omega^1_X = k \cdot dx \wedge dy \).

EXERCISE 2.112 (An instance of Jouanolou’s trick). In this exercise, we show how to compute the algebraic de Rham cohomology of \( \mathbb{P}^1 \) using global differential forms on an affine variety.

i) Let \( \Delta \to \mathbb{P}^1 \times \mathbb{P}^1 \) be the diagonal and set \( X = \mathbb{P}^1 \times \mathbb{P}^1 \setminus \Delta \). Prove that \( X \) is the affine variety
\[
\text{Spec}(k[x, y, z]/(x(x - 1) - yz))
\]
and that the projection onto the first factor \( \pi: X \to \mathbb{P}^1 \) is given in these coordinates by \( \pi(x, y, z) = [x : y] = [x - 1 : z] \). Observe that all the fibers of \( \pi \) are affine lines. [Hint: first identify \( \mathbb{P}^1 \times \mathbb{P}^1 \) with a quadric in \( \mathbb{P}^3 \) through the Segre embedding.]

ii) Prove that the complexes \( \Omega^* \) and \( R\pi_* \Omega^*_X \) of locally free sheaves on \( \mathbb{P}^1 \) are quasi-isomorphic. Deduce that the algebraic de Rham cohomologies \( H^1_{\text{dR}}(\mathbb{P}^1) \) and \( H^1_{\text{dR}}(X) \) are isomorphic. [Hint: since the morphism \( \pi \) is affine, \( R\pi_* \Omega^*_X = \pi_* \Omega^*_X \). Then use the Leray spectral sequence.]
iii) Write down a global differential form $\omega \in \Omega^2(X)$ generating $H^2_{\text{dR}}(X)$.

Exercise 2.113. A way to rephrase the fact that the Poincaré lemma fails for the Zariski topology, as explained in Remark 2.130, is by saying that, for a smooth connected variety $X$ over $k$, the Zariski sheaves

$$H^q_X = \frac{\text{Ker}(d: \Omega^q_X \to \Omega^{q+1}_X)}{\text{Im}(d: \Omega^{q-1}_X \to \Omega^q_X)}$$

are not zero in general. Observe that $H^q_X$ is the sheaf associated with the presheaf $U \mapsto H^q_{\text{dR}}(U)$. As for any hypercohomology of sheaves, there is a spectral sequence

$$E_2^{p,q} = H^p(X, H^q_X) \Rightarrow H^{p+q}_{\text{dR}}(X).$$

i) Prove that the sheaf $H^0_X$ is flasque, and hence acyclic.

ii) Deduce that the presheaf $U \mapsto H^1_{\text{dR}}(U)$ is already a sheaf on $X$.

2.3. The comparison isomorphism. The goal of this section is to prove an algebraic counterpart of de Rham’s theorem 2.62, namely Grothendieck’s theorem [Gro66] according to which the Betti and the de Rham cohomology of a smooth algebraic variety over a subfield of the complex numbers become canonically isomorphic after extension of scalars.

Theorem 2.114 (Grothendieck). Let $k$ be a subfield of the complex numbers and let $X$ be a smooth variety over $k$. There is a canonical isomorphism

$$\text{comp}_{\text{B, dR}}: H^i_{\text{dR}}(X) \otimes_k \mathbb{C} \xrightarrow{\sim} H^i_B(X) \otimes_{\mathbb{Q}} \mathbb{C}.$$  

We will often refer to $\text{comp}_{\text{B, dR}}$ as the comparison isomorphism.

2.3.1. From algebraic to analytic: Serre’s GAGA theorem. The first step in the proof of the comparison isomorphism consists in relating the cohomology of coherent sheaves on algebraic varieties to the cohomology of their analytifications. This is the content of Serre’s GAGA theorem, named after the title “Géométrie Algébrique et Géométrie Analytique” of his landmark paper [Ser56]. We refer the reader to Section A.9.9 of the appendix for a short reminder of the notions of coherent sheaf in algebraic and analytic geometry, as well as the vanishing theorems for coherent sheaves on affine and Stein varieties that are used below. Neeman’s book [Nee07] is a self-contained introduction to algebraic and analytic geometry with the GAGA theorem as guiding principle.

Let $X$ be a smooth algebraic variety over the field of complex numbers. The set of complex points $X(\mathbb{C})$ of $X$, together with the topology inherited from that of $\mathbb{C}$, carries the structure of a complex manifold $X^{\text{an}}$. We let $\mathcal{O}_{X^{\text{an}}}$ denote the sheaf of holomorphic functions on $X^{\text{an}}$ and $\psi: X^{\text{an}} \to X$ the map of topological spaces that sends an element of $X(\mathbb{C}) = \text{Hom}(\text{Spec}(\mathbb{C}), X)$ to the corresponding closed point of $X$. Since the complex points of every Zariski open subset of $X$ form an open subset of $X(\mathbb{C})$, this map is continuous. Moreover, there is a morphism

$$\psi^{-1}\mathcal{O}_X \to \mathcal{O}_{X^{\text{an}}}$$

of sheaves of rings on $X^{\text{an}}$. Indeed, recall from Definition A.219 that the inverse image $\psi^{-1}\mathcal{O}_X$ is the sheaf associated with the presheaf

$$U \mapsto \varprojlim V \mapsto \mathcal{O}_X(V),$$

where $V$ runs through the Zariski open subsets of $U$. We will sometimes use the notation $\mathcal{O}_X^{\text{an}}$ for $\psi^{-1}\mathcal{O}_X$. Since $X$ is smooth, the sheaf $\mathcal{O}_X^{\text{an}}$ is locally isomorphic to $\mathcal{O}_{X^{\text{an}}}$, and $\text{comp}_{\text{B, dR}}$ induces a map

$$H^i_B(X) \otimes \mathbb{Q} \to H^i_{\text{dR}}(X).$$

This map is an isomorphism in degree $0$ and an injection in degree $1$. The strategy is to construct an injective map of complexes $\mathcal{O}_X^{\text{an}} \to \mathcal{O}_{X^{\text{an}}}$ so that the comparison isomorphism descends to a map of complexes on the cohomology. This injective map is constructed using the comparison isomorphism for affine schemes.
where $U$ is an open subset of $X(\mathbb{C})$ and the limit runs over all Zariski open subsets $V$ of $X$ containing $\psi(U)$. Since every regular function $f$ on $V$ induces a holomorphic function $f^{an}$ on $V(\mathbb{C})$, and hence on $U(\mathbb{C})$ upon restriction, there is an obvious morphism of presheaves from (2.115) to $\mathcal{O}_{X^{an}}$. As the target $\mathcal{O}_{X^{an}}$ is itself a sheaf, the universal property of sheafification (Proposition A.188) yields the sought morphism of sheaves $\psi^{-1}\mathcal{O}_X \to \mathcal{O}_{X^{an}}$.

**Definition 2.116.** Let $F$ be a sheaf of $\mathcal{O}_X$-modules on $X$. The **analytification** of $F$ is the sheaf of $\mathcal{O}_{X^{an}}$-modules on $X^{an}$ given by

$$F^{an} = \psi^{-1}F \otimes_{\psi^{-1}\mathcal{O}_X} \mathcal{O}_{X^{an}}.$$ 

In other words, $F^{an}$ is the sheaf associated with the presheaf

$$(2.117) \quad U \mapsto \psi^{-1}F(U) \otimes_{\psi^{-1}\mathcal{O}_X(U)} \mathcal{O}_{X^{an}}(U).$$

If $F$ is coherent in the sense of algebraic geometry, then $F^{an}$ is coherent in the sense of analytic geometry.

**Example 2.118.** By its very definition, the analytification of the sheaf of regular functions on $X$ is the sheaf of holomorphic functions on $X^{an}$, that is: $\mathcal{O}_{X^{an}}^{an} = \mathcal{O}_{X^{an}}$. Moreover, on each complex manifold $M$ one can define the **sheaf of holomorphic differential forms**. Namely, for $j \geq 0$, the sheaf $\Omega^j_M$ consist of differential forms that can be written locally as

$$\omega = \sum_{i_1 < i_2 < \cdots < i_j} f_{i_1, \ldots, i_j} dz_{i_1} \wedge \cdots \wedge dz_{i_j},$$

where $(z_1, \ldots, z_d)$ are local complex coordinates of $M$ and the functions $f_{i_1, \ldots, i_j}$ are holomorphic. The sheaves $\Omega^*_M$ together with the differential $d$ form a complex of sheaves that is called the **holomorphic de Rham complex**.

For each $j \geq 1$,

$$\Omega^j_M^{an} = \Omega^j_{X^{an}},$$

where the sheaf on the right-hand side is the sheaf of holomorphic differential forms on the complex manifold $X^{an}$.

The morphism of presheaves from $\psi^{-1}F$ to (2.117) that sends a local section $e$ to $e \otimes 1$ yields a morphism of sheaves $\psi^{-1}F \to F^{an}$, and hence a morphism of sheaves $F \to \psi_*F^{an}$ using the adjunction between inverse and direct image functors, see (A.221) from the appendix. Composing with the map from a functor to its derived functor, we get morphisms of complexes of sheaves

$$F \to \psi_*F^{an} \to R\psi_*F^{an}.$$ 

**Lemma 2.120.** If $F$ is a coherent sheaf on $X$, then $R^i\psi_*F^{an} = 0$ for all $i \geq 1$, and hence the map $\psi_*F^{an} \to R\psi_*F^{an}$ is an isomorphism.

**Proof.** Using Proposition A.214, the stalk at a closed point $x \in X$ of the higher direct image sheaf $R^i\psi_*F^{an}$ is the inductive limit of $H^i(\psi^{-1}(U), F^{an})$, as $U$ runs through all Zariski open subsets of $X$ containing $x$. Since affine open subsets form a basis of the Zariski topology, we can restrict to affine $U$ in this limit. Now, for such an open $U$, the cohomology $H^i(\psi^{-1}(U), F^{an})$ vanishes for all $i \geq 0$ by Cartan’s theorem A.241, since $\psi^{-1}(U)$ is Stein and $F^{an}$ is coherent. Therefore, $R^i\psi_*F^{an} = 0$ for all $i \geq 1$, and hence the map $\psi_*F^{an} \to R\psi_*F^{an}$ is an isomorphism. \qed
The celebrated GAGA theorem by Serre [Ser56] is the result that, for $X$ projective, the analytification functor $F \mapsto F_{\text{an}}$ is an equivalence of categories from coherent sheaves on $X$ to coherent sheaves on $X_{\text{an}}$ and that this functor preserves cohomology. This was later generalized to proper (non-necessarily projective) varieties by Grothendieck [Gro03, Exp. XII, Thm. 4.4]. In what follows, we will only need the comparison of algebraic and analytic cohomology on smooth varieties (using the language of analytic spaces instead of complex manifolds, the statement below remains valid for singular varieties).

**Theorem 2.121 (GAGA theorem).** For any smooth proper variety $X$ over the field of complex numbers and any coherent sheaf $F$ on $X$, the analytification map (2.119) induces isomorphisms

$$H^i(X, F) \xrightarrow{\sim} H^i(X_{\text{an}}, F_{\text{an}}).$$

**Remark 2.122.** The GAGA theorem fails dramatically when the properness assumption is dropped. For example, if $X = \mathbb{A}^1 = \text{Spec}(\mathbb{C}[x])$ is the affine line and $F = \mathcal{O}_X$ is the structure sheaf, in degree $i = 0$ the left-hand side is the set of polynomials $\mathbb{C}[x]$, whereas the right-hand side is the set of all entire functions.

By a limiting process, Theorem 2.121 still holds for quasi-coherent sheaves, as explained e.g. in [Del70, Lem. 6.5]. Indeed, any quasi-coherent sheaf $F$ on $X$ can be written as an inductive limit $F = \varinjlim F_i$ of coherent sheaves $F_i$; taking into account that the inverse image functor and the tensor product commute with inductive limits, its analytification is given by $F_{\text{an}} = \varinjlim F_{i\text{an}}$. Besides, on a compact topological space cohomology commutes with inductive limits, and hence $H^*(X, F)$ and $H^*(X_{\text{an}}, F_{\text{an}})$ are the inductive limits of $H^*(X, F_i)$ and $H^*(X_{\text{an}}, F_{i\text{an}})$ respectively, which are isomorphic by the GAGA theorem for coherent sheaves.

**Corollary 2.123.** For any smooth proper variety $X$ over the field of complex numbers and any quasi-coherent sheaf $F$ on $X$, the analytification map (2.119) induces isomorphisms

$$H^i(X, F) \xrightarrow{\sim} H^i(X_{\text{an}}, F_{\text{an}}).$$

### 2.3.2. Algebraic and analytic de Rham cohomology.

**Definition 2.124.** Let $M$ be a complex manifold. The analytic de Rham cohomology of $X$ is the hypercohomology of the holomorphic de Rham complex (Example 2.118)

$$H^*_dR(M) = H^*(M, \Omega^*_M).$$

Let $X$ be a smooth algebraic variety over $\mathbb{C}$ and let $X_{\text{an}}$ be the associated complex manifold. Since the sheaf of holomorphic differentials $\Omega^j_{X_{\text{an}}}$ is the analytification of the sheaf of Kähler differentials $\Omega^j_X$ for all $j \geqslant 0$ by Example 2.118, the morphisms (2.119) specialize to $\Omega^j_X \rightarrow \psi^* \Omega^j_{X_{\text{an}}} \rightarrow R^j \psi_* \Omega^j_X$. Moreover, since the sheaves $\Omega^j_X$ are coherent (in fact, locally free), the second map is an isomorphism by Lemma 2.120. Besides, these maps are compatible with the differential, as the differential of a regular function is the same whether we consider it as an algebraic or as an analytic function. Therefore, we get a morphism $\Omega^*_X \rightarrow R^j \psi_* \Omega^*_X$ of complexes of sheaves on $X$. It induces a $\mathbb{C}$-linear map on cohomology (2.125)

$$H^*_dR(X) = H^*(X, \Omega^*_X) \rightarrow H^*(X, R^j \psi_* \Omega^*_X) = H^*(X_{\text{an}}, \Omega^*_X) = H^*_dR(X_{\text{an}}).$$
that we call the *analytification map*. We shall prove later (see the proof of Theorem 2.149 below) that this map is always an isomorphism. For the time being, we restrict ourselves to proper varieties.

**Proposition 2.126.** If $X$ is proper, then the analytification map (2.125) is an isomorphism:

$$H^*_d(X) \sim \rightarrow H^*_d(X^{an}).$$

**Proof.** Since algebraic and analytic de Rham cohomology are defined as the hypercohomology of the complexes of sheaves $\Omega^* X$ and $\Omega^* X^{an}$ respectively, they are the abutments of the spectral sequences

$$E^{p,q}_1 = H^q(X, \Omega^p X) \Rightarrow H^{p+q}_d(X)$$

$$E^{p,q}_1 = H^q(X^{an}, \Omega^p X^{an}) \Rightarrow H^{p+q}_d(X^{an}).$$

By the construction of the map between algebraic and analytic de Rham cohomology, there is a morphism of spectral sequences compatible with this map. By the GAGA theorem 2.121, for every $p, q$ the map

$$H^q(X, \Omega^p X) \rightarrow H^q(X^{an}, \Omega^p X^{an})$$

is an isomorphism, hence the result. □

2.3.3. *Analytic de Rham cohomology and the Poincaré lemma.* The next tool in the proof of the comparison theorem, is a result relating analytic de Rham cohomology with singular cohomology. If $M$ is a complex manifold of dimension $d$, then the holomorphic de Rham complex is the complex of sheaves

$$0 \rightarrow \mathcal{O}_M \rightarrow \Omega^1_M \rightarrow \cdots \rightarrow \Omega^d_M \rightarrow 0,$$

where $\mathcal{O}_M$ denotes now the sheaf of holomorphic functions and $\Omega^*_M$ the sheaf of holomorphic differential forms.

**Theorem 2.127** (Poincaré lemma). Let $M$ be a complex manifold. The inclusion of the sheaf of locally constant functions $\mathbb{C}_M$ into the sheaf of holomorphic functions $\mathcal{O}_M$ induces a quasi-isomorphism $\iota: \mathbb{C}_M \rightarrow \Omega^*_M$.

**Proof.** Let $M$ be a complex manifold of dimension $d$. Proving that the morphism of complexes of sheaves

$$\iota: \mathbb{C}_M \rightarrow \Omega^*_M$$

is a quasi-isomorphism amounts to showing that $\iota$ is a quasi-isomorphism after taking the stalk at each point of $M$. Since $M$ is a complex manifold, every point has an open neighborhood biholomorphic to the polydisc

$$\mathbb{D}^d = \{ z = (z_1, \ldots, z_d) \in \mathbb{C}^d \mid |z_i| < 1 \text{ for } i = 1, \ldots, d \},$$

and it suffices to show that the morphism $\iota: \mathbb{C} \rightarrow \Omega^*_M(\mathbb{D}^d)$ of complexes of sections on $\mathbb{D}^d$ is a quasi-isomorphism. We shall in fact prove that it is a homotopy equivalence (see Definition A.57 from the appendix).

Let $o = (0, \ldots, 0) \in \mathbb{D}^d$ denote the center of the polydisc, and let

$$r: \Omega^*_M(\mathbb{D}^d) \rightarrow \mathbb{C}$$

be the map that sends a function $g \in \mathcal{O}_M(\mathbb{D}^d)$ to its value at $o$ and any differential form $\omega \in \Omega^j_M(\mathbb{D}^d)$, with $j \geq 1$, to zero. Clearly, $r \circ \iota = \text{Id}_\mathbb{C}$ and the goal is to prove that $\iota \circ r$ is homotopic to the identity on $\Omega^*_M(\mathbb{D}^d)$. For this, we shall construct a
map \( h : \Omega^j_M(\mathbb{D}^d) \to \Omega^{j-1}_M(\mathbb{D}^d) \) for each \( j \geq 0 \). Let \( H : [0, 1] \times \mathbb{D}^d \to \mathbb{D}^d \) be the map given by \( H(t, z) = tz \). For each differential form \( \omega \in \Omega^j_M(\mathbb{D}^d) \), we define

\[
(2.128) \quad h(\omega) = \int_0^1 i_{\partial_t} H^*(\omega) dt,
\]

where \( i_{\partial_t} \) stands for the contraction of a differential form on \([0, 1] \times \mathbb{D}^d\) with the vector field tangent to \([0, 1]\). Recalling that a differential \( j \)-form on a manifold is a linear functional on the \( j \)-th alternating power of its tangent bundle, the contraction \( i_{\partial_t} H^*(\omega) \) is defined as the \((j - 1)\)-th form which takes the value

\[
(\iota_{\partial_t} H^*(\omega))(X_1 \wedge \cdots \wedge X_{j-1}) = H^*(\omega)(\partial_t \wedge X_1 \wedge \cdots \wedge X_{j-1})
\]

on vector fields \( X_1, \ldots, X_{j-1} \). To get a grasp on what \( h \) does to a differential form, let us compute an example. If \( \omega = z_1 z_2 dz_1 \wedge dz_2 \), then

\[
H^*(\omega) = (tz_1)(tz_2) d(tz_1) \wedge d(tz_2) = z_1 z_2 t^3 dz_1 \wedge dz_2 + z_1 z_2 t^3 dz_1 \wedge dt.
\]

Concretely, \( i_{\partial_t} \) deletes the summands not involving \( dt \) and replaces \( dt \) with a sign depending on its position in the remaining ones. In the case at hand,

\[
i_{\partial_t} H^*(\omega) = z_1^2 z_2 t^3 dz_2 - z_1 z_2^2 t^3 dz_1,
\]

and integration with respect to \( t \) yields

\[
h(\omega) = \frac{1}{4}(z_1^2 z_2^2 dz_2 - z_1 z_2^3 dz_1).
\]

If \( \omega \in \Omega^j_M(\mathbb{D}^d) \), then \( h(\omega) \) is a holomorphic differential \((j - 1)\)-form on \( \mathbb{D}^d \), whence a map \( h : \Omega^j_M(\mathbb{D}^d) \to \Omega^{j-1}_M(\mathbb{D}^d) \) for each \( j \geq 0 \). By the fundamental theorem of calculus,

\[
dh(\omega) + h(d\omega) = H^*(\omega)|_{t=1} - H^*(\omega)|_{t=0} = \omega - \iota \circ r(\omega),
\]

which shows that \( \iota \circ r \) is homotopic to the identity.

Since the singular cohomology with complex coefficients of \( M \) is canonically isomorphic to the sheaf cohomology of \( \mathcal{C}_M \) by Theorem A.236 from the appendix, we immediately derive:

**Corollary 2.129.** *Singular cohomology with complex coefficients is canonically isomorphic to analytic de Rham cohomology:*

\[
H^*(M, \mathbb{C}) \xrightarrow{\sim} \mathcal{H}^*_{dR}(M).
\]

**Remark 2.130.** The Poincaré lemma fails for the Zariski topology: if \( X \) is an algebraic variety over \( k \), the complex

\[
(2.131) \quad 0 \to \text{Ker}(d) \to \mathcal{O}_X \to \Omega^1_X \to \cdots
\]

of sheaves for the Zariski topology is not exact. For example, if \( X = \mathbb{G}_m \) with coordinate \( t \), then a non-empty Zariski open subset of \( X \) is the complement \( U = X \setminus S \) of a finite set of closed points \( S \), and the complex

\[
0 \to k \to \mathcal{O}_X(U) \to \Omega^1_X(U) \to 0
\]

always has cohomology in degree two since the class of \( dt/t \) still does not vanish in \( \Omega^1_X(U)/\text{Im}(d) \). In fact, the smaller the Zariski open gets the bigger the cohomology group becomes (see Exercise 2.113).
2.3.4. *The case of smooth proper varieties.* We are now ready to establish the comparison isomorphism for smooth proper varieties as a mere combination of the Poincaré lemma and the isomorphism between algebraic and analytic de Rham cohomology deduced from the GAGA theorem.

**Theorem 2.132.** Let $k$ be a subfield of $\mathbb{C}$ and let $X$ be a smooth proper variety over $k$. There is a canonical isomorphism

$$H^\ast_{dR}(X) \otimes_k \mathbb{C} \sim \rightarrow H^\ast_{dR}(X_{\mathbb{C}}) \otimes_{\mathbb{C}} \mathbb{C}.$$  

**Proof.** The sought isomorphism is the composition of the maps \(\circlearrowleft\), \(\circlearrowright\), the inverse of \(\circlearrowright\), and \(\circlearrowleft\) below:

\[
\begin{align*}
H^\ast_{dR}(X) \otimes_k \mathbb{C} & \xrightarrow{\circlearrowleft} H^\ast_{dR}(X_{\mathbb{C}}) & \xrightarrow{\circlearrowright} H^\ast_{dR}(X^{an}) & \xrightarrow{\circlearrowleft} H^\ast(X(\mathbb{C}), \mathbb{C}) & \xrightarrow{\circlearrowleft} H^\ast_B(X) \otimes_{\mathbb{C}} \mathbb{C}.
\end{align*}
\]

The isomorphism \(\circlearrowleft\) comes from the compatibility of algebraic de Rham cohomology with extension of scalars (Lemma 2.85). The isomorphism \(\circlearrowright\) between algebraic and analytic de Rham cohomology is the content of Proposition 2.126. The isomorphism \(\circlearrowleft\) follows from the Poincaré lemma (Theorem 2.127). Finally, Theorem A.236 in the appendix and the universal coefficient theorem yield the isomorphism \(\circlearrowright\). \(\square\)

In order to extend this result to arbitrary smooth varieties we need to introduce the sheaf of differential forms with logarithmic poles.

2.3.5. *Cohomology in terms of logarithmic differentials.* Recall the notion of simple normal crossing divisor from Definition 2.95. In this paragraph, we explain how to compute algebraic de Rham cohomology of a smooth variety as the hypercohomology of the complex of sheaves of logarithmic differentials on a smooth compactification by a simple normal crossing divisor.

We begin with Hironaka’s theorem on the *resolution of singularities*, which ensures that any compactification can be transformed into a smooth compactification by a simple normal crossing divisor. By a resolution of singularities of a variety $Y$, we mean a proper birational morphism $\pi: \tilde{Y} \rightarrow Y$ from a smooth variety $\tilde{Y}$. Recall that being birational means that there exists a dense open subset $U \subset Y$ such that the map $\pi^{-1}(U) \rightarrow U$ is an isomorphism; the closed complement $E \subset Y$ of the largest open subset with this property is called the *exceptional locus* of the morphism $\pi$.

**Theorem 2.133 (Hironaka).** Let $k$ be a field of characteristic zero. Let $Y$ be a variety over $k$ and let $Z \subset Y$ be a closed subvariety. There exists a proper birational map $\pi: \tilde{Y} \rightarrow Y$ such that

i) $\tilde{Y}$ is smooth,

ii) the union of $\pi^{-1}(Z)$ and the exceptional locus of $\pi$ is a simple normal crossing divisor,

iii) $\pi$ is an isomorphism outside the union of $Z$ and the singular locus of $Y$. Moreover, such a morphism can be obtained as an iterated blow-up along smooth subvarieties of $Y$. 

The map $\pi: \tilde{Y} \to Y$ in the previous theorem is called a \textit{resolution of singularities} of the pair $(Y, Z)$.

We will mainly use the following consequence of Hironaka’s theorem. Start with a smooth variety $X$ over $k$ and choose a proper variety $Y$ over $k$ containing $X$ as an open dense subvariety (for example, if $X$ is quasi-projective, one can pick as $Y$ the closure of $X$ into some projective space on which $X$ embeds as a locally closed subset; the general case requires Nagata’s compactification theorem). Applied to $Y$ and $Z = Y \setminus X$, Hironaka’s theorem yields a resolution of singularities $\pi: \tilde{Y} \to Y$ that is an isomorphism outside $Z$ and such that $\pi^{-1}(Z)$ is a normal crossing divisor.

\textbf{Corollary 2.134.} \textit{Given a smooth variety $X$ over $k$, there exists a smooth proper variety $\overline{X}$ over $k$ and an open immersion $j: X \hookrightarrow \overline{X}$ such that $D = \overline{X} \setminus X$ is a simple normal crossing divisor.}

We shall call such an $\overline{X}$ a smooth \textit{compactification} of $X$ by the simple normal crossing divisor $D$. With these preliminaries out of the way, we now turn to the definition of the complex of logarithmic differentials.

\textbf{Definition 2.135 (Deligne).} The \textit{complex of sheaves of logarithmic differentials along $D$} is the smallest subcomplex

$$\Omega^\ast_{\overline{X}}(\log D) \hookrightarrow j_\ast \Omega^\ast_X$$

that is stable under wedge product and contains $\Omega^\ast_X$ and the logarithmic derivatives $df/f$ of all local sections $f$ of $j_\ast \mathcal{O}_X$.

The sheaf $j_\ast \mathcal{O}_X$ consists of the rational functions that can be written locally as $h/g$ with $h, g \in \mathcal{O}_{\overline{X}}$ and $h|_X, g|_X \in \mathcal{O}_X$. It follows that $\Omega^1_{\overline{X}}(\log D)$ is a locally free $\mathcal{O}_{\overline{X}}$-module of rank $d = \dim X$. Indeed, if $z_1, \ldots, z_d$ is a regular system of parameters with respect to which $D$ is cut out by the equation $z_1 \cdots z_r = 0$, then the sheaf $\Omega^1_{\overline{X}}(\log D)$ is locally generated by the differential forms

$$dz_1/z_1, \ldots, dz_r/z_r, dz_{r+1}, \ldots, dz_d.$$ 

Moreover, one has $\Omega^p_{\overline{X}}(\log D) = \Lambda^p \Omega^1_{\overline{X}}(\log D)$ for all $p \geq 0$.

We will also need to consider logarithmic differentials in the analytic setting. We start with the definition of a simple normal crossing divisor on a complex manifold.

\textbf{Definition 2.136.} Let $M$ be a complex manifold of dimension $d$. A closed analytic subset $Z \subset M$ of codimension one is called a \textit{simple normal crossing divisor} if all its irreducible components are smooth and, for each point $p \in D$, there exist local coordinates $x_1, \ldots, x_d$ around $p$ on which $D$ is defined by $x_1 \cdots x_r = 0$ for some $1 \leq r \leq d$.

\textbf{Remark 2.137.} If $M$ is a complex manifold and $Z \subset M$ is a normal crossing divisor, then there is an analogous definition of the sheaf of holomorphic forms on $M$ with logarithmic poles along $Z$. If $X$ is a smooth algebraic variety over $\mathbb{C}$ and $\overline{X}$ a smooth compactification by a simple normal crossing divisor $D = \overline{X} \setminus X$, then

$$\Omega^\ast_{\overline{X}}(\log D)^{an} = \Omega^\ast_X(\log D)^{an}.$$ 

\textbf{Definition 2.138.} Let $M$ be a complex manifold, $Z \subset M$ a normal crossing divisor, $U = M \setminus Z$ its complement, and $j: U \to M$ the inclusion. The subcomplex
of \( j_* \Omega^m_U \), consisting of the sheaves of holomorphic differential forms on \( U \) that are meromorphic along \( Z \) is denoted by \( j^m_* \Omega^m_Z \). In concrete terms, \( j^m_* \Omega^m_Z \) is the sheaf of differential forms on \( M \), possibly with singularities along \( Z \), that can be written locally as \( \omega/f \) for local sections \( \omega \) of \( \Omega^m_M \) and \( f \) of \( \mathcal{O}_M \) such that the restriction \( f|_U \) is invertible, i.e., a local section of \( \mathcal{O}_U^* \).

**Example 2.139.** Let \( X \) be a smooth variety over \( \mathbb{C} \) and \( \overline{X} \) a smooth compactification with \( D = \overline{X} \setminus X \) a simple normal crossing divisor. By abuse of notation we denote by \( j \) both open immersions, the algebraic \( X \to \overline{X} \) and the analytic one \( X^{an} \to \overline{X}^{an} \). Then we can identify

\[ j^m_* \Omega^m_X^{an} = (j_* \Omega^m_X)^{an}. \]

Indeed, both sheaves are subsheaves of \( j_* \Omega^m_X^{an} \). A section of this last sheaf belongs to \( (j_* \Omega^m_X)^{an} \) if it can be written locally as \( \omega/f \) with \( \omega \in \Omega^m_X^{an} \) and \( f \in \mathcal{O}_X \) such that \( f|_X \in \mathcal{O}_X^* \). Since any holomorphic function \( g \in \mathcal{O}_X^{an} \) with \( g|_X \in \mathcal{O}_X^* \) can be written locally as \( g = fu \) with \( f \) as before and \( u \in \Omega^m_X^{an} \), we deduce the claimed identification by using the concrete description of \( j^m_* \Omega^m_X^{an} \) given in Definition 2.138.

The proof of the next theorem is taken from [Del70, Lem. 6.9].

**Theorem 2.140.** With the notation of Definition 2.138, the inclusions of complexes

\[ \iota^m: \Omega^m_M(\log Z) \hookrightarrow j^m_* \Omega^m_U \quad \iota: \Omega^m_M(\log Z) \hookrightarrow j_* \Omega^m_U \]

are quasi-isomorphisms.

**Proof.** To fix ideas we start by proving the result in dimension one. Since the statement is local take a small ball \( B \) with coordinate \( z \) such that \( Z \cap B = \{ z = 0 \} \). Then taking Laurent series, elements \( \omega_1 \in (j_* \Omega^m_U)(B) \), \( \omega_2 \in (j^m_* \Omega^m_U)(B) \), can be written as

\[ \omega_1 = \sum_{n \in \mathbb{Z}} a_n z^n + \sum_{n \in \mathbb{Z}} b_n z^n \frac{dz}{z}, \quad \omega_2 = \sum_{n \geq n_0} a_n z^n + \sum_{n \geq n_1} b_n z^n \frac{dz}{z}. \]

We consider the map \( r: (j_* \Omega^m_U)(B) \to (\Omega^m_M(\log Z))(B) \) consisting on forgetting the polar non-logarithmic part:

\[ \sum_{n \in \mathbb{Z}} a_n z^n + \sum_{n \in \mathbb{Z}} b_n z^n \frac{dz}{z} \mapsto \sum_{n \geq 0} a_n z^n + \sum_{n \geq 0} b_n z^n \frac{dz}{z}. \]

We denote by \( r^m \) the restriction of \( r \) to \( (j^m_* \Omega^m_U)(B) \). Then \( r \circ \iota = r^m \circ \iota^m = \text{Id} \). So we have to prove that the compositions \( \iota \circ r \) and \( \iota^m \circ r^m \) are homotopically equivalent to the identity. We define the homotopy

\[ h: (j_* \Omega^m_U)(B) \to (j_* \Omega^m_U)(B) \]

as

\[ \sum_{n \in \mathbb{Z}} b_n z^n \frac{dz}{z} \mapsto \sum_{n < 0} b_n z^n. \]

We denote by \( h^m \) the restriction of \( h \) to \( (j^m_* \Omega^m_U)(B) \) whose image is contained in \( (j^m_* \Omega^m_U)(B) \). A direct verification shows that

\[ d \circ h + h \circ d = \text{Id} - \iota \circ r, \quad d \circ h^m + h^m \circ d = \text{Id} - \iota^m \circ r^m. \]

The case of arbitrary dimension is just an iterate of the one-dimensional case.
We now assume that $M$ is $d$-dimensional. Let $P \subset M$ be an open polydisc with coordinates $z_1, \ldots, z_d$ such that $Z \cap P$ has equation $z_1 \cdots z_k = 0$. For $i = 1, \ldots, d$, we define arrows $r_i: (j_* \Omega_U^*)(P) \to (j_* \Omega_U^*)(P)$ by the rule
\[
\sum_{J \subset \{1, \ldots, k\}} a_{I,J,\alpha} \frac{dz J}{z I} dz J \mapsto \sum_{J \subset \{1, \ldots, k\}} a_{I,J,\alpha} \frac{dz J}{z I} dz J.
\]
That is, the map $r_i$ erases the polar non-logarithmic part on the coordinate $z_i$. The maps $r_i$ are homotopy equivalences, and hence their composition is a quasi-isomorphism for all $i$. Moreover, the image of $r_1 \circ \cdots \circ r_k$ is $(\Omega^*_M(\log Z))(P)$.

We now define the homotopies $H_i: (j_* \Omega_U^*)(P) \to (j_* \Omega_U^*)(P)$ by the rule
\[
\sum_{J \subset \{1, \ldots, k\}} a_{I,J,\alpha} \frac{dz J}{z I} dz J \mapsto \sum_{J \subset \{1, \ldots, k\}} \varepsilon_i a_{I,J,\alpha} \frac{dz J}{z I} dz J,
\]
where $\varepsilon_i = \varepsilon(I \setminus \{i\}, I)$ is the sign of the permutation $(i, I \setminus \{i\})$ of $I$, seeing $I$ as an ordered set, as in Construction 2.97.

The homotopies $H_i$ satisfy
\[H_i \circ d + d \circ H_i = \text{Id} - r_i\]
for all $i$ and $H_i \circ r_j = r_j \circ H_i$ for all $i \neq j$. This implies that all the maps in the chain
\[(2.141) \quad (j_* \Omega_U^*)(P) \xrightarrow{r_i} \text{Im}(r_1) \xrightarrow{r_2} \text{Im}(r_2 \circ r_1) \longrightarrow \cdots \longrightarrow (\Omega^*_M(\log Z))(P)\]
are homotopy equivalences, and hence their composition is a quasi-isomorphism from the complex $(j_* \Omega_U^*)(P)$ to the complex $(\Omega^*_M(\log Z))(P)$. Since the map $\iota$ in the statement is a right-inverse of the composition (2.141), it is a quasi-isomorphism as well. The result for $(j_* \Omega_U^*)(P)$ follows from the observation that the operators $r_i$ and $H_i$ send this last space to itself.

As an immediate consequence of this theorem, we see that the complexes $j_* \Omega_U^*$ and $j_* \Omega_U^*$ are quasi-isomorphic.

**Corollary 2.142.** The inclusion of complexes of sheaves
\[j_* \Omega_U^* \hookrightarrow j_* \Omega_U^*\]
is a quasi-isomorphism.

Another consequence of Theorem 2.140, combined with the GAGA theorem for quasi-coherent sheaves, is that the complex of logarithmic differentials computes algebraic de Rham cohomology.

**Proposition 2.143.** Let $k$ be a field of characteristic zero. Let $X$ be a smooth variety and $\overline{X}$ a smooth compactification of $X$ by a simple normal crossing divisor $D$, with everything defined over $k$. Let $j: X \hookrightarrow \overline{X}$ denote the inclusion. The morphism of complexes
\[(2.144) \quad \Omega_{\overline{X}}(\log D) \hookrightarrow j_* \Omega_X^*\]
induces an isomorphism in hypercohomology, hence an isomorphism of $k$-vector spaces

$$\mathbb{H}^n(X, \Omega_X^*(\log D)) \xrightarrow{\sim} \mathbb{H}^n_{dR}(X).$$

**Proof.** We first use a standard trick in algebraic geometry to reduce to varieties over the field of complex numbers. Since the varieties $X$ and $\overline{X}$ are of finite type, there is a finitely generated subfield $\mathbb{Q} \subset k_0 \subset k$ and varieties $(X_0, \overline{X}_0)$ defined over $k_0$ such that the pair $(X, \overline{X})$ is deduced from $(X_0, \overline{X}_0)$ by extension of scalars. Set $D_0 = \overline{X}_0 \setminus X_0$. Any field extension being flat, the map (2.144) induces an isomorphism in hypercohomology if and only if the same holds for the map

$$\Omega_{\overline{X}_0}^*(\log D_0) \longrightarrow j_\ast \Omega_{X_0}^*. $$

The advantage is that $k_0$ can now be embedded into the complex numbers. We choose an embedding $k_0 \subset \mathbb{C}$ and we write $(X_C, \overline{X}_C)$ for the pair of complex varieties obtained from $(X_0, \overline{X}_0)$ by extension of scalars. Again, the map (2.145) induces an isomorphism in hypercohomology if and only if the map

$$\Omega_{\overline{X}_C}^*(\log D_C) \longrightarrow j_\ast \Omega_{X_C}^* $$

does, and hence we may assume $k = \mathbb{C}$ without loss of generality.

Recall the continuous map $\psi: \overline{X}_{an} \rightarrow \overline{X}$ from Section 2.3.1 and consider the commutative diagram

$$
\begin{array}{ccc}
\psi_* j^\ast \Omega_{X_{an}}^* & \longrightarrow & \psi_* j^\ast \Omega_{X_{an}}^* \\
\downarrow & & \downarrow \\
\Omega_{\overline{X}}^*(\log D) & \longrightarrow & \psi_* \Omega_{\overline{X}_{an}}^*(\log D_{an}).
\end{array}
$$

Using the GAGA theorem for quasi-coherent sheaves (Corollary 2.123) and the identification $(j_\ast \Omega_{X})^{an} = j^\ast_{an} \Omega_{X_{an}}$ from Example 2.139, a spectral sequence argument similar to that in the proof of Proposition 2.126 shows that the upper arrow induces an isomorphism in hypercohomology. Again a spectral sequence argument and the GAGA theorem shows that the lower arrow also induces an isomorphism in hypercohomology. Theorem 2.140, together with the fact that the involved sheaves are $\psi$-acyclic, implies that the right vertical arrow is a quasi-isomorphism. We deduce that the left vertical arrow induces an isomorphism in hypercohomology. This gives the first statement and the isomorphism $\otimes$ in the following diagram:

$$\mathbb{H}^n_{dR}(X) = \mathbb{H}^n(X, \Omega_X^*) \xrightarrow{\otimes} \mathbb{H}^n(\overline{X}, Rj_\ast \Omega_X^* ) $$

$$\mathbb{H}^n(\overline{X}, \Omega_{\overline{X}}^*(\log D)) \xrightarrow{\otimes} \mathbb{H}^n(\overline{X}, j_\ast \Omega_X^* )$$

(2.146)

The remaining isomorphisms are obtained as follows. Since the morphism $j$ is affine (see Example A.242), and the sheaves $j_\ast \Omega_X^*$ are quasi-coherent, by Theorem A.243 the morphism $\otimes$ is an isomorphism. Finally, the isomorphism $\otimes$ follows from the analogue of equation (A.215) for bounded complexes of sheaves. Composing the maps $\otimes$, $\otimes$, and the inverse of $\otimes$ we obtain the second part of the statement. □
Remark 2.147. We have proved Proposition 2.143 using the GAGA principle and the corresponding result for complex manifolds. A purely algebraic proof using étale cohomology can be found in [HMS17, Prop. 3.1.16].

Corollary 2.148. Let $X$ be a smooth algebraic variety of dimension $d$ over $k$. The algebraic de Rham cohomology $H^i_{dR}(X)$ is a finite-dimensional $k$-vector space. Moreover, $H^i_{dR}(X) = 0$ for all $n > 2d$.

Proof. By Proposition 2.143, it suffices to prove that the hypercohomology of the complex of logarithmic differentials is finite-dimensional. This cohomology group is the abutment of the spectral sequence

$$E^{p,q}_1 = H^q(X, \Omega^p_X(\log D)).$$

Since the logarithmic differentials $\Omega^q_X(\log D)$ are coherent sheaves on the proper variety $\overline{X}$, all terms $E^{p,q}_1$ of the spectral sequence have finite dimension and vanish unless $0 \leq p \leq d$ and $0 \leq q \leq d$. □

2.3.6. The comparison isomorphism. We now have all the ingredients needed to prove Grothendieck’s comparison isomorphism.

Theorem 2.149 (Grothendieck, [Gro66]). Let $X$ be a smooth variety over a subfield $k$ of $\mathbb{C}$. There is a canonical isomorphism

$$H^i_{dR}(X) \otimes_k \mathbb{C} \xrightarrow{\sim} H^i_B(X) \otimes_{\mathbb{Q}} \mathbb{C}.$$ (2.150)

Proof. As discussed in Section 2.3.4, one may assume $k = \mathbb{C}$ and it suffices to prove that the analytification map

$$H^*_{dR}(X) \rightarrow H^*_d(X^{an})$$

is an isomorphism. Let $j : X \hookrightarrow \overline{X}$ be a smooth compactification by a simple normal crossing divisor. Since $j$ is an affine morphism and $\Omega^*_X$ is a complex of coherent sheaves, $Rj_* \Omega^*_X = j_* \Omega^*_X$, and hence

$$H^*_d(X) = H^*(X, \Omega^*_X) = H^*(X, Rj_* \Omega^*_X) = H^*(\overline{X}, j_* \Omega^*_X).$$

Similarly, since $j : X^{an} \hookrightarrow \overline{X}^{an}$ is a Stein morphism and the sheaves $\Omega^*_{X^{an}}$ are coherent, $Rj_* \Omega^*_{X^{an}} = j_* \Omega^*_{X^{an}}$, and hence

$$H^*_d(X^{an}) = H^*(X^{an}, \Omega^*_{X^{an}}) = H^*(\overline{X}^{an}, Rj_* \Omega^*_{X^{an}}) = H^*(\overline{X}^{an}, j_* \Omega^*_{X^{an}}).$$

By Corollary 2.142, the complex $j_* \Omega^*_{X^{an}}$ is quasi-isomorphic to $j^{an}_* \Omega^*_X$, which is nothing but the analytification of $j_* \Omega^*_X$ (Example 2.139). Therefore, the first pages of the spectral sequences

$$H^q(\overline{X}, j_* \Omega^*_X) \Rightarrow H^q_{dR}(X)$$
$$H^q(\overline{X}^{an}, j^{an}_* \Omega^*_{X^{an}}) \Rightarrow H^q_{dR}(X^{an})$$

are isomorphic by the GAGA theorem for quasi-coherent sheaves, and so are the abutments. □

Remark 2.151. When $X$ is an affine variety, all classes in de Rham cohomology are represented by differential forms. Then the comparison isomorphism is induced by the pairing

$$H^i_{dR}(X) \otimes H_i(X(\mathbb{C}), \mathbb{Q}) \rightarrow \mathbb{C}$$

$$(\omega \otimes \sigma) \mapsto \int_\sigma \omega.$$ (2.152)
This pairing is called the period pairing. The fact that it depends only on the classes of \( \omega \) and \( \sigma \), and is thus well defined, follows from Stokes’ theorem.

**Remark 2.153.** Later on, we will also need the inverse of the comparison isomorphism \( \text{comp}_{B,\text{dR}} \), which will be written as

\[
\text{comp}_{\text{dR},B} : H^i_B(X) \otimes_k \mathbb{C} \to H^i_{\text{dR}}(X) \otimes_k \mathbb{C}.
\]

**Remark 2.154.** The comparison isomorphism (Theorem 2.149) does not hold if the smoothness assumption is removed. For instance, if \( X \) is the affine plane curve defined by the equation \( x^5 + y^5 + x^2y^2 = 0 \), one can show that \( \dim H^1_{\text{dR}}(X) \) is bigger than \( \dim H^1_B(X) \) [AK11, Ex. 4.4]. However, the theorem remains true for singular varieties \( X \) with the “correct” definition of de Rham cohomology [HMS17].

There is also a relative version of the comparison isomorphism:

**Theorem 2.155.** Let \( k \) be a subfield of the complex numbers, \( X \) a smooth variety, and \( Z \subseteq X \) either a smooth closed subvariety or a normal crossing divisor, with everything defined over \( k \). Then there is a canonical isomorphism

\[
(2.156) \quad H^i_{\text{dR}}(X, Z) \otimes_k \mathbb{C} \to H^i_B(X, Z) \otimes_k \mathbb{C}.
\]

**Remark 2.157.** Recall that if \( X \) is affine and \( \iota : Z \hookrightarrow X \) is a smooth closed subvariety, relative cohomology classes are represented by pairs \( (\omega_X, \omega_Z) \) and \( (\sigma_X, \sigma_Z) \) satisfying

\[
\partial \sigma_X = -\iota_*\sigma_Z, \quad \iota^*\omega_X = d\omega_Z, \quad d\omega_X = 0.
\]

As in Remark 2.151, the comparison isomorphism is also given by a period pairing:

\[
(\omega_X, \omega_Z) \otimes (\sigma_X, \sigma_Z) \mapsto \int_{\sigma_X} \omega_X + \int_{\sigma_Z} \omega_Z.
\]

***

**Exercise 2.158.** Use the GAGA theorem for quasi-coherent sheaves (Corollary 2.123) to prove the following statement. Let \( X \) be a smooth complex variety and let \( \overline{X} \) be a smooth proper compactification of \( X \) by a simple normal crossing divisor. Let \( f \) be a meromorphic function on \( \overline{X} \) that is holomorphic on \( X \). Then \( f \) is algebraic, that is, comes from a rational function on \( \overline{X} \). For example, an entire function on the complex plane that extends meromorphically to \( \infty \) is a polynomial.

**Exercise 2.159.** Let \( k \) be a subfield of \( \mathbb{C} \) and \( X \) a smooth variety over \( k \). Let \( X^n \) be the corresponding complex manifold. Let \( \mathcal{E}^*_{X^n} \) be the sheaf of real-valued differential forms on \( X^n \), \( E^*(X^n, \mathbb{R}) \) its complex of global sections and \( S^*(X^n, \mathbb{R}) \) the complex of smooth singular cochains. Let \( \psi_k : X^n \to X \) be the continuous map between the complex manifold and the scheme. Show that the comparison isomorphism of Theorem 2.149 is induced by the inclusion of sheaves

\[
\Omega^*_{X/k} \to (\psi_k)_*\mathcal{E}^*_{X^n} \otimes \mathbb{C}
\]

and the morphism of complexes

\[
\int : E^*(X^n, \mathbb{R}) \otimes \mathbb{C} \to S^*(X^n, \mathbb{R}) \otimes \mathbb{C}.
\]
2.4. Periods. In this paragraph, we introduce a class of numbers called *periods*. They form a countable subring of the ring of complex numbers that sits halfway between the algebraic and the transcendental numbers: although they tend to be transcendental, periods share with algebraic numbers the property that they contain “a finite amount of information”. Moreover, this information is of geometric nature. From the modern point of view, periods appear when comparing de Rham and Betti cohomology of algebraic varieties over number fields. We refer the reader to [HMS17] for a detailed exposition of the subject.

2.4.1. An elementary definition of periods. The following elementary definition was first written down by Kontsevich and Zagier [KZ01, §1.1]:

**Definition 2.160.** A *period* is a complex number whose real and imaginary parts can be written as absolutely convergent integrals of the form

\[(2.161) \int_S f(x_1, \ldots, x_n) dx_1 \cdots dx_n,\]

where the integrand is a rational function \(f\) with rational coefficients (i.e. a quotient of polynomials in \(\mathbb{Q}[x_1, \ldots, x_n]\)), and the integration domain is a \(\mathbb{Q}\)-semi-algebraic subset \(S \subset \mathbb{R}^n\) (i.e. a finite union and intersection of subsets of the form \(\{g(x_1, \ldots, x_n) \geq 0\}\) with \(g\) a rational function with rational coefficients).

Periods form a countable subring of the complex numbers (see exercise 2.169). Moreover, one may replace “rational function” with “algebraic function” and “rational coefficients” with “algebraic coefficients” in the above definition, and still obtain the same class of numbers. Standard examples of naive periods include the following:

- All algebraic numbers (see Exercise 2.170).
- The number \(\pi = \int_{x^2+y^2\leq 1} dxdy\).
- Logarithms of rational numbers \(\log(q) = \int_1^q \frac{dx}{x}\), where \(q \in \mathbb{Q}_{>1}\).
- Elliptic integrals \(\int_1^\infty \frac{dx}{\sqrt{x(x-1)(x-\lambda)}}\) where \(\lambda \in \mathbb{Q} \setminus \{0, 1\}\).
- Multiple zeta values, certain Feynman integrals (see Section 2.8.9), periods of modular forms, some special values of \(L\)-functions, etc.

2.4.2. A cohomological interpretation of periods. The comparison isomorphism of Theorem 2.149 does not respect the rational structures, as it will be clear from next basic example. In particular, in the case where \(k = \mathbb{Q}\), the vector spaces \(H_{dR}^i(X)\) and \(H_B^i(X)\) are isomorphic (they have the same dimension), but there is no canonical isomorphism between them!

**Example 2.162.** Let \(X = \mathbb{G}_m = \text{Spec} (\mathbb{Q}[t, t^{-1}])\), so that \(X(\mathbb{C}) = \mathbb{C} \setminus \{0\}\). We know from examples 2.24 and 2.73 that

\(H_{dR}^1(X) = \mathbb{Q} dt, \quad H_B^1(X, \mathbb{Q}) = \mathbb{Q}\sigma,\)

where \(\sigma\) is the counterclockwise oriented unit circle. Then the comparison isomorphism is given by multiplication by:

\[\int_\sigma \frac{dt}{t} = 2\pi i.\]

The fact that the comparison isomorphism does not respect the rational structures gives rise to the cohomological interpretation of periods. The following result is shown in [HMS17, §11.2].
Theorem 2.163. The set of periods is equal to the set of complex numbers that appear as a coefficient of a matrix of the comparison isomorphism (2.156) between the de Rham cohomology and the Betti cohomology of some pair \((X, Z)\) consisting of a smooth variety \(X\) defined over \(\mathbb{Q}\) and a normal crossing divisor \(Z \subset X\) also defined over \(\mathbb{Q}\), with respect to \(\mathbb{Q}\)-bases of de Rham cohomology and Betti cohomology.

2.4.3. Examples.

Example 2.164. All algebraic numbers are periods. Indeed, let \(k\) be a number field and consider the zero-dimensional variety \(X = \text{Spec}(k)\), which we regard as defined over \(\mathbb{Q}\). Then \(H^0_{\text{dR}}(X)\) is canonically identified with the \(\mathbb{Q}\)-vector space \(k\). By its very definition, \(X(\mathbb{C}) = \text{Hom}(\text{Spec}(\mathbb{C}), \text{Spec}(k)) = \text{Hom}(k, \mathbb{C})\) is the set of complex embeddings of \(k\), and hence \(H^0_{\text{B}}(X) = \text{Hom}(k, \mathbb{C})\). If we choose a basis \(a_1, \ldots, a_n\) of \(k\) over \(\mathbb{Q}\) and \(\sigma_1, \ldots, \sigma_n\) denote the complex embeddings of \(k\), the period matrix is \((\sigma_i(a_j))_{i,j}\).

In fact this example can be generalized as follows. Let \(k \subset \mathbb{C}\) be a number field. A period over \(k\) is defined as a complex number that appears as a coefficient of a matrix of the comparison isomorphism (2.156) between the de Rham cohomology and the Betti cohomology of some pair \((X, Z)\) consisting of a smooth variety \(X\) defined over \(k\) and a normal crossing divisor \(Z \subset X\) also defined over \(k\), with respect to \(k\)-bases of de Rham cohomology and a \(\mathbb{Q}\)-basis of Betti cohomology. This apparently more general definition of periods does not produce new numbers.

Proposition 2.165 ([HMS17, §11.2]). The set consisting of all periods over all number fields agrees with the set of periods over \(\mathbb{Q}\).

Example 2.166. Let \(X = \mathbb{G}_{m, \mathbb{Q}}\) and \(Z = \{1, q\}\) for \(q \in \mathbb{Q} \setminus \{0, 1\}\). In Example 2.32 we obtained generators \(\sigma_1\) and \(\sigma_2\) of \(H^1_{\text{B}}(X, Z)\) and in Example 2.91 generators \(\omega_1\) and \(\omega_2\) of \(H^1_{\text{dR}}(X, Z)\). With respect to these bases the period matrix is
\[
\begin{pmatrix}
\int_{\sigma_2} \omega_1 & \int_{\sigma_2} \omega_2 \\
\int_{\sigma_1} \omega_1 & \int_{\sigma_1} \omega_2
\end{pmatrix} = \begin{pmatrix}
1 \log(q) \\
0 & 2\pi i
\end{pmatrix},
\]
which shows that logarithms of rational numbers are periods.

2.4.4. Compatibility with complex conjugation. We finish this section by proving a result of compatibility of the comparison isomorphism with complex conjugation that will be used in Chapter 4. Assume that \(k\) is a subfield of the real numbers. Complex conjugation \(c: \mathbb{C} \to \mathbb{C}\) induces a continuous map \(X(\mathbb{C}) \to X(\mathbb{C})\) on the complex points of any algebraic variety \(X\) over \(k\), and hence an involution \(\rho: H^i_{\text{B}}(X) \to H^i_{\text{B}}(X)\) on its Betti cohomology.

Proposition 2.167. Assume \(k \subset \mathbb{R}\). The comparison isomorphism (2.150) is equivariant for the action of \(\mathbb{Z}/2\) by \(\text{Id} \otimes c\) on the left-hand side (de Rham) and by \(\rho \otimes c\) on the right-hand side (Betti).
Proof. We assume, as we may without loss of generality after extension of scalars, that $k$ is the field of real numbers. Let $X$ be a smooth variety over $\mathbb{R}$ and let $X_{\mathbb{C}}^{an}$ be the corresponding complex manifold. We denote by $\mathcal{E}_{X_{\mathbb{C}}^{an}}^*$ the sheaf of real-valued differential forms on $X_{\mathbb{C}}^{an}$, by $\text{E}^*(X_{\mathbb{C}}^{an}, \mathbb{R})$ its complex of global sections, and by $\text{S}^*(X_{\mathbb{C}}^{an}, \mathbb{R})$ the complex of smooth singular cochains. Let $\psi_{\mathbb{R}}: X_{\mathbb{C}}^{an} \to X$ be the continuous map between the complex manifold and the real scheme. By exercise 2.159, the comparison isomorphism is induced by the inclusion of sheaves $\Omega^*_{X/\mathbb{R}} \to (\psi_{\mathbb{R}})_* \mathcal{E}_{X_{\mathbb{C}}^{an}}^* \otimes \mathbb{C}$ and the morphism of complexes

$$
\int: \text{E}^*(X_{\mathbb{C}}^{an}, \mathbb{R}) \otimes \mathbb{C} \to \text{S}^*(X_{\mathbb{C}}^{an}, \mathbb{R}) \otimes \mathbb{C}
$$

given by integration. By the functoriality of the de Rham theorem for differentiable maps (Theorem 2.62), $\int$ commutes with the map $\rho \otimes c$ that is defined on both sides.

Let $V$ be a Zariski open subset of $X$ and let $U = \psi_{\mathbb{R}}^{-1}(V)$. Then $U$ is invariant under $\rho$. Then we claim that the sections of $\Omega^*_{X/\mathbb{R}}(V) \subset (\psi_{\mathbb{R}})_* \mathcal{E}_{X_{\mathbb{C}}^{an}}^*(V) \otimes \mathbb{C} = \text{E}^*(U) \otimes \mathbb{C}$ are invariant under the action of $\rho \otimes c$. To this end we can assume that $V$ is affine and there is a closed immersion $V \subset \mathbb{A}_{\mathbb{R}}^N$. Since every differential form in $V$ is the restriction of a differential form in $\mathbb{A}_{\mathbb{R}}^N$, we are reduced to the case $X = \mathbb{A}_{\mathbb{R}}^N$ where we can use coordinates $x = (x_1, \ldots, x_N)$.

Let $\omega = \sum_I f_I(x)dx^I$ be a holomorphic differential form. Then

$$
\rho \otimes c(\omega) = \sum_I f_I(x)dx^I.
$$

If $\omega$ is a section of $\Omega^*_{X/\mathbb{R}}$, then the $f_I$ are polynomials with real coefficients and we deduce that $\rho \otimes c(\omega) = \omega$ proving the claim.

The claim implies that $\text{comp}_{\text{B}, \text{dR}}(H^i_{\text{dR}}(X))$ is invariant under the action of $\rho \otimes c$, which in turn, thanks to Exercise 2.173, implies that the action induced by $\rho \otimes c$ in $H^i_{\text{dR}}(X) \otimes \mathbb{C}$ by the comparison isomorphism is $\text{Id} \otimes c$, proving the proposition. \[\square\]

We illustrate the proposition for $X = \mathbb{G}_m$ viewed as a variety over $\mathbb{Q}$ (see Exercise 2.172 below for another instance).

Example 2.168. We know from Example 2.162 that the comparison isomorphism $\text{comp}_{\text{B}, \text{dR}}$ sends $dt/t$ to $\sigma^\vee \otimes (2\pi i)$. The differential form being rational, it is invariant under complex conjugation, so $\sigma^\vee \otimes (2\pi i)$ should also be invariant. For this, observe that the image of $\sigma$ by complex conjugation is the clockwise oriented unit circle, whose cohomology class is $-\sigma$. Thus,

$$
(\rho \otimes c)(\sigma \otimes (2\pi i)) = -\sigma \otimes (-2\pi i) = \sigma \otimes (2\pi i).
$$

\[\ast\ast\ast\]

Exercise 2.169. Show that the set of periods is a countable ring. \[\text{Hint: to prove that it is closed under products use Fubini’s theorem. To show that it is closed under sums show first that any complex number is a period if and only if it can be written as a difference of volumes of $\mathbb{Q}$-semi-algebraic sets and then show that the sum of two differences of volumes can be written as a difference of volumes.}\]
Exercise 2.170. In this exercise, we show that all algebraic numbers are naive periods in the sense of Definition 2.160. For example, the integral representation
\[ \sqrt{2} = \int_{x^2 \leq 2} dx \]
shows that \( \sqrt{2} \) is a naive period.

i) Let \( P \in \mathbb{Q}[x] \) be an irreducible polynomial and let \( \alpha_1, \ldots, \alpha_r \) be its real roots. Generalize the above example to show that all \( \alpha_i \) are naive periods.

ii) Using that the real and the imaginary part of a complex algebraic number are real algebraic numbers, deduce that all algebraic numbers are naive periods.

Exercise 2.171. Let \( X \) be a smooth affine variety of dimension \( d \) over a subfield \( k \) of the complex numbers. Prove the vanishing \( H_i^i_B(X) = 0 \) for all \( i > d \).

Exercise 2.172. Let \( C \subset \mathbb{A}_Q^2 \) be the affine conic given by \( x^2 + y^2 = 1 \).

i) Show that the de Rham cohomology group \( H^1_{\text{dR}}(C) \) is generated by the class of the differential form \( xdy - ydx \) and that the singular homology \( H_1(C(C), \mathbb{Q}) \) is generated by the chain
\[ \sigma : [0, 1] \to C(\mathbb{R}), \quad t \mapsto (\cos(2\pi t), \sin(2\pi t)) \].

ii) Prove that the associated period is equal to
\[ \int_{\sigma} xdy - ydx = 2\pi \]
and check Proposition 2.167 in this case.

iii) Find generators of the singular homology of the conics \( C \) defined by the equations \( x^2 + y^2 = -1 \) and \( x^2 - y^2 = 1 \) and check Proposition 2.167 in these cases as well.

Exercise 2.173. Let \( (V, \sigma) \) be a finite-dimensional complex vector space, together with an antilinear involution. Prove that the set of fixed points \( V_R = V^\sigma \) is a real vector space, there is a unique isomorphism \( V_R \otimes \mathbb{C} \to V \) compatible with the inclusion \( V_R \subset V \) and the involution \( \sigma \) agrees with the involution \( \text{Id} \otimes c \) on \( V_R \otimes \mathbb{C} \to V \) under this isomorphism.

2.5. Multiple zeta values as periods of algebraic varieties. The examples in the previous section show that algebraic numbers, logarithms of rational numbers, as well as the ubiquitous \( 2\pi i \) are all periods. From the integral representation (1.116), it follows immediately that multiple zeta values are periods in the sense of Kontsevich and Zagier (Definition 2.160). However, it is not so easy to exhibit the corresponding algebraic varieties. The main goal of this section is to work out the example of \( \zeta(2) \) in detail in order to give an idea of the difficulties involved.

2.5.1. The example of \( \zeta(2) \). Recall from Example 1.109 that \( \zeta(2) \) admits the integral representation
\[ (2.174) \quad \zeta(2) = \int_{t_1 \geq t_2 \geq 0} \frac{dt_1}{t_1} \wedge \frac{dt_2}{1-t_2}. \]
The integrand is the differential form
\[ \omega = \frac{dt_1}{t_1} \wedge \frac{dt_2}{1-t_2} \]
on the affine plane, which is singular along the union of the lines
\[ \ell_0 = \{ t_1 = 0 \} \quad \text{and} \quad \ell_1 = \{ t_2 = 1 \}. \]
Thus, \( \omega \) is a global differential 2-form on \( Y = \mathbb{A}^2 \setminus (\ell_0 \cup \ell_1) \).

The domain of integration is the simplex \( \sigma = \{(t_1, t_2) \mid 1 \geq t_1 \geq t_2 \geq 0\} \subset \mathbb{A}^2(\mathbb{C}) \).

However, if we want to consider the integral (2.174) as a period of \( Y \), relative to some divisor containing the boundary of \( \sigma \), we immediately face the problem that \( \sigma \) is not contained in \( Y \), as the points \( p = (0, 0) \) and \( q = (1, 1) \) belong to \( \sigma \cap (\ell_0 \cup \ell_1) \) (see Figure 5).

![Figure 5](image)

**Figure 5.** The simplex \( \sigma \) and the singular locus \( \ell_0 \cup \ell_1 \)

A way to remedy this is to perform a geometric construction called blow-up, which replaces a point on a variety with a divisor. It is a very useful technique in the study of singularities. In our case, we have to blow up the two problematic points \( p \) and \( q \). More precisely, the blow-up of \( \mathbb{A}^2 \) along \( p \) and \( q \) is the closed subvariety \( X \subset \mathbb{A}^2 \times \mathbb{P}^1 \times \mathbb{P}^1 \) defined by the equations
\[
\begin{align*}
t_1 \alpha_1 &= t_2 \beta_1, \\
(t_1 - 1) \alpha_2 &= (t_2 - 1) \beta_2,
\end{align*}
\]
where \([\alpha_1 : \beta_1]\) are homogeneous coordinates on the two copies of \( \mathbb{P}^1 \). The projection onto the first factor induces a proper surjective map
\[ \pi: X \longrightarrow \mathbb{A}^2. \]

It is easy to verify that \( \pi^{-1}(p) \) is the projective line
\[ E_p = (0, 0) \times \mathbb{P}^1 \times [1 : 1] \subset \mathbb{A}^2 \times \mathbb{P}^1 \times \mathbb{P}^1, \]
while \( \pi^{-1}(q) \) is the projective line
\[ E_q = (1, 1) \times [1 : 1] \times \mathbb{P}^1 \subset \mathbb{A}^2 \times \mathbb{P}^1 \times \mathbb{P}^1. \]
They are called the *exceptional divisors* of the blow-up. Moreover, the restriction
\[ \pi \Big|_{X \setminus (E_p \cup E_q)} : X \setminus (E_p \cup E_q) \rightarrow \mathbb{A}^2 \setminus \{p, q\} \]
is an isomorphism. For any closed subset \( C \subset \mathbb{A}^2 \), the *strict transform* \( \tilde{C} \) of \( C \) is the closed subset of \( X \) given by
\[ \tilde{C} = \pi^{-1}(C \setminus \{p, q\}) . \]
In words: we first remove the points \( p \) and \( q \) if they are in \( C \), then we pull-back to \( X \) by \( \pi \), and finally we take the Zariski closure. The strict transform is contained in the *total transform* \( \pi^{-1}(C) \) but it may be smaller. For instance, the strict transform of \( \ell_0 \) is the affine line
\[ L_0 = \tilde{\ell}_0 = \{(0, t_2), [1 : 0], [1 - t_2 : 1] \mid t_2 \in \mathbb{A}^1\} , \]
while the total transform is \( L_0 \cup E_p \). Note that \( L_0 \) and \( E_p \) have only one common point:
(2.175) \[ L_0 \cap E_p = \{(0, 0), [1 : 0], [1 : 1]\} . \]
Similarly, the strict transform of \( \ell_1 \) is the affine line
\[ L_1 = \tilde{\ell}_1 = \{(t_1, 1), [1 : t_1], [0 : 1] \mid t_1 \in \mathbb{A}^1\} , \]
which is disjoint from the exceptional divisor \( E_p \), intersects the line \( L_0 \) at the point \((0, 1), [1 : 0], [0 : 1]\), and intersects \( E_q \) at \((1, 1), [1 : 1], [0 : 1]\).

In principle, the pull-back \( \pi^*(\omega) \) of \( \omega \) might have singularities along the total transform of \( \ell_0 \cup \ell_1 \), which would only worsen the initial situation. Fortunately, it is only singular on the strict transform \( L_0 \cup L_1 \). This can be seen using local coordinates in \( X \). For instance, a local chart of \( X \) around the intersection of \( L_0 \) and \( E_p \) is given by the coordinates
\[ t = \frac{\beta_1}{\alpha_1} = \frac{t_1}{t_2} , \quad s = t_2 , \]
in which \( E_p \) and \( L_0 \) have local equations \( s = 0 \) and \( t = 0 \), respectively. Then
\[ \pi^*(\omega) = \frac{d(st)}{st} \land \frac{ds}{1 - s} = \frac{ds}{s} \land \frac{ds}{1 - s} + \frac{dt}{t} \land \frac{ds}{1 - s} = \frac{dt}{t} \land \frac{ds}{1 - s} , \]
where we have used the Leibniz rule and the fact that \( ds \land ds = 0 \). It follows that \( \pi^*(\omega) \) is only singular along \( L_0 \) and not along \( E_p \setminus L_0 \). An analogous computation shows that \( \pi^*(\omega) \) has singularities along \( L_1 \) but not along \( E_q \).

The closed points of the exceptional divisor \( E_p \) can be interpreted as lines passing through the point \( p \). This allows us to find the points of \( E_p \) that are contained in \( \tilde{\sigma} \):
\[ \tilde{\sigma} \cap E_p = \{(0, 0), [m : 1], [1 : 1]\} \mid 0 \leq m \leq 1\} . \]
Combined with (2.175), this implies that \( \tilde{\sigma} \cap L_0 = \emptyset \). A similar argument shows that \( \tilde{\sigma} \cap L_1 = \emptyset \), so, after passing to the blow-up \( X \), the singular locus of \( \pi^*(\omega) \) and the domain of integration \( \tilde{\sigma} \) are disjoint (Figure 6).

Write \( L = L_0 \cup L_1 \). The complement \( X \setminus L \) is still an affine variety; in fact, it is the closed subvariety of \( \mathbb{A}^2 \times \mathbb{A}^1 \times \mathbb{A}^1 \) defined by
\[ t_1 t = t_2 , \]
\[ (t_1 - 1) = (t_2 - 1) s , \]
Figure 6. The strict transform of $\sigma$ and the singular locus $L_0 \cup L_1$ of the form $\pi^*(\omega)$

where $t, s$ are the coordinates of the first and the second affine lines. By the previous discussion, $\pi^*(\omega)$ is an element of $\Omega^2(X \setminus L)$.

The next issue one needs to deal with is that $\sigma$ is not a closed chain. Its boundary is contained in the union of the affine lines

$$m_2 = \{t_1 = t_2\}, \ m_3 = \{t_2 = 0\}, \ m_4 = \{t_1 = 1\},$$

so we are naturally led to consider the normal crossing divisor

$$M = \pi^{-1}(m_2 \cup m_3 \cup m_4) = E_p \cup E_q \cup M_2 \cup M_3 \cup M_4 \subset X,$$

where $M_i$ denotes the strict transform of $m_i$. One checks that the intersection $L \cap M$ is reduced to the points $L_0 \cap E_p$ and $L_1 \cap E_q$ which we have already computed.

Since $\widehat{\sigma}$ is contained in $X \setminus L$ and its boundary lies in $M$, using Remark 2.28 we see that $\widehat{\sigma}$ determines a relative homology class

$$\widehat{\sigma} \in H_2(X \setminus L, M \setminus (L \cap M)).$$

Besides, the restriction of $\pi^*(\omega)$ to every irreducible component of $M$ is zero for dimension reasons, so it defines a relative cohomology class

$$\pi^*(\omega) \in H^{2}_{dR}(X \setminus L, M \setminus (L \cap M)).$$

Pairing these classes through the comparison isomorphism (2.156) yields, as we wanted, the period

$$\int_{\widehat{\sigma}} \pi^*(\omega) = \int_{\pi^*(\widehat{\sigma})} \omega = \int_{\sigma} \omega = \zeta(2).$$

This example was generalized by Terasoma in [Ter02]. For any multiple zeta value $\zeta(s)$, he starts with $A^n$ for some $n$ and shows that, after blowing up some subvarieties, one obtains a smooth algebraic variety $X$ and normal crossing divisors $L$ and $M$ on $X$ such that $\zeta(s)$ is a period of the pair $(X \setminus L, M \setminus (L \cap M))$.

An important feature of Terasoma’s construction is that the subvarieties one has to blow up are given by linear equations with all coefficients equal to 0 and 1. This implies that the “motive” of the pair $(X \setminus L, M \setminus (L \cap M))$ is a “mixed Tate motive
over $\mathbb{Z}^n$ and he uses this observation to prove Theorem A from the introduction. The notion of motive and mixed Tate motive over $\mathbb{Z}$ will be explained in Chapter 4.

The combinatorial work in Terasoma’s approach is very detailed and hard. Simultaneously Goncharov and Manin [GM04] found a clever trick to make geometry do the hard work for us. They showed that multiple zeta values appear as periods of the moduli space $M_{0,n}$. We will explain this point of view in the next section with a little more detail. Thanks to the properties of these moduli spaces, they also show that multiple zeta values are periods of “mixed Tate motive over $\mathbb{Z}$”. This can be used to give another proof of Theorem A.

In these notes, we will rather follow a third approach by Deligne and Goncharov [DG05] to show that multiple zeta values are periods associated with the pro-unipotent completion of the fundamental group of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$. A reason to prefer this approach is that it becomes easier to study the question whether relations between multiple zeta values come from geometry.

2.5.2. Multiple zeta values as periods of the moduli spaces $\overline{M}_{0,n}$. For each integer $n \geq 3$, let $M_{0,n}$ be the moduli space of $n$ ordered distinct points in $\mathbb{P}^1$ up to projective equivalence. In other words, every point of $M_{0,n}(\mathbb{C})$ is given by a tuple $(x_1, \ldots, x_n)$ of distinct complex points in $\mathbb{P}^1(\mathbb{C})$; two tuples $(x_1, \ldots, x_n)$ and $(y_1, \ldots, y_n)$ are identified if there exists an element $g \in \mathrm{PGL}_2(\mathbb{C})$ satisfying $g(x_i) = y_i$ for all $i$. Since there exists a unique automorphism of $\mathbb{P}^1$ sending any given three points to $0, 1, \infty$, we can fix an identification

$$(x_1, \ldots, x_n) = (0, 1, \infty, t_1, \ldots, t_{n-3})$$

to get rid of the quotient. This induces an isomorphism

$$(2.176) \quad M_{0,n} \simeq (\mathbb{P}^1 \setminus \{0, 1, \infty\})^{n-3} \setminus \{(t_1, \ldots, t_{n-3}) \mid t_i = t_j \text{ for some } i \neq j\},$$

which shows that $M_{0,n}$ is a smooth variety of dimension $n-3$. In particular, $M_{0,3}$ is reduced to a point and $M_{0,4} = \mathbb{P}^1 \setminus \{0, 1, \infty\}$. Even better, $M_{0,n}$ can be represented by a smooth scheme over $\mathbb{Z}$.

Deligne, Mumford, and Knudsen [Knu83] constructed a smooth compactification $\overline{M}_{0,n}$ of $M_{0,n}$ by a normal crossing divisor. The complex points $\overline{M}_{0,n}(\mathbb{C})$ are identified with stable marked curves of genus 0.

**Definition 2.177.** A stable $n$-marked curve of genus 0 over $\mathbb{C}$ is a curve $X$ over $\mathbb{C}$ with at worst nodal singularities and an ordered tuple $(x_1, \ldots, x_n)$ of distinct smooth points, such that every irreducible component of $X$ is a $\mathbb{P}^1$, the space $X(\mathbb{C})$ is connected and simply connected and every irreducible component has at least three special points. By special point we mean a point of intersection with another component or a marked point.

The points of $M_{0,n}(\mathbb{C})$ correspond to the irreducible curves. The space $\overline{M}_{0,n}(\mathbb{C})$ can be stratified into locally closed subsets corresponding to the different combinatorial types of the curves. In particular, the irreducible components of the boundary are in one-to-one correspondence with the partitions of the marked points into subsets of cardinality at least 2. We refer the reader to [KV07] for a nice introduction to these spaces and their compactifications.

**Example 2.178.** The space $M_{0,4}$ can be identified with $\mathbb{P}^1 \setminus \{0, 1, \infty\}$. The compactification $\overline{M}_{0,4}$ can be identified with $\mathbb{P}^1$. Thus, there are three boundary components of dimension 0 that correspond to the three possible partitions of the set $\{1, 2, 3, 4\}$ into two subsets of size 2 (see Figure 7).
Example 2.179. The irreducible components of the boundary of $\overline{M}_{0,5}$ are in one-to-one correspondence with the 10 ways of dividing the set $\{1, \ldots, 5\}$ into two subsets, one of size 3 and the other of size 2. For instance, the component corresponding to the partition $\{1, 2, 3\} \cup \{4, 5\}$ has an open dense subset corresponding to the curves with two components, one with the marked points $(x_1, x_2, x_3)$ and the other with the points $(x_4, x_5)$ intersecting at a non-marked point. This open set is isomorphic to $M_{0,4} \times M_{0,3}$. This component and the component corresponding to the partition $\{1, 2\} \cup \{3, 4, 5\}$ meet transversely at a single point that corresponds to a curve with three components as in Figure 8. Intuitively, we can think that, to move the point $x_3$ from one component to another, we have to cross the singular point. Since this is forbidden we have to add a new component.
Remark 2.180. The Deligne-Mumford compactification $\overline{M}_{0,5}$ of the moduli space of genus zero curves with 5 marked points is isomorphic to the blow-up of $\mathbb{P}^1 \times \mathbb{P}^1$ at the points $(0,0)$, $(1,1)$, and $(\infty,\infty)$. The boundary $\overline{M}_{0,5} \setminus M_{0,5}$ consists of 10 smooth divisors intersecting transversally. They correspond to the three exceptional divisors $E_{(0,0)}$, $E_{(1,1)}$ and $E_{(\infty,\infty)}$ and the strict transforms of the divisors $\{t_1 = 0\}$, $\{t_1 = 1\}$, $\{t_1 = \infty\}$, $\{t_2 = 0\}$, $\{t_2 = 1\}$, $\{t_2 = \infty\}$ and $\{t_1 = t_2\}$. The correspondence is given in Table 2.1. The boundary components of $\overline{M}_{0,5}$ are distributed into two normal crossings divisors $A$ and $B$. The discussion in Section 2.5.1 shows that $\zeta(2)$ is a period of

$$H^2(\overline{M}_{0,5} \setminus A, B \setminus (A \cap B)).$$

This example was generalized by Goncharov and Manin:

**Theorem 2.181** (Goncharov-Manin [GM04]). Let $s$ be an admissible multi-index $s$ of weight $n$. There exist two normal crossing divisors $A_s$ and $B$, supported on the boundary of $M_{0,n+3}$ and with no common irreducible components, such that the multiple zeta value $\zeta(s)$ is a period of

$$(2.182) \quad H^n(\overline{M}_{0,n+3} \setminus A_s, B \setminus (A_s \cap B)).$$

**Sketch of the proof.** We explain the logic of the proof without entering in the combinatorial details that are encapsulated in two lemmas.

For any $n \geq 3$, we have identified in (2.176) the moduli space $M_{0,n+3}$ with an open subset of $(\mathbb{P}^1 \setminus \{0,1,\infty\})^n$. Using this identification, the open simplex

$$\Delta^n = \{(t_1, \ldots, t_n) \in \mathbb{R}^n | 1 > t_1 > t_2 > \cdots > t_n > 0\}$$

is contained in $M_{0,n+3}(\mathbb{R})$. We denote by $\tilde{\sigma}$ the closure of $\Delta^n$ in $\overline{M}_{0,n+3}$. On the marked points $x_1 = 0$, $x_2 = 1$, $x_3 = \infty$, $x_4 = t_1$, $\ldots$, $x_{n+3} = t_n$, we consider the cyclic order $x_1 < x_3 < x_2 < x_4 < \cdots < x_{n+3} < x_1$ (note that we switched $x_2$ and $x_3$ from the standard cyclic order). Recall that the boundary components of $\overline{M}_{0,n+3}$ are indexed by the partitions of the set $\{1, \ldots, n+3\}$ into two subsets of size at least 2. Let $B$ be the union of boundary components of $\overline{M}_{0,n+3}$

<table>
<thead>
<tr>
<th>Component</th>
<th>Partition</th>
<th>Divisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{(0,0)}$</td>
<td>${2,3} \cup {1,4,5}$</td>
<td>$B$</td>
</tr>
<tr>
<td>$E_{(1,1)}$</td>
<td>${1,3} \cup {2,4,5}$</td>
<td>$B$</td>
</tr>
<tr>
<td>$E_{(\infty,\infty)}$</td>
<td>${1,2} \cup {3,4,5}$</td>
<td>$A$</td>
</tr>
<tr>
<td>${t_1 = 0}$</td>
<td>${1,4} \cup {2,3,5}$</td>
<td>$A$</td>
</tr>
<tr>
<td>${t_1 = 1}$</td>
<td>${2,4} \cup {1,3,5}$</td>
<td>$B$</td>
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<tr>
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<td>${3,4} \cup {1,2,5}$</td>
<td>$A$</td>
</tr>
<tr>
<td>${t_2 = 0}$</td>
<td>${1,5} \cup {2,3,4}$</td>
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<td>${t_2 = \infty}$</td>
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<td>$A$</td>
</tr>
<tr>
<td>${t_1 = t_2}$</td>
<td>${4,5} \cup {1,2,3}$</td>
<td>$B$</td>
</tr>
</tbody>
</table>

Table 2.1. Boundary components of $\overline{M}_{0,5}$
indexed by the partitions such that both subsets consist of consecutive elements for the above cyclic order. See for instance the components labeled $B$ in Table 2.1.

**Lemma 2.183.** For every $n$ the boundary of $\hat{\sigma}$ is contained in $B$.

This lemma implies that $\hat{\sigma}$ defines a relative homology class

$$[\hat{\sigma}] \in H_n(M_{0,n+3}, B).$$

Let now $\omega_s$ be the differential form given by equation (1.114). By the explicit formula of $\omega_s$ it is an algebraic differential form on $M_{0,n+3}$ of top degree $n$. We can see $\omega_s$ as a singular form of $M_{0,n+3}$. Let $A_s$ denote the divisor where $\omega_s$ is singular. That is, $M_{0,n+3} \setminus A_s$ is the maximal open set where $\omega_s$ can be extended as a regular algebraic differential form. By dimension reasons the differential form $\omega_s$ vanishes when restricted to $B$. Therefore, $\omega_s$ defines a class

$$[\omega_s] \in H^n(M_{0,n+3} \setminus A_s, B \setminus (A_s \cap B)).$$

The divisor $A_s$ depends on $s$. The main point in the proof of the theorem is:

**Lemma 2.184.** The divisors $A_s$ and $B$ do not have any common component. Moreover, $\hat{\sigma}$ and $A_s$ are disjoint.

In view of this lemma the class $[\hat{\sigma}]$ can be lifted to a class

$$[\hat{\sigma}] \in H_n(M_{0,n+3} \setminus A_s, B \setminus (A_s \cap B)).$$

In consequence the value $\langle [\omega_s], [\hat{\sigma}] \rangle$ is a period of $H^n(M_{0,n+3} \setminus A_s, B \setminus (A_s \cap B))$.

This period is given by

$$\langle [\omega_s], [\hat{\sigma}] \rangle = \int \omega_s = \int_{\Delta^n} \omega_s = \zeta(s),$$

concluding the proof of the theorem. $\square$

**Remark 2.185.** A converse to this theorem, due to Brown [Bro09], affirms that, for any choice of boundary divisors $A$ and $B$, all periods of the cohomology groups $H^n(M_{0,n+3} \setminus A, B \setminus (A \cap B))$ are $\mathbb{Q}[2\pi i]$-linear combinations of multiple zeta values. This can now be seen as a consequence of Brown’s theorem characterizing the periods of mixed Tate motives over $\mathbb{Z}$ (Corollary 5.122).

**Exercise 2.186.** Show that the boundary of the Deligne-Mumford compactification of $M_{0,n}$ has $2^{n-1} - n - 1$ irreducible components.

**Exercise 2.187.** Draw a stable curve of genus zero with 6 marked points that has four components, one of them without any marked points. What is the dimension of the stratum of $M_{0,6}$ containing the point representing the curve you draw? Write down the components of the boundary divisor that contain the point in question.

**Exercise 2.188.** How many irreducible components does the boundary divisor $B$ from Lemma 2.183 contain?
2.6. Mixed Hodge structures. Thanks to the comparison isomorphism, the Betti cohomology of an algebraic variety has richer properties than the singular cohomology of a random topological space. As we will explain in this section, it is endowed with a mixed Hodge structure, which can be thought of as a first approximation to the notion of motive. This theory was developed by Deligne in the 70s, taking as source of inspiration on the one hand Hodge’s theorem for compact Kähler manifolds and, on the other hand, ℓ-adic cohomology of varieties over finite fields. For a more systematic treatment, we refer the reader to Deligne’s original papers [Del71, Del74] or the monographs [Voi02] and [PS08]. The paper [Dur83] is a user-friendly introduction to the subject. Usually, the study of a period begins by understanding the mixed Hodge structure on the cohomology of the pair of varieties from which it arises.

2.6.1. Pure Hodge structures. Let \( M \) be a compact Kähler manifold of dimension \( d \), for instance a smooth projective complex variety. For each pair of integers \( (p, q) \in \mathbb{Z}^2 \), let \( H^{p,q}(M) \subseteq H^{p+q}(M, \mathbb{C}) \) be the subspace of cohomology classes that can be represented by a \( C^\infty \)-closed differential \((p+q)\)-form of type \((p, q)\), i.e. that can be locally written as
\[
\sum_{I,J} f_{I,J}(z_1, \ldots, z_d) dz_{i_1} \wedge \cdots \wedge dz_{i_p} \wedge d\bar{z}_{j_1} \wedge \cdots \wedge d\bar{z}_{j_q},
\]
where the sum runs over subsets \( I = \{i_1, \ldots, i_p\} \) and \( J = \{j_1, \ldots, j_q\} \) of \( \{1, \ldots, d\} \), and \( f_{I,J} \) are \( C^\infty \)-functions.

The starting point of Hodge theory is the following theorem:

**Theorem 2.189 (Hodge).** There is a direct sum decomposition
\[
H^n(M, \mathbb{Q}) \otimes \mathbb{C} = \bigoplus_{p+q=n} H^{p,q}(M).
\]

Complex conjugation acts on the right-hand side of (2.190) through the action on the coefficients of the left-hand side, that is,
\[
\sigma \otimes w = \sigma \otimes \overline{w} \quad \text{for all } \sigma \in H^n(M, \mathbb{Q}) \text{ and } w \in \mathbb{C}.
\]
This action transforms the subspace \( H^{p,q}(M) \) into \( H^{q,p}(M) \), a property commonly referred to as Hodge symmetry. Abstractly, the data appearing in Hodge’s theorem is captured in the following definition:

**Definition 2.191.** Let \( n \) be an integer. A pure Hodge structure of weight \( n \) is the data of a finite-dimensional \( \mathbb{Q} \)-vector space \( H \) and a bigrading
\[
H \otimes \mathbb{C} = \bigoplus_{(p,q) \in \mathbb{Z}^2} H^{p,q}
\]
of its complexification satisfying \( \overline{H^{p,q}} = H^{q,p} \) for all \( p, q \in \mathbb{Z} \). The set of pairs \((p, q)\) for which \( H^{p,q} \) is non-zero is called the Hodge type of \( H \).

**Lemma 2.192.** The data defining a pure Hodge structure of weight \( n \) are equivalent to give an exhaustive decreasing filtration \( F \) on \( H \) (the Hodge filtration) such that, for all integers \( p \), the following equality holds:
\[
H = F^p \oplus F^{p+1}.
\]
Proof. Given a pure Hodge structure of weight \( n \), one sets
\[
F^p = \bigoplus_{r \geq p} H^{r,s},
\]
which is visibly an exhaustive and decreasing filtration of \( H_\mathbb{C} \). Since
\[
F^{n+1-p} = \bigoplus_{r \geq n+1-p} H^{r,s} = \bigoplus_{s \leq p-1} H^{s,r}
\]
by Hodge symmetry, condition (2.193) holds. Conversely, given a filtration \( F \) as in the lemma, define
\[
H^{p,n-\rho} = F^p \cap F^{n-\rho}.
\]
With this definition \( H^{\rho,n-\rho} = H^{n-\rho} \). It remains to be shown that \( H = \bigoplus_p H^{p,n-\rho} \).
We prove this statement by induction over \( r = \max\{p \mid F^p \neq 0\} \). If \( r < n/2 \), then
\[
F^{n+1-[r/2]} = F^{n+1-[\lceil r/2 \rceil]} = 0,
\]
where \( \lceil x \rceil \) denotes the ceiling of \( x \) (that is, the smallest integer that is greater than or equal to \( x \)). Therefore, \( H_\mathbb{C} = 0 \) and there is nothing to prove. Let us now assume that \( r \geq n/2 \). By Exercise 2.217 there is a direct sum decomposition
\[
H_\mathbb{C} = F^r \oplus (F^{n+1-r} \cap F^{n+1-[\lceil r/2 \rceil]}) \oplus F^r.
\]
Condition (2.193) and the definition of \( r \) easily implies that
\[
F^r = H^{r,n-r}, \quad F^{n-r} = H^{n-r,r}.
\]
Write \( H'_C = F^{n+1-r} \cap F^{n+1-[\lceil r/2 \rceil]} \). This complex vector space has a real structure. Using the induction hypothesis, one derives
\[
H'_C = \bigoplus_{p=r+1}^{n-r-1} H^{p,n-\rho}
\]
proving the statement. \( \square \)

The conditions in Definition 2.191 or Lemma 2.192 constitute the definition that one usually finds in textbooks about Hodge theory. However, for the purpose of studying periods it is important to remember that, for a Hodge structure of the form \( H^n(M, \mathbb{Q}) \), the filtration \( F \) comes from de Rham cohomology of \( M \). If \( M \) is given by the complex points of an algebraic variety \( X \) defined over a subfield \( k \) of the complex numbers, then
\[
H^n(M, \mathbb{C}) \simeq H^n_{\text{dR}}(X) \otimes_k \mathbb{C}
\]
and the Hodge filtration is already defined on the \( k \)-vector space \( H^n_{\text{dR}}(X) \). The following definition keeps track of all these elements:

Definition 2.194. Let \( k \) be a subfield of \( \mathbb{C} \). A pure Hodge structure over \( k \) is the datum
\[
H = (H_B, (H_{\text{dR}}, F), \text{comp}_{B,\text{dR}})
\]
of a finite-dimensional \( \mathbb{Q} \)-vector space \( H_B \), a finite-dimensional \( k \)-vector space \( H_{\text{dR}} \), together with an exhaustive decreasing filtration \( F \), and an isomorphism of complex vector spaces
\[
\text{comp}_{B,\text{dR}} : H_{\text{dR}} \otimes_k \mathbb{C} \to H_B \otimes \mathbb{Q} \mathbb{C},
\]
such that the induced filtration on $H_C = H_B \otimes_{\mathbb{Q}} \mathbb{C}$, still denoted by $F$, satisfies that there exists an integer $n$ such that, for all $p$, the equality

$$(2.195) \quad H_C = F^p H_C \oplus F^{n-p+1} H_C$$

holds. We call $n$ the weight of $H$. Abusing language, we will often say that $H_B$ carries a pure Hodge structure.

**Definition 2.196.** A morphism of pure Hodge structures over $k$

$$f : H \longrightarrow H'$$

is a pair $f = (f_B, f_{dR})$ consisting of a $\mathbb{Q}$-linear map $f_B : H_B \rightarrow H'_B$ and a $k$-linear map $f_{dR} : H_{dR} \rightarrow H'_{dR}$ such that $f_{dR}(F^p H_{dR}) \subseteq F^p H'_{dR}$, for all $p \in \mathbb{Z}$, and that the following diagram commutes:

$$
\begin{array}{ccc}
H_{dR} \otimes_k \mathbb{C} & \xrightarrow{\text{comp}_{B,dR}} & H_B \otimes_{\mathbb{Q}} \mathbb{C} \\
\downarrow f_{dR} \otimes_k \text{Id}_C & & \downarrow f_B \otimes_{\mathbb{Q}} \text{Id}_C \\
H'_{dR} \otimes_k \mathbb{C} & \xrightarrow{\text{comp}'_{B,dR}} & H'_B \otimes_{\mathbb{Q}} \mathbb{C}.
\end{array}
$$

It follows from this definition that a morphism of Hodge structures of different weight is always zero (Exercise 2.220).

We let $\mathbf{HS}(k)$ denote the category of pure Hodge structures over $k$. If $L$ is another subfield of $\mathbb{C}$ containing $k$, there is an “extension of scalars” functor

$$(2.197) \quad - \otimes_k L : \mathbf{HS}(k) \longrightarrow \mathbf{HS}(L)$$

such that $(H \otimes_k L)_B = H_B$ and $(H \otimes_k L)_{dR} = H_{dR} \otimes_k L$ together with the induced filtration and the induced comparison isomorphism via the canonical identification

$$(H_{dR} \otimes_k L) \otimes_L \mathbb{C} = H_{dR} \otimes_k \mathbb{C}.$$

**Example 2.198 (Hodge–Tate structures).** For each integer $n \in \mathbb{Z}$, set

$$\mathbb{Q}(n) = (\mathbb{Q}, (\mathbb{Q}, F), \text{comp}_{B,dR}),$$

where $F$ is the filtration

$$\mathbb{Q} = F^{-n} \mathbb{Q} \supsetneq F^{-n+1} \mathbb{Q} = \{0\},$$

and the isomorphism $\text{comp}_{B,dR} : \mathbb{C} \rightarrow \mathbb{C}$ is given by multiplication by $(2\pi i)^{-n}$. Then $\mathbb{Q}(n)$ is a one-dimensional pure Hodge structure of weight $-2n$ over $\mathbb{Q}$. Upon application of the functor (2.197), we obtain a Hodge structure over any subfield $k$ of $\mathbb{C}$ that will be still denoted by $\mathbb{Q}(n)$. Note, however, that the special role of $2\pi i$ will be more or less significant depending on the nature of $k$. For example, if $k = \mathbb{C}$, the Hodge structure $\mathbb{Q}(n)$ is isomorphic to the one where $\text{comp}_{B,dR}$ is given by the identity, and indeed to any one-dimensional pure Hodge structure of weight $-2n$ (Exercise 2.218).

We will call the Hodge structures $\mathbb{Q}(n)$ **Hodge–Tate structures**. Observe that we already encountered $\mathbb{Q}(-1)$. By Example 2.162, this Hodge structure is isomorphic to the triple

$$H^1(\mathbb{G}_m) = (H^1_B(\mathbb{G}_m), (H^1_{dR}(\mathbb{G}_m), F), \text{comp}_{B,dR}),$$

where $F$ is the trivial filtration concentrated in degree 1, and $\text{comp}_{B,dR}$ stands for Grothendieck’s comparison isomorphism from Theorem 2.149.
Once we have introduced these notions, we can state the following algebraic variant of Hodge’s theorem:

**Theorem 2.199.** Let $k$ be a subfield of $\mathbb{C}$ and let $X$ be a smooth proper variety over $k$. The Betti cohomology $H^n_B(X)$ carries a functorial pure Hodge structure of weight $n$ over $k$.

More precisely, we consider the triple

$$H^n(X) = (H^n_B(X), (H^n_{dR}(X), F), \text{comp}_{B, dR}).$$

As in the previous example, $\text{comp}_{B, dR}$ is the comparison isomorphism of Theorem 2.149. The Hodge filtration $F$ is given by

$$F^p H^n_{dR}(X) = \text{Im}(H^n(X, \Omega^{\geq p}_X) \to H^n(X, \Omega^*_X)),$$

where $\Omega^{\geq p}_X$ stands for the $bête$ truncation of the de Rham complex, namely

$$\Omega^{\geq p}_X : 0 \to \cdots 0 \to \Omega^p_X \to \Omega^{p+1}_X \to \cdots.$$ 

That the Hodge structure on $H^n(X)$ is functorial means the following: for any morphism $f : X \to Y$ of smooth proper varieties, the induced map on cohomology $f^* : H^n(Y) \to H^n(X)$ is a morphism of Hodge structures.

As we have already mentioned, by Exercise 2.220, there are no non-zero morphisms between pure Hodge structures of different weight. However, such maps naturally occur in geometry. For example, if $Z \to X$ is a smooth closed subvariety of codimension $c$, then there is a Gysin morphism

$$H^n(Z) \to H^{n+2c}(X).$$

In order to turn the Gysin morphism into a morphism of Hodge structures, we introduce Tate twists: given a pure Hodge structure $H$ of weight $n$ and an integer $m$, we denote by $H(m)$ the pure Hodge structure of weight $n - 2m$ with the same underlying $\mathbb{Z}$-module and $k$-vector space, filtration shifted by $m$ and comparison isomorphism multiplied by $(2\pi i)^{-m}$. In fact (see Exercise 2.221), there is a tensor product of Hodge structures and $H(m) = H \otimes \mathbb{Q}(m)$. With this notation, the Gysin map becomes a morphism of Hodge structures $H^n(Z)(-c) \to H^{n+2c}(X)$. See Definition 2.277 for more details.

**Example 2.200.** As Hodge structure, the cohomology of projective space $\mathbb{P}^n$ is given by

$$H^j(\mathbb{P}^n, \mathbb{Q}) = \begin{cases} \mathbb{Q}(-j/2), & \text{if } 0 \leq j \leq 2n \text{ is even}, \\ 0, & \text{otherwise}. \end{cases}$$

### 2.6.2. Mixed Hodge structures

Before discussing mixed Hodge structures, we recall some terminology concerning filtrations and morphisms (see Section A.7 for a more thorough discussion in the context of an arbitrary abelian category).

**Definition 2.201.** Let $k$ be a field, and let $(V, F)$ and $(V', F')$ be filtered $k$-vector spaces. A morphism $f : V \to V'$ is called filtered if $f(F^p V) \subset F^p V'$ and strict (with respect to $F'$) if, in addition,

$$f(F^p V) = F^p V' \cap \text{Im}(f).$$
Hodge’s theorem says that the cohomology in degree \( n \) of a smooth proper complex variety carries a pure Hodge structure of weight \( n \). This theorem is no longer true when \( X \) fails to be smooth or proper. For instance, we saw in Example 2.24 that \( H^1(\mathbb{G}_m) \) is one-dimensional, so it cannot carry a pure Hodge structure of weight one. Nevertheless, Deligne proved that the cohomology of any complex variety is an “iterated extension” of pure Hodge structures.

**Theorem 2.202** (Deligne). Let \( X \) be a variety over the field of complex numbers.

i) There exists an increasing filtration  
\[ W_{-1} = 0 \subseteq W_0 \subseteq W_1 \subseteq \cdots \subseteq W_{2n} = H^n(X), \]
and a decreasing filtration  
\[ F^0 = H^n(X, \mathbb{C}) \supseteq F^1 \supseteq \cdots \supseteq F^n \supseteq F^{n+1} = 0 \]
such that \( F \) induces a pure Hodge structure of weight \( m \) on each graded piece  
\[ \text{Gr}^W_{m} H^n(X) = W_m / W_{m-1}. \]

ii) Moreover, if \( f : X \to Y \) is a morphism of complex varieties, the induced map on cohomology \( f^* : H^n(Y) \to H^n(X) \) is a filtered morphism with respect to both filtrations, i.e.
\[ f^*(W_m H^n(Y)) \subseteq W_m H^n(X), \]
\[ f^*_C(F^p H^n(Y)) \subseteq F^p H^n(X). \]

iii) If \( X \) is smooth, then \( \text{Gr}^W_m H^n(X) = 0 \) for all \( m < n \) and, if \( X \) is proper, \( \text{Gr}^W_m H^n(X) = 0 \) for all \( m > n \).

Later, in Section 2.8 we will give some ingredients of the proof of the above theorem.

This motivates the following definition:

**Definition 2.203.** Let \( k \) be a subfield of \( \mathbb{C} \). A mixed Hodge structure over \( k \) is a triple  
\[ H = ((H_\mathbb{B}, W_\mathbb{B}), (H_\text{dR}, F, W_\text{dR}), \text{comp}_{B,dR}) \]
consisting of:
- a finite-dimensional \( \mathbb{Q} \)-vector space \( H_\mathbb{B} \), together with an increasing filtration \( W_\mathbb{B} \),
- a finite-dimensional \( k \)-vector space \( H_\text{dR} \), together with an increasing filtration \( W_\text{dR} \) and a decreasing filtration \( F \),
- an isomorphism of complex vector spaces
  \[ \text{comp}_{B,dR} : H_\text{dR} \otimes_k \mathbb{C} \simto H_\mathbb{B} \otimes \mathbb{Q} \mathbb{C} \]
that is filtered with respect to the weight filtration. That is,
\[ \text{comp}_{B,dR}(W_\text{dR} \otimes_k \mathbb{C}) = W_\mathbb{B} \otimes \mathbb{Q} \mathbb{C} \]
We require that these data verify the following: for each integer \( m \),
\[ \text{Gr}^W_m H = (\text{Gr}^W_m H_\mathbb{B}, (\text{Gr}^W_m H_\text{dR}, F), \text{comp}_{B,dR}) \]
is a pure Hodge structure over \( k \) of weight \( m \).
If $H$ is a mixed Hodge structure we will denote $H_C = H_B \otimes \mathbb{Q} \mathbb{C}$ provided with the complex conjugation coming from this rational structure and the Hodge filtration induced by the one in $H_{\text{dR}}$ through the comparison isomorphism. Then $H_C$ has a complex conjugate filtration $\overline{\mathcal{F}}$.

**Definition 2.205.** A morphism $f : H \rightarrow H'$ of mixed Hodge structures over $k$ is a pair $f = (f_B, f_{\text{dR}})$ consisting of

- a morphism of $\mathbb{Q}$-vector spaces $f_B : H_B \rightarrow H'_B$,
- a morphism of $k$-vector spaces $f_{\text{dR}} : H_{\text{dR}} \rightarrow H'_{\text{dR}}$

such that $f_B$ is filtered with respect to the weight filtration, $f_{\text{dR}}$ is filtered with respect to the weight and the Hodge filtrations, and both maps are compatible with the comparison isomorphisms. In other words

$$f_B(W^B H_B) \subseteq W^B H'_B,$$
$$f_{\text{dR}}(F H_{\text{dR}}) \subseteq F H'_{\text{dR}},$$
$$f_{\text{dR}}(W^\text{dR} H_{\text{dR}}) \subseteq W^\text{dR} H'_{\text{dR}},$$
$$f_{\text{dR}} \circ \text{comp}_{B, \text{dR}} = \text{comp}_{B, \text{dR}} \circ (f_B \otimes \text{Id}_C).$$

We shall denote by $\mathbf{MHS}(k)$ the category of mixed Hodge structures over $k$. When $k = \mathbb{C}$, we shall simply speak of “mixed Hodge structures” and write $\mathbf{MHS}$ instead of $\mathbf{MHS}(\mathbb{C})$.

**Definition 2.206.** We call Betti fiber functor and de Rham fiber functor on the category $\mathbf{MHS}(k)$ the forgetful functors

$$\omega_B : \mathbf{MHS}(k) \rightarrow \mathbf{Vec}_\mathbb{Q},$$
$$\omega_{\text{dR}} : \mathbf{MHS}(k) \rightarrow \mathbf{Vec}_k$$

that map $H$ to $H_B$ and $H_{\text{dR}}$ respectively.

The reason for the name “fiber functor” will be explained when we discuss tannakian categories in Chapter 4.

**Definition 2.207.** A mixed Hodge structure $H$ over $k$ is called split if there is an isomorphism of mixed Hodge structures

$$H \sim \bigoplus_{m \in \mathbb{Z}} \text{Gr}^W_m H,$$

and hence $H$ is a direct sum of pure Hodge structures.

As was explained in Remark 2.191, the Hodge filtration of a pure Hodge structure $H$ induces a natural bigrading on $H_C$. A similar, albeit more involved construction applies to mixed Hodge structures as well.

**Proposition 2.208 (Deligne’s splitting).** Let $H$ be a mixed Hodge structure defined over $k$. There is a unique decomposition of $H_C$ into a direct sum

$$H_C = \bigoplus_{p-q} H^{p,q}$$

(2.209)
satisfying the conditions

\[ W_n H_\mathbb{C} = \bigoplus_{p+q \leq n} H^{p,q}, \]
\[ F^p H_\mathbb{C} = \bigoplus_{p' \geq p} H^{p',q}, \]
\[ H^{p,q} \simeq H^{q,p} \mod \bigoplus_{r < p, s < q} H^{r,s}. \]

Moreover, this splitting is functorial: given a morphism of mixed Hodge structures \( f: H_1 \to H_2 \), there are induced maps \( f^{p,q}: H_1^{p,q} \to H_2^{p,q} \) compatible with the decomposition (2.209).

**Idea of the proof.** The graded pieces are defined as

\[ H^{p,q} = F^p \cap W_{p+q} \cap \left( F^q \cap W_{p+q} + \sum_{j \geq 2} F^{q-j+1} \cap W_{p+q-j} \right) \]

The proof that this decomposition satisfies the required conditions and is characterized by them can be found in [PS08, Lem.–Def. 3.4].

The functoriality follows from this explicit description. □

**Theorem 2.210 (Deligne).** The category \( \text{MHS}(k) \) is abelian.

In [Del71] Deligne proves this result for \( k = \mathbb{C} \), but the proof carries over to the general case.

Deligne’s proof of this theorem is sometimes called “a masterpiece of linear algebra”. The main difficulty stems from the fact that the category of bifiltered vector spaces is not abelian. The key property that makes everything work in this setting is that any morphism of mixed Hodge structures is strict with respect to the weight and the Hodge filtrations. More precisely we have the following lemma that is a consequence of Proposition 2.208.

**Lemma 2.211.** If \( f: H \to H' \) is a morphism of mixed Hodge structures, then \( f_B \) is strict with respect to the weight filtration and \( f_{\text{dR}} \) is strict with respect to the weight and Hodge filtrations.

A first consequence of this lemma is:

**Corollary 2.212.** The weight and the Hodge filtration are exact functors from the category of Hodge structures to the category of vector spaces. That is, if

\[ 0 \to H \to H' \to H'' \to 0 \]

is an exact sequence of Hodge structures, then

\[ 0 \to W_n H \to W_n H' \to W_n H'' \to 0 \]

is an exact sequence of vector spaces for each \( n \), and similarly for \( F^p \).

Another important consequence of Lemma 2.211 is the following:

**Proposition 2.213.** Let \( f \) be a morphism of mixed Hodge structures. The following are equivalent:

i) \( f \) is an isomorphism

ii) \( \omega_B(f) \) is an isomorphism
iii) \( \omega_{\text{dR}}(f) \) is an isomorphism.

**Proof.** Thanks to the comparison isomorphism, \( \omega_B(f) \) is an isomorphism if and only if \( \omega_{\text{dR}}(f) \) is an isomorphism. Thus, we only need to prove that \( f \) is an isomorphism if and only if \( \omega_{\text{dR}}(f) \) is an isomorphism. Note that this is not a general property of filtered vector spaces. A morphism \( g : (V, F) \to (V', F') \) that induces an isomorphism on the underlying vector spaces is not necessarily an isomorphism because the filtrations, although being compatible, may not match exactly. That is, \( g(F^pV) \subset F^pV' \), \( g(F^pV) \neq F^pV' \).

If \( f : H \to H' \) is a morphism of mixed Hodge structures, then the de Rham component \( f_{\text{dR}} : (H, W, F) \to (H', W, F) \) is strict with respect to both filtrations. Hence

\[
\begin{align*}
 f_{\text{dR}}(F^pH_{\text{dR}}) &= F^pH'_{\text{dR}} \cap \text{Im}(f_{\text{dR}}) = F^pH'_{\text{dR}}, \\
 f_{\text{dR}}(W_nH_{\text{dR}}) &= W_nH'_{\text{dR}} \cap \text{Im}(f_{\text{dR}}) = W_nH'_{\text{dR}},
\end{align*}
\]

which implies the result. \( \square \)

### 2.6.3. Mixed Hodge structures of Tate type.

**Definition 2.214.** A mixed Hodge structure \( H \) over \( k \) is said to be of **Tate type** if \( \text{Gr} W_{2m+1} H = 0 \) and \( \text{Gr} W_{2m} H \) is a sum of copies of the pure Hodge–Tate structure \( \mathbb{Q}(-m) \) for all integers \( m \). Mixed Hodge structures of Tate type are also called mixed Hodge–Tate structures.

We shall denote by \( \text{MHTS}(k) \) the full subcategory of \( \text{MHS}(k) \) consisting of mixed Hodge structures of Tate type over \( k \).

**Remark 2.215.** One can think of mixed Hodge structures as “iterated extensions” of pure Hodge structures. Indeed, given two successive steps of the weight filtration, there is an exact sequence of vector spaces

\[
0 \to W_{m-1}H \to W_{m}H \to \text{Gr}^W_m H \to 0.
\]

When \( m \) is the highest weight of \( H \) (i.e. \( W_m H = H \)), this exhibits \( H \) as an extension of the pure Hodge structure \( \text{Gr}^W_m H \) by \( W_{m-1}H \), which in turn is an extension of \( \text{Gr}^W_{m-1} H \) by \( W_{m-2}H \), and so on. Then mixed Hodge–Tate structures are those obtained as iterated extensions of the simplest ones, that is, sums of \( \mathbb{Q}(n) \).

In the case of mixed Hodge structures \( H \) of Tate type, the bifiltered space \( H_{\text{dR}} \) admits a canonical grading. Hence, the fiber functor \( f_{\text{dR}} \) factors through the category of graded vector spaces.

**Lemma 2.216.** Let \( H \) be a mixed Hodge structure of Tate type over \( k \). Then \( H_{\text{dR}} \) is endowed with the canonical grading

\[
H_{\text{dR}} = \bigoplus_p F^pH_{\text{dR}} \cap W_{2p}H_{\text{dR}}
\]

and the forgetful functor \( H \to H_{\text{dR}} \) factors through the category of graded vector spaces. Moreover, the weight and the Hodge filtration on \( H_{\text{dR}} \) can be recovered from
this grading as follows:

\[ F^p H_{dR} = \bigoplus_{r \geq p} F^r H_{dR} \cap W_{2r} H_{dR}, \]

\[ W_{2m} H_{dR} = W_{2m+1} H_{dR} = \bigoplus_{r \leq m} F^r H_{dR} \cap W_{2r} H_{dR}. \]

**Proof.** Exercise 2.222. \( \square \)

**Exercise 2.217.** Let \( H \) be a finite-dimensional real vector space with an exhaustive and separated filtration \( F \) of \( H_C = H \otimes \mathbb{C} \) satisfying the condition (2.193). Prove that, for every \( r \in \mathbb{Z} \), there is a direct sum decomposition

\[ H_C = F^n \oplus (F^{n+1} \cap F^{n+1-r}) \oplus F^r. \]

**Exercise 2.218.** Let \( k \) be a subfield of \( \mathbb{C} \). Prove that the set of isomorphism classes of one-dimensional pure Hodge structures over \( k \) is in one-to-one correspondence with the set \( \mathbb{Z} \times (\mathbb{C}^* / k^*) \).

**Exercise 2.219.** Let \( H \) be a pure Hodge structure of weight \( n \) over \( k \). For each integer \( p \), we define the space of \((p, p)\)-classes of \( H \) as

\[ H^{(p, p)} = \left\{ \begin{array}{ll}
\text{comp}_{B, dR}(F^p H_{dR}) \cap (2\pi i)^p H_B, & \text{if } n = 2p, \\
\{0\}, & \text{if } n \neq 2p.
\end{array} \right. \]

Prove the equality

\[ \text{Hom}_{\text{MHS}(k)}(\mathbb{Q}(-p), H) = H^{(p, p)}, \]

where \( \mathbb{Q}(-p) \) is the pure Hodge structure of weight \( 2p \) over \( k \) from Example 2.198.

**Exercise 2.220.** Let \( H \) and \( H' \) be pure Hodge structures over \( k \) of weights \( n \) and \( m \) respectively.

i) Show that the vector space \( \text{Hom}_\mathbb{Q}(H_B, H'_B) \) admits a pure Hodge structure over \( k \) of weight \( m - n \), denoted \( \text{Hom}(H, H') \).

ii) Show that the group of morphisms of Hodge structures from \( H \) to \( H' \) agrees with the subspace \( \text{Hom}(H, H')^{(0, 0)} \). [Hint: given filtered vector spaces \((A, W)\) and \((B, W)\) with increasing filtrations, one defines an increasing filtration on \( \text{Hom}(A, B) \) as

\[ W_n \text{Hom}(A, B) = \{ f \in \text{Hom}(A, B) \mid f(W_k A) \subset W_{k+n} B \}. \]

A similar construction is valid for decreasing filtrations.]

iii) Conclude that there are no non-zero morphisms between pure Hodge structures of different weights.

**Exercise 2.221.** Let \( H \) and \( H' \) be mixed Hodge structures over \( k \). Define a natural mixed Hodge structure on the tensor product \( H \otimes H' \). Show that for any pure Hodge structure \( H \), we have

\[ H(m) = H \otimes \mathbb{Q}(m). \]

**Exercise 2.222.** In this exercise, we prove Lemma 2.216. Let \( H \) be a mixed Hodge structure of Tate type.
i) Use negative induction over \( n \) to prove the equality
\[
W_r H_{\text{dR}} = \sum_{2p \leq r} W_{2p} H_{\text{dR}} \cap F^p H_{\text{dR}}.
\]

ii) Show that, for every \( p \in \mathbb{Z} \),
\[
W_{2p-1} H_{\text{dR}} \cap F^p H_{\text{dR}} = \{0\}.
\]

iii) Conclude the proof of Lemma 2.216.

Exercise 2.223. There are two possible ways of inducing \( F \) on \( \text{Gr}_m^W H \). Show that they are equivalent.

Exercise 2.224. Given a morphism \( f : H \to H' \) of mixed Hodge structures, prove that the induced maps \( f_m : \text{Gr}_m^W H \to \text{Gr}_m^W H' \) are morphism of pure Hodge structures.

Exercise 2.225. Let \( H = (H_B, H_{\text{dR}}, \alpha) \) be a triple consisting of
- a finite-dimensional \( \mathbb{Q} \)-vector space \( H_B \), equipped with an increasing filtration \( WH_B \) indexed by even integers,
- a finite-dimensional \( \mathbb{Q} \)-vector space \( H_{\text{dR}} \), together with a grading indexed by even integers \( H_{\text{dR}} = \bigoplus_n (H_{\text{dR}})_{2n} \),
- a comparison isomorphism \( \alpha : H_{\text{dR}} \otimes \mathbb{Q} \mathbb{C} \sim \to H_B \otimes \mathbb{Q} \mathbb{C} \),

subject to the condition that \( \alpha \) maps \((H_{\text{dR}})_{2n} \otimes \mathbb{Q} \mathbb{C} \) to \( W_{2n} H_B \otimes \mathbb{Q} \mathbb{C} \), and induces an isomorphism
\[
\alpha_n : (H_{\text{dR}})_{2n} \otimes \mathbb{Q} \mathbb{C} \sim \to (W_{2n} H_B/W_{2(n-1)} H_B) \otimes \mathbb{Q} \mathbb{C}
\]
which sends \((H_{\text{dR}})_{2n}\) to \((W_{2n} H_B/W_{2(n-1)} H_B) \otimes (2\pi i)^n \mathbb{Q}\).

Prove that the category \( \text{MHTS}(\mathbb{Q}) \) is equivalent to the category whose objects are such triples and whose morphisms are the obvious ones.

2.7. Extensions of mixed Hodge structures. We now turn to the description of the extension groups in the category of mixed Hodge structures. Recall that, when no field of definition is explicitly mentioned, by a mixed Hodge structure we mean a mixed Hodge structure over \( \mathbb{C} \).

2.7.1. Definition of the group of extensions.

Definition 2.226. Let \( A \) and \( B \) be mixed Hodge structures.

i) An extension of \( A \) by \( B \) is a short exact sequence
\[
0 \to B \to H \to A \to 0,
\]
where \( \alpha \) and \( \beta \) are morphisms of mixed Hodge structures.

ii) Two extensions are equivalent if there exists a morphism of mixed Hodge structures \( f : H \to H' \) such that the diagram
\[
\begin{array}{ccc}
0 & \to & B \\
\downarrow & & \downarrow \\
0 & \to & B \\
\end{array}
\begin{array}{ccc}
\beta & \to & H \\
\downarrow \alpha & & \downarrow \beta' \\
\alpha & \to & A \\
\end{array}
\begin{array}{ccc}
\to & 0 \\
\downarrow & & \downarrow \\
\to & 0 \\
\end{array}
\]

(2.227)
commutes. This defines indeed an equivalence relation (see Exercise 2.239) whose set of equivalence classes will be denoted by

$$\text{Ext}^1_{\text{MHS}}(A, B).$$

iii) An extension $0 \to B \to H \to A$ is said to be **split** if it is equivalent to the trivial extension $0 \to B \to A \oplus B \to A \to 0$.

**Remark 2.229.** An extension (2.227) is split if and only if the map $\alpha: H \to A$ admits a section, that is, a morphism of mixed Hodge structures $s: A \to H$ such that $\alpha \circ s = \text{Id}_A$. Indeed, if the extension is split, then the projection to $A$ of a map $f: H \to A \oplus B$ making the diagram (2.228) commutative provides a section. Conversely, out of a section one can form the following commutative diagram:

\[
\begin{array}{ccc}
0 & \longrightarrow & B \\
\downarrow{\beta} & & \downarrow{s+\beta} \\
0 & \longrightarrow & B & \longrightarrow & A \\
\end{array}
\]

Equivalently, the extension is split if and only if the map $\beta: B \to H$ admits a retraction, that is, a morphism of mixed Hodge structures $r: H \to B$ such that $r \circ \beta = \text{Id}_B$. Concretely, if $s: A \to H$ is a section, one checks that the map $\text{Id}_H - s \circ \alpha: H \to H$ takes values in $B$ and is a retraction, and similarly a retraction gives rise to a section. Such a section or retraction is often called a **splitting**.

**2.7.2. Computation of the group of extensions.** We present Carlson’s computation of the extension groups in the category of mixed Hodge structures [Car80]. In writing down his formula, it will be convenient to use the following filtration on the space of linear maps between filtered vector spaces already introduced in Exercise 2.220. Given vector spaces with increasing filtrations $(A, W)$ and $(B, F)$, we endow $\text{Hom}(A, B)$ with the increasing filtration

$$W_n \text{Hom}(A, B) = \{ f \in \text{Hom}(A, B) | f(W_m A) \subset W_{m+n} B \text{ for all } m \}.$$  

Similarly, if $(A, F)$ and $(B, W)$ are vector spaces with decreasing filtrations, the space of linear maps $\text{Hom}(A, B)$ is endowed with the decreasing filtration

$$F^m \text{Hom}(A, B) = \{ f \in \text{Hom}(A, B) | f(F^m A) = F^{m+n} B \text{ for all } m \}.$$  

**Theorem 2.230 (Carlson).** Let $A$ and $B$ be mixed Hodge structures. The extension group of $A$ by $B$ is isomorphic to

$$\text{Ext}^1_{\text{MHS}}(A, B) = \frac{W_0 \text{Hom}_\mathbb{C}(A_C, B_C)}{W_0 \cap F^0 \text{Hom}_\mathbb{C}(A_C, B_C) + W_0 \text{Hom}_\mathbb{Q}(A_B, B_B)}.$$  

**Proof.** Given an extension of mixed Hodge structures

$$0 \longrightarrow B \xrightarrow{\beta} H \xrightarrow{\alpha} A \longrightarrow 0,$$

we first choose a section $\varphi_1: A_C \to H_C$ of the underlying complex vector spaces that is compatible with the weight and the Hodge filtration. This is always possible, for example using Deligne’s splitting (Proposition 2.208). We then choose a second section $\varphi_2: A_C \to H_C$, this time compatible with the rational structures $A_B$ and $H_B$ as well as the weight filtration. For every $a \in A_C$, the element $\varphi_1(a) - \varphi_2(a)$ is mapped to zero under $\alpha_C$, and hence there exists a unique element $b \in B_C$ such that $\beta_C(b) = \varphi_1(a) - \varphi_2(a).$ We set $f(a) = b$. This assignment yields a
linear map \( f : A_C \to B_C \) that respects the weight filtration, i.e. an element of \( W_0 \text{Hom}_A(A_C, B_C) \). Hence a map

\[
\text{(2.232)} \quad \text{Ext}^1_{\text{MHS}}(A, B) \longrightarrow W_0 \text{Hom}_C(A_C, B_C).
\]

This map depends on the sections \( \varphi_1 \) and \( \varphi_2 \), and we need to understand how it changes for different choices of sections.

Let \( \varphi'_2 \) be another section compatible with the weight filtration and the rational structure, and let \( f' \) be the corresponding map. Then \( f(a) - f'(a) = \varphi'_2(a) - \varphi_2(a) \), so \( f - f' \) respects the rational structure and the weight filtration. In other words,

\[
f - f' \in W_0 \text{Hom}_A(A_B, B_B).
\]

Similarly, if \( \varphi''_1 \) is another choice of section compatible with the weight and the Hodge filtrations and \( f'' \) is the corresponding linear map, then

\[
f - f'' \in W_0 \cap F^0 \text{Hom}_C(A_C, B_C).
\]

In consequence, the class of \( f \) in the quotient is independent of the choice of the sections \( \varphi_1 \) and \( \varphi_2 \). Let now \( H' \) be an equivalent extension. This means that there is a commutative diagram with exact rows

\[
\begin{array}{cccccc}
0 & \longrightarrow & B & \longrightarrow & H & \longrightarrow & A & \longrightarrow & 0 \\
\end{array}
\]

If \( \varphi_1 \) and \( \varphi_2 \) are choices of splittings for \( H \) then \( \psi \circ \varphi_1 \) and \( \psi \circ \varphi_2 \) are choices of splittings for \( H' \) that yield the same function \( f \). Therefore, we have constructed a map from the left-hand side of (2.231) to the right-hand side.

If the class of \( f \) in the quotient is zero, then we can modify \( \varphi_1 \) by an element of \( W_0 \cap F^0 \text{Hom}_C(A_C, B_C) \) to get a new splitting \( \varphi'_1 \) and \( \varphi_2 \) by an element of \( W_0 \text{Hom}_A(A_B, B_B) \) to get \( \varphi'_2 \) so that \( \varphi'_1 = \varphi'_2 \). This implies that \( \varphi'_1 = \varphi'_2 \) defines a splitting of mixed Hodge structures, and the extension was trivial. Therefore, the map (2.232) is injective.

To see that it is surjective, we start with a function \( f \in W_0 \text{Hom}_C(A_C, B_C) \).

Then we write

\[
(H_B, W) = (A_B, W) \oplus (B_B, W), \quad (H_{dR}, W) = (A_{dR}, W) \oplus (B_{dR}, W),
\]

define the comparison isomorphism in \( H \) as the direct sum of the comparison isomorphisms of \( A \) and \( B \) and define the Hodge filtration on \( H_{dR} \) by

\[
F^p H_{dR} = F^p B_{dR} \oplus \{ a + f(a) \mid a \in F^p A_{dR} \}.
\]

The fact that

\[
(H_B, W) = (H_{dR}, W), (H_{dR}, W, F), \text{comp}_{B,dR}
\]

is a mixed Hodge structure is the content of Exercise 2.240. By construction, the function corresponding to \( H \) is the original function \( f \). This shows that the map (2.232) is an isomorphism and concludes the proof of the theorem. \( \square \)

As a consequence of Carlson’s formula, we next see that the category of mixed Hodge structures has cohomological dimension one, meaning that all higher extension groups vanish.
Theorem 2.234. For any mixed Hodge structures $A$ and $B$ and any integer $n \geq 2$, we have

$$\text{Ext}^n_{\text{MHS}}(A, B) = 0.$$  

Proof. According to Lemma A.46 from the appendix, the vanishing of the higher extension groups would follow if we knew that $\text{Ext}^1_{\text{MHS}}(A, -)$ is a right exact functor for every mixed Hodge structure $A$. Since the functors $\text{Ext}^*_{\text{MHS}}(A, -)$ form a cohomological functor, it is enough to show that, if $B_1 \to B_2$ is an epimorphism of mixed Hodge structures, then

$$\text{Ext}^1_{\text{MHS}}(A, B_1) \to \text{Ext}^1_{\text{MHS}}(A, B_2)$$

is surjective. But this is a direct consequence of Carlson’s formula. \qed

2.7.3. Extensions of Hodge–Tate structures. In the case of Hodge–Tate structures we describe the extensions of mixed Hodge structures defined over $\mathbb{Q}$.

Theorem 2.235. Let $m$ and $n$ be integers. Then

$$\text{Ext}^1_{\text{MHS}(\mathbb{Q})}(\mathbb{Q}(m), \mathbb{Q}(n)) = \begin{cases} \mathbb{C}/(2\pi i)^{n-m}\mathbb{Q}, & \text{if } m < n, \\ 0, & \text{otherwise.} \end{cases}$$

Proof. Tensoring the extension by $\mathbb{Q}(-n)$, we can assume without loss of generality that $n = 0$. So we consider an extension

$$0 \to \mathbb{Q}(0) \xrightarrow{\beta} H \xrightarrow{\alpha} \mathbb{Q}(m) \to 0.$$  

Assume first that $m > 0$. Then $W_{-2m}H \subseteq H$ is a rank one sub-Hodge structure over $\mathbb{Q}$ and the composition

$$W_{-2m}H \hookrightarrow H \xrightarrow{\alpha} \mathbb{Q}(m)$$

is an isomorphism. Thus, the extension is necessarily split.

For $m = 0$, the weight and the Hodge filtration of $H$ are trivial (the corresponding subobjects are either zero or everything), and hence any section $s_B$ of the map $\alpha_B: H_B \to \mathbb{Q}(0)_B$ induces a morphism of Hodge structures $s: \mathbb{Q}(0) \to H$, so the extension is again split.

Now assume that $m < 0$. The $\mathbb{Q}$-vector space $H_{\text{dR}}$ has a canonical splitting

$$H_{\text{dR}} = W_0H_{\text{dR}} \oplus F^{-m}H_{\text{dR}}.$$  

Choose a basis $e_0, e_1$ of $H_B$ satisfying $e_0 = \beta(1)$ and $\alpha_1 e) = e$, where 1 is the generator of $\mathbb{Q}(0)_B$ and $e$ is the generator of $\mathbb{Q}(m)_B$. This basis uniquely determines a basis $f_0, f_1$ of $H_{\text{dR}}$ by the conditions

$$f_0 \in W_0H_{\text{dR}}, \quad \text{comp}_{B, \text{dR}}(f_0) = e_0,$$

$$f_1 \in F^{-m}H_{\text{dR}}, \quad \text{comp}_{B, \text{dR}}(f_1) \in (2\pi i)^{-m}e_1 + W_{2m}H_B \otimes \mathbb{C}.$$  

In these bases, the morphism $\text{comp}_{B, \text{dR}}$ can be written as

$$\begin{pmatrix} 1 & a \\ 0 & (2\pi i)^{-m} \end{pmatrix}$$

for a complex number $a$ that determines the class of the extension.

We are allowed to change the basis $(e_0, e_1)$ by an upper triangular matrix with diagonal entries 1 and a rational coefficient $b$ in the upper right corner. The
basis \((f_0, f_1)\) remains unchanged. In this new bases, the comparison isomorphism will be given by

\[
\begin{pmatrix}
1 & a' \\
0 & (2\pi i)^{-m}
\end{pmatrix}
= \begin{pmatrix}
1 & b \\
0 & (2\pi i)^{-m}
\end{pmatrix}
\begin{pmatrix}
1 & a \\
0 & (2\pi i)^{-m}
\end{pmatrix}
= \begin{pmatrix}
1 & a + (2\pi i)^{-m}b \\
0 & (2\pi i)^{-m}
\end{pmatrix}.
\]

Hence, two complex numbers \(a, a' \in \mathbb{C}\) determine the same extension if and only if \(a - a' \in (2\pi i)^{-m}\mathbb{Q}\), from which the result follows.

\[\square\]

2.7.4. Examples. According to Theorem 2.235, the extensions of \(\mathbb{Q}(0)\) by \(\mathbb{Q}(n)\) are parametrized by elements in \(\mathbb{C}/(2\pi i)^n\mathbb{Q}\). It follows that, for each \(n \geq 2\), there is a mixed Hodge structure \(\zeta^{MHS}(n)\) sitting in an exact sequence

\[
0 \to \mathbb{Q}(n) \to \zeta^{MHS}(n) \to \mathbb{Q}(0) \to 0,
\]

whose extension class corresponds to the zeta value \(\zeta(n)\). Hence, this extension is split if and only if \(\zeta(n) \in (2\pi i)^n\mathbb{Q}\). By Theorem 1.3 and the fact that elements of \((2\pi i)^n\mathbb{Q}\) are purely imaginary for odd \(n\), the extension (2.236) is split if and only if \(n\) is even. It is an open question to construct geometrically these extensions, e.g. as a relative cohomology group.

We now particularize to the case \(n = 1\) and show that all the extensions of \(\mathbb{Q}(0)\) by \(\mathbb{Q}(1)\) have geometric origin.

Example 2.237 (Kummer mixed Hodge structure). For each complex number \(t \in \mathbb{C}^\times \setminus \{1\}\), consider the relative cohomology

\[
H_t = H^1(P^1 \setminus \{0, \infty\}, \{1, t\}).
\]

The long exact sequence (2.94) gives

\[
0 \to H^0(P^1 \setminus \{0, \infty\}) \to H^0(\{1, t\}) \to H_t \to H^1(P^1 \setminus \{0, \infty\}) \to 0.
\]

By Example 2.283, one has \(H^1(P^1 \setminus \{0, \infty\}) = \mathbb{Q}(-1)\), and hence we obtain a short exact sequence

\[
0 \to \mathbb{Q}(0) \to H_t \to \mathbb{Q}(-1) \to 0.
\]

The Kummer mixed Hodge structure \(K^H_t\) is defined to be the dual of \(H_t\), so

\[
K^H_t \in \text{Ext}^1_{\text{MHS}(\mathbb{C})}(\mathbb{Q}(0), \mathbb{Q}(1)).
\]

For \(t = 1\), the Kummer extension is defined as the trivial extension of \(\mathbb{Q}(0)\) by \(\mathbb{Q}(1)\). This yields a map \(\mathbb{C}^\times \to \text{Ext}^1_{\text{MHS}(\mathbb{C})}(\mathbb{Q}(0), \mathbb{Q}(1))\).

Example 2.238. As another example of how arithmetic information can be encoded through extensions of mixed Hodge structures, let us consider extensions of the first cohomology of a smooth projective curve \(C\) by \(\mathbb{Q}(-1)\). Then Carlson’s theorem implies that

\[
\text{Ext}^1_{\text{MHS}(\mathbb{C})}(\mathbb{Q}(-1), H^1(C)) = \text{Jac}(C)(\mathbb{C}) \otimes_{\mathbb{Z}} \mathbb{Q}
\]

By Example 2.283, the cohomology of \(C \setminus \{p, q\}\) for any pair of points gives such an extension. Through the above isomorphism, the class of the extension is given by the class of the divisor \([p] - [q]\) in \(\text{Jac}(C)(\mathbb{C})\). In particular, the extension splits if and only if this divisor is torsion.
Exercise 2.239. Show that being equivalent in the sense of Definition 2.226 defines an equivalence relation on the set of extensions of mixed Hodge structures.

Exercise 2.240. Let $H$ be the structure given in (2.233). Use that $A$ and $B$ are mixed Hodge structures to prove that, for all $n, p \in \mathbb{Z}$,

$$\text{Gr}^W_n H_C = F^p \text{Gr}^W_n H_C \oplus F^{n-p+1} \text{Gr}^W_n H_C.$$

Conclude that $H$ is a mixed Hodge structure.

2.8. Construction of mixed Hodge structures. We now explain some ideas behind the construction of mixed Hodge structures on the cohomology of algebraic varieties. The basic tool is the notion of mixed Hodge complex introduced by Deligne in [Del74]. There are several variants of such concept and we will deal here with the one that is relevant for the study of periods.


Definition 2.241. Let $k$ be a subfield of $\mathbb{C}$. A mixed Hodge complex over $k$ is a 5-tuple

$$A = ((A^*_B, W), (A^*_{\text{dR}}, W, F), (A^*_C, W), \alpha, \beta),$$

where

i) $(A^*_B, W)$ is a bounded below complex of $\mathbb{Q}$-vector spaces with an increasing filtration,

ii) $(A^*_{\text{dR}}, W, F)$ is a bounded below complex of $k$-vector spaces with an increasing filtration $W$ and a decreasing filtration $F$,

iii) $(A^*_C, W)$ is a bounded below complex of $\mathbb{C}$-vector spaces with an increasing filtration $W$,

iv) $\alpha: (A_B^* \otimes_{\mathbb{Q}} \mathbb{C}, W) \to (A^*_C, W)$ is a filtered quasi-isomorphism (Definition A.146),

v) $\beta: (A^*_{\text{dR}} \otimes_k \mathbb{C}, W) \to (A^*_C, W)$ is a filtered quasi-isomorphism,

subject to the following two conditions:

i) for every integer $n \in \mathbb{Z}$, the differential induced on the complex $\text{Gr}^W_n A^*_{\text{dR}}$ is strict with respect to the filtration $F$;

ii) for all integers $n, m \in \mathbb{Z}$, the triple

$$(H^m(\text{Gr}^W_n A^*_B), (H^m(\text{Gr}^W_n A^*_{\text{dR}}), F), H^m(\alpha)^{-1} \circ H^m(\beta)),$$

is a pure Hodge structure over $k$ of weight $n + m$ in the sense of Definition 2.194.

A morphism of mixed Hodge complexes $f: A \to A'$ is a triple

$$f = (f_B, f_{\text{dR}}, f_C)$$

of morphisms of filtered or bifiltered complexes that commute with the comparison quasi-isomorphisms.

The basic properties of mixed Hodge complexes are summarized in the following result ([Del74, Sch. 8.1.9])

Proposition 2.242. Let $A$ be a mixed Hodge complex over $k$. 
For every \( n \), the triple 
\[
((H^n(A), W[n]), (H^n(A_{dR}), W[n], F), \text{comp}_{B,dR} = H^n(\alpha)^{-1} \circ H^n(\beta))
\]
is a mixed Hodge structure over \( k \).

ii) A morphism of mixed Hodge complexes induces a morphism of mixed Hodge structures in cohomology.

iii) The spectral sequences associated with the filtered complexes \((A_B, W)\) and \((A_{dR}, W)\) degenerate at the term \( E_2 \).

iv) The spectral sequence associated with the filtered complex \((A_{dR}, F)\) degenerates at the term \( E_1 \).

As we will see later it is very useful to combine several mixed Hodge complexes in a single one. This is done using dg-mixed Hodge complexes (differential graded) and the associated total complex.

**Definition** 2.243. A dg-mixed Hodge complex over \( k \) is a 5-tuple 
\[
A = ((A_B^{*,*}, W), (A_{dR}^{*,*}, W, F), (A_C^{*,*}, W, F), \alpha, \beta),
\]
where
i) \((A_B^{*,*}, W)\) is a bounded below double complex of \( \mathbb{Q} \)-vector spaces with an increasing filtration,

ii) \((A_{dR}^{*,*}, W, F)\) is a bounded below double complex of \( k \)-vector spaces with an increasing filtration \( W \) and a decreasing filtration \( F \),

iii) \((A_C^{*,*}, W)\) is a bounded below double complex of \( \mathbb{C} \)-vector spaces with an increasing filtration \( W \),

iv) \( \alpha : (A_B^{*,*} \otimes Q, W) \to (A_C^{*,*}, W) \) is a filtered morphism of double complexes,

v) \( \beta : (A_{dR}^{*,*} \otimes k, W) \to (A_C^{*,*}, W) \) is a filtered morphism of double complexes,
such that, for every integer \( p \in \mathbb{Z} \), the 5-tuple 
\[
A = ((A_B^{p,*}, W), (A_{dR}^{p,*}, W, F), (A_C^{p,*}, W, F), \alpha, \beta),
\]
is a mixed Hodge complex defined over \( k \) in the sense of Definition 2.203.

**Proposition** 2.246. If \( A \) is a dg-mixed Hodge complex defined over \( k \), then \( \text{Tot}(A) \) is a mixed Hodge complex defined over \( k \).
Remark 2.247. The need to introduce the diagonal filtration instead of the induced filtration is that the weight filtration in cohomology is not the induced weight filtration, but the shifted filtration:

\[ W_n H^m = \text{Im}(W_{n-m}). \]

Let us see this with an example. Let \( A \) be a dg-mixed Hodge complex and let \( x \in W_r A^{p,q} \) be a cycle. In the cohomology group \( H^q(A^{p,*}) \), the class of \( x \) is an element of weight \( r+q \), not \( r \). We want all the maps to be compatible with the weight, so in \( H^{p+q}(\text{Tot}(A)) \), the element \( x \) should also have weight \( r+q \). This implies that in the complex \( \text{Tot}(A) \), the element \( x \) should be in the piece \( r+q-p-q = r-p \) of the filtration. This is exactly the role of the diagonal filtration:

\[ x \in W_r A^{p,q} = \delta(W, L)_{r-p} A^{p,q}. \]

Every time we construct a simple complex from a double complex, it comes equipped with a spectral sequence that relates the cohomology of the total complex with the individual cohomologies of the columns or the rows of the double complex. The added information in the case of dg-mixed Hodge complexes is that this spectral sequence is a spectral sequence of mixed Hodge structures.

Proposition 2.248. Let \( A \) be a dg-mixed Hodge complex over \( k \). Let \( G \) denote the decreasing filtration induced by the first degree of \( \text{Tot}(A) \). That is,

\[ G^p \text{Tot}(A)^n = \bigoplus_{p' \geq p} A^{p',n-p'}. \]

The spectral sequence associated with \( G \) converges to

\[ GE_1^{p,q} = H^q(A^{p,*}) \implies H^{p+q}(\text{Tot}(A)). \]

Moreover,

i) all the terms \( GE_r^{p,q} \) carry a mixed Hodge structure and all the maps \( d_r \) are morphisms of mixed Hodge structures;

ii) the mixed Hodge structure on the graded piece \( \text{Gr}_G^p H^n(\text{Tot}(A)) \) agrees with the mixed Hodge structure on \( GE_{\infty}^{p,n-p} \).

In many cases, this proposition allows one to prove that a spectral sequence degenerates. Indeed, since the differentials \( d_r \) are morphisms of mixed Hodge structures, they not only respect the weight filtration but are strict with respect to this filtration. In particular, whenever two terms have disjoint weights, any map between them is zero.

2.8.2. Smooth proper varieties. Let \( k \) be a subfield of \( \mathbb{C} \) and let \( X \) be a smooth proper variety over \( k \). As a warming up, we construct a mixed Hodge complex defined over \( k \) that produces the pure Hodge structure of the cohomology of \( X \) discussed in Theorem 2.199.

The difficulties we have to overcome are twofold. First, algebraic de Rham cohomology of \( X \) is defined as the hypercohomology of the algebraic de Rham complex. Therefore, in order to compute it we need to replace this complex with a complex made out of acyclic sheaves. The second is that de Rham cohomology is computed in the algebraic scheme \( X \) with its Zariski topology, while Betti cohomology is computed as a sheaf cohomology in the analytic space \( X(\mathbb{C}) \) with its
analytic topology. All the game of Hodge structures is to compare two cohomologies that live in completely different worlds. Luckily, the Godement resolution of Section A.9.3 has so good properties that solves for us both difficulties.

We start with the de Rham complex $\Omega^*_{X/k}$, define on it the weight filtration as the trivial filtration

$$ W_{-1} \Omega^*_{X/k} = \{0\}, \quad W_0 \Omega^*_{X/k} = \Omega^*_{X/k}, $$

and the Hodge filtration as the bête filtration

$$ F^p \Omega^*_{X/k} = \Omega^*_{X/k}^{\geq p}. $$

For each sheaf $\Omega^p_{X/k}$ we construct the Godement resolution $Gd(\Omega^p_{X/k})$. Thanks to the functorial properties of the Godement resolution, $Gd^*(\Omega^*_{X/k})$ is a double complex with induced weight and Hodge filtrations. Its total complex is the Godement resolution of the de Rham complex $Gd(\Omega^*_{X/k})$ (Definition A.208). Then the de Rham part of the sought mixed Hodge complex is the complex of global sections

$$ (A_{\text{dR}}, W, F) = (\Gamma(X, Gd(\Omega^*_{X/k})), W, F). $$

We now look at the complex manifold $X(\mathbb{C})$ and let $\mathbb{Q}$ be the constant sheaf on this manifold. Since $X(\mathbb{C})$ satisfies the hypothesis of Theorem A.236, its singular cohomology with rational coefficients agrees with the sheaf cohomology of $\mathbb{Q}$. Define the weight filtration of $\mathbb{Q}$ as the trivial filtration

$$ W_{-1} \mathbb{Q} = \{0\}, \quad W_0 \mathbb{Q} = \mathbb{Q}. $$

Then the Godement resolution $Gd(\mathbb{Q})$ has an induced weight filtration and we define the Betti part of the mixed Hodge complex again as the complex of global sections of that complex:

$$ (A_{\text{B}}, W) = (\Gamma(X(\mathbb{C}), Gd(\mathbb{Q})), W). $$

Now we need to compare both sides. That is, we need a complex that receives arrows from both complexes, and these arrows are filtered quasi-isomorphisms. To this end we use the complex of holomorphic differential forms $\Omega^*_{X(\mathbb{C})}$. We introduce again the weight filtration as the trivial filtration

$$ W_{-1} \mathbb{Q} = \{0\}, \quad W_0 \mathbb{Q} = \mathbb{Q}. $$

Next we need the comparison maps. The map $\alpha$ is easy because the complexes involved are both global sections of sheaves living in the same topological space. Since $\mathbb{Q}$ agrees with the sheaf of locally constant functions on $X(\mathbb{C})$ and locally constant functions are holomorphic, we deduce a map

$$ \mathbb{Q} \rightarrow \mathcal{O}_{X(\mathbb{C})} = \Omega^0_{X(\mathbb{C})} \rightarrow \Omega^*_{X(\mathbb{C})}. $$

By the functoriality of the Godement resolution we deduce a map

$$ \alpha: A_{\text{B}} \otimes \mathbb{Q} \rightarrow A_{\text{C}} $$

that, thanks to the Poincaré Lemma is a quasi-isomorphism, and hence a filtered quasi-isomorphism with respect to the weight filtration.
The map \( \beta \) is more complicated as we have to change not only sheaves but also spaces. There is a continuous map between the manifold \( X(\mathbb{C}) \) with the analytic topology and the underlying topological space of \( X \) with its Zariski topology. Denote momentarily this map as

\[ \psi: X(\mathbb{C}) \rightarrow X. \]

Applying Lemma A.217, for each \( p \), we obtain a map

\[ \psi^{-1}(\text{Gd}(\Omega^p_{X/k})) \rightarrow \text{Gd}(\psi^{-1}\Omega^p_{X/k}). \]

Since an algebraic differential form is always holomorphic, we also have a map of sheaves

\[ \psi^{-1}\Omega^p_{X/k} \rightarrow \Omega^p_{X(\mathbb{C})}. \]

Taking the Godement resolution of this last map, global sections and total complexes we deduce a map

\[ (2.249) \qquad \beta: A_{\text{dR}} \otimes_k \mathbb{C} \rightarrow A_{\mathbb{C}} \]

that, thanks to the GAGA theorem (Theorem 2.121) it is a quasi-isomorphism, and hence a filtered quasi-isomorphism with respect to the (trivial) weight filtration.

For future reference we wrap the previous complexes in a single symbol.

**Definition 2.250.** Let \( X \) be a smooth proper variety over \( k \). We denote by \( A^H_X \) the mixed Hodge complex constructed in this section.

**Proposition 2.251.** Let \( X \) be a smooth proper variety over \( k \). The mixed Hodge complex \( A^H_X \) induces in the cohomology of \( X \) the Hodge structure of Theorem 2.199. Moreover, the assignment \( X \mapsto A^H_X \) is functorial, so, if \( f: X \rightarrow Y \) is a morphism of smooth proper varieties over \( k \), then there is an induced morphism of mixed Hodge complexes \( A^H_f: A^H_Y \rightarrow A^H_X \). Moreover, the morphism \( A^H_f \) induces the morphism of pure Hodge structures \( f^*: H^*(Y) \rightarrow H^*(X) \).

**2.8.3. The smooth case.** Let \( X \) be a smooth variety over a subfield \( k \) of \( \mathbb{C} \). By Theorem 2.149, there is a canonical isomorphism

\[ (2.252) \qquad \text{comp}_{B,\text{dR}}: H^n_{\text{dR}}(X) \otimes_k \mathbb{C} \simeq H^n_{\underline{\text{B}}}(X) \otimes_{\mathbb{Q}} \mathbb{C}. \]

We would like to endow \( H^n_{\underline{\text{B}}}(X) \) with a filtration \( W^B \) and \( H^n_{\text{dR}}(X) \) with two filtrations \( W^{\text{dR}} \) and \( F \) making the triple

\[ ((H^m_{\underline{\text{B}}}(X), W^B), (H^m_{\text{dR}}(X), F, W^{\text{dR}}), \text{comp}_{B,\text{dR}}) \]

into a mixed Hodge structure over \( k \). However, if de Rham cohomology is computed using the complex \( \Omega^*_X \) of Kähler differentials on \( X \), as in Definition 2.78, we face two problems:

- One may define a Hodge filtration using the \( \text{bête} \) filtration \( \Omega^p_\text{dR} \), but it will not give much information. For example, if \( X \) is affine, we saw in Remark 2.79 that \( H^n_{\text{dR}}(X) \) is the cohomology of the global de Rham complex, so in this case the definition would yield the trivial filtration \( F^n H^n_{\text{dR}}(X) = H^n_{\text{dR}}(X) \).
- There is no obvious way to get the weight filtration from \( \Omega^*_X \).
To solve these difficulties, we shall instead use the complex of logarithmic differentials, as introduced in Section 2.3.5. In view of Proposition 2.143, the strategy is to define the Hodge and the weight filtrations on the complex $\Omega_X^*(\log D)$. The Hodge filtration is given by the \textit{bête} filtration, that is

$$F^p\Omega_X^*(\log D) = \Omega_X^{\geq p}(\log D).$$

Note that $F$ is defined over $k$. The weight filtration is given by the order of poles:

$$W^m\Omega_X^p(\log D) = \begin{cases} 0, & \text{if } m < 0, \\ \Omega_X^p(\log D), & \text{if } 0 \leq m \leq p, \\ \ker d, & \text{if } m = p, \\ \{0\}, & \text{if } m > p. \end{cases}$$

Once we have a complex of sheaves with two filtrations, in order to produce the de Rham part of a mixed Hodge complex we follow the same strategy used in the smooth proper case. Namely, we define $A'_{dR}$ as the complex of global sections of the total complex of the Godement resolution of $\Omega_X^*(\log D)$ with the induced weight and Hodge filtrations.

$$(A_{dR}, W, F) = (\Gamma(X, Gd(\Omega_X^*(\log D))), W, F)$$

The weight filtration defined by the order of the poles does not look a priori as a “topological” filtration, so it is not clear how to translate it to the Betti side. The key idea now is to use a different filtration that has a more topological flavour. But this new filtration is only available in the analytic topology. So let $X^\text{an}$ be the complex manifold associated to the complex variety $X \times \text{Spec}(\mathbb{C})$ and similarly, we denote $X^\text{an}$ the one associated to $X \times \text{Spec}(\mathbb{C})$ and $D^\text{an} = X^\text{an} \setminus X^\text{an}$. We also denote by $j: X^\text{an} \rightarrow X^\text{an}$ the open immersion of complex manifolds.

The \textit{canonical filtration} on $\Omega_{X^\text{an}}^*(\log D^\text{an})$, as defined in Example A.147 from the appendix, is the filtration

$$\tau_{\leq n} \Omega_X^p(\log D^\text{an}) = \begin{cases} \Omega_X^p(\log D^\text{an}), & \text{if } p < n, \\ \ker d, & \text{if } p = n, \\ \{0\}, & \text{if } p > n. \end{cases}$$

Consider the complex of sheaves $j_* \Omega_{X^\text{an}}^*$ on $X^\text{an}$. Note that, since $j$ is an affine morphism and the sheaves $\Omega_X^p$ are coherent sheaves, all higher direct images vanish. Let $\tau$ denote also the canonical filtration of this complex.

The following result is [Del71, Prop. 3.1.8].

**Proposition 2.254.** The arrows

$$\begin{align*} (\Omega_{X^\text{an}}^*(\log D^\text{an}), W) &\leftarrow (\Omega_{X^\text{an}}^*(\log D^\text{an}), \tau) \rightarrow (j_* \Omega_{X^\text{an}}^*, \tau) \end{align*}$$

are filtered quasi-isomorphisms.

Proposition 2.254 also gives us an idea of how to define the weight filtration in the Betti part of the mixed Hodge complex. Let $\mathbb{Q}$ be the constant sheaf on $X^\text{an}$, let $\text{Gd}(\mathbb{Q})$ be its Godement’s resolution. Since the sheaves composing this complex are flasque, they are acyclic with respect to the functor $j_*$. Therefore, the complex $j_* \text{Gd}(\mathbb{Q})$ is isomorphic in the derived category of sheaves to $Rj_* \mathbb{Q}$. Let now $\tau$ denote again the increasing canonical filtration, but this time of the
Note finally that, since each sheaf $Gd^p(Q)$ is flasque, the same is true for $j_*$ $Gd^p(Q)$. Therefore,

$$H^*(\Gamma(\mathcal{X}^{an}, j_* Gd(\mathcal{Q}))) = H^*(\mathcal{X}^{an}, Q).$$

So, we define the Betti part of the mixed Hodge complex as

$$(A_B, W) = \left( \Gamma(\mathcal{X}^{an}, j_* Gd(\mathcal{Q})), \tau \right).$$

We now consider the diagram of filtered complexes of vector spaces given in Figure 9. All the arrows in that diagram exist and are filtered quasi-isomorphisms. The existence of the arrow $\odot$ follows a similar argument that the existence of the map $\beta$ in (2.249). The fact that this arrow is a filtered quasi-isomorphism is a consequence of GAGA theorem. For the arrows $\otimes$ and $\oplus$ this follows from Proposition 2.254. For the arrow $\otimes$, it follows from Exercise A.254. For the arrow $\otimes$ follows Lemma A.217 and the fact that the sheaves $\Omega^p_{\mathcal{X}^{an}}$, $p \geq 0$, are acyclic for the functor $j_*$. Finally for the arrow $\otimes$ follows from the exactness of $Gd$ (Lemma A.205) and Exercise A.161.

We are almost done in constructing the sought Hodge complex but we still have to solve the small technical problem that some of the arrows in the previous
diagram go in the wrong direction. To invert the arrow we apply Exercise A.159 three times, once to the arrows 2 and 3, another to the arrows 4 and 5 and the last time to arrows obtained in the previous iteration. In this way we obtain a big filtered complex $(A^*_C, W)$ together with filtered quasi-isomorphisms

$$(A^*_dR, W) \otimes \mathbb{C} \rightarrow (A^*_C, W) \leftarrow (A^*_B, W).$$

**Definition 2.255.** Let $X$ be a smooth variety over $k$ and $j: X \rightarrow \overline{X}$ a smooth compactification with $D = \overline{X} \setminus X$ a simple normal crossing divisor. We denote by $A^*_H X (\log D)$ the 5-tuple $((A^*_dR, W), (A^*_B, W), (A^*_C, W), \alpha, \beta)$ constructed in this section.

**Proposition 2.256.** Let $X$ be a smooth variety defined over $k$ and let $\overline{X}$ be a smooth compactification with $D = \overline{X} \setminus X$ a simple normal crossing divisor. Then the 5-tuple $A^*_H X (\log D)$ is a mixed Hodge complex. In particular, it induces in the cohomology of $X$ the Hodge structure of Theorem 2.202. Moreover, the assignment $X \mapsto A^*_H X (\log D)$ is functorial with respect to pairs of compactifications. Namely, given a commutative diagram

$$
\begin{array}{ccc}
X & \rightarrow & Y \\
\downarrow & & \downarrow \\
\overline{X} & \rightarrow & \overline{Y}
\end{array}
$$

where $X$ and $Y$ are smooth varieties, $\overline{X}$ and $\overline{Y}$ are smooth proper varieties, and $D_X = \overline{X} \setminus X$ and $D_Y = \overline{Y} \setminus Y$ are simple normal crossing divisors, there is a morphism of mixed Hodge complexes $f^*: A^*_H Y (\log D_Y) \rightarrow A^*_H X (\log D_X)$

that induces the morphism of mixed Hodge structures $f^*: H^*(Y) \rightarrow H^*(X)$.

Consider the weight and the Hodge filtrations on cohomology given by

$$(2.257) \quad W^p_m H^n_{\text{dR}} (X) = \text{Im} \left( H^n (X, W_{m-n} \Omega_X^*(\log D)) \rightarrow H^n_{\text{dR}} (X) \right),$$

$$(2.258) \quad F^p_{\text{dR}} H^n_{\text{dR}} (X) = \text{Im} \left( H^n (X, F^p \Omega_X^*(\log D)) \rightarrow H^n_{\text{dR}} (X) \right),$$

We refer the reader e.g. to [Del71] or [PS08, §4] for a proof that the filtrations we have introduced define a mixed Hodge structure on $H^n_B (X)$.

**Definition 2.259.** We say that a mixed Hodge structure $H$ has weights in a subset $I \subseteq \mathbb{Z}$ if $\text{Gr}^m_I H = 0$ whenever $m \notin I$.

It follows from (2.257) that the cohomology group $H^n_B (X)$ of a smooth variety $X$ has weights in $[n, 2n]$. Moreover, noting that $W_0 \Omega_X^*(\log D) = \Omega_X^*$ and the shift of indices in (2.257), one finds that the first step in the weight filtration is the piece of the cohomology coming from the compactification:

$$(2.259) \quad W^n H^n_B (X) = \text{Im} \left( H^n_B (\overline{X}) \rightarrow H^n_B (X) \right).$$

In contrast, when $X$ is proper, the mixed Hodge structure $H^n (X)$ defined in [Del74] has weights in $[0, n]$. The combination of these two statements implies that the cohomology of a smooth proper variety carries a pure Hodge structure.
As we have seen, the definition of de Rham cohomology involves hypercohomology of sheaves; therefore, to compute it concretely, in general we cannot use directly the algebraic de Rham complex but we need a resolution of it, like the Godement resolution. As we have seen in Remark 2.79 for an affine variety \( X \), every coherent sheaf is acyclic and we can represent de Rham cohomology with algebraic differentials directly. Nevertheless, the Hodge structure involves a hypercohomology computed on a proper compactification of \( X \); therefore, even in the case of affine varieties, in order to compute the Hodge structure we will need an acyclic resolution of the complex of logarithmic differentials, compatible with the weight and the Hodge filtrations.

**Example 2.260.** Let us compute everything for \( X = \mathbb{P}^1 \setminus \{0, 1, \infty\} \), viewed as a variety over \( \mathbb{Q} \). As for any smooth curve, there is a canonical smooth compactification, in this case \( \overline{X} = \mathbb{P}^1 \). Write \( D = \{0, 1, \infty\} \) for the divisor at infinity. Recall that \( \mathcal{O}_{\mathbb{P}^1}(D) \) stands for the sheaf of rational functions having at most simple poles at \( D \) and nowhere else. We have:

\[
\Omega^0_{\mathbb{P}^1}(\log D) = \mathcal{O}_{\mathbb{P}^1}, \quad \Omega^1_{\mathbb{P}^1}(\log D) = \mathcal{O}_{\mathbb{P}^1}(D) \otimes_{\mathcal{O}_{\mathbb{P}^1}} \Omega^1_{\mathbb{P}^1}.
\]

Since \( \Omega^1_{\mathbb{P}^1} \simeq \mathcal{O}_{\mathbb{P}^1}(-2) \), one sees that \( \Omega^1_{\mathbb{P}^1}(\log D) \simeq \mathcal{O}_{\mathbb{P}^1}(1) \). By the standard computation of the cohomology of line bundles on \( \mathbb{P}^1 \) [Har77, Chap. III, §5], none of the terms in the complex of logarithmic differentials has higher cohomology. Besides, setting \( \omega_0 = dt/t \) and \( \omega_1 = dt/(1-t) \), one has:

\[
H^0(\mathbb{P}^1, \mathcal{O}_{\mathbb{P}^1}) = \mathbb{Q}, \quad H^0(\mathbb{P}^1, \Omega^1_{\mathbb{P}^1}(\log D)) = \mathbb{Q} \omega_0 \oplus \mathbb{Q} \omega_1
\]

(note that these differentials \( \omega_0 \) and \( \omega_1 \) have a simple pole at \( \infty \) as well). From the spectral sequence (A.209), it follows that

\[
H^1_{\text{dR}}(X) = H^*(\mathcal{O}_{\mathbb{P}^1} \longrightarrow \mathcal{O}_{\mathbb{P}^1}(D) \otimes_{\mathcal{O}_{\mathbb{P}^1}} \Omega^1_{\mathbb{P}^1}) = H^*(\mathbb{Q} \longrightarrow \mathbb{Q} \omega_0 \oplus \mathbb{Q} \omega_1),
\]

where the differential in the second complex is the zero map. Thus,

\[
H^1_{\text{dR}}(X) = \mathbb{Q} \omega_0 \oplus \mathbb{Q} \omega_1.
\]

We now turn to the filtrations. For the Hodge filtration, (2.253) gives

\[
H^1_{\text{dR}}(X) = F^0 = F^1 \supseteq F^2 = \{0\}.
\]

Moreover, the weight filtration on the complex of logarithmic differentials is given by \( \Omega^1_{\mathbb{P}^1} = W_0 \subseteq W_1 = \Omega^1_{\mathbb{P}^1}(\log D) \). Since \( H^1_{\text{dR}}(\mathbb{P}^1) \) vanishes, we find:

\[
\{0\} = W_1 \subseteq W_2 = H^1_{\text{dR}}(X).
\]

On the other hand, the first homology group \( H_1(X(\mathbb{C}), \mathbb{Q}) \) has as a basis the classes of two loops \( \sigma_0 \) and \( \sigma_1 \) winding once counterclockwise around the punctures 0 and 1. By Cauchy’s residue theorem, the period matrix reads:

\[
\begin{pmatrix}
\int_{\sigma_0} \omega_0 & \int_{\sigma_1} \omega_0 \\
\int_{\sigma_0} \omega_1 & \int_{\sigma_1} \omega_1
\end{pmatrix} = \begin{pmatrix}
2\pi i & 0 \\
0 & 2\pi i
\end{pmatrix}.
\]

In other words, letting \( \sigma_0^\vee \) and \( \sigma_1^\vee \) denote the dual elements in cohomology, the isomorphism \( \text{comp}_{B,H^1_{\text{dR}}} \) sends \( \omega_0 \) to \( \sigma_0^\vee \otimes 2\pi i \) and \( \omega_1 \) to \( \sigma_1^\vee \otimes 2\pi i \). Comparing with Example 2.198, one concludes that there is an isomorphism

\[
H^1(\mathbb{P}^1 \setminus \{0, 1, \infty\}) \simeq \mathbb{Q}(1)^{\oplus 2}
\]
of mixed Hodge structures over $\mathbb{Q}$.

Observe that all the information in the de Rham part of the mixed Hodge structure over $\mathbb{Q}$ of the variety $X = \mathbb{P}^1_\mathbb{Q} \setminus \{0, 1, \infty\}$ can be read from the complex

\begin{equation}
A^* = A^0 \oplus A^1, \quad A^0 = \mathbb{Q}, \quad A^1 = \mathbb{Q} \omega_0 \oplus \mathbb{Q} \omega_1,
\end{equation}

together with the trivial differential and the filtrations

\begin{align}
F^0 &= A^* \supset F^1 = A^1 \supset F^2 = \{0\}, \\
W_{-1} &= 0 \subset W_0 = A^0 \subset W_1 = A^*.
\end{align}

Note that $A^*$ has an algebra structure given by $\omega_i \wedge \omega_j = 0$, for $i, j \in \{0, 1\}$.

For later reference, we summarize the results of this example in a proposition.

**Proposition 2.263.** Set $X = \mathbb{P}^1_\mathbb{Q} \setminus \{0, 1, \infty\}$ and let $A^* = A^*_p$, be the filtered algebra introduced in (2.261) and (2.262). The algebraic de Rham cohomology of $X$ is given by

$$H^*_\text{dR}(X) = H^*(A^*).$$

The Hodge and the weight filtration are induced by the filtrations (2.262):

$$F^p H^*_\text{dR}(X) = H^*(F^p A^*),$$

$$W_k H^*_\text{dR}(X) = H^*(W_k A^*).$$

Moreover, the inclusion of algebras

$$A^* \longrightarrow E^*_{p, (\mathbb{C})}(\log D)$$

induces a bifiltered quasi-isomorphism

$$(A^* \otimes_\mathbb{Q} \mathbb{C}, W, F) \longrightarrow (E^*_{p, (\mathbb{C})}(\log D), W, F).$$

**2.8.4. Normal crossing divisors.** Following the same method we used to define the de Rham cohomology of a normal crossing divisor in Section 2.2.7, we can construct a mixed Hodge complex that endows it with a mixed Hodge structure.

Let $X$ be a smooth variety over $k$ and let $D$ be a simple normal crossing divisor on $X$. We keep notation from Section 2.2.7. In particular, $D_I$ for the intersection of irreducible components indexed by a subset $I$ and $D^p$ for the disjoint union of all $D_I$ such that $I$ has cardinal $p$. By resolution of singularities (Theorem 2.133), we can choose a smooth compactification $\overline{X}$ of $X$ such that, for each subset $I$, the Zariski closure $\overline{D_I}$ is a smooth compactification of $D_I$ whose complement $E_I = \overline{D_I} \setminus D_I$ is a simple normal crossing divisor. Let $E^p$ be the disjoint union of all $E_I$ such that $I$ has cardinal $p$.

The mixed Hodge complexes $A^H_{\mathcal{D}}(\log E^p)$ for $p \geq 1$ form a dg-mixed Hodge complex with the same differentials used in Section 2.2.7. More precisely, the double complex

\begin{equation}
A^H_{\mathcal{D}}(\log E)^{p,q} = A^H_{\mathcal{D}^{p+1}}(\log E^{p+1})^q, \quad p, q \geq 0
\end{equation}

is a dg-mixed Hodge complex and then

\begin{equation}
A^H_{\mathcal{D}}(\log E) = \text{Tot}(A^H_{\mathcal{D}}(\log E)^{*,*})
\end{equation}
is also a mixed Hodge complex that defines a mixed Hodge structure in the cohomology of \( D \). Since all \( D^p \) and \( E^p \) are smooth, we deduce from Proposition 2.251 a morphism of mixed Hodge complexes

\[
A_H^X(\log(\overline{X} \setminus X)) \rightarrow A_H^D(\log E).
\]

In case \( X \) is proper, so that there is no need to compactify, we will denote the complex (2.264) simply as \( A_H^D \). There is then a morphism of mixed Hodge complexes

\[
A_H^X \rightarrow A_H^D.
\]

**Example 2.265.** We consider Example 2.102 again. Now, instead of computing the relative cohomology \( H^∗(X, D) \) we will compute the cohomology \( H^∗(D) \) with its mixed Hodge structure. The added information is that, by Proposition 2.248, there is a spectral sequence of mixed Hodge structures. Taking into account that the mixed Hodge structure in the \( H^0 \) of an irreducible smooth variety is always a copy of \( \mathbb{Q}(0) \) we obtain that the \( E_1 \) term of the spectral sequence reads

\[
\begin{array}{c}
0 \\
\mathbb{Q}(0) \oplus \mathbb{Q}(0) \oplus \mathbb{Q}(0) \rightarrow \mathbb{Q}(0) \oplus \mathbb{Q}(0) \oplus \mathbb{Q}(0)
\end{array}
\]

where the horizontal map is \((a, b, c) \mapsto (b - a, c - a, c - b)\). From this we easily deduce that

\[ H^0(D) = H^1(D) = \mathbb{Q}(0). \]

In fact, using hyper-resolutions, the technique we have used for a normal crossing divisor can be extended to any quasi-projective variety [Del74].

2.8.5. **Mixed Hodge structures on cohomology with compact support and relative cohomology.** The cohomology with compact support of complex algebraic varieties or, more generally, the relative cohomology is also endowed with a mixed Hodge structure. The basic technique is the following. Let \( f: A \rightarrow B \) be a morphism of mixed Hodge complexes. We can see \( f \) as a dg-mixed Hodge complex. Then

\[
\text{Tot}(f) = \text{cone}(-f)[-1]
\]

is a mixed Hodge complex (Proposition 2.246) and the long exact sequence

\[
\cdots \rightarrow H^n(\text{Tot}(f)) \rightarrow H^n(A) \rightarrow H^n(B) \rightarrow H^{n+1}(\text{Tot}(f)) \rightarrow \cdots
\]

is a long exact sequence of mixed Hodge structures (Proposition 2.242 ii)). We will apply this technique to two situations: the cohomology with compact support and the cohomology with support in a subvariety.

**Definition 2.266.** Let \( k \) be a subfield of \( \mathbb{C} \) and let \( X \) be an algebraic variety over \( k \). The *Betti cohomology with compact support* \( H^∗_{B,c}(X) \) is the cohomology with compact support (as introduced in Definition 2.43) of the set of complex points \( X(\mathbb{C}) \) equipped with the classical topology:

\[ H^∗_{B,c}(X) = H^∗(X(\mathbb{C}), \mathbb{Q}). \]

By Exercise A.252, the cohomology with compact support of \( X \) can be identified with a relative cohomology group on a compactification. Namely, if \( \overline{X} \) is a proper
variety containing $X$ as a dense open subset and $D = \overline{X} \setminus X$, there is a canonical isomorphism

$$H^*_b, c(X) \simeq H^*_b(\overline{X}, D),$$

and hence a long exact sequence

$$\cdots \to H^*_b, c(X) \to H^*_b(\overline{X}) \to H^*_b(D) \to H^{n+1}_b(U) \to \cdots$$

More generally, for any open subvariety $U$ of $X$, with closed complement subset $Z$, there is a long exact sequence

$$\cdots \to H^*_b, c(U) \to H^*_b, c(X) \to H^*_b, c(Z) \to H^{n+1}_b(U) \to \cdots$$

The Betti cohomology with compact support of an algebraic variety is equipped with a mixed Hodge structure for which (2.268) is a long exact sequence of mixed Hodge structures. We content ourselves with explaining the construction for a smooth variety $X$. Then $X$ has a smooth compactification $\overline{X}$ such that $D = \overline{X} \setminus X$ is a simple normal crossing divisor. Let $A^H_X$ and $A^H_D$ be the mixed Hodge complexes from Definition 2.250 and section 2.8.4. Then there is a map $f : A^H_X \to A^H_D$ and the mixed Hodge structure of $H^*_b(X)$ is the one induced by $\text{Tot}(f)$. Alternatively, we can use a variant of the construction we made in Section 2.8.4 to define $A^H_D$. We keep the notation from that section and consider the double complex

$$A^H_{b, p, q} = A^H_{b, p, q}, \quad p, q \geq 0.$$ 

This complex is a dg-mixed Hodge complex. Moreover, $\text{Tot}(f) = \text{Tot}(A^H_{b, p, q})$.

**Remark 2.269** (A spectral sequence computing the weight filtration on cohomology with compact support). One advantage of this second point of view is that it enables us to use the spectral sequence associated with the dg-mixed Hodge complex $A^H_{b, p, q}$. This spectral sequence has first page

$$E_{1}^{p, q} = H^q(D^p),$$

and the term $E_{1}^{p, q}$ carries a pure Hodge structure of weight $q$ since the variety $D^p$ is smooth and proper for each $p$. Since the differentials are morphisms of Hodge structures by Proposition 2.248 i), the terms of the second page

$$E_{2}^{p, q} = \frac{\ker(d_1 : E_{1}^{p, q} \to E_{1}^{p+1, q})}{\text{Im}(d_1 : E_{1}^{p-1, q} \to E_{1}^{p, q})}$$

are pure of weight $q$ as well, and hence all differentials $d_2 : E_{2}^{p, q} \to E_{2}^{p+2, q-1}$ vanish (the source and the target are pure of different weights). Since the spectral sequence degenerates at the second page, Proposition 2.248 ii) gives

$$\text{Gr}^W_{m} H^n_b(X) = E^{n-m, m}_2.$$

More generally, if $X$ is a smooth variety and $D$ a simple normal crossing divisor on $X$, one can find a compactification $\overline{X}$ of $X$ as in Section 2.8.4. The relative cohomology of $(X, D)$ has a mixed Hodge structure induced by the total complex $\text{Tot}(f)$ of the morphism of mixed Hodge complexes

$$f : A^H_X(\log \overline{X} \setminus X) \to A^H_D(\log \overline{D} \setminus D).$$

Note, however, that in this case the analogue of Remark 2.269 is no longer true since, although the varieties $D^p$ are still smooth, they will in general not be proper, and hence the Hodge structure of $H^q(D^p)$ can be mixed of different weights.
Example 2.270. Let $X$ and $D$ be as in Example 2.102. Then the spectral sequence considered in that example is a spectral sequence of mixed Hodge structures whose $E_1$ term reads

\[
\begin{array}{ccc}
0 & 0 & 0 \\
0 & 0 & 0 \\
Q(0) & Q(0) & Q(0) \\
\end{array}
\]

from which we derive the equalities

\[
H^i(X, D) = \begin{cases} 
Q(0), & \text{if } i = 2, \\
0, & \text{otherwise}. 
\end{cases}
\]

Similarly, let $X$ be a smooth variety, $Z \subset X$ a closed subvariety, and $U = X \setminus Z$ its complement. By resolution of singularities (Theorem 2.133), we can find a compactification $\overline{X}$ such that $D = \overline{X} \setminus X$ and $E = \overline{X} \setminus U$ are simple normal crossing divisors. By functoriality, there is a map of Hodge complexes

\[
f: A^H_\overline{X}(\log D) \to A^H_\overline{X}(\log E).
\]

Definition 2.271. The mixed Hodge structure on the cohomology with support is defined as

\[
H^*_Z(X) = H^*(X, U) = H^*(\text{Tot}(f)).
\]

By construction, the cohomology with support $H^*_Z(X)$ sits into a long exact sequence of mixed Hodge structures

\[
\cdots \to H^*_Z(X) \to H^n(X) \to H^n(U) \to H^*_Z(U) \to \cdots
\]

For an example, see Exercise 2.295.

2.8.6. Poincaré duality and the Gysin morphism. The cup-product in cohomology is also a morphism of mixed Hodge structures.

Proposition 2.273. Let $X$ and $Y$ be varieties over $k$. The external product

\[
H^n(X) \otimes H^m(Y) \to H^{n+m}(X \times Y)
\]

is a morphism of mixed Hodge structures over $k$. In particular, the cup-product

\[
H^n(X) \otimes H^m(X) \to H^{n+m}(X)
\]

is a morphism of mixed Hodge structures over $k$.

Corollary 2.274 (Künneth formula). The external product induces an isomorphism of mixed Hodge structures

\[
\bigoplus_{i+j=n} H^i(X) \otimes H^j(Y) \to H^n(X \times Y).
\]

Another useful property is:

Lemma 2.275. Let $X$ be a smooth irreducible proper variety of dimension $d$ over $k$. There is an isomorphism of Hodge structures

\[
H^{2d}(X) \simeq Q(-d).
\]
**Proof.** Since \( X \) is irreducible, the topological space \( X(\mathbb{C}) \) is connected. Hence, its singular cohomology in top degree \( H^{2d}(X(\mathbb{C}), \mathbb{Z}) \) is isomorphic to \( \mathbb{Z} \) by Poincaré duality (2.25). We first assume that \( X \) is projective, so that there is an embedding \( X \subset \mathbb{P}^N \) into some projective space. Then the map

\[
H^d_B(\mathbb{P}^N) \rightarrow H^d_B(X)
\]

that sends the class of a general linear subvariety of codimension \( d \) in \( \mathbb{P}^N \) to its intersection with \( X \) is an isomorphism. The map \( H^d_B(\mathbb{P}^N) \rightarrow H^d_B(X) \) is hence an isomorphism of mixed Hodge structures by Proposition 2.213. Since \( H^d_B(\mathbb{P}^N) \) is the Hodge structure \( \mathbb{Q}(−d) \), the result follows. If \( X \) is proper but non-projective, by Chow’s lemma [Gro61, Thm. 5.6.1] there exists a birational morphism \( X' \rightarrow X \) from a smooth projective irreducible variety \( X' \). Such a morphism induces an isomorphism \( H^d_B(X) \rightarrow H^d_B(X') \), and we can then use the first part of the proof to conclude. \( \square \)

Putting together Proposition 2.273 and Lemma 2.275 we deduce that Poincaré duality is a morphism of mixed Hodge structures after a twist.

**Proposition 2.276 (Poincaré duality).** Let \( X \) be a smooth variety of dimension \( d \) over \( k \). Poincaré duality gives an isomorphism of mixed Hodge structures

\[
H^n(X) \simeq \text{Hom}(H^{2d−n}_c(X), \mathbb{Q}(−d)).
\]

For certain morphisms of algebraic varieties, such as the inclusions of smooth closed subvarieties, Poincaré duality can be used to define direct images in cohomology.

**Definition 2.277.** Let \( X \) be a smooth variety of dimension \( d \) and let \( Z \subset X \) be a smooth closed subvariety of codimension \( p \). For each \( n \geq 0 \), the Gysin map

\[
\gamma: H^n(Z)(−p) \rightarrow H^{n+2p}(X)
\]

is defined as the composition

\[
H^n(Z)(−p) \xrightarrow{\simeq} \text{Hom}(H^{2d−2p−n}_c(Z), \mathbb{Q}(p−d))(−p) \xrightarrow{\text{induced by inclusion}} \text{Hom}(H^{2d−2p−n}_c(X), \mathbb{Q}(−d))
\]

of Poincaré duality and the dual of the map \( H^{2d−2p−n}_c(X) \rightarrow H^{2d−2p−n}_c(Z) \) induced by the inclusion \( Z \rightarrow X \).

The Gysin map has the following very useful property.

**Proposition 2.278 (Gysin long exact sequence).** Let \( X \) be a smooth variety over \( k \) and let \( Z \subseteq X \) be a smooth closed subvariety of codimension \( p \) with open complement \( U = X \setminus Z \). For each \( n \geq 0 \), the Gysin map can be lifted to an isomorphism of mixed Hodge structures \( H^n(Z)(−p) \rightarrow H^{n+2p}(X) \). Therefore, there is a long exact sequence of mixed Hodge structures

\[
\cdots \rightarrow H^{j−1}(X) \xrightarrow{\alpha} H^{j−1}(U) \xrightarrow{\beta} H^{j−2p}(Z)(−p) \xrightarrow{\gamma} H^j(X) \rightarrow \cdots
\]
where $\alpha$ is the usual restriction map and $\gamma$ is the Gysin map.

As we will see in Exercise 2.298, the smoothness assumption on $Z$ is necessary.

2.8.7. $E$-polynomials and the Grothendieck ring of varieties. The $E$-polynomial of a complex algebraic variety $X$ is the polynomial in two variables defined as

$$E_X(u, v) = \sum_{p, q} \left( \sum_{i} (-1)^i h^{p, q}(\text{Gr}^{W}_{p+q} H^i_c(X)) \right) u^p v^q,$$

where $h^{p, q}(\text{Gr}^{W}_{p+q} H^i_c(X))$ denotes the dimension of the $H^{p, q}$ piece in the Hodge decomposition of the pure Hodge structure $\text{Gr}^{W}_{p+q} H^i_c(X)$ of weight $p + q$. From the fact that (2.268) is a long exact sequence of mixed Hodge structures, we get the equality of $E$-polynomials

(2.280) $$E_X = E_Z + E_{X \setminus Z}$$

for each variety $X$ and each closed subvariety $Z \subset X$. Besides, since the Künneth isomorphism is compatible with the mixed Hodge structures by Corollary 2.274, the $E$-polynomial is multiplicative:

(2.281) $$E_{X \times Y} = E_X \cdot E_Y.$$

The above identities suggest to consider the following universal setting. For any field $k$, the Grothendieck ring of varieties $K_0(\text{Var}_k)$ is the quotient of the free abelian group on the set of isomorphism classes of varieties over $k$ by the subgroup generated by elements of the form

$$[X] - [Z] - [X \setminus Z],$$

where $Z \subset X$ is a closed subvariety, together with the ring operation

$$[X] \cdot [Y] = [X \times_k Y].$$

In the case where $k$ is a subfield of $\mathbb{C}$, a compact way to summarize the equalities (2.280) and (2.281) is then to say that the $E$-polynomial gives rise to a ring morphism, also known as a motivic measure,

(2.282) $$E : K_0(\text{Var}_k) \to \mathbb{Z}[u, v].$$

Another typical example of a motivic measure, when $k$ is a finite field, is the function $K_0(\text{Var}_k) \to \mathbb{Z}$ that sends $[X]$ to the cardinal of $X(k)$. The definition of the Grothendieck ring of varieties extends verbatim to schemes over any base (for example $\text{Spec}(\mathbb{Z})$, which is particularly interesting since it provides a common framework for counting points over closed points and computing Hodge numbers over the generic point). We refer the reader to [CLNS18, Chap. 2] for a full-fledged treatment of the Grothendieck ring of varieties and motivic measures.

2.8.8. More examples. We close this section with a few more examples of mixed Hodge structures.

Example 2.283 (Smooth open curves). Let $\overline{C}$ be a smooth projective complex curve and let $S \subset \overline{C}$ be a non-empty finite subset consisting of $s$ points. In this example, we describe the mixed Hodge structure on the first cohomology group of the open curve $C = \overline{C} \setminus S$. Since $S$ is non-empty, the curve $C$ is affine, and hence $H^2(C)$ vanishes by Exercise 2.171. Thanks to this vanishing, the Gysin long exact sequence (2.279) reads

$$0 \to H^1(\overline{C}) \to H^1(C) \to H^0(S)(-1) \xrightarrow{\gamma} H^2(\overline{C}) \to 0.$$
By Lemma 2.275, the last two non-zero terms are isomorphic to the Hodge structures $\mathbb{Q}(-1)^{\oplus s}$ and $\mathbb{Q}(-1)$. Through this identification, the Gysin map $\gamma$ is given by the sum of the coordinates. From this we get a short exact sequence

$$0 \rightarrow H^1(\mathcal{C}) \rightarrow H^1(C) \rightarrow \mathbb{Q}(-1)^{\oplus (s-1)} \rightarrow 0.$$ 

Since taking a step of the weight filtration is an exact functor (Corollary 2.212) and the Hodge structures $H^1(\mathcal{C})$ and $\mathbb{Q}(-1)$ are pure of weights 1 and 2 respectively, the weight filtration on $H^1(C)$ is given by

$$0 = W_0 H^1(C) \subset W_1 H^1(C) = H^1(\mathcal{C}) \subset W_2 H^1(C) = H^1(C).$$

The graded pieces are therefore

$$\text{Gr}^W_1 H^1(C) \simeq H^1(\mathcal{C}), \quad \text{Gr}^W_1 H^1(C) \simeq \mathbb{Q}(-1)^{\oplus (s-1)},$$

which are indeed pure Hodge structures of weights 1 and 2 respectively. In particular, $H^1(C)$ is of Tate type if and only if $H^1(\mathcal{C})$ vanishes, which is equivalent to asking that the curve is a punctured projective line $C = \mathbb{P}^1 \setminus S$.

**Example 2.284 (Moduli spaces $M_{0,n}$).** Recall the moduli spaces $M_{0,n}$ from Section 2.5.2. In this example, we compute the Hodge structure on their cohomology using a method we learnt from Consani and Faber [CF06, Lem. 3].

**Proposition 2.285.** For each $i \geq 0$ and $n \geq 3$, the cohomology group $H^i(M_{0,n})$ carries a pure Hodge–Tate structure of weight $2i$. More precisely, there is an isomorphism of pure Hodge structures

$$H^i(M_{0,n}) \simeq \mathbb{Q}(-i)^{\oplus b_{i,n}},$$

where the Betti numbers $b_{i,n}$ are given by the generating series

$$\sum_{i \geq 0} b_{i,n} t^i = (1 + 2t)(1 + 3t) \cdots (1 + (n - 2)t).$$

**Proof.** We proceed by induction on $n$. For $n = 3$, the moduli space is reduced to a point, and hence all cohomology groups but $H^0(M_{0,3}) = \mathbb{Q}(0)$ vanish. The case $n = 4$ was already settled in Example 2.283, where we saw that the only non-trivial cohomology groups of $M_{0,4} \simeq \mathbb{P}^1 \setminus \{0, 1, \infty\}$ are $H^0(M_{0,4}) = \mathbb{Q}(0)$ and $H^1(M_{0,4}) = \mathbb{Q}(-1)^{\oplus 2}$. Assume $n \geq 5$, and let $(0, 1, \infty, t_1, \ldots, t_{n-3})$ denote the coordinates on $M_{0,n}$. The map

$$M_{0,n} \rightarrow M_{0,4} \times M_{0,n-1},$$

$$(0, 1, \infty, t_1, \ldots, t_{n-3}) \mapsto ((0, 1, \infty, t_1), (0, 1, \infty, t_2, \ldots, t_{n-3}))$$

induces an isomorphism from $M_{0,n}$ to the complement of the smooth closed subvariety $Z \subset M_{0,4} \times M_{0,n-1}$ defined as

$$Z = \bigsqcup_{i=2}^{n-3} \{t_i = t_1\} \cong \bigsqcup_{i=2}^{n-3} M_{0,n-1}.$$

We compute the cohomology of $M_{0,n} \simeq (M_{0,4} \times M_{0,n-1}) \setminus Z$ by combining the Gysin exact sequence, the Künneth formula, and the induction hypothesis. First, the Gysin sequence (2.279) gives

$$\cdots \rightarrow H^{i-2}(Z)(-1) \rightarrow H^i(M_{0,4} \times M_{0,n-1}) \rightarrow H^i(M_{0,n}) \rightarrow H^{i-1}(Z)(-1) \rightarrow H^{i+1}(M_{0,4} \times M_{0,n-1}) \rightarrow \cdots$$

(2.286)
By the Künneth formula (Corollary 2.274) and the induction hypothesis, there are isomorphisms of Hodge structures
\begin{equation}
\begin{aligned}
H^i(M_{0,4} \times M_{0,n-1}) &\simeq \bigoplus_{a+b=i} H^a(M_{0,4}) \otimes H^b(M_{0,n-1}) \\
&\simeq H^i(M_{0,n-1}) \oplus H^{i-1}(M_{0,n-1})(-1)^{\otimes 2} \\
&\simeq \mathbb{Q}(-i)^{b_{i,n-1}} + (n-2)b_{i-1,n-1}.
\end{aligned}
\end{equation}

It follows that the maps $\alpha$ and $\beta$ in (2.286) are morphisms between pure Hodge structures of different weights, and hence identically zero. From this we derive the short exact sequence
\begin{equation}
0 \longrightarrow H^i(M_{0,4} \times M_{0,n-1}) \longrightarrow H^i(M_{0,n}) \longrightarrow H^{i-1}(M_{0,n-1})(-1)^{\otimes (n-4)} \longrightarrow 0.
\end{equation}

Thanks to the isomorphism (2.287) and the induction hypothesis, the cohomology $H^i(M_{0,n})$ is an extension of two pure Hodge–Tate structures of the same weight. Since all such extensions are split by Theorem 2.235, we deduce
\begin{equation}
H^i(M_{0,n}) \simeq \mathbb{Q}(-i)^{b_{i,n}}, \quad b_{i,n} = b_{1,n-1} + (n-2)b_{i-1,n-1}.
\end{equation}

One immediately checks that this recurrence relation amounts to the expression for the Betti numbers given in the statement. □

2.8.9. Graph hypersurfaces. Let $G = (V, E)$ be a finite graph with vertex set $V$ and edge set $E$. Assume that $G$ is connected. A subgraph $T \subseteq G$ is called a spanning tree if $T$ is a tree (i.e. a connected graph with no loops) and contains all vertices of $G$. Consider a collection of formal variables $(x_e)_{e \in E}$ indexed by the edges of $G$. The first Symanzik polynomial of the graph $G$ is defined as
\begin{equation}
\psi_G = \sum_{T \subseteq G} \prod_{e \in T} x_e \in \mathbb{Z}[(x_e)_{e \in E}],
\end{equation}
where the sum runs over all spanning trees in $G$. Let $n_G$ be the number of edges of $G$ and $h_G$ the number of loops. One readily checks that $\psi_G$ is a homogeneous polynomial of degree $h_G$ (Exercise 2.303). After choosing a numbering of the vertices, we can see $\psi_G$ as a polynomial in the variables $x_0, \ldots, x_{n_G-1}$.

DEFINITION 2.289. The graph hypersurface $X_G \subseteq \mathbb{P}^{n_G-1}$ is the vanishing locus of the polynomial $\psi_G$.

Graph hypersurfaces appear in perturbative quantum field theory, which associates an integral called Feynman amplitude with each graph describing a possible interaction between particles. In the case of primitive log divergent graphs, which are those satisfying the conditions $n_G = 2h_G$ and $n_\gamma > 2h_\gamma$ for all non-empty strict subgraphs $\gamma \subseteq G$, the Feynman amplitude is given by the convergent integral
\begin{equation}
I_G = \int_S \frac{\Omega}{\psi^2_G},
\end{equation}
up to a normalization factor that will play no role in our discussion. In the above formula, $\Omega$ stands for the differential form
\begin{equation}
\Omega = \sum_{j=0}^{n_G-1} (-1)^j x_j dx_0 \wedge \cdots \wedge dx_j \wedge \cdots \wedge dx_{n_G-1},
\end{equation}
and the integration domain is the real coordinate simplex 
\[ \sigma = \{ [x_0: \cdots : x_{nG-1}] \in \mathbb{P}^{nG-1}(\mathbb{R}) \mid x_j \geq 0 \} . \]

Note that the condition \( n_G = 2h_G \) implies that the integrand of (2.290), which is written in homogeneous coordinates, is well defined. Setting \( t_i = x_i/x_0 \), the amplitude \( I_G \) can also be written as the affine integral
\[
I_G = \int_0^{\infty} dt_1 \int_0^{\infty} dt_2 \cdots \int_0^{\infty} \frac{dt_{nG-1}}{\psi_G^2(1, t_1, t_2, \ldots, t_{nG-1})} .
\]

That the integral converges is proved for instance in [BEK06, Prop. 5.2].

The extensive numerical calculations of Broadhurst and Kreimer [BK97] identified many Feynman amplitudes of primitive log divergent graphs, such as those shown in Figure 10, with \( \mathbb{Q} \)-linear combinations of multiple zeta values. This happens to be a general phenomenon for “small graphs” (for example, those with at most 6 loops), and it was believed for some time that \( I_G \) might always be a \( \mathbb{Q} \)-linear combination of multiple zeta values. In our current state of knowledge, giving a negative answer to this question seems completely out of reach, as it would require to prove the very strong diophantine statement that some Feynman amplitude is \( \mathbb{Q} \)-linearly independent from all multiple zeta values. Nevertheless, we can approach the question from a cohomological point of view to get compelling evidence for a negative answer. Indeed, multiple zeta values are periods of Hodge structures of mixed Tate type built on algebraic varieties over \( \mathbb{Q} \). Conversely, a form of Grothendieck’s period conjecture implies that, if all periods of such a mixed Hodge structure are \( \mathbb{Q} \)-linear combinations of multiple zeta values, then it is necessarily of mixed Tate type. One can then ask instead if the mixed Hodge structure that naturally arises from the integral representation (2.290) is of mixed Tate type. An easier question to begin with is whether the cohomology of \( Y_G = \mathbb{P}^{nG-1} \setminus X_G \) is always of mixed Tate type. This variety being smooth, the question amounts by Poincaré duality to asking whether the cohomology with compact support of \( Y_G \) is always of mixed Tate type or, using the long exact sequence (2.268), whether the cohomology of \( X_G \) is always of mixed Tate type.

\[
6\zeta(3) \quad 20\zeta(5) \quad \frac{417}{120}\zeta(3, 5) + \frac{333}{260}\zeta(5, 3) - \frac{8}{7}\zeta(8)
\]

**Figure 10.** Three examples of primitive log divergent graphs and the corresponding Feynman amplitudes
This last question was answered in the negative by Belkale and Brosnan, who showed in [BB03] that varieties of the form $Y_G$ are general enough to span the Grothendieck ring of varieties (see Section 2.8.7). Note that the polynomial $\psi_X$ has integer coefficients, and hence the graph hypersurface $X_G$ and its complement $Y_G$ are schemes defined over $\text{Spec}(\mathbb{Z})$. Their result can then be stated as follows:

**Theorem 2.291** (Belkale-Brosnan, [BB03]). For each scheme $X$ of finite type over $\text{Spec}(\mathbb{Z})$, there exist finitely many graphs $G_i$, polynomials $p_i \in \mathbb{Z}[T]$, and integers $n_j \geq 2$ such that, setting $L = [\mathbb{A}^1_T]$, the equality

$$[X] = \prod_j (L^{n_j} - L) \cdot \sum_i p_i(L)[Y_{G_i}]$$

holds in the Grothendieck ring $K_0(\text{Var}_\mathbb{Z})$.

By base change, the same identity holds between the classes of the corresponding varieties over the field of complex numbers. Now recall from (2.282) that there is a unique ring morphism $K_0(\text{Var}_{\mathbb{C}}) \to \mathbb{Z}[u, v]$ that sends the class of a variety to its $E$-polynomial. If all the cohomology with compact support groups of a variety are of mixed Tate type, then its $E$-polynomial is a polynomial in the variable $uv$. This is, for example, the case for the affine line, since its only non-zero cohomology with compact support is $H^2_\text{c}(\mathbb{A}^1, \mathbb{Q}(1)) = \mathbb{Q}(1)$; the $E$-polynomial of $L$ is thus equal to $uv$. It then follows from Theorem 2.291 that, if the cohomology with compact support of $Y_G$ were of mixed Tate type for all graphs $G$, then the same would hold for any variety. But this is clearly not true: for example, the $E$-polynomial of an elliptic curve is $(1 - u)(1 - v)$. Therefore, there exists at least one graph $G$ such that not all cohomology with compact support groups of $Y_G$ (or, equivalently, all cohomology groups of $X_G$) are of mixed Tate type.

In a different line of thought, the fact that the cohomology of $X_G$ is of mixed Tate type is also expected to impose strong constraints on the number of points of this variety over finite fields. Indeed, since $\psi_G$ has integral coefficients, it makes sense to consider for each finite field $\mathbb{F}_q$ of characteristic $p$ the number of $\mathbb{F}_q$-points

$$|X_G(\mathbb{F}_q)| = \{[x_0 : \ldots : x_{n_G-1}] \in \mathbb{P}^{n_G-1}(\mathbb{F}_q) \mid \psi_G(x_0, \ldots, x_{n_G-1}) = 0\}$$

of the reduction modulo $p$ of the graph hypersurface. In 1997, Kontsevich informally conjectured that, for each graph $G$, the function

$$(2.292) \quad q \mapsto |X_G(\mathbb{F}_q)|$$

is a polynomial in $q$. Again, this happens to be true for “small graphs” (for example, those with at most 12 edges [Ste98]), but the theorem of Belkale and Brosnan also disproves the expectation that it might be a general phenomenon. Indeed, Theorem 2.291 implies that the functions (2.292) span all counting functions of schemes over $\mathbb{Z}$: for each scheme of finite type $X$ over $\text{Spec}(\mathbb{Z})$, there exist finitely many graphs $G_i$, polynomials $p_i \in \mathbb{Z}[T]$, and integers $n_j \geq 2$ satisfying

$$|X(\mathbb{F}_q)| = \prod_j (q^{n_j} - q) \cdot \sum_i p_i(q)|X_{G_i}(\mathbb{F}_q)|$$

for all $q$. Therefore, if the function $q \mapsto |X_G(\mathbb{F}_q)|$ were a polynomial in $q$ for each graph $G$, then the same would hold for all varieties. This is again false, for example, for an elliptic curve. Later on, Brown and Schnetz [BS12] constructed explicit graphs that are counter-examples to Kontsevich’s conjecture. For example,
there exists a primitive log divergent graph $G$ with 8 loops and 16 edges such that the counting function of $X_G$ is given modulo $pq^2$ by a modular form arising from a certain K3 surface with complex multiplication.

In order to interpret the Feynman amplitude $I_G$ as a period, we observe that the integrand of (2.290) is a global top-degree differential form $\omega_G$ on $\mathbb{P}^{n_G-1} \setminus X_G$ and that the boundary of the integration domain $\sigma$ is contained in the union $D$ of the coordinate hyperplanes $\{x_i = 0\}$. In general, $\sigma$ intersects the graph hypersurface $X_G$, so we are faced again with the problem we encountered in Section 2.5 when dealing with $\zeta(2)$ that the integration cycle does not define an element in the naive relative cohomology group

$$H^{n_G-1}_B(\mathbb{P}^{n_G-1} \setminus X_G, D \setminus D \cap X_G).$$

However, the fact that the coefficients of $\psi_G$ are positive makes this intersection easy to describe. In fact, it is equal to

$$X_G(\mathbb{C}) \setminus \sigma = \bigcup_{h, >0} L_{\gamma}(\mathbb{R}_{>0}),$$

where $\gamma$ is a subgraph of $G$ with at least one loop, $L_{\gamma}$ is the linear subvariety of $\mathbb{P}^{n_G-1}$ defined by the equations $x_e = 0$ for all vertices $e$ of $\gamma$, and we set

$$L_{\gamma}(\mathbb{R}_{>0}) = \{[x_e]_{e \in E} \in L_{\gamma}(\mathbb{R}) \mid x_e > 0\}.$$

This allowed Bloch, Esnault, and Kreimer to obtain the following result:

**Theorem 2.293 (Bloch-Esnault-Kreimer, [BEK06, Prop. 7.3]).** There exists a tower of blow-ups $\pi: P = P_0 \longrightarrow \cdots \longrightarrow P_{n_G-1} = \mathbb{P}^{n_G-1}$ such that each $P_i$ is obtained by blowing up $P_{i-1}$ along the strict transform of a coordinate linear space $L_i$ and the following conditions hold:

i) The differential $\pi^* \omega_G$ has no poles along the exceptional divisors associated with the blow-ups.

ii) The total transform $B$ of $D$ is a normal crossing divisor such that none of the non-empty intersections of its irreducible components is contained in the strict transform $Y$ of $X_G$.

iii) The strict transform of $\sigma$ does not meet $Y$.

**Corollary 2.294.** Keeping the notation from the previous theorem, the Feynman amplitude $I_G$ is a period of the mixed Hodge structure

$$H^{n_G-1}(\mathbb{P} \setminus Y, B \setminus (B \cap Y)).$$

***

**Exercise 2.295.** Set $X = \mathbb{P}^1_0$ and let $Z \subset X$ be a closed subvariety consisting of a rational point. Compute the mixed Hodge structure on the cohomology with support $H^*_Z(X)$ introduced in Definition 2.271.

**Exercise 2.296.** Let $X$ be a smooth complex variety, let $Z \subset X$ be a smooth subvariety of codimension $c$, and write $U = X \setminus Z$. Use the Gysin long exact sequence (2.279) to prove that the restriction map $H^i(X) \to H^i(U)$ is an isomorphism for $i < 2c - 1$, and is injective for $i = 2c - 1$. 
Exercise 2.297 (Varieties which admit a compactification by a smooth divisor). Let $U$ be a smooth complex variety. In this exercise, we show that the existence of a smooth compactification by a smooth divisor imposes strong restrictions on the mixed Hodge structure on the cohomology of $U$.

i) Use the Gysin exact sequence (2.279) to show that if $U = X \setminus D$ is the complement of a smooth divisor $D$ on a smooth proper variety $X$, then the mixed Hodge structure $H^n(U)$ has only weights in $[n, n + 1]$.

ii) Give an example of a smooth surface which does not admit a smooth proper compactification by a smooth divisor.

Exercise 2.298. In this exercise, we show that Proposition 2.278 does not hold without the smoothness assumption.

i) Let $H_1 \to H_2 \to H_3$ be an exact sequence of mixed Hodge structures. Assume that $H_1$ has weights in $I \subset \mathbb{Z}$ and $H_3$ has weights in $J \subset \mathbb{Z}$. Prove that $H_2$ has weights in $I \cup J$.

ii) Let $X$ be a smooth proper variety and $Z$ a closed subvariety. Use the exact sequence (2.272) to prove that, for any $n \geq 0$, the mixed Hodge structure $H^n_Z(X)$ has weights in $[n - 1, \max(n, 2n - 2)]$. (In fact, it can be shown that weight $n - 1$ does not occur.)

iii) Let $X$ be a smooth proper variety and $D$ a normal crossing divisor. Show that $H^{n-2}_D(X)$ has weights in $[2, n]$. (In fact, a similar result holds for any closed subvariety.)

iv) It follows from the previous points that the mixed Hodge structures $H^n_2(X)$ and $H^{n-2}(D)(-1)$ can only be isomorphic if they are both pure of weight $n$. Consider $X = \mathbb{P}^2$ and $D = D_1 \cup D_2 \cup D_3$ the union of the coordinate hyperplanes. Show the equalities $H^n_3(X) = \mathbb{Q}(-2)$ and $H^1(D)(-1) = \mathbb{Q}(-1)$.

v) Even if the weights match, the Hodge structures need not be isomorphic. Consider $X = \mathbb{P}^2$ and $D = D_1 \cup D_2$ the union of two coordinate hyperplanes. Then prove the equalities

$$H^n_D(X) = \begin{cases} 
\mathbb{Q}(-2), & \text{if } n = 4, \\
\mathbb{Q}(-1) \oplus \mathbb{Q}(-1), & \text{if } n = 2, \\
0, & \text{otherwise},
\end{cases}$$

$$H^n(D) = \begin{cases} 
\mathbb{Q}(-1) \oplus \mathbb{Q}(-1), & \text{if } n = 2, \\
\mathbb{Q}(0), & \text{if } n = 0, \\
0, & \text{otherwise}.
\end{cases}$$

Therefore, $H^n_3(X)$ is not isomorphic to $H^{n-2}(D)(-1)$.

Exercise 2.299. Let $\overline{X}$ be a smooth proper complex variety, and let $Y_0, Y_1$ be two smooth divisors on $\overline{X}$ such that $Y_0 \cup Y_1$ has normal crossings. Set

$$X = \overline{X} \setminus Y_0, \quad Y = Y_1 \setminus (Y_0 \cap Y_1).$$
Show that the weight filtration on the relative cohomology group 
\( M = H^n(X, Y) \) is given by

\[
\begin{align*}
W_{n-2}M &= 0, \\
W_{n-1}M &= \text{Im}(H^{n-1}(Y_1) \to M), \\
W_nM &= \text{Ker}(M \to H^{n-1}(Y_0)(-1)), \\
W_{n+1}M &= M.
\end{align*}
\]

[Hint: Consider a diagram of mixed Hodge structures whose rows are Gysin long exact sequences and whose columns are long exact sequences of relative cohomology. Use the fact that \( W_m \) is an exact functor and Lemma 2.211.]

**Exercise 2.300** (The graded pieces of the mixed Hodge structure of a smooth variety). Let \( X \) be a smooth proper variety, \( D \) a simple normal crossing divisor, and \( U = X \setminus D \). As in Construction 2.97, we use the notation

\[
D^0 = X, \quad D^p = \coprod_{i_1, i_2, \ldots, i_p} D_{i_1} \cap \cdots \cap D_{i_p} \quad (p \geq 1)
\]

Prove that the weight filtration of \( H^n(U) \) is given by

\[
\text{Gr}^W_m H^n(U) = H^{n-m}((\cdots \to H^{n-2}(D^1)(-1) \to H^m(X) \to 0),
\]

where the term \( H^{n-2p}(D^p)(-p) \) sits in degree \(-p\) and the arrows are alternating sums of Gysin maps.

**Exercise 2.302.** Let \( n \geq 3 \) be an integer and \( q \) a power of a prime number. As the moduli space \( M_{0,n} \) is defined over the integers, we can consider its base change to any finite field \( \mathbb{F}_q \). Consider the polynomial of degree \( n - 3 \) given by

\[ P(T) = (T - 2)(T - 3) \cdots (T - n + 2). \]

i) Show that the number of points of \( M_{0,n} \) over \( \mathbb{F}_q \) is equal to \( P(q) \).

ii) Building on Proposition 2.285, prove that the \( E \)-polynomial of \( M_{0,n} \) is given by

\[ E_{M_{0,n}}(u, v) = P(uv). \]

More generally, given any complex variety \( X \), there exists a subring \( R \subset \mathbb{C} \) that is finitely generated over \( \mathbb{Z} \) and a scheme \( \mathcal{X} \) over \( R \) that gives \( X \) back after extension of scalars. We say that \( X \) has strong polynomial count if \( R \) and \( \mathcal{X} \) can be chosen in such a way that there exists a polynomial \( P \in \mathbb{Z}[t] \) with the property that, for each finite field \( \mathbb{F}_q \) and each ring morphism \( R \to \mathbb{F}_q \), the number of points of \( \mathcal{X}(\mathbb{F}_q) \) is \( P(q) \). It is then a general result, proved in Katz’s appendix to [HRV08], that the \( E \)-polynomial of a variety with strong polynomial count is equal to \( P(uv) \).

**Exercise 2.303.** Prove that the first Symanzik polynomial of a graph, as defined in (2.288), is homogeneous of degree the number of loops in \( G \).

**Exercise 2.304 (Deletion-contraction relations).** Let \( G \) be a connected graph and \( e \) an edge of \( G \). We denote by \( G \setminus e \) the graph obtained by deleting the edge \( e \) and by \( G/e \) the graph obtained by contracting the edge \( e \). Assuming that \( G \setminus e \) is still connected and that the two endpoints of \( e \) are different, show that the identity

\[ \psi_G = x_e \psi_{G \setminus e} + \psi_{G/e}, \]

relating the first Symanzik polynomials of \( G, G \setminus e \) and \( G/e \) holds.
Exercise 2.305 (The trivial Feynman amplitude). Consider the graph $G$ with two vertices and two edges connecting them, as in Figure 11. Compute the Feynman amplitude $I_G$ and write down a Hodge structure for which it is a period (no blow-up is needed in this case).

![Figure 11. A simple graph](image)

2.9. Back to $\zeta(2)$ and irrationality proofs. We end the chapter\(^1\) by showing that the relative cohomology group attached to $\zeta(2)$ in 2.5.1 is an extension of $\mathbb{Q}(-2)$ by $\mathbb{Q}(0)$. We then discuss the problem of constructing other extensions and a potential application to irrationality proofs.

2.9.1. The extension associated with $\zeta(2)$. We prove that the relative cohomology group built in Section 2.5.1 out of the integral representation of $\zeta(2)$ is an extension of $\mathbb{Q}(-2)$ by $\mathbb{Q}(0)$. Recall that we considered the blow-up $X$ of $\mathbb{A}^2$ at the points $p = (0,0)$ and $q = (1,1)$, together with the normal crossing divisors

$L = L_0 \cup L_1$, \quad $M = M_0 \cup M_1 \cup M_2 \cup M_3 \cup M_4$,

where

- $L_0$ and $L_1$ are the strict transforms of $\{t_1 = 0\}$ and $\{t_2 = 1\}$ (affine lines),
- $M_0 = E_p$ and $M_1 = E_q$ are the exceptional divisors (projective lines),
- $M_2$, $M_3$ and $M_4$ are the strict transforms of $\{t_1 = t_2\}$, $\{t_2 = 0\}$ and $\{t_1 = 1\}$ (affine lines).

Proposition 2.306. There exists a short exact sequence of mixed Hodge structures

\[
0 \rightarrow \mathbb{Q}(0) \rightarrow H^2(X \setminus L, M \setminus (L \cap M)) \rightarrow \mathbb{Q}(-2) \rightarrow 0.
\]

Proof. Let $X$ be any smooth complex variety of dimension $d$, and $L$ and $M$ two normal crossing divisors on $X$ with no common irreducible components and such that $L \cup M$ has normal crossings as well. By [Dup17, App. A.1], there is a spectral sequence of mixed Hodge structures

\[
E_1^{p,q} = \bigoplus_{j - i = p, |J| = i} H^{q - 2i}(L_J \cap M_J)(-i) \Rightarrow Gr^W H^{p+q}(X \setminus L, M \setminus (M \cap L)),
\]

where the indexes run over $-d \leq p \leq d$ and $0 \leq q \leq 2d$, and the differential

\[
d_1 : E_1^{p,q} \rightarrow E_1^{p+1,q}
\]

is the sum of

\(^1\)Many thanks to Clément Dupont and Peter Jossen for their help with this section.
i) the restriction maps

$$H^{q-2i}(L_I \cap M_J)(-i) \to H^{q-2i}(L_I \cap M_{J \cup \{s\}})(-i)$$

induced from the inclusions $L_I \cap M_{J \cup \{s\}} \to L_I \cap M_J$, multiplied by the signs $\varepsilon(J, J \cup \{s\})$;

ii) the Gysin morphisms

$$H^{q-2i}(L_I \cap M_J)(-i) \to H^{q-2i+2}(L_{I\setminus\{r\}} \cap M_J)(-i+1)$$

associated with the inclusions $L_I \cap M_J \to L_{I\setminus\{r\}} \cap M_J$, multiplied by the signs $\varepsilon(I \setminus \{r\}, I)$.

Recall from 2.2.7 that, if $J = \{j_0, \ldots, j_r\}$ is an index set with $j_0 < \cdots < j_r$ and $I$ is obtained from $J$ by removing $j_r$, we set $\varepsilon(I, J) = (-1)^{\ell}$.

Assume that all the terms $E_1^{p,q}$ in the spectral sequence carry a pure Hodge structure of weight $q$. The second page is given by

$$E_2^{p,q} = \frac{\text{Ker}(d_1 : E_1^{p,q} \to E_1^{p+1,q})}{\text{Im}(d_1 : E_1^{p-1,q} \to E_1^{p,q})},$$

together with a differential $d_2 : E_2^{p,q} \to E_2^{p+2,q-1}$. Thus, $E_2^{p,q}$ has a pure Hodge structure of weight $q$ as well, which implies $d_2 = 0$ since there are no non-trivial morphisms between Hodge structures of different weight. It follows that the spectral sequence degenerates at $E_2$ and

$$(2.309) \quad E_2^{p,q} = \text{Gr}_q^W H^{p+q}(X \setminus L, M \setminus (M \cap L)).$$

Let us now turn to our particular situation. Setting

$$r = L_0 \cap L_1, \quad s = L_0 \cap E_p, \quad t = L_1 \cap E_q, \quad M_{ij} = M_i \cap M_j,$$

the spectral sequence takes the form of Figure 12. By way of illustration, the piece $E_1^{1,2}$ is the sum of all possible $H^{2-2i}(L_I \cap M_J)(-i)$ with $j = i+1$. Then necessarily $i = 0$ or $i = 1$, and the second case does not occur since there are no non-empty intersections of one component of $L$ and two components of $M$. For $i = 0$, we get $\bigoplus H^2(M_i) = H^2(E_p) \oplus H^2(E_q)$, taking into account that the remaining components are affine lines. Observe that odd values of $q$ do not need to be considered, since all intersections $L_I \cap M_J$ have cohomology concentrated in even degrees. For this same reason, the assumption that $E_1^{p,q}$ has pure weight $q$ is satisfied in our case.

We need to prove that

$$(2.310) \quad \text{Gr}^W H^2(X \setminus L, M \setminus (L \cap M)) = \mathbb{Q}(0) \oplus \mathbb{Q}(-2).$$

In this equality, the piece $\mathbb{Q}(-2)$ comes from the top-left corner of the spectral sequence, while $\mathbb{Q}(0)$ arises as the cokernel of the map $\bigoplus H^0(M_i) \to \bigoplus H^0(M_{ij})$, which has rank 4. Indeed, this map is given by

$$(a, b, c, d, e) \mapsto (c - a, d - a, c - b, e - b, e - d).$$

Since the map $H^0(X) \to \bigoplus H^0(M_i)$ sends $a$ to $(a, a, a, a)$, the cohomology of the bottom line is concentrated in $E_2^{0,0} = \mathbb{Q}(0)$.

We are thus reduced to show that the complex $E_1^{1,2}$ is exact at the middle term. For this, we first observe that the Gysin maps induce an isomorphism of Hodge structures

$$(2.311) \quad H^0(E_p)(-1) \oplus H^0(E_q)(-1) \xrightarrow{\sim} H^2(X).$$
Since (2.312) the isomorphism (2.311), by the total transform of \( \ell \) where the last equality follows from the fact that the equality (2.313) holds. This is an instance of the general computation of the Hodge structure of a blow-up, e.g. see [Voi02, §7.3.3]. In the case at hand, it can be seen as follows: the Gysin long exact sequence (2.279) for \( U = X \setminus (E_p \cup E_q) \) reads

\[
\cdots \longrightarrow H^1(U) \longrightarrow H^0(E_p)(-1) \oplus H^0(E_q)(-1) \longrightarrow H^2(X) \longrightarrow H^2(U) \longrightarrow \cdots
\]

Since \( U \) and \( \mathbb{A}^2 \setminus \{p, q\} \) are isomorphic via the blow-up map, the cohomology groups \( H^1(U) \) and \( H^2(U) \) vanish (use Exercise 2.296). It follows that the differential \( d_1 : E_1^{0,2} \to E_1^{1,2} \) in the spectral sequence is given, in suitable bases compatible with the isomorphism (2.311), by

\[
H^2(X) \oplus H^0(s)(-1) \oplus H^0(t)(-1) \longrightarrow H^2(E_p) \oplus H^2(E_q) \]

\[
(a, b, c, d) \quad \longrightarrow \quad (a + c, b + d).
\]

To compute the remaining map in the spectral sequence, we take a closer look at the cohomology classes \( [L_i] \in H^2(X) \). We claim that \( [L_0] = -[E_p] \). Indeed, since the total transform of \( \ell_0 \) is the union \( L_0 \cup E_p \), we get

\[
[L_0] + [E_p] = [\pi^{-1}(\ell_0)] = \pi^*[\ell_0] = 0,
\]

where the last equality follows from the fact that \([\ell_0]\) lives in \( H^2(\mathbb{A}^2) = 0 \). Similarly, the equality \([L_1] = -[E_q]\) holds, so that \( d_1 : E_1^{-1,2} \to E_1^{0,2} \) is given by

\[
H^0(L_0)(-1) \oplus H^0(L_1)(-1) \longrightarrow H^2(X) \oplus H^0(s)(-1) \oplus H^0(t)(-1) \]

\[
(a, b) \quad \longrightarrow \quad (-a, -b, a, b).
\]

\[\text{Figure 12. The first page of the spectral sequence computing the grading } Gr^W H^2(X \setminus L, M \setminus (L \cap M))\]
It is now obvious that the middle row of the spectral sequence is exact. Indeed, its whole second page reads

\[ Q(-2) \quad 0 \quad 0 \quad 0 \quad 0 \]
\[ \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]
\[ \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]
\[ \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]
\[ \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \]

This concludes the proof of the equality (2.310) and shows, moreover, the vanishing

\[ H^i(X \setminus L, M \setminus (L \cap M)) = 0 \]

in all degrees \( i \neq 2 \).

\[ \square \]

**Remark 2.314.** A byproduct of the proof is that we have canonical identifications (see Exercise 2.319)

\[ \begin{align*}
Gr^W_4 H^2(X \setminus L, M \setminus (L \cap M)) &= H^2(X \setminus L) = Q(-2), \\
Gr^W_0 H^2(X \setminus L, M \setminus (L \cap M)) &= H^2(X, M) = Q(0).
\end{align*} \tag{2.315} \]

Recall from Section 2.5.1 that the differential form \( \pi^*(\omega) \) defines a class in the de Rham cohomology group \( H^2_{dR}(X \setminus L) \) and the simplex \( \sigma \) belongs to \( H^2(X, M) \). By Theorem 2.235, the class of the extension

\[ [H^2(X \setminus L, M \setminus (L \cap M))] \in \text{Ext}^{1}_{\text{MHS}}(Q(-2), Q(0)) = \mathbb{C}/(2\pi i)^2 \mathbb{Q} \]

is thus given by \( \int_\sigma \pi^*(\omega) = \zeta(2) \). One would like to use this information as follows: imagine that we knew by “pure thought” that all such extensions given by relative cohomology of varieties defined over \( \mathbb{Q} \) are split. Then \( \zeta(2) \) would have to vanish in the quotient \( \mathbb{C}/(2\pi i)^2 \mathbb{Q} \), which would yield a more conceptual explanation of why \( \zeta(2) \) is a rational multiple of \( \pi^2 \). To carry out this program, one needs however to leave the category of mixed Hodge structures and work with the more abstract notion of mixed Tate motives which will be introduced in Chapter 4.

**2.9.2. Odd zeta extensions.** In general, it is a difficult problem to give a geometric construction of the extension of \( Q(-n) \) by \( Q(0) \) whose class in

\[ \text{Ext}^{1}_{\text{MHS}}(Q(-n), Q(0)) = \mathbb{C}/(2\pi i)^n \mathbb{Q} \]

is the zeta value \( \zeta(n) \). Besides Proposition 2.306, only the case \( n = 3 \) is known by work of Brown [Bro16] and Dupont [Dup18].

More precisely, Dupont starts with affine space \( \mathbb{A}^n \) and the hypersurfaces

\[ \ell_n = \{ x_1 \cdots x_n = 1 \}, \quad m_n = \bigcup_{1 \leq i \leq n} \{ x_i = 0 \} \cup \bigcup_{1 \leq i \leq n} \{ x_i = 1 \}. \]

The divisor \( \ell_n \) is smooth and \( m_n \) is a normal crossing divisor; however, their union \( \ell_n \cup m_n \) fails to have normal crossings at the point \( p_n = (1, \ldots, 1) \), where \( n+1 \) irreducible components intersect. Let \( \pi_n : X_n \to \mathbb{A}^n \) be the blow-up of \( \mathbb{A}^n \) at \( p_n \) and let \( E_n \) denote the exceptional divisor. We write \( L_n \) for the strict transform of \( \ell_n \) and \( M_n \) for the union of the strict transform of \( m_n \) and \( E_n \). We form the relative cohomology:

\[ Z_n = H^n(X_n \setminus L_n, M_n \setminus (L_n \cap M_n)) \].
Dupont proves that $Z_n$ fits into an exact sequence of mixed Hodge structures

$$0 \longrightarrow \mathbb{Q}(0) \longrightarrow Z_n \longrightarrow \mathbb{Q}(-2) \oplus \cdots \oplus \mathbb{Q}(-n)$$

and that there is a natural isomorphism

$$(2.316) \quad Z_n/\mathbb{Q}(0) \isom \bigoplus_{1 \leq i \leq n} H^{n-1}(\ell_n, \{ x_i = 1 \})(-1).$$

Moreover, with respect to appropriate bases of de Rham and Betti cohomology, the period matrix of $Z_n$ is given by

$$\begin{pmatrix}
1 & \zeta(2) & \zeta(3) & \ldots & \zeta(n-1) & \zeta(n) \\
(2\pi i)^2 & (2\pi i)^3 & 0 & \ddots & \ddots & \\
& & & \ddots & 0 & (2\pi i)^{n-1} \\
& & & & (2\pi i)^n &
\end{pmatrix}.$$  

To separate the values of the zeta function at even and odd integers, he uses the involution

$$\tau(x_1, \ldots, x_n) = (x_1^{-1}, \ldots, x_n^{-1})$$
on $\ell_n$. Since $\tau$ leaves the union of the subvarieties $\{ x_i = 1 \}$ invariant, it induces an involution on the right-hand side of $(2.316)$. According to [Dup18, Thm. 1.4], the invariants are given by

$$(Z_n/\mathbb{Q}(0))^\tau \simeq \bigoplus_{3 \leq 2k+1 \leq n} \mathbb{Q}(-(2k+1)).$$

Therefore, letting $p: Z_n \rightarrow Z_n/\mathbb{Q}(0)$ denote the quotient map and defining

$$Z_n^{\text{odd}} = p^{-1}((Z_n/\mathbb{Q}(0))^\tau)^{-1},$$

we obtain an exact sequence of mixed Hodge structures

$$0 \longrightarrow \mathbb{Q}(0) \longrightarrow Z_n^{\text{odd}} \longrightarrow \bigoplus_{3 \leq 2k+1 \leq n} \mathbb{Q}(-(2k+1)) \longrightarrow 0.$$  

The period matrix of $Z_n^{\text{odd}}$ is given by

$$\begin{pmatrix}
1 & \zeta(3) & \zeta(5) & \zeta(7) & \ldots & \ldots \\
(2\pi i)^3 & (2\pi i)^5 & 0 & \ddots & \ddots & \\
& & & (2\pi i)^7 & 0 & \ddots \\
& & & & \ddots & \ddots \\
& & & & & \ddots 
\end{pmatrix}.$$
2.9.3. Irrationality proofs. Here is how a typical irrationality proof works. To show that a real number $\alpha$ is irrational, we proceed in three steps:

i) we construct linear forms

\[
I_n = a_n + b_n \alpha, \quad a_n, b_n \in \mathbb{Q},
\]

such that $0 < |I_n| < C^n$ for some $0 < C < 1$ and $n$ all sufficiently big;

ii) if $r_n$ is the common denominator of $a_n$ and $b_n$, then we require that $r_n < D^n$ for some real number $D$, again when $n$ is big enough;

iii) $C$ and $D$ should be related by the inequality $CD < 1$.

If one succeeds in carrying out these three steps, then $\alpha$ is irrational. Indeed, assume by contradiction that $\alpha$ is of the form $p/q$ for some integers $p$ and $q$. Multiplying $I_n$ by $r_nq$, we get

\[
0 < |r_n a_n q + r_n b_n p| < qr_n C^n < q(CD)^n,
\]

so the sequence inside the absolute value converges to zero by the assumption that $CD < 1$. But then, for $n$ sufficiently big, we would find integers strictly bigger than 0 and strictly smaller than 1, which is of course a contradiction!

Algebraic geometry could be useful in producing the linear forms (2.317). Indeed, assume that we can construct a mixed Hodge structure over $\mathbb{Q}$ which is an extension of $\mathbb{Q}(0)$ by $\mathbb{Q}(n)$ with period matrix

\[
\begin{pmatrix}
1 & \alpha \\
0 & (2\pi i)^n
\end{pmatrix}
\]

with respect to some bases $\{\omega_0, \omega_1\}$ of $H_{dR}$ and $\{\sigma_0, \sigma_1\}$ of $H_B$. Then, given an $\omega \in H_{dR}$, there exist rational numbers $a$ and $b$ such that $a\omega_0 + b\omega_1$, and the integral $\int_{\sigma_0} \omega$ is equal to $a + b\alpha$. Typically, $H$ is given by a relative cohomology group and one considers a sequence $\omega_n = f^\omega$ where $\omega$ is a fixed differential form and $f$ is a function vanishing on the boundary.

**Example 2.318.** Consider the differential form

\[
\omega_{a,b,c} = \frac{(x - 1)^a (t - x)^b}{x^{c+1}} dx,
\]

where $a, b, c \geq 1$ and $t \geq 2$ are integers. Since $\omega_{a,b,c}$ is only singular along $x = 0, \infty$ and has top degree, it defines a class in $H_{dR}^c(\mathbb{P}^1 \setminus \{0, \infty, \{1, t\})$. By Example 2.91, a basis of this relative cohomology group is given by the differentials $\omega_1 = dx/(t - 1)$ and $\omega_2 = dx/x$, so there exist rational numbers $A$ and $B$ such that

\[
\omega_{a,b,c} = A\omega_1 + B\omega_2.
\]

Indeed, elementary manipulations using Exercise 2.108 ii) yield the values

\[
A = \sum_{\substack{0 \leq i \leq a \\ 0 \leq j \leq b \\ i+j\neq c}} \binom{a}{i} \binom{b}{j} (-1)^{a-i-j} (t^{b-c+i} - t^{b-j})
\]

and

\[
B = \sum_{\substack{0 \leq i \leq a \\ 0 \leq j \leq b \\ i+j\neq c}} \binom{a}{i} \binom{b}{j} (-1)^{a-i-j} t^{b-j}.
\]
Note that $B$ is an integer. In view of Example 2.166, it follows that
\[ \int_1^t \omega_{a,b,c} = A + B \log(t), \]
and choosing the parameters $a, b, c$ as functions of $n$ gives a sequence of linear forms in $1$ and $\log(t)$ as in Step i).

Let us specialize to the case $a = b = c = n$ and $t = 2$. Then
\[ I_n = \int_1^2 \omega_{n,n,n} = a_n + b_n \log(2), \]
where $b_n$ is an integer and $a_n$ is given by the formula
\[ a_n = \sum_{0 \leq i \leq n, 0 \leq j \leq n, i+j \neq n} \binom{n}{i} \binom{n}{j} (-1)^{n-i-j} (t^i - t^{n-j}) / (i+j-n). \]

Since the denominators of the summands in $a_n$ run through $[-n, n]$, one can take $r_n = \text{lcm}(1, 2, \ldots, n)$. We have:
\[ r_n = \prod_{p \leq n \text{ prime}} p^{|\log_n p - \log_2 n|} < \prod_{p \leq n \text{ prime}} p^{\log_n p} = n \pi(n), \]
where $\pi(n)$ is the number of primes smaller than or equal to $n$. Here is where some deep arithmetic input enters: the prime number theorem asserts that
\[ \lim_{n \to \infty} \frac{\pi(n)}{n/\log(n)} = 1, \]
see e.g. [IK04, Chap. 2]. It follows that, for all $\varepsilon > 0$ and $n$ big enough, the inequality $r_n \pi(n) < e^{(1+\varepsilon)n}$ holds. Being generous, $D = 3$ thus works in Step ii).

Next observe that, by the choice of the parameters, the integral $I_n$ can be written as
\[ I_n = \int_1^2 f^n \frac{dx}{x}, \quad f(x) = \frac{(x-1)(2-x)}{x}. \]
The function $f$ is strictly positive on the open interval $(1, 2)$ and bounded above by its maximal value $3 - 2\sqrt{2}$. Therefore,
\[ 0 < I_n < (3 - 2\sqrt{2})^n \log(2) < (3 - 2\sqrt{2})^n, \]
so $C = 3 - 2\sqrt{2}$ satisfies the assumptions. Luckily, $CD = 0.5147186\ldots < 1$ and, all in all, we have proved that $\log(2)$ is irrational!

\[ \star \star \star \]

Exercise 2.319. Specialize the spectral sequence (2.308) to the cases $I = \emptyset$ and $J = \emptyset$. Deduce the identifications (2.315).

Exercise 2.320. Let $L = L_0 \cup L_1 \cup L_2$ and $M = M_0 \cup M_1 \cup M_2$ be two triangles in $\mathbb{P}^2$ such that no three lines intersect at a common point. Use the spectral sequence (2.308) to show that
\[ \text{Gr}^W \mathbb{H}^2(\mathbb{P}^2 \setminus L, M \setminus (L \cap M)) = \mathbb{Q}(0) \oplus \mathbb{Q}(-1) \oplus \mathbb{Q}(-2). \]
The question of what happens when the lines are not in general position is studied in great detail in [BGSV90].
Exercise 2.321 (Irrationality of $\zeta(3)$). The goal of this exercise is to show that $\zeta(3)$ is irrational following the proof given by Beukers [Beu79] shortly after Apéry's announcement. We keep the notation $r_n = \text{lcm}(1, 2, \ldots, n)$.

i) Let $n, m \geq 0$ be integers and $\sigma \geq 0$ a real number. Prove the identity

$$\int_{[0,1]^2} \frac{x^{n+\sigma} y^{m+\sigma}}{1-xy} \, dx \, dy = \begin{cases} \frac{1}{n-m} \left( \frac{1}{m+1+\sigma} + \cdots + \frac{1}{n+m} \right), & \text{if } n > m, \\ \sum_{k=1}^{\infty} \frac{1}{(k+n+\sigma)^2} & \text{if } n = m. \end{cases}$$

ii) Let $n, m \geq 0$ be integers and consider the integral

$$I_{n,m} = \int_{[0,1]^2} -\log xy \, x^n y^m \, dx \, dy.$$ 

Show that, if $n > m$, then $I_{n,m}$ is a rational number whose denominator divides $r_n^3$, and that

$$I_{n,n} = \begin{cases} 2\zeta(3), & \text{if } n = 0, \\ 2 \left( \zeta(3) - 1 - 2^{-3} - \cdots - n^{-3} \right), & \text{if } n > 0. \end{cases}$$

[Hint: differentiate the formulas of part i) with respect to $\sigma$.]

iii) For each integer $n \geq 1$, let $P_n \in \mathbb{Z}[x]$ be the polynomial defined by

$$n! P_n(x) = \frac{d^n}{dx^n} (x^n(1-x)^n)$$

and consider the integral

$$I_n = \int_{[0,1]^3} -\log xy \, P_n(x) P_n(y) \, dx \, dy.$$ 

Prove that there exist rational numbers $a_n, b_n \in \mathbb{Q}$ whose denominators divide $r_n^3$ such that

$$I_n = a_n + b_n \zeta(3).$$

iv) Prove that the above integral can be rewritten as

$$I_n = \int_{[0,1]^3} \frac{x^n(1-x)^n y^n(1-y)^n z^n(1-z)^n}{(1-(1-xy)z)^{n+1}} \, dx \, dy \, dz.$$ 

[Hint: use the integral representation

$$-\log xy \frac{1}{1-xy} = \int_0^1 \frac{dw}{1-(1-xy)w}$$

and the change of variables $z = (1-w)(1-(1-xy)w)^{-1}$.]

v) Show that, for all $0 \leq x, y, z \leq 1$, one has

$$\frac{x(1-x)y(1-y)z(1-z)}{(1-(1-xy)z)^4} \leq (\sqrt{2} - 1)^4$$

and deduce that $0 < |I_n| < 2\zeta(3)(\sqrt{2} - 1)^{4n}$. [Hint: first prove that the maximum occurs for $x = y$.]

vi) Conclude that $\zeta(3)$ is irrational.
3. Multiple zeta values and the fundamental group of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$

In this chapter, we start moving towards the goal of upgrading multiple zeta values to their motivic counterparts, which are functions on an algebro-geometric construction associated with the fundamental group of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$. To this end, we first look for homotopy functionals on the space of paths on a differentiable manifold $M$. By Stokes’ theorem, line integrals of closed 1-forms are examples of such functionals; however, the corresponding functions on the fundamental group $\pi_1(M)$ always factor through its abelianization and cannot detect loops with trivial homology classes. Trying to go further, K-T. Chen had the fundamental insight that iterated integrals yield finer invariants, which are in fact sufficient to recover all finite-dimensional unipotent representations of $\pi_1(M)$ and not only the abelian ones. In Section 3.1, we present the definition and algebraic properties of iterated integrals, and tackle the question of when they define homotopy functionals. Chen’s results are most conveniently phrased in terms of Hopf algebras and algebraic groups, notions that we review in Section 3.2. Then, in Section 3.4, we explain how to associate with any abstract group its pro-unipotent completion, an algebraic group whose finite-dimensional representations are the unipotent ones of the initial group. Chen’s celebrated $\pi_1$-de Rham theorem asserts that the Hopf algebra of regular functions on the pro-unipotent completion of the fundamental group $\pi_1(M)$ is isomorphic to the cohomology in degree zero of the bar complex of any connected model of the algebra of differential forms on $M$. After introducing the bar complex of a dg-algebra, we state this theorem in Section 3.5. As an example, we observe that the bar complex of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$ is the Hoffman algebra $\mathcal{H}$ which we already encountered in the combinatorial study of multiple zeta values. The proof of Chen’s theorem presented in Section 3.6 relies on a result of Beilinson identifying the algebra of functions on the pro-unipotent completion with a limit of certain relative cohomology groups. As we explain in Section 3.7, Chen’s theorem has a number of important consequences, notably the fact due to Hain that the pro-unipotent completion of the fundamental group of a complex algebraic variety carries a mixed Hodge structure; thanks to Beilinson’s theorem, we will even be able to show that the resulting mixed Hodge structure is motivic. In the remaining of the chapter, we focus on the case of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$. The integral representation of polylogarithms and multiple zeta values suggests that these numbers are iterated integrals on $\mathbb{P}^1 \setminus \{0, 1, \infty\}$, and hence periods of the corresponding mixed Hodge structure on the pro-unipotent completion of the fundamental group, except for the fact that the endpoints of the integration path do not lie on the ambient space. To remedy this, we resort to the notion of tangential base points in Section 3.8. Armed with this tool, in Section 3.9 we make the comparison isomorphism in Chen’s theorem explicit for $\mathbb{P}^1 \setminus \{0, 1, \infty\}$ using polylogarithms and the Drinfeld associator. In the final Section 3.10, we introduce the tangential fundamental groupoid of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$ and study its automorphisms. As an outcome, we obtain a new structure on the Hoffman algebra $\mathcal{H}$ called Goncharov’s coproduct that will play a pivotal role in the proof of Brown’s theorem.

3.1. Iterated integrals and parallel transport. Our presentation follows closely the first sections of Hain’s survey [Hai87b]. Other nice references are Cartier’s Bourbaki seminar [Car88] and Brown’s notes [Bro13].
3.1.1. The fundamental groupoid. Let $M$ be a connected differentiable manifold. A continuous function $\gamma: [0,1] \to M$ is said to be piecewise smooth if there exists a partition $0 = a_0 < a_1 < \ldots < a_{n+1} = 1$ of the unit interval such that the restriction of $\gamma$ to each $[a_i, a_{i+1}]$ is smooth, meaning that it can be extended to a smooth function on an open neighborhood of $[a_i, a_{i+1}]$. Similarly, a continuous map $F: [0,1]^2 \to M$ is said to be piecewise smooth if there exists a finite decomposition $[0,1]^2 = \bigcup_i C_i$ into polyhedra $C_i$ such that all the restrictions $F|_{C_i}$ are smooth, in the sense that they extend to a smooth function on an open neighborhood of $C_i$.

From now on, we will call a continuous piecewise smooth map from $[0,1]$ to $M$ simply a path (see Remark 3.8 below), and denote the space of paths by $P(M) = \{\gamma: [0,1] \to M \mid \gamma$ continuous and piecewise smooth$\}$. Given points $x$ and $y$ in $M$, the subspace of $P(M)$ consisting of paths from $x$ to $y$ will be denoted by $yP(M)_x = \{\gamma \in P(M) \mid \gamma(0) = x, \gamma(1) = y\}$. When the endpoints of $\gamma$ agree, we will often call it a loop.

**Definition 3.1.** Let $\gamma_1, \gamma_2 \in yP(M)_x$ be paths from $x$ to $y$. We say that $\gamma_1$ and $\gamma_2$ are homotopic if there exists a continuous piecewise smooth function

$$F: [0,1]^2 \to M$$

$$(t, s) \mapsto F(t, s)$$

satisfying the following conditions:

$$F(t, 0) = \gamma_1(t), \quad F(t, 1) = \gamma_2(t), \quad \text{for all } t \in [0,1],$$
$$F(0, s) = x, \quad F(1, s) = y, \quad \text{for all } s \in [0,1].$$

In other words, $F$ is a continuous family of paths

$$f_s: [0,1] \to M$$
$$t \mapsto f_s(t) = F(t, s)$$

parameterized by $s \in [0,1]$ that interpolates between $\gamma_1$ and $\gamma_2$, while keeping the endpoints fixed (see Figure 13).

![Figure 13. A homotopy between two paths](image-url)
It is straightforward to check that “being homotopic” defines an equivalence relation \( \sim \) on \( _yP(M)_x \). We write

\[
\pi_1(M; y, x) = _yP(M)_x/\sim
\]

for the set of equivalence classes. When the endpoints agree, we will abbreviate this notation to \( \pi_1(M, x) \).

Note that there is a \textit{reversal of paths} operation

\[
yP(M)_x \longrightarrow zP(M)_y \\
\gamma \longmapsto \gamma^{-1}
\]

defined as \( \gamma^{-1}(t) = \gamma(1-t) \). Moreover, given a point \( z \) in \( M \), there is a \textit{composition of paths} operation

\[
zP(M)_y \times yP(M)_x \longrightarrow zP(M)_x, \\
(\gamma_1, \gamma_2) \longmapsto \gamma_1 \gamma_2
\]
given by first going along \( \gamma_2 \) and then along \( \gamma_1 \). Explicitly, \( \gamma_1 \gamma_2 \) is defined as

\[
\gamma_1 \gamma_2(t) = \begin{cases} 
\gamma_2(2t), & \text{if } 0 \leq t \leq \frac{1}{2}, \\
\gamma_1(2t-1), & \text{if } \frac{1}{2} \leq t \leq 1.
\end{cases}
\]

Both the reversal and the composition of paths are compatible with the homotopy equivalence relation, and hence induce operations

\[
\pi_1(M; y, x) \longrightarrow \pi_1(M; x, y) \quad \text{(3.4)} \\
\pi_1(M; z, y) \times \pi_1(M; y, x) \longrightarrow \pi_1(M; z, x) \quad \text{(3.5)}
\]
on the set of equivalence classes, which will be called “inverse” and “composition” respectively. It is a simple matter to check that the composition is associative and that the class of the constant path \( \gamma(t) = x \) for all \( t \in [0,1] \) in \( \pi_1(M, x) \) is a neutral element. As such, it will be usually denoted by 1. If the endpoints are fixed and agree, the above operations endow \( \pi_1(M, x) \) with the structure of a group: the \textit{fundamental group} of \( M \). In general, when we allow the endpoints to vary and be distinct, we obtain a groupoid. The definition of such a structure is in fact tailored to study this example.

\textbf{Definition 3.6.} A \textit{groupoid} \( G \) is the data of a set \( G_0 \) of “objects” and a set \( G_1 \) of “arrows”, together with the following five operations:

- a \textit{source} map \( s: G_1 \rightarrow G_0 \);
- a \textit{target} map \( t: G_1 \rightarrow G_0 \);
- a \textit{unit} map \( u: G_0 \rightarrow G_1 \) satisfying \( s(u(x)) = t(u(x)) = x \) for all \( x \in G_0 \);
- a \textit{composition} map \( m: G_1 \times G_1 \rightarrow G_1 \) defined on the set

\[
G_1 \times G_1 = \{(f, g) \in G_1 \times G_1 \mid s(f) = t(g)\}
\]
such that the equalities \( s(m(f, g)) = s(g) \) and \( t(m(f, g)) = t(f) \) hold for all arrows \( f, g \in G_1 \), and that \( u \) is a two-sided unit for \( m \). Moreover, the composition is required to be associative;

- an \textit{inverse} map \( i: G_1 \rightarrow G_1 \) satisfying \( s(i(f)) = t(f) \) and \( t(i(f)) = s(f) \) for all arrows \( f \in G_1 \), and which is a two-sided inverse for the composition.

Equivalently, a groupoid can be viewed as a small category in which all morphisms are isomorphisms (Exercise 3.38).
Example 3.7 (The fundamental groupoid). The **fundamental groupoid** of \( M \) is the groupoid where \( G_0 \) is the set of points of \( M \) and \( G_1 \) is the set of homotopy classes of paths in \( M \), that is:

\[
G_1 = \coprod_{x,y \in M} \pi_1(M; y, x).
\]

The source, the target, and the unit are defined in the obvious way, and the inverse and the composition maps are given by (3.4) and (3.5) respectively.

Remark 3.8. When doing homotopy theory on a differentiable manifold, one can choose to work with continuous, piecewise smooth, or smooth paths. By Whitney’s approximation theorem (see e.g. [Lee13, Thm. 6.19]), each homotopy class of continuous paths admits a smooth representative; the resulting fundamental group or groupoid is hence the same in all three cases. To make the link with differential forms, it is convenient to work with piecewise smooth or smooth paths. However, since the composition of smooth paths as defined in (3.3) is in general only piecewise smooth, we work with piecewise smooth paths from the beginning to avoid replacing \( \gamma_1 \gamma_2 \) with a homotopic smooth path.

3.1.2. Homotopy functionals. We would like to construct functions on the fundamental groupoid of a manifold.

**Definition 3.9.** A function on \( \mathcal{P}(M) \) is called a **homotopy functional** if the image of every element of \( \mathcal{P}(M) \) depends only on its homotopy class, and hence induces a function on \( \pi_1(M; y, x) \) for all \( x, y \in M \).

The simplest method to construct homotopy functionals is by means of differential forms, as we now recall. Let \( k \) be either the field of real numbers or the field of complex numbers. We consider the \( k \)-algebra

\[
E^\ast(M, k) = \bigoplus_{p=0}^{\dim M} E^p(M, k)
\]

of smooth \( k \)-valued differential forms on \( M \). Let \( \omega \in E^1(M, k) \) be a differential form and \( \gamma \in \mathcal{P}(M) \) a path. Since \( \gamma \) is assumed to be piecewise smooth, we can pullback \( \omega \) to the interval \([0,1]\); the pullback takes the form \( \gamma^*\omega = f(t)dt \) for some bounded function \( f \) that may be discontinuous at the points at which \( \gamma \) is not smooth. The **line integral** of \( \omega \) along \( \gamma \) is then defined as

\[
(3.10) \quad \int_\gamma \omega = \int_0^1 \gamma^*\omega = \int_0^1 f(t)dt.
\]

Since the integral converges by the assumption on \( \gamma \), this yields a function

\[
\int \omega : \mathcal{P}(M) \to k \quad \gamma \mapsto \int_\gamma \omega.
\]

**Lemma 3.11.** The function \( \int \omega \) is a homotopy functional if and only if \( \omega \) is a closed 1-form.

**Proof.** The result follows from Stokes’ theorem. We first assume that \( \omega \) is closed, and that we are given paths \( \gamma_1 \) and \( \gamma_2 \) and a homotopy \( F \) between them.
Using the conditions \((3.2)\) in the definition of \(F\), we find
\[
\int_{\gamma_1} \omega - \int_{\gamma_2} \omega = \int_{[0,1]} \gamma_1^* \omega - \int_{[0,1]} \gamma_2^* \omega = \int_{\partial[0,1]^2} F^* \omega,
\]
where \(\partial[0,1]^2\) stands for the boundary of the square \([0,1]^2\). Since \(F\) is piecewise smooth, there exists a finite decomposition \([0,1]^2 = \bigcup_i C_i\) into polyhedra \(C_i\) such that \(F|_{C_i}\) is smooth. By Stokes’ theorem and the fact that taking pullback by \(F\) commutes with the differential, we get
\[
\int_{\partial[0,1]^2} F^* \omega = \sum_i \int_{\partial C_i} F^* \omega = \sum_i \int_{C_i} F^*(d\omega) = 0,
\]
which proves that the line integral is a homotopy functional.

Conversely, assume that the 1-form \(\omega\) is not closed, i.e. \(d\omega \neq 0\). We can then find a smooth map \(f: D \to M\) from the unit disc
\[
D = \{(x, y) \in \mathbb{R}^2 \mid x^2 + y^2 \leq 1\}
\]
to the manifold \(M\) satisfying
\[
\int_D f^*(d\omega) \neq 0.
\]
On the one hand, the paths from \(x = f(1,0)\) to \(y = f(-1,0)\) given by
\[
\gamma_1(t) = f(\cos(\pi t), \sin(\pi t)) \quad \text{and} \quad \gamma_2(t) = f(\cos(\pi t), -\sin(\pi t))
\]
are homotopic through the homotopy
\[
F(x, y) = f(\cos(\pi x), (1 - 2y) \sin(\pi x)).
\]
On the other hand, another application of Stokes’s theorem gives
\[
\int_{\gamma_1} \omega - \int_{\gamma_2} \omega = \int_{\partial D} f^* \omega = \int_D f^*(d\omega) \neq 0,
\]
which proves that \(\omega\) being closed is a necessary condition as well.

\[\square\]

Line integrals of closed 1-forms produce, however, only a very special kind of homotopy functionals. Indeed, from \((3.10)\) we get the relations
\[
\int_{\gamma_1 \gamma_2} \omega = \int_{\gamma_2} \omega + \int_{\gamma_1} \omega \quad \text{and} \quad \int_{\gamma^{-1}} \omega = -\int_\gamma \omega,
\]
which together imply that the equality
\[
(3.12) \quad \int_{\gamma_1^{-1} \gamma_2^{-1} \gamma_1 \gamma_2} \omega = 0
\]
holds for all loops \(\gamma_1, \gamma_2 \in \pi_1(M,x)\). From this, it follows that line integrals of closed 1-forms factor through the abelianization of the fundamental group.

**Definition 3.13.** The abelianization of a group \(G\) is the quotient
\[
G^{\text{ab}} = G/[G,G]
\]
of \(G\) by the normal subgroup \([G,G]\) generated by the commutators
\[
[g,h] = g^{-1} h^{-1} gh \quad (g, h \in G).
\]
The abelianization $G^{ab}$ of $G$ is an abelian group satisfying the universal property that any homomorphism from $G$ to an abelian group factors through $G^{ab}$. In particular, for every closed 1-form $\omega$ the homomorphism

$$\int \omega : \pi_1(M, x) \rightarrow k$$

factors through $\pi_1(M, x)^{ab}$. Now, viewing a loop $\gamma : [0, 1] \rightarrow M$ as a closed singular 1-chain, as defined in Section 2.1, yields a canonical homomorphism $Z_{\omega} : \pi_1(M, x) \rightarrow H_1(M, \mathbb{Z})$, which is often called the Hurewicz map. The following is a basic result from algebraic topology, see for instance [Hat02, Thm. 2A.1] for a proof.

**Theorem 3.14.** The kernel of the homomorphism $h$ consists exactly of the commutator subgroup $[\pi_1(M, x), \pi_1(M, x)]$ of $\pi_1(M, x)$. Moreover, if $M$ is connected, then $h$ is surjective and thus induces an isomorphism $\pi_1(M, x)^{ab} \cong H_1(M, \mathbb{Z})$.

Summarizing, line integrals of closed 1-forms always factors through the first homology group of the manifold. Since the fundamental group is a finer invariant, we would like to construct other homotopy functionals that are able to detect the extra information carried by $\pi_1(M, x)$.

**3.1.3. Iterated integrals.** The theory of iterated integrals started with the fundamental observation by K.T. Chen [Che77] that homotopy functionals obtained by successive integration of 1-forms can detect elements of $\pi_1(M, x)$ with trivial homology classes in $H_1(M, \mathbb{Z})$.

**Definition 3.15.** Let $\omega_1, \ldots, \omega_r$ be smooth $k$-valued 1-forms on $M$. The iterated integral of $\omega_1, \ldots, \omega_r$ is the function

$$\int_{\gamma} \omega_1 \cdots \omega_r : \mathcal{P}(M) \rightarrow k$$

\(\gamma \mapsto \int_{\gamma} \omega_1 \cdots \omega_r\)

defined by the formula

$$\int_{\gamma} \omega_1 \cdots \omega_r = \int_{1 \geq t_1 \geq \cdots \geq t_r \geq 0} f_1(t_1) \cdots f_r(t_r)dt_1 \cdots dt_r,$$

where $\gamma^* \omega_i = f_i(t)dt$ is the pullback of $\omega_i$ to $[0, 1]$ along the path $\gamma$.

More generally, we will call iterated integral every function on $\mathcal{P}(M)$ that can be written as a $k$-linear combination of (3.16) and the constant function 1, which we view as an iterated integral of length 0. We say that an iterated integral has length $\leq s$ if each summand is of the form $\int \omega_1 \cdots \omega_r$ with $r \leq s$.

**Remark 3.17.** Here is an explanation of the term “iterated integral” taken from [Del13, p. 163]. Let $S$ be the operator that transforms a 1-form $\eta$ on the interval $[0, 1]$ into the function $S[\eta](t) = \int_0^t \eta$. To obtain the iterated integral we apply $S$ to $\gamma^* \omega_r$, then multiply the resulting function by $\gamma^* \omega_{r-1}$, apply $S$ again, multiply by $\gamma^* \omega_{r-2}$, etc., and finally evaluate at $t = 1$. That is,

$$\int_{\gamma} \omega_1 \cdots \omega_r = S[\gamma^* \omega_1 \cdot S[\gamma^* \omega_2 \cdots S[\gamma^* \omega_r] \cdots]](1).$$
Observe that the integral representations of multiple zeta values and polylogarithms from Theorems 1.115 and 1.124 look very similar to iterated integrals but do not quite fit into the framework of Definition 3.15 because the differential forms $dx/x$ and $dx/(1-x)$ are singular at the endpoints of the integration path. We will come back to this question in Section 3.8.

3.1.4. Basic properties of iterated integrals. The first important property is that iterated integrals are functorial and independent of the parametrization of the path. The proof is left to the reader (see Exercise 3.40).

**Proposition 3.18 (Functoriality).** Let $f : N \to M$ be a smooth map of differentiable manifolds. For all $\gamma \in \mathcal{P}(N)$ and $\omega_1, \ldots, \omega_r \in \Omega^1(M, k)$, the equality
\[
\int_\gamma f^* \omega_1 \cdots f^* \omega_r = \int_{f \circ \gamma} \omega_1 \cdots \omega_r
\]
holds. In particular, the iterated integral $\int_\gamma \omega_1 \cdots \omega_r$ does not depend on the choice of parametrization of the path $\gamma$.

We now turn to the basic algebraic properties of iterated integrals, which are formulas for the reversal and composition of paths, as well as for the product of iterated integrals.

**Theorem 3.19.** Let $\omega_1, \ldots, \omega_{r+s}$ be smooth $k$-valued 1-forms on $M$ and $\gamma, \gamma_1, \gamma_2$ be piecewise smooth paths on $M$ satisfying $\gamma_2(1) = \gamma_1(0)$. Then the following three equalities hold:
\[
(3.20) \quad \int_\gamma \omega_1 \cdots \omega_r = (-1)^r \int_{\gamma^{-1}} \omega_r \cdots \omega_1,
\]
\[
(3.21) \quad \int_{\gamma_1 \gamma_2} \omega_1 \cdots \omega_r = \sum_{i=0}^r \int_{\gamma_1} \omega_1 \cdots \omega_i \int_{\gamma_2} \omega_{i+1} \cdots \omega_r,
\]
\[
(3.22) \quad \int_\gamma \omega_1 \cdots \omega_r \int_{\gamma_r+1} \cdots \omega_{r+s} = \sum_{\sigma \in \Sigma(r,s)} \int_\gamma \omega_{\sigma^{-1}(1)} \cdots \omega_{\sigma^{-1}(r+s)}.
\]
In the last identity, the sum runs over the subset $\Omega(r,s) \subset \mathcal{S}_{r+s}$ of the symmetric group on $r+s$ elements consisting of shuffles of type $(r,s)$, as in Definition 1.127.

**Proof.** The identity (3.20) follows from a simple computation, using the fact that the equality $\gamma^* \omega_i = f_i(t)dt$ implies $(\gamma^{-1})^* \omega_i = -f_i(1-t)dt$, and hence
\[
\int_{\gamma^{-1}} \omega_r \cdots \omega_1 = (-1)^r \int_{1 \geq t_1 \geq \cdots \geq t_r \geq 0} f_r(1-t_1) \cdots f_1(1-t_r)dt_1 \cdots dt_r
\]
\[
= (-1)^r \int_{u_r \geq \cdots \geq u_1 \geq 0} f_r(u_r) \cdots f_1(u_1) du_1 \cdots du_r
\]
\[
= (-1)^r \int_{\gamma} \omega_1 \cdots \omega_r.
\]
To get the second equality above we made the change of variables $u_i = 1-t_{r-i+1}$, whose Jacobian has absolute value 1.

We next prove formula (3.21). Writing
\[
(\gamma_1 \gamma_2)^* \omega_i = f_i(t)dt, \quad \gamma_1^* \omega_i = g_i(t)dt, \quad \gamma_2^* \omega_i = h_i(t)dt,
\]
the functions $f_i, g_i, h_i$ are related by

\[(3.23) \quad f_i(t) = \begin{cases} 2h_i(2t), & \text{if } 0 \leq t \leq \frac{1}{2}, \\ 2g_i(2t - 1), & \text{if } \frac{1}{2} \leq t \leq 1, \end{cases}\]

thanks to the composition rule (3.3). We decompose the domain of integration as a union $\Delta^r = \bigcup_{i=0}^r C_i$, where

\[C_i = \{(t_1, \ldots, t_r) \in \mathbb{R}^r \mid 1 \geq t_1 \geq \cdots \geq t_i \geq \frac{1}{2} \geq t_{i+1} \geq \cdots \geq t_r \geq 0\}.

Observe that projecting to the first $i$ and the last $r-i$ coordinates yields an isomorphism $C_i \simeq \Delta^i \times \Delta^{r-i}$. Figure 14 illustrates the case $r = 2$.

![Figure 14. The decomposition $\Delta^2 = C_0 \cup C_1 \cup C_2$](image)

Formula (3.21) now follows from the computation

\[
\int_{C_i} f_1(t_1) \cdots f_r(t_r) dt_1 \cdots dt_r = \int_{1 \geq t_1 \geq \cdots \geq t_r \geq \frac{1}{2} \geq \cdots \geq t_r \geq 0} f_1(t_1) \cdots f_r(t_r) dt_1 \cdots dt_r
\]

\[
= \frac{2^r}{2^r} \int_{1 \geq u_1 \geq \cdots \geq u_i \geq 0 \geq \cdots \geq u_r \geq 0} g_1(u_1) \cdots g_i(u_i) h_{i+1}(u_{i+1}) \cdots h_r(u_r) du_1 \cdots du_r
\]

\[
= \int_{\gamma_1} \omega_1 \cdots \omega_i \int_{\gamma_{i+1}} \omega_{i+1} \cdots \omega_r,
\]

together with the fact that the overlaps of the $C_i$ do not contribute to the integral because they all have codimension at least 1, and hence their Lebesgue measure is zero. The second equality is obtained by the change of variables

\[u_j = \begin{cases} 2t_j - 1, & \text{if } j \leq i, \\ 2t_j, & \text{if } j > i. \end{cases}\]

The $2^r$ in the numerator comes from the identity (3.23), whereas the $2^r$ in the denominator is the Jacobian of the change of variables.

Finally, formula (3.22) is a consequence of the decomposition

\[\Delta^r \times \Delta^s = \bigcup_{\sigma \in \Omega(r,s)} \{(t_1, \ldots, t_{r+s}) \mid 1 \geq t_{\sigma^{-1}(1)} \geq \cdots \geq t_{\sigma^{-1}(r+s)} \geq 0\},\]

which was already used in the proof of Proposition 1.130. \qed
3.1.5. When are iterated integrals homotopy functionals? We have seen that iterated integrals do not depend on the parametrization of the path (Proposition 3.18). However, even when all the forms $\omega_i$ are closed, they do not always give rise to homotopy functionals, as this example borrowed from [Bro13] shows:

**Example 3.24.** Take $M = \mathbb{R}^2$ with the standard coordinates $x$ and $y$. Let $a, b > 0$ be real numbers and consider the path $\gamma_{a,b} : [0, 1] \to \mathbb{R}^2$ from $(0, 0)$ to $(1, 1)$ given by $\gamma_{a,b}(t) = (t^a, t^b)$. Let $\omega_1 = dx$ and $\omega_2 = dy$. Taking the equalities $\gamma^*_{a,b} \omega_1 = at^{a-1} dt$, $\gamma^*_{a,b} \omega_2 = bt^{b-1} dt$ into account, the iterated integral of $\omega_1 \omega_2$ along $\gamma_{a,b}$ is equal to

$$\int_{\gamma_{a,b}} \omega_1 \omega_2 = \int_0^1 (at_1^{a-1} \int_0^{t_1} bt_2^{b-1} dt_2) dt_1 = \frac{a}{a+b},$$

which obviously depends on the choice of $a$ and $b$. However, all the paths $\gamma_{a,b}$ are homotopic to each other! This example will be revisited in Exercise 3.41.

A natural question is thus: when is an iterated integral invariant under homotopy? Theorem 3.261 gives a full answer to this question in terms of an algebraic construction called the *bar complex*. For the moment, we content ourselves with a partial answer by linking iterated integrals to connections on trivial bundles through the notion of parallel transport.

3.1.6. Iterated integrals and connections on trivial bundles. We continue writing $k$ for either the real or the complex numbers. Let $V = k^n \times M$ be the trivial vector bundle of rank $n$ over $M$. Since $V$ is trivial, we can identify the space of sections of $V$ with the space of functions $x : M \to k^n$. We let $C^\infty(V)$ denote the space of all smooth sections of $V$.

**Definition 3.25.** A connection on $V$ is a $k$-linear map $\nabla : C^\infty(V) \to C^\infty(V) \otimes_{C^\infty(M)} E^1(M, k)$ that satisfies Leibniz’s rule

$$\nabla(fx) = x \otimes df + f \nabla x$$

for each smooth function $f \in C^\infty(M)$ and each smooth section $x \in C^\infty(V)$.

A connection $\nabla$ on $V$ canonically extends to a $k$-linear map on the space of $C^\infty(V)$-valued $p$-forms on $M$ as follows:

$$C^\infty(V) \otimes_{C^\infty(M)} E^p(M, k) \to C^\infty(V) \otimes_{C^\infty(M)} E^{p+1}(M, k).$$

$x \otimes \eta \mapsto x \otimes d\eta + \nabla(x) \wedge \eta$

We will still denote by $\nabla$ this extension.

**Definition 3.26.** The operator $\nabla^2 = \nabla \circ \nabla$ is called the curvature of the connection and $\nabla$ is said to be flat (or integrable) if $\nabla^2$ vanishes.

We call *global canonical frame* of $V$ the tuple $e = (e_1, \ldots, e_n)$ consisting of the constant functions $e_i : M \to k^n$ with value the $i$-th standard basis vector
(0, \ldots, 1, \ldots, 0) of \k^n. By virtue of Leibniz’s rule, the connection \nabla is uniquely determined by the image of the global canonical frame. Indeed, write
\[ \nabla e_j = \sum_{i=1}^{n} e_i \otimes \eta_{ij} \quad (j = 1, \ldots, n) \]
with \( \eta_{ij} \in \mathcal{E}^1(M, k) \). The matrix
\[ \omega = (\eta_{ij}) \in \mathcal{E}^1(M, k) \otimes_{C^\infty(M)} \text{End}(V) = \mathcal{E}^1(M, k) \otimes_k \text{End}(\k^n), \]
whose entries are smooth \( k \)-valued 1-forms on \( M \), is called the matrix of the connection in the global canonical frame \( e \). Seeing a section \( x: M \to \k^n \) as a column vector of smooth functions and invoking Leibniz’s rule again, \( \nabla \) is given by
\[ \nabla x = dx + \omega x. \]
Sometimes we will simply write \( \nabla = d + \omega \). From this, one easily finds the curvature
\[ \nabla^2 x = \nabla(dx + \omega x) = d^2 x + d(\omega x) + \omega dx + \omega \wedge \omega x = (dx + \omega \wedge \omega)x, \]
where \( \omega \wedge \omega \) stands for the product of matrices of 1-forms induced by the usual wedge product. In explicit terms, writing \( \omega = \sum M_i \eta_i \) for some \( \eta_i \in \mathcal{E}^1(M, k) \) and some \( M_i \in \text{GL}_n(k) \), this product is equal to
\[ \omega \wedge \omega = \frac{1}{2} \sum_{i,j} [M_i, M_j] \eta_i \wedge \eta_j, \]
where we have used that wedge products anti-commute. The matrix
\[ R = d\omega + \omega \wedge \omega \]
is called the curvature matrix of the connection \( \nabla \).

Besides, associated with the trivial rank \( n \) vector bundle \( V \) is the bundle
\[ \text{GL}(V) \simeq \text{GL}_n(k) \times M \]
with fibers \( \text{GL}_n(k) \). The action of the connection \( \nabla \) column by column gives then rise to a differential operator
\[ \nabla X = dx + \omega X \]
on the space of smooth functions \( X: M \to \text{GL}_n(k) \).

3.1.7. Parallel transport. Given a smooth path \( \gamma: [0, 1] \to M \) and a section
\[ X: [0, 1] \to \text{GL}_n(k) \times M \quad t \mapsto (X(t), \gamma(t)) \]
of \( \text{GL}(V) \) along \( \gamma \), we say that \( X \) is horizontal if the vanishing
\[ \nabla X(t) = 0 \tag{3.27} \]
holds. This amounts to the equality \( dX(t) = -\gamma^*(\omega)X(t) \). Writing \( \gamma^*(\omega) = A(t)dt \), then (3.27) becomes the linear differential equation
\[ X'(t) + A(t)X(t) = 0. \]
The parallel transport function
\[ T: \mathcal{P}(M) \to \text{GL}_n(k) \]
associated with the connection $\nabla$ is defined as follows. We first restrict ourselves to smooth paths $\gamma: [0,1] \to M$ and set
$$T(\gamma) = X(1),$$
where $X: [0,1] \to \text{GL}_n(k)$ is the unique section along the path $\gamma: [0,1] \to M$ that is horizontal with respect to $\nabla$ and has initial value $X(0) = \text{Id}_n$, the identity matrix of size $n$. From the theorems of existence and uniqueness of solutions to linear ordinary differential equations, one also gets (see [KN96, Chap. II, §3]):

**Proposition 3.28.** Let $\gamma$ and $\gamma'$ be smooth paths in $M$ with $\gamma'(1) = \gamma(0)$. Then the following holds:

i) The value $T(\gamma)$ is independent of the parametrization of $\gamma$.

ii) If $\gamma'\gamma$ is smooth, then the equality $T(\gamma'\gamma) = T(\gamma)T(\gamma')$ holds.

Using Proposition 3.28, we can extend the definition of parallel transport to piecewise smooth paths by reparameterizing them as a finite composition of smooth paths. The equality $T(\gamma'\gamma) = T(\gamma)T(\gamma')$ remains true for piecewise smooth paths.

We now have all ingredients to state the main result relating connections and homotopy functionals. Recall that the connection $\nabla = d + \omega$ is flat if the curvature matrix
$$R = d\omega + \omega \wedge \omega$$
is zero.

**Theorem 3.29.** The connection $\nabla$ is flat if and only if each of the entries of the parallel transport function is a homotopy functional.

**Proof.** Fix a point $x \in M$. The restricted holonomy group of $\nabla$ is the subgroup $\text{Hol}_0^x(\nabla) \subset \text{GL}_n(k)$ consisting of the automorphisms $T(\gamma)$ for all contractible loops $\gamma$ based at $x$. It is a connected Lie group, which is reduced to the identity matrix if and only if each of the entries of the parallel transport function is a homotopy functional. According to the Ambrose–Singer theorem [KN96, Thm. 8.1], the Lie algebra of $\text{Hol}_0^x(\nabla)$ is the $k$-vector space generated by the matrices
$$T(\gamma)^{-1}R(\partial_1, \partial_2)T(\gamma),$$
where $\gamma$ is any path from $x$ to a point $y$, $\partial_1$ and $\partial_2$ are tangent vectors at $y$, and $R(\partial_1, \partial_2)$ is the result of applying the vectors $\partial_1$ and $\partial_2$ to the entries of the matrix of 2-forms $R$. Therefore, $\text{Hol}_0^x(\nabla)$ is trivial if and only if $\nabla$ is flat. $lacksquare$

3.1.8. **Parallel transport and iterated integrals.** Using iterated integrals, one can give the following explicit formula for the parallel transport function:

**Proposition 3.30.** Let $\nabla = d + \omega$ be a connection on the trivial bundle $k^n \times M \to M$. Then the parallel transport function of $\nabla$ is given by
$$T(\gamma) = \text{Id}_n - \int_{\gamma} \omega + \int_{\gamma} \omega \omega - \int_{\gamma} \omega \omega \omega + \ldots,$$
where the products in the integrands are formal products of matrices of 1-forms and the iterated integrals are computed componentwise.

**Proof.** Setting $\gamma^*\omega = A(t)dt$, the iterated integrals of formal products of matrices of 1-forms are given by
$$\int_{\gamma} \omega \omega \omega \ldots = \int_{t_1 \geq 0 \ldots t_r \geq 0} A(t_1)A(t_2) \ldots A(t_r)dt_1 \ldots dt_r.$$

(3.31)
Moreover, the parallel transport function is \( T(\gamma) = X(1) \), where \( X(t) \) is the unique solution of the differential equation

\[
X'(t) + A(t)X(t) = 0
\]

with initial condition \( X(0) = \text{Id}_n \). Observe that the function \( X(t) \) satisfies (3.32) and \( X(0) = \text{Id}_n \) if and only if the following integral equation holds

\[
X(t) = \text{Id}_n - \int_0^t A(s)X(s)ds.
\]

We will solve (3.33) by applying the method of Picard-Lindelöf. For this, we define recursively a sequence of approximations to the solution:

\[
X_0(t) = \text{Id}_n,
\]

\[
X_r(t) = \text{Id}_n - \int_0^t A(s)X_{r-1}(s)ds \quad (r \geq 1).
\]

We need to show that the sequence \( \{X_r(t)\} \) converges. In order to do so, we first prove by induction that the equality

\[
X_r(t) - X_{r-1}(t) = (-1)^r \int_{t \geq s_1 \geq \cdots \geq s_r \geq 0} A(s_1) \cdots A(s_r)ds_1 \cdots ds_r
\]

holds for all \( r \geq 1 \). Indeed, by definition

\[
X_1(t) - X_0(t) = - \int_0^t A(s)ds,
\]

which settles the case \( r = 1 \). Assume then that (3.34) holds for all indices smaller than \( r \). By the induction hypothesis, the equalities

\[
X_r(t) - X_{r-1}(t) = - \int_0^t A(s)(X_{r-1}(s) - X_{r-2}(s))ds
\]

\[
= - \int_0^t A(s)(-1)^{r-1} \int_{s \geq s_2 \geq \cdots \geq s_r \geq 0} A(s_2) \cdots A(s_r)ds_2 \cdots ds_r ds
\]

\[
= (-1)^r \int_{t \geq s_1 \geq \cdots \geq s_r \geq 0} A(s_1) \cdots A(s_r)ds_1 \cdots ds_r
\]

hold. Using that the volume of the simplex \( \Delta^r \) is \( 1/r! \), we deduce that there exists a constant \( K > 0 \) satisfying

\[
\int_{t \geq s_1 \geq \cdots \geq s_r \geq 0} A(s_1) \cdots A(s_r)ds_1 \cdots ds_r = O\left(\frac{K^r}{r!}\right).
\]

This estimate proves that \( \{X_r(t)\} \) is a Cauchy sequence and that its limit is given by the convergent series

\[
X_\infty(t) = \sum_{r \geq 0} (-1)^r \int_{t \geq s_1 \geq \cdots \geq s_r \geq 0} A(s_1) \cdots A(s_r)ds_1 \cdots ds_r.
\]
Clearly, $X_\infty(0) = \text{Id}_n$ holds, and a telescopic argument shows that $X_\infty(t)$ satisfies the differential equation (3.32). Therefore, the parallel transport is given by
\[
T(\gamma) = X_\infty(1) = \text{Id}_n - \int_\gamma \omega + \int_\gamma \omega \omega + \ldots,
\]
which is what we wanted to prove. \hfill \Box

The entries of the parallel transport matrix involve an infinite series, and therefore they are not iterated integrals according to our Definition 3.15. On the contrary, if we can ensure that the products appearing in the right-hand side of equation (3.31) vanish for large enough $r$, then all the entries would be finite sums. One can then combine Theorem 3.29 and Proposition 3.30 to give examples of iterated integrals that are homotopy functionals.

Example 3.35. A strictly upper triangular matrix $A(t)$ is nilpotent, so there exists an integer $r_0 \geq 1$ satisfying $A(s_1) \ldots A(s_{r_0}) = 0$. In this case, the parallel transport function reduces to the iterated integral
\[
T = 1 - \int \omega + \ldots + (-1)^{r_0-1} \int \frac{\omega \omega \ldots \omega}{r_0-1}.
\]

For instance, in the example of the connection matrix
\[
\omega = \begin{pmatrix} 0 & \omega_1 & \omega_{12} \\ 0 & 0 & \omega_2 \\ 0 & 0 & 0 \end{pmatrix},
\]
the parallel transport function is given by
\[
T = \begin{pmatrix} 1 & -\int \omega_1 & \int \omega_1 \omega_2 - \int \omega_{12} \\ 0 & 1 & -\int \omega_2 \\ 0 & 0 & 1 \end{pmatrix}
\]
and the curvature of the connection is equal to
\[
d\omega + \omega \wedge \omega = \begin{pmatrix} 0 & d\omega_1 & \omega_1 \wedge \omega_2 + d\omega_{12} \\ 0 & 0 & d\omega_2 \\ 0 & 0 & 0 \end{pmatrix}.
\]

Thus, $\nabla = d + \omega$ is flat if and only if the equalities
\begin{equation}
(3.36) \quad d\omega_1 = d\omega_2 = 0 \quad \text{and} \quad d\omega_{12} + \omega_1 \wedge \omega_2 = 0
\end{equation}
hold. It follows that the iterated integral $\int \omega_1 \omega_2 - \int \omega_{12}$ is a homotopy functional if and only if the conditions (3.36) are satisfied.

More generally, the following result is proved in [Hai87b, Prop. 3.1]:

Proposition 3.37. Let $\omega, \omega_1, \ldots, \omega_r$ be smooth $k$-valued 1-forms on $M$. Assume that all the forms $\omega_i$ are closed. An iterated integral of length two
\[
\sum_{1 \leq i, j \leq r} a_{ij} \int \omega_i \omega_j - \int \omega
\]
is a homotopy functional if and only if $d\omega + \sum_{1 \leq i, j \leq r} a_{ij} \omega_i \wedge \omega_j = 0$ holds.
Exercise 3.38 (Groupoids as categories). Let $C$ be a small category in which all morphisms are isomorphisms. Show that $C$ gives rise to a groupoid in the sense of Definition 3.6. Conversely, given a groupoid, construct such a category. Note that groups correspond to the case where the set of objects is a singleton.

Exercise 3.39 (Integration by parts). Let $\omega_1, \ldots, \omega_r$ be smooth $k$-valued 1-forms on a differentiable manifold $M$ and let $f$ be a smooth function on $M$. Prove that the equalities

\[
\int_\gamma (df) \omega_1 \cdots \omega_r = (f \circ \gamma)(1) \int_\gamma \omega_1 \cdots \omega_r - \int_\gamma (f \omega_1) \omega_2 \cdots \omega_r,
\]

\[
\int_\gamma \omega_1 \cdots \omega_{i-1} (df) \omega_i \cdots \omega_r = \int_\gamma \omega_1 \cdots (f\omega_{i-1}) \omega_i \cdots \omega_r - \int_\gamma \omega_1 \cdots \omega_{i-1} (f \omega_i) \omega_{i+1} \cdots \omega_r,
\]

\[
\int_\gamma \omega_1 \cdots \omega_r (df) = \int_\gamma \omega_1 \cdots \omega_{r-1} (f \omega_r) - (f \circ \gamma)(0) \int_\gamma \omega_1 \cdots \omega_r,
\]

hold for all paths $\gamma \in \mathcal{P}(M)$.


Exercise 3.41. Recall from Example 3.24 that the iterated integral of the 1-forms $\omega_1 = dz$ and $\omega_2 = dy$ on $\mathbb{R}^2$ is not a homotopy functional. According to Proposition 3.37, this is explained by the fact that $\omega_1 \wedge \omega_2$ does not vanish. Find a 1-form $\omega_{12}$ satisfying $d\omega_{12} + \omega_1 \wedge \omega_2 = 0$ and check that the iterated integral

\[
\int \omega_1 \omega_2 - \int \omega_{12} : \mathcal{P}(\mathbb{R}^2) \to \mathbb{R}
\]

now takes the same value on all the paths $\gamma_{a,b}$ from Example 3.24.

Exercise 3.42 (Another proof of formulas (3.20) and (3.21)). Let $\omega_1, \ldots, \omega_r$ be 1-forms on a differentiable manifold $M$. Consider the connection $\nabla = d + \omega$ on the trivial vector bundle of rank $r + 1$ on $M$ given by the matrix

\[
\omega = \begin{pmatrix}
0 & \omega_1 & 0 & \cdots & 0 \\
0 & 0 & \omega_2 & \cdots & 0 \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & 0 & \cdots & \omega_r \\
0 & 0 & 0 & \cdots & 0
\end{pmatrix}.
\]

Show that the parallel transport associated with $\nabla$ is the matrix $T = (T_{ij})$ of size $r + 1$ with entries

\[
T_{ij} = \begin{cases}
\int \omega_i \cdots \omega_{j-1}, & \text{if } i < j, \\
1, & \text{if } i = j, \\
0, & \text{if } i > j.
\end{cases}
\]

Using the equality $T(\gamma_1 \gamma_2) = T(\gamma_1)T(\gamma_2)$ from Proposition 3.28, deduce from the above computation another proof of the algebraic properties (3.20) and (3.21) of iterated integrals.
3.2. Affine group schemes, Lie algebras, and Hopf algebras. In this section, we explain the definition of affine group schemes and of two intimately related algebraic structures: Lie algebras and Hopf algebras. The book [Wat79] is an excellent entry point for readers unfamiliar with these notions. A classical reference for Hopf algebras is [Swe69], and we also recommend [Car07] for a motivated introduction. As in Chapter 2, we assume that the reader is familiar with the relation between affine schemes and commutative algebras as explained, for instance, in [Har77, Chap. II, § 2] and very briefly recalled below.

Throughout this section, we fix a field $k$ of characteristic zero (later, in the applications, it will always be equal to $\mathbb{Q}$). All undecorated cartesian and tensor products are assumed to be over $k$. When we want to emphasize that a group is simply a group and does not carry any additional structure (such as a scheme structure or a topology), we will call it an “abstract group”.

3.2.1. Affine group schemes. The category of affine schemes over $k$ is equivalent to the category of commutative $k$-algebras through the contravariant functors

$$A \mapsto \text{Spec}(A), \quad X \mapsto \mathcal{O}(X),$$

where $\mathcal{O}(X)$ denotes the ring of regular functions on an affine scheme $X$.

**Definition 3.44.** An affine group scheme $G$ over $k$ is the data of an affine scheme $G = \text{Spec}(A)$ and of three morphisms of schemes

\[ \begin{align*}
\mu &: G \times G \to G \quad \text{(product)}, \\
e &: \text{Spec}(k) \to G \quad \text{(unit)}, \\
i &: G \to G \quad \text{(inverse)},
\end{align*} \]

satisfying the usual axioms in the definition of a group, which are expressed by the commutativity of the following three diagrams:

**Associativity:**

\[
\begin{array}{ccc}
G \times G \times G & \overset{\mu \times \text{Id}}{\longrightarrow} & G \times G \\
\downarrow \mu & & \downarrow \mu \\
G \times G & \overset{\mu}{\longrightarrow} & G
\end{array}
\]

**Unit:**

\[
\begin{array}{ccc}
G \times \text{Spec}(k) & \overset{\text{Id} \times c}{\longrightarrow} & G \times G \\
\downarrow \mu & & \downarrow \mu \\
\text{Spec}(k) \times G & \overset{\text{Id} \times \text{Id}}{\longrightarrow} & \text{Spec}(k) \times G
\end{array}
\]

**Inverse:**

\[
\begin{array}{ccc}
G \times G & \overset{\mu}{\longrightarrow} & G \\
\downarrow \mu & & \downarrow \mu \\
G \times G & \overset{\text{Id} \times \text{Id}}{\longrightarrow} & G \times G
\end{array}
\]

where $\pi$ denotes the structural map of $G$ as a $k$-scheme.
We say that $G$ is \textit{commutative} if the product $\mu$ is commutative, which can also be expressed as the commutativity of the diagram

$$
\begin{array}{ccc}
G \times G & \xrightarrow{\mu} & G \\
\downarrow{\tau} & & \downarrow{\mu} \\
G \times G & \xrightarrow{\mu} & G,
\end{array}
$$

where $\tau$ is the map that swaps the factors. If the algebra $A$ is finitely generated, we say that $G$ is an \textit{algebraic affine group scheme} or simply an \textit{affine algebraic group}.

A \textit{morphism of affine group schemes} $f: G \rightarrow H$ is a morphism of the underlying schemes such that the diagram

$$
\begin{array}{ccc}
G \times G & \xrightarrow{f \times f} & H \times H \\
\downarrow{\mu} & & \downarrow{\mu} \\
G & \xrightarrow{f} & H
\end{array}
$$

commutes. We let $\text{AGS}(k)$ denote the category of affine group schemes over $k$ and $\text{AAGS}(k)$ the full subcategory of $\text{AGS}(k)$ consisting of affine algebraic groups.

\textbf{Remark 3.45.} In fact, every affine group scheme is a projective limit of algebraic affine groups. What is more, $\text{AGS}(k)$ is equivalent to the category of pro-algebraic affine group schemes; see Lemma 3.50 and Theorem 3.51 below.

3.2.2. \textit{Hopf algebras}. The defining data of an affine group scheme can be transferred to the corresponding algebra by means of the equivalence (3.43). This gives rise to the concept of Hopf algebra. We begin by explaining the definitions of algebra, coalgebra, bialgebra, and Hopf algebra.

\textbf{Definition 3.46.} Let $H$ be a $k$-vector space.

i) An \textit{algebra} structure on $H$ is the data of two $k$-linear morphisms

$$
\nabla: H \otimes H \rightarrow H \quad \text{(product)},
$$

$$
\eta: k \rightarrow H \quad \text{(unit),}
$$

such that the following diagrams commute:

\textbf{Associativity:}

$$
\begin{array}{ccc}
H \otimes H \otimes H & \xrightarrow{\nabla \otimes \text{Id}} & H \otimes H \\
\text{Id} \otimes \nabla & & \downarrow{\nabla} \\
H \otimes H & \xrightarrow{\nabla} & H.
\end{array}
$$

\textbf{Unit:}

$$
\begin{array}{ccc}
H \otimes k & \xrightarrow{\text{Id} \otimes \eta} & H \otimes H \\
\nabla & & \xrightarrow{\eta \otimes \text{Id}} \\
& \xrightarrow{\eta} & k \otimes H.
\end{array}
$$
where the left and right diagonal maps are the canonical isomorphisms $h \otimes \lambda \mapsto \lambda h$ and $\lambda \otimes h \mapsto \lambda h$ respectively.

The algebra structure is said to be *commutative* if the diagram

\[
\begin{array}{ccc}
H \otimes H & \xrightarrow{\tau} & H \\
\downarrow & & \downarrow \\
H \otimes H & \xrightarrow{\Delta \otimes \text{Id}} & H \otimes H \otimes H.
\end{array}
\]

commutes, where $\tau: H \otimes H \to H \otimes H$ is the swap of the factors.

ii) The notion of *coalgebra* is dual to that of algebra. That is, a coalgebra structure on $H$ is the data of two $k$-linear morphisms

\[
\begin{align*}
\Delta &: H \to H \otimes H \text{ (coproduct)}, \\
\epsilon &: H \to k \text{ (counit)},
\end{align*}
\]

such that the following diagrams commute:

**Coassociativity:**

\[
\begin{array}{ccc}
H & \xrightarrow{\Delta} & H \otimes H \\
\downarrow & & \downarrow \text{Id} \otimes \Delta \\
H \otimes H & \xrightarrow{\Delta \otimes \text{Id}} & H \otimes H \otimes H.
\end{array}
\]

**Counit:**

\[
\begin{array}{ccc}
H \otimes k & \xleftarrow{\text{Id} \otimes \epsilon} & H \otimes H & \xrightarrow{\epsilon \otimes \text{Id}} & k \otimes H \\
\downarrow & & \downarrow & & \downarrow \\
H & & H & & H
\end{array}
\]

where the left and right diagonal maps are the canonical isomorphisms $h \mapsto h \otimes 1$ and $h \mapsto 1 \otimes h$ respectively.

The coalgebra is called *cocommutative* if the following diagram commutes:

\[
\begin{array}{ccc}
H \otimes H & \xrightarrow{\tau} & H \\
\downarrow & & \downarrow \\
H \otimes H & \xrightarrow{\Delta} & H \otimes H.
\end{array}
\]

iii) A *bialgebra* structure on $H$ is the data of an algebra and a coalgebra structure that are compatible with each other in the sense that the coproduct and the counit are morphisms of algebras and that the product and the unit are morphisms of coalgebras. This amounts to the commutativity of the following diagrams:
Product and coproduct:
\[
\begin{array}{c}
H \otimes H \xrightarrow{\nabla} H \\
\downarrow \Delta \otimes \Delta \\
H \otimes H \otimes H \otimes H \xrightarrow{\text{Id} \otimes \tau \otimes \text{Id}} H \otimes H \otimes H \otimes H \\
\end{array}
\]

Unit and counit:
\[
\begin{array}{c}
k \xrightarrow{\text{Id}} k \\
\downarrow \eta \\
H \\
\end{array}
\]

Unit and coproduct:
\[
\begin{array}{c}
H \xrightarrow{\Delta} H \otimes H \\
\downarrow \eta \\
k \simeq k \otimes k
\end{array}
\]

Counit and product:
\[
\begin{array}{c}
H \otimes H \xrightarrow{\nabla} H \\
\downarrow \epsilon \otimes \epsilon \\
k \otimes k \simeq k
\end{array}
\]

iv) A Hopf algebra structure on \( H \) is the data of a bialgebra structure and a \( k \)-linear morphism
\[
S : H \to H \quad \text{(antipode)}
\]
such that the following diagram commutes:

\[
\begin{array}{c}
H \otimes H \xrightarrow{S \otimes \text{Id}} H \otimes H \\
\downarrow \Delta \\
H \otimes H \xrightarrow{\text{Id} \otimes S} H \otimes H \\
\end{array}
\]

v) A bialgebra \( H \) is called commutative if the product \( \nabla \) is commutative, and cocommutative if the coproduct \( \Delta \) is commutative.

The diagram concerning the antipode can be interpreted in terms of a convolution product as follows. If \( H \) is a bialgebra, then the space of \( k \)-linear endomorphism \( \text{End}(H) \) of \( H \) is endowed with the product structure in which the product \( f \ast g \) of elements \( f, g \in \text{End}(H) \) is given by the composition
\[
H \xrightarrow{\Delta} H \otimes H \xrightarrow{f \otimes g} H \otimes H \xrightarrow{\nabla} H.
\]
The associativity of $\nabla$ and the coassociativity of $\Delta$ imply that this convolution product is associative. Besides, its unit element is $\eta \circ \epsilon$. In these terms, the commutativity of the antipode diagram is equivalent to asking that $S$ is a two-sided inverse of the identity map $\text{Id}$ for the convolution product. In particular, $S$ is unique provided it exists.

Remark 3.47. A bialgebra does not always admit an antipode (see Exercise 3.127 for an example).

There is no need to impose further compatibilities between the antipode and the remaining structures in the definition of a Hopf algebra; they all follow from the axioms. A proof of the next result can be found in [Swe69, Prop. 4.0.1].

**Proposition 3.48.** Let $H$ be a Hopf algebra.

i) The antipode $S$ is an antihomomorphism of algebras. That is,

$$S \circ \nabla = \nabla \circ \tau \circ (S \otimes S).$$

In particular, if $H$ is commutative, then $S$ is an algebra homomorphism.

ii) The antipode $S$ is an antihomomorphism of coalgebras. That is,

$$(S \otimes S) \circ \tau \circ \Delta = \Delta \circ S.$$

iii) $S$ respects the unit and the counit. That is,

$$S \circ \eta = \eta \quad \text{and} \quad \epsilon \circ S = \epsilon.$$

iv) If $H$ is commutative or cocommutative, then $S \circ S = \text{Id}$. 

Given a commutative Hopf algebra $A$, we can use the algebra structure to define an affine scheme $\text{Spec}(A)$. Then the coproduct, counit, and antipode of $A$ give rise to the dual notions of product, unit, and inverse on $\text{Spec}(A)$. We immediately obtain the following result:

**Proposition 3.49.** The assignment $A \mapsto \text{Spec}(A)$ is a contravariant equivalence between the category of commutative Hopf $k$-algebras and the category of affine group schemes over $k$. A quasi-inverse equivalence is given by $G \mapsto \mathcal{O}(G)$. Moreover, the affine group scheme $G$ is commutative if and only if the Hopf algebra $\mathcal{O}(G)$ is cocommutative.

By way of illustration, we show how to use this correspondence to prove the promised result that affine group schemes are pro-algebraic.

**Lemma 3.50.** Every Hopf algebra is the inductive limit of its Hopf subalgebras that are finitely generated as $k$-algebras. Therefore, every affine group scheme is a projective limit of algebraic affine group schemes.

**Proof.** Let $H$ be a Hopf algebra. It suffices to show that every $x \in H$ is contained in a finitely generated Hopf subalgebra of $H$. Choose a basis $\{h_i\}$ (maybe infinite and even uncountable) of $H$ and write $\Delta(x) = \sum x_i \otimes h_i$, where only finitely many $x_i$ are non-zero. Let $V \subseteq H$ be the vector subspace spanned by $x$ and the $x_i$. We claim that there is an inclusion $\Delta(V) \subseteq V \otimes H$, which amounts of course to
saying that \( \Delta(x_i) \) belongs to \( V \otimes H \) for all \( i \). Indeed, writing \( \Delta(h_i) = \sum_{j,\ell} a_{ij\ell} h_j \otimes h_{\ell} \) with \( a_{ij\ell} \in k \), the equalities
\[
\sum_i \Delta(x_i) \otimes h_i = (\Delta \otimes \text{Id})\Delta(x) = (\text{Id} \otimes \Delta)\Delta(x) = \sum_{i,j,\ell} x_i \otimes a_{ij\ell} h_j \otimes h_{\ell}
\]
hold by the associativity of the coproduct. Comparing the coefficients of \( h_{\ell} \) yields
\[
\Delta(x_{\ell}) = \sum_{i,j} x_i \otimes a_{ij\ell} h_j \in V \otimes H,
\]
as we wanted. Now let \( \{v_i\} \) be a basis of \( V \) and write \( \Delta(v_j) = \sum_i v_i \otimes h_{ij} \) with \( h_{ij} \in H \). By Exercise 3.126, it follows that \( \Delta(h_{ij}) = \sum_\ell h_{i\ell} \otimes h_{j\ell} \), and hence the vector space \( U \) generated by \( \{v_i\} \) and \( \{h_{ij}\} \) satisfies \( \Delta(U) \subseteq U \otimes U \). If \( W \) is the vector space spanned by \( U \) and \( S(U) \), then \( \Delta(W) \subseteq W \otimes W \) and \( S(W) \subseteq W \) using Exercise 3.126 again. Finally, let \( A \) be the subalgebra of \( H \) generated by \( W \). Since \( \Delta \) and \( S \) are morphisms of algebras, we also have \( \Delta(A) \subseteq A \otimes A \) and \( S(A) \subseteq A \). It is thus a finitely generated Hopf subalgebra of \( H \) containing \( x \).

Not only every affine group scheme is pro-algebraic, but the pro-algebraic structure is, in some sense, unique. This is the content of the following result.

**Theorem 3.51.** The functor \( \text{Pro}(\text{AAGS}(k)) \to \text{AGS}(k) \) given by
\[
(G_d)_{d \in D} \mapsto \lim_{d \in D} G_d
\]
is an equivalence of categories.

**Proof.** In view of Lemma 3.50 and Theorem A.131 from the appendix, it suffices to show that \( \text{AAGS}(k) \) is the full subcategory of \( \text{AGS}(k) \) consisting of cocompact objects. By duality, this amounts to proving that the compact objects of the category of commutative Hopf algebras are the finitely generated algebras.

Let \( H \) be such a Hopf algebra. To prove that \( H \) is a compact object we need to check that the canonical map
\[
\lim_{d \in D} \text{Hom}(H, B_d) \to \text{Hom}(H, \lim_{d \in D} B_d)
\]
is a bijection for each inductive system of Hopf algebras \((B_d)_{d \in D}\). We first prove injectivity. Given \( f \in \lim_{d \in D} \text{Hom}(H, B_d) \), there is an object \( d_0 \) of \( D \) and a morphism \( f_{d_0} : H \to B_{d_0} \) whose image in the limit is \( f \). For each \( d_0 \to d \), we write \( f_{d_0 \to d} \) for the composition
\[
H \to B_{d_0} \to B_d.
\]
The image of \( f \) by the map (3.52) is the composition
\[
H \to B_{d_0} \to \lim_{d \in D} B_d.
\]
Let \( a_1, \ldots, a_n \) be a set of generators of \( H \). If the image of \( f \) under (3.52) is zero, then for each \( i = 1, \ldots, n \), there is an arrow \( d_0 \to d_i \) such that \( f_{d_0 \to d_i}(a_i) = 0 \). Taking \( d' \) that receives arrows \( d_i \to d' \), for \( i = 1, \ldots, n \), then \( f_{d_0 \to d'} = 0 \), which implies that \( f = 0 \). Hence, the map (3.52) is injective.
To prove surjectivity, we use that $H$ is noetherian, being a finitely generated $k$-algebra. There is hence an exact sequence of $H$-modules

$$0 \longrightarrow I \longrightarrow k[x_1, \ldots, x_n] \longrightarrow H \longrightarrow 0,$$

where $I$ is a finitely generated ideal. Let $f \in \text{Hom}(H, \lim_{d \in D} B_d)$. There is a $d \in D$ such that, for $i = 1, \ldots, n$, the element $f(a_i) \in \text{Im}(B_d)$. Choosing representatives in $B_d$, we construct a map $\tilde{f}_d$ that fits in a commutative diagram

$$\begin{array}{ccc}
k[x_1, \ldots, x_n] & \longrightarrow & H \\
\downarrow & f & \\
B_d & \longrightarrow & \lim_{d \in D} B_d.
\end{array}$$

Since $f(I) = 0$ and $I$ is finitely generated, there is an arrow $d \to d'$ such that the composition

$$k[x_1, \ldots, x_n] \xrightarrow{\tilde{f}_d} B_d \longrightarrow B_d'$$

maps $I$ to zero. Therefore, we obtain a map $f' : H \to B_d'$, and hence an element $f''$ in $\lim_{d \in D} (\text{Hom}(H, B_d))$. By construction, this element is in the preimage of $f$ and the map (3.52) is surjective.

On the other direction, we have to show that, if $\text{Hom}(H, -)$ commutes with direct limits, then $H$ is finitely generated as algebra. As in the proof of Lemma 3.50, we can write $H$ as a limit

$$H = \lim_{d \in D} H_d$$

of Hopf algebras $H_d$ that are finitely generated as algebras. Consider the identity map

$$\text{Id}_H \in \text{Hom}(H, H) = \text{Hom}(H, \lim_{d \in D} H_d).$$

Since we are assuming that $\text{Hom}(H, -)$ commutes with direct limits, the map (3.52) is an isomorphism. Therefore, there is a $d \in D$ and a map $H \to H_d$ such that the composition $H \to H_d \to H$ is $\text{Id}_H$. The map $H_d \to H$ is hence surjective and we deduce that $H$ is finitely generated as an algebra, which finishes the proof. □

3.2.4. Comodules and Hopf modules.

**Definition 3.53.** Let $(H, \Delta, \epsilon)$ be a coalgebra over $k$. A right comodule over $H$ is the data of a $k$-vector space $V$ and a $k$-linear map

$$\Delta : V \longrightarrow V \otimes H$$

called the coaction such that the following diagrams commute:

**Associativity:**

$$\begin{array}{ccc}
V & \xrightarrow{\Delta} & V \otimes H \\
\Delta & & \downarrow \text{id} \otimes \Delta \\
V \otimes H & \xrightarrow{\Delta \otimes \text{id}} & V \otimes H \otimes H.
\end{array}$$
Compatibility with the counit:

\[
V \xrightarrow{\Delta} V \otimes H \\
\cong \\
V \otimes k
\]

Left comodules over \( H \) are defined similarly.

Examples 3.54. The following are examples of comodules.

i) Every coalgebra is a (right and left) comodule over itself.

ii) Let \( A \) be a finite-dimensional \( k \)-algebra and \( M \) a finite-dimensional (left or right) \( A \)-module. Then the dual space \( A^\vee = \text{Hom}(A, k) \) is a coalgebra and \( M^\vee \) is a comodule over \( A^\vee \).

iii) Consider the \( k \)-vector space \( H = \bigoplus_{n \in \mathbb{Z}} ke_n \) with the counit \( \epsilon(e_n) = 1 \) for all \( n \) and the coproduct

\[
\Delta(e_n) = e_n \otimes e_n.
\]

Then \( H \) is a coalgebra and every graded vector space \( V^* = \bigoplus_{n \in \mathbb{Z}} V^n \) is a right comodule over \( H \) with coaction

\[
\Delta v = v \otimes e_n,
\]

for \( v \in V^n \) (Exercise 3.125). Similarly, \( V^* \) can be viewed as a left comodule because the Hopf algebra \( H \) is cocommutative.

Definition 3.55. Let \( H \) be a commutative Hopf algebra. A left Hopf module is a vector space \( V \) that is a module over the algebra structure of \( H \) and a left comodule over its coalgebra structure. Moreover, both structures are compatible in the sense that the equality

\[
\Delta(hv) = \Delta(h)\Delta(v)
\]

holds for all \( h \in H \) and for all \( v \in V \).

3.2.5. Graded Hopf algebras.

Definition 3.56.

i) A bialgebra \( H \) is said to be graded if the underlying \( k \)-vector space has a direct sum decomposition

\[
H = \bigoplus_{n \in \mathbb{Z}} H_n
\]

compatible with the operations in the sense that the inclusions

\[
\nabla(H_p \otimes H_q) \subseteq H_{p+q}, \quad \Delta H_n \subseteq \bigoplus_{i+j=n} H_i \otimes H_j
\]

hold for all \( p, q, n \geq 0 \). If, moreover, \( H_n = \{0\} \) for \( n < 0 \) and \( H_0 = k \) we say that \( H \) is connected.

ii) A graded Hopf algebra is a Hopf algebra such that the underlying bialgebra is graded and the antipode satisfies \( S(H_n) \subseteq H_n \).
One advantage of working with graded connected bialgebras is that they automatically admit a unique antipode turning them into (graded) Hopf algebras (see Exercise 3.128).

3.2.6. Examples. In this paragraph, we give a few examples of affine group schemes and their corresponding Hopf algebras. Of particular interest for the sequel is the Hoffman algebra from Example 3.62.

In order to define affine group schemes, it is useful the language of representable functors. An affine group scheme over $k$ defines a functor from the category of commutative $k$-algebras to the category of abstract groups. Namely, given $G = \text{Spec}(A)$ as in Definition 3.44, the set-valued functor

$$R \mapsto G(R) = \text{Hom}_{k\text{-alg}}(A, R)$$

actually takes values in the category of groups, since the structure of group scheme of $G$ endows $G(R)$ with a group structure for all $R$. This gives rise to the following definition.

**Definition 3.57.** We say that a functor $F$ from commutative $k$-algebras to groups is **representable** if there exist an affine group scheme $G$ and a natural isomorphism of functors between $F$ and $G$.

**Examples 3.58.**

i) The **trivial** group scheme is $\text{Spec}(k)$ with all operations equal to the identity. The corresponding commutative Hopf algebra is $k$ with all operations equal to the identity once $k \otimes k$ is identified with $k$.

ii) The **multiplicative group** $\mathbb{G}_m$. The functor from commutative $k$-algebras to groups given by $R \mapsto R^\times$ is represented by an affine group scheme $\mathbb{G}_m$. The corresponding Hopf algebra is $k[x, x^{-1}]$, together with the coproduct uniquely determined by the formulas

$$\Delta(x) = x \otimes x, \quad \Delta(x^{-1}) = x^{-1} \otimes x^{-1},$$

the counit $\epsilon(x) = \epsilon(x^{-1}) = 1$, and the antipode determined by $S(x) = x^{-1}$ and $S(x^{-1}) = x$.

iii) The **additive group** $\mathbb{G}_a$. The functor from commutative $k$-algebras to groups given by $R \mapsto (R, +)$ is represented by an affine group scheme $\mathbb{G}_a$. The corresponding Hopf algebra is $k[x]$ with the coproduct, the counit, and the antipode being the only algebra morphisms satisfying

$$\Delta(x) = 1 \otimes x + x \otimes 1, \quad \epsilon(x) = 0, \quad S(x) = -x.$$

iv) More generally, if $V$ is a finite-dimensional $k$-vector space, then the functor $R \mapsto (V \otimes_R, +)$ is representable. The corresponding Hopf algebra is the symmetric algebra $\text{Sym}(V^\vee)$, which is the free associative and commutative $k$-algebra generated by $V^\vee$. Generalizing the previous example, the coproduct, the counit and the antipode in $\text{Sym}(V^\vee)$ are the algebra morphisms determined by $\Delta v = 1 \otimes v + v \otimes 1$, $\epsilon(v) = 0$ and $S(v) = -v$ respectively, for all $v \in V^\vee$.

v) When $V$ is infinite-dimensional, the functor $R \mapsto V \otimes R$ is not representable (see Exercise 3.130). Nevertheless, for pro-finite-dimensional vector spaces there is a substitute. Let $V$ be a $k$-vector space that can be
written as

\[ V = \lim_{\alpha} V_{\alpha} \]

with every \( V_{\alpha} \) finite-dimensional. Then the functor

\[ R \mapsto \lim_{\alpha} (V_{\alpha} \otimes R) \]

is representable by an affine group scheme whose Hopf algebra is

\[ A = \lim_{\alpha} \text{Sym}(V_{\alpha}^\vee). \]

vi) The linear group \( \text{GL}_n \). The functor that maps a commutative \( k \)-algebra \( R \) to the group \( \text{GL}_n(R) \) of invertible \( n \times n \) matrices with entries in \( R \) is representable by an affine group scheme \( \text{GL}_n \). The corresponding Hopf algebra is

\[ k[t, (x_{ij})_{i,j=1,...,n}] / (t \det(x_{ij}) - 1). \]

Recall that this means that the determinant \( \det(x_{ij}) \), which is a homogeneous polynomial of degree \( n \) in the entries \( x_{ij} \), is invertible. Its inverse is the variable \( t \). The coproduct is given by

\[ (3.59) \quad \Delta t = t \otimes t, \quad \Delta x_{ij} = \sum_{l=1}^{n} x_{il} \otimes x_{lj}. \]

The counit is the map

\[ \epsilon(x_{ij}) = \begin{cases} 1, & \text{if } i = j, \\ 0, & \text{if } i \neq j. \end{cases} \]

Finally, the antipode can be expressed using Cramer’s rule for the inverse of a matrix in terms of cofactors, that is,

\[ S(t) = t^{-1}, \quad S(x_{ij}) = tC_{ji}, \]

where \( C_{ij} \) is \((-1)^{i+j}\) times the determinant of the matrix obtained by deleting the \( i \)-th row and the \( j \)-th column of \((x_{lm})_{l,m}\). Observe that \( C_{ij} \) is a homogeneous polynomial of degree \( n - 1 \).

vii) Similarly, for every finite-dimensional \( k \)-vector space \( V \), the functor

\[ R \mapsto \text{Aut}_R(R \otimes V) \]

that sends a \( k \)-algebra \( R \) to the set of \( R \)-linear automorphisms of the \( R \)-module \( R \otimes V \) is representable by an algebraic affine \( k \)-group scheme \( \text{GL}(V) \). If \( V \) has dimension \( n \), the choice of a basis of \( V \) induces an isomorphism between \( \text{GL}(V) \) and \( \text{GL}_n \).

viii) Again, one needs to be cautious when working with infinite-dimensional vector spaces. In fact, given a \( k \)-vector space \( V \), the functor

\[ R \mapsto \text{Aut}_R(R \otimes V) \]

is representable by an affine group \( k \)-scheme if and only if \( V \) is finite-dimensional (see Exercise 3.131). Observe that the rule (3.59) from Example vi) above does not define a coproduct in the infinite-dimensional case since the sum appearing in the right-hand side will be infinite.
Example 3.60. Further examples of affine group schemes arise from Zariski closed subsets of $\text{GL}_n$ that are stable under matrix multiplication and matrix inversion, and contain the identity matrix, namely classical algebraic groups such as

i) the special linear group

$$\text{SL}_n = \text{Spec} \left( k[(x_{ij})_{i,j=1,\ldots,n}] / (\det(x_{ij}) - 1) \right),$$

that represents the functor that sends $k$-algebra $R$ to the group $\text{SL}_n(R)$ of $n \times n$ matrices with entries in $R$ and determinant equal to 1;

ii) the group of unipotent matrices

$$\text{Up}_n = \text{Spec} \left( k[(x_{ij})_{i,j=1,\ldots,n}] / ((x_{ii} - 1), (x_{ij})_{i<j}) \right),$$

that represents the functor that sends a $k$-algebra $R$ to the group $\text{Up}_n(R)$ of $n \times n$ upper triangular matrices with entries in $R$ and all diagonal entries equal to 1;

iii) the orthogonal group

$$\text{O}_n = \text{Spec} \left( k[(x_{ij})_{i,j=1,\ldots,n}] / \left( \sum_j x_{ji} x_{j\ell} - \delta_{i\ell} \right)_{i,\ell=1,\ldots,n} \right),$$

that represents the functor that sends a $k$-algebra $R$ to the group $\text{O}_n(R)$ of $n \times n$ matrices $M$ with entries in $R$ and $M^t M = 1$ (see Exercise 3.134).

As we will prove later (Corollary 3.120), every affine algebraic group arises this way.

Example 3.61. Let $\Gamma$ be an abstract group. The group algebra $k[\Gamma] = \{ \sum g_a g | g_a \in k, a_g = 0 \text{ except for finitely many } g \}$ carries the structure of a Hopf algebra. The product is determined by the group law of $\Gamma$, as follows:

$$\sum_{g \in \Gamma} a_g g \cdot \sum_{h \in \Gamma} b_h h = \sum_{g, h \in \Gamma} a_g b_h g h = \sum_{f \in \Gamma} \left( \sum_{g \in \Gamma} a_g b_{g^{-1} f} \right) f.$$

The unit is the $k$-linear map $k \to k[\Gamma]$ that sends 1 to the neutral element. The coproduct and the antipode on $k[\Gamma]$ are the $k$-linear extensions of the maps given by $\Delta g = g \otimes g$ and $S(g) = g^{-1}$ respectively, and the counit sends $\sum a_g g$ to $\sum a_g$. This Hopf algebra is cocommutative but not commutative, unless $\Gamma$ is abelian.

Example 3.62. For the purpose of these notes, the main example will be the Hoffman algebra $\mathcal{H}$ of Section 1.6. Recall that the underlying vector space of $\mathcal{H}$ is the vector space $\mathbb{Q}\langle X \rangle$ generated by (non-commutative) words in two letters $x_0, x_1$. The Hopf algebra structure is given by

- **Shuffle product:**
  $$x_{\varepsilon_1} \cdots x_{\varepsilon_r} \shuffle x_{\varepsilon_{r+1}} \cdots x_{\varepsilon_{r+s}} = \sum_{\sigma \in \omega(r,s)} x_{\varepsilon_{\sigma^{-1}(1)}} \cdots x_{\varepsilon_{\sigma^{-1}(r+s)}}.$$

- **Unit:** The map $\eta: \mathbb{Q} \to \mathcal{H}$ that sends 1 to the empty word.
Deconcatenation coproduct:
\[ \Delta x_{e_1} \cdots x_{e_n} = \sum_{j=0}^{n} x_{e_1} \cdots x_{e_j} \otimes x_{e_{j+1}} \cdots x_{e_n}. \]

Counit: The map \( \epsilon : \mathcal{H} \to \mathbb{Q} \) that sends every non-empty word to 0 and the empty word to 1.

Antipode:
\[ S(x_{e_1} \cdots x_{e_n}) = (-1)^n x_{e_n} \cdots x_{e_1} \]
For convenience, if \( w \) is a word on the letters \( x_0 \) and \( x_1 \), we will also use the notation
\[ (3.63) \quad w^* = S(w). \]
Consider the grading of \( \mathcal{H} \) that gives weight \( n \) to \( x_{e_1} \cdots x_{e_n} \). Since all the above operations respect the weight, \( \mathcal{H} \) is a graded Hopf algebra. Moreover, it is connected.

3.2.7. The dual of a Hopf algebra. Let \( H \) be a Hopf algebra over \( k \). If \( H \) is a finite-dimensional \( k \)-vector space, then its dual
\[ H^\vee = \text{Hom}(H, k) \]
is again equipped with a Hopf algebra structure. The product of \( H^\vee \) is the dual of the coproduct of \( H \), the coproduct is the dual of the product, and similarly for the antipode. In other words, the axioms in Definition 3.46 are self-dual. This relies on the fact that the canonical morphism
\[ (3.64) \quad H^\vee \otimes H^\vee \longrightarrow (H \otimes H)^\vee \]
is an isomorphism. If \( H \) is infinite-dimensional, the morphism (3.64) fails to be an isomorphism, and hence the dual of the product does not give rise to a coproduct but only to what is called a completed coproduct. Let us explain why. Let \( V \) be an infinite-dimensional \( k \)-vector space and write
\[ V = \lim_{\longrightarrow} V_I, \]
where \( I \) runs over the directed set of finite-dimensional subspaces of \( V \). Since the functor \( \text{Hom}(\cdot, k) \) exchanges inductive and projective limits, the dual of \( V \) equals
\[ (3.65) \quad V^\vee = \text{Hom}(V, k) = \text{Hom}(\lim_{\longrightarrow} V_I, k) = \lim_{\longrightarrow} \text{Hom}(V_I, k) = \lim_{\longrightarrow} V_I^\vee. \]
Thus, \( V^\vee \) has a natural structure of pro-finite-dimensional \( k \)-vector space.

Definition 3.66. Given a pro-finite-dimensional \( k \)-vector space
\[ W = \lim_{\longrightarrow} W_I, \]
the completed tensor product of \( W \) with itself is defined as
\[ W \hat{\otimes} W = \lim_{\longrightarrow} (W_I \otimes W_I). \]
Note that the definition requires a structure of pro-finite-dimensional space. When dealing with the dual of an infinite-dimensional vector space \( V \), we will tacitly assume that \( V^\vee \) is endowed with the structure (3.65).
There are canonical maps
\[ V^\vee \otimes V^\vee \longrightarrow (V \otimes V)^\vee \longrightarrow V^\vee \hat{\otimes} V^\vee, \]
which are not isomorphisms in general. Hence, the dual of the product $A \otimes A \to A$ of an algebra gives only rise to a morphism
\[(3.67) \quad A^\vee \to (A \otimes A)^\vee \to A^\vee \hat{\otimes} A^\vee\]
and not necessarily to a coproduct $A^\vee \to A^\vee \otimes A^\vee$. Such a map is called a completed coproduct.

**Definition 3.68.** A completed Hopf algebra $A$ is a pro-finite-dimensional vector space satisfying the analogous properties of a Hopf algebra (Definition 3.46) where all tensor products are replaced by completed tensor products and all the maps are compatible with the pro-finite-dimensional structure. In particular, it has a completed coproduct
\[\Delta: A \to A \hat{\otimes} A.\]
Moreover, the algebra product $\nabla: A \otimes A \to A$ factorizes through a completed product
\[A \otimes A \to A \hat{\otimes} A \xrightarrow{\nabla} A,\]
and the antipode $S$ is compatible with the pro-finite-dimensional structure.

The dual of an infinite-dimensional Hopf algebra is a completed Hopf algebra. Typically, we will consider the dual of connected graded Hopf algebra with finite-dimensional graded pieces, in which case the completed Hopf algebra can be conveniently written in terms of the topology induced by the augmentation ideal.

**Example 3.69.** Let $A = k[x]$ be the Hopf algebra from Example 3.58 iii). We denote by $\langle \cdot, \cdot \rangle$ the pairing between a vector space and its dual. Let $y_m \in A^\vee$ be the element determined by $\langle y_m, x^n \rangle = \delta_{n,m}$. As $k$-vector space
\[A^\vee = \prod_{n \geq 0} ky_n.\]
Although this space is a product space, we will use additive notation and write an element $(a_n)_{n \geq 0}$ as a formal infinite sum $\sum_{n \geq 0} a_n y_n$. To determine the algebra structure, we compute
\[\langle \nabla(y_m \otimes y_n), x^j \rangle = \langle y_m \otimes y_n, \Delta x^j \rangle = \langle y_m \otimes y_n, (1 \otimes x + x \otimes 1)^j \rangle = \begin{cases} \frac{(m+n)!}{n!m!}, & \text{if } j = n + m, \\ 0, & \text{otherwise.} \end{cases}\]
Therefore,
\[y_m \cdot y_n = \frac{(m+n)!}{n!m!} y_{n+m}.\]
From this equation we deduce that $y_m = y_1^m/m!$ and that $A^\vee$ is the algebra of formal series on divided powers. Since we are working over a field of characteristic zero, it is isomorphic to the algebra of formal power series. Thus, writing $y = y_1$, there is an isomorphism of algebras
\[A^\vee = k[[y]].\]
One easily checks that the completed coproduct is determined by $\Delta y = 1 \otimes y + y \otimes 1$, the dual antipode by $S(y) = -y$, the unit $\eta(1) = 1$ and the counit $\epsilon(y^n) = \delta_{0,n}$. In particular,

$$\Delta y_m = \sum_{j=0}^{m} y_j \otimes y_{m-j}, \quad S(y_m) = -y_m.$$ 

The completed coproduct cannot be factored through a true coproduct. Consider the element $\eta = \sum_{n \geq 0} n y_n$. Then

$$\Delta \eta = \sum_{n \geq 0} \sum_{j=0}^{n} n y_j \otimes y_{n-j}.$$ 

This element does not belong to $A^\vee \otimes A^\vee$. This can be seen as follows. Any element

$$\sum_{i,j \geq 0} a_{i,j} y_i \otimes y_j \in A^\vee \otimes A^\vee$$

satisfies that the rank of the matrix $(a_{i,j})$ is finite. By contrast, the rank of the matrix $(b_{i,j})$ with $b_{i,j} = i + j$ is not bounded.

**Example 3.70.** Let $A = k[x, x^{-1}]$ be the Hopf algebra from Example 3.58 ii). As in the previous example, we denote by $\langle \cdot, \cdot \rangle$ the pairing between a vector space and its dual and we let $y_m \in A^\vee$ be the element determined by $\langle y_m, x^n \rangle = \delta_{n,m}$.

As a $k$-vector space, the dual $A^\vee$ is given by

$$A^\vee = \bigotimes_{n \in \mathbb{Z}} k y_n.$$ 

As in the previous example, we will use additive notation and formal infinite sums. To determine the algebra structure, we compute

$$\langle \nabla (y_m \otimes y_n), x^j \rangle = \langle y_m \otimes y_n, \Delta x^j \rangle = \langle y_m \otimes y_n, x^j \otimes x^j \rangle \begin{cases} 1, & \text{if } j = n = m, \\ 0, & \text{otherwise.} \end{cases}$$

Therefore,

$$y_n \cdot y_m = \begin{cases} y_n, & \text{if } n = m, \\ 0, & \text{otherwise.} \end{cases}$$

So the elements $y_n$ are mutually orthogonal projectors. It is easy to check that the completed coproduct is given by

$$\Delta y_n = \sum_{a + b = n} y_a \otimes y_b,$$

which is not an element of $A^\vee \otimes A^\vee$ since the sum is infinite. Hence, this completed coproduct is not a true coproduct. The dual antipode is given by $S(y_n) = y_{-n}$, the counit by $\epsilon(y_n) = \delta_{0,n}$ and the unit by

$$\eta(1) = \sum_{n \in \mathbb{Z}} y_n.$$ 

It is amusing to observe that Spec$(A^\vee)(k)$ is isomorphic to $\mathbb{Z}$, realizing in some sense the duality between $G_m$ and $\mathbb{Z}$ given by characters. The completed coproduct in
$A^V$ is compatible with the addition in $\mathbb{Z}$. But even if Spec$(A^V)$ is a scheme over $k$, it is not a group scheme, because the completed coproduct is not a true coproduct.

Example 3.71. The dual of the Hoffman Hopf algebra $\mathfrak{H}$ from Example 3.62 is the space $\mathfrak{H}^V = \mathbb{Q}(e_0, e_1)$ of series on the non-commutative words in two letters $e_0$ and $e_1$. Given a binary sequence $\alpha$ and an element $\gamma \in \mathbb{Q}(e_0, e_1)$, the duality is given by the pairing

$$\langle x_\alpha, \gamma \rangle = \text{coefficient of } e_\alpha \text{ in } \gamma.$$  

This duality and the Hopf algebra structure of $\mathfrak{H}$ endows $\mathbb{Q}(e_0, e_1)$ with the following structures:

**Concatenation product:** The product $\Delta^V : \mathfrak{H}^V \otimes \mathfrak{H}^V \rightarrow \mathfrak{H}^V$ is given by

$$e_{\varepsilon_1} \cdots e_{\varepsilon_r} \cdot e_{\varepsilon_{r+1}} \cdots e_{\varepsilon_{r+s}} = e_{\varepsilon_1} \cdots e_{\varepsilon_{r+s}}.$$  

**Unit:** It is the morphism

$$\epsilon^V : \mathbb{Q} \rightarrow \mathbb{Q}(e_0, e_1)$$

that sends 1 to the empty word.

**Completed coproduct:** It is the unique morphism of algebras

$$\nabla^V : \mathfrak{H}^V \rightarrow \mathfrak{H}^V \otimes \mathfrak{H}^V$$

such that the equality

$$\nabla^V e_\varepsilon = 1 \otimes e_\varepsilon + e_\varepsilon \otimes 1$$

holds for $\varepsilon = 0, 1$. This implies the equality

$$\nabla^V w = \sum_{w_1, w_2} \shuffle(w_1, w_2; w)w_1 \otimes w_2,$$

for any word $w$ on the alphabet $\{e_0, e_1\}$, where the shuffle multiplicity $\shuffle(w_1, w_2; w)$ was introduced in 1.160.

**Counit:** The map

$$\eta^V : \mathbb{Q}(e_0, e_1) \rightarrow \mathbb{Q}$$

sending all non-empty words to 0 and the empty word to 1.

**Dual antipode:** It is given by

$$S^V(e_{\varepsilon_1} \cdots e_{\varepsilon_n}) = (-1)^n e_{\varepsilon_n} \cdots e_{\varepsilon_1}.$$  

By analogy with (3.63), for a word $w$ in the letters $e_0$ and $e_1$, we use the notation

$$w^* = S^V(w).$$

3.2.8. Hopf ideals, quotients, and completions. Let $A$ be a $k$-algebra. Recall that a left (resp. right) ideal of $A$ is a left (resp. right) $A$-submodule of $A$, that is, a vector subspace $I \subset A$ satisfying $AI \subset I$ (resp. $IA \subset I$). An ideal $I \subset A$ is a vector subspace that is both a left and a right ideal. If $I \subset A$ is an ideal, then $A/I$ inherits a product structure. The corresponding notion for coalgebras is that of a coideal.

**Definition 3.72.** Let $H$ be a coalgebra with coproduct $\Delta$ and counit $\epsilon$. A vector subspace $I \subset H$ is

- a **left coideal** if $\Delta I \subset H \otimes I$;
- a **right coideal** if $I \subset H \otimes I$;
• a coideal if \( \Delta I \subset H \otimes I + I \otimes H \) and \( \epsilon(I) = 0 \).

**Lemma 3.73.** Let \( H \) be a coalgebra with coproduct \( \Delta \) and counit \( \epsilon \). Let \( I \subset H \) be a coideal. Then \( H/I \) inherits a coalgebra structure.

**Proof.** Since \( \epsilon(I) = 0 \), the counit \( \epsilon \) induces a map \( \epsilon_{H/I} : H/I \to k \). For each class \([c] \in H/I\), with representative \( c \in H \), we define \( \Delta_{H/I}[c] \) as the class of \( \Delta c \) in \( H/I \otimes H/I \). The condition that \( \Delta c \) belongs to \( H \otimes I + I \otimes H \) for all \( c \in I \) implies that the coproduct \( \Delta_{H/I} \) is well defined. The coassociativity of \( \Delta_{H/I} \) and its compatibility with the counit \( \epsilon_{H/I} \) then follow from the corresponding properties of \( \Delta \) and \( \epsilon \).

**Definition 3.74.** Let \( H \) be a Hopf algebra. A *Hopf ideal* is a vector subspace \( I \subset H \) that is both an ideal and a coideal and, moreover, satisfies \( S(I) \subset I \).

If \( H \) is a Hopf algebra and \( I \) is a Hopf ideal, then \( H/I \) is also a Hopf algebra.

**Examples 3.75.** Let \( H \) be a Hopf algebra with coproduct \( \Delta \) and counit \( \epsilon \).

i) The augmentation ideal \( I = \ker \epsilon \) is a Hopf ideal. Indeed, writing the coproduct of an element \( a \in I \) as \( \Delta a = \sum b_i \otimes c_i \), the condition that \( (\epsilon \otimes \text{Id}) \circ \Delta \) is the identity map under the canonical identification \( k \otimes H = H \) implies the equality \( \sum_i \epsilon(b_i) c_i = a \in I \), and hence

\[
\Delta a = \sum_i b_i \otimes c_i = \sum_i (b_i - \epsilon(b_i)) \otimes c_i + 1 \otimes a \in I \otimes H + H \otimes I.
\]

Since \( \epsilon \circ S = \epsilon \) by Proposition 3.48 iii), the ideal \( I \) is also stable under the antipode.

ii) Let \( I \subset H \) be a Hopf ideal. The powers \( I^n \) are not necessarily coideals, but they always satisfy the weaker condition

(3.76) \( \Delta(I^n) \subset H \otimes I^n + I \otimes I^{n-1} + \cdots + I \otimes I \).

**Definition 3.77.** Let \( H \) be a Hopf algebra and \( I \subset H \) a Hopf ideal. The *completion* of \( H \) with respect to \( I \) is the projective limit

\[ H_I^\wedge = \lim_{\to n} H/I^{n+1}. \]

When \( I \) is the augmentation ideal, we will simply write \( H^\wedge \).

**Proposition 3.78.** Let \( H \) be a Hopf algebra and \( I \subset H \) a Hopf ideal. The completion \( H_I^\wedge \) is a completed Hopf algebra.

**Proof.** Since the powers of an ideal are again ideals, each \( H/I^{n+1} \) inherits an algebra structure from \( H \), and hence so does the projective limit \( H_I^\wedge \). Although the powers of a coideal are not necessarily coideals, condition (3.76) is enough to have coproducts

\[ \Delta : H/I^{2n+1} \to H/I^{n+1} \otimes H/I^{n+1}, \]

that induce a completed coproduct

\[ \lim_{\to n} H/I^{n+1} \to \lim_{\to n} (H/I^{n+1} \otimes H/I^{n+1}) \to \lim_{\to n} H/I^{n+1} \otimes \lim_{\to n} H/I^{n+1}. \]

The unit and the counit are also defined at each level \( H(I^{n+1}) \), therefore they are defined in the limit. Since \( I \) is stable under the antipode \( S \), the same is true for the powers \( I^n \). Therefore \( H_I^\wedge \) also has an induced antipode. The compatibilities among the structures in \( H_I^\wedge \) follow from the compatibilities in \( H \).
3.2.9. **Lie algebras.** We next introduce the notion of Lie algebra of an affine group scheme. The definition is modelled after the more classical notion of Lie algebra of a Lie group, which is the tangent space at the neutral element of the underlying differentiable manifold together with an antisymmetric product that reflects the non-commutativity of the group law. Throughout the next sections, $k$ still denotes a field of characteristic zero.

**Definition 3.79.** A **Lie algebra** over $k$ is the data $L = (L, \cdot, \cdot)$ of a $k$-vector space $L$ and a bilinear product $\cdot : L \otimes L \to L$ called the **Lie bracket** that satisfies the following two conditions:

**Antisymmetry:** $[a, b] + [b, a] = 0$ for all $a, b \in L$.

**Jacobi identity:** $[[a, b], c] + [[b, c], a] + [[c, a], b] = 0$ for $a, b, c \in L$.

A **morphism of Lie algebras** is a $k$-linear map $\varphi : L \to L'$ that is compatible with the Lie brackets, in that the equality $\varphi([a, b]_L) = [\varphi(a), \varphi(b)]_{L'}$ holds for all $a, b \in L$.

If the underlying vector space of $L$ has a grading $L = \bigoplus_{n \in \mathbb{Z}} L_n$ such that $[L_n, L_m] \subseteq L_{n+m}$, we say that $L$ is a **graded Lie algebra**.

An **abelian** Lie algebra is a Lie algebra with identically zero Lie bracket.

**Remark 3.80.**

i) The antisymmetry of the Lie bracket implies that it factors through the exterior product $L \wedge L$.

ii) The commutator $[a, b] = ab - ba$ endows any associative $k$-algebra $L$ with a Lie algebra structure. The Jacobi identity reflects the associativity of the product.

iii) There is a dual notion to that of Lie algebra called **Lie coalgebra**. We let the reader explore its properties in Exercise 3.137.

3.2.10. **The Lie algebra of an affine group scheme.** With an affine group scheme is associated a Lie algebra that is the algebraic analogue of the Lie algebra of a Lie group. This Lie algebra can be directly built out of the Hopf algebra of regular functions on the group, as we now explain. Let $G$ be an affine group scheme over $k$ and let $A = O(G)$ be the corresponding commutative Hopf algebra. We keep the notation $(\nabla, \eta, \Delta, \epsilon, S)$ from Definition 3.46.

**Definition 3.81.** The **augmentation ideal** of $A$ is the kernel of the counit map $\epsilon : A \to k$. It will be denoted by $I = \text{Ker}(\epsilon)$.

The augmentation ideal is the maximal ideal of regular functions on $G$ that vanish at the unit $e = \eta(1)$. Since $\epsilon \circ \eta = \text{Id}_k$ there is a a canonical projection $A \to I$, and therefore a canonical direct sum decomposition $A = k \oplus I$.

**Definition 3.82.** The tangent space of the affine group scheme $G$ at the unit element is the $k$-vector space $\mathfrak{g} = (I/I^2)^\vee$. 

To make \( g \) into a Lie algebra, we need a bracket
\[ [\cdot, \cdot] : g \wedge g \rightarrow g. \]
We will first define the dual map. For this we observe that the compatibilities of the coproduct with the unit and the counit imply that, if \( f \in I \), then
\[ \Delta f - f \otimes 1 - 1 \otimes f \in I \otimes I. \] (3.83)
We now consider the map
\[ I \xrightarrow{\Delta} A \otimes A \xrightarrow{\pi} (I/I^2) \otimes (I/I^2) \xrightarrow{\pi \wedge \pi} (I/I^2) \wedge (I/I^2), \]
where the second arrow is induced by the projection \( A \rightarrow I \rightarrow I/I^2 \) and the third arrow is the projection from the tensor product to the exterior product. It follows from property (3.83) that the composition of these maps vanishes on \( I^2 \). Therefore, we obtain a map
\[ d : I/I^2 \rightarrow \bigwedge^2 (I/I^2). \] (3.84)
By duality, we obtain a map
\[ [\cdot, \cdot] : g \wedge g = (I/I^2)^\vee \wedge (I/I^2)^\vee \rightarrow (I/I^2 \wedge (I/I^2)^\vee \xrightarrow{d^\vee} (I/I^2)^\vee = g. \]
Following Exercise 3.138, the pair \((I/I^2, d)\) is a Lie coalgebra over \( k \). In Exercise 3.139 you will give a more down to earth formula for the bracket.

**Definition 3.85.** Let \( G = \text{Spec}(A) \) be an affine group scheme. The Lie coalgebra associated with the commutative Hopf algebra \( A \) is the pair \((I/I^2, d)\). Its dual \((g, [\cdot, \cdot])\) is called the Lie algebra of \( G \) and denoted \( \text{Lie}(G) \).

The construction of the Lie algebra is functorial for morphisms of affine group schemes. Indeed, given \( G = \text{Spec}(A) \) and \( H = \text{Spec}(B) \), a morphism \( f : G \rightarrow H \) of affine group schemes corresponds to a morphism of Hopf algebras \( f : B \rightarrow A \). In particular, \( f \) is compatible with the counits of \( A \) and \( B \), and hence maps the augmentation ideal \( J \) of \( B \) to the augmentation ideal \( I \) of \( A \). The dual of the induced map \( J/J^2 \rightarrow I/I^2 \) is then a \( k \)-linear map \( \text{Lie}(G) \rightarrow \text{Lie}(H) \), usually denoted by \( df \), which is compatible with the Lie bracket.

In practice, to compute the Lie algebra of an affine group scheme \( G \), one looks for the elements of \( G(k[\varepsilon]) \) mapping to the identity in \( G(k) \), which is an algebraic characterization of the tangent space at the unit. Here \( k[\varepsilon] = k[x]/x^2 \) denotes the ring of dual numbers, in which \( \varepsilon^2 = 0 \). We make this observation more precise.

Let \( G = \text{Spec}(A) \) be an affine group scheme over \( k \) and \( g = \text{Lie}(G) \) its Lie algebra. Recall that the set of \( R \)-points of \( G \) is given by \( G(R) = \text{Hom}_{k\text{-alg}}(A, R) \) for each \( k \)-algebra \( R \). Consider the map
\[ e^x : g \otimes R \rightarrow G(R[\varepsilon]) \]
\[ x \mapsto e^{\varepsilon x} \] (3.86)
constructed as follows. By definition of the Lie algebra, an element \( x \in g \otimes R \) corresponds to a \( k \)-linear map \( \mu_x : (I/I^2) \rightarrow R \), where \( I \subset A \) is the ideal of regular functions on \( G \) that vanish at the unit element \( e \in G(k) \). We then set
\[ e^{\varepsilon x} : A \rightarrow R[\varepsilon] \]
\[ f \mapsto f(e) + \mu_x(f - f(e))\varepsilon. \] (3.87)
One checks that the maps (3.86) are functorial with respect to morphisms of affine group schemes.

**Proposition 3.88.** There is a split short exact sequence

\[ 0 \longrightarrow \mathfrak{g} \xrightarrow{e^e} G(k[\varepsilon]) \longrightarrow G(k) \longrightarrow 0, \]

where the rightmost arrows are induced by the maps \( k \rightarrow k[\varepsilon] \rightarrow k \).

**Proof.** We first show that the map (3.87) is a morphism of \( k \)-algebras. That it is \( k \)-linear is clear, so we have to show that it is an algebra homomorphism. This amounts to checking the equality

\[ f(e)g(e) + \mu_x(fg - f(e)g(e))\varepsilon = [f(e) + \mu_x(f - f(e))\varepsilon][g(e) + \mu_x(g - g(e))\varepsilon] \]

in \( k[\varepsilon] \) for all \( f, g \in A \). Developing both sides and using that \( \mu_x \) is linear, we see that this equality is equivalent to

\[ \mu_x(fg + f(e)g(e) - g(e)f - f(e)g) = 0, \]

which is satisfied because

\[ fg + f(e)g(e) - g(e)f - f(e)g = (f - f(e))(g - g(e)) \in I^2. \]

We next show that the map \( e^e \) is injective. The unit in the group \( G(k[\varepsilon]) \) corresponds to the algebra morphism \( A \rightarrow k[\varepsilon] \) given by \( f \mapsto f(e) + 0\varepsilon \). Therefore, if \( x \in \mathfrak{g} \) is mapped to the unit element in \( G(k[\varepsilon]) \), then \( \mu_x \) is identically zero, and hence \( x = 0 \).

To prove exactness at the middle, notice that any element in \( \text{Hom}_{k\text{-alg}}(A, k[\varepsilon]) \) can be written as \( f \mapsto \rho(f) + \lambda(f)\varepsilon \) for some \( k \)-linear maps \( \rho, \lambda: A \rightarrow k \). Such an algebra morphism is mapped to the unit element in \( G(k) \) if and only if \( \rho(f) = f(e) \). One checks directly that a linear map of the form \( f \mapsto f(e) + \lambda(f)\varepsilon \) is an algebra homomorphism if and only if \( \lambda(1) = 0 \) and \( \lambda(I^2) = 0 \). Therefore, there exists some \( x \in \mathfrak{g} \) such that \( \lambda(f) = \mu_x(f - f(e)) \).

Finally, since the composition of the inclusion \( k \rightarrow k[\varepsilon] \) and the projection \( k[\varepsilon] \rightarrow k \) is the identity, the map \( G(k) \rightarrow G(k[\varepsilon]) \) is a section of \( G(k[\varepsilon]) \rightarrow G(k) \). In particular, the latter is surjective. \( \square \)

**Remark 3.89.** In fact, we can define a functor from \( k \)-algebras to groups

\[ g(R) = \ker(G(R[\varepsilon]) \rightarrow G(R)). \]

We have seen in Proposition 3.88 that \( g(k) = \mathfrak{g} \). Moreover, if \( G \) is algebraic, then \( g(R) = \mathfrak{g} \otimes R \) (see [DG70, II §4, Prop. 4.8]), so that we can endow \( g \) with the structure of an affine algebraic group as in Example 3.58 iv). If \( G \) is an affine group scheme, then, by Lemma 3.50 it is pro-algebraic. We write \( G = \varprojlim G_\alpha \). Hence, for every \( k \)-algebra \( R \), we have \( G(R) = \varprojlim G_\alpha(R) \). Let \( g_\alpha \) be the Lie algebra of \( G_\alpha \). Using the left-exactness of the projective limit, we deduce that

\[ g(R) = \varprojlim g_\alpha \otimes R. \]

Therefore, we can endow \( g \) with the scheme structure of Example 3.58 v).
EXAM PLES 3.90.

i) The group $G = \text{GL}_n$ is the open subscheme of the affine space $\mathbb{A}^{n^2}$ defined as the complement of the determinant hypersurface $\{\det = 0\}$. Thus, the tangent space at the origin can be identified with the space $\text{Mat}_n(k)$ of all $n \times n$ matrices over $k$ and the Lie bracket is just the usual commutator of matrices $[A, B] = AB - BA$. This Lie algebra is denoted by $\mathfrak{gl}_n$. More generally, if $V$ is a finite-dimensional vector space over $k$, then the Lie algebra $\mathfrak{gl}(V)$ of $\text{GL}(V)$ consists of all endomorphisms of $V$.

ii) The group $G = \text{SL}_n$ is the closed subscheme of $\text{GL}_n$ defined by the equation $\det = 1$. It represents the functor $R \mapsto \text{SL}_n(R)$. The Lie algebra of $G$ is a subalgebra of $\text{Lie}(\text{GL}_n) = \mathfrak{gl}_n$. Using the characterization of Proposition 3.88, it consists of the matrices $M$ such that $1 + \varepsilon M$ has determinant 1. From the equality $\det(1 + \varepsilon M) = 1 + \varepsilon \text{Tr}(M)$ in $k[\varepsilon]$, that can be proved for example by expanding the determinant along the first column and induction, we deduce that $\text{Lie}(\text{SL}_n)$ can be identified with the space of traceless $n \times n$ matrices. This Lie algebra is denoted by $\mathfrak{sl}_n$.

iii) The Lie algebra of the group $G = \text{Up}_n$ of $n \times n$ unipotent matrices is the subalgebra $\mathfrak{u}_n \subset \mathfrak{gl}_n$ consisting of strictly upper triangular matrices. Indeed, $G$ represents the functor that sends a $k$-algebra $R$ to the group $\text{Up}_n(R)$ of upper triangular matrices with diagonal entries equal to 1. The elements of $G(k[\varepsilon])$ can be thus written as $U + \varepsilon N$ with $U \in G(k)$ and $N$ strictly upper triangular with entries in $k$, and the kernel of the map $G(k[\varepsilon]) \to G(k)$ is identified with the space of such matrices $N$.

3.2.11. The universal enveloping algebra. It is sometimes more convenient to work within the framework of associative algebras instead of Lie algebras. This is possible thanks to the construction of the universal enveloping algebra. Recall from Remark 3.80 that every associative algebra is endowed with a canonical Lie algebra structure in which the Lie bracket is given by the commutator. We keep the assumption that $k$ is a field of characteristic zero.

DEFINITION 3.91. Let $(L, [\cdot, \cdot])$ be a Lie algebra over $k$. The universal enveloping algebra of $L$ is an associative $k$-algebra $U(L)$ with a morphism of Lie algebras $\iota_L : L \to U(L)$ that satisfies the following universal property: for each associative $k$-algebra $A$ and each morphism of Lie algebras $\iota : L \to A$, there exists a unique morphism of $k$-algebras $\varphi : U(L) \to A$ such that $\iota = \varphi \circ \iota_L$.

Concretely, that $\iota_L$ is a morphism of Lie algebras means that the equality $\iota_L([a, b]) = \iota_L(a)\iota_L(b) - \iota_L(b)\iota_L(a)$ holds for all $a, b \in L$. To construct $U(L)$, we begin with the tensor algebra $T(L) = \bigoplus_{n \geq 0} L^\otimes n$.
This algebra is non-commutative if $L$ with the associative product uniquely determined by
\[(a_1 \otimes \cdots \otimes a_r) \cdot (a_{r+1} \otimes \cdots \otimes a_{r+s}) = a_1 \otimes \cdots \otimes a_{r+s}.
\]
This algebra is non-commutative if $L$ has dimension bigger than 1. Consider the two-sided ideal $R(L) \subseteq T(L)$ generated by the elements
\[(3.92)\quad a \otimes b - b \otimes a - [a, b] \quad \text{for all} \quad a, b \in L.
\]
We claim that the universal enveloping algebra of $L$ is the quotient
\[(3.93)\quad U(L) = T(L)/R(L),
\]
along with the morphism $\iota_L: L \to U(L)$ given by the composition of the natural inclusion $L \to T(L)$ with the quotient map $T(L) \to U(L)$. Indeed, every $k$-linear map $\iota: L \to A$ with target an associative $k$-algebra $A$ factors uniquely through a morphism of $k$-algebras $T(L) \to A$ and, if $\iota$ is a morphism of Lie algebras, then the two-sided ideal $R(L)$ of $T(L)$ maps to zero.

**Remark 3.94.** The universal enveloping algebra $U(L)$ is endowed with the filtration (in the sense of Definition 1.85) by length given by
\[(3.95)\quad F_n U(L) = \text{image of } \bigoplus_{0 \leq m \leq n} L^\otimes m \quad \text{for } n \geq 0 \quad \text{and} \quad F_{-1} U(L) = \{0\}.
\]

The Poincaré–Birkhoff–Witt theorem encapsulates the structure of the universal enveloping algebra. The version we give below is not the most general possible (see [Bou60, §1, n° 7, Thm. 1]), but it will be enough for our purposes.

**Theorem 3.96** (Poincaré–Birkhoff–Witt). Assume that the Lie algebra $L$ admits a totally ordered basis $\{y_i\}_{i \in I}$. Then a basis of the universal enveloping algebra $U(L)$ is given by the classes of the so-called standard monomials
\[y_{i_1} \otimes \cdots \otimes y_{i_n} \in T(L) \quad \text{with} \quad i_1 \leq \cdots \leq i_n.
\]
Note that the empty monomial $1 \in T(L)$ is standard. In what follows, we will mainly use the Poincaré–Birkhoff–Witt theorem through some of its corollaries.

**Corollary 3.97.** The map $\iota_L: L \to U(L)$ is injective.

**Proof.** The map $\iota_L$ sends a basis element $y_i$ of $L$ to the standard monomial $y_i$, which is part of a basis of $U(L)$ by Theorem 3.96. \qed

The universal enveloping algebra $U(L)$ can be naturally viewed as a Hopf algebra, with the coproduct uniquely determined by the rule
\[\Delta_{\iota_L}(a) = \iota_L(a) \otimes 1 + 1 \otimes \iota_L(a),
\]
the counit $\epsilon: U(L) \to k$ induced by the zero map $L \to k$, and the antipode uniquely characterized by $S(a) = -a$ for all $a \in L$ (see Exercise 3.135 below). The counit $\epsilon$ is also called the augmentation of $U(L)$. This Hopf algebra structure allows one to recover the original Lie algebra $L$ from its universal enveloping algebra $U(L)$ as the space of primitive elements. We first define them.

**Definition 3.98.** Let $H$ be a coalgebra with coproduct $\Delta: H \to H \otimes H$. An element $a \in H$ is called primitive if it satisfies
\[\Delta a = 1 \otimes a + a \otimes 1.
\]

**Corollary 3.99.** Let $L$ be a Lie algebra that admits a totally ordered basis. Then the image $\iota_L(L)$ agrees with the set of primitive elements of $U(L)$.
The inclusion $ι_L(L) \subset P(U(L))$ is clear. To prove the converse inclusion, consider, for each integer $n \geq 0$, the vector subspace $U(L)_n$ of $U(L)$ spanned by all standard monomials of length $n$. As the image $ι_L(L)$ agrees with $U(L)_1$, we need to prove the inclusion $P(U(L)) \subset U(L)_1$. For this, we observe that the operator $∇ \circ Δ$ acts as multiplication by 2 on $P(U(L))$, whereas

\[
(∇ \circ Δ)x = 2^n x + \text{(terms of length} < n) \tag{3.100}
\]

holds for all $x \in U(L)_n$ (solve Exercise 3.136). Let $a \in P(U(L))$ be a primitive element. By the Poincaré–Birkhoff–Witt theorem, we can write $a = a_0 + \cdots + a_r$ for some elements $a_n \in U(L)_n$. Upon application of the operator $∇ \circ Δ$, we get $r = 1$, then $a_0 = 0$ from (3.100). Thus, $P(U(L)) \subset U(L)_1$ and $ι_L(L)$ agrees with the space of primitive elements.

Another consequence of the Poincaré–Birkhoff–Witt theorem is an expression for the abelianization of a Lie algebra. Let $J = \text{Ker}(ϵ) \subset U(L)$ be the augmentation ideal, that is, the quotient of $\bigoplus_{n>0} L^n$ by the two-sided ideal $R(L)$.

**Corollary 3.101.** Let $L$ be a Lie algebra that admits a totally ordered basis. The inclusion $ι_L: L \to U(L)$ induces an isomorphism


**Proof.** There is an inclusion $ι_L(L) \subset J$ by definition of the augmentation ideal. Since $ι_L$ is a morphism of Lie algebras and the Lie bracket on $U(L)$ is given by the commutator $[x, y] = xy - yx$, there is also an inclusion $ι_L([L, L]) \subset J^2$. The map $ι'_L$ is hence well defined. Since every monomial of length bigger or equal to 2 belongs to $J^2$, by Theorem 3.96, every element of $J/J^2$ can be represented by an element of $L$, so $ι'_L$ is surjective. To prove injectivity, we need to show that $ι^{-1}_L(J^2)$ is contained in $[L, L]$. For this, let us first observe that any linear combination of monomials of length $n$ can be written, using the relations (3.92) defining the ideal $R(L)$, as the sum of a linear combination of standard monomials of length 1 and a linear combination of monomials of length at most $n - 1$ in which all terms contain at least one commutator. Now, an element $a \in J^2$ can be written as a linear combination of monomials of length at least 2. Applying repeatedly the above remark, $a$ can be written as $a_t + \cdots + a_2 + b_1$, where $a_n$ is a linear combination of standard monomials of length $n$ and $b_1$ is a commutator. If $a$ lies in the image of $L$, then it is a linear combination of standard monomials of length 1. Since standard monomials form a basis of $U(L)$ by Theorem 3.96, we deduce that $a$ is equal to $b_1$, and hence lies in the image of $[L, L]$. The map $ι'_L$ is thus an isomorphism.

Applying Definition 3.77 to the Hopf algebra $U(L)$, we obtain:

**Definition 3.102.** Let $L$ be a Lie algebra. The **completed universal enveloping algebra** $U(L)^\wedge$ is the completion of $U(L)$ with respect to the augmentation ideal $J = \text{Ker}(ϵ)$, where $ϵ$ is the counit of $U(L)$. Explicitly, $\hat{U}(L)$ is the projective limit

$U(L)^\wedge = \lim_{\text{proj}} U(L)/J^{N+1}$.

Let us now explain the relationship between the dual of the ring of regular functions on an affine group scheme and the universal enveloping algebra of its Lie
Let $G$ be an affine group scheme over $k$ and $\mathfrak{g} = \text{Lie}(G)$ its Lie algebra. Since $\mathcal{O}(G)$ is a Hopf algebra, its $k$-linear dual
\[ \mathcal{O}(G)^\vee = \text{Hom}_k(\mathcal{O}(G), k) \]
has the structure of an associative algebra, in which the product of linear forms $\lambda, \mu \in \mathcal{O}(G)^\vee$ is given by the rule
\[ (\lambda \cdot \mu)(f) = (\lambda \otimes \mu)(\Delta f) \]
on functions $f \in \mathcal{O}(G)$. The associativity of this product follows from the coassociativity of the coproduct in the definition of Hopf algebra. Using the definition of the Lie algebra as $\mathfrak{g} = (I/I^2)\vee$, we get a canonical map
\[ (3.103) \quad \varphi_G : \mathfrak{g} \longrightarrow \mathcal{O}(G)^\vee \]
that sends an element $X \in \mathfrak{g}$ to the composition
\[ \mathcal{O}(G) \longrightarrow I/I^2 \xrightarrow{X} k, \]
where the first map sends $f$ to the class of $f - f(e)$. From the fact that $\varphi_G$ is a morphism of Lie algebras (Exercise 3.140) and the universal property of the universal enveloping algebra, we obtain a canonical map
\[ (3.104) \quad U(\mathfrak{g}) \longrightarrow \mathcal{O}(G)^\vee. \]
In general, this map is not an isomorphism (see Example 3.105 below). In some cases (see Theorem 3.177), the above map can be extended to the completed universal enveloping algebra $U(\mathfrak{g})^{\wedge}$. As we will see later, this is a characteristic property of pro-unipotent groups.

**Examples 3.105.**

i) Let $G = \mathbb{G}_a$ be the additive group over $\mathbb{Q}$. Its algebra of functions is the polynomial ring $\mathcal{O}(G) = \mathbb{Q}[x]$ and its Lie algebra is the abelian (i.e. with identically zero bracket) Lie algebra $\mathbb{Q}$. Its universal enveloping algebra is the algebra of polynomials $\mathbb{Q}[y]$, while its completed universal enveloping algebra is the algebra of formal power series $\mathbb{Q}[[y]]$. The canonical map (3.104) is the map $\mathbb{Q}[y] \rightarrow \mathcal{O}(G)^\vee$ that sends the divided power $y^n/n!$ to the dual of $x^n$. This map is not an isomorphism, but it extends to an isomorphism $\mathbb{Q}[[y]] \rightarrow \mathcal{O}(G)^\vee$.

ii) Let $G = \mathbb{G}_m$ be the multiplicative group over $\mathbb{Q}$. Its algebra of functions is the ring of Laurent polynomials $\mathcal{O}(G) = \mathbb{Q}[x, x^{-1}]$ and its Lie algebra is again the one-dimensional abelian Lie algebra $\mathbb{Q}$. As in the previous example, the universal enveloping algebra is the algebra of polynomials $\mathbb{Q}[y]$, and its completion is the algebra of formal power series $\mathbb{Q}[[y]]$. The map $\mathbb{Q}[y] \rightarrow \mathcal{O}(G)^\vee$ sends $y$ to the linear form $p \mapsto p'(1)$, which in the representation of Example 3.70 corresponds to the element
\[ \sum_{n \in \mathbb{Z}} n y_n. \]
Therefore, $y^\ell$ is sent to $\sum n^\ell y_n$. In this case, the map $\mathbb{Q}[y] \rightarrow \mathcal{O}(G)^\vee$ cannot be extended to the completed universal enveloping algebra.
3.2.12. Universal enveloping algebras and distributions. In this section, we explain a theorem by Cartier relating the universal enveloping algebra of the Lie algebra of an algebraic group with certain linear functionals on its regular functions that are called distributions.

Let $G = \text{Spec}(A)$ be an affine group scheme over $k$ with Lie algebra $\mathfrak{g}$. The unit element $e \in G(k)$ corresponds to a morphism of $k$-algebras $A \to k$ that we denote by $\varphi \mapsto \varphi(e)$. For each linear map $\mu : A \to k$ and each $\varphi \in A$, define

$$ (\text{ad} \varphi)\mu : A \to k \quad x \mapsto \varphi(e)x - \mu(\varphi x). $$

\textbf{Definition 3.107. A distribution on $G$ centered at $e$ of order $\leq n$ is a linear map $\mu : A \to k$ such that the equality}

$$ (\text{ad} \varphi_0) \ldots (\text{ad} \varphi_n)\mu = 0 $$

\text{holds for all } \varphi_0, \ldots, \varphi_n \in A. The space of all distributions centered at $e$ of order $\leq n$ will be denoted by $\text{Dist}_n(G)$. We also write

$$ \text{Dist}_+(G) = \{ \mu \in \text{Dist}_n(G) \mid \mu(1) = 0 \}, $$

$$ \text{Dist}(G) = \bigcup_{n \geq 0} \text{Dist}_n(G), $$

$$ \text{Dist}^+(G) = \bigcup_{n \geq 0} \text{Dist}^+_n(G). $$

\textbf{Examples 3.108. Let $G = \text{Spec}(A)$ be an affine group scheme and $\mathfrak{g}$ its Lie algebra. In this example, we compute the space of distributions in terms of the ideal $I \subset A$ of functions vanishing at the neutral element $e \in G(k)$.}

i) An element $\mu \in \text{Dist}_0(G)$ is determined by the value $\mu(1)$ through the rule $\mu(\varphi) = \varphi(e)\mu(1)$. In particular, $\mu$ vanishes on $I$, whence

$$ \text{Dist}_0(G) = (A/I)^\vee = k \quad \text{and} \quad \text{Dist}^+_0(G) = \{0\}. $$

ii) Let $\mu \in \text{Dist}_1(G)$. By definition, the linear map $(\text{ad} \varphi)\mu$ lies in $\text{Dist}_0(G)$ for all $\varphi \in A$, which by i) amounts to saying that it vanishes on $I$. This map sends $x$ to $\mu((\varphi(e) - \varphi)(x))$ by linearity of $\mu$, and hence

$$ \text{Dist}_1(G) = (A/I^2)^\vee. $$

If $\mu$ vanishes at $1$, then $\mu$ defines an element of $\mathfrak{g} = (I/I^2)^\vee$ and

$$ \mathfrak{g} \simeq \text{Dist}^+_1(G). $$

From the vanishing on $I^2$ and at $1$, we see that all $\mu \in \text{Dist}^+_1(G)$ satisfy

$$ \mu(\varphi_0 \varphi_1) = \varphi_0(e)\mu(\varphi_1) + \varphi_1(e)\mu(\varphi_0). $$

iii) More generally, $\mu$ belongs to $\text{Dist}_n(G)$ if and only $(\text{ad} \varphi)\mu$ belongs to $\text{Dist}_{n-1}(G)$ for all $\varphi \in A$. By induction, this is equivalent to the condition that $\mu$ vanishes on $I^{n+1}$, hence an isomorphism

$$ \text{Dist}_n(G) = (A/I^{n+1})^\vee. $$

The coproduct and the product of the Hopf algebra $A = \mathcal{O}(G)$ induce, by duality, a product and a coproduct in the space of distributions. Namely, there is a convolution product given by

$$ (\mu_0 * \mu_1)(\varphi) = (\mu_0 \otimes \mu_1)(\Delta \varphi). $$
The coassociativity of $\Delta$ implies that this product is associative. In addition, since the ideal $I$ is the kernel of the counit, it satisfies $\Delta I \subset A \otimes I + I \otimes A$. Therefore

$$\Delta I^{n+1} \subset \sum_{i=0}^{n+1} I^i \otimes I^{n+1-i}. \quad (3.109)$$

By the characterization of Example 3.108 iii), the inclusion (3.109) implies

$$\text{Dist}_n(G) \ast \text{Dist}_m(G) \subset \text{Dist}_{n+m}(G). \quad (3.110)$$

The coproduct

$$\Delta : \text{Dist}(G) \rightarrow \text{Dist}(G) \otimes \text{Dist}(G)$$

is given by the formula

$$\Delta \mu(\varphi_0 \otimes \varphi_1) = \mu(\varphi_0 \varphi_1).$$

For this coproduct, all elements of $\text{Dist}_1^+(G)$ are primitive (Definition 3.98). Indeed, if $\mu \in \text{Dist}_1^+(G)$, then

$$\Delta \mu(\varphi_0 \otimes \varphi_1) = \mu(\varphi_0 \varphi_1) = \varphi_0(e)\mu(\varphi_1) + \varphi_1(e)\mu(\varphi_0) = (1 \otimes \mu + \mu \otimes 1)(\varphi_0 \otimes \varphi_1).$$

**Theorem 3.111** (Cartier). Let $G$ be an affine algebraic group and $\mathfrak{g}$ its Lie algebra. Then there is a unique isomorphism of algebras

$$U(\mathfrak{g}) \rightarrow \text{Dist}(G)$$

that agrees with the isomorphism of Example 3.108 ii) for $\mathfrak{g}$. Moreover, this isomorphism is compatible with the coproduct and sends $F_nU(\mathfrak{g})$ to $\text{Dist}_n(G)$.

**Sketch of proof.** The map $U(\mathfrak{g}) \rightarrow \text{Dist}(G)$ is constructed using the universal property of the universal enveloping algebra. Indeed, $\text{Dist}(G)$ is an associative algebra, and Example 3.108 ii) gives map $\iota : \mathfrak{g} \rightarrow \text{Dist}(G)$ that satisfies

$$\iota([a, b]) = a \ast b - b \ast a$$

by Exercise 3.139. Therefore, the universal property of $U(\mathfrak{g})$ yields a morphism of algebras $U(\mathfrak{g}) \rightarrow \text{Dist}(G)$. Recall that the coproduct of $U(\mathfrak{g})$ is characterized by the fact that it is a morphism of algebras and that elements of $\mathfrak{g}$ are primitive. Since the coproduct of $\text{Dist}(G)$ is a morphism of algebras by construction and $\mathfrak{g}$ is mapped to $\text{Dist}_1^+(G)$, which consists of primitive elements, the map $U(\mathfrak{g}) \rightarrow \text{Dist}(G)$ is compatible with the coproducts on the source and the target. Moreover, it sends $F_nU(\mathfrak{g})$ to $\text{Dist}_n(G)$ because the elements of $F_nU(\mathfrak{g})$ are those that can be written as a linear combination of products of at most $n$ elements of $\mathfrak{g}$. Thanks to (3.110), those elements are sent to $\text{Dist}_n(G)$. Finally, the proof that the map is an isomorphism is a long computation using the Poincaré–Birkhoff–Witt theorem, whose details can be found in [DG70, II §6, Thm. 1.1].

### 3.2.13. Representations

We introduce the notion of representation of an abstract group and an affine group scheme. In the latter case, one needs to be careful because the group-valued functor $\text{Aut}(V)$ is not representable by a scheme when $V$ is an infinite-dimensional vector space (see part viii) of Example 3.58).

**Definition 3.112.** Let $\Gamma$ be an abstract group. A $k$-linear representation of $\Gamma$ is a $k$-vector space $V$ together with a group homomorphism

$$\Gamma \rightarrow \text{Aut}_k(V).$$

Let $G$ be an affine group scheme over $k$. A $k$-linear representation of $G$ is the data of a $k$-vector space $V$ and a natural transformation of group-valued functors
$G \to \text{Aut}(V)$. This means that we are given the data of a group homomorphism $G(R) \to \text{Aut}_R(R \otimes V)$ for every $k$-algebra $R$ and, for each morphism of $k$-algebras $R \to R'$, of a commutative diagram

$$
\begin{array}{ccc}
G(R) & \longrightarrow & \text{Aut}_R(R \otimes V) \\
\downarrow & & \downarrow \\
G(R') & \longrightarrow & \text{Aut}_{R'}(R' \otimes V).
\end{array}
$$

**Remark 3.113.** Recall from Example 3.58 that the automorphisms of a finite-dimensional vector space $V$ form an affine group scheme $\text{GL}(V)$. It turns out that, to give a finite-dimensional representation of $G$, is equivalent to give a pair consisting of a $k$-vector space $V$ and a morphism of group schemes $\rho: G \to \text{GL}(V)$. Since we will be mainly interested in finite-dimensional representations, this is the point of view that we will use the most.

Every $k$-linear representation of an affine group scheme determines a representation of the group of $k$-points $G(k)$, but of course not all representations of $G(k)$ arise this way (see Lemma 3.117 and Exercise 3.213 below for an example). Since we will be only working with $k$-linear representations, we will omit the adjective “$k$-linear” and refer to them in what follows simply as “representations”.

In some cases it is more convenient to use the point of view of comodules. For a more detailed proof of the next result see [Mil17, Rem. 4.1].

**Lemma 3.114.** Let $G$ be an affine group scheme over $k$, and let $V$ be a $k$-vector space. There is a natural one-to-one correspondence between linear representations of $G$ on $V$ and right $\mathcal{O}(G)$-comodule structures on $V$.

**Proof.** For shorthand we write $A = \mathcal{O}(G)$. In fact, the correspondence is in two steps. First each linear representation of $G$ corresponds to a left $A$-comodule structure on the dual vector space $V^\vee$. Then the left $A$-comodule structure on $V^\vee$ corresponds to a right $A$-comodule structure on $V$.

More precisely, let $\rho: G \to \text{Aut}(V)$ be a representation of $G$. For each $\omega \in V^\vee$, we consider the element

$$\Delta_\rho \omega \in A \otimes V^\vee \simeq \text{Hom}(V, A)$$

uniquely defined by the formula

$$\langle \Delta_\rho(\omega), v \rangle = \langle \omega, \rho(g)(v) \rangle.$$

Note that here $\langle \Delta_\rho(\omega), v \rangle$ is meant to be an element of $A = \mathcal{O}(G)$ and we determine it by evaluating at elements $g \in G(R)$ for any $k$-algebra $R$. By duality, this defines a right coaction $\Delta_\rho: V \to V \otimes A$, denoted with the same letter, by the rule

$$(\omega, \Delta_\rho(v))(g) = \langle \Delta_\rho(\omega), v \rangle(g) = \langle \omega, \rho(g)(v) \rangle.$$  \hspace{1cm} (3.115)

for each $v \in V$ and $\omega \in V^\vee$. It is easy to check that, in equation (3.115), the maps $\Delta_\rho$ and $\rho$ determine each other and that $\Delta_\rho$ is a right coaction of $A$ on $V$ if and only if $\rho$ is a representation of $G$.

In the finite-dimensional case this can be made more concrete by choosing basis. Let $e_1, \ldots, e_r$ be a basis of $V$. Each linear representation $\rho$ of $G$ on $V$ is an affine group homomorphism $\rho: G \to \text{GL}(V)$. After choosing the basis, we can identify $\text{GL}(V)$ with $\text{GL}_n$. Thus, $\rho: \text{Spec}(A) = G \to \text{GL}_n$ defines a point $M \in \text{GL}_n(A)$.
That is, an invertible \( r \times r \) matrix \( M = (M_{i,j}) \) with entries in \( A \). The fact that \( \rho \) is a group homomorphism is equivalent to

\[
M_{i,j}(g \cdot g') = \sum_k M_{i,k}(g)M_{k,j}(g'), \quad M_{i,j}(e) = \delta_{i,j},
\]

for \( e \) the unit of \( G \).

On the other hand, a right coaction \( \Delta : V \to V \otimes A \) defines also a matrix \( M_{i,j} \) with entries in \( A \) by the rule

\[
\Delta e_j = \sum_i e_i \otimes M_{i,j}.
\]

The fact that \( \Delta \) is a coaction is again equivalent to (3.116). Both the set of linear representations of \( G \) on \( V \) and the set of right \( A \)-coactions on \( V \) are thus given by the set of \( r \times r \) matrices with entries in \( A \) satisfying conditions (3.116). \( \square \)

From the first part of the proof of Lemma 3.50 we also derive the following result (see also [DM82, Cor. 2.4]).

**Lemma 3.117.** Every linear representation of an affine group scheme is a directed union of finite-dimensional subrepresentations.

**Definition 3.118.** Let \( G \) be an affine algebraic group. A finite-dimensional representation \( \rho : G \to \text{GL}(V) \) is called faithful if \( \text{Ker}(\rho) \) is trivial.

A useful property of affine algebraic groups is the following (see, for instance, [Bri17, Prop. 2.7.1]).

**Proposition 3.119.** Let \( f : G \to H \) be a morphism of affine algebraic groups.

i) The image \( f(G) \) is closed in \( H \).

ii) \( f \) is a closed immersion if and only if \( \text{Ker}(f) \) is zero.

In view of Proposition 3.119, a representation \( \rho \) is faithful if and only if \( \rho \) is a closed immersion.

**Corollary 3.120.** Every affine algebraic group admits a faithful finite-dimensional representation. In other words, any affine algebraic group can be realized as a closed subgroup of some general linear group \( \text{GL}(V) \).

**Proof.** Let \( G \) be an affine algebraic group, so that the algebra \( \mathcal{O}(G) \) is finitely generated. Let \( f_1, \ldots, f_n \) be a set of generators. By Lemma 3.117, there exist finite-dimensional subrepresentations \( W_1, \ldots, W_n \) of \( \mathcal{O}(G) \) such that \( W_i \) contains \( f_i \). Consider their sum \( W = W_1 + \cdots + W_n \) and the dual representation \( \rho : G \to \text{GL}(W^\vee) \). Since \( W \) contains a set of generators of \( \mathcal{O}(G) \), the map \( \text{Sym}(W) \to \mathcal{O}(G) \) given by the universal property of the symmetric algebra is surjective. Therefore, there is a closed \( G \)-equivariant immersion

\[
G \to \text{Spec}(\text{Sym}(W)) = W^\vee,
\]

which implies that \( \text{Ker}(\rho) \) is trivial. \( \square \)

We next introduce Lie algebra representations.

**Definition 3.121.** Let \( L \) be a Lie algebra over \( k \). A representation of \( L \) is a \( k \)-vector space \( V \) along with a morphism of Lie algebras

\[
\rho : L \to \text{End}(V),
\]
i.e. a $k$-linear map such that, for all $x, y \in L$, the following equality holds:

\begin{equation}
\rho([x, y]) = \rho(x)\rho(y) - \rho(y)\rho(x).
\end{equation}

**Proposition 3.123.** Let $L$ be a Lie algebra. The category of representations of $L$ is equivalent to the category of $U(L)$-modules.

**Proof.** Let $\rho: L \to \text{End}(V)$ be a representation of $L$. Thanks to the universal property of the enveloping algebra, $\rho$ factors through a unique $k$-algebra morphism $U(L) \to \text{End}(V)$, which turns $V$ into a $U(L)$-module. Conversely, a $U(L)$-module is the data of a $k$-vector space $V$ and a $k$-algebra morphism $U(L) \to \text{End}(V)$. Precomposing with the natural map from $L$ to $U(L)$, we obtain a Lie algebra morphism $L \to \text{End}(V)$. It is straightforward to check that these constructions are functorial and quasi-inverse to each other. \hfill \Box

We next relate Lie group representations with Lie algebra representations.

**Definition 3.124.** Let $G$ be an affine group scheme and $g$ its Lie algebra. With a representation $\rho$ of $G$ on a vector space $V$, we associate a representation $d\rho$ of $g$ as the unique map $d\rho: g \to \text{End}_k(V)$ that fits in the commutative diagram with exact rows

\begin{equation}
\begin{array}{ccccccccc}
0 & \longrightarrow & g & \longrightarrow & G(k[\varepsilon]) & \longrightarrow & G(k) & \longrightarrow & 0 \\
& & \downarrow{d\rho} & & \downarrow{\rho} & & \downarrow{\rho} & & \\
0 & \longrightarrow & \text{End}_k(V) & \longrightarrow & \text{Aut}_k(V \otimes k[\varepsilon]) & \longrightarrow & \text{Aut}_k(V) & & \\
\end{array}
\end{equation}

See Exercise 3.133 for the exactness of the bottom row.

---

**Exercise 3.125.** Prove that the space $H$ of Example 3.54 is a coalgebra and that $V^*$ is an $H$-comodule.

**Exercise 3.126.** Let $H$ be a Hopf algebra.

i) Consider a finite-dimensional subvector space $V$ of $H$ satisfying $\Delta(V) \subseteq V \otimes H$. Pick a basis $\{v_i\}$ of $V$ and write $\Delta(v_j) = \sum_i v_i \otimes h_{ij}$. Prove that $\Delta(h_{ij}) = \sum_i h_{i\ell} \otimes h_{\ell j}$. 

ii) Show that $\Delta \circ S = \tau \circ (S \otimes S) \circ \Delta$, where $\tau$ is the flip of the factors of $H \otimes H$. Concretely, if $\Delta(h) = \sum_i a_i \otimes b_i$, then $\Delta(S(h)) = \sum_i S(b_i) \otimes S(a_i)$.

**Exercise 3.127 (A bialgebra without antipode).** Let $H = k[x]$ be the polynomial algebra in one variable. The coproduct $\Delta(x) = x \otimes x$ and the counit $\epsilon(x) = 1$ endow $H$ with the structure of a cocommutative bialgebra. Show that $H$ does not admit an antipode.

**Exercise 3.128 (A connected graded bialgebra has an antipode).** Let $H$ be a connected graded bialgebra.

i) Use the commutativity of diagram (2) in Definition 3.46 to prove that the counit $\epsilon: H \to k$ vanishes on $H_n$ for all $n \geq 1$, and hence induces an isomorphism $H_0 \simeq k$. 

---
Show that the antipode \( S : H \to H \) is the unique algebra morphism such that \( S_{|H_0} = \text{Id} \) and, if \( x \in H_n \) for \( n \geq 1 \),
\[
S(x) = -x - \sum \nabla(S(x') \otimes x''),
\]
where the sum runs over all elements \( x'' \) appearing in the coproduct \( \Delta(x) = 1 \otimes x + x \otimes 1 + \sum x' \otimes x'' \).

**Exercise 3.129.** Let \( \mathfrak{H} \) be the Hoffman algebra.

i) Verify that the operations described in Example 3.62 endow \( \mathfrak{H} \) with a Hopf algebra structure.

ii) Recall that \( \mathfrak{H} \) is graded by assigning weight \( n \) to \( x \in \mathfrak{H} \cdot n \). Prove by induction on \( n \) that the recipe to compute the antipode presented in Exercise 3.128 yields
\[
S(x_1 \cdots x_n) = (-1)^n x_n \cdots x_1.
\]

**Exercise 3.130.** Let \( V \) be an infinite-dimensional vector space over a field \( k \).

In this exercise, we show that the functor \( F(R) = V \otimes R \) from \( k \)-algebras to sets is not representable by an affine scheme.

i) Assume that \( F \) is representable by an affine scheme \( \text{Spec}(A) \), so that the equality \( F(R) = \text{Hom}(A, R) \) holds. Prove that the natural map
\[
F(k[t]) \longrightarrow \lim_n F(k[t]/t^{n+1})
\]
is then bijective.

ii) Show that the natural map
\[
V \otimes k[t] \longrightarrow \lim_n (V \otimes k[t]/t^{n+1})
\]
is not surjective.

iii) By contrast, prove that in case \( V \) is a projective limit \( V = \lim_{\alpha} V_\alpha \) of finite-dimensional vector spaces \( V_\alpha \), the natural map
\[
\lim_{\alpha} (V_\alpha \otimes k[t]) \longrightarrow \lim_n \lim_{\alpha} (V_\alpha \otimes k[t]/t^{n+1})
\]
is a bijection.

**Exercise 3.131.** Let \( V \) be an infinite-dimensional vector space over a field \( k \).

In this exercise, we show that the functor
\[
\text{(3.132)} \quad R \longrightarrow \text{Aut}_R(R \otimes V)
\]
is not representable by an affine group scheme over \( k \).

i) Use [Har77, Lem. II.2.1] to prove that, if \( A \) is any ring, then the topological space underlying \( S = \text{Spec}(A) \) is quasi-compact. That is, every open covering of \( S \) admits a finite subcovering.

ii) Consider the functor \( \mathbb{A}^1_k \) that sends any \( k \)-algebra \( R \) to the set \( R \). Similarly to Example 3.58 iii), it is represented by the scheme \( \text{Spec}(k[x]) \). Let \( A \) be any \( k \)-algebra and \( S = \text{Spec}(A) \). Denote by \( \mathbb{S} \) the corresponding functor. Use Yoneda’s lemma [Mac71, Lem. II.2] to prove that we can recover \( A \) from \( \mathbb{S} \) as
\[
A = \text{Hom}_\text{functors}(\mathbb{S}, \mathbb{A}^1_k).
\]
Therefore, if we want to prove that a functor is representable by an affine scheme, there is a unique candidate for the corresponding algebra.
iii) Let $V$ be an infinite-dimensional $k$-vector space and let $\{v_\alpha\}_{\alpha \in I}$ be a basis. For every $\alpha \in I$, define the dual element $\omega_\alpha \in V^\vee = \text{Hom}_k(V,k)$ given by

$$\omega_\alpha(v_\beta) = \begin{cases} 1, & \text{if } \alpha = \beta, \\ 0, & \text{if } \alpha \neq \beta. \end{cases}$$

Assume that the functor $R \mapsto \text{Aut}_R(R \otimes V)$ is representable by an affine scheme $S = \text{Spec}(A)$. By ii), for all $\alpha, \beta \in I$ the morphism of functors $x_{\alpha,\beta} : S \to \mathbb{A}^1$ given by

$$x_{\alpha,\beta}(\psi) = \omega_\alpha(\psi(v_\beta))$$

determines an element of $A$. Let $D(x_{\alpha,\beta})$ be the open subset of $S$ where $x_{\alpha,\beta}$ does not vanish (see [Har77, § II.2]). Then prove that $S = \bigcup_{\alpha,\beta \in I} D(x_{\alpha,\beta})$ but that this covering does not admit a finite subcovering. This contradicts i), and hence shows that the functor (3.132) is not representable by an affine $k$-scheme.

Exercise 3.133. Let $V$ be a $k$-vector space of arbitrary dimension. Prove that there is an exact sequence

$$0 \to \text{End}_k(V) \to \text{Aut}_{k[\varepsilon]}(V \otimes k[\varepsilon]) \to \text{Aut}_k(V) \to 0,$$

where $k[\varepsilon]$ is the ring of dual numbers.

Exercise 3.134. Let $k$ be a field and let $A$ be an invertible $n \times n$ matrix with coefficients in $k$. Prove that the functor

$$R \mapsto G(R) = \{B \in \text{GL}_n(R) \mid B^tAB = A\}$$

defined on commutative $k$-algebras to groups is representable by an affine algebraic group scheme over $k$, and write down the associated Hopf algebra. In the case where $A$ is the identity matrix, one obtains the orthogonal group from Example 3.60.

Exercise 3.135. Let $(L, [\cdot, \cdot])$ be a Lie algebra. Recall the tensor algebra $T(L)$, the two-sided ideal $R(L)$, and the universal enveloping algebra $U(L) = T(L)/R(L)$ from Section 3.2.11. Consider the coproduct

$$\Delta : T(L) \to T(L) \otimes T(L)$$

defined as the unique morphism of $k$-algebras satisfying $\Delta a = 1 \otimes a + a \otimes 1$ for all $a \in L$. Prove that there is an inclusion

$$\Delta R(L) \subset R(L) \otimes T(L) + T(L) \otimes R(L),$$

hence an induced coproduct $\Delta : U(L) \to U(L) \otimes U(L)$.


Exercise 3.137 (Lie coalgebras). We introduce Lie coalgebras.

i) Let $L$ be a finite-dimensional Lie algebra over $k$. The dual of the Lie bracket $[\cdot, \cdot] : L \otimes L \to L$ is a map $d : L^\vee \to L^\vee \otimes L^\vee$. Write down the properties dual to the anti-symmetry and the Jacobi identity from Definition 3.79.
ii) A *Lie coalgebra* over $k$ is a pair $(C, d)$ consisting of a $k$-vector space $C$ and a $k$-linear map $d: C \to C \wedge C$ such that $d \circ d = 0$ holds (when $d$ is appropriately extended to $C \wedge C$). Prove that the dual of a Lie coalgebra, not necessarily of finite dimension, is a Lie algebra.

**Exercise 3.138.** In this exercise, we show that $I/I^2$ is a Lie coalgebra, and hence $L$ is a Lie algebra.

i) Check the property (3.83).

ii) Extend $d$ to an operator $d: n^\bigotimes (I/I^2) \to (I/I^2)_{n+1}$ by using the Leibniz rule with appropriate signs. Then show that $d^2 = 0$. This implies that $I/I^2$ is a Lie coalgebra. Deduce from Exercise 3.137 that $L$ is a Lie algebra.

**Exercise 3.139.** Let $G$ be an affine group scheme and $\mathfrak{g}$ its Lie algebra. Let $\Delta$ be the coproduct in $O(G)$. Let $a, b \in \mathfrak{g}$ and $f \in I \subset O(G)$. Show that the bracket in $\mathfrak{g}$ is given explicitly by

$$[a, b](f) = (a \otimes b - b \otimes a)(\Delta f).$$

**Exercise 3.140.** Show that the map $\varphi_G$ in (3.103) satisfies

$$\varphi_G([X, Y]) = \varphi_G(X) \cdot \varphi_G(Y) - \varphi_G(Y) \cdot \varphi_G(X).$$

**Exercise 3.141.** Prove the equality

$$\Delta(x^n) = \sum_{r=0}^{n} \binom{n}{r} x^r \otimes x^{n-r}$$

in the Hopf algebra $k[x]$ associated with the additive group $G_a$.

**Exercise 3.142 (The Hopf algebra of rooted trees).** In this exercise, we describe the *Hopf algebra of rooted trees* introduced by Connes and Kreimer, in connection with the renormalization of quantum field theories [CK98]. Another nice reference is [Foi]. We begin with a couple of definitions. A *rooted tree* is an oriented finite graph which is connected and simply connected (in other words, a tree), and has a distinguished vertex with no incoming edges called the root. Continuing the metaphor, the vertices with no outcoming edges are called the leaves. A *rooted forest* is a disjoint union of rooted trees.

Let $\mathcal{H}_R$ be the $\mathbb{Q}$-algebra of polynomials in rooted trees, *i.e.* $\mathcal{H}_R$ is the free commutative $\mathbb{Q}$-algebra with unit generated by (isomorphism classes of) rooted trees. The product of two rooted trees can be identified with their disjoint union and the unit is the empty tree $1$. Therefore, as vector space,

$$\mathcal{H}_R = \mathbb{Q}\{\text{rooted forests up to isomorphism}\}.$$

Let $t$ be a rooted tree. An *admissible cut* $c$ of $t$ is the choice of a non-empty subset of the edges such that any path from the root to the leaves meets at most one of them. Deleting the edges in $c$, one gets a rooted forest $W^c(t)$. Among the connected components of $W^c(t)$, there is a unique tree $R^c(t)$ containing the
original root. The rooted forest consisting of the remaining components will be
denoted by $P^c(t)$. Writing $\text{Adm}_*(t)$ for the set admissible cuts of $t$, we define
\begin{equation}
\Delta t = 1 \otimes t + t \otimes 1 + \sum_{c \in \text{Adm}_*(t)} P^c(t) \otimes R^c(t).
\end{equation}
Since $\mathcal{H}_R$ is the free algebra in rooted trees, (3.143) extends uniquely to a coproduct
$\Delta: \mathcal{H}_R \to \mathcal{H}_R \otimes \mathcal{H}_R$.

Figure 15 below gives an example of an admissible cut of a rooted tree and its
contribution to the coproduct.

![Figure 15. Coproduct of rooted trees](image)

The counit is the map $\epsilon: \mathcal{H}_R \to \mathbb{Q}$ which sends the empty tree to 1 and everything else to zero.

i) Prove that $\Delta$ and $\epsilon$ satisfy the associativity and counit axioms from Definition 3.46. In other words, $\mathcal{H}_R$ is a bialgebra.

ii) For each integer $n \geq 0$, let $\mathcal{H}_R(n) \subseteq \mathcal{H}_R$ be the vector subspace generated
by rooted forests with $n$ vertices, so that $\mathcal{H}_R = \bigoplus_{n \geq 0} \mathcal{H}_R(n)$.

Observe that $\Delta \mathcal{H}_R(n) \subseteq \bigoplus_{i+j=n} \mathcal{H}_R(i) \otimes \mathcal{H}_R(j)$. Since $\mathcal{H}_R$ is obviously a
graded connected algebra, by Exercise 3.128 there is a unique antipode $S$
turning $\mathcal{H}_R$ into a Hopf algebra.

iii) Given a rooted tree $t$ and a cut $c$, write $n_c$ for the number of edges in $c$.
Prove that the antipode is given by
$\begin{equation}
S(t) = -t - \sum_{c \in \text{Adm}_*(t)} (-1)^{n_c} W_c(t).
\end{equation}$

Exercise 3.144. Let $G$ be an affine group scheme. By Lemma 3.50, we can
write $G$ as a projective limit $G = \varprojlim G_\alpha$ of affine algebraic groups $G_\alpha$. Use
Proposition 3.119 to prove that we can assume that all maps $G \to G_\alpha$ are surjective.
3.3. Unipotent and pro-unipotent groups. In this section, we gather various properties of unipotent affine algebraic groups and pro-unipotent affine group schemes and their Lie algebras that will enter the study of the pro-unipotent completion of a group in the next section.

3.3.1. Definition of unipotent and pro-unipotent groups. Recall that we proved in Lemma 3.50 that every affine group scheme is pro-algebraic, that is, can be written as a projective limit of affine algebraic groups.

**Definition 3.145.** An affine algebraic group $G$ over $k$ (resp. an affine group scheme over $k$) is called unipotent (resp. pro-unipotent) if every non-zero representation of $G$ has a non-zero fixed vector.

**Remark 3.146.** In view of Lemma 3.117, in order to check if an affine algebraic group is unipotent or if an affine group scheme is pro-unipotent, it is enough to check that non-zero finite-dimensional representations have a non-zero fixed vector.

**Example 3.147.** Let $U_p^n$ be the affine algebraic group from Example 3.60 ii), that is, the functor that associates with each $k$-algebra $R$ the subgroup of $GL_n(R)$ consisting of upper triangular matrices with all diagonal entries equal to 1. For every $k$-vector space $V$ of dimension $n$, a choice of a basis of $V$ induces a closed immersion $U_p^n \rightarrow GL(V)$. We will prove in Corollary 3.158 below that an affine algebraic group is unipotent if and only if it is isomorphic to a closed subgroup of some $U_p^n$. One implication follows from the existence of faithful finite-dimensional representations; the other relies on the characterization of unipotent groups in terms of the conilpotency filtration proved in the next section.

**Proposition 3.148.** Every unipotent affine algebraic group is isomorphic to a closed subgroup of $U_p^n$.

**Proof.** Let $G$ be a unipotent algebraic group and let $\rho: G \rightarrow GL(V)$ be a faithful representation of $G$ of dimension $n$, which exists by Corollary 3.120. By definition of unipotency, $V$ contains a non-zero fixed vector $v_1$. Let us choose inductively vectors $v_2, \ldots, v_n$ in such a way that the image of $v_{i+1}$ in the quotient representation $V/\langle v_1, \ldots, v_i \rangle$ is a non-zero fixed vector. Then $v_1, \ldots, v_n$ form a basis of $V$ and, via the corresponding identification of $GL(V)$ with $GL_n$, the image of $\rho$ is contained in $U_p^n$. Since $\rho$ is faithful, we get a closed immersion $G \rightarrow U_p^n$ by Proposition 3.119. \hfill \Box

**Definition 3.149.** Let $G$ be either an abstract group or an affine group scheme. A finite-dimensional representation $\rho: G \rightarrow GL(V)$ is called unipotent if there exists a basis of $V$ with respect to which the image of $\rho$ lies inside $U_p^n$.

It follows readily from Definitions 3.145 and 3.149 that an affine algebraic group is unipotent if and only if all its non-zero finite-dimensional representations are unipotent. The terminology pro-unipotent is justified by the following result.

**Proposition 3.150.** An affine group scheme $G$ is pro-unipotent if and only if it can be written as a projective limit of unipotent affine algebraic groups.

**Proof.** Let $G$ be a pro-unipotent affine group scheme. By Lemma 3.50, it can be written as a projective limit

$$G = \lim_{\alpha} G_{\alpha}$$ (3.151)
of affine algebraic groups $G_\alpha$. We assume that all the morphisms $\pi_\alpha: G \to G_\alpha$ are surjective, as we may by Exercise 3.144. Let $V$ be a finite-dimensional representation of $G_\alpha$. Then $V$ defines a finite-dimensional representation of $G$ through the map $\pi_\alpha$. Since $G$ is pro-unipotent, $V$ has a fixed vector $v$ for the action of $G$. Using the surjectivity of $\pi_\alpha$, this vector is also fixed for the action of $G_\alpha$, and hence the affine algebraic group $G_\alpha$ is unipotent.

Conversely, assume that each $G_\alpha$ in the limit (3.151) is unipotent, and let $V$ be a non-zero finite-dimensional representation of $G$. Let $H \subset \text{GL}(V)$ be the closure of the image of the representation. Then the map $\mathcal{O}(H) \to \mathcal{O}(G)$ is injective and $\mathcal{O}(H)$ is finitely generated. Taking the equality $\mathcal{O}(G) = \bigcup_\alpha \mathcal{O}(G_\alpha)$ into account, there is an inclusion $\mathcal{O}(H) \subset \mathcal{O}(G_\alpha)$ for some $\alpha$. This means that the representation $V$ factors through $G_\alpha$, and hence has a non-zero fixed vector since $G_\alpha$ is unipotent. □

3.3.2. The conilpotency filtration. We give an alternative characterization of pro-unipotent affine group schemes. Let $G = \text{Spec}(A)$ be an affine group scheme over $k$. Recall from Section 3.2.7 that $A^\vee = \text{Hom}(A, k)$ has the structure of a completed Hopf algebra. In particular, it is endowed with a counit $\epsilon: A^\vee \to k$, that is also called an augmentation. Its kernel $J = \text{Ker}(\epsilon) \subset A^\vee$ is called the augmentation ideal. Denote by $J^n$ the $n$-th power of the ideal $J$ defined using the algebra structure of $A^\vee$, and consider the annihilator

$$C_i = \text{Ann}_A J^{i+1},$$

that is, the set of elements $a \in A$ satisfying $\langle a, x \rangle = 0$ for all $x \in J^{i+1} \subset A^\vee$. Here we are using again the notation $\langle \cdot, \cdot \rangle$ for the pairing between a vector space and its dual. The conilpotency filtration is the filtration of $A$ defined by

$$0 \subset C_0 \subset C_1 \subset \cdots \subset C_i \subset \cdots$$

It is easy to see that $C_0 = k \cdot 1$, where $1$ is the unit of $A$, and that the conilpotency filtration is compatible with the coproduct, in that there is an inclusion

$$\Delta C_i \subset \sum_{a+b=i} C_a \otimes C_b.$$  

(3.152)

**PROPOSITION 3.153.** The affine group scheme $G = \text{Spec}(A)$ is pro-unipotent if and only if the conilpotency filtration of $A$ is exhaustive, that is:

$$A = \bigcup_{i=0}^{\infty} C_i.$$  

**PROOF.** We first assume that the conilpotency filtration is exhaustive. Let $V$ be a non-zero representation of $G = \text{Spec}(A)$ and denote by $\Delta: V \to V \otimes A$ the corresponding comodule structure given by Lemma 3.114. The filtration $\{C_i\}_{i \geq 0}$ of $A$ being exhaustive, we deduce that the filtration $\{V_i\}_{i \geq 0}$ of $V$ given by

$$V_i = \{v \in V \mid \Delta v \in V \otimes C_i\}$$

is also exhaustive. By the compatibility with the counit in the axioms defining a comodule (see Definition 3.53), if $v \in V_0$, then $\Delta v = v \otimes 1$. Any vector $v \in V_0$ is hence a fixed vector for the representation, and to prove that $G$ is pro-unipotent is enough to show that $V_0$ is non-zero. To this end, we show that the vanishing
of $V_i$ implies that of $V_{i+1}$. Indeed, assume that $V_i = 0$ and let $v \in V_{i+1}$. Using the inclusion (3.152), we get

$$(1 \otimes \Delta) \Delta v \in \sum_{a+b=i+1} V \otimes C_a \otimes C_b.$$ 

Since $a$ and $b$ cannot be both bigger than $i$, the vector $v$ is sent to zero by the map

$$V \xrightarrow{\Delta} V \otimes A \xrightarrow{1 \otimes \Delta} V \otimes A \otimes A \xrightarrow{} V \otimes A/C_i \otimes A/C_i.$$ 

But, by the associativity property of comodules, this map agrees with the map

$$V \xrightarrow{\Delta} V \otimes A \xrightarrow{\Delta \otimes 1} V \otimes A \otimes A \xrightarrow{} V \otimes A/C_i \otimes A/C_i,$$

which is an injection since $V_i = 0$. Thus, $v = 0$, and hence $V_{i+1} = 0$.

Conversely, assume that every non-zero representation of $G$ has a non-zero fixed vector. Then every representation $V$ has an increasing filtration $\{V_i\}_{i \geq 0}$ inductively defined by taking the set of fixed vectors as $V_0$, and the set of elements whose image in the representation $V/V_i$ are fixed vectors as $V_{i+1}$. This filtration is exhaustive by Lemma 3.117. Let now $V$ be the representation given by $A$ itself with the coaction determined by the coproduct of $A$. Then

$$V_0 = \{a \in A \mid \Delta a = a \otimes 1\} = k \quad \text{and} \quad V_i = \{a \in A \mid \Delta a \in a \otimes 1 + V_i-1 \otimes A\}$$

for all $i \geq 1$. We show by induction that $V_i \subset C_i$, that is, the conilpotency filtration contains this filtration. Since $V_0 = k = C_0$ the case $i = 0$ is clear. Assume that $V_i \subset C_i$ and let $a \in V_{i+1}$. By the characterization of $V_{i+1}$ we see that $\Delta a$ can be written as

$$\Delta a = a \otimes 1 + \sum_j b_j \otimes c_j$$

with $b_j \in V_j$. Let $x \in J^{i+1}$ and $y \in J$. Then

$$\langle a, xy \rangle = \langle \Delta a, x \otimes y \rangle = \langle a, x \rangle \langle 1, y \rangle + \sum_j \langle b_j, x \rangle \langle c_j, y \rangle = 0$$

because $\langle 1, y \rangle = 0$ and $\langle b_i, x \rangle = 0$. Therefore, $a \in \text{Ann}(J^{i+2}) = C_{i+1}$. Since the filtration $\{V_i\}_{i \geq 0}$ is exhaustive, the same is true for the filtration $\{C_i\}_{i \geq 0}$. 

**Example 3.154.** The multiplicative group $G_m$ is isomorphic to $GL_1$ and the standard representation of $GL_1$ on the one-dimensional vector space does not have any non-zero fixed vector. Thus, $G_m$ is not unipotent. By contrast, the additive group $G_a$ is isomorphic to $U_{p_2}$ through the morphism $x \mapsto (\frac{1}{0} 1)$, and hence is a unipotent group. In this example, we illustrate Proposition 3.153 using both groups. As seen in Example 3.70, the dual $\mathcal{O}(G_m)^\vee$ is the algebra

$$\prod_{n \in \mathbb{Z}} ky_n$$

with product $(y_n)^2 = y_n$ and $y_n y_m = 0$ for $n \neq m$. The augmentation is given by $\epsilon(y_0) = 1$ and $\epsilon(y_n) = 0$ for $n \neq 0$. Hence, the augmentation ideal is equal to

$$J = \prod_{n \neq 0} ky_n$$

and all its powers $J^i$ are equal to $J$, whence

$$C_i = \text{Ann} J^{i+1} = \text{Ann} J = k.$$
It follows that the conilpotency filtration is not exhaustive, in accordance with the fact that \( \mathbb{G}_m \) is not a unipotent group.

On the other hand, as shown in Example 3.69, the dual \( \mathcal{O}(\mathbb{G}_a)^\vee \) is the algebra of power series \( k[[y]] \) with augmentation \( \epsilon(1) = 1 \) and \( \epsilon(y^n) = 0 \) for \( n \neq 0 \). Therefore, the augmentation ideal is equal to \( J = y k[[y]] \) and the equality

\[
J^i = y^i k[[y]]
\]

holds for all \( i \geq 1 \). Since \( y^n/n! \) is the dual of \( x^n \), the annihilator

\[
C_i = \text{Ann } J^{i+1} = k[x]_{\leq i}
\]

is the space of polynomials of degree less than or equal to \( i \). The conilpotency filtration is hence exhaustive, in agreement with the fact that \( \mathbb{G}_a \) is unipotent.

Although the conilpotency filtration has the advantage of being canonical, a closer inspection to the proof of Proposition 3.153 shows that any filtration with similar properties would be enough to characterize pro-unipotent groups. This is made explicit in the following lemma, which is useful in situations where it might be tricky to determine the exact shape of the conilpotency filtration. We will use it in Proposition 3.156 below to prove that \( U_p_n \) and its subgroups are unipotent.

**Lemma 3.155.** Let \( G = \text{Spec}(A) \) be an affine group scheme. Assume that there exists an increasing exhaustive filtration \( \{F_i\}_{i \geq 0} \) of the \( k \)-vector space \( A \) satisfying the conditions \( F_0 = k \) and \( \Delta F_i \subseteq \sum_{a+b=i} F_a \otimes F_b \). Then the conilpotency filtration on \( A \) is exhaustive, and hence \( G \) is pro-unipotent.

**Proof.** Consider the decreasing filtration \( \{W^{i+1}\}_{i \geq 0} \) on \( A^\vee \) defined by

\[
W^{i+1} = \text{Ann}_{A^\vee} F_i.
\]

That is, \( W^{i+1} \subseteq A^\vee \) consists of those linear forms that vanish on all elements of \( F_i \). Since \( J \) is the kernel of the counit, which is nothing but the evaluation map at constants inside \( A \), the condition \( F_0 = k \) is equivalent to \( W^1 = J \). Moreover, the compatibility between the filtration and the coproduct implies \( W^a \cdot W^b \subseteq W^{a+b} \), for the algebra structure on \( A^\vee \) dual to the coalgebra structure on \( A \). Indeed, the coproduct of an element \( z \in F_{a+b-1} \) takes the form \( \Delta z = \sum_{r+s=a+b-1} z_r \otimes z_s \) for some \( z_r \in F_r \) and \( z_s \in F_s \); hence, \( \langle z, x \cdot y \rangle = \langle \Delta z, x \otimes y \rangle = 0 \) holds for all \( x \in W^a \) and \( y \in W^b \), since the terms appearing in the sum either satisfy \( r < a \), in which case \( \langle z_r, x \rangle = 0 \), or \( s < b \), in which case \( \langle z_s, y \rangle = 0 \). From \( W^1 = J \) and the multiplicativity of \( W^* \), we deduce an inclusion \( J^{i+1} \subseteq W^{i+1} \), and hence the annihilator \( C_i = \text{Ann}_{A^\vee} J^{i+1} \) contains \( F_i \). The latter filtration being exhaustive by assumption, so is the conilpotency filtration.

**Proposition 3.156.** Every closed subgroup of \( U_p_n \) is unipotent.

**Proof.** Recall that the algebraic group \( U_p_n \) is the spectrum of the Hopf algebra \( A = k[[x_{ij}]]_{1 \leq i < j \leq n} \), on which the coproduct is given by the formula

\[
\Delta x_{ij} = 1 \otimes x_{ij} + \sum_{i < k < j} x_{ik} \otimes x_{kj} + x_{ij} \otimes 1
\]

for all \( i < j \) (see Example 3.58 vi) for the case of \( \text{GL}_n \)). Let \( F_i \) be the increasing filtration of \( A \) associated with the algebra grading \( A = \bigoplus_{r \geq 0} A_r \) determined by the properties \( A_0 = k \) and \( x_{ij} \in A_{j-i} \), that is, \( F_i = \bigoplus_{r \leq i} A_r \). Clearly, \( F_* \) is exhaustive.
and satisfies $F_0 = k$. Moreover, the condition $\Delta F_i \subseteq \sum_{a+b=i} F_a \otimes F_b$ follows from the formula (3.157). It then results from Lemma 3.155 that $\text{Up}_n$ is unipotent.

Let us now consider a closed subgroup $H \subset \text{Up}_n$, given by $H = \text{Spec}(B)$ with $B = A/I$. The filtration $F_\ast$ of $A$ induces a filtration $F_\ast$ of $B$, which satisfies the conditions $F_0 = k$ and $\Delta F_i \subseteq \sum_{a+b=i} F_a \otimes F_b$ because the map $A \to B$ is a morphism of Hopf algebras. Since $F_\ast$ is exhaustive and $A$ surjects onto $B$, the filtration $F_\ast$ is also exhaustive, and hence $H$ is unipotent. □

Combined with Proposition 3.148, this yields the following characterization of unipotent affine algebraic groups.

**Corollary 3.158.** An affine algebraic group is unipotent if and only if it is isomorphic to a closed subgroup of some $\text{Up}_n$.

### 3.3.3. Nilpotent and quasi-nilpotent Lie algebras

In this section, we isolate a class of Lie algebras that are the counterpart of pro-unipotent affine group schemes.

**Definition 3.159.** Let $L$ be a Lie algebra over $k$. The lower central series of $L$ is the descending filtration $L \supset L^{(1)} \supset L^{(2)} \supset \cdots$ given by $L^{(0)} = L$ and $L^{(i+1)} = [L, L^{(i)}]$ for all integers $i \geq 0$.

**Definition 3.160.** A Lie algebra $L$ over $k$ is said to be nilpotent if its lower central series $L^{(i)}$ is eventually zero, i.e. there exists an integer $n$ such that

$$[x_1, [x_2, \cdots [x_n, y] \cdots] = 0 \text{ for all } x_1, \ldots, x_n, y \in L.$$  

It is said to be quasi-nilpotent if the lower central series is a separated filtration:

$$\bigcap_{i \geq 0} L^{(i)} = \{0\}.$$

Every nilpotent Lie algebra is obviously quasi-nilpotent, and the two notions agree in finite dimension. Free Lie algebras (see Definition 3.189 below) provide examples of infinite-dimensional quasi-nilpotent Lie algebras that are not nilpotent.

**Example 3.162.** For each $n \geq 1$, the vector subspace $u_n \subset \mathfrak{gl}_n$ consisting of all strictly upper triangular matrices is a nilpotent Lie algebra. Indeed, $u_n$ is a Lie subalgebra since the property of being strictly upper triangular is preserved under products and sums of matrices. It is nilpotent because in the product of $r$ elements of $u_n$, and hence in all elements of the $(r-1)$th step of the lower central series, all the entries $x_{ij}$ with $j - i \leq r$ are zero.

For finite-dimensional Lie algebras $L$, condition (3.161) holds as soon as, for each $x \in L$, there exists an integer $n \geq 1$ such that

$$[x, [\cdots [x, y] \cdots] = 0$$

holds for all $y \in L$. This is the statement of *Engel’s theorem*. One of its consequences, sometimes also referred to by the same name, is the following.

**Proposition 3.163.** Let $V$ be a vector space of dimension $n$ and let $L \subset \mathfrak{gl}(V)$ be a Lie subalgebra consisting of nilpotent endomorphisms. Then there exists a basis of $V$ such that, under the identification $\mathfrak{gl}(V) = \mathfrak{gl}_n$, the subalgebra $L$ is contained in the Lie algebra $u_n$ from Example 3.162. In other words, by a single choice of basis, all the endomorphisms of $L$ can be turned into strictly upper triangular matrices.
A proof is given in [Jac62, Ch. 2 §3].

**Lemma 3.164.** The Lie algebra of a unipotent affine algebraic group is nilpotent.

**Proof.** Let $U$ be a unipotent affine algebraic group and let $u = \text{Lie}(U)$ be its Lie algebra. By Proposition 3.148, the group $U$ can be embedded as a closed subgroup of $U_p^n$ for some integer $n$, whose Lie algebra is $u_n$, the Lie algebra of strictly upper triangular matrices, by Example 3.90 iii). Hence, $u$ is a Lie subalgebra of $u_n$. The result then follows from the fact that $u_n$ is nilpotent by Example 3.162 and that any Lie subalgebra of a nilpotent algebra is again nilpotent. □

**Corollary 3.165.** The Lie algebra of a pro-unipotent affine group scheme is quasi-nilpotent.

**Proof.** Let $U$ be a pro-unipotent affine group scheme, written as

$$U = \lim\limits_{\alpha} U_{\alpha},$$

for a projective system of unipotent affine algebraic groups $U_{\alpha}$. By functoriality, the Lie algebra $u$ of $U$ can then be written as the projective limit $u = \lim\limits_{\alpha} u_{\alpha}$ of the finite-dimensional Lie algebras $u_{\alpha} = \text{Lie}(U_{\alpha})$. In particular, there is an injection $u \hookrightarrow \prod_{\alpha} u_{\alpha}.

By Lemma 3.164, each Lie algebra $u_{\alpha}$ is nilpotent, which means that $u_{\alpha}^{(n_{\alpha})}$ vanishes for some $n_{\alpha}$. Therefore, an element $x \in \bigcap_{i \geq 0} u^{(i)}$ has zero image in all $u_{\alpha}^{(i)}$, and is hence zero itself. This shows that the Lie algebra $u$ is quasi-nilpotent. □

**Definition 3.166.** A Lie algebra $L$ is called regular if it can be written as a projective limit of finite-dimensional nilpotent Lie algebras:

$$L = \lim\limits_{\alpha} L_{\alpha}.$$

This definition is analogous to that of pro-unipotent affine group scheme in that we enforce the finite-dimensionality condition on each Lie algebra $L_{\alpha}$. The same argument as in the proof of Corollary 3.165 implies that every pro-nilpotent Lie algebra is quasi-nilpotent.

**Definition 3.167.** Let $L$ be a Lie algebra with finite-dimensional abelianization $L/[L, L]$. The pro-nilpotent completion of $L$ is the pro-nilpotent Lie algebra

$$\hat{L} = \lim\limits_{\alpha} L/[L^{(i)}].$$

Every finitely generated Lie algebras (for example, a free Lie algebra on a finite set of generators) satisfies the assumption of this definition. The pro-nilpotent completion $\hat{L}$ is indeed pro-nilpotent, since the finite-dimensionality of $L/[L, L]$ implies that of $L/L^{(i)}$ by mimicking the proof of Lemma 3.221 (see Exercise 3.214) and the lower central series of $L/L^{(i)}$ is given by $L^{(i)}/L^{(i+1)}$. If the Lie algebra $L$ is quasi-nilpotent, then the canonical map $L \to \hat{L}$ is injective.

**Remark 3.168.** The completion could be defined without the assumption that $L/[L, L]$ is finite-dimensional, but in general it will not be a pro-nilpotent Lie algebra. A variant of this construction for graded Lie algebras will be introduced in Section 3.3.8.
The exponential map. One of the main tools in the classical theory of Lie groups is the exponential map from Lie($G$) to $G$. Even if $G$ is algebraic, this map is not algebraic in general (for example, it is the usual exponential function for $G = \mathbb{G}_m$), so it is not straightforward how to construct it in the setting of affine group schemes and their Lie algebras. In the case of unipotent group schemes, however, the exponential map turns to be algebraic. In what follows, we write

$$R[\varepsilon] = R[x]/x^2 = R[[x]]/x^2$$

for the ring of dual numbers associated with a $k$-algebra $R$.

**Proposition 3.169.** Let $G$ be an affine group scheme over $k$ and $\mathfrak{g}$ its Lie algebra. For each $k$-algebra $R$ and each $x \in \mathfrak{g} \otimes R$, there exists a unique element $\exp(Tx) \in G(R[[T]])$ satisfying the following conditions:

i) the image $\exp(\varepsilon x)$ of $\exp(Tx)$ in $G(R[\varepsilon])$ is equal to $e^{\varepsilon x}$, where $e^{\varepsilon x}$ is the element defined in (3.87);

ii) the equality $\exp((T + T')x) = \exp(Tx) \exp(T'x)$ holds in $G(R[[T,T']])$. Here $\exp((T + T')x)$ represents the image of $\exp(Tx)$ in $G(R[[T,T']])$ under the map induced by the algebra morphism $R[[T]] \to R[[T,T']]$ that sends $T$ to $T + T'$.

This result is proved in [DG70, II §6, Prop. 3.1]. We now look for conditions ensuring that the element $\exp(Tx)$ lies in $G(R[T])$.

**Definition 3.170.** Let $G$ be an affine algebraic group and $\mathfrak{g}$ its Lie algebra. An element $x \in \mathfrak{g} \otimes R$ is called nilpotent if there exists a faithful representation $\rho: G \to \text{GL}(V)$ such that $d\rho(x)$ is a nilpotent endomorphism of $V \otimes R$.

The next result is [DG70, II §6 Cor. 3.5].

**Proposition 3.171.** If $x$ is nilpotent, then $\exp(Tx)$ belongs to $G(R[T])$.

Thanks to Proposition 3.171, we can make the following definition.

**Definition 3.172.** Let $x \in \mathfrak{g} \otimes R$ be a nilpotent element. Then we define $\exp(x)$ as the image of $\exp(Tx)$ under the map $G(R[[T]]) \to G(R)$ induced by $T \mapsto 1$.

Let us now assume that $U$ is a unipotent affine algebraic group, and let $\mathfrak{u}$ be its Lie algebra. By Proposition 3.148, there exists a faithful representation $\rho: U \to \text{GL}(V)$ such that $\rho(U)$ lies in $\text{Up}_n$ for a suitable choice of basis of $V$. Every element of $\mathfrak{u} \otimes R$ is hence nilpotent, and we obtain maps

$$\exp: \mathfrak{u} \otimes R \to U(R)$$

thanks to Proposition 3.171. These maps are functorial with respect to morphisms of $k$-algebras. Since $\mathfrak{u}$ is finite-dimensional, the functor $R \mapsto \mathfrak{u} \otimes R$ is represented by a $k$-scheme that we will also denote by $\mathfrak{u}$, and (3.173) is the evaluation on $R$-points of a morphism of schemes $\exp: \mathfrak{u} \to U$.

**Theorem 3.174.** Let $U$ be a unipotent affine algebraic group and $\mathfrak{u}$ its Lie algebra, viewed as a scheme. Then $\exp: \mathfrak{u} \to U$ is an isomorphism of schemes. In particular, $\mathcal{O}(U)$ is a polynomial algebra (i.e. a free commutative algebra).

This result is proved in [DG70, IV §2 Prop. 4.1].
Corollary 3.175. Let $U$ be a pro-unipotent affine group scheme and $u$ its Lie algebra. If $u$ is given the pro-algebraic scheme structure from Remark 3.89, then the exponential $\exp: u \rightarrow U$ is an isomorphism of pro-algebraic schemes.

Proof. Write $U$ as a projective limit $U = \lim_{\alpha} U_{\alpha}$ of unipotent affine algebraic groups $U_{\alpha}$, and let $u_{\alpha} = \text{Lie}(U_{\alpha})$. Since the isomorphisms of schemes $\exp: u_{\alpha} \rightarrow U_{\alpha}$ from Theorem 3.174 are functorial, they induce an isomorphism of pro-algebraic schemes $\exp: u \rightarrow U$.

Definition 3.176. Let $U$ be a pro-unipotent affine group scheme and $u$ its Lie algebra, with the structure of a pro-algebraic scheme from Remark 3.89. The logarithm is the isomorphism of schemes $\log: U \rightarrow u$ inverse to $\exp$.

The phenomenon we saw in Example 3.105 i), namely the existence of an isomorphism from the completed universal enveloping algebra of the additive group to the dual of its ring of functions, is characteristic of pro-unipotent groups.

Theorem 3.177. Let $U$ be a pro-unipotent affine group scheme and $u$ be its Lie algebra. Assume that $u/[u, u]$ is finite-dimensional. Then the canonical map $U(u) \rightarrow \mathcal{O}(U)^\vee$ from (3.104) extends to an isomorphism $U(u)^\vee \rightarrow \mathcal{O}(U)^\vee$ on the completed universal enveloping algebra.

Proof. We first show that the canonical map $U(u) \rightarrow \mathcal{O}(U)^\vee$ can be extended to a map $U(u)^\vee \rightarrow \mathcal{O}(U)^\vee$. Indeed, let $f \in \mathcal{O}(U)$ and $\mu \in U(u)^\vee$. Since the conilpotency filtration on $\mathcal{O}(U)$ is exhaustive by Proposition 3.153, there exists an integer $i$ such that $f$ lies in the annihilator $C_i = \text{Ann}_{\mathcal{O}(U)} J^{i+1}$. We can then define $\mu(f)$ as the image of $f$ by the image of $\mu$ in $U(u)/J^{i+1}$. Since the original map $U(u) \rightarrow \mathcal{O}(U)^\vee$ is compatible with the product and the (completed) coproduct on the Hopf algebras $U(u)$ and $\mathcal{O}(U)^\vee$, the same holds for this extension.

Let us now show that the map $U(u)^\vee \rightarrow \mathcal{O}(U)^\vee$ is an isomorphism, for which it suffices to check that it is an isomorphism of vector spaces. We first consider the case of a unipotent affine algebraic group $U$. Let $A = \mathcal{O}(U)$ be its ring of regular functions and $I \subset A$ the ideal of those vanishing at the neutral element $e \in U(k)$. By Theorem 3.174, $A$ is a polynomial algebra, say $A = k[T_1, \ldots, T_r]$. Up to translating the variables by elements of $k$, we may assume that $I$ is generated by $T_1, \ldots, T_r$. Let $A_{\leq n}$ denote the vector space of polynomials of degree less than or equal to $n$. As vector spaces, there is a decomposition

\begin{equation}
A = A_{\leq n} \oplus I^{n+1},
\end{equation}

hence isomorphisms of vector spaces $A_{\leq n} \simeq A/I^{n+1}$. Since $A = \varprojlim A_{\leq n}$, we have

\begin{equation}
A^\vee \simeq \varprojlim (A_{\leq n})^\vee.
\end{equation}

By Theorem 3.111, the universal enveloping algebra of $u$ and the space of distributions on $U$ are isomorphic: $U(u) \simeq \text{Dist}(U)$. This isomorphism sends $F_n U(u)$ to $\text{Dist}_n(U)$. Besides, we saw in Example 3.108 iii) that the space $\text{Dist}_n(U)$ is isomorphic to the dual of $A/I^{n+1}$. Hence, we obtain an identification

\begin{equation}
F_n U(u) \simeq (A/I^{n+1})^\vee.
\end{equation}

There is a decomposition

\begin{equation}
U(u) = F_n U(u) \oplus J^{n+1}.
\end{equation}
Together with the decomposition (3.178) and the identification (3.179) it gives an identification

\[ U(u)/J_n^{n+1} \simeq (A_{\leq n})^\vee. \]

By construction, the map \( U(u)^\wedge \to A^\vee \) fits into a commutative diagram

\[
\begin{array}{cccc}
U(u)^\wedge & \longrightarrow & U(u)/J_n^{n+1} & \cong \\
\downarrow & & \downarrow & \\
A^\vee & \longrightarrow & (A_{\leq n})^\vee & 
\end{array}
\]

for each \( n \), which implies that it is an isomorphism.

Let us now move to the general case where \( U \) is a pro-unipotent affine group scheme such that \( u/\{u,u\} \) is finite-dimensional. Let \( J \subset U(u) \) be the augmentation ideal. By Corollary 3.101, the space \( J/J^2 \) is finite-dimensional. It follows that all quotients \( J^N/J^{N+1} \) are finite-dimensional, since the map \( (J/J^2)^\otimes N \to J^N/J^{N+1} \) is surjective. Then, induction and the short exact sequence

\[
0 \longrightarrow J^N/J^{N+1} \longrightarrow U(u)/J^{N+1} \longrightarrow U(u)/J^N \longrightarrow 0
\]

imply that \( U(u)/J^{N+1} \) is finite-dimensional for all \( N \).

Write now \( U \) as

\[ U = \lim_{\alpha} U_\alpha \]

with the groups \( U_\alpha \) unipotent and the maps \( U \to U_\alpha \) surjective (Exercise 3.144).

Let \( u_\alpha \) be the Lie algebra of \( U_\alpha \) and \( J_\alpha \) the augmentation ideal of \( U(u_\alpha) \). The fact that \( U(u)/J^{N+1} \) is finite-dimensional implies that, for each \( N \) there is a big enough \( \alpha_0 \) such that, for \( \alpha \geq \alpha_0 \) we have \( U(u_\alpha)/J_\alpha^{N+1} = U(u)/J^{N+1} \). Therefore, using that projective limits commute

\[ (3.180) \quad U(u)^\wedge = \lim_{\alpha} U(u)/J_\alpha^{N+1} = \lim_{\alpha} \lim_{N} U(u_\alpha)/J_\alpha^{N+1} \]

\[ = \lim_{N} \lim_{\alpha} U(u_\alpha)/J_\alpha^{N+1} = \lim_{N} U(u_\alpha)^\wedge \]

Since the maps \( U \to U_\alpha \) are surjective, the maps \( A_\alpha = \mathcal{O}(U_\alpha) \to \mathcal{O}(U) = A \) are injective and we have isomorphisms

\[ U(u)^\wedge = \lim_{\alpha} U(u_\alpha)^\wedge \simeq \lim_{\alpha} A_\alpha^\vee = A^\vee \]

proving the result.

In any completed Hopf algebra \( H \), such as the completed universal enveloping algebra \( U(u)^\wedge \), the notion of primitive element is the same as in Definition 3.98. Namely, an element \( v \in H \) is called primitive if it satisfies

\[ \Delta v = 1 \otimes v + v \otimes 1. \]

We let \( P(H) \) denote the set of primitive elements of \( H \).

**Lemma 3.181.** Let \( H \) be a completed Hopf algebra. If \( v \) is a primitive element of \( H \), then \( \epsilon(v) = 0 \). In other words, \( v \in \text{Ker}(\epsilon) \).

**Proof.** We use the relation \( (\text{Id} \otimes \epsilon) \circ \Delta = \text{Id} \) to obtain

\[ v = (\text{Id} \otimes \epsilon)(1 \otimes v + v \otimes 1) = \epsilon(v) + v, \]

and hence \( \epsilon(v) = 0 \). \( \square \)
Corollary 3.182. Let $U$ be a pro-unipotent affine group scheme and let $u$ be its Lie algebra. Assume that $u/[u,u]$ is finite-dimensional. Then the composition
\[ u \rightarrow U(u) \rightarrow U(u)^\wedge \]
is injective and identifies $u$ with the set of primitive elements of $U(u)^\wedge$.

Proof. We identify $U(u)^\wedge$ with $O(G)^\vee$ through the isomorphism from Theorem 3.177. Under this identification, the map $u \rightarrow U(u)^\wedge$ corresponds to the inclusion $(I/I^2)^\vee \rightarrow O(G)^\vee$, which is injective. Clearly, the image of $u$ is contained in the space of primitive elements of $U(u)^\wedge$. Conversely, let us show that each primitive element $a \in O(G)^\vee$ vanishes on $I^2$ and on $\eta(k)$. Indeed, if $x, y \in I$, then
\[ \langle a, xy \rangle = \langle \Delta a, x \otimes y \rangle = \langle 1 \otimes a + a \otimes 1, x \otimes y \rangle \]
\[ = \epsilon(x)\langle a, y \rangle + \epsilon(y)\langle a, x \rangle = 0. \]
Besides, by Lemma 3.181, we have
\[ \langle a, \eta(1) \rangle = \langle \epsilon(a), 1 \rangle = 0. \]
We deduce that a primitive element lies in $u$, as wanted. \qed

3.3.5. Group-like and primitive elements. Let $H$ be a Hopf algebra, with augmentation ideal $J = \ker \epsilon$, and let $H^\wedge$ be its completion with respect to $J$.

Definition 3.183. An element $x \in H^\wedge$ is called group-like if the equalities $\epsilon(x) = 1$ and $\Delta x = x \otimes x$ hold. We write $G(H^\wedge)$ for the set of group-like elements of $H^\wedge$.

Lemma 3.184. Group-like elements of $H^\wedge$ form a group under product.

Proof. Since the counit and the coproduct are morphisms of algebras, the product of two group-like elements is also group-like. The compatibility $\nabla \circ (S \otimes \Id) \circ \Delta = \eta \circ \epsilon$ for a group-like element reads $S(x)x = 1$. Therefore, for a group-like element $S(x)$ is the inverse of $x$. \qed

In $H^\wedge$, we define the ideals
\[ J_n = \ker(H^\wedge \rightarrow H/J^n). \]
In particular $J_1 = \ker(\epsilon: H^\wedge \rightarrow k)$. It is clear that $(J_1)^n \subset J_n$, and that
\[ H^\wedge = \varprojlim H^\wedge/J_{n+1}. \]
With a primitive element $v \in H^\wedge$ we associate its exponential
\[ \exp(v) = \sum_{n=0}^{\infty} \frac{v^n}{n!} \in H^\wedge, \tag{3.185} \]
which is to be understood as the element of the projective limit $H^\wedge = \varprojlim H^\wedge/J_{n+1}$ consisting of the class of the partial sum $\sum_{m=0}^{n} \frac{v^m}{m!}$ in $H^\wedge/J_{n+1}$ for each $n$. This makes sense because $v^n$ belongs to $J_1^n$ by Lemma 3.181.

With a group-like element $x$ we associate its logarithm
\[ \log(x) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}(x - 1)^n}{n} \in H^\wedge, \tag{3.186} \]
understood as above since it follows from the definition of group-like element that $x - 1$ belongs to $J_1$. 


Proposition 3.187. The series $\exp$ and $\log$ determine bijections

$$G(H^\wedge) \xrightarrow{\log} P(H^\wedge)$$

inverse of each other.

Proof. The fact that the exponential and the logarithm are inverse of each other is standard, so that we only need to check that the exponential sends primitive elements to group-like elements and that the logarithm sends group-like elements to primitive elements. For this, let $v$ be a primitive element. The condition $\epsilon(\exp(v)) = 1$ holds since the exponential series starts with 1. Moreover,

$$\Delta \sum_{n=0}^{\infty} \frac{v^n}{n!} = \sum_{n=0}^{\infty} \frac{(1 \otimes v + v \otimes 1)^n}{n!}$$

$$= \sum_{n=0}^{\infty} \sum_{p=0}^{n} \binom{n}{p} \frac{v^p \otimes v^{n-p}}{n!}$$

$$= \sum_{p=0}^{\infty} \sum_{q=0}^{\infty} \frac{p!}{q!} v^p \otimes v^q$$

$$= \exp(v) \otimes \exp(v).$$

Therefore, $\exp(v)$ is group-like. Let now $x$ be a group-like element. The identity

$$\log(1 + a + b + ab) = \log((1 + a)(1 + b)) = \log(1 + a) + \log(1 + b)$$

gives the identity of power series in commuting variables

$$\sum_{n=1}^{\infty} (-1)^{n} \frac{(a + b + ab)^n}{n} = \sum_{n=1}^{\infty} (-1)^{n} \frac{a^n}{n} + \sum_{n=1}^{\infty} (-1)^{n} \frac{b^n}{n}.$$  \hfill (3.188)

Using this equation, we compute

$$\Delta \sum_{n=1}^{\infty} (-1)^{n} \frac{(x - 1)^n}{n} = \sum_{n=1}^{\infty} (-1)^{n} \frac{(x \otimes x - 1 \otimes 1)^n}{n}$$

$$= \sum_{n=1}^{\infty} (-1)^{n} \frac{(1 \otimes (x - 1) + (x - 1) \otimes 1 + (x - 1) \otimes (x - 1))^n}{n}$$

$$= \sum_{n=1}^{\infty} (-1)^{n} \frac{(x - 1)^n}{n} + \sum_{n=1}^{\infty} (-1)^{n} \frac{(x - 1) \otimes 1)^n}{n}$$

$$= 1 \otimes \log(x) + \log(x) \otimes 1,$$ which shows that $\log(x)$ is primitive. \hfill \Box

3.3.6. Free Lie algebras and the Baker–Campbell–Hausdorff formula. We now study some properties of free Lie algebras and free associative algebras and use them to derive the Baker–Campbell–Hausdorff formula.

Definition 3.189. Let $S$ be a set. The free Lie algebra $\text{Lie}(S)$ generated by $S$ is the unique Lie algebra with a map $S \rightarrow \text{Lie}(S)$ that satisfies the following
universal property. For each Lie algebra $L$ and each map $S \to L$, there exists a unique morphism of Lie algebras $\text{Lie}(S) \to L$ that makes the diagram

$$
\begin{array}{c}
S \\
\downarrow \\
\text{Lie}(S) \\
\downarrow \\
L
\end{array}
$$

commutative. Similarly, the free associative algebra $k\langle S \rangle$ generated by $S$ is the unique associative $k$-algebra with a map $S \to k\langle S \rangle$ that satisfies the following universal property. For each associative $k$-algebra $A$ and each map $S \to A$, there exists a unique morphism of $k$-algebras $k\langle S \rangle \to A$ that makes the diagram

$$
\begin{array}{c}
S \\
\downarrow \\
k\langle S \rangle \\
\downarrow \\
A
\end{array}
$$

commutative.

Observe that the free associative algebra generated by $S$ is nothing else than the algebra of non-commuting polynomials introduced in Notation 1.146. Therefore, if $\langle S \rangle_k$ is the $k$-vector space with basis $S$, then

$$
k\langle S \rangle = T(\langle S \rangle_k)
$$

is the tensor algebra generated by $\langle S \rangle_k$. The free Lie algebra and the associative algebra generated by the same set of elements are related by the following result.

**Proposition 3.190.** Let $S$ be a set. Then

$$
U(\text{Lie}(S)) = k\langle S \rangle.
$$

**Proof.** Let $X$ be an associative $k$-algebra, that by forgetting some structure we will consider also a Lie algebra or even a set. We have the following chain of equalities that follow from the universal properties of the involved objects.

$$
\begin{align*}
\text{Hom}_{k\text{-alg}}(U(\text{Lie}(S)), X) &= \text{Hom}_{\text{Lie}}(\text{Lie}(S), X) \\
&= \text{Hom}_{\text{sets}}(S, X) \\
&= \text{Hom}_{k\text{-alg}}(k\langle S \rangle, X).
\end{align*}
$$

By Yoneda’s Lemma, $U(\text{Lie}(S)) = k\langle S \rangle$. \hfill \Box

We assume from now on that $S$ is at most countable. From Proposition 3.190 and Corollary 3.99, we recover a theorem by Friedrichs (see [Jac62, V Thm. 9]).

**Corollary 3.191.** Let $S$ be a countable set and let $F = k\langle S \rangle$ be the free associative algebra generated by $S$. Let $\Delta$ be the coproduct on $F$ determined by being an algebra morphism and satisfying $\Delta x = 1 \otimes x + x \otimes 1$ for all $x \in S$. Then the space of primitive elements $P(F)$ is the free Lie algebra generated by $S$.

**Proof.** By Proposition 3.190, $k\langle S \rangle = U(\text{Lie}(S))$ and this identification respects the coproduct, so it sends primitive elements to primitive elements. By Corollary 3.99,

$$
P(U(\text{Lie}(S))) = \text{Lie}(S).
$$

\hfill \Box
We are now ready to prove the existence of the Baker–Campbell–Hausdorff formula in the unipotent setting.

**Theorem 3.192.** There exists a power series

\[ H(X, Y) = X + Y + \frac{1}{2}[X, Y] + \cdots \in \mathbb{Q}(X, Y), \]

whose entries are iterated commutators between \( X \) and \( Y \) with rational coefficients, such that, for every pro-unipotent group \( U \) with Lie algebra \( u \), every \( k \)-algebra \( R \), and every pair of elements \( x, y \in u \otimes R \), the following identity holds:

\[ \exp(x) \exp(y) = \exp(H(x, y)). \] (3.193)

**Proof.** We consider the case \( k = \mathbb{Q} \) and let \( S = \{X, Y\} \) be the set with two elements. We define the power series \( H(X, Y) \in U(\text{Lie} \langle S \rangle) \) by

\[ H(X, Y) = \log(\exp(X) \exp(Y)). \]

This is well defined because, by Proposition 3.187 and Lemma 3.184, the element \( \exp(X) \exp(Y) \) is group-like. By Proposition 3.187 again, \( H(X, Y) \) is a primitive element. If we induce a grading where \( X \) and \( Y \) are both of degree 1, the coproduct is a graded morphism. Therefore, each homogeneous term in the power series \( H(X, Y) \) is primitive as well. By Corollary 3.191, each homogeneous term in \( H(X, Y) \) belongs to \( \text{Lie} \langle S \rangle \). Therefore, \( H(X, Y) \) is a formal power series whose entries are linear combinations of iterated commutators of \( X \) and \( Y \) with rational coefficients.

Since the equation (3.193) is true in the pro-nilpotent completion of the free Lie algebra in two elements, it is also true for \( x \) and \( y \) two nilpotent matrices with entries in any \( k \)-algebra \( R \). Since any unipotent group is a closed subgroup of \( \text{Up}_n \) for certain \( n \), we deduce from Exercise 3.215 that formula (3.193) is true for any unipotent group \( U \) with Lie algebra \( u \), with \( \exp \) now denoting the exponential map from \( u \otimes R \) to \( U(R) \). Note that, since \( u \) is nilpotent, \( H(x, y) \) is a polynomial in commutators between \( x \) and \( y \), and hence a well defined element of \( u \otimes R \). Let now \( U \) be a pro-unipotent group and \( u \) its Lie algebra. Write

\[ U = \lim_{\alpha} U_{\alpha}, \quad u = \lim_{\alpha} u_{\alpha}. \]

Then there is a commutative diagram

\[ \begin{array}{ccl}
  u & \longrightarrow & \prod_{\alpha} u_{\alpha} \\
  \exp & \downarrow & \prod_{\alpha} \exp \\
  U & \longrightarrow & \prod_{\alpha} U_{\alpha}
\end{array} \] (3.194)

For an element \( x \) in \( u \otimes R \) or in \( U(R) \) we write \( (x_{\alpha}) \) for its image on the right hand side of the diagram (3.194). For \( x, y \in u \otimes R \) the chain of equalities

\[ (\exp(x) \exp(y))_{\alpha} = \exp(x_{\alpha}) \exp(y_{\alpha}) = \exp(H(x_{\alpha}, y_{\alpha})) = \exp(H(x, y))_{\alpha} \]

and the injectivity of the horizontal maps in diagram (3.194) show that equation (3.193) is also true for \( U \). \( \square \)

**Corollary 3.195.** Let \( U_1 \) and \( U_2 \) be pro-unipotent groups and \( u_1 \) and \( u_2 \) their Lie algebras. Any morphism of Lie algebras \( u_1 \to u_2 \) induces a morphism of affine group schemes \( U_1 \to U_2 \).
Proof. Recall the map log from Definition 3.176. We define a morphism of schemes by the composition
\[ U_1 \xrightarrow{\log} u_1 \longrightarrow u_2 \xrightarrow{\exp} U_2. \]
The fact that this map is a group morphism follows from the fact that the Baker–Campbell–Hausdorff formula holds universally. □

We can use the previous ideas to recover the group of $k$-valued points of a pro-unipotent group from its Lie algebra.

Proposition 3.196. Let $U$ be a pro-unipotent group with Lie algebra $u$. Assume that $u/[u,u]$ is finite-dimensional. Then the group $U(k)$ is canonically isomorphic to the group $G(U(u)\wedge)$.

Proof. The map exp gives us an isomorphism of schemes $\exp: u \to U$, hence a bijection $u(k) \to U(k)$. On the other hand, the power series exp gives a bijection between the space of primitive elements of $U(u)\wedge$ and the set of group-like elements of $U(u)\wedge$. By Corollary 3.182, we can identify the space of primitive elements of $U(u)\wedge$ with $u(k)$. With this identification, the abstract exponential map gets identified with the power series $\exp$, as in the proof of Theorem 3.192. Hence, we obtain a bijection between $U(k)$ and $G(U(u)\wedge)$. The fact that it is a group isomorphism follows from the fact that the Baker–Campbell–Hausdorff formula holds universally. □

3.3.7. Nilpotent representations. Let $U$ be a unipotent affine algebraic group and $u$ its nilpotent Lie algebra. As the following example shows, a finite-dimensional representation of $u$ does not need to come from a representation of $U$.

Example 3.197. Consider the groups $\mathbb{G}_m$ and $\mathbb{G}_a$. Both have as Lie algebra, the unidimensional algebra $k$ with trivial bracket. Consider the one-dimensional representation given by the identification $\mathbb{G}_m = \text{GL}_1$. This defines a representation of $k$ that sends an element $a \in k$ to the one-dimensional matrix $(a)$. This representation of $k$ does not come from an algebraic representation of $\mathbb{G}_a$. This can be seen, for instance, arguing that the exponential map $\exp: k \to \mathbb{G}_a(k) = k$ is the identity, while as matrices, $\exp(a)$ does not need to be an element of $k$.

We see in Example 3.197 that the problem to lift a representation $\rho$ from $u$ to a representation of $U$ comes from the fact that $\rho(x)$ may be non-nilpotent and the exponential of non-nilpotent elements does not need to be algebraic.

Definition 3.198. Let $u$ be a finite-dimensional nilpotent Lie algebra. A finite-dimensional representation $\rho: u \to \mathfrak{gl}(V)$ is called nilpotent if $\rho(x)$ is a nilpotent endomorphism of $V$ for all $x \in u$. We let $\text{Rep}^{\text{nil}}(u)$ denote the category of finite-dimensional nilpotent representations.

The nilpotent representation solve the problem of lifting representations from the Lie algebra to the Lie group.

Proposition 3.199. Let $U$ be a unipotent Lie group and $u$ its nilpotent Lie algebra. There is a canonical equivalence of categories
\[ \text{Rep}(U) \xrightarrow{\rho \mapsto d\rho} \text{Rep}^{\text{nil}}(u) \]
given by $\rho \mapsto d\rho$. 
PROOF. Let \( \rho \) be a representation of \( U \) in \( \text{GL}(V) \). Then we can choose a basis of \( V \) such that the image of \( \rho \) is contained in \( U_{p_n} \). Therefore, \( d\rho \) is contained in \( \text{Lie}(U_{p_n}) = u_n \), the space of strictly upper triangular matrices. Hence \( d\rho \in \text{Rep}_{\text{nil}}(u) \). Conversely, let \( \rho : u \to \text{gl}(V) \) be a nilpotent representation of \( u \). By Engel’s theorem (Proposition 3.163), there is a basis of \( V \) such that \( \rho(u) \subset u_n \). By Corollary 3.195, there is an algebraic group morphism \( \mu : U \to U_{p_n} \) such that \( d\mu = \rho \).

3.3.8. Graded Lie algebras. In the sequel, we will need to deal with Lie algebras \( L \) with infinite-dimensional abelianization \( L/[L, L] \), for which the pro-nilpotent completion from Definition 3.166 does not have the properties we want. However, in most cases of interest, \( L \) comes with a grading with finite-dimensional graded pieces and one can use the grading to define a better behaved notion.

**Definition 3.200.** Let \( L = \bigoplus_{n<0} L_n \) be a negatively graded Lie algebra such that \( L_n \) is finite-dimensional for all \( n < 0 \), and let

\[
F^n L = \bigoplus_{m \leq -n} L_m
\]

be the associated decreasing filtration. The pro-nilpotent completion of \( L \) (with respect to the grading) is the projective limit

\[
\hat{L} = \lim_{\leftarrow n} L/F^n L.
\]

The next lemma shows that this is a reasonable definition.

**Lemma 3.201.** Let \( L = \bigoplus_{n<0} L_n \) be a negatively graded Lie algebra.

i) If \( \dim L_n < \infty \) for \( n < 0 \), then \( \hat{L} \) is pro-nilpotent.

ii) If \( \dim L/[L, L] < \infty \), then \( \dim L_n < \infty \) for \( n < 0 \) and the pro-nilpotent completions from definitions 3.166 and 3.200 are canonically isomorphic to each other.

**Proof.** It follows from the equality \( L/F^n L = \bigoplus_{i=1}^{m-1} L_{-i} \) that \( L_n \) is finite-dimensional for all \( n \) if and only if \( L/F^n L \) is finite-dimensional for all \( n \). Moreover, \( L^{(i)} \) is contained in \( F^{i+1} \) for all \( i \geq 0 \) since \( L \) is negatively graded, and hence \( L/F^n L \) is nilpotent. This proves i). For ii), we first observe that \( L/L^{(n)} \) surjects onto \( L/F^{n+1} L \) for all \( n \geq 0 \). Since the finite-dimensionality of \( L/[L, L] \) implies that of \( L/L^{(n)} \), we deduce that all graded pieces \( L_i \) are finite-dimensional. Besides, since \( L/[L, L] \) is finite-dimensional, there exists a finite set of homogeneous Lie algebra generators of \( L \). Letting \( r \) denote the largest degree among them, we get \( F^r L^{(i+1)} \subset L^{(i)} \) for all \( i \geq 0 \). By a standard argument in projective limits, the inclusions \( F^r L^{(i+1)} \subset L^{(i)} \subset F^{i+1} \) imply that the two pro-nilpotent completions are canonically isomorphic to each other. \( \square \)

**Definition 3.202.** Let \( L \) be a graded Lie algebra satisfying the conditions of Definition 3.200. The Poincaré–Birkhoff–Witt theorem (Theorem 3.96) implies that the universal enveloping algebra \( U(L) \) is a graded algebra with \( U(L)_0 = k \), \( U(L)_n = 0 \) for \( n \geq 0 \) and \( \dim U(L)_n < \infty \) for \( n < 0 \). The decreasing filtration \( F^n U(L) \) is defined as before as

\[
F^n U(L) = \bigoplus_{n' \leq -n} U(L)_n.
\]
The graded completion of $U(L)$ is defined as the projective limit

$$U(L)^\vee = \lim_{\leftarrow n} U(L)/F^nU(L).$$

**Remark 3.203.** One can give an analogous definition in the case when $L$ is concentrated in positive degrees.

The theory of graded Lie algebras applies notably in the following case.

**Definition 3.204.** A graded pro-unipotent group is a pro-unipotent group $U$ in which the group $\mathbb{G}_m$ acts compatibly with the pro-unipotent structure and the group structure.

The fact that the action is compatible with the pro-unipotent structure means that we can write

$$U = \lim_{\leftarrow \alpha} U_{\alpha},$$

with each $U_{\alpha}$ unipotent and that the group $\mathbb{G}_m$ acts on each $U_{\alpha}$ is such a way that the maps $\pi_{\alpha,\beta}: U_{\beta} \to U_{\alpha}$ are equivariant.

The fact that the action is compatible with the groups structure means, at the level of $k$ points, that, for $t \in k^\times$ and $g_1, g_2 \in U_{\alpha}(k)$ the equations

$$t(g_1g_2) = t(g_1)t(g_2),$$

$$t(g_1^{-1}) = t(g_1)^{-1},$$

$$t(e) = e$$

hold. We leave to the reader the care to translate conditions (3.205) into diagrams of group schemes and diagrams of Hopf algebras.

Let $U$ be a graded pro-unipotent group and $A = \mathcal{O}(U)$ its associated Hopf algebra. Then $A$ is a graded algebra as we explain now. As seen in Example 3.58, the Hopf algebra of $\mathbb{G}_m$ is $k[x, x^{-1}]$ with coaction $\Delta x = x \otimes x$ and counit $\epsilon(x) = 1$.

The action of $\mathbb{G}_m$ on $U$ gives a coaction $\Delta: A \to A \otimes k[x, x^{-1}]$ and we define $A_n = \Delta^{-1}(A \otimes x^n)$. For $a \in A$ we have a decomposition into a finite sum

$$\Delta a = \sum_{n \in \mathbb{Z}} a_n x^n.$$  

The properties of a coaction readily imply that

$$a = \sum_n a_n, \quad a_n \in A_n.$$  

Therefore, $A = \bigoplus_n A_n$. If $a \in A_n$ and $b \in A_m$ the computation

$$\Delta(ab) = \Delta(a)\Delta(b) = a \otimes x^n \cdot b \otimes x^m = ab \otimes x^{n+m}$$

shows that $ab \in A_{n+m}$ so $A$ is a graded algebra. Since $e$ is a fixed point for the action of $\mathbb{G}_m$ we deduce that the ideal $I$ is homogeneous. Hence $I$ and $(I/I^2)$ inherit a structure of graded vector space.

**Definition 3.206.** Let $U$ be a graded pro-unipotent group. Write $u_n = ((I/I^2)_{-n})^\vee$. Then the graded Lie algebra of $U$ is

$$u^\text{gr} = \bigoplus_n u_n.$$  

In general $u^\text{gr}$ is not the Lie algebra of $U$ but we have the following compatibility.
LEMMA 3.207. Let $U$ be a graded pro-unipotent group with $A = \mathcal{O}(U)$ connected (that is, $A_n = 0$ for $n < 0$ and $A_0 = k$) and satisfying $\dim A_n < \infty$ for all $n$. If $u = \text{Lie}(U)$, then

$$u = \hat{u}^{gr}.$$

Several results that we stated in the case when $L/[L,L]$ is finite-dimensional can be generalized to the graded case.

PROPOSITION 3.208. Let $U$ be a graded pro-unipotent group with $A = \mathcal{O}(U)$ connected and $\dim A_n < \infty$ for all $n$. If $u = \text{Lie}(U)$, then

i) there is a canonical isomorphism $U(u^{gr})^\wedge = A^\vee$;

ii) the group $G(k)$ of $k$-points of $G$ is canonically isomorphic to the group of group-like elements $\mathcal{G}(U(u^{gr})^\wedge)$.

We end this section discussing finite-dimensional graded representations.

DEFINITION 3.209. Let $U$ be a graded pro-unipotent affine group scheme. We denote by $\text{Rep}_{G_m}(U)$ the category of graded finite-dimensional representations of $U$. This means that $(v, \rho) \in \text{Rep}_{G_m}(U)$ if $V$ is a graded finite-dimensional $k$-vector space and $\rho$ is $G_m$-equivariant. In other words, for $t \in k^\times$ and $g \in U$, the equation

$$\rho(tg) = t\rho(g)t^{-1}$$

holds.

Similarly, if $L$ is a graded Lie algebra, then $\text{Rep}_{G_m}(L)$ denotes the category of graded finite-dimensional representations. That is, the representations $\rho$ in a graded vector space $V$ satisfying that,

$$\rho(L_n)V_m \subset V_{n+m},$$

THEOREM 3.210. Let $U$ be a graded pro-unipotent group, satisfying that $A = \mathcal{O}(U)$ is connected and that $\dim A_n < \infty$ for all $n > 0$. Write $G = U \times G_m$. This is a pro-algebraic group. Then there are equivalences of categories

$$\text{Rep}(G) \simeq \text{Rep}_{G_m}(U) \simeq \text{Rep}_{G_m}(u^{gr}).$$

PROOF. For simplicity of the exposition, we will argue using $k$-points of $G$ and $U$. Let $\rho: G \to GL(V)$ be a finite-dimensional representation of $G$. Since $G = U \times G_m$, there is a map $G_m \to G$ that we use to identify $G_m$ with a subtorus of $G$. Therefore, there is an induced representation of $G_m$ on $V$. By Exercise 3.212 this representation induces a grading on $V$. Moreover the action of $G_m$ on $U$ is given, for $t \in G_m(k)$ and $g \in U(k)$, by $t(g) = tgt^{-1}$. Consequently, $\rho(t'(g)) = tp(g)t^{-1}$ and $\rho$ defines an element of $\text{Rep}_{G_m}(U)$. Conversely, if $(\rho, V) \in \text{Rep}_{G_m}(U)$, then $V$ is a graded vector space, and hence carries an action of $G_m$. The condition $\rho(t(g)) = tp(g)t^{-1}$ implies that the action of $U$ and the action of $G_m$ on $V$ are compatible with the semi-direct product $G = U \times G_m$ and hence they define an element of $\text{Rep}(G)$.

That there is a functor $\text{Rep}_{G_m}(U) \to \text{Rep}_{G_m}(u^{gr})$ is clear. The interesting part is to show that every graded finite-dimensional representation of $u^{gr}$ comes from a representation of $U$. Let $V$ be such a representation. Let $m$ be the difference between the maximal degree and the minimal degree of $V$. Then the action of $F^{m+1}u^{gr}$ on $V$ is trivial. By Lemma 3.207 there is a surjection

$$u \twoheadrightarrow u^{gr} / F^{m+1}u^{gr}$$

(3.211)
compatible with the action of $\mathbb{G}_m$. And $V$ factors through a representation of the finite-dimensional nilpotent Lie algebra $u^{gr}/F^{m+1}u^{gr}$. Write

$$U = \lim_{\leftarrow} U_\alpha$$

with $\mathbb{G}_m$ acting on each $U_\alpha$ and the maps $U \to U_\alpha$ surjective. Let $u_\alpha$ be the Lie algebra of $U_\alpha$. Since $u^\alpha_n$ is finite-dimensional for all $n$, there is an $\alpha$ such that the surjection (3.211) factors as

$$u/\mathfrak{F}_{m+1}u^{gr} \to u^\alpha.$$ 

Thus the representation $V$ defines a graded representation of $u_\alpha$. Since $u_\alpha$ is a graded Lie algebra with only negative grades, we deduce that any graded finite-dimensional representation of $u_\alpha$ is nilpotent. By Proposition 3.199, this representation of $u_\alpha$ comes from a graded representation of $U_\alpha$. Thus defines a graded representation of $U$. \hfill \Box

***

Exercise 3.212. Let $V = \bigoplus_{n \in \mathbb{Z}} V^n$ be a graded $k$-vector space. Then there is an induced left action of $\mathbb{G}_m$ on $V$ given by $\lambda \cdot v = \lambda^n v$ on each $v \in V^n$. In fact, giving a $\mathbb{Z}$-grading on $V$ is equivalent to giving an action of $\mathbb{G}_m$.

i) Prove that the coalgebra $O(\mathbb{G}_m)$ is isomorphic to the coalgebra $H$ from Example 3.54.

ii) Prove that the coaction of $O(\mathbb{G}_m)$ on $V$ determined by Lemma 3.114 agrees with the coaction of $H$ from Example 3.54.

Exercise 3.213. Let $G$ be an affine group scheme. We see in this exercise that not every linear representation of the abstract group $G(k)$ has “geometric origin” is an algebraic representation of $G$. For instance, consider the $\mathbb{C}$ vector space $V = K(\mathbb{P}^1_{\mathbb{C}})$ of rational functions on the complex projective line. The group $G(\mathbb{C}) = \text{SL}_2(\mathbb{C})$ acts on $\mathbb{P}^1_{\mathbb{C}}$ by Möbius transformations, and hence linearly on $V$.

i) Let $W \subset V$ be a finite-dimensional vector subspace. Show that the set of poles of the functions belonging to $W$ is finite.

ii) Show that the set of poles that appear in the orbit of the function $t$ is infinite.

iii) Use Lemma 3.117 to conclude that the linear representation $V$ of $G(\mathbb{C})$ does not come from a representation of the affine algebraic group $G = \text{SL}_2$.

Exercise 3.214. Let $L$ be a Lie algebra. Construct a surjective linear map

$$\left( L/[L,L] \right)^{\otimes n+1} \to L^n/L^{(n+1)},$$

and prove that, if $L/[L,L]$ is finite-dimensional, then so is $L/L^{(n+1)}$ for all $i$. 

Exercise 3.215. Consider the unipotent group $U_n$ with Lie algebra $u_n$. Prove that the exponential map $\exp: u_n \to U_n$ from Section 3.3.4 can be written explicitly as a truncated exponential series. Namely, for $N \in u_n$, it is given by

$$\exp(N) = \sum_{k=0}^{n-1} \frac{N^k}{k!}.$$ 

Exercise 3.216. Translate conditions (3.205) into the existence of commutative diagrams of affine schemes and the corresponding dual diagrams of algebras.

### 3.4. The pro-unipotent completion of a group

In this section, we develop some abstract machinery that will be used in the sequel to rephrase the constructions from Section 3.1 in a more conceptual way. There we saw that iterated integrals carry information about the fundamental group of a differentiable manifold. The question we would like to address now is how much of it can be recovered using differential forms. Stated in a vaguer form: what information about the fundamental group is “cohomological”, or even “motivic” if we are dealing with algebraic varieties? Throughout, $k$ still denotes a field of characteristic zero.

#### 3.4.1. The abelianization of the fundamental group

The obvious piece of information that can be recovered via differential forms is the abelianization of the fundamental group. Indeed, recall from Theorem 3.14 that

$$\pi_1(M, x)^{ab} \simeq H_1(M, \mathbb{Z}),$$

so that, passing to the dual, de Rham’s Theorem 2.62 yields an isomorphism

$$H^1_{dR}(M, \mathbb{R}) \iso \text{Hom}(\pi_1(M, x)^{ab}, \mathbb{R}).$$

Moreover, in the case where $k$ is a subfield of $\mathbb{C}$ and $M = X(\mathbb{C})$ is the set of complex points of a smooth variety $X$ over $k$, we get

$$H^1_{dR}(X) \otimes \mathbb{C} \iso \text{Hom}(\pi_1(M, x)^{ab}, \mathbb{C}),$$

where the left-hand side stands for algebraic de Rham cohomology (as in Definition 2.78) and has thus a purely algebraic definition.

However, the abelianization of the fundamental group is a very crude invariant that, for example, only knows about abelian representations. We should be able to see much more than just the abelianization of the fundamental group using differential forms. A glimpse of this appeared in Section 3.1 when we saw that iterated integrals are related to nilpotent flat connections, that in turn are related to unipotent representations of the fundamental group. In the next paragraphs, we elaborate on this idea.

#### 3.4.2. The pro-unipotent completion

The central concept of the whole section is the following:

**Definition 3.217.** Let $\Gamma$ be an abstract group. The *pro-unipotent completion* $\Gamma^{un}$ of $\Gamma$ over $k$ is the universal pro-unipotent affine group scheme $G$ over $k$ endowed with a morphism of abstract groups $\Gamma \to G(k)$. More precisely,

- $\Gamma^{un}$ is a pro-unipotent affine group scheme over $k$ with a morphism
  $$\Gamma \longrightarrow \Gamma^{un}(k),$$
- for each pro-unipotent affine group scheme $G$ over $k$ with a morphism $\Gamma \to G(k)$, there is a unique morphism of affine group schemes $\Gamma^{un} \to G$.
such that the following diagram commutes
\[
\begin{array}{ccc}
\Gamma & \longrightarrow & \Gamma^{un}(k) \\
\downarrow & & \downarrow \\
G(k) & & \\
\end{array}
\]
The pro-unipotent completion of \( \Gamma \) over \( \mathbb{Q} \) will be simply called the pro-unipotent completion of \( \Gamma \).

Similarly, the pro-algebraic completion \( \Gamma^{alg} \) of \( \Gamma \) over \( k \) is defined as the universal pro-algebraic affine group scheme \( G \) over \( k \) endowed with a morphism of abstract groups \( \Gamma \to G(k) \).

The pro-unipotent completion was introduced by Quillen in [Qui69] based on work by Malcev [Mal49] and it is also called the Malcev completion in the literature.

As it is always the case with universal objects, when they exist they are unique up to unique isomorphism.

**Remark 3.218.** Whenever the pro-unipotent completion exists, the groups \( \Gamma \) and \( \Gamma^{un} \) have the same finite-dimensional unipotent representations. Therefore, one cannot recover \( \Gamma \) by just looking at this kind of representations.

We now present Quillen’s construction of the pro-unipotent completion of a group satisfying a finiteness condition. Basically, the idea is to build an object that looks like the completed universal enveloping algebra of a quasi-nilpotent Lie algebra \( L \) such that \( L/[L, L] \) is finite-dimensional.

For the moment, let \( \Gamma \) be any abstract group and consider the Hopf algebra \( k[\Gamma] = \{ \sum_{g \in \Gamma} a_g g \mid a_g \in k, \ a_g = 0 \text{ except for finitely many } g \} \) from Example 3.61, which is cocommutative but in general non-commutative. Its counit is also called augmentation.

**Definition 3.219.** The augmentation of \( k[\Gamma] \) is the algebra morphism
\[
\epsilon: \ k[\Gamma] \longrightarrow k \\
\sum_{g \in \Gamma} a_g g \longmapsto \sum_{g \in \Gamma} a_g
\]
and its kernel \( J = \text{Ker}(\epsilon) \) is called the augmentation ideal:
\[
J = \{ \sum_{g \in \Gamma} a_g g \mid \sum_{g \in \Gamma} a_g = 0 \}.
\]

The completion of \( k[\Gamma] \) with respect to \( J \) is the projective limit
\[
k[\Gamma]^\wedge = \lim_{\leftarrow N} k[\Gamma]/J^{N+1},
\]
where the transition maps are the projections \( k[\Gamma]/J^{M+1} \to k[\Gamma]/J^{N+1} \) induced by the inclusions \( J^{M+1} \subseteq J^{N+1} \) for \( M \geq N \). The Hopf algebra structure on \( k[\Gamma] \) induces a completed Hopf algebra structure on \( k[\Gamma]^\wedge \) in the sense of Definition 3.68.

The space \( k[\Gamma]^\wedge \) being infinite-dimensional, unless \( \Gamma \) is finite, its linear dual will be intractable for most of our purposes. We will instead work with the inductive limit of the linear duals of the quotients \( k[\Gamma]/J^{N+1} \), which is best behaved when they are all finite-dimensional; for example, we will see that under this assumption it carries the structure of a Hopf algebra.
Definition 3.220. Let $V = \lim_{\leftarrow N} V_N$ be a projective limit of finite-dimensional $k$-vector spaces. The topological dual of $V$ is the inductive limit

$$V^{\vee_{\text{top}}} = \lim_{\rightarrow N} V_N^{\vee}$$

of the linear duals of the $k$-vector spaces $V_N$.

Let us from now on assume that $\Gamma$ satisfies the finiteness condition that $\Gamma^{ab} \otimes \mathbb{Z} k$ is a finite-dimensional $k$-vector space. By Theorem 3.14, this is for instance satisfied when $\Gamma$ is the fundamental group of a topological space with the homotopy type of a finite CW-complex, e.g. when $\Gamma$ is the fundamental group of the space of complex points $X(\mathbb{C})$ of an algebraic variety $X$ over $\mathbb{C}$.

Lemma 3.221. If the vector space $\Gamma^{ab} \otimes \mathbb{Z} k$ is finite-dimensional, then all the quotients $k[\Gamma]/J^{N+1}$ are finite-dimensional as well.

Proof. Since $k[\Gamma] = k \oplus J$, it suffices to prove that $J/J^{N+1}$ has finite dimension for all $N \geq 0$. Looking at the filtration

$$J^{N+1} \subseteq J^N \subseteq \cdots \subseteq J^2 \subseteq J,$$

this amounts to proving that the successive quotients $J^i/J^{i+1}$ are finite-dimensional for all $i \geq 1$. To treat the case $i = 1$, we note that the map

$$\Gamma \to J/J^2,$$

$$g \to (g-1) + J^2$$

factors through the abelianization of $\Gamma$, as can be seen by writing

$$gh - 1 = (g-1) + (h-1) + (g-1)(h-1).$$

In fact, it induces an isomorphism

$$\Gamma^{ab} \otimes \mathbb{Z} k \xrightarrow{\sim} J/J^2$$

(its inverse being the map that sends the class of a generator $g-1$ to the class of $g$ in $\Gamma^{ab}$). This shows that $J/J^2$ is finite-dimensional. Taking into account that the multiplication map

$$(J/J^2)^{\otimes i} \to J^i/J^{i+1}$$

is surjective for all $i \geq 1$, the general result follows.

Proposition 3.222. Let $\Gamma$ be a group such that $\Gamma^{ab} \otimes \mathbb{Z} k$ is finite-dimensional. Then the topological dual of $k[\Gamma]^\wedge$, given by the inductive limit

$$A = (k[\Gamma]^\wedge)^{\vee_{\text{top}}} = \lim_{\rightarrow N} (k[\Gamma]/J^{N+1})^{\vee},$$

carries the structure of a Hopf algebra.

Proof. The key points of the proof are, first that $J$ is a Hopf ideal of $k[\Gamma]$ (Example 3.75 i)), hence by Proposition 3.78, $k[\Gamma]^\wedge$ is a completed Hopf algebra. Second, that each term $k[\Gamma]/J^{N+1}$ in the limit is finite-dimensional by Lemma 3.221, which implies that the completed Hopf algebra structure of $k[\Gamma]^\wedge$ defines a Hopf algebra structure in its product. We first explain the construction of the coproduct. The product of $k[\Gamma]$ induces products

$$k[\Gamma]/J^{N+1} \otimes k[\Gamma]/J^{N+1} \to k[\Gamma]/J^{N+1}$$

for each $N \geq 0$ that, using finite-dimensionality, give rise to coproducts

$$\Delta_N: (k[\Gamma]/J^{N+1})^\vee \to (k[\Gamma]/J^{N+1})^\vee \otimes (k[\Gamma]/J^{N+1})^\vee$$

for each $N \geq 0$. For each $a \in \Lambda$, there exists a sufficiently large $N$ such that $a$ is the image of an element $a_N \in (k[\Gamma]/J^{N+1})^\vee$. Then $\Delta a$ is defined as the image of $\Delta_N a_N$ in $\Lambda \otimes \Lambda$; the resulting element is independent of the choices of $N$ and $a_N$ since the transition maps $k[\Gamma]/J^{M+1} \to k[\Gamma]/J^{N+1}$ are morphisms of algebras.

We next explain the construction of the product. The ideal $J$ is also a coideal. This implies that $k[\Gamma]/J$ is a coalgebra. By contrast, $J^{N+1}$ is not a coideal, since it only satisfies the inclusion

$$\Delta(J^{N+1}) \subset k[\Gamma] \otimes J^{N+1} + J^{N} \otimes J + \cdots + J \otimes J^{N} + J^{N+1} \otimes k[\Gamma].$$

As a result, $k[\Gamma]/J^{N+1}$ is not a coalgebra in general. Nevertheless, as long as $M \geq 2N + 1$, the coproduct on $k[\Gamma]$ induces maps

$$\Delta: k[\Gamma]/J^M \to k[\Gamma]/J^{N+1} \otimes k[\Gamma]/J^{N+1}$$

that commute with the transition maps. Their duals are maps

$$(k[\Gamma]/J^{N+1})^\vee \otimes (k[\Gamma]/J^{N+1})^\vee \to (k[\Gamma]/J^M)^\vee$$

using finite-dimensionality again. This is enough to define a product

$$\lim_{N \to \infty} (k[\Gamma]/J^{N+1})^\vee \otimes \lim_{N \to \infty} (k[\Gamma]/J^{N+1})^\vee \to \lim_{N \to \infty} (k[\Gamma]/J^{N+1})^\vee,$$

as follows: given $a, b \in \lim_{N \to \infty} (k[\Gamma]/J^{N+1})^\vee$, choose representatives $a_N, b_N \in k[\Gamma]/J^{N+1}$ for some big enough $N$, and define the product $a \cdot b$ as the image in $A$ of the element $a_N \cdot b_N \in (k[\Gamma]/J^{2N+1})^\vee$ obtained by applying (3.223). The compatibility of these maps and the transition maps implies that the result is independent of the choices.

The counit of $A$ is induced from the maps $(k[\Gamma]/J^{N+1})^\vee \to k$, which are the duals of the compositions of the unit $k \to k[\Gamma]$ and the projection $k[\Gamma] \to k[\Gamma]/J^{N+1}$, and are compatible with the transition maps.

The unit of $A$ is induced from the maps $k[\Gamma]/J^{N+1} \to k$ obtained from the augmentation $\varepsilon$ on noting that $\varepsilon(J^{N+1}) = 0$, by dualizing and composing with the natural map $(k[\Gamma]/J^{N+1})^\vee \to A$.

Finally, the antipode on $k[\Gamma]$, given by $S(g) = g^{-1}$, satisfies $S(J^{N+1}) \subseteq J^{N+1}$ for all $N$, and hence induces a map $S: k[\Gamma]/J^{N+1} \to k[\Gamma]/J^{N+1}$ compatible with the inductive system.

The compatibilities between the various operations in the definition of Hopf algebra are easily deduced from the compatibilities between those on $k[\Gamma]$.

We now turn to Quillen’s construction of the pro-unipotent completion. The following result can be deduced from [Qui69, App. A], although the language there is different. A translation into the language of algebraic groups is given in [Hai93, Thm. 3.3]. We sketch the proof.

**Theorem 3.224 (Quillen [Qui69]).** Let $\Gamma$ be an abstract group such that the vector space $\Gamma^{ab} \otimes \mathbb{Z}$ has finite dimension. Then the pro-unipotent completion of $\Gamma$ over $k$ is the affine group scheme $\text{Spec}(k[\Gamma]^\wedge)^{\text{unip}}$.

**Proof.** As before, write $A = (k[\Gamma]^\wedge)^{\text{unip}}$ and $G = \text{Spec}(A)$. The conilpotency filtration of $A$ is given by $\text{Ann}_A J^{N+1} k[\Gamma]^\wedge$. By the definition of $k[\Gamma]^\wedge$ as a projective
limit, is clear that
\[ \bigcap_{N \geq 0} J^{N+1} k[\Gamma]^{\wedge} = 0. \]
Therefore, the conilpotency filtration of \( A \) is exhaustive. By Proposition 3.153, we deduce that \( G \) is pro-unipotent.

Let now \( H = \text{Spec}(B) \) be a pro-unipotent group and \( f : \Gamma \to H(k) \) a group morphism. Let \( B^\vee \) be the non-commutative algebra dual to the co-algebra \( B \). There is an inclusion \( H(k) \to B^\vee \) given by evaluating functions at points. The map \( f \) extends to a map \( k[\Gamma] \to B^\vee \) also denoted \( f \). The augmentations of \( k[\Gamma] \) and of \( B^\vee \) are compatible with \( f \). Thus, we obtain maps
\[ k[\Gamma]/J^{N+1} \to B^\vee/J^{N+1}, \]
where \( J \) denotes the augmentation ideal in both algebras. Dualizing we obtain maps
\[ \text{Ann}_B J^{N+1} \longrightarrow \text{Ann}_A J^{N+1} \longrightarrow A. \]
Since \( H \) is pro-unipotent, by Proposition 3.153 the conilpotency filtration of \( B \) is exhaustive and we obtain a map \( B \to A \), therefore a map of pro-unipotent groups \( G \to H \). By construction, this is the only map of pro-unipotent groups that preserves the image of \( \Gamma \). Thus, \( G \) satisfies the universal property defining \( \Gamma_{\text{un}} \).

Let now \( g \) be the Lie algebra of \( G \). Then \( g \) satisfies the finiteness condition \( \dim g/ [g, g] < \infty \) and by Theorem 3.177 we deduce that \( k[\Gamma]^{\wedge} = U(g)^{\wedge} \). Therefore, Proposition 3.196 and Corollary 3.99 yield:

**Proposition 3.225.** Let \( \Gamma \) be an abstract group such that \( \Gamma_{\text{ab}} \otimes \mathbb{Z} k \) has finite dimension. Then \( G(k[\Gamma]^{\wedge}) = \Gamma_{\text{un}}(k) \), and the natural map \( \Gamma \to k[\Gamma]^{\wedge} \) agrees with the structural map \( \Gamma \to \Gamma_{\text{un}}(k) \). Moreover, the Lie algebra of \( \Gamma_{\text{un}} \) agrees with \( P(k[\Gamma]^{\wedge}) \).

**Example 3.226.** Let us illustrate the above proposition for \( \Gamma = \mathbb{Z} \). As we will see in Exercise 3.234, the pro-unipotent completion of \( \Gamma \) is the additive group \( \mathbb{G}_{\text{a}} \) over \( k \), so we need to show that group-like elements in \( k[[y]] \) are in one-to-one correspondence with \( k \). Let \( \sum_{n \geq 0} a_n y^n \) be a group-like element. Then \( a_0 = 1 \) and

\[
\nabla^\vee \left( \sum_{n \geq 0} a_n y^n \right) = \left( \sum_{n \geq 0} a_n y^n \right) \otimes \left( \sum_{n \geq 0} a_n y^n \right).
\]

Since \( \nabla^\vee y = 1 \otimes y + y \otimes 1 \), we have
\[ \nabla^\vee y^n = \sum_{k=0}^n \binom{n}{k} y^k \otimes y^{n-k}. \]
Equation (3.227) is thus equivalent to the relation
\[ a_k a_m = \binom{k + m}{k} a_{k+m} \]
for all \( k, m \geq 0 \). In particular, all the coefficients \( a_n \) are determined by the first one: \( a_n = a_1^n / n! \). Hence the group-like element is of the form \( \exp(a_1 y) \) and this gives the correspondence.

From the compatibility between the antipode, the product and the completed coproduct we easily deduce the following (see Lemma 3.184 for a similar statement and solve Exercise 3.236):
Lemma 3.228. If \( x \) is a primitive element, then \( S(x) = -x \) holds. If \( g \) is a group-like element, then \( g \) is invertible in the algebra \( k[\Gamma]^\wedge \) and satisfies \( S(g) = g^{-1} \).

Example 3.229. Let \( \Gamma \) be the free group on two generators \( \gamma_0 \) and \( \gamma_1 \). In this example, we compute the pro-unipotent completion of \( \Gamma \) over \( \mathbb{Q} \). Since the elements \( \gamma_0 - 1 \) and \( \gamma_1 - 1 \) belong to the augmentation ideal, we can define
\[
\log(\gamma_0) = \log(1 + (\gamma_0 - 1)) = \gamma_0 - 1 - \frac{(\gamma_0 - 1)^2}{2} + \cdots
\]
\[
\log(\gamma_1) = \log(1 + (\gamma_1 - 1)) = \gamma_1 - 1 - \frac{(\gamma_1 - 1)^2}{2} + \cdots
\]
as elements of \( \mathbb{Q}[\Gamma]^\wedge \). Recall the algebra \( \mathbb{Q}\langle e_0, e_1 \rangle \) from Example 3.71. We define a morphism of algebras \( \mathbb{Q}\langle e_0, e_1 \rangle \to \mathbb{Q}[\Gamma]^\wedge \) by sending \( e_0 \) to \( \log(\gamma_0) \) and \( e_1 \) to \( \log(\gamma_1) \). It is easy to verify that this map is an isomorphism compatible with all the extra structures (unit, counit, completed coproduct, and antipode) carried by these completed Hopf algebras. The pro-unipotent completion of \( \Gamma \) is hence given by
\[
\Gamma^\text{un} = \text{Spec}(\mathfrak{h}),
\]
where \( \mathfrak{h} \) is the Hoffman algebra from Example 3.62. In particular, we can identify the group of rational points \( \Gamma^\text{un}(\mathbb{Q}) \) with the set of group-like elements of \( \mathbb{Q}\langle e_0, e_1 \rangle \), the Lie algebra \( \text{Lie}(\Gamma^\text{un}) \) with the set of primitive elements of \( \mathbb{Q}\langle e_0, e_1 \rangle \) and the completed universal enveloping algebra of \( \text{Lie}(\Gamma^\text{un}) \) with \( \mathbb{Q}\langle e_0, e_1 \rangle \).

3.4.3. The pro-unipotent completion of a torsor. Quillen’s construction can be extended to define the pro-unipotent completion of a torsor. Let us first recall the definition:

Definition 3.230. Let \( \Gamma \) be a group. A left \( \Gamma \)-torsor is a non-empty set \( P \) together with a free and transitive action \( \Gamma \times P \to P \). Similarly, a right \( \Gamma \)-torsor is a non-empty set \( P \) together with a free and transitive action \( P \times \Gamma \to P \).

Variant 3.231. Assume that \( \Gamma \) satisfies the condition that \( \Gamma_{ab} \otimes \mathbb{Z} k \) has finite dimension and let \( A \) be as in Proposition 3.222. Let \( P \) be a left \( \Gamma \)-torsor. We write \( k[P] \) for the \( k \)-vector space with basis \( P \), which has the structure of a left \( k[\Gamma] \)-module. Moreover, there is a commutative coproduct on \( k[P] \) determined by \( \Delta(p) = p \otimes p \). The completion of \( k[P] \) is defined as
\[
k[P]^\wedge = \lim_{\leftarrow N} k[P]/J^{N+1}k[P].
\]
Consider its topological dual, defined as
\[
R = (k[P]^\wedge)^{\text{top}} = \lim_{\leftarrow N}(k[P]/J^{N+1}k[P])^\vee.
\]
Arguing as in the proof of Proposition 3.222, we deduce that \( R \) is a commutative algebra provided with a comodule structure
\[
\Delta: R \to A \otimes R,
\]
where \( A \) denotes again \( A = (k[P]^\wedge)^\vee \). In other words, \( R \) is a Hopf module over \( A \). The unipotent completion of \( P \) is defined as the spectrum
\[
P^\text{un} = \text{Spec}(R).
\]
The coaction (3.233) induces an action \( \Gamma^\text{un} \times P^\text{un} \to P^\text{un} \) that turns \( P^\text{un} \) into a left \( \Gamma^\text{un} \)-torsor.
Mutatis mutandis, the same construction can be made for a right $\Gamma$-torsor $P'$. Our basic example will be the case when $\Gamma$ is the fundamental group $\pi_1(M, x)$ and $P$ and $P'$ are the torsors of paths $\pi_1(M; x, y)$ and $\pi_1(M; y, x)$ respectively. In this case, there is also an antipode-like map

$$S: (\mathbb{Q}[P])^{\wedge}_{\text{top}} \to (\mathbb{Q}[P'])^{\wedge}_{\text{top}}$$

induced by the rule $S(\gamma) = \gamma^{-1}$ for a path $\gamma \in P$.

\*

**Exercise 3.234.** Consider the group $\Gamma = \pi_1(S^1, 1) \simeq \mathbb{Z}$. Let $\gamma_0$ be a generator of $\Gamma$ and consider $X_0 = \log(\gamma_0)$ as a power series in $(\gamma_0 - 1) \in J$. Use $\gamma_0$ and $X_0$ to describe explicitly

$$\mathbb{Q}[\pi_1(S^1, 1)]/J^{N+1}, \quad \mathbb{Q}[\pi_1(S^1, 1)]^\wedge, \quad \mathcal{O}(\pi_1(S^1, 1)^{un}), \quad \pi_1(S^1, 1)^{un}, \quad \text{Lie}(\pi_1(S^1, 1)^{un}).$$

In particular, deduce that the pro-unipotent completion of $\mathbb{Z}$ is given by the additive group $G_a$. Compare this with Exercise 4.28 in the next chapter.

**Exercise 3.235.** Prove that the pro-unipotent completion of the group $\mathbb{Z}/2\mathbb{Z}$ is the trivial group $\text{Spec}(\mathbb{Q})$.

**Exercise 3.236.** Using the diagram for the antipode in Definition 3.46, prove Lemma 3.228.

3.5. The bar complex and Chen’s $\pi_1$-de Rham theorem. In this section, we make the relation between differential forms and the pro-unipotent completion of the fundamental group of a smooth manifold precise. If one views the latter as the singular side of a picture (or the Betti side if we are dealing with algebraic varieties), then the de Rham side is given by the cohomology of the bar complex. Both points of view will be related through Chen’s $\pi_1$-de Rham Theorem 3.264.

3.5.1. The bar complex of a dg-algebra. We start with the definition of a differential graded algebra.

**Definition 3.237.** Let $k$ be a field of characteristic zero. A differential graded algebra (dg-algebra for short) over $k$ is the data $A = (A^*, \wedge, d)$ of

- a graded $k$-vector space $A^* = \bigoplus_{n \in \mathbb{Z}} A^n$,
- a multiplication $\wedge: A^n \otimes A^m \to A^{n+m}$ for all integers $n, m \in \mathbb{Z}$ that makes $A$ into an associative $k$-algebra with unit $1 \in A^0$;
- a differential $d: A^* \to A^{*+1}$ such that $d^2 = 0$, $d(A^n) \subseteq A^{n+1}$, and $d(a \wedge b) = da \wedge b + (-1)^n a \wedge db, \quad a \in A^n$.

We say that $A$ is (graded) commutative if the relation $a \wedge b = (-1)^{nm} b \wedge a$ holds for $a \in A^n$ and $b \in A^m$, and connected if $A^n = 0$ for $n < 0$ and $A^0 = k$. The sign operator $J: A \to A$ is defined on homogeneous elements by $Ja = (-1)^{\deg(a)}a$

and extended to the whole $A$ by linearity.
A morphism of dg-algebras is a linear map compatible with the grading, the multiplication and the differential. The field $k$ has a structure of dg-algebra concentrated in degree 0 with zero differential.

An augmentation of a dg-algebra is a map of dg-algebras $\epsilon: A \to k$. It follows immediately from the definitions that a connected dg-algebra has a unique augmentation.

An example to keep in mind throughout this section, when $k = \mathbb{R}$ or $\mathbb{C}$, is the algebra $E^*(M, k)$ of smooth $k$-valued differential forms on a smooth manifold $M$, together with the wedge product $\wedge$ and the exterior differential $d$ (see Section 2.2.1). A typical augmentation is the evaluation map on a point of $M$. Note that $E^*(M, k)$ is not a connected dg-algebra. Similarly, for an arbitrary field $k$, if $X$ is a smooth affine variety over $k$, then $\Omega^*(X)$ is also a dg-algebra and every $k$-rational point induces an augmentation by evaluation. As we will mainly apply the general constructions to this setting, we chose the notation $\wedge$ for the product in $A$.

**Definition 3.238.** Let $A$ be a dg-algebra with augmentations $\epsilon_1$ and $\epsilon_2$. The simplicial bar complex $B_\bullet(A, \epsilon_2, \epsilon_1)$ is the simplicial complex of $k$-vector spaces given by

$$B_n(A, \epsilon_2, \epsilon_1) = A^{\otimes n} = A \otimes A \otimes \cdots \otimes A,$$

with faces

$$\delta_0[x_1 \ldots | x_n] = \epsilon_2(x_1)[x_2 \ldots | x_n],$$

$$\delta_i[x_1 \ldots | x_n] = [J x_1 | \ldots | J x_i \wedge x_{i+1} | \ldots | x_n] \quad \text{for} \quad i = 1, \ldots, n-1,$$

$$\delta_n[x_1 \ldots | x_n] = \epsilon_1(J x_n)[J x_1 | \ldots | J x_{n-1}],$$

and degeneracies

$$s_i[x_1 \ldots | x_n] = [J x_1 | \ldots | J x_{i-1} | 1 | x_i | \ldots | x_n] \quad \text{for} \quad i = 1, \ldots, n.$$

In these formulas, we use the bar notation

$$[x_1 \ldots | x_n] = x_1 \otimes \cdots \otimes x_n, \quad [\ ] = 1.$$

The differential in the tensor complex $A^{\otimes n}$ is defined as

$$d^{\text{ver}}[x_1 \ldots | x_n] = \sum_{i=1}^n (-1)^{n-i}[J x_1 | \ldots | J x_{i-1} | dx_i | x_{i+1} | \ldots | x_n].$$

Note that $d^{\text{ver}}$ is not the usual differential in the tensor algebra, but has an extra sign $(-1)^{n-i}$ in each term. This makes it commute with the faces and degeneracies and is also natural from the point of view of the Leibniz rule (see Remark 3.245). Therefore, $B_\bullet(A, \epsilon_2, \epsilon_1)$ is a simplicial complex in the category of complexes of $k$-vector spaces.

Since $B_\bullet(A, \epsilon_2, \epsilon_1)$ is a simplicial cochain complex, we can associate with it two complexes. First we can take the associated chain complex, $CB(A, \epsilon_2, \epsilon_1)$, as in Definition A.170. This is a chain complex of cochain complexes; we convert it into a double cochain complex by changing the sign of the chain degree as in Definition A.7 vi), and form the total complex (Definition A.25). Or, second, we can take the normalized complex (Definition A.171), change it to a double cochain complex and form the total complex. In both cases when forming the total complex, we consider the simplicial degree as the horizontal or first degree.
The reduced bar complex is defined as:

\[ B^*(A, \epsilon_2, \epsilon_1) = \text{Tot} \, CB(A, \epsilon_2, \epsilon_1). \]

The reduced bar complex is

\[ \tilde{B}^*(A, \epsilon_2, \epsilon_1) = \text{Tot} \, NB(A, \epsilon_2, \epsilon_1). \]

A direct consequence of Theorem A.172 is:

**Theorem 3.240.** There are natural quasi-isomorphisms

\[ \tilde{B}^*(A, \epsilon_2, \epsilon_1) \to B^*(A, \epsilon_2, \epsilon_1) \to \tilde{B}^*(A, \epsilon_2, \epsilon_1) \]

The bar complex has the following structures. The grading and the differential come from the construction as a total complex, while the others are inherited from the tensor algebra.

**Grading:** An element of \( B^*(A, \epsilon_2, \epsilon_1) \) of the form \([x_1 \ldots |x_n]\) is homogeneous if all the components \( x_i \in A \) are homogeneous. If this is the case, its degree is defined by

\[ \deg([x_1 | \ldots | x_n]) = \sum_{i=1}^{n} \deg(x_i) - n, \]

where \( \deg(x_i) \) is the degree of \( x_i \) in \( A^* \). In particular, if \( x_i \in A^n \), then \( \deg([x_i]) = n - 1 \), so the map \( x_i \mapsto [x_i] \) does not preserve the degree.

**Length filtration:** It is the increasing filtration where

\[ L_m B^*(A, \epsilon_2, \epsilon_1) \subseteq B^*(A, \epsilon_2, \epsilon_1) \]

is the subspace generated by elements \([x_1 | \ldots | x_n]\) with \( n \leq m \).

**Differential:** The differential is that of a total complex and takes into account the differential, the product and the augmentations of \( A \):

\[
\begin{align*}
d[x_1 \cdot |x_n] &= \sum_{i=0}^{n} (-1)^i \delta_i [x_1 \cdot |x_n] + (-1)^n \text{d}^{\text{ver}} [x_1 \cdot |x_n] \\
&= \epsilon_2(x_1)[x_2 \cdot |x_n] + (-1)^n \epsilon_1(J x_n)[J x_1 \cdot |J x_{n-1}] \\
&\quad + \sum_{i=1}^{n-1} (-1)^i[J x_1 \cdot |J x_i \wedge x_{i+1} | \cdot |x_n] \\
&\quad + \sum_{i=1}^{n} (-1)^i[J x_1 | \cdot |J x_{i-1} |dx_i |x_{i+1} | \cdot |x_n].
\end{align*}
\]

**Product:** It is the shuffle product

\[
\nabla([x_1 | \cdot |x_r] \otimes [x_{r+1} | \cdot |x_{r+s}]) = \sum_{\sigma \in \mathcal{W}(r,s)} \eta(\sigma)[x_{\sigma^{-1}(1)} | \cdot |x_{\sigma^{-1}(r+s)}].
\]

Here \( \eta(\sigma) \) is the sign determined by the equation

\[ a_1 \wedge \cdots \wedge a_{r+s} = \eta(\sigma)a_{\sigma^{-1}(1)} \wedge \cdots \wedge a_{\sigma^{-1}(r+s)}, \]

where \( \deg(a_i) = \deg(x_i) - 1 = \deg([x_i]) \). Although \( \eta(\sigma) \) is not determined by \( \sigma \) alone, but also depends on the degrees of the involved elements, this abusive notation is the standard one.
**Coproduct:** If \( \epsilon_3 \) is a third augmentation (that may agree with the previous ones) there is a coproduct
\[
\Delta: B^*(A, \epsilon_3, \epsilon_1) \rightarrow B^*(A, \epsilon_3, \epsilon_2) \otimes B^*(A, \epsilon_2, \epsilon_1)
\]
given by deconcatenation
\[
\Delta[x_1 \cdots x_n] = \sum_{i=0}^{n} [x_1 \cdots x_i] \otimes [x_{i+1} \cdots x_n].
\]

**Antipode:** It is given by
\[
(3.244) \quad S([x_1 \cdots x_n]) = (-1)^n \eta(\tau_n) [x_n \cdots x_1],
\]
where the sign \( \eta(\tau_n) \) is determined by equation (3.243) as before, for the permutation \( \tau_n(i) = n - i \).

The above structures induce the corresponding structures in the reduced bar complex \( B(A, \epsilon_2, \epsilon_1) \).

The differential (3.242) can be rewritten, for homogeneous elements, using the total degrees \( \deg([x_i]) = \deg(x_i) - 1 \) as follows:
\[
d[x_1 \cdots x_n] = \epsilon_2(x_1)[x_2 \cdots x_n] + (-1)^{\sum_{i=1}^{n-1} \deg([x_i])} \epsilon_1(x_1)[x_1 \cdots x_{n-1}]
\]
\[
+ \sum_{i=1}^{n-1} (-1)^{\sum_{j=1}^{i} \deg([x_j])} [x_1 \cdots x_i \wedge x_{i+1} \cdots x_n]
\]
\[
- \sum_{i=1}^{n} (-1)^{\sum_{j=1}^{i-1} \deg([x_j])} [x_1 \cdots dx_i \cdots x_n].
\]

In checking the compatibility of the differential with other structures, it might be useful to remember that \( \epsilon_1(x_n) \) is zero unless \( x_n \) has degree 0.

**Remark 3.245.** There are many possible choices of signs in the definition of the bar complex. For instance in [BK94] the faces and degeneracies do not have any sign and the differential \( d^\text{ver} \) is the usual differential in the tensor complex. By contrast, we follow the sign convention of [EM53] and [Hai87a] because in this other convention, the coproduct defined below does not have any sign and the total differential satisfies the Leibniz rule with respect to the product in the tensor algebra and the degree in the bar complex. See [EM53, §10] for a discussion.

**Remark 3.246.** The bar complex \( B^*(A, \epsilon_1, \epsilon_2) \) only depends on the semisimplicial structure of \( B_*(A, \epsilon_1, \epsilon_2) \) that does not use the unit of \( A \). Therefore, it can be extended to non-unital algebras. By contrast, the reduced bar complex depends on the degeneracies and thus on the unit of \( A \).

3.5.2. **The reduced bar complex of a connected dg-algebra.** Let \( A \) be a dg-algebra and \( \epsilon \) an augmentation. We denote
\[
IA = \text{Ker}(\epsilon).
\]
This is a non-unital algebra. By Remark 3.246, we can define the bar complex
\[
B^*(IA, \epsilon_2|_{IA}, \epsilon_1|_{IA}).
\]
The augmentation, together with the unit of \( A \) defines a splitting \( A = k \oplus IA \), from which we deduce the following result:
Lemma 3.247. Let \((A, \epsilon)\) be an augmented \(k\) algebra and let \(\epsilon_1\) and \(\epsilon_2\) be another two augmentations. Then the splitting defined by the augmentation induces an isomorphism
\[
\tilde{B}^*(A, \epsilon_2, \epsilon_1) \xrightarrow{\sim} B^*(IA, \epsilon_2|IA, \epsilon_1|IA)
\]
that together with Theorem 3.240 gives us a quasi-isomorphism
\[
B^*(IA, \epsilon_2|IA, \epsilon_1|IA) \rightarrow B^*(A, \epsilon_2, \epsilon_1).
\]

Proof. By the definition of the degeneracies, the subcomplex of degenerate elements (Definition A.171) is given by
\[
DB_n(A, \epsilon_2, \epsilon_1) = \sum_{i=0}^{n-1} A^i \otimes k \otimes A^{n-i-1} \subset A^\oplus n.
\]
Therefore, the splitting induces an isomorphism
\[
B_n(A, \epsilon_2, \epsilon_1)/DB_n(A, \epsilon_2, \epsilon_1) \xrightarrow{\sim} B_n(IA, \epsilon_2|IA, \epsilon_1|IA).
\]
By Theorem A.172, we obtain the sought after isomorphism at the level of graded \(k\)-vector spaces. Since all structures on both sides are given by the same formulas we see that the isomorphism respects all the structures. \(\square\)

We now make the definition of the reduced bar complex explicit in the case of a connected dg-algebra. An advantage of working in this setting is that connected dg-algebras have a unique augmentation \(\epsilon\), whose kernel is concentrated in positive degrees. All augmentations (those entering the definition of the faces and the coproduct and the one used to construct the splitting) will thus be equal. We omit them from the notation, and write simply
\[
B^*(A) = \tilde{B}^*(A, \epsilon, \epsilon).
\]

Definition 3.248. Let \((A^*, \wedge, d)\) be a connected dg-algebra over \(k\). Set
\[
A^+ = \bigoplus_{n>0} A^n.
\]
The reduced bar complex associated with \(A\), denoted by \(B^*(A)\), is the total tensor algebra of \(A^+\):
\[
B^*(A) = k \oplus A^+ \oplus (A^+ \otimes A^+) \oplus (A^+ \otimes A^+ \otimes A^+) \oplus \ldots
\]
The reduced bar complex is provided with the following structures:

Grading: An element of \(B^*(A)\) of the form \([x_1] \cdots [x_n]\) is homogeneous if all the components \(x_i \in A^+\) are homogeneous. If this is the case, its degree is defined by
\[
\deg([x_1] \cdots [x_n]) = \sum_{i=1}^n \deg(x_i) - n,
\]
where \(\deg(x_i)\) is the degree of \(x_i\) in \(A\). In particular, if \(x_i \in A^n\), then \(\deg([x_i]) = n - 1\), so the map \(x_i \mapsto [x_i]\) does not preserve the degree.

Length filtration: It is the increasing filtration where
\[
L_mB^*(A) \subseteq B^*(A)
\]
is the subspace generated by elements \([x_1] \cdots [x_n]\) with \(n \leq m\).
Differential: The differential takes into account both the differential and the product structures of $A$:

\[(3.249) \quad d[x_1|\cdots|x_n] = -\sum_{i=1}^{n} (-1)^{\sum_j \deg([x_j])} [x_1|\cdots|dx_i|\cdots|x_n] \]

\[+ \sum_{i=1}^{n-1} (-1)^{\sum_j \deg([x_j])} [x_1|\cdots|x_i \wedge x_{i+1}|\cdots|x_n].\]

It is easy to check that $d$ is homogeneous of degree 1 and that $d \circ d = 0$.

We will write $d = d_I - d_C$, where

\[(3.250) \quad d_I[x_1|\cdots|x_n] = -\sum_{i=1}^{n} (-1)^{\sum_j \deg([x_j])} [x_1|\cdots|dx_i|\cdots|x_n] \]

\[(3.251) \quad d_C[x_1|\cdots|x_n] = -\sum_{i=1}^{n-1} (-1)^{\sum_j \deg([x_j])} [x_1|\cdots|x_i \wedge x_{i+1}|\cdots|x_n].\]

Here $I$ stands for “internal” and $C$ for “combinatorial”.

Product: It is the shuffle product

\[\nabla([x_1|\cdots|x_r] \otimes [x_{r+1}|\cdots|x_{r+s}]) = \sum_{\sigma \in \Omega(r,s)} \eta(\sigma) [x_{\sigma^{-1}(1)}|\cdots|x_{\sigma^{-1}(r+s)}].\]

Here $\eta(\sigma)$ is the sign determined by the equation (3.243).

Coproduct: The coproduct is the deconcatenation coproduct

\[\Delta[x_1|\cdots|x_n] = \sum_{i=0}^{n} [x_1|\cdots|x_i] \otimes [x_{i+1}|\cdots|x_n].\]

Antipode: It is given again by equation (3.244).

Since $A^+$ is concentrated in positive degrees, we deduce that $B^*(A)$ is concentrated in non-negative degrees. This has the following consequence:

**Lemma 3.252.** Let $A = (A^*, d, \wedge)$ be a connected commutative dg-algebra. Then the above operations endow $H^0(B^*(A))$, the zeroth cohomology group of the reduced bar complex, with a commutative Hopf algebra structure.

**Proof.** The bar complex $B^*(A)$ is a commutative differential graded Hopf algebra. This means that the product, coproduct and antipode are compatible with the grading and the differential. The latter compatibility is written as

\[d \circ \nabla = \nabla \circ d,\]

\[\Delta \circ d = d \otimes d,\]

\[S \circ d = d \circ S,\]

where $d_\otimes$ is the differential induced in $B^*(A) \otimes B^*(A)$ that carries the usual sign. All these statements can be checked directly. Once we know that all these operations are compatible with the differential, they are transferred to cohomology. Since they are compatible with the grading, they induce operations on $H^0$, except, maybe, the coproduct. In principle the coproduct would give a map

\[\Delta: H^0(B^*(A)) \rightarrow \bigoplus_{i+j=0} H^i(B^*(A)) \otimes H^j(B^*(A)).\]
Since the $B^*(A)$ is non-negatively graded, the only non-zero term on the right is $H^0(B^*(A)) \otimes H^0(B^*(A))$, and hence the coproduct is also well defined at the level of zeroth cohomology.

\begin{remark}
\begin{enumerate}
\item The commutativity of the product in $A^*$ is essential in the previous proof. In fact if the product on $A^*$ is not commutative, it is not true that the shuffle product in $B^*(A)$ is compatible with the differential.
\item Since the complex $B^*(A)$ is concentrated in non-negative degrees, so the cohomology we are interested in is simply

\[ H^0(B^*(A)) = \text{Ker}(d: B^0(A) \rightarrow B^1(A)). \]

Note that $B^0(A)$ consists of $k$-linear combinations of $[,]$ and $[x_1 \cdots |x_n]$ with $n \geq 1$ and $\deg(x_i) = 1$ for all $i = 1, \ldots, n$. Also, observe that, restricted to $B^0(A)$, the differentials are given by the formulas

\[
\begin{align*}
    d_I[x_1|\cdots|x_n] &= -\sum_{i=1}^{n} [x_1|\cdots|dx_i|\cdots|x_n], \\
    d_C[x_1|\cdots|x_n] &= -\sum_{i=1}^{n-1} [x_1|\cdots|x_i \wedge x_{i+1}|\cdots|x_n].
\end{align*}
\]

In practice, one would like to use the de Rham dg-algebra that is not connected, even if the space is connected. In order to use Lemma 3.252, it is convenient to use a quasi-isomorphic connected dg-algebra.

\begin{lemma}
Take $k = \mathbb{R}$ or $\mathbb{C}$ and let $M$ be a connected differentiable manifold. Let $x, y \in M$ and let $A^* \subset E^*(M, k)$ be a connected dg-subalgebra such that the inclusion $A^* \rightarrow E^*(M, k)$ is a quasi-isomorphism. Let $\epsilon_x, \epsilon_y$ be the augmentations given by evaluation at the points $x$ and $y$ respectively. Then there is a quasi-isomorphism $B^*(A) \rightarrow B(E^*(M, k), \epsilon_y, \epsilon_x)$. In particular,

\[ H^0(B^*(A^*)) = H^0(B(E^*(M, k), \epsilon_y, \epsilon_x)). \]
\end{lemma}

\begin{proof}
Let $f: A \rightarrow B$ be a morphism of dg-algebras and let $\epsilon_1$ and $\epsilon_2$ be two augmentations on $B$. By composition they induce augmentations $\epsilon_1'$ and $\epsilon_2'$ on $A$. Then there is a map

\[ B(f): B(A, \epsilon_1', \epsilon_2') \rightarrow B(B, \epsilon_1, \epsilon_2). \]

A consequence of a result by Chen (see [Hai87a, Cor.1.2.3]) is that if $f$ is a quasi-isomorphism, then $B(f)$ is also a quasi-isomorphism. This, together with Theorem 3.240 implies the result.
\end{proof}

3.5.3. The reduced bar complex and iterated integrals. Let $M$ be a connected differentiable manifold with the homotopy type of a finite CW complex. Let $E^*(M, \mathbb{C})$ be the differential graded algebra of complex smooth differential forms on $M$. For simplicity of the exposition, we will assume that we have chosen a dg-$\mathbb{C}$-algebra $A^*$ provided with an injective morphism of dg-algebras $\varphi: A^* \rightarrow E^*(M)$ such that

\begin{enumerate}
\item $A^*$ is connected, that is $A^0 = \mathbb{C}$ and $A^n = 0$ for $n < 0$.
\end{enumerate}
ii) The induced map in cohomology
\[ \varphi: H^*(A^*) \longrightarrow H^*(E^*(M, \mathbb{C})) \]
is an isomorphism.

By Lemma 3.254, the reduced bar complex of \( A^* \) is quasi-isomorphic to the bar complex of \( E^*(M, \mathbb{C}) \) with respect to any pair of augmentations. So it will be enough to consider the reduced bar complex of \( A^* \). A similar discussion can be made with the bar complex of the whole dg-algebra \( E^*(M, \mathbb{C}) \). See Exercise 3.271.

The condition of \( A^* \) being connected implies that the elements of degree zero of \( B_0(A^*) \) are linear combinations of the shape
\[ \sum [\eta_1|\cdots|\eta_r] \]
with \( \eta_i \in A^1 \subset E^1(M) \) 1-forms. Thus, with any element \( x \in B_0(A^*) \) we can associate an iterated integral
\[ \gamma \mapsto \int_\gamma \eta_1 \cdots \eta_r. \]

For each pair of points \( x, y \in M \), we define a pairing
\[ \langle \quad , \quad \rangle: B^0(A^*) \otimes \mathbb{Q}[y \mathcal{P}(M)_x] \longrightarrow \mathbb{C} \]
\[ [\eta_1|\cdots|\eta_r] \otimes \gamma \mapsto \int_\gamma \eta_1 \cdots \eta_r, \]
where \( y \mathcal{P}(M)_x \) is the set of piecewise smooth paths as in Section 3.1, and \( \mathbb{Q}[y \mathcal{P}(M)_x] \) denotes the \( \mathbb{Q} \)-vector space with basis \( y \mathcal{P}(M)_x \).

We can now translate Theorem 3.19 into the language of the bar complex and the pairing (3.255).

**Theorem 3.256.** Let \( \gamma, \gamma_1, \gamma_2 \) be piecewise smooth paths in \( M \) and let \( \eta, \eta_1, \eta_2 \in B^0(A^*) \) be degree zero elements of the reduced bar complex of \( A^* \). Then the following three equalities are satisfied:
\[ \langle S(\eta), \gamma \rangle = \langle \eta, S(\gamma) \rangle. \] (3.257)
\[ \langle \eta, \gamma_1 \gamma_2 \rangle = \langle \Delta \eta, \gamma_1 \otimes \gamma_2 \rangle. \] (3.258)
\[ \langle \eta_1 \otimes \eta_2, \nabla^\gamma \gamma \rangle = \langle \eta_1 \cup \eta_2, \gamma \rangle. \] (3.259)

A consequence of the previous theorem is the following result that says that the length filtration of the reduced bar complex is dual to the filtration by the augmentation ideal in the group algebra of paths.

**Proposition 3.260.** Let \( x, y \) be points of \( M \). Let \( J \) be the augmentation ideal of \( \mathbb{Q}[x \mathcal{P}(M)_x] \), \( N \geq 0 \) an integer and \( \gamma \in J^{N+1}\mathbb{Q}[x \mathcal{P}(M)_y] \) or \( \gamma \in \mathbb{Q}[y \mathcal{P}(M)_y]J^{N+1} \). If \( \eta \in L_N B^0(A^*) \) has length less than or equal to \( N \), then
\[ \langle \eta, \gamma \rangle = 0. \]

**Proof.** We only treat the case \( \gamma \in J^{N+1}\mathbb{Q}[x \mathcal{P}(M)_y] \) (the other one is completely analogous). The proof proceeds by induction on \( N \).

If \( N = 0 \), every element of \( \gamma \in J\mathbb{Q}[x \mathcal{P}(M)_y] \) can be written as
\[ \gamma = \sum_{i=1}^r q_i \gamma_i, \quad q_i \in \mathbb{Q}, \quad \sum_{i=1}^r q_i = 0, \quad \gamma_i \in x \mathcal{P}(M)_y. \]
If $\eta \in L_0B^0(A^*)$, then $\eta = \alpha[\ ]$ for $\alpha \in \mathbb{C}$. Since
$$\langle [\ ], \gamma_i \rangle = 1, \quad \text{for} \quad \gamma_i \in \mathcal{P}(M)_y,$$
we deduce the result in the case $N = 0$.

Now fix $N > 0$ and assume that the result holds for all $N' < N$. To prove it for $N$, we may assume that $\gamma = \gamma_1\gamma_2$ with $\gamma_1 \in J$, $\gamma_2 \in J^N\mathbb{Q}[\mathcal{P}(M)_y]$, and $\eta = [\omega_1|\cdots|\omega_N]$. Then the relation 3.258 yields
$$\langle \eta, \gamma \rangle = (\Delta \eta, \gamma_1 \otimes \gamma_2) = \sum_{i=0}^{N} \langle [\omega_1|\cdots|\omega_i], \gamma_1 \rangle \langle [\omega_{i+1}|\cdots|\omega_N], \gamma_2 \rangle$$
$$= \langle [\ ], \gamma_1 \rangle \langle [\omega_1|\cdots|\omega_N], \gamma_2 \rangle + \sum_{i=1}^{N} \langle [\omega_1|\cdots|\omega_i], \gamma_1 \rangle \langle [\omega_{i+1}|\cdots|\omega_N], \gamma_2 \rangle.$$
The first summand in the last equality vanishes since $\langle [\ ], \gamma_1 \rangle = 0$ and all the factors $\langle [\omega_{i+1}|\cdots|\omega_N], \gamma_2 \rangle$ in the second sum vanishes by the induction hypothesis. Thus, $\langle \eta, \gamma \rangle = 0$, as we wanted to show. \hfill \Box

3.5.4. The reduced bar complex and the pro-unipotent completion of the fundamental group. One of the main interests of the reduced bar complex is that it provides us with a criterion to decide whether an iterated integral is a homotopy functional, thus solving the question raised in Section 3.1.

**Theorem 3.261.** Let $\omega \in B^0(A^*)$. If $d\omega = 0$, then the iterated integral associated with $\omega$ is a homotopy functional.

**Proof.** Let $x, y \in M$. Consider two homotopic paths $\gamma_1$ and $\gamma_2$ from $x$ to $y$ and let $F$ be a homotopy between them. Recall from Definition 3.1 that $F : [0, 1]^2 \to M$ satisfies the conditions

$$F(t, 0) = \gamma_1(t), \quad F(t, 1) = \gamma_2(t), \quad F(0, s) = x, \quad F(1, s) = y.$$  

For simplicity, we will assume that $F$ is smooth; the general case follows by taking a polyhedral decomposition, as in the proof of Lemma 3.11. Set
$$F_i : [0, 1]^n \times [0, 1] \to M, \quad ((t_1, \ldots, t_n), s) \mapsto F(t_i, s).$$

The elements of $B^1(A^*)$ are linear combinations of $\nu = [\nu_1|\cdots|\nu_n]$ with exactly one 2-form among the $\nu_i$’s and the remaining ones being 1-forms. Given such a $\nu$, with the 2-form in the $i$-th position, we define the **integral along $F$** as

$$\int_F \nu = (-1)^i \int_{[0, 1]^n} F^*_{i} \nu_1 \wedge \cdots \wedge F^*_{n} \nu_n,$$

where the second integral is oriented by $ds \wedge dt_1 \wedge \cdots \wedge dt_n$. In this integral $\Delta^n$ denotes, as in Notation 1.113, the simplex

$$\Delta^n = \{(t_1, \ldots, t_n) \mid 1 \geq t_1 \geq \cdots \geq t_n \geq 0\}.$$  

The definition of the integral along $F$ extends to $B^1(A^*)$ by $\mathbb{C}$-linearity. We claim that

$$\int_{\gamma_2} \omega - \int_{\gamma_1} \omega = \int_F d\omega,$$

where $d\omega = \sum \partial \omega_i \wedge \nu_i$ is the exterior derivative of $\omega$. \hfill \Box
and the statement of the theorem will of course be an immediate consequence.

The equality (3.263) is proved by a careful application of Stokes’s theorem. To prove it we can assume that \( \omega = [\omega_1 \mid \cdots \mid \omega_n] \in B^0(A^*) \). First observe that

\[
d(F^*_1 \omega_1 \wedge \cdots \wedge F^*_n \omega_n) = \sum_{i=1}^{n} (-1)^{i+1} F^*_i \omega_1 \wedge \cdots \wedge F^*_i (d \omega_i) \wedge \cdots \wedge F^*_n \omega_n
\]

by the properties defining the exterior derivative (see Section 2.2.1) and the commutativity of \( d \) and \( F \). Combining this with the definitions of \( d_I \) and the integral along \( F \), one gets:

\[
\int_F d_I \omega = \int_{[0,1] \times \Delta^n} d(F^*_1 \omega_1 \wedge \cdots \wedge F^*_n \omega_n).
\]

We now apply Stokes’ theorem. Set \( \Omega = F^*_1 \omega_1 \wedge \cdots \wedge F^*_n \omega_n \).

\[
\int_F d_I \omega = \int_{\partial([0,1] \times \Delta^n)} F^*_1 \omega_1 \wedge \cdots \wedge F^*_n \omega_n
\]

\[
= \int_{s=1}^{t=1} \Omega - \int_{s=0}^{t=1} \Omega + \sum_{i=1}^{n-1} (-1)^{i+1} \int_{t=t_{i+1}} \Omega - (-1)^n \int_{t=n=0} \Omega
\]

By the relations satisfied by \( F \),

\[
\Omega|_{s=1} = \gamma^*_2 \omega_1 \wedge \cdots \wedge \gamma^*_2 \omega_n,
\]

\[
\Omega|_{s=0} = \gamma^*_1 \omega_1 \wedge \cdots \wedge \gamma^*_1 \omega_n,
\]

\[
\Omega|_{t=t_{i+1}} = F^*_1 \omega_1 \wedge \cdots \wedge F^*_i (\omega_i \wedge \omega_{i+1}) \wedge F^*_n \omega_n
\]

and \( \Omega|_{t=1} \) (resp. \( \Omega|_{t=0} \)) vanishes since in that case \( F_1 \) (resp. \( F_n \)) is a constant function. Besides,

\[
\int_F d_C \omega = \sum_{i=1}^{n} (-1)^{i+1} \int_{[0,1] \times \Delta^{n-1}} F^*_1 \omega_1 \wedge \cdots \wedge F^*_i (\omega_i \wedge \omega_{i+1}) \wedge \cdots \wedge F^*_n \omega_n.
\]

Putting everything together yields

\[
\int_F d_I \omega = \int_{\gamma_2} \omega - \int_{\gamma_1} \omega + \int_F d_C \omega,
\]

which is exactly the content of the claim (3.263) noting that \( d = d_I - d_C \).

Let \( x \in M \) and write \( \Gamma = \pi_1(M,x) \). The condition that \( M \) has the homotopy type of a finite CW complex implies that \( H_1(M) \) is finite-dimensional. Thus, \( \Gamma \) satisfies the hypothesis of Theorem 3.224 and its pro-unipotent completion is given by \( \text{Spec}((\mathbb{Q}[\Gamma])^\vee) \).

Recall that the zero cohomology group of the reduced bar complex of \( A^* \) is just the kernel of the differential map,

\[
H^0(B^*(A^*)) = \text{Ker}(d: B^0(A^*) \rightarrow B^1(A^*))
\]

which, by Theorem 3.261, consists of homotopy functionals.

Putting together Theorem 3.261 and Proposition 3.260 we obtain a map

\[
H^0(L_NB^*(A^*)) \rightarrow ((\mathbb{Q}[\pi_1(M;y,x)]/\mathbb{Q}[\pi_1(M;y,x)])J^{N+1} \otimes \mathbb{C})^\vee.
\]
**Theorem 3.264 (Chen’s π₁-de Rham theorem).** For each integer \( N \geq 0 \) and points \( x, y \in M \), the integration map gives an isomorphism

\[
H^0(L_N B^*(A^*)) \xrightarrow{\sim} \text{Hom}_\mathbb{Q}(\mathbb{Q}[\pi_1(M;y,x)]/\mathbb{Q}[\pi_1(M;y,x)]J^{N+1}, \mathbb{Q}),
\]

and consequently it induces an isomorphism of ind-vector spaces between

\[
H^0(B^*(A^*)) = \lim_{\rightarrow} H^0(L_N B^*(A^*))
\]

and

\[
(\mathbb{C}[\pi_1(M;y,x)]^\vee)^{\vee} = \lim_{\rightarrow} (\mathbb{C}[\pi_1(M;y,x)]/\mathbb{C}[\pi_1(M;y,x)]J^{N+1})^{\vee}.
\]

We will give a proof of this result in the next section. Note moreover, that Theorem 3.256 implies that the last isomorphism of Theorem 3.264 is compatible with the Hopf algebra structures on both sides.

**Corollary 3.265.** For every point \( x \in M \), the iterated integral induces an isomorphism of Hopf algebras

\[
H^0(B^*(A^*)) \xrightarrow{\sim} \mathcal{O}(\pi_1(M,x)^{un}) \otimes \mathbb{C}.
\]

**Remark 3.266.** The isomorphism of Corollary 3.265 depends on the choice of a base point \( x \).

**3.5.5. The case of \( \mathbb{P}^1 \setminus \{0,1,\infty\} \).** The main example to which we would like to apply Corollary 3.265 is the manifold \( M = \mathbb{P}^1(\mathbb{C}) \setminus \{0,1,\infty\} \). This example will be central for the remainder of the book. The fundamental group of \( M \) is the free group in two generators. Thus, its pro-unipotent completion is isomorphic to the spectrum of the Hoffman algebra \( \mathcal{H} \) by Example 3.229. We want to recover this fact as a particular case of Chen’s theorem. For this, we consider the differential forms

\[
\omega_0 = \frac{dt}{t}, \quad \omega_1 = \frac{dt}{1-t}.
\]

Let \( A^*_\mathbb{C} \) be the dg-algebra over \( \mathbb{C} \) given by

\[
A^0_\mathbb{C} = \mathbb{C}, \quad A^1_\mathbb{C} = \mathbb{C} \omega_0 \oplus \mathbb{C} \omega_1, \quad A^{\geq 2}_\mathbb{C} = 0,
\]

together with the trivial differential and the obvious multiplication. Thus, \( A^*_\mathbb{C} = A^* \otimes \mathbb{C} \), where \( A \) is the \( \mathbb{Q} \) algebra introduced in Example 2.260. In particular, the inclusion \( A^*_\mathbb{C} \subset E^*(M,\mathbb{C}) \) is a quasi-isomorphism.

Since \( d\omega_i = 0 \) for \( i = 0,1 \) and \( \omega_0 \wedge \omega_1 = 0 \), formula (3.249) shows that the differential in the reduced bar complex \( B^*(A^*) \) is identically zero, and hence

\[
H^0(B^*(A^*)) = B^0(A^*).
\]

Moreover, there is an isomorphism of Hopf algebras

\[
H^0(B^*(A^*)) \xrightarrow{\sim} \mathcal{H}
\]

\[
\omega_0 \mapsto x_0 \]

\[
\omega_1 \mapsto x_1.
\]

That induces an isomorphism of Hopf algebras

\[
H^0(B^*(A^*_\mathbb{C})) \xrightarrow{\sim} \mathcal{H} \otimes \mathbb{Q} \mathbb{C}.
\]

Following Notation 1.160, for a binary sequence \( \alpha \), we will denote by \( \omega_\alpha \) the element of \( H^0(B^*(A^*_\mathbb{C})) \) corresponding to \( x_\alpha \).
Exercise 3.269. Show that the differentials $d_I$ and $d_C$ from equations (3.250) and (3.251) in the definition of the bar complex satisfy

$$d_I^2 = d_C^2 = 0 \quad d_Id_C + d_Cd_I = 0.$$  

Deduce that $d = d_I - d_C$ satisfies $d^2 = 0$ as well.

Exercise 3.270. Let $\eta_1$, $\eta_2$ and $\eta_{12}$ be 1-forms on a differentiable manifold. What conditions should they satisfy for $[\eta_1|\eta_2] - [\eta_{12}]$ to be closed?

Exercise 3.271. Let $M$ be a connected differentiable manifold with the homotopy type of a finite CW complex and let $E^*(M, \mathbb{C})$ be the differential graded algebra of smooth complex-valued differential forms on $M$. Consider the projection $E^1(M, \mathbb{C}) \to E^1(M, \mathbb{C})/dE^0(M, \mathbb{C})$.

Let $r$ be any retraction of this projection as complex vector spaces. Show that the subspace

$$\mathbb{C} \oplus \text{Im}(r) \oplus \bigoplus_{n \geq 2} E^n(M, \mathbb{C}) \subset E^*(M, \mathbb{C})$$

inherits the structure of a complex dg-algebra. It is connected and the inclusion is a quasi-isomorphism.

3.6. A geometric description of the pro-unipotent completion of the fundamental group. We now explain a proof of Chen’s $\pi_1$-de Rham theorem (Theorem 3.264). This is not the classical proof that one can find in Hain’s paper [Hai87b, §4], but the strategy we follow will later enable us to exhibit the motivic nature of the pro-unipotent completion of the fundamental group of an algebraic variety. The first step in the proof is to show that the reduced bar complex of the de Rham complex of a differentiable manifold can be seen as the de Rham complex of a cosimplicial manifold. We will be using simplicial techniques and the unfamiliar reader is referred to Section A.8 of the appendix.

3.6.1. The normalized cochain complex and the reduced bar complex. Let $M$ be a connected differentiable manifold with the homotopy type of a finite CW complex, and let $x, y \in M$ be base points.

Construction 3.272. We denote by $yM^\bullet_x$ the cosimplicial manifold with components

$$yM^n_x = M \times \cdots \times M,$$

coface maps

$$\delta^i : yM^n_x \to yM^{n+1}_x, \quad i = 0, \ldots, n + 1,$$

given by

$$\delta^i(x_1, \ldots, x_n) = \begin{cases} (y, x_1, \ldots, x_n), & \text{if } i = 0, \\ (x_1, \ldots, x_i, x_i, \ldots, x_n), & \text{if } 0 < i < n + 1, \\ (x_1, \ldots, x_n, x), & \text{if } i = n + 1, \end{cases}$$

and codegeneracy maps

$$\sigma^i : yM^{n+1}_x \to yM^n_x, \quad i = 0, \ldots, n,$$
given by
\[
\sigma^i(x_1, \ldots, x_{n+1}) = (x_1, \ldots, x_i, x_{i+2}, \ldots, x_{n+1}).
\]

As in Section 3.5.3, let \( E^*(M, \mathbb{C}) \) be the dg-algebra of smooth complex-valued differential forms on \( M \). For simplicity, we will assume that we have chosen a connected differential graded \( \mathbb{C} \)-algebra \( A^*(M) \subseteq E^*(M, \mathbb{C}) \) such that the inclusion is a quasi-isomorphism (see Exercise 3.271). We set \( \sigma^i(x_1, \ldots, x_{n+1}) \). The assignment \( \Delta_n \mapsto A^*(y, M^n_x) \) being functorial (Exercise 3.329), these complexes define a simplicial dg-algebra \( A^*(y, M^n_x) \).

**Remark 3.274.** Since \( A^*(M) \) is connected, the dg-algebra \( A^*(y, M^n_x) \) does not depend on the base points \( x, y \in M \). The reason to keep them in the notation is that, later on, we will build out of \( A^*(y, M^n_x) \) the de Rham component of a mixed Hodge structure whose Betti component does depend on \( x \) and \( y \).

The normalization \( \mathcal{N} A^*(y, M^n_x) \) (Definition A.171) is a chain complex of cochain complexes. We convert it into a double cochain complex by changing the sign of the difference are some signs in the faces, degeneracies and de Rham differential on \( \mathcal{N} A^*(y, M^n_x) \). It follows that the map \( \psi: B^*(A^*(M)) \longrightarrow \text{Tot} \mathcal{N} A^*(y, M^n_x) \) is an isomorphism of complexes that sends the \( N \)-th step of the length filtration \( L_N B^*(A^*(M)) \) to \( \text{Tot} \sigma_{\leq N} \mathcal{N} A^*(y, M^n_x) \). Similarly, if \( \varepsilon \) is the unique augmentation of \( A^*(M) \), then the same formula gives us an isomorphism
\[
B^*(A^*(M), \varepsilon, \varepsilon) \longrightarrow \text{Tot} \mathcal{C} A^*(y, M^n_x),
\]
where \( \mathcal{C} \) denotes the associated chain complex (Definition A.170).

**Proof.** Recall the identification \( B^*(A^*(M)) = \text{Tot} \mathcal{N} B_\bullet(A^*(M)) \) and that the constituents of \( B_\bullet(A^*(M)) \) and of \( A^*(y, M^n_x) \) are the same. The only difference are some signs in the faces, degeneracies and de Rham differential on \( B_\bullet(A^*(M)) \). It follows that the map \( \psi \) is an isomorphism of graded vector spaces that respects the filtrations. We next compute the differential in the complex \( \text{Tot} \mathcal{N} A^*(y, M^n_x) \). Let
\[
\omega = \omega_1 \otimes \cdots \otimes \omega_n \in \mathcal{N} A^m(y, M^n_x) \subset \text{Tot}^{m-n} \mathcal{N} A^*(y, M^n_x).
Then $d\omega = d_1\omega + (-1)^n d_2\omega$, where $d_1$ is the differential in the normalized complex and $d_2$ is the differential in the de Rham complex. Therefore,

\[(3.276)\quad d\omega = \sum_{i=1}^{n-1} (-1)^i \omega_1 \otimes \cdots \otimes \omega_i \wedge \omega_{i+1} \otimes \cdots \otimes \omega_n + (-1)^n \sum_{i=1}^{n} (-1)^{\sum_{j=1}^{i} \deg(\omega_j)} \omega_1 \otimes \cdots \otimes d\omega_i \otimes \cdots \otimes \omega_n.\]

Comparing this formula with the differential in Definition 3.248 one checks that $\psi \circ d = d \circ \psi$. This finishes the proof.

\[\square\]

### 3.6.2. A Mayer-Vietoris complex of sheaves

The next step is to construct a complex of sheaves that computes certain relative cohomology groups. In fact, we are giving a variant of Construction 2.97 that was used to compute the relative de Rham cohomology in the case of a normal crossing divisor.

As in the previous sections, let $M$ be a connected differentiable manifold which has the homotopy type of a finite CW complex, and let $Y_0, \ldots, Y_N$ be a finite collection of closed subsets of $M$. Write $Y = Y_0 \cup \cdots \cup Y_N$.

**Notation 3.277.** The following notation will be used:

- Recall that $\Delta_N$ stands for the index set $\{0, \ldots, N\}$.
- For each subset $I \subseteq \Delta_N$, we write $Y_I$ for the intersection $\bigcap_{j \in I} Y_j$. We also write $|I|$ for the cardinal of $I$.
- Given a topological space $T$, we denote by $\mathcal{Q}_T$, the constant sheaf on $T$ with values on $\mathbb{Q}$. If there is a clear closed immersion $\iota : T \to M$, by abuse of notation, we will denote also by $\mathcal{Q}_T$ the extension by zero $\iota_* \mathcal{Q}_T$. For example, if $x \in M$ is a point, we will write $\mathcal{Q}_x$ for the skyscraper sheaf with stalk $\mathbb{Q}$ at $x$. For shorthand, in the situation at hand, we write $\mathcal{Q}_I$ for the constant sheaf on $Y_I$ extended by zero to $M$, that is,

\[\mathcal{Q}_I = (\iota_I)_* \mathcal{Q}_{Y_I},\]

where $\iota_I : Y_I \to M$ is the inclusion. In particular, $\mathcal{Q}_\emptyset = \mathcal{Q}_M$.

- Given subsets $I \subseteq K \subseteq \Delta_N$, there is an inclusion $Y_K \subseteq Y_I$. We denote by $d_{K,I} : \mathcal{Q}_I \to \mathcal{Q}_K$ the corresponding restriction map.

- If $K = \{i_0, \ldots, i_p\}$ with the indices $i_\ell$ ordered as $i_0 < \cdots < i_p$, and if $I = \{i_0, \ldots, \hat{i}_i, \ldots, i_p\}$, then we set

\[\varepsilon(I, K) = (-1)^i\]

as in equation (2.99). We also write

\[(3.278)\quad \varepsilon(K) = \prod_{i \in K} (-1)^i.\]

For $0 \leq p \leq N$, we define a morphism of sheaves

\[d : \bigoplus_{|I|=p} \mathcal{Q}_I \to \bigoplus_{|K|=p+1} \mathcal{Q}_K, \quad \text{by} \quad d = \bigoplus_{p=|I|=|K|-1} \varepsilon(I, K)d_{K,I}.\]
We define the complex of sheaves $\tilde{K}(M; Y_0, \ldots, Y_N)$ as
\begin{equation}
0 \rightarrow \bigoplus_{|I|=0} \mathbb{Q}_I \rightarrow \bigoplus_{|I|=1} \mathbb{Q}_I \rightarrow \cdots \rightarrow \bigoplus_{|I|=N} \mathbb{Q}_I \rightarrow \bigoplus_{|I|=N+1} \mathbb{Q}_I \rightarrow 0,
\end{equation}
where the sheaf $\bigoplus_{|I|=p} \mathbb{Q}_I$ lies in degree $p$.

We also define the complex $K(M; Y_0, \ldots, Y_N)$ as
\begin{equation}
0 \rightarrow \bigoplus_{|I|=0} \mathbb{Q}_I \rightarrow \bigoplus_{|I|=1} \mathbb{Q}_I \rightarrow \cdots \rightarrow \bigoplus_{|I|=N} \mathbb{Q}_I \rightarrow 0.
\end{equation}
Note that the second complex agrees with the first one except for the last term $\mathbb{Q}_{\Delta_N}$ that has been deleted.

**Lemma 3.281.** If $Y$ is locally contractible, then
\[H^n(M, \tilde{K}(M; Y_0, \ldots, Y_N)) = H^n(M, Y; \mathbb{Q}),\]
where the right-hand side is relative singular cohomology.

**Proof.** Since the sequence of sheaves
\[0 \rightarrow \bigoplus_{|I|=0} \mathbb{Q}_Y \rightarrow \bigoplus_{|I|=1} \mathbb{Q}_I \rightarrow \cdots \rightarrow \bigoplus_{|I|=p} \mathbb{Q}_I \rightarrow \cdots \rightarrow \bigoplus_{|I|=N+1} \mathbb{Q}_I \rightarrow 0\]
is exact (Exercise 3.330), the complex $\tilde{K}(M; Y_0, \ldots, Y_N)$ is quasi-isomorphic to the complex
\[0 \rightarrow \mathbb{Q}_M \rightarrow \mathbb{Q}_Y \rightarrow 0.\]
Since we are assuming that $M$ is a differentiable manifold, it is paracompact as well as all its closed and open subsets. Moreover, it is locally contractible. Since $Y$ is also locally contractible, the result follows then from (2.38), that ultimately, is a consequence of Theorem A.236. \hfill $\Box$

We now specialize the previous construction to a particular case. Let $x, y \in M$ be base points, and $N \geq 0$ an integer. Let $M^N$ be the $N$-fold cartesian product of $M$. Given a point of $M^N$, we denote by $x_1, \ldots, x_N$ its components. Consider the union $Y = Y_0 \cup \cdots \cup Y_N$ of the closed subspaces $Y_i \subset M^N$ given by:
\begin{align*}
Y_0 &= \{ y = x_1 \}, \\
Y_i &= \{ x_i = x_{i+1} \}, \quad i = 1, \ldots, N - 1, \\
Y_N &= \{ x_N = x \}.
\end{align*}

Sometimes it will useful to introduce the notation $x_0 = y$ and $x_{N+1} = x$ and write $Y_i = \{ x_i = x_{i+1} \}$ for all $i = 0, \ldots, N$.

Applying the previous construction we define the complexes
\begin{align*}
\mathcal{K}_x(N) &= K(M^N; Y_0, \ldots, Y_N), \\
\tilde{\mathcal{K}}_x(N) &= \tilde{K}(M^N; Y_0, \ldots, Y_N).
\end{align*}

If the base points $x$ and $y$ are different from each other, then $Y_0 \cap \cdots \cap Y_N = \emptyset$ and hence the two complexes agree: $\mathcal{K}_x(N) = \tilde{\mathcal{K}}_x(N)$. By Lemma 3.281, the hypercohomology of $\mathcal{K}_x(N)$ also computes the relative cohomology group:
\[H^n(M^N, \mathcal{K}_x(N)) = H^n(M^N, Y; \mathbb{Q}), \quad \text{when } x \neq y.\]
In the case where \( x = y \), the intersection \( Y_0 \cap \cdots \cap Y_N = \{(x, \ldots, x)\} \) consists of a single point and there is a short exact sequence of complexes

\[
0 \to \mathbb{Q}_{(x,\ldots,x)}[-N-1] \to xK_x(N) \to xK_x(N) \to 0.
\]

Note that the leftmost complex has only non-trivial hypercohomology in degree \( N+1 \), where it is isomorphic to \( H^0(M^N, \mathbb{Q}_{(x,\ldots,x)}) = \mathbb{Q} \). Thus, taking hypercohomology from (3.282) yields a long exact sequence

\[
0 \to H^N(M^N, Y; \mathbb{Q}) \to \mathbb{H}^N(M^N, xK_x(N)) \xrightarrow{f} \mathbb{Q} \to \cdots
\]

The map \( f \) is surjective because it fits into a commutative diagram

\[
\begin{array}{ccc}
\bigoplus_{|I|=N} H^0(Y_I, \mathbb{Q}) & \to & \mathbb{H}^N(M^N, xK_x(N)) \\
\downarrow f & & \downarrow f \\
H^0(M^N, \mathbb{Q}_{(x,\ldots,x)}) & & \end{array}
\]

where the diagonal arrow is surjective. The kernel of \( f \) is thus \( H^N(M^N, Y; \mathbb{Q}) \) and we have a short exact sequence

\[
0 \to H^N(M^N, Y; \mathbb{Q}) \to \mathbb{H}^N(M^N, xK_x(N)) \xrightarrow{f} \mathbb{Q} \to 0.
\]

3.6.3. An isomorphism of cohomology groups. The next step is to relate the cohomology of the cosimplicial manifold \( M^\bullet \) with the cohomology of the sheaf \( yM^\bullet_x \). Since we want an isomorphism on the level of singular cohomology over \( \mathbb{Q} \) we will use smooth cochains instead of differential forms.

Given a differentiable manifold \( M \), we denote by \( S^\bullet(M, \mathbb{Q}) \) the complex of smooth singular cochains on \( X \) with rational coefficients as in Remark A.239. Recall that the complex \( S^\bullet(M, \mathbb{Q}) \) computes the singular cohomology of \( M \) and that there is a quasi-isomorphism

\[
E^\bullet(M, C) \longrightarrow S^\bullet(M, \mathbb{Q}) \otimes C,
\]

given by integration of differential forms over smooth chains, that represents the comparison isomorphism between de Rham and singular cohomology in the differentiable case. As a consequence we have quasi-isomorphisms

\[
A^\bullet(M) \xrightarrow{\sim} S^\bullet(M, \mathbb{Q}) \otimes C, \quad A^\bullet(yM^\bullet_x) \xrightarrow{\sim} S^\bullet(M^n, \mathbb{Q}) \otimes C.
\]

Now we write

\[
S^\bullet_x = S^\bullet(yM^\bullet_x, \mathbb{Q}).
\]

This is a simplicial object in the category of complex of \( \mathbb{Q} \)-vector spaces and there is a quasi-isomorphism

\[
\text{Tot} \mathcal{N} \ast A^\bullet(yM^\bullet_x) \xrightarrow{\sim} \text{Tot} \mathcal{N} \ast S^\bullet_x \otimes C.
\]

Moreover, we can apply to \( S^\bullet_x \) the functor \( C_\ast(\Delta_N, \cdot) \) defined at the end of Section A.8.2. To describe the resulting complex, for each \( \emptyset \neq I \subset \Delta_N \) we denote

\[
yM^I_x = Y_I \subset M^N.
\]

where \( I^c = \Delta_N \setminus I \). Then

\[
yM^I_x \simeq M^{|I|-1}
\]
To realize this isomorphism we just delete the redundant coordinates. Given a point $(x_0, \ldots, x_n) \in y M^I_x$ and each $i \in I'$ the coordinate $x_i$ agrees with the coordinate $x_{i+1}$. Thus, the coordinate $x_i$ is not needed. Furthermore, the first coordinate is always equal to $y$ so it is also redundant. Hence, if $I = (i_0, \ldots, i_k)$ we only need to keep the coordinates $x_{i_1}, \ldots, x_{i_k}$. More precisely, we denote by $\iota_I: M^{|I|-1} \to M^N$ the composition of the inverse of the isomorphism (3.286) with the inclusion $Y_I \to M^N$. Then, if $I = (i_0, \ldots, i_n)$ and

$$p = (x_1, \ldots, x_{i_n}) \in y M^I_x,$$

writing $x_{i_0} = y$ and $x_{i_n+1} = x$, we have

$$\iota_I(p) = (y_1, \ldots, y_N),$$

where

$$y_i = \min\{j \in I \cup \{n+1\} | j \geq i\}.$$

For instance, if $N = 6$ and $I = \{2, 3, 5\}$, the map $\iota_I: M^2 \to M^6$ is given by

$$\iota_I(x_3, x_5) = (y, y, x_3, x_5, x_5, x).$$

If $K = \{j_0, \ldots, j_n\}$ and $I = \{j_0, \ldots, j_i, \ldots, j_n\}$, there is a face map

$$\delta_{I,K}: y M^I_x \to y M^K_x$$

defined by the commutative diagram

$$(3.287)\quad \begin{array}{ccc} y M^I_x & \xrightarrow{\delta_{I,K}} & y M^K_x \\ \parallel & & \parallel \\ Y_I & \subseteq & Y_K. \end{array}$$

Explicitly,

$$\delta_{I,K}(x_{j_1}, \ldots, x_{j_i}, \ldots, x_{j_n}) = \begin{cases} (y, x_{j_2}, \ldots, x_{j_n}), & \text{if } i = 0, \\ (\ldots, x_{j_{i-1}}, x_{j_i+1}, x_{j_{i+1}}, \ldots), & \text{if } 0 < i < n, \\ (x_{j_1}, \ldots, x_{j_{i-1}}, x), & \text{if } i = n. \end{cases}$$

We now write

$$S^*_I = S^*(y M^I_x) \simeq S^*(M^{|I|-1}) = S^*_{|I|-1}.$$

Then, for each $p \geq 0$, we have

$$C_p(\Delta_N, S^*_I) = \bigoplus_{I \subseteq \Delta_N, |I| = p+1} S^*_I$$

with differential $d: C_p(\Delta_N, S^*_I) \to C_{p-1}(\Delta_N, S^*_I)$ given by

$$d = \bigoplus_{I \subseteq K} \varepsilon(I, K) \delta^*_{I,K}.$$

See equation (A.177).

By Proposition A.178 there is a functorial homotopy equivalence

$$(3.288)\quad \phi: \Tot \sigma_{\leq N} N_s S^*_I \simeq \Tot C_*(\Delta_N, S^*_I).$$

Explicitly this morphism is given as follows. Let

$$\omega = (\omega_i)_{0 \leq i \leq N} \in \Tot^* \sigma_{\leq N} N_s S^*_I.$$
Then $\phi(\omega) = (\omega_I)_{I \subset \Delta_N}$, where

$$\omega_I = \begin{cases} 
\omega_i, & \text{if } I = \Delta_i, \\
0, & \text{otherwise}.
\end{cases}$$

Next we compare the cohomology of the complex $\text{Tot} C_* (\Delta_N, S^*_{\bullet})$ with that of the complex of sheaves $\gamma K_{\mathbb{R}} (N)$. To this end we represent the latter using also smooth singular cochains.

We define the double complex $S^*_{\bullet}$ by

$$S^p_q = \bigoplus_{|I|=p} S^q(Y_I, \mathbb{Q}), \quad p \geq 0, \ 0 \leq p < N,$

with horizontal differential

$$d' : \bigoplus_{|I|=p-1} S^q(Y_I, \mathbb{Q}) \longrightarrow \bigoplus_{|K|=p} S^q(Y_K, \mathbb{Q}), \quad d' = \bigoplus_{I,K} \varepsilon(I,K) d_{K,I}.$$

Let $\text{Tot}^* S_Y$ be the associated total complex. By construction

$$H^* (M^N, \gamma K_{\mathbb{R}} (N)[N]) = H^* (\text{Tot}^* S_Y [N]).$$

**Lemma 3.289.** There is a functorial isomorphism

$$\text{Tot} C_* (\Delta_N, S^*_{\bullet}) \xrightarrow{\cong} \text{Tot}^* S_Y [N]$$

that induces an isomorphism

$$H^* (\text{Tot} C_* (\Delta_N, S^*_{\bullet})) \xrightarrow{\cong} H^* (M^N, \gamma K_{\mathbb{R}} (N)[N]).$$

**Proof.** For every $\emptyset \neq I \subset \Delta_N$ we have $\gamma M^I_x = Y_f$. Denote by

$$f_I : S^* (\gamma M^I_x, \mathbb{Q}) \longrightarrow S^* (Y_f, \mathbb{Q})$$

the identity at the level of smooth singular cochains. The morphisms $f_I$, as $I$ runs through non-empty subsets of $\Delta_N$, define an isomorphism between the graded $\mathbb{Q}$-vector spaces $\text{Tot} C_* (\Delta_N, S^*_{\bullet})$ and $\text{Tot}^* S_Y [N]$.

To have an isomorphism of complexes we need to check the compatibility with the differentials. Let $0 \neq I \subset K \subset \Delta_N$, with $|K| = |I| + 1$. The component of the horizontal differential of $C_* (\Delta_N, S^*_{\bullet})$ between $S^I_K$ and $S^I_{|K|}$ is $\varepsilon(I,K) \delta^I_{K,K}$, while the component of the horizontal differential in the complex $S^*_{\bullet}$ between $S^* (Y_K)$ and $S^* (Y_f)$ is $(-1)^N \varepsilon(K^e, I^e) d_{I^e,K^e}$. By the commutativity of diagram (3.287), the maps $\delta^I_{K,K}$ and $d_{I^e,K^e}$ agree. Hence we only need to adjust the signs.

Let $\varepsilon(I) = \prod_{i \in I} (-1)^i$ be the sign introduced in (3.278). It is immediate to check that

$$\varepsilon(I,K) \varepsilon(K^e, I^e) = \varepsilon(I) \varepsilon(K).$$

In consequence, the map

$$\text{Tot} C^* (\Delta_N, S^*_{\bullet}) \longrightarrow \text{Tot} S^*_{\bullet} [N]$$

that sends $S^p (\gamma M^I_x, \mathbb{Q})$ to $S^p (Y_f, \mathbb{Q})$ through the map

$$(-1)^{|I|} \varepsilon(I) f_I$$

is an isomorphism of complexes, thus proving the lemma. The sign $(-1)^{|I|}$ is needed to take into account that in the complex $\text{Tot} S^*_{\bullet} [N]$ there is an extra sign $(-1)^N$ in the differential due to the shift. \(\square\)
Combining Lemma 3.289 with Lemma 3.275, the homotopy equivalence (3.288) and the fact that, for any differentiable manifold the map $E^*(M, \mathbb{C}) \to S^*(M, \mathbb{Q}) \otimes \mathbb{C}$ is a quasi-isomorphism, we deduce the following result.

**Corollary 3.291.** There is a functorial morphism

$$L_N B^*(A^*(M)) \longrightarrow \text{Tot}^* S_Y \otimes \mathbb{C}$$

that induces an isomorphism

$$H^0(L_N B^*(A^*(M))) \simeq \mathbb{H}^N(M^N, y\mathcal{K}_x(N)) \otimes \mathbb{C}.$$  

In particular, if $y \neq x$ we deduce an isomorphism

$$H^0(L_N B^*(A^*(M))) \simeq H^N(M^N, Y; \mathbb{Q}) \otimes \mathbb{C}.$$

3.6.4. **Beilinson’s theorem, global version.** As discussed before Theorem 3.264, there is a map

$$H^0(L_N B^*(A^*(M))) \longrightarrow ((\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J^{N+1}) \otimes \mathbb{C})^\vee$$

that we want to prove that it is an isomorphism. In view of Corollary 3.291 we deduce a morphism

$$\mathbb{H}^N(M^N, y\mathcal{K}_x(N)) \otimes \mathbb{C} \longrightarrow ((\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J^{N+1}) \otimes \mathbb{C})^\vee.$$

The latter morphism is defined over $\mathbb{Q}$. To prove this we construct directly another morphism

$$\mathbb{H}^N(M^N, y\mathcal{K}_x(N)) \longrightarrow ((\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J^{N+1}))^\vee.$$  

compatible with the previous one.

Let $\gamma: [0, 1] \to M$ be a smooth path such that $\gamma(0) = x$ and $\gamma(1) = y$. For each $\emptyset \neq I \subset \Delta_N$, we denote by $\sigma_{\gamma,y}^{N,I}$ the map $\Delta^{|I|-1} \longrightarrow yM_I^y = Y_I \simeq M^{|I|-1}$ given by

$$\sigma_{\gamma,y}^{N,I}(t_1, \ldots, t_{|I|-1}) = (\gamma(t_1), \ldots, \gamma(t_{|I|-1})).$$

If $|I| = 1$, then $Y_I$ is reduced to a single point and the map $\sigma_{\gamma,y}^{N,1}$ is constant. Using the maps $\sigma_{\gamma,y}^{N,I}$ we define a map

$$\sigma_{\gamma,y}^N: S_Y^* \otimes [N] \longrightarrow \mathbb{Q},$$

that sends $\omega = (\omega_I)_{I \subset \Delta_N}$ to

$$\sigma_{\gamma,y}^N(\omega) = \sum_{I \subset \Delta_N} (-1)^{(\vert I \vert - 1)(\vert I \vert - 2)} (-1)^N(\varepsilon)(I^c) \omega_I(\sigma_{\gamma,y}^{N,I^c}).$$

Observe the sign relation

$$(-1)^{\frac{(\vert I \vert - 1)(\vert I \vert - 2)}{2}}(-1)^N(\varepsilon) = (-1)^{\frac{|I|(|I|+1)}{2}}(-1)^{N(N-1)}.$$ 

The reason for the complicated sign in equation (3.292) will be apparent in the proof of the next proposition.

**Proposition 3.294.** The maps $\sigma_{\gamma,y}^N$ for different $\gamma$ define a morphism

$$\sigma_y: \mathbb{H}^N(M^N, y\mathcal{K}_x(N)) \longrightarrow ((\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J^{N+1}))^\vee,$$
such that the diagram

$$
\begin{array}{ccc}
\mathbb{H}^0(L_N B^*(A^*(M))) & \rightarrow & (\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J^{N+1}) \otimes \mathbb{C})^\vee \\
\downarrow & & \downarrow \\
\mathbb{H}^N(M_N, \gamma K_x(N)) \otimes \mathbb{C} & \rightarrow & (\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J^{N+1}) \otimes \mathbb{C})^\vee
\end{array}
$$

is commutative.

PROOF. We start by proving that, if $\omega$ is exact then $\sigma_{N, y}^N(\omega) = 0$. For this, we compute the boundary of the singular chain $\sigma_{N, y}^N$ and we obtain

$$
(3.295) \quad \partial \sigma_{N, y}^N = \sum_{I \subseteq K, |K| = |I| + 1} \varepsilon(I, K) \sigma_{N, y}^{N, I}.
$$

If $\omega = d\eta$ is exact in the complex $S_X^*[N]$, then

$$
(3.296) \quad (-1)^N \omega_I = (-1)^{|I|} d\eta_I + \sum_{K \subseteq I, |K| = |I| - 1} \varepsilon(K, I) \eta_K |_{\gamma, y}.
$$

Using the sign relation (3.293),

$$
(-1)^{N(K+1)} \sigma_{N, y}^N(\omega) = (-1)^N \sum_I (-1)^{|I|(|I|+1)} \varepsilon(I^c) \omega_I(\sigma_{N, y}^{N, I^c}) = \sum_I (-1)^{|I|(|I|+1)} \varepsilon(I^c) (-1)^{|I|} d\eta_I(\sigma_{N, y}^{N, I^c})
$$

$$
+ \sum_I \sum_{K \supseteq I, |K| = |I| - 1} (-1)^{|I|(|I|+1)} \varepsilon(K^c) \varepsilon(K, I) \eta_K(\sigma_{N, y}^{N, I^c})
$$

$$
= \sum_I \sum_{K \supseteq I, |K| = |I| + 1} (-1)^{|I|(|I|+1)} \varepsilon(K^c) (-1)^{|I|} \varepsilon(K, I^c) \eta_I(\sigma_{N, y}^{N, K^c})
$$

$$
+ \sum_I \sum_{K \supseteq I, |K| = |I| + 1} (-1)^{|I|(|K|+1)} \varepsilon(K^c) \varepsilon(K, I) \eta_I(\sigma_{N, y}^{N, K^c}).
$$

In the above computation, the first equality is the definition of $\sigma_{N, y}^N(\omega)$, the second equality is equation (3.296), and in the third equality we apply equation (3.295) to the first term and we interchange the roles of $I$ and $K$ in the second term. The fact that $\sigma_{N, y}^N(\omega) = 0$ follows from the sign identities

$$
\varepsilon(I, K) \varepsilon(K^c, I^c) = \varepsilon(I^c) \varepsilon(K^c), \quad \text{and } (-1)^{|I|(|I|+1)} (-1)^{|I|} = (-1)^{|K|(|K|+1)}
$$

for $I \subseteq K$ with $|K| = |I| + 1$. Therefore, for $\omega$ closed, the value $\sigma_{N, y}^N(\omega)$ only depends on the class of $\omega$ in $\mathbb{H}^N(M_N, \gamma K_x(N))$. In consequence we obtain a pairing

$$
\mathbb{H}^N(M_N, \gamma K_x(N)) \otimes \mathbb{Q}[\mathcal{P}(M)]_x \rightarrow \mathbb{Q},
$$

where $\mathbb{Q}[\gamma \mathcal{P}(M)]_x$ is as in (3.255).

We next show that the above pairing is compatible with the pairing (3.255). To state some morphisms explicitly we recall the notation of the external product.
Let $M_1, \ldots, M_n$ be differential manifolds and $\omega_i$ a differential form on $M_i$ for each $i$. Denote by

$$\text{pr}_i : M_1 \times \cdots \times M_n \longrightarrow M_i$$

the projection over the $i$-th component. Then the external product of differential forms is defined as

$$\omega_1 \boxtimes \cdots \boxtimes \omega_n = \text{pr}_1^* \omega_1 \wedge \cdots \wedge \text{pr}_n^* \omega_n.$$ 

Let $[\omega_1| \ldots |\omega_n] \in H^0 \left( L_N B^* (A^* (M)) \right)$, since the total degree of this element is zero, every component form $\omega_i$ has degree one, i.e. $\omega_i \in A^1 (M)$. Then the isomorphism

$$H^0 \left( L_N B^* (A^* (M)) \right) \longrightarrow \mathbb{H}^N (M^N, y \mathcal{K}_x (N)) \otimes \mathbb{C}$$

sends $[\omega_1| \ldots |\omega_n]$ to the form $\omega = (\omega_I)_{I \subseteq \Delta_N}$ with $\omega_I \in S^n (Y_I, \mathbb{C})$ given by

$$\omega_I = \begin{cases} (-1)^{\frac{n(n+1)}{2}} (-1)^{n(n+1)} \varepsilon (\Delta_n) \omega_1 \boxtimes \cdots \boxtimes \omega_n, & \text{if } I = \Delta_n^c, \\ 0, & \text{otherwise}. \end{cases}$$

In consequence

$$(3.297) \quad \sigma_{\gamma,y}^N (\omega) = (-1)^{\frac{n(n+1)}{2}} (-1)^{n(n+1)} \varepsilon (\Delta_n) \omega_1 \boxtimes \cdots \boxtimes \omega_n (\sigma_{\gamma,y}^N \Delta^n)$$

$$\quad \quad \quad \quad = \langle [\omega_1| \ldots |\omega_n], \gamma \rangle,$$

where the last term is the pairing (3.255). So the signs in equation (3.292) are chosen to obtain the sign cancellation in (3.297) and the fact that for $\omega$ exact, $\sigma_{\gamma,y}^N (\omega) = 0$.

Once we have established the compatibility with the pairing (3.255), then Theorem 3.261, Proposition 3.260 and Corollary 3.291 imply the proposition. \( \square \)

The following result, due to Beilinson, gives a cohomological interpretation of the finite-dimensional pieces in the pro-unipotent completion of the fundamental group.

**Theorem 3.298.** The map $\sigma_y$ of Proposition 3.294 is an isomorphism. In particular, when $x \neq y$ there is an isomorphism

$$\sigma_y : \mathbb{H}^N (M^N, Y; \mathbb{Q}) \longrightarrow (\mathbb{Q}[\pi_1 (M; y, x)]/\mathbb{Q}[\pi_1 (M; y, x)])^{J_N + 1}).$$

The proof of this result is by induction on $N$. To put all the pieces in the right position, we need a relative version of the morphism $\sigma_y$. This is done in the next section.

**3.6.5. Beilinson’s theorem, relative version.** We next introduce a relative version of the complex $y \mathcal{K}_x (N)$, where we fix $x$ but let $y$ vary. For this, we consider the $(N + 1)$-fold product

$$M^{1,N} = M \times M^N = M^{N+1}$$

regarded as a fibration over $M$ with fiber $M^N$. That is to say, we put coordinates $x_0, \ldots, x_N$ on $M^{1,N}$ and denote by

$$\pi : M^{1,N} \longrightarrow M$$

the projection over the first factor. We introduce the closed subsets

$$Z_i = \{ x_i = x_{i+1} \} \subseteq M^{1,N}, \quad i = 0, \ldots, N,$$
where we are still using the convention \( x_{N+1} = x \). For \( y \in M \) and \( i \in \Delta_N \), under the identification \( \pi^{-1}(y) = M^N \), we have
\[
Y_i = Z_i \cap \pi^{-1}(y).
\]
Thus, we can see the subsets \( Z_i \) as the family of sets \( Y_i \) for moving \( y \) (in fact, only \( Y_0 \) depends on \( y \)). Moreover, by the previous identification, for any subset \( I \subseteq \Delta_N \), we have
\[
Z_I \cap \pi^{-1}(y) = Y_I.
\]
We now define the complexes of sheaves
\[
\mathcal{K}_x(N) = K(M^{1,N}; Z_0, \ldots, Z_N) \quad \text{and} \quad \mathcal{K}_x(N) = K(M^{1,N}; Z_0, \ldots, Z_N),
\]
so that
\[
(3.309) \quad \mathcal{K}_x(N)|_{\pi^{-1}(y)} = y\mathcal{K}_x(N).
\]
It is in this sense that \( K_Kx(N) \) is a relative version of \( K_Kx(N) \).

The complexes \( \mathcal{K}_x(N) \) and \( y\mathcal{K}_x(N) \) satisfy a recurrence relation that will be useful later. The identity morphism between \( M^{1,N-1} \) and \( M^N \) changes the numbering of the components because in the convention we are using, the coordinates of \( M^{1,N-1} \) start with \( x_0 \), while those of \( M^N \) start with \( x_1 \). This identification sends the subset \( Z_i \subset M^{1,N-1} \) to the subset \( Y_{i+1} \subset M^N \) for \( i = 0, \ldots, N-1 \).

Let \( \iota_y : M^{N-1} \to M^N \) be the map
\[
\iota_y(x_1, \ldots, x_{N-1}) = (y, x_1, \ldots, x_{N-1}).
\]
For each \( N \geq 1 \), there is an exact sequence of sheaves of complexes
\[
(3.300) \quad 0 \to (\iota_y)_*y\mathcal{K}_x(N-1)[-1] \to y\mathcal{K}_x(N) \to \mathcal{K}_x(N-1) \to 0.
\]
To describe this sequence we use the notation that, if \( I = (i_1, \ldots, i_k) \) is a multi-index, then the multi-index \( I + 1 \) is
\[
I + 1 = (i_1 + 1, \ldots, i_k + 1).
\]
Then in degree \( 0 \leq j \leq N \), the sequence (3.300) reads
\[
0 \to \bigoplus_{I \subseteq \{0, \ldots, N-1\}} \mathcal{Q}_Y \to \bigoplus_{I \subseteq \{0, \ldots, N\}} \mathcal{Q}_Y \to \bigoplus_{I \subseteq \{1, \ldots, N\}} \mathcal{Q}_Y \to 0.
\]
To identify the rightmost term of this sequence with a piece of \( y\mathcal{K}_x(N-1) \) we are using the identification between the sheaf \( \mathcal{Q}_{x_i} \) on \( M^{1,N-1} \) and the sheaf \( \mathcal{Q}_{x_{i+1}} \) on \( M^N \). Finally, we have to be sure that the map
\[
(\iota_y)_*y\mathcal{K}_x(N-1)[-1] \to y\mathcal{K}_x(N)
\]
is compatible with the differential. This amount to the sign relation, for \( I \subseteq K \), with \( |I| + 1 = |K| \),
\[
-\varepsilon(I, K) = \varepsilon(\{0\} \cup (I + 1), \{0\} \cup (K + 1)).
\]
The exact sequence (3.282) induces an exact sequence
\[
(3.301) \quad 0 \to \mathcal{Q}_{\{x, \ldots, x\}}[-N] \to \mathcal{K}_x(N-1) \to \mathcal{K}_x(N-1) \to 0.
\]
When considering a relative situation, like the family \( \pi : M^{1,N} \to M \), the analogue of the hypercohomology groups of the complex \( y\mathcal{K}_x(N) \) are the higher direct image sheaves \( R^i\pi_*y\mathcal{K}_x(N) \). As explained in Section A.9.5, they are defined
as the sheaves of vector spaces associated with the presheaves that, to an open subset \( U \subseteq M \), assign the vector space

\[
\mathbb{H}^i(\pi^{-1}(U), \mathcal{K}_x(N)).
\]

To understand them, we shall use the following concrete description of the cohomology. As in the previous sections, let \( S^*(T, \mathbb{Q}) \) denote the complex of smooth singular cochains on a differentiable manifold \( T \). Using the construction (3.280) applied to \( M^{1,N} \) and the subsets \( Z_0, \ldots, Z_N \), we obtain a double complex

\[
0 \longrightarrow \bigoplus_{|I|=0} S^*(Z_I \cap \pi^{-1}(U), \mathbb{Q}) \longrightarrow \bigoplus_{|I|=1} S^*(Z_I \cap \pi^{-1}(U), \mathbb{Q}) \longrightarrow \cdots
\]

which will be denoted by \( S^*(Z_\bullet \cap \pi^{-1}(U), \mathbb{Q}) \). The associated total complex computes the hypercohomology

\[
\mathbb{H}^i(\pi^{-1}(U), \mathcal{K}_x(N)) = \mathbb{H}^i(\text{Tot}(S^*(Z_\bullet \cap \pi^{-1}(U), \mathbb{Q}))).
\]

**Lemma 3.303.** For every contractible open subset \( U \) of \( M \) and every point \( y \in U \), the inclusion \( \pi^{-1}(y) \rightarrow \pi^{-1}(U) \) and the identification \( \pi^{-1}(y) \simeq M^N \) induce an isomorphism

\[
\mathbb{H}^i(\pi^{-1}(U), \mathcal{K}_x(N)) \rightarrow \mathbb{H}^i(M^N, y\mathcal{K}_x(N)).
\]

**Proof.** For every \( I \subseteq \Delta_N \) with \( |I| \leq N \), the morphism \( \pi|_{Z_I} : Z_I \rightarrow M \) is a fibration. Therefore, given any contractible open subset \( U \subseteq M \) and any point \( y \in U \), the inclusion \( Z_I \cap \pi^{-1}(y) \rightarrow Z_I \cap \pi^{-1}(U) \) is a homotopy equivalence. The induced morphism of complexes

\[
S^*(Z_I \cap \pi^{-1}(U), \mathbb{Q}) \longrightarrow S^*(Z_I \cap \pi^{-1}(y), \mathbb{Q}) = S^*(Y_I, \mathbb{Q})
\]

is a homotopy equivalence as well. The lemma follows from this. \( \square \)

Thanks to this lemma, the sheaf \( R^i\pi_*(\mathcal{K}_x(N)) \) is a local system on \( M \) whose fiber at a point \( y \) is given by the hypercohomology group

\[
R^i\pi_*(\mathcal{K}_x(N))_y = \mathbb{H}^i(M^N, y\mathcal{K}_x(N)).
\]

We refer the reader to Section A.9.10 from the appendix for a quick reminder on the different ways to think about local systems. In particular, the sheaf \( R^i\pi_*(\mathcal{K}_x(N)) \) “glues together” the hypercohomology groups \( \mathbb{H}^i(M^N, y\mathcal{K}_x(N)) \) for all possible base points \( y \). The map \( f \) in the exact sequence (3.283) yields a morphism from this local system to a skyscraper sheaf

\[
R^N\pi_*(\mathcal{K}_x(N)) \longrightarrow \mathbb{Q}_x.
\]

We have just described some local systems constructed using cohomology. Now we consider some local systems defined using the fundamental groupoid. The point \( x \in M \) continues to be fixed. There are left actions of \( \pi_1(M, x) \) on the \( \mathbb{Q} \)-vector spaces

\[
\mathbb{Q}[\pi_1(M, x)] \quad \text{and} \quad \mathbb{Q}[\pi_1(M, x)]/J^{N+1}
\]

given by path composition. These actions define local systems (see Section A.9.10)

\[
\mathbb{Q}[\pi_1(M; \bullet, x)] \quad \text{and} \quad \mathbb{Q}[\pi_1(M; \bullet, x)]/\mathbb{Q}[\pi_1(M; \bullet, x)]J^{N+1}.
\]
The first one may be infinite-dimensional, but the second one is always finite-dimensional. The fiber at a point \( y \) of the first local system is given by
\[
\mathbb{Q}[\pi_1(M; \bullet, x)]_y = \mathbb{Q}[\pi_1(M; y, x)].
\]
Thus, for every contractible open subset \( U \), the sections of \( \mathbb{Q}[\pi_1(M; \bullet, x)](U) \) are functions
\[
s: U \to \prod_{y \in U} \mathbb{Q}[\pi_1(M; y, x)]
\]
satisfying that, for each pair of points \( y, y' \in U \) and class of paths \( \gamma \in \pi_1(U; y, y') \), the relation
\[
s(y) = \gamma \cdot s(y')
\]
holds. Note that, since \( U \) is assumed to be contractible, \( \pi_1(U; y, y') \) contains a single element. Therefore, for every point \( y \in U \), there is a canonical identification \( \mathbb{Q}[\pi_1(M; \bullet, x)](U) = \mathbb{Q}[\pi_1(M; y, x)] \).

The description of \( \mathbb{Q}[\pi_1(M; \bullet, x)]/\mathbb{Q}[\pi_1(M; \bullet, x)]J^{N+1} \) is similar. The unit of \( \pi_1(M; x) \) induces maps
\[
\begin{align*}
Q & \to Q[\pi_1(M; \bullet, x)]_x, \\
Q & \to (Q[\pi_1(M; \bullet, x)]/Q[\pi_1(M; \bullet, x)]J^{N+1})_x.
\end{align*}
\]
(3.305)

We next construct a morphism between the local systems \( R^N\pi_*(\mathcal{K}_x(N)) \) and \( (Q[\pi_1(M; \bullet, x)]/Q[\pi_1(M; \bullet, x)]J^{N+1})^\vee \). This map is a relative version of the map \( \sigma_y \) of Proposition 3.294.

**Lemma 3.306.** The maps \( \sigma_y \) of Proposition 3.294 for varying \( y \) glue together to a morphism of local systems
\[
\sigma: R^N\pi_*(\mathcal{K}_x(N)) \to (Q[\pi_1(M; \bullet, x)]/Q[\pi_1(M; \bullet, x)]J^{N+1})^\vee.
\]

**Proof.** We have two local systems and a collection of morphisms between their fibers. To see that they glue together to a morphism of local systems, we need to prove that they are compatible with parallel transport. Assume that we have two local systems \( F \) and \( G \) on \( M \) and for each \( y \in M \) a morphism \( f_y: F_y \to G_y \).

To glue all these morphisms we have to see that, given a contractible open subset \( U \subset M \) and points \( y, y' \in U \), then the diagram
\[
\begin{array}{ccc}
F_y & \xrightarrow{\sim} & F(U) & \xrightarrow{\sim} & F_y' \\
\downarrow f_y & & \downarrow f_y' & & \downarrow f_y' \\
G_y & \xrightarrow{\sim} & G(U) & \xrightarrow{\sim} & G_y'
\end{array}
\]
is commutative. If this is the case, one can show that the \( f_y \) define a morphism of representations of the fundamental group and apply Theorem A.245.

Let \( U \subset M \) be a contractible subset and \( y, y' \in U \) two points. An element of \( (Q[\pi_1(M; \bullet, x)]/Q[\pi_1(M; \bullet, x)]J^{N+1})_y \) is represented by a linear combination of paths from \( x \) to \( y \) and the parallel transport is given by composition of paths. The fiber of the first local system is
\[
R^N\pi_*(\mathcal{K}_x(N))_y = \mathbb{H}^N(\pi^{-1}(y), y\mathcal{K}_x(N))
\]
and the parallel transport is the composition
\[
\mathbb{H}^N(\pi^{-1}(y), y\mathcal{K}_x(N)) \xrightarrow{\sim} \mathbb{H}^N(\pi^{-1}(U), \mathcal{K}_x(N)) \xrightarrow{\sim} \mathbb{H}^N(\pi^{-1}(y'), y\mathcal{K}_x(N)).
\]
Let \( \omega \in S^N(Z_\bullet \cap \pi^{-1}(U), \mathbb{Q}) \) be a closed singular cochain and denote by \( \omega_y \) and \( \omega_{y'} \) the restrictions of \( \omega \) to \( S^*(Z_\bullet \cap \pi^{-1}(y), \mathbb{Q}) \) and \( S^*(Z_\bullet \cap \pi^{-1}(y'), \mathbb{Q}) \) respectively. Let \( \gamma \in \gamma(P_M) \) and \( \gamma' \in \gamma(P(U)_y) \) be paths. By the previous discussion, to prove the lemma we have to show the equality

\[
\sigma_N^{\gamma,y} (\omega_y) = \sigma_N^{\gamma',y'} (\omega_{y'}).
\]

The idea to prove this equality is to construct a singular chain whose boundary is \( \sigma_N^{\gamma,y} - \sigma_N^{\gamma',y'} \).

Recall that any oriented polyhedron \( P \) defines a singular chain after choosing a triangulation. The chains obtained with different triangulations are cohomologous. Any facet of \( P \) (i.e., a codimension one face) inherits an orientation from the orientation of \( P \) and a triangulation of \( P \) defines a triangulation of the facets. Fixing a triangulation of \( P \) and identifying \( P \) and its facets with the corresponding singular chains, the equation

\[
\partial P = \sum_{F \text{ facet of } P} F
\]

holds. In this equation, the signs of the boundary of a chain are concealed in the orientation of the facets.

Next we observe that the map \( H : [0, 1] \times [0, 1] \to M \) defined as

\[
H(s, t) = \gamma'(1 + s)t/2
\]

satisfies

\[
H(0, t) = \gamma(t), \quad H(1, t) = \gamma'(t),
\]

\[
H(s, 0) = x, \quad H(s, 1) = \gamma'(s).
\]

In the previous section we have identified \( Y_I \) with \( M^{1/2} \) by deleting the redundant coordinates. In the same way we can identify \( Z_{Ic} \) with \( M^{1/2} \). With this identification the projection \( Z_{Ic} \to M \) is the projection over the first coordinate.

For each \( \emptyset \neq I \subset \Delta^N \) we denote by

\[
H^{N,I}_{\gamma,y} : [0, 1] \times \Delta^{1/2} \to Z_{Ic} \cap \pi^{-1}(U)
\]

the map given by

\[
H^{N,I}_{\gamma,y}(s, t_1, \ldots, t_{1/2}) = \left( \gamma'(s), \gamma'(1 + s)t_1/2, \ldots, \gamma'((1 + s)t_{1/2}) \right).
\]

After triangulating \( [0, 1] \times \Delta^{1/2} \) this defines a singular chain in \( Z_{Ic} \cap \pi^{-1}(U) \). Viewed as a chain in \( \pi^{-1}(U) \) satisfies the boundary equation

\[
\partial H^{N,I}_{\gamma,y} = \sigma^{N,K}_{\gamma,y} - \sigma^{N,K}_{\gamma',y'} - \sum_{|I|+1} \varepsilon(I, K) H^{N,I}_{\gamma,y}.
\]

For a form \( \eta \in S^{N+1}(Z_\bullet \cap \pi^{-1}(U), \mathbb{Q}) \) we write

\[
H^{N}_{\gamma,y}(\eta) = \sum_{I \subseteq \Delta_N} (-1)^{(I^c)_{|I|-2}} (-1)^N |I^c| \varepsilon(I^c) \eta (H^{N,I}_{\gamma,y}).
\]

Then computing as in the first part of the proof of Proposition 3.294, we have

\[
0 = H^{N}_{\gamma,y} (d\omega) = \sigma^{N}_{\gamma,y} (\omega_y) - \sigma^{N}_{\gamma',y'} (\omega_{y'}),
\]

proving the lemma.
The following result, due to Beilinson, is the relative version of Theorem 3.298 and implies it. This gives a cohomological interpretation of the finite-dimensional pieces in the pro-unipotent completion of the fundamental group. There are two proofs of this theorem in the literature [Gon01, § 4] and [DG05, § 3.3].

**Theorem 3.307 (Beilinson).**

i) The sheaf $R^i\pi_*(\mathcal{K}_x(N))$ vanishes for all $i \leq N - 1$. In particular,

$$\mathbb{H}^i(M^N, y\mathcal{K}_x(N)) = 0, \quad i \leq N - 1.$$ 

ii) The map $\sigma$ defined in Lemma 3.306 is an isomorphism of local systems $\sigma: R^N\pi_*(\mathcal{K}_x(N)) \to (\mathbb{Q}[\pi_1(M; \bullet, x)]/\mathbb{Q}[\pi_1(M; \bullet, x)]J^{N+1})^\vee$.

In particular, there are natural isomorphisms

$$\mathbb{H}^N(M^N, y\mathcal{K}_x(N)) \to (\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J^{N+1})^\vee.$$ 

iii) The diagram of sheaves on $M$

$$R^N\pi_*(\mathcal{K}_x(N)) \overset{\sigma}{\longrightarrow} (\mathbb{Q}[\pi_1(M; \bullet, x)]/\mathbb{Q}[\pi_1(M; \bullet, x)]J^{N+1})^\vee$$

where the diagonal arrow is (3.304) and the vertical arrow is induced by the dual of the unit (3.305), is commutative.

**Proof.** We first prove statement iii) in the theorem. Since for $y \neq x$ the fiber $(\mathbb{Q}_y)_y = 0$ we only need to check what happens when point $y = x$. Then the statement reduces to the commutativity of the diagram

(3.308)

$$\mathbb{H}^N(M^N, x\mathcal{K}_x(N)) \longrightarrow (\mathbb{Q}[\pi_1(M, x)]/\mathbb{Q}[\pi_1(M, x)]J^{N+1})^\vee$$

$$\mathbb{H}^N(M^N, \mathbb{Q}(x, \ldots, x)[-N]) \longrightarrow \mathbb{Q}$$

For simplicity, we compute $\mathbb{H}^N(M^N, x\mathcal{K}_x(N))$ as the cohomology of the complex

$$C^* = \bigoplus_{\substack{I \subset \Delta_N \cap \bar{I} \leq N}} \text{Tot}^*(\mathcal{N}\mathcal{S}^*(Y_I; \mathbb{Q})),$$

where $\mathcal{N}\mathcal{S}^*$ denotes the normalized complex of smooth cochains. See Section A.8.2 for the definition of the normalized complex associated with a simplicial abelian group. The advantage of this point of view is that the elements of $C^*$ vanish on degenerate chains, simplifying slightly the argument below.

Let $\gamma_x$ be the constant path $x$ in $M$. Since $\gamma_x$ is constant, for $I \subset \Delta_N$, $|I| \leq N$, the singular chain $\sigma^N, I$ is supported on $Z_I \cap \pi^{-1}(x) \subset M^{1, N}$. Identifying $\pi^{-1}(x)$ with $M^N$ we can see it as a singular chain on $Y_I$. This chain is degenerate unless $|I| = N$. When $|I| = N$, $\sigma^N, I$ is the zero-dimensional simplex at the point $(x, \ldots, x)$. 

Let $\omega = \sum \omega_I \in C^N$ be a closed element. The left vertical map on the diagram followed by the bottom arrow sends $\omega$ to

$$\sum_{|I|=N} \varepsilon(I, \Delta_N) \omega_I(x, \ldots, x). \tag{3.309}$$

We apply the top arrow followed by the right vertical arrow to $\omega$, using equation (3.292) and taking into account that we are working in the complex of normalized cochains, and we obtain the element

$$\sum_{|I|=N} \varepsilon(I^c) \omega_I(\sigma_{\gamma_x}^{N,I}). \tag{3.310}$$

The equality between (3.309) and (3.310) follows from the identity $\varepsilon(I^c) = \varepsilon(I, \Delta_N)$, for $|I| = N$.

This proves iii).

We now turn to the proof of statements i) and ii) in the theorem. We proceed by induction on $N$. The case $N = 0$ is obvious. Since we already know that $\sigma$ is a morphism of sheaves, it is enough to prove the statements fiberwise. Let $y \in M$.

From the exact sequence (3.300), we deduce a long exact sequence

$$\begin{aligned}
\mathbb{H}^{N-1}(\mathcal{K}_x^y(N-1)) &\to \mathbb{H}^{N-1}(\mathcal{K}_x^y(N-1)) \\
\mathbb{H}^{N}(\mathcal{K}_x^y(N)) &\to \mathbb{H}^{N}(\mathcal{K}_x^y(N)) \\
\mathbb{H}^{N}(\mathcal{K}_x^y(N-1)) &\to \mathbb{H}^{N}(\mathcal{K}_x^y(N-1))
\end{aligned} \tag{3.311}$$

For space reasons in this exact sequence we have omitted the spaces as they can be deduced from the sheaves. We use the sequence (3.311) to write down the following diagram with exact rows:

$$\begin{aligned}
\mathbb{H}^{N-1}(\mathcal{K}_x^y(N-1)) &\to \mathbb{H}^{N}(\mathcal{K}_x^y(N)) \\
\mathbb{H}^{N}(\mathcal{K}_x^y(N)) &\to \mathbb{H}^{N}(\mathcal{K}_x^y(N-1)) \\
0 &\to (\mathbb{Q}[\pi_1(M; y, x)]/J^N)^\vee \\
&= (\mathbb{Q}[\pi_1(M; y, x)]/J^{N+1})^\vee \\
&= (J^N/J^{N+1})^\vee \to 0.
\end{aligned} \tag{3.312}$$

Claim: The left square in the above diagram is commutative.

The first horizontal map sends a closed smooth cochain $\omega = \sum_{I \subseteq \Delta_{N-1}} \omega_I$ representing a class in $\mathbb{H}^{N-1}(M^N, \mathcal{K}_x^y(N-1))$ to the cochain $\iota(\omega) = \sum_{I \subseteq \Delta_{N-1}} \omega_I$. 

\[ \begin{array}{cccc}
\text{Claim: The left square in the above diagram is commutative.} \\
\text{The first horizontal map sends a closed smooth cochain} \\
\omega = \sum_{I \subseteq \Delta_{N-1}} \omega_I \\
\text{representing a class in } \mathbb{H}^{N-1}(M^N, \mathcal{K}_x^y(N-1)) \text{ to the cochain} \\
\iota(\omega) = \sum_{I \subseteq \Delta_{N-1}} \omega_I.
\end{array} \]
where \( \omega_I \) is now seen as a cochain in \( Y_{\{0\} \cup (I+1)} \). Therefore, for every class \( \gamma \in \mathbb{Q}[\pi_1(M; y, x)] \),
\[
\sigma(\omega)(\gamma) = \sum_{I \subseteq \Delta_{N-1}} (-1)^{\frac{(I+1)(N-1)(N-2)}{2}} \varepsilon(I') \omega_I(\sigma^{N-1,I}_{\gamma}) \\
\sigma(\iota(\omega))(\gamma) = \sum_{I \subseteq \Delta_{N-1}} (-1)^{\frac{(I+1)(I+2)(N-1)}{2}} \varepsilon((I')^c) \omega_I(\sigma^{N,I'}_{\gamma}),
\]
where \( I' = \{0\} \cup (I + 1) \). Since the chains \( \sigma^{N-1,I}_{\gamma} \) and \( \sigma^{N,(0)\cup I}_{\gamma} \) agree and the equality of signs
\[
(-1)^{\frac{(I+1)(N-1)(N-2)}{2}} (-1)^{\frac{(I+1)(I+2)(N-1)}{2}} = (-1)^{|I|} \varepsilon(I') \varepsilon((I')^c)
\]
is satisfied, we deduce that the square commutes. Once we know this, an easy diagram chase shows that there is a map
\[
\sigma: \text{Ker}(g) \to (J^N/J^{N+1})^\vee,
\]
slightly abusively still denoted by \( \sigma \), which completes (3.312) to a commutative diagram.

**Lemma 3.313.**

i) The equality \( H^i(M^{1,N-1},\mathcal{K}_x(N-1)) = 0 \) holds for all \( i \leq N - 1 \).

ii) The map \( \sigma: \text{Ker}(g) \to (J^N/J^{N+1})^\vee \) is an isomorphism.

**Proof.** As before, let \( \pi: M^{1,N-1} \to M \) be the projection onto the first factor. We shall compute \( H^i(M^{1,N-1},\mathcal{K}_x(N-1)) \) using the Leray spectral sequence associated with \( \pi \):
\[
E_2^{p,q} = H^p(M, R^q\pi_*\mathcal{K}_x(N-1)) \Rightarrow H^{p+q}(M^{1,N-1},\mathcal{K}_x(N-1)).
\]

(3.314)

Taking higher direct images with respect to \( \pi \) from the exact sequence of complexes (3.301) yields isomorphisms
\[
R^i\pi_*(\mathcal{K}_x(N-1)) \simeq R^i\pi_*(\mathcal{K}_x(N-1)), \quad i \leq N - 2,
\]
and an exact sequence of sheaves
\[
0 \to R^{N-1}\pi_*(\mathcal{K}_x(N-1)) \to R^{N-1}\pi_*(\mathcal{K}_x(N-1)) \to Q_x \to 0.
\]

The exactness on the right follows, after passing to the fiber at \( x \), from the surjectivity of the map \( f \) in the sequence (3.283).

Now recall that the induction hypothesis in the proof of the theorem is that \( R^i\pi_*(\mathcal{K}_x(N-1)) \) vanishes for all \( i \leq N - 2 \), and hence
\[
R^i\pi_*(\mathcal{K}_x(N-1)) = 0 \quad \text{for all} \quad i \leq N - 2.
\]

Therefore, the Leray spectral sequence (3.314) looks as depicted in Figure 16. There can also be non-zero groups above row \( N \). The important point is that all rows strictly below \( N - 1 \) are zero.

From the shape of the spectral sequence, we deduce the equality
\[
H^i(M^N,\mathcal{K}_x(N-1)) = \begin{cases} 
0, & \text{if } i \leq N - 2, \\
H^0(M, R^{N-1}\pi_*(\mathcal{K}_x(N-1))), & \text{if } i = N - 1,
\end{cases}
\]

(3.316)
and a short exact sequence of vector spaces
\[
0 \longrightarrow H^1(M, R^{N-1} \pi_*(\mathcal{K}_x(N-1))) \rightarrow H^N(M^N, \mathcal{K}_x(N-1)) \rightarrow H^0(M, R^{N} \pi_*(\mathcal{K}_x(N-1))) \rightarrow 0.
\]

To prove statement i) in the lemma, it remains to show that
\[
H^0(M, R^{N-1} \pi_*(\mathcal{K}_x(N-1))) = 0.
\]
The long exact sequence of cohomology associated with the short exact sequence
of sheaves (3.315) yields
\[
0 \rightarrow H^0(R^{N-1} \pi_*(\mathcal{K}_x(N-1))) \rightarrow H^0(R^{N-1} \pi_*(\mathcal{K}_x(N-1))) \overset{a}{\rightarrow} \mathbb{Q} \rightarrow H^1(R^{N-1} \pi_*(\mathcal{K}_x(N-1))) \overset{b}{\rightarrow} H^1(R^{N-1} \pi_*(\mathcal{K}_x(N-1))) \rightarrow 0.
\]

We shall prove that the map \(a\) is an isomorphism. From this fact we obtain equation (3.318) and that the map \(b\) is an isomorphism as well. For this we need to compute the cohomology of the sheaf \(R^{N-1} \pi_*(\mathcal{K}_x(N-1))\). By the induction hypothesis in the theorem, the map
\[
\sigma: R^{N-1} \pi_*(\mathcal{K}_x(N-1)) \rightarrow (\mathbb{Q}[\pi_1(M; x)]/J^N)'^{\vee}
\]
is an isomorphism and, in particular, the sheaf \(R^{N-1} \pi_*(\mathcal{K}_x(N-1))\) is a local system on \(M\) with fiber
\[
R^{N-1} \pi_*(\mathcal{K}_x(N-1))_x \simeq (\mathbb{Q}[\pi_1(M, x)]/J^N)'^{\vee}.
\]

Setting \(\Gamma = \pi_1(M, x)\), as explained in Remark A.247, the cohomology of \(R^{N-1} \pi_*(\mathcal{K}_x(N-1))\) can be computed as the group cohomology of \(\Gamma\) acting on
\[
H^i(M, R^{N-1} \pi_*(\mathcal{K}_x(N-1))) = H^i(\Gamma, (\mathbb{Q}[\Gamma]/J^N)'^{\vee}).
\]

![Figure 16. The Leray spectral sequence for \(\mathcal{K}_x(N-1)\).](image)
Consider the short exact sequence of $\Gamma$-modules
\begin{equation}
0 \longrightarrow (\mathbb{Q}[\Gamma]/J^N)\overset{\vee}{\longrightarrow} \mathbb{Q}[\Gamma]\overset{\vee}{\longrightarrow} (J^N)\overset{\vee}{\longrightarrow} 0.
\end{equation}

The $\Gamma$-module $\mathbb{Q}[\Gamma]\overset{\vee}{\longrightarrow}$ being injective, its cohomology is concentrated in degree zero and there is an exact sequence
\begin{equation}
0 \longrightarrow H^{0}(\Gamma,(\mathbb{Q}[\Gamma]/J^N)\overset{\vee}{\longrightarrow}) \longrightarrow H^{0}(\Gamma,\mathbb{Q}[\Gamma]\overset{\vee}{\longrightarrow}) \longrightarrow H^{0}(\Gamma,(J^N)\overset{\vee}{\longrightarrow}) \longrightarrow 0.
\end{equation}

If $A$ is a $\Gamma$-module, then $H^{0}(\Gamma,A)$ is the group of invariants $A^{\Gamma}$. From this one easily checks:

- The cohomology $H^{0}(\Gamma,\mathbb{Q}[\Gamma]\overset{\vee}{\longrightarrow})$ is the one-dimensional $\mathbb{Q}$-vector space generated by the function $\sum_{\gamma \in \Gamma} a_{\gamma} \gamma \mapsto \sum_{\gamma \in \Gamma} a_{\gamma}$

and the dual of the unit (3.305) induces an isomorphism $H^{0}(\Gamma,\mathbb{Q}[\Gamma]\overset{\vee}{\longrightarrow}) \xrightarrow{\sim} \mathbb{Q}$.

- The cohomology $H^{0}(\Gamma,(J^N)\overset{\vee}{\longrightarrow})$ is equal to $(J^N/J^{N+1})\overset{\vee}{\longrightarrow}$ and the map $H^{0}(\Gamma,\mathbb{Q}[\Gamma]\overset{\vee}{\longrightarrow}) \longrightarrow (J^N/J^{N+1})\overset{\vee}{\longrightarrow}$

in the long exact sequence (3.323) is the zero map.

Putting together the above facts, the isomorphism (3.321), and the long exact sequence (3.323), we deduce
\begin{equation}
H^{0}(M,R^{N-1}\pi_{*}(\mathbb{K}_{x} \langle N-1 \rangle)) \simeq \mathbb{Q}
\end{equation}
\begin{equation}
H^{1}(M,R^{N-1}\pi_{*}(\mathbb{K}_{x} \langle N-1 \rangle)) \simeq (J^N/J^{N+1})\overset{\vee}{\longrightarrow}.
\end{equation}

Besides, the map $a$ in (3.319) agrees with the isomorphism (3.324) by statement iii) in the theorem. From this and (3.316), we derive
\begin{equation}
\mathbb{H}^{N-1}(M^{1,N-1,\bullet},\mathbb{K}_{x} \langle N-1 \rangle) = H^{0}(M,R^{N-1}\pi_{*}(\mathbb{K}_{x} \langle N-1 \rangle)) = 0,
\end{equation}
thus concluding the proof of statement i) in the lemma.

We now turn to the proof of ii). Combining the fact that the map $b$ in (3.319) is an isomorphism with (3.325), we get
\begin{equation}
H^{1}(M,R^{N-1}\pi_{*}(\mathbb{K}_{x} \langle N-1 \rangle)) \simeq (J^N/J^{N+1})\overset{\vee}{\longrightarrow}.
\end{equation}

Besides, by the exact sequence (3.317), there is an inclusion
\begin{equation}
H^{1}(M,R^{N-1}\pi_{*}(\mathbb{K}_{x} \langle N-1 \rangle)) \subseteq \mathbb{H}^{N}(M^{N},\mathbb{K}_{x} \langle N-1 \rangle).
\end{equation}

Claim: This subspace is equal to Ker($g$).

To prove the claim, we consider the long exact sequence of sheaves obtained by taking higher direct images from (3.300):
\begin{equation}
\cdots \longrightarrow R^{N-1}\pi_{*}(t_{y})_{*}(y\mathbb{K}_{x} \langle N-1 \rangle) \xrightarrow{\pi_{*}(t_{y})} R^{N}\pi_{*}(y\mathbb{K}_{x} \langle N \rangle) \longrightarrow R^{N}\pi_{*}(\mathbb{K}_{x} \langle N-1 \rangle) \longrightarrow \cdots
\end{equation}
Note that the sheaves \( R^q \pi_* (\iota_y)_* (y) K_x (N - 1) \) are all skyscraper sheaves supported at the point \( y \in M \), and hence have only cohomology in degree zero. Therefore, in the exact sequence
\[
(3.327) \quad 0 \to H^1 (M, R^{N-1} \pi_* (\iota_y)_* (y) K_x (N - 1)) \to H^N (M^{N-1}, y) K_x (N - 1) \to H^0 (M, R^{N} \pi_* (\iota_y)_* (y) K_x (N - 1)) \to 0
\]
obtained by applying the Leray spectral sequence to \( (\iota_y)_* (y) K_x (N - 1) \), the leftmost term vanishes and the last but one map is an isomorphism.

Let us introduce the sheaf \( F = \text{Coker}(\varphi) \) and consider the commutative diagram with exact columns
\[
\begin{array}{ccc}
0 & \to & H^1 (R^{N-1} \pi_* (\tilde{K}_x (N - 1))) \\
& \downarrow & \downarrow \\
& H^N (M^{1,N-1}, \tilde{K}_x (N - 1)) \\
& \downarrow & \downarrow \\
H^0 (F) & \to & H^0 (R^{N} \pi_* (\tilde{K}_x (N - 1))) \\
& \downarrow & \downarrow \\
& 0 & \to \\
\end{array}
\]
where the first column is (3.317), the second column is (3.327), and the last row is part of the exact sequence obtained by taking cohomology from (3.326). The above diagram immediately implies that
\[
H^1 (M, R^{N-1} \pi_* (\tilde{K}_x (N - 1))) \subseteq \text{Ker}(g)
\]
and to prove the reverse inclusion it is enough to show that \( H^0 (M, F) = 0 \). To get this vanishing we will show that the sheaf \( F \) is the extension by zero of a local system on \( M \setminus \{y\} \). We need to distinguish whether the base points \( x \) and \( y \) are distinct or equal.

Case \( x \neq y \). Write \( U = M^{1,N-1} \setminus \pi^{-1} (y) \). Since the complex \( (\iota_y)_* (y) K_x (N - 1) \) is supported at \( \pi^{-1} (y) \), one first sees from (3.300) that
\[
y K_x (N)|_U \cong \tilde{K}_x (N - 1)|_U
\]
and combining this with (3.301) one obtains a short exact sequence
\[
0 \to \mathbb{Q}_{(x,\ldots,x)} [-N] \to y K_x (N)|_U \to K_x (N - 1)|_U \to 0.
\]
In the associated long exact sequence
\[
R^{N-1} \pi_* (K_x (N - 1)|_U) \to R^N \pi_* \mathbb{Q}_{(x,\ldots,x)} [-N] \to R^N \pi_* (y K_x (N)|_U) \to R^N \pi_* (\tilde{K}_x (N - 1)|_U) \to 0,
\]
the map $h$ is surjective, by repeating the argument that yields the surjectivity of the map $f$ in (3.283). We thus get an isomorphism

$$R^N \pi_*(\mathcal{K}_x(N))|_{M \setminus \{y\}} \rightarrow R^N \pi_*(\mathcal{K}_x(N - 1))|_{M \setminus \{y\}}.$$ 

Since the right-hand side is a local system by Lemma 3.303, the same is true for the left-hand side. Let now $V \subseteq M$ be a contractible open subset containing $y$ but not $x$. Then the restrictions of $\mathcal{K}_x(N - 1)$ and $\mathcal{K}_x(N - 1)$ to $\pi^{-1}(V)$ are isomorphic, so that (3.300) induces a long exact sequence

$$\cdots \rightarrow \mathbb{H}^i(\pi^{-1}(V), y \mathcal{K}_x(N)) \rightarrow \mathbb{H}^i(\pi^{-1}(V), y \mathcal{K}_x(N - 1)) \rightarrow \cdots$$

By Lemma 3.303, the map $j$ is an isomorphism in all degrees $i \geq 0$. This implies, in particular, the vanishing $\mathbb{H}^N(\pi^{-1}(V), y \mathcal{K}_x(N)) = 0$ for all contractible open sets $V$ containing the point $y$, and hence

$$R^N \pi_*(\mathcal{K}_x(N))|_{\{y\}} = 0.$$

Finally, since the source of the map

$$\varphi: R^{N-1} \pi_*(\mathcal{K}_x(N - 1)) \rightarrow R^N \pi_*(\mathcal{K}_x(N))$$

is a skyscraper sheaf supported at the point $y$, it follows that $\varphi$ is identically zero. We have thus shown that $\mathcal{F} = R^N \pi_*(\mathcal{K}_x(N))$ is the extension by zero of a local system on $M \setminus \{y\}$.

**Case $x = y$.** On $U = M^{1,N-1} \setminus \pi^{-1}(x)$, the exact sequence (3.301) yields an isomorphism

$$\mathcal{K}_x(N)|_U \simeq \mathcal{K}_x(N - 1)|_U,$$

that implies that $\mathcal{F}|_{M \setminus \{x\}} = R^N \pi_*(\mathcal{K}_x(N))|_{M \setminus \{x\}}$ is a local system. Let $V$ be a contractible open subset of $M$ containing $x$. In this case, it is no longer true that $j_\pi^{-1}(V)$ has vanishing hypercohomology. Identifying $Y_{\{1,\ldots,N\}}$ with the point $(x,\ldots,x)$, there is a map

$$\mathbb{Q}(x,\ldots,x)[-N] \rightarrow y \mathcal{K}_x(N)|_{\pi^{-1}(V)}.$$

Using that $V$ is contractible, this map induces an isomorphism in hypercohomology

$$\mathbb{Q} = \mathbb{H}^N(\pi^{-1}(V), \mathbb{Q}(x,\ldots,x)[-N]) \simeq \mathbb{H}^N(\pi^{-1}(V), y \mathcal{K}_x(N)).$$

Therefore,

$$R^N \pi_*(\mathcal{K}_x(N))|_x = \mathbb{Q} \neq 0.$$

In this case the map

$$R^{N-1} \pi_*(\mathcal{K}_x(N - 1))|_x \xrightarrow{\varphi} R^N \pi_*(\mathcal{K}_x(N))|_x$$

is surjective and we again deduce that $\mathcal{F}|_x = 0$. Therefore, $\mathbb{H}^0(M, \mathcal{F}) = 0$, the map labeled $e$ is injective and

$$\text{Ker}(g) = \mathbb{H}^1(M, R^{N-1} \pi_*(\mathcal{K}_x(N - 1))) \simeq (J^N/J^{N+1})^\vee.$$

To finish the proof of the lemma one needs to check that the above isomorphism is compatible with the map $\sigma$. We leave this verification to the reader. $\square$
We can now finish the proof of Beilinson’s Theorem 3.307.
Recall that statement i) is the vanishing \( H^i(M^{N,y}, K^x(N)) = 0 \) in all degrees \( i \leq N - 1 \). By (3.311), this group fits into a long exact sequence
\[
\cdots \rightarrow H^{i-1}(M^{N-1,y}, K^x(N-1)) \rightarrow H^i(M^N, K^x(N)) \rightarrow H^i(M^{N-1,\cdot}, K^x(N-1)) \rightarrow \cdots
\]
For \( i \leq N - 1 \), the leftmost term vanishes by the induction hypothesis and the rightmost term vanishes by the first part of Lemma 3.313, and hence the middle term vanishes as well.

Finally, to prove statement ii) we combine the long exact sequence (3.311), Lemma 3.313, and the induction hypothesis to obtain that, in the following commutative diagram, the rows are exact and the first and third vertical maps are isomorphisms:
\[
\begin{align*}
0 \rightarrow & \mathbb{H}^{N-1}(M^{N-1,y}, K^x(N-1)) \rightarrow H^N(M^N, K^x(N)) \rightarrow \text{Ker}(g) \rightarrow 0 \\
& \downarrow \sigma \downarrow \sigma \downarrow \sigma \\
0 \rightarrow & (\mathbb{Q}[\pi_1(M; y, x)]/J^N)^\vee \rightarrow (\mathbb{Q}[\pi_1(M; y, x)]/J^{N+1})^\vee \rightarrow (J^N/J^{N+1})^\vee \rightarrow 0
\end{align*}
\]
By the five lemma, the second vertical arrow is also an isomorphism. This concludes the proof. \( \square \)

3.6.6. Proof of Chen’s \( \pi_1 \)-de Rham theorem. We are now in position to prove Chen’s \( \pi_1 \)-de Rham theorem using Beilinson’s theorem 3.307.

Proof of Theorem 3.264. If \( N = 0 \), then \( L_0B^*(A^*(M)) = \mathbb{C} \) is given by the constant functions, while
\[
\mathbb{Q}[\pi_1(M; y, x)]/\mathbb{Q}[\pi_1(M; y, x)]J = \mathbb{Q}.
\]
Moreover, the map in Theorem 3.264 sends the constant function \( a \in \mathbb{C} \) to the map that sends \( 1 \in \mathbb{Q} \) to \( a \), that is clearly an isomorphism.

Fix now \( N > 0 \). Applying Lemma 3.275 and Proposition A.178 we obtain a quasi-isomorphism
\[
L_NB^*(A^*(M)) \overset{\sim}{\longrightarrow} \text{Tot} \ C_*(\Delta_N, A^*(y, M^\bullet_x)).
\]
For each \( n \), the composition
\[
A^*(M)^\otimes_n \otimes \mathbb{C} \rightarrow E^*(y, M^n_x, \mathbb{C}) \rightarrow S^*(y, M^n_x, \mathbb{Q}) \otimes \mathbb{C}
\]
is a quasi-isomorphism, functorial in \( n \), from which we deduce a quasi-isomorphism
\[
L_NB^*(A^*(M)) \otimes \mathbb{C} \overset{\sim}{\longrightarrow} \text{Tot} C_*(\Delta_N, S^*_x) \otimes \mathbb{C}.
\]
Combining this quasi-isomorphism with Lemma 3.289 and Theorem 3.307 we deduce the isomorphism
\[
\mathbb{H}^0(L_NB^*(A^*(M)) \otimes \mathbb{C}) \rightarrow (\mathbb{C}[\pi(M; y, x)]/\mathbb{C}[\pi(M; y, x)]J^{N+1})^\vee.
\]
Therefore, we get an isomorphism
\[ H^0(B^*(A^*(M)) \otimes \mathbb{C}) = \lim_{\longrightarrow} H^0(L_N B^*(A^*(M)) \otimes \mathbb{C}) \rightarrow (\lim_{\longrightarrow} \mathbb{C}[\pi(M; y, x)]/\mathbb{C}[\pi(M; y, x)]J^{N+1})^\lor = (\mathbb{C}[\pi(M; y, x)]^\lor)^\lor, \]
as we wanted to prove. \(\square\)

\[ \star \star \star \]

Exercise 3.329. Let \( n, m \geq 0 \) be integers and \( f: \Delta_n \rightarrow \Delta_m \) a non-decreasing map. Using the fact that \( A^*(M) \subset E^*(M, \mathbb{C}) \) is a subalgebra, prove that \( f^*: E^*(M^m, \mathbb{C}) \rightarrow E^*(M^n, \mathbb{C}) \)

restricts to a morphism of dg-algebras \( f^*: A^*(M^m) \rightarrow A^*(M^n) \), thus making the

assignment \( \Delta_n \mapsto A^*(M^n) \) functorial.

Exercise 3.330. Recall the finite ordered set \( \Delta_n = \{0, \ldots, n\} \) and, for each integer \( i \geq 0 \), let \( P_i(\Delta_n) \) denote the set of subsets of \( \Delta_n \) of cardinal \( i \). Consider the complex

\[ 0 \rightarrow \mathbb{Q}^P_i(\Delta_n) \xrightarrow{d} \mathbb{Q}^P_{i+1}(\Delta_n) \rightarrow \cdots \],

where the differential \( d: \mathbb{Q}^P_i(\Delta_n) \rightarrow \mathbb{Q}^P_{i+1}(\Delta_n) \) sends a function \( \varphi: P_i(\Delta_n) \rightarrow \mathbb{Q} \) to the function

\[ d\varphi(K) = \sum_{I \subset K; |I| = |K| - 1} \varepsilon(I, K)\varphi(I). \]

(a) Show that (3.331) is exact [Hint: consider the homotopy \( s: \mathbb{Q}^P_i(\Delta_n) \rightarrow \mathbb{Q}^P_{i-1}(\Delta_n) \) defined by \( s\varphi(I) = \varphi(\{0\} \cup I) \) if \( 0 \notin I \) and \( s\varphi(I) = 0 \) otherwise].

Let \( M \) be a topological space, let \( Y_0, \ldots, Y_n \) be closed subspaces of \( M \), and set \( Y = Y_0 \cup \cdots \cup Y_n \). Consider the complex

\[ 0 \rightarrow \mathbb{Q}^P_Y \rightarrow \bigoplus_{|I|=1} \mathbb{Q}^P_I \rightarrow \cdots \rightarrow \bigoplus_{|I|=p} \mathbb{Q}^P_I \rightarrow \cdots \rightarrow \bigoplus_{|I|=k+1} \mathbb{Q}^P_I \rightarrow 0 \]

from Lemma 3.281.

(b) Show that this complex is exact.

3.7. A mixed Hodge structure on the pro-unipotent completion of the fundamental group.

3.7.1. Construction of the mixed Hodge structure. Hain [Hai87a] and Morgan [Mor78] show that, if \( M = X(\mathbb{C}) \) is the set of complex points of a smooth algebraic variety, then each of the quotients of the pro-unipotent completion of the fundamental group of \( M \) carries a natural mixed Hodge structure. Using the geometric interpretation of such quotients provided by Beilinson’s theorem (Theorem 3.307), one can improve this result a little bit, showing that, in fact, if a variety is defined over a subfield \( k \subset \mathbb{C} \) we obtain a mixed Hodge structure over \( k \). Later we will see that Beilinson’s Theorem allow us to upgrade these mixed Hodge structures to motives. For now, the precise statement is the following.
Theorem 3.332. Let $k$ be a subfield of $\mathbb{C}$, let $X$ be a smooth algebraic variety over $k$, let $M = X(\mathbb{C})$ be the set of complex points of $X$ viewed as a differentiable manifold, and let $x, y \in X(k) \subseteq M$ two $k$-rational base points. For each $N \geq 0$, the finite-dimensional $\mathbb{Q}$-vector space

$$
Q[\pi_1(M; y, x)]/J^{N+1}Q[\pi_1(M; y, x)]
$$

carries a mixed Hodge structure over $k$ which is functorial with respect to morphisms of pointed varieties. Moreover, given integers $N_1 \geq N_2 \geq 0$, the quotient map

$$
Q[\pi_1(X(\mathbb{C}); y, x)]/J^{N_1+1} \longrightarrow Q[\pi_1(X(\mathbb{C}); y, x)]/J^{N_2+1}
$$
is a morphism of mixed Hodge structures over $k$.

Proof. The result is a direct consequence of Beilinson’s theorem. In fact, by Beilinson’s Theorem 3.307, we know that, for every $N \geq 0$, there is an isomorphism $H^N(M^N, y\mathcal{K}_x(N)) \longrightarrow (Q[\pi(M; y, x)]/J^{N+1}Q[\pi(M; y, x)])^\vee$.

When $x \neq y$, by Lemma 3.281 the groups $H^N(M^N, y\mathcal{K}_x(N))$ can be interpreted as certain relative singular cohomology groups of algebraic varieties over $k$, thus can be endowed with a mixed Hodge structure over $k$. In the case $x = y$, the short exact sequence (3.333) can be upgraded to an extension of Mixed Hodge structures.

Alternatively, we can also use Lemma 3.289 and Proposition A.178 to identify the groups $H^N(M^N, y\mathcal{K}_x(N))$ with certain singular cohomology groups of a simplicial manifold $yM^*_x$. All the maps involved in $yM^*_x$ are algebraic and defined over $k$, therefore $yM^*_x$ is the simplicial manifold obtained by taking complex points of a simplicial smooth variety over $k$. Using a variant over $k$ of the main construction of [Del74], we endow $H^N(M^N, y\mathcal{K}_x(N))$ with a mixed Hodge structure over $k$.

By duality, the groups (3.333) are endowed with mixed Hodge structures defined over $k$.

The claimed functoriality properties follow from the functorial properties of the mixed Hodge structures on the cohomology of simplicial varieties.

□

Taking the projective limit over $N$ in Theorem 3.332, we obtain a pro-mixed Hodge structure on the pro-unipotent completion of the fundamental group by abstract means. Following Hain [Hai87a], Chen’s theorem provides us with a very clear and transparent way to understand such mixed Hodge structure. We now explain how to define the Hodge and weight filtrations when $X$ is smooth and defined over $\mathbb{C}$. Consider the dg-algebra $E^*_{X,an}(\log D)$ as in Section 2.8.3. It has two augmentations $\varepsilon_1$ and $\varepsilon_2$ given by evaluating at $x$ and $y$ respectively. The Hodge and weight filtrations of $E^*_{X,an}(\log D)$ determine the Hodge and weight filtration on $B^*(E^*_{X,an}(\log D))$, by saying that, if $\omega_i \in F^{p_i}$ for $i = 1, \ldots, r$, then

$$
[\omega_1] \cdots [\omega_r] \in F^{p_1+\cdots+p_r},
$$

while, if $\omega_i \in W_{n_i}$, then

$$
[\omega_1] \cdots [\omega_r] \in W_{n_1+\cdots+n_r+r},
$$

that is, the Hodge type is the sum of Hodge types, while the weight is the sum of weights plus the length of the element. Then

$$
F^p H^0 \left( B^*(E^*_{X,an}(\log D)) \right) = \text{Im} \left( H^0 \left( F^p B^*(E^*_{X,an}(\log D)) \right) \right),
$$

$$
W^m H^0 \left( B^*(E^*_{X,an}(\log D)) \right) = \text{Im} \left( H^0 \left( W^m B^*(E^*_{X,an}(\log D)) \right) \right).
$$
3.7.2. The case of $\mathbb{P}^1_\mathbb{Q} \setminus \{0, 1, \infty\}$. We now specialize the general discussion to the varieties $X = \mathbb{P}^1_\mathbb{Q} \setminus \{0, 1, \infty\}$ and $M = X(\mathbb{C})$, as in section 3.5.5, and two rational points $x, y \in X(\mathbb{Q})$. As we have seen in Example 2.260, we do not need to work with the whole infinite-dimensional dg-algebra $E^*_X(\log D)$, but we can work with the smaller $\mathbb{Q}$-algebra

$$A = \mathbb{Q} \oplus \mathbb{Q} \omega_0 \oplus \mathbb{Q} \omega_1.$$ 

The Hodge and weight filtrations are given by

$$F^0 A = W_1 A = A, \quad F^2 A = W_{-1} A = 0,$$

$$F^1 A = \mathbb{Q} \omega_0 \oplus \mathbb{Q} \omega_1 \quad W_0 A = \mathbb{Q}.$$ 

In this case both augmentations $\varepsilon_1$ and $\varepsilon_2$ given by evaluating at $x$ and $y$ respectively agree with the trivial augmentation

$$\varepsilon: A \longrightarrow \mathbb{Q}$$

$$1 \mapsto 1$$

$$\omega_0 \mapsto 0$$

$$\omega_1 \mapsto 0.$$

This has the added advantage to give us already a mixed Hodge structure over $\mathbb{Q}$. Since $A$ is connected we can use the reduced bar complex. Arguing as in Section 3.5.5, the Hopf algebra $H^0(B^*(A))$ is isomorphic to the Hoffman algebra.

By (3.334), the Hodge filtration in each finite-dimensional subspace $H^0(L_N B^*(A_C))$ is the decreasing filtration determined by

$$[\omega_{i_1} | \cdots | \omega_{i_p}] \in F^p$$

and the weight filtration is the increasing filtration determined by

$$[\omega_{i_1} | \cdots | \omega_{i_n}] \in W_{2n}.$$ 

We now describe an ind-mixed Hodge structure $\{y A^{H,N}_x\}_{N \geq 0}$ that corresponds to the algebra of functions over the pro-unipotent completion of the fundamental group, and a dual pro-mixed Hodge structure $\{U^{H,N}_x\}_{N \geq 0}$ that corresponds to the universal enveloping algebra of the Lie algebra of the pro-unipotent completion of the fundamental group.

For the Betti part of $y A^{H,N}_x$, we write

$$y A^{H,N}_x = (\mathbb{Q}[\pi(M; y, x)]/J^{N+1}\mathbb{Q}[\pi(M; y, x)])^\vee$$

with the weight filtration given, for $-1 \leq p \leq N$, by

$$W_{2p}(y A^{B,N}_x) = W_{2p+1}(y A^{B,N}_x) = (J^{p+1}\mathbb{Q}[\pi(M; y, x)]/J^{N+1}\mathbb{Q}[\pi(M; y, x)])^\perp.$$

For the de Rham side, we have

$$y A^{dR,N}_x = L_N H^0(B^*(A^*))$$

with the weight filtration given, for $-1 \leq p \leq N$, by

$$W_{2p}(y A^{dR,N}_x) = W_{2p+1}(y A^{dR,N}_x) = L_p H^0(B^*(A^*))$$.
The Hodge filtration is given by defining
\[ F^p(yA^{\text{dR},N}_x) \]
as the subspace generated by words of length \( p \leq \ell \leq N \). Note that only the Betti part depends on the points \( x, y \).

By duality, we write
\[
yU_{x}^{B,N} = Q[\pi(M; y, x)] / J^{N+1}Q[\pi(M; y, x)]
yU_{x}^{\text{dR},N} = L_N H^0(B^*(A^*)) \gamma,
\]
and endow these spaces with the dual filtrations.

We denote by \( \text{comp}_{\text{dR},B} \) the isomorphism of Theorem 3.264 and by \( \text{comp}_{B,\text{dR}} \) its dual. Then the mixed Hodge structures \( yA^{H,N}_x \) and \( yU^{H,N}_x \) form an inductive system of mixed Hodge structures over \( Q \) and a projective system of mixed Hodge structures over \( Q \).

The mixed Hodge structure we have constructed is of Hodge–Tate type.

**Proposition 3.336.** The filtrations \( F \) and \( W \) of \( yA^{\text{dR},N}_x \) satisfy the conditions
\[ W^2_p = W^2_p + 1, \quad W^{2p-1} \cap F^p = \{0\}, \quad W_{2p} \subset W_{2p-1} + F_p. \]

Therefore, the pure Hodge structure of weight \( 2p \) induced on \( \text{Gr}_W \) is of type \( (p, p) \) and the mixed Hodge structure \( yA^{H,N}_x \) is of Hodge–Tate type for every pair of base points.

**Proof.** This is clear because the subspaces \( W_{2p} \) and \( W_{2p+1} \) agree with the subspace of length less than or equal to \( p \), while \( F^p \) is generated by monomials of length greater than or equal to \( p \).

In fact, we could have guessed the previous result by pure thought from Beilinson’s Theorem 3.298. Since the varieties \( M^N \) and the components of \( Y \) and their intersections that appear when applying that theorem to our case are constructed from products of \( M = \mathbb{P}^1(C) \setminus \{0, 1, \infty\} \) and the cohomology of \( M \) is of Hodge–Tate type, it is clear that the mixed Hodge structure we have constructed is also on mixed Hodge–Tate type.

**3.7.3. Iterated integrals as periods of the fundamental group.** We now show that iterated integrals along paths between \( x \) and \( y \) are periods of the mixed Hodge structure \( yA^{H,N}_x \). We keep the notation \( X = \mathbb{P}^1 \setminus \{0, 1, \infty\} \) and \( M = X(C) \).

**Example 3.337.** Let \( s = (s_1, \ldots, s_n) \) be a positive multi-index of weight \( N \) and write \( bs(s) = (\varepsilon_1, \ldots, \varepsilon_N) \) for the associated binary sequence. On the one hand, we consider the element
\[ [\omega_{\varepsilon_1} \cdot \cdots \cdot \omega_{\varepsilon_N}] \in yA^{\text{dR},N}_x, \]
where \( \omega_0 = \frac{dt}{t} \) and \( \omega_1 = \frac{dt}{t-1} \), as usual. On the other hand, every path \( \gamma : [0, 1] \to M \) with \( \gamma(0) = x \) and \( \gamma(1) = y \), determines an element
\[ [\gamma] \in Q[\pi(M; y, x)] / J^{N+1}Q[\pi(M; y, x)] = (yA^{B,N}_x) \gamma. \]
By the shape of the comparison isomorphism in Theorem 3.264 we deduce that the period associated with these two classes is the iterated integral

$$\langle [\omega_1 \cdots | \omega_N], [\gamma] \rangle = \int_{[\gamma]} \omega_1 \cdots \omega_N.$$ 

Here we have used two points \(x, y \in X(\mathbb{Q})\). In order to obtain multiple zeta values we need to consider the case \(x = 0\) and \(y = 1\), but these points do not belong to \(X(\mathbb{Q})\). For this reason we will need to consider tangential base points in the next section.

**Example 3.338.** We can give a more “classical” interpretation of the period of Example 3.337 in terms of relative cohomology. For simplicity we assume \(x \neq y\) and let \(s\) and \(bs(s)\) and \(\gamma\) be as in that example. We consider the algebraic differential form on \(X^N\) given by

$$\omega = \text{pr}_1^* \omega_1 \wedge \cdots \wedge \text{pr}_N^* \omega_N,$$

where \(\text{pr}_i: X^N \to X\) denote the various projections. Since \(\omega\) has maximal degree, it defines a class \([\omega; 0]\) in the relative de Rham cohomology \(H^N_{\text{dR}}(X^N, Y)\), where \(Y\) is as in Section 3.6.5.

From lemmas 3.281, 3.289 and 3.275 and Proposition A.178, we derive an isomorphism

$$H^N_{\text{dR}}(X^N, Y) \cong y^* A^{\text{dR},N}_x$$

that sends \(\omega\) to \([\omega_1 \cdots | \omega_N]\).

The path \(\gamma\) determines a singular simplex

$$\sigma: \Delta^N \to M^N$$

$$(t_1, \ldots, t_N) \mapsto (\gamma(t_1), \ldots, \gamma(t_N)),$$

where \(\Delta^N\) is the simplex of Notation 1.113. Clearly, the support of the chain \(\partial \sigma\) is contained in \(Y\). Therefore, \(\sigma\) determines a class \([\sigma]\) in the relative singular homology group \(H_N(M^N, Y, \mathbb{Q})\). By Lemma 3.281 and Theorem 3.307, there is an isomorphism

$$H_N(M^N, Y) = (y^* A^{\text{B},N}_x)^\vee,$$

that sends the class of \(\sigma\) to the class of \(\gamma\).

The period associated with these two classes is the iterated integral

$$\langle [\omega; 0], [\sigma] \rangle = \int_{\sigma} \omega = \int_{[\gamma]} \omega_1 \cdots \omega_N.$$

therefore we have also realized the iterated integral as a period of the relative cohomology \(H^N(X^N, Y)\).

***

**Exercise 3.339.** Describe explicitly the mixed Hodge structure on the pro-unipotent completion of the fundamental group of \(\mathbb{G}_m\).
3.8. Tangential base points. In this section, we keep working with the manifold $M = \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\}$, the differential forms $\omega_0$ and $\omega_1$, and the dg-algebra $A^C_\ast$ from Section 3.5.5. Theorems 1.115 and 1.124 show that multiple zeta values and polylogarithms can be seen as iterated integrals. Nevertheless we face the following technical problem: The differential forms $\omega_0$ and $\omega_1$ that appear in these theorems have singularities at the points 0, 1 and $\infty$. Hence they are differential forms on $M$, but to obtain multiple zeta values we need to integrate along the straight path

$\text{dch}: [0, 1] \rightarrow \mathbb{P}^1(\mathbb{C})$,

$t \mapsto t$

(3.340)

which is not contained in $M$ because the endpoints are 0 and 1. Since $\text{dch}$ is not a path in $M$, the formulas in theorems 1.115 and 1.124 are not strictly speaking iterated integrals. Thus, to see multiple zeta values and polylogarithms as iterated integrals we have to consider tangential base points. As we will see, these are related to the regularization discussed in Section 1.7. Tangential base points will also play an important role later when we consider the algebraic structure of $\mathbb{P}^1$:

the variety $\mathbb{P}^1_\mathbb{Z} \setminus \{0, 1, \infty\}$ does not contain any smooth integral point, thus we will need tangential base points to have a motivic version of the fundamental group of $\mathbb{P}^1_\mathbb{Z} \setminus \{0, 1, \infty\}$ defined over $\mathbb{Z}$.

3.8.1. Paths with tangential base points. For simplicity, we will introduce tangential base points only in the case of $M = \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\}$, the only one we need, but the reader should be aware that the constructions extend easily to any smooth projective curve minus a finite number of points.

Definition 3.341. Let $x \in \{0, 1\}$ be either the point zero or the point one in $\mathbb{P}^1(\mathbb{C})$. A tangential base point is a pair $(x, v)$, where $v$ is a non-zero tangent vector to $\mathbb{P}^1(\mathbb{C})$ at $x$.

Intuitively, a path has an endpoint at a tangential base point $(x, v)$ if the endpoint is $x$ and the tangent vector at the endpoints $v$. However, the presence of tangential base points causes a nuisance. On the one hand, in order to be able to compose paths we need to allow tangential points to be reached by the paths at intermediate points. On the other hand, to define homotopy between paths in an easy way it is better to avoid tangential points at intermediate points along the path. To remedy this problem we define two kind of paths, the ones that allow tangential points at intermediate steps (and hence can be composed) and the ones that avoid tangential points. The former will be called cuspidal paths because of the shape we will impose at the tangential points, while the latter will be called clean paths. Then we define a homotopy equivalence of clean paths and a map from the space of cuspidal paths to the space of homotopy classes of clean paths.

The definition of piecewise smooth map given at the beginning of Section 3.1.1 implies that, if $\gamma: [0, 1] \rightarrow M$ is a piecewise smooth map, then the right and left derivatives of $\gamma$ exist at every point $t \in (0, 1)$, although they may not agree. They are denoted by

$\frac{d^+ \gamma}{dt}(t)$ and $\frac{d^- \gamma}{dt}(t)$

respectively. Moreover, the right derivative at $t = 0$ and the left derivative at $t = 1$ also exist.
Definition 3.342. Let $x = (x, v)$ and $y = (y, w)$ be two tangential base points. A cuspidal path from $x$ to $y$ is a piecewise smooth map $\gamma : [0, 1] \rightarrow M \cup \{0, 1\}$ satisfying the following conditions

i) the endpoints of the path are
$$\gamma(0) = x, \quad \frac{d^+ \gamma}{dt}(0) = v,$$
$$\gamma(1) = y, \quad \frac{d^- \gamma}{dt}(1) = -w;$$

ii) the set $\{ t \in (0, 1) \mid \gamma(t) \in \{0, 1\} \}$ is finite. Moreover, if $t_0$ belongs to this set, the left and right tangent vector to $\gamma$ at $t_0$ are non-zero and opposed:
$$0 \neq \frac{d^+ \gamma}{dt}(t_0) = -\frac{d^- \gamma}{dt}(t_0).$$

This set is called the set of cusps of $\gamma$.

When the set of cusps is empty, $\gamma$ is called a clean path from $x$ to $y$.

The space of cuspidal paths from $x$ to $y$ is denoted by $\mathcal{P}(M)_x$ while the subspace of clean paths is denoted $\mathcal{P}(M)^0_x$.

3.8.2. Composition of paths with tangential base points. The composition of paths (3.3) cannot be applied directly to define
$$\mathcal{P}(M)_y \otimes \mathcal{P}(M)_x \rightarrow \mathcal{P}(M)_z$$
for tangential base points $x$, $y$ and $z$ because condition i) imposes that the derivative of the path at zero and one is a fixed vector, while the parametrization used in (3.3) would multiply this vector by 2. Thus, to define the composition of paths we consider the functions
$$\phi_1(t) = t + 2t^2, \quad \phi_2(t) = 5t - 2 - 2t^2.$$

These functions are smooth and satisfy the properties
$$\phi_1(0) = 0, \quad \phi_1(1/2) = 1, \quad \phi_1'(0) = 1,$$
$$\phi_2(1/2) = 0, \quad \phi_2(1) = 1, \quad \phi_2'(1) = 1,$$
$$\phi_1'(t) > 0, \quad t \in [0, 1/2], \quad \phi_2'(t) > 0, \quad t \in [1/2, 1],$$
$$\phi_1'(1/2) = \phi_2'(1/2).$$

In fact, any pair of smooth functions satisfying all the above properties would serve for our purposes.

We define the composition of paths as
$$\mathcal{P}(M)_y \otimes \mathcal{P}(M)_x \rightarrow \mathcal{P}(M)_x$$
where
$$\gamma_1 \gamma_2(t) = \begin{cases} \gamma_2(\phi_1(t)), & \text{if } 0 \leq t \leq \frac{1}{2}, \\ \gamma_1(\phi_2(t)), & \text{if } \frac{1}{2} \leq t \leq 1. \end{cases}$$
3.8.3. Homotopy of paths. Let $\gamma_1, \gamma_2 \in yP(M)_x^0$ be two clean paths. A homotopy between $\gamma_1$ and $\gamma_2$ is a map

$$F : [0,1] \times [0,1] \to M \cup \{0,1\}$$

such that

$$F(t, 0) = \gamma_1(t), \quad F(t, 1) = \gamma_2(t), \quad t \in [0,1]$$

$$F(0, s) = x, \quad F(1, s) = y, \quad s \in [0,1]$$

$$\frac{\partial F}{\partial t}(0, s) = v, \quad \frac{\partial F}{\partial t}(1, s) = w, \quad s \in [0,1]$$

$$F(t, s) \in M, \quad 0 < t < 1, \quad 0 \leq s \leq 1.$$

The space $\pi(M; y, x)$ is the set of homotopy classes of clean paths from $x$ to $y$. Similar notation will be used when only one of the base points is tangential.

We next construct a map $\psi$ from $yP(M)_x$ to $\pi(M; y, x)$. Let $d(x, y)$ be the standard Euclidean distance in $\mathbb{C} = \mathbb{P}^1(\mathbb{C}) \setminus \{\infty\}$. Let $\gamma \in yP(M)_x$. For each $t_i$ in the set of cusps of $\gamma$, we can find real numbers $0 < \varepsilon_i, \eta_i, \eta_i' < \frac{1}{2}$ satisfying the conditions

i) $t_i$ is the only cusp in the interval $[t_i - \eta_i', t_i + \eta_i]$ and $\gamma$ is smooth in the intervals $[t_i - \eta_i', t_i]$, $[t_i, t_i + \eta_i]$;

ii) the intervals $[t_i - \eta_i', t_i + \eta_i]$ are disjoint and do not contain 0 or 1;

iii) the image of $[t_i - \eta_i', t_i + \eta_i]$ satisfies

$$d(\gamma(t_i + \eta_i), \gamma(t_i)) = \varepsilon_i,$$

$$d(\gamma(t_i), \gamma(t_i)) < \varepsilon_i,$$ for $t_i < t < t_i + \eta_i$;

$$d(\gamma(t_i - \eta_i'), \gamma(t_i)) = \varepsilon_i,$$

$$d(\gamma(t_i), \gamma(t_i)) < \varepsilon_i,$$ for $t_i - \eta_i' < t < t_i$;
iv) the tangent vector to \( \gamma \) does not change very much

\[
\left\| \frac{d\gamma}{dt}(t) - \frac{d^{-}\gamma}{dt}(t) \right\| \leq \frac{1}{2} \left\| \frac{d^{-}\gamma}{dt}(t_i) \right\|, \text{ for } t \in [t_i - \eta_i', t_i)
\]

\[
\left\| \frac{d\gamma}{dt}(t) - \frac{d^{+}\gamma}{dt}(t) \right\| \leq \frac{1}{2} \left\| \frac{d^{+}\gamma}{dt}(t_i) \right\|, \text{ for } t \in (t_i, t_i + \eta_i].
\]

Note that condition iv) implies that the path \( \gamma \) cannot turn around the point \( \gamma(t_i) \) between \( t_i - \eta_i' \) and \( t_i + \eta_i \).

For each cusp \( t_i \) let \( B(\gamma(t_i), \varepsilon_i) \) be the open ball of centre \( \gamma(t_i) \) and radius \( \varepsilon_i \) and let \( r_i : \mathbb{C} \setminus \{ \gamma(t_i) \} \to \mathbb{C} \setminus B(\gamma(t_i), \varepsilon_i) \) be the radial retraction. Then we define a new path \( \gamma^{\circ} \) defined outside the cusps by

\[
\gamma^{\circ}(s) = \begin{cases} 
\gamma(s), & \text{if } s \notin [t_i - \eta_i', t_i + \eta_i] \text{ for all } i, \\
r_i(\gamma(s)), & \text{if } s \in [t_i - \eta_i', t_i + \eta_i] \text{ and } s \neq t_i.
\end{cases}
\]

Condition ii) in the Definition 3.342 implies that \( \gamma^{\circ} \) can be extended continuously to the cusps \( t_i \) defining a clean path also denoted \( \gamma^{\circ} \). The retraction at a cusp is represented in figure 18.

The following proposition is clear.

**Proposition-Definition 3.345.** The homotopy class of clean paths of \( \gamma^{\circ} \) does not depend on the choice of the numbers \( \varepsilon_i, \eta_i, \eta_i' \). The homotopy class of \( \gamma^{\circ} \) in \( \pi(M; y, x) \) is denoted by \( \psi(\gamma) \).

Using the map \( \psi \) we can define a composition of clean paths

\[
\pi(M; z, y) \times \pi(M; y, x) \to \pi(M; z, x).
\]

**Definition 3.346.** Let \( x, y \) and \( z \) be base points, tangential or not. Given classes \( \gamma_1 \in \pi(M; z, y) \) and \( \gamma_2 \in \pi(M; y, x) \), we choose representatives \( \tilde{\gamma}_1 \in _z\mathcal{P}(M)^0_y \) and \( \tilde{\gamma}_2 \in _y\mathcal{P}(M)^0_x \). Then \( \tilde{\gamma}_1 \tilde{\gamma}_2 \in _z\mathcal{P}(M) \) and we define

\[
\gamma_1 \gamma_2 = \psi(\tilde{\gamma}_1 \tilde{\gamma}_2).
\]

**Proposition 3.347.** The composition of clean paths given in Definition 3.346 does not depend on the choice of liftings and turns \( \pi(M; x, x) \) into a group and \( \pi(M; y, x) \) (resp. \( \pi(M; x, y) \)) into a right (resp. left) \( \pi(M; x, x) \)-torsor.

The fact that the fundamental groups with different base points are isomorphic can be easily extended to tangential base points. The next proposition is proved like the corresponding one for ordinary base points.

**Proposition 3.348.** Let \( x_i, i = 1, \ldots, 4 \) be base points of \( M \) (tangential or not). Let \( \gamma_1 \in _{x_4}\mathcal{P}(M)_{x_3} \) and \( \gamma_2 \in _{x_2}\mathcal{P}(M)_{x_1} \). Then the following map is an
isomorphism:
\[ \pi(M; x_3, x_2) \rightarrow \pi(M; x_4, x_1) \]
\[ \gamma \rightarrow \gamma_1 \gamma_2. \]

3.8.4. Logarithmic asymptotic developments. We would like to extend the notion of iterated integral to tangential base points. The main problem is that the integral may diverge, so one needs to regularize it. We start by discussing some preliminaries about asymptotic developments.

**Definition 3.349.** Let \( 0 < \tau \leq 1 \) be a real number and \( f : (0, \tau) \rightarrow \mathbb{C} \) a continuous function. We say that \( f \) admits a logarithmic asymptotic development (of degree less than or equal to \( r \)) if it can be written as
\[
f(t) = f_0(t) + \sum_{k=0}^{r} a_k \log(t)^k.
\]
with \( |f_0(t)| = O(t^{1-\delta}) \) for some \( \delta < 1 \) and \( a_k \in \mathbb{C} \).

**Lemma 3.350.** Let \( 0 < \tau \leq 1 \) be a real number and \( f : (0, \tau) \rightarrow \mathbb{C} \) a continuous function. If it admits a logarithmic asymptotic development then the development is unique.

**Proof.** Let \( f : (0, \tau) \rightarrow \mathbb{C} \) be a continuous function that admits an asymptotic development
\[
f(t) = f_0(t) + \sum_{k=0}^{r} a_k \log(t)^k.
\]
We can recover \( a_r \) as
\[
a_r = \lim_{t \to 0} \frac{f(t)}{\log(t)^r}.
\]
Once we know \( a_{s+1}, \ldots, a_r \) we can recover \( a_s \) as
\[
a_s = \lim_{t \to 0} \frac{f(t) - \sum_{k=s+1}^{r} a_k \log(t)^k}{\log(t)^s}.
\]
Finally, \( f_0 = f(t) - \sum_{k=0}^{r} a_k \log(t)^k \). Hence the development is unique. \( \square \)

3.8.5. Asymptotic developments of iterated integrals. We now fix the two tangential base points \( 0 = (0, 1) \) and \( 1 = (1, -1) \), that is, the tangent vector 1 at the point 0 and the tangent vector \(-1\) at the point 1. For instance, the path \( dch(t) = t \) belongs to \( \gamma P(M)_0 \).

Let \( x, y \in \{0, 1\} \cup M \) be base points (tangential or not), \( \gamma \in \gamma P(M)_x \) a piecewise smooth clean path, and \((\varepsilon_1, \ldots, \varepsilon_r)\) a binary sequence with \( \varepsilon_i \in \{0, 1\} \).

We consider the iterated integral
\[
\int_{\gamma} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}.
\]
Since the form \( \omega_0 \) has a pole at 0 and the form \( \omega_1 \) has a pole at 1, this integral may diverge. For instance
\[
\int_{dch} \omega_0 = \infty.
\]
However, if the form \( \omega_{\varepsilon_1} \) has no pole at the point \( y \) and the form \( \omega_{\varepsilon_r} \) has no pole at the point \( x \), then the above integral is convergent. For instance, if \( \gamma = dch \),
the integral will be convergent when \( \varepsilon_1 = 0 \) and \( \varepsilon_r = 1 \), that is, when the binary sequence is admissible.

We now describe the regularization process. Let \( \gamma \in \mathcal{P}(M)^0 \) be a clean path. For \( 0 < \eta < \frac{1}{2} \), we write
\[
\gamma_\eta(t) = \gamma(t(1 - \eta) + (1 - t)\eta).
\]
This is a path from \( \gamma(\eta) \) to \( \gamma(1 - \eta) \), and hence completely contained in \( M \).

**Lemma 3.351.** Let \((\varepsilon_1, \ldots, \varepsilon_r)\) be a binary sequence. The function \((0, 1/2) \to \mathbb{C}\) given by
\[
\eta \mapsto \int_{\gamma_\eta} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}
\]
admits a logarithmic asymptotic development of degree \( \leq r \).

**Proof.** We write
\[
\gamma_{\eta,1}(t) = \gamma(t(1 - \eta) + (1 - t)/2),
\gamma_{\eta,2}(t) = \gamma(t/2 + (1 - t)\eta).
\]
The path \( \gamma_{\eta,2} \) goes from \( \gamma(\eta) \) to \( \gamma(1/2) \) and \( \gamma_{\eta,1} \) is a path from \( \gamma(1/2) \) to \( \gamma(1 - \eta) \). Moreover, \( \gamma_\eta = \gamma_{\eta,1} \gamma_{\eta,2} \) (recall that, according to our convention for the composition of paths (3.3), this means that we first walk along \( \gamma_{\eta,2} \), then along \( \gamma_{\eta,1} \)). Using equations 3.20 and 3.21 in Theorem 3.19, it is enough to show that the functions
\[
\eta \mapsto \int_{\gamma_{\eta,i}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}, \quad i = 1, 2
\]
admit a logarithmic asymptotic development of degree less than or equal to \( r \). Since both cases are analogous, we will only consider \( i = 2 \). We prove the existence of a logarithmic asymptotic development by induction on \( r \). The result is clear for \( r = 0 \). Let us assume that it holds for a binary sequence of length less than or equal to \( r \). If \( \gamma_{\eta,2}^* \omega_{\varepsilon_i} = g_{\varepsilon_i}(t)dt \) and \( \gamma_{\eta}^* \omega_{\varepsilon_i} = h_{\varepsilon_i}(t)dt \), then:
\[
\int_{\gamma_{\eta,2}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = \int_{1 \geq t_1 \geq \cdots \geq t_r \geq 0} g_{\varepsilon_1}(t_1) \cdots g_{\varepsilon_r}(t_r)dt_1 \cdots dt_r
\]
\[
= \int_{1/2 \geq t_1 \geq \cdots \geq t_r \geq \eta} h_{\varepsilon_1}(t_1) \cdots h_{\varepsilon_r}(t_r)dt_1 \cdots dt_r.
\]
Now we compute
\[
I(\eta) = \int_{1/2 \geq t_1 \geq \cdots \geq t_r \geq \eta} h_{\varepsilon_1}(t_1) \cdots h_{\varepsilon_r}(t_r)dt_1 \cdots dt_r
\]
\[
= \int_{1/2 \geq t_r \geq \eta} h_{\varepsilon_r}(t_r) \left( \int_{1/2 \geq t_1 \geq \cdots \geq t_{r-1} \geq t_r} h_{\varepsilon_1}(t_1) \cdots h_{\varepsilon_{r-1}}(t_{r-1})dt_1 \cdots dt_{r-1} \right)dt_r.
\]
By the shape of \( \omega_{\varepsilon_r} \) we deduce that
\[
h_{\varepsilon_r}(t_r) = \alpha/t_r + O(1),
\]
where \( \alpha \) is non-zero if \( \omega_{\epsilon_r} \) has a pole at the point \( x \) and is zero otherwise. We also apply the induction hypothesis to the inner integral to get

\[
I(\eta) = \int_{1/2 \geq t_r \geq \eta} \left( \frac{\alpha}{t_r} + O(t_r^0) \right) \left( O(t_r^{1-\delta}) + \sum_{k=0}^{r-1} b_k \log(t_r)^k \right) dt_r.
\]

Estimating this integral, we deduce that \( I(\eta) \) admits a logarithmic asymptotic development of the sought shape, proving the result. \( \Box \)

3.8.6. Regularized iterated integrals.

Definition 3.352. Let \((\varepsilon_1, \ldots, \varepsilon_r)\) be a binary sequence and let \( \gamma \in \mathcal{P}(M)^0_y \) be a clean path. Let

\[
\int_{\gamma_{\eta}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = f_0(\eta) + \sum_{k=0}^{r} a_k \log(\eta)^k
\]

be the logarithmic asymptotic development provided by Lemma 3.351. Then the regularized iterated integral along \( \gamma \) is defined as

\[
\int_{\gamma}^{\text{reg}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = a_0.
\]

Proposition 3.353. Let \( \gamma \in \mathcal{P}(M)^0_y \) be a cuspidal path and \( \gamma^0 \) a representative of the class \( \psi(\gamma) \) obtained as in (3.344). The regularized integral

\[
\int_{\gamma^0}^{\text{reg}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}
\]

does not depend on the choice of \( \gamma^0 \).

Proof. Let \( \gamma_1^0 \) and \( \gamma_2^0 \) be two choices. Since \( \gamma_1^0 \) and \( \gamma_2^0 \) only differ from \( \gamma \) in a small neighborhood of the cusps, for small enough \( \eta \),

\[
\gamma_1^0(\eta) = \gamma_2^0(\eta), \quad \gamma_1^0(1-\eta) = \gamma_2^0(1-\eta).
\]

Moreover, \( \gamma_1^0 \) and \( \gamma_2^0 \) are homotopic. As we saw in Section 3.5.5, there is an equality \( H^0(B^*(A^*)) = B^0(A) \). Thus, all the iterated integrals that can be constructed from \( \omega_0 \) and \( \omega_1 \) are homotopy functionals. Therefore,

\[
\int_{\gamma_1^0}^{\text{reg}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = \int_{\gamma_2^0}^{\text{reg}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}
\]

from which the result follows. \( \Box \)

Definition 3.354. Let \( \gamma \in \mathcal{P}(M)^0_y \) be a cuspidal path. Let \( \gamma^0 \) be a representative of the class \( \psi(\gamma) \) obtained as in (3.344). We define

\[
\int_{\gamma}^{\text{reg}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = \int_{\gamma^0}^{\text{reg}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}.
\]

Clearly, when the iterated integral is convergent, the value of the regularized integral agrees with the value of the integral.

Regularized iterated integrals share many of the properties of iterated integrals. In particular, Theorem 3.19 can be extended to the new setting.

Theorem 3.355. Let \( \gamma_1, \gamma_2 \) be cuspidal in \( M \) whose endpoints are either \( 0, 1 \), or belong to \( M \) and such that \( \gamma_2(1) = \gamma_1(0) \). Let \((\varepsilon_1, \ldots, \varepsilon_{r+s})\) be a binary sequence. Then
i) \[
\int_{\gamma} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = (-1)^r \int_{\gamma^{-1}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_1}.
\]

ii) \[
\int_{\gamma_1 \gamma_2} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = \sum_{i=0}^{r} \int_{\gamma_1} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_i} \int_{\gamma_2} \omega_{\varepsilon_{i+1}} \cdots \omega_{\varepsilon_r}.
\]

iii) \[
\int_{\gamma} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} \int_{\gamma} \omega_{\varepsilon_{r+1}} \cdots \omega_{\varepsilon_{r+s}} = \sum_{\sigma \in \omega(r,s)} \int_{\gamma} \omega_{\varepsilon_{\sigma(1)}} \cdots \omega_{\varepsilon_{\sigma(r+s)}}
\]

Proof. We first prove i). If \(\gamma\) is cuspidal and \(\gamma^0\) is a clean path in the homotopy class \(\psi(\gamma)\) obtained as in (3.344), then \((\gamma^0)^{-1}\) is a clean path in the homotopy class \(\psi(\gamma^{-1})\) obtained as in (3.344). Therefore, we can assume that \(\gamma\) is a clean path. By construction, \((\gamma^{-1})_\varepsilon = (\gamma_\varepsilon)^{-1}\). By Theorem 3.19 the asymptotic expansions of \(Z_{\gamma,\varepsilon} = \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}\) and \((\gamma^{-1})_\varepsilon = (\gamma_\varepsilon)^{-1}\) agree. Thus, we have the equality of regularized integrals.

Statement iii) also follows from the corresponding statement in Theorem 3.19. Statement ii) is slightly more difficult due to the possibility that the joining point is a tangential base point. The proof goes as follows.

Assume that \(\gamma_1\) and \(\gamma_2\) are clean paths. Let \(\gamma = \gamma_1 \gamma_2\) be their composition and \(\gamma^0\) a clean path representing \(\gamma\) as in (3.344). For sufficiently small \(\eta\), the path \((\gamma^0)_\eta\) is homotopic to \(\gamma_1,0,\eta \gamma_2,0,\eta\), where \(\gamma_0,\eta\) denotes the straight path form \(\gamma_2(1-\eta)\) to \(\gamma_1(\eta)\) (see Figure 19 below). By the usual formula for the composition of paths

\[
\int_{(\gamma^0)_\eta} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r} = \sum_{j=0}^{r} \sum_{k=j}^{r} \int_{\gamma_1,0} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_j} \int_{\gamma_0,0} \omega_{\varepsilon_{j+1}} \cdots \omega_{\varepsilon_k} \int_{\gamma_2,0} \omega_{\varepsilon_{k+1}} \cdots \omega_{\varepsilon_r}.
\]

**Figure 19.** \((\gamma^0)_\eta \sim \gamma_2,\eta \gamma_0,\eta \gamma_1,\eta\)

**Lemma 3.357.** One has \(\int_{\gamma_0,\eta} \omega_{\varepsilon_{j+1}} \cdots \omega_{\varepsilon_k} = O(\eta^{k-j})\).

Proof. The key point is that we have power series expansions

\[
\gamma_2(1-\eta) = \gamma_2(1) - \gamma'_2(1)\eta + O(\eta^2)
\]

\[
\gamma_1(\eta) = \gamma_1(0) + \gamma'_1(0)\eta + O(\eta^2).
\]
Since \( \gamma_2(1) = \gamma_1(0) \) and \( \gamma'_2(1) = -\gamma'_1(0) \), it follows that
\[
|\gamma_2(1 - \eta) - \eta_1(\eta)| = O(\eta^2).
\]
Using the equation \( \gamma_{0,\eta} = t\gamma_1(\eta) + (1 - t)\gamma_2(1 - \eta) \), one sees that
\[
\gamma_{0,\eta} \frac{dz}{z} = \frac{(\gamma_1(\eta) - \gamma_2(1 - \eta))}{t\gamma_2(\eta) + (1 - t)\gamma_2(1 - \eta)} dt,
\]
Since the numerator is \( O(\eta^2) \) and the denominator is \( O(\eta) \), it follows that
\[
\gamma_{0,\eta} \omega = O(\eta^k - j),
\]
proving the lemma.

To conclude the proof of the theorem, we observe that, by the lemma, the integral
\[
\int_{\gamma_{0,\eta}} \omega_{\varepsilon_j+1} \cdots \omega_k = O(\eta^{k-j}),
\]
from which the result follows. Here \( \text{const} \) means the constant term in the logarithmic asymptotic expansion.

As we did before for “honest” base points, the properties of iterated integrals can be concisely rephrased in terms of the bracket. If \( \gamma \) is a piecewise smooth path and \( \eta, \eta_1, \eta_2 \in B^0(A^*) \) be elements of the bar complex of \( A^* \) of degree zero. Then
\[
\text{(i)} \quad \langle \eta, \gamma \rangle \text{reg} = \langle S(\eta), \gamma^{-1} \rangle \text{reg},
\]
\[
\text{(ii)} \quad \langle \eta, \gamma_1 \gamma_2 \rangle \text{reg} = \langle \Delta \eta, \gamma_1 \gamma_2 \rangle \text{reg},
\]
\[
\text{(iii)} \quad \langle \eta_1, \gamma \rangle \text{reg} \cdot \langle \eta_2, \gamma \rangle \text{reg} = \langle \eta_1 \cup \eta_2, \gamma \rangle \text{reg}.
\]

3.8.7. Regularized iterated integrals and regularized zeta values.

Example 3.359. Let us compute an example of a regularized iterated integral in length 3:
\[
\zeta(1, 2) \text{reg} = \int_{\text{deh}}^\text{reg} \omega_1 \omega_2 \omega_1.
\]
By definition, this is the constant term in the asymptotic logarithmic development of the function
\[
\eta \mapsto \int_{1 - \eta \geq t_1 \geq t_2 \geq t_3 \geq 0} \frac{dt_1 dt_2 dt_3}{(1 - t_1)(1 - t_2)(1 - t_3)}.
\]
To be completely precise, according to the above recipe we should have required \( t_3 \geq \eta \) as well. Note, however, that the last form \( \omega_1 \) has no pole at 0, so the constant term of the two asymptotic logarithmic developments agree.
We first compute the integral following the method of examples 1.109 and 1.111. We obtain

\begin{equation}
\int_{1-\eta \geq t_1 \geq t_2 \geq t_3 \geq 0} \frac{dt_1 dt_2 dt_3}{(1-t_1)t_2(1-t_3)} = \sum_{m,n \geq 0} \frac{(1-\eta)^m}{n^2m}.
\end{equation}

This power series converges for $0 < \eta < 1$ but diverges for $\eta = 0$ and we have to find an asymptotic expansion in $\log \eta$. To this end, we use the equality

\begin{equation}
\int_{1-\eta \geq t_1 \geq t_2 \geq t_3 \geq 0} \frac{dt_1 dt_2 dt_3}{(1-t_1)t_2(1-t_3)} = \int_{1-\eta \geq t_2 \geq t_3 \geq 0} \frac{dt_1 dt_2 dt_3}{(1-t_1)t_2(1-t_3)} - 2 \int_{1-\eta \geq t_2 \geq t_3 \geq 0} \frac{dt_1 dt_2 dt_3}{(1-t_1)t_2(1-t_3)},
\end{equation}

which is a simple consequence of the decomposition of the integration domain, together with the fact that the integrand is symmetric in $t_1$ and $t_3$ (this explains why the last term appears twice). Observe that

\begin{equation}
\int_{1-\eta \geq t_1 \geq 0} \frac{dt_1}{1-t_1} = \sum_{k \geq 1} \frac{(1-\eta)^k}{k} = -\log(\eta).
\end{equation}

Combining this with the power series expansions as in Example 1.111, one sees that the right-hand side of (3.361) is equal to

\begin{equation}
-\log(\eta) \sum_{n \geq 1} \frac{(1-\eta)^n}{n^2} - 2 \sum_{m,n \geq 1} \frac{(1-\eta)^m}{m^2n}.
\end{equation}

One can check (Exercise 3.370) directly that this expansion agrees with the right-hand side of (3.360).

To see that the power expansion (3.362) is useful we have to prove that the series appearing in that expansion define continuous functions of $\eta$.

**Lemma 3.363.** The following estimates hold when $\eta$ goes to $0^+$:

\begin{align}
\sum_{n \geq 1} \frac{(1-\eta)^n}{n^2} &= \zeta(2) + O(\log \eta), \\
\sum_{m,n \geq 1} \frac{(1-\eta)^m}{m^2n} &= \zeta(2,1) + O(\log^2 \eta).
\end{align}

**Proof.** To prove the estimate (3.364), we need to study

\[ \zeta(2) - \sum_{n \geq 0} \frac{(1-\eta)^n}{n^2} = \sum_{n \geq 0} \frac{1 - (1-\eta)^n}{n^2}. \]

For $0 < \eta < 1$, we have the inequalities

\[ 0 < 1 - (1-\eta)^n < 1, \quad 0 < 1 - (1-\eta)^n < n\eta. \]

Therefore,

\[ 0 < \sum_{n \geq 1} \frac{1 - (1-\eta)^n}{n^2} < \sum_{n=1}^{\lfloor \frac{1}{\eta} \rfloor} \frac{\eta}{n} + \sum_{n > \lfloor \frac{1}{\eta} \rfloor} \frac{1}{n^2}. \]
Since the first sum is \( O(\eta \log \eta) \) and the second is \( O(\eta) \), the first estimate follows. The second one is obtained in a similar way.

From Lemma 3.363 we obtain
\[
\int_{1-\eta^2} \frac{dt_1 dt_2 dt_3}{(1-t_1)(1-t_2)(1-t_3)} = -2\zeta(2,1) - \zeta(2) \log \eta + O(\eta \log^2 \eta),
\]
from which it follows that
\[
\zeta(1,2)^{\text{reg}} = -2\zeta(2,1).
\]

The value of \( \zeta(1,2)^{\text{reg}} \) is equal to the one obtained by \emph{shuffle regularization} in Example 1.185. This is of course no coincidence, as we now prove:

**Theorem 3.366.** Let \((\varepsilon_1, \ldots, \varepsilon_r)\) be a binary sequence and consider the corresponding word \( w = x_{\varepsilon_1} \cdots x_{\varepsilon_r} \). Then:
\[
\zeta_w(w) = \int_{\eta}^{\text{reg}} \omega_{\varepsilon_1} \cdots \omega_{\varepsilon_r}.
\]

**Proof.** By Proposition 1.180, we need to show that the integral on the right-hand side satisfies the conditions determining \( \zeta_w(w) \). Condition (1.181) follows from Theorem 1.115 combined with the observation that, when the binary sequence is admissible, then the regularized integral agrees with the usual integral. Condition (1.182) is checked by a direct computation. Finally, condition (1.183) is Theorem 3.355 (ii).

3.8.8. Chen’s theorem for tangential base points. We finish this section by stating a version of Chen’s theorem with tangential base points. Recall that we are writing \( M = \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\} \), and \( A_n^\ast \) is the dg-algebra of paragraph 3.5.5.

**Theorem 3.367** (Chen’s \( \pi_1 \) theorem for tangential base points). For each integer \( N \geq 0 \) and each pair of points \( x, y \) (tangential or not), the regularized iterated integrals induce an isomorphism
\[
L_N H^0(B^*(A_n^\ast)) \cong \text{Hom}_Q(\mathbb{Q}[\pi_1(M; y, x)]/J^{N+1} \mathbb{Q}[\pi_1(M; x)], \mathbb{C}).
\]
Passing to the limit, we deduce an isomorphism between \( H^0(B^*(A_n^\ast)) \) and the topological dual \((\mathbb{C}[\pi_1(M; y, x)]^\vee)^\vee\).

**Proof.** We need to show that the pairing between the spaces \( L_N H^0(B^*(A_n^\ast)) \) and \( \pi_1(M; y, x)/J^{N+1} \) is non-degenerate. Since both are finite-dimensional, it suffices to prove that there is no non-zero \( \gamma \in \pi_1(M; x, y)/J^{N+1} \) such that \( \langle \omega, \gamma \rangle = 0 \) for all \( \omega \). Indeed, assume that such a \( \gamma \) exists. Choose usual base points \( x' \) and \( y' \) and paths \( \gamma_1, \gamma_2 \) going from \( x \) to \( x' \) and from \( y \) to \( y' \). Then, by Theorem 3.358 (ii), for \( \omega \in L_N H^0(B^*(A^\ast)) \)
\[
\langle \omega, \gamma_1 \gamma_2 \rangle = \sum \langle \omega_1, \gamma_1 \rangle \langle \omega_2, \gamma \rangle \langle \omega_3, \gamma_2 \rangle,
\]
where all the elements \( \omega_1, \omega_2, \omega_3 \) are of length \( \leq N \). Thus, \( \langle \omega, \gamma_1 \gamma_2 \rangle = 0 \) for all \( \omega \in L_N H^0(B^*(A^\ast)) \). By Chen’s Theorem 3.264, \( \gamma_1 \gamma_2 = 0 \) and hence the same is true for \( \gamma \).
3.8.9. A mixed Hodge structure in the case of tangential base points. We now extend the definition of the ind-mixed Hodge structure \( \{ y^A_{x, y} \} \) to the case of tangential base points \( x \) and \( y \). The definition follows the pattern of that from Section 3.7.2.

For the Betti part of \( y^A_{x, y} \), we write
\[
A_{B, x, y}^{y N} = \left( \mathbb{Q} \left[ \pi (M; y, x) \right] / J^{N+1} \mathbb{Q} \left[ \pi (M; y, x) \right] \right)^{\vee}
\]
with the weight filtration given, for \(-1 \leq p \leq N\), by
\[
W_{2p} (y^A_{x, y}^{B, N}) = W_{2p+1} (y^A_{x, y}^{B, N}) = \left( J^{p+1} \mathbb{Q} \left[ \pi (M; y, x) \right] / J^{N+1} \mathbb{Q} \left[ \pi (M; y, x) \right] \right) .
\]

For the de Rham side \( y^A_{x, y}^{dR, N} \), we just copy the definition of \( y^A_{x, y}^{dR, N} \) for honest base points \( x \) and \( y \) as the de Rham side is independent of this choice. Now the comparison map \( \text{comp}_{dR, B} \) is given by Theorem 3.367 and the inverse is denoted by \( \text{comp}_{B, dR} \).

In the case of points at finite distance, thanks to Beilinson’s theorem we knew that the previous structures define a mixed Hodge structure. But Beilinson’s theorem is not available for tangential base points, so we need to prove this fact in the case at hand.

**Proposition 3.368.** For every \( N \geq 0 \), the triple
\[
H = \left( (y^A_{x, y}^{B, N}, W), (y^A_{x, y}^{dR, N}, W, F \cdot \text{comp}_{B, dR}) \right)
\]
is a mixed Hodge structure over \( \mathbb{Q} \).

**Proof.** The fact that \( \text{comp}_{dR, B} \) is an isomorphism of filtered vector spaces is the content of Theorem 3.367. So we only need to prove that the triple
\[
\text{Gr}_m^W H = (\text{Gr}_m^W H_{B}, (\text{Gr}_m^W H_{dR}^W, F \cdot \text{comp}_{B, dR}))
\]
is a pure Hodge structure of weight \( m \). By Proposition 3.336, we know that \( \text{Gr}_{2p+1}^W H_{dR} = \{0\} \) and that the filtration \( F \cdot \text{comp}_{B, dR} \) induced in \( \text{Gr}_m^W H_{dR} \) satisfies
\[
F^p \text{Gr}_{2p}^W H_{dR} = \text{Gr}_{2p}^W H_{dR} \quad \text{and} \quad F^{p+1} \text{Gr}_{2p}^W H_{dR} = \{0\}.
\]
Therefore, regardless of the precise action of complex conjugation, the equality
\[
\text{Gr}_m^W H_{dR} = F^p \oplus F^{m+1-p}
\]
holds for all \( m \) and \( p \), which completes the proof. \( \square \)

**Remark 3.369.** As a consequence of Proposition 3.368 and Theorem 3.366 we have exhibit all regularized multiple zeta values as periods of mixed Hodge structures. Nevertheless, since we do not have Beilinson’s theorem for tangential base points we do not know yet that these mixed Hodge structures come from geometry as in Theorem 2.163. This will be discussed in Section 4.3.4.

***

**Exercise 3.370.** By expanding \( \log(\eta) \) as a power series in \( (1 - \eta) \), prove the following equality of functions for \( 0 < \eta < 1 \):
\[
\sum_{m > n > 0} \frac{(1 - \eta)^m}{n^2 m} = -\log(\eta) \sum_{n \geq 0} \frac{(1 - \eta)^n}{n^2} - 2 \sum_{m > n \geq 1} \frac{(1 - \eta)^m}{m^2 n}.
\]
Exercise 3.371. Let \( n \geq 2 \) be an integer. Adapt Example 3.359 to compute the regularized iterated integral
\[
\int_{\text{dch}}^{\text{reg}} \omega_1 \omega_1^{n-1} \omega_1
\]
and show that the result coincides with \( \zeta_{\omega}(1, n) \).

3.9. Polylogarithms and their monodromy. In this section, we explain how to make the isomorphism of Chen’s Theorem 3.367 more explicit in the case of \( M = \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\} \) by using polylogarithms.

3.9.1. Generators of the fundamental group of \( M \). In the previous section, we have introduced the tangential base points \( 0 \) and \( 1 \). The fundamental group \( \pi_1(M, 0) \) is generated by the paths \( \gamma_0 \) and \( \gamma_1 \) of Figure 20. The space of paths \( \pi(M; 0, 0) \) is generated as a right \( \pi_1(M, 0) \)-module by the straight path \( \text{dch} \) also represented in Figure 20.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure20.png}
\caption{Generators}
\end{figure}

The fundamental group \( \pi_1(M, 1) \) is generated by the paths
\[
\gamma'_0 = \text{dch} \cdot \gamma_0 \cdot \text{dch}^{-1}, \quad \gamma'_1 = \text{dch} \cdot \gamma_1 \cdot \text{dch}^{-1},
\]
and the space \( \pi(M; 0, 1) \) is generated as a right \( \pi_1(M, 1) \)-module or as a left \( \pi_1(M, 0) \)-module by the path \( \text{dch}^{-1} \).

3.9.2. The dual of Chen’s map. We saw in Section 3.5.5 that the cohomology in degree zero of the reduced bar complex associated with \( A^*_\mathbb{C} \) is isomorphic to the complex Hoffman algebra \( \mathcal{H} \otimes \mathbb{C} \). In Example 3.71 we identified the dual \( \mathcal{H}^\vee \) with the algebra \( \mathbb{Q}\langle e_0, e_1 \rangle \). We extend Notation 1.160 as follows.

Notation 3.372. If \( \alpha \) is a binary sequence, we will denote by \( x_\alpha \) the corresponding word in the Hoffman algebra \( \mathcal{H} \), by \( \omega_\alpha \) the differential form \( \omega_\alpha \) in \( B^0(A^*) \simeq \mathcal{H} \) and by \( e_\alpha \) the dual element to \( x_\alpha \) in \( \mathbb{Q}\langle e_0, e_1 \rangle \).

Let \( x \) and \( y \) be two base points (tangential or not) of \( M = \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\} \). Given a path \( \gamma \) from \( x \) to \( y \) and \( \omega \in B^0(A^*_\mathbb{C}) \), we define
\[
L_\omega(\gamma) = \int_{\gamma}^{\text{reg}} \omega \in \mathbb{C}.
\]
Or, in the notation of Theorem 3.358
\[
L_\omega(\gamma) = \langle \omega, \gamma \rangle^{\text{reg}}.
\]
For a binary sequence \( \alpha \), we set \( L_\alpha(\gamma) = L_{\omega_\alpha}(\gamma) \). Consider the generating series

\[
L(\gamma) = \sum_\alpha L_\alpha(\gamma)e_\alpha \in \mathbb{C}\langle e_0, e_1 \rangle.
\]

Therefore, if \( \omega \in B^0(A^*_C) \simeq J \otimes \mathbb{C} \simeq \mathbb{C}\langle e_0, e_1 \rangle^\vee \), we have

\[
L(\gamma)(\omega) = L_\omega(\gamma).
\]

### 3.9.3. The map \( L \) and polylogarithms.

Recall that in Definition 1.117 we attached, to a positive multi-index \( s \), a complex-valued function \( \text{Li}_s \), the polylogarithm, defined on the open unit disc \( |z| < 1 \). The relation between the polylogarithm and the series \( L \) is explained by the following lemma, whose proof is parallel to that of Theorem 1.124. We leave the details to the reader.

**Lemma 3.373.** Let \( z \) be a complex number such that \( 0 < |z| < 1 \), \( \gamma \) a path from 0 to \( z \) contained in the disk \( |z| < 1 \), and \( s \) a positive multi-index. Let \( b_s(s) \) denote the associated binary sequence. Then:

\[
\text{Li}_s(z) = L_{b_s(s)}(\gamma).
\]

### 3.9.4. Computation of \( L(\gamma_0) \).

For any \( z \in \mathbb{C} \setminus \{0, 1\} \), any path \( \gamma \) from 0 to \( z \) and any binary sequence \( \alpha \), \( L_\alpha(\gamma) \) is defined. By abuse of notation, we will write \( L_\alpha(z) \) and think of it as a multivalued function.

**Example 3.374.** Let \( z \in \mathbb{C} \setminus \{0, 1\} \). Let us show that, for each \( n \geq 1 \), the following equality of multivalued functions holds:

\[
L_0^n(z) = \frac{1}{n!}(\log z)^n.
\]

Let \( \gamma \) be any path from 0 to \( z \). We argue by induction on \( n \). First, for \( n = 1 \), to compute the value

\[
L_0(\gamma) = \int_\gamma^{\mathrm{reg}} \frac{dt}{t}
\]

one needs to find a logarithmic asymptotic development for

\[
\eta \mapsto \int_\eta^{1-\eta} \gamma^*(\frac{dt}{t}) = \int_\eta^{1-\eta} \gamma' \frac{dt}{\gamma}.
\]

Since \( \gamma(0) = 0 \) and \( \gamma'(0) = 1 \), one has \( \gamma(\eta) = \eta(1 - O(\eta)) \) as \( \eta \) goes to zero. On the other hand, \( \gamma(1 - \eta) = z + O(\eta) \). Thus,

\[
\log \gamma(1 - \eta) - \log \gamma(\eta) = \log z + O(\eta) - \log \eta
\]

and the regularization assigns the value

\[
L_0(\gamma) = \log z.
\]

Let us now assume that the identity (3.375) holds for \( n - 1 \). Since the number of shuffles of type \((1, n-1)\) is \( n \) (cf. Exercise 1.141), relation iii) of Theorem 3.355 gives the result we want:

\[
nL_0^n(z) = \int_\gamma^{\mathrm{reg}} \omega_0 \int_\gamma \omega_0^{n-1} \omega_0 = \frac{1}{(n-1)!}(\log z)^n.
\]
Example 3.376. We are now ready to compute \( L(\gamma_0) \). Arguing as in Example 3.374, one gets
\[
L_0(\gamma_0) = \frac{1}{n!}(2\pi i)^n.
\]
If \( \alpha \) is a non-empty positive binary sequence, Lemma 3.373 implies that
\[
L_\alpha(\gamma_0) = 0.
\]
In fact, it follows from the compatibility with the shuffle product, part iii) of Theorem 3.358, that \( L_\alpha(\gamma_0) = 0 \) for all \( \alpha \neq \emptyset \) and all \( k \geq 0 \). Summing up, we deduce that
\[
L(\gamma_0) = \sum_{\alpha} L_\alpha(\gamma_0)e_\alpha = \sum_{n \geq 0} \frac{(2\pi i)^n}{n!}e_0^n = \exp(2\pi i e_0).
\]
Thanks to the symmetry \( z \mapsto 1 - z \), it follows that
\[
L(\gamma_1) = \exp(2\pi i e_1).
\]

3.9.5. \( L \) evaluated at \( dch \) and the Drinfeld associator.

Example 3.379. Theorem 3.366 implies that, for each binary sequence \( \alpha \), the equality \( L_\alpha(\text{dch}) = \zeta_\omega(x_\alpha) \) holds. Therefore,
\[
L(\text{dch}) = \sum_{\alpha} \zeta_\omega(x_\alpha)e_\alpha.
\]
We write \( \Phi(e_0, e_1) \) for this power series with real coefficients. We also write
\[
\Phi_{\text{KZ}}(e_0, e_1) = \Phi(e_0, -e_1) = \sum_{\alpha} (-1)^{l(\alpha)}\zeta_\omega(x_\alpha)e_\alpha,
\]
where \( l(\alpha) \) is the number of entries equal to 1 in \( \alpha \) as in Definition 1.131.

Definition 3.382. The power series \( \Phi_{\text{KZ}}(e_0, e_1) \in \mathbb{R}\langle e_0, e_1 \rangle \) is called the Drinfeld associator.

3.9.6. Chen’s theorem revisited.

Theorem 3.383. For any two base points \( x \) and \( y \), the map \( L \) can be extended to a continuous \( C \)-linear isomorphism
\[
L: \mathbb{C}[\pi_1(M; y, x)]^\wedge \rightarrow \mathbb{C}\langle e_0, e_1 \rangle = \text{Hom}(\mathfrak{H}, \mathbb{C}).
\]
The following properties hold:

i) If \( u \in \mathbb{C}[\pi_1(M; y, x)]^\wedge \), then
\[
S^\vee(L(u)) = L(S(u)).
\]
In particular, if \( \gamma \in \pi_1(M; y, x) \) is a path, \( S^\vee(L(\gamma)) = L(\gamma^{-1}) \).

ii) Given three points \( x, y \) and \( z \), and elements \( v \in \mathbb{C}[\pi_1(M; y, x)]^\wedge \) and \( u \in \mathbb{C}[\pi_1(M; z, y)]^\wedge \), one has
\[
L(uv) = L(u)L(v).
\]

iii) If \( u \in \mathbb{C}[\pi_1(M; y, x)]^\wedge \), then
\[
\nabla^\vee(L(u)) = (L \otimes L)(\Delta(u)).
\]
In particular, if \( \gamma \in \pi_1(M; y, x) \) is a path, then \( L(\gamma) \) is a group-like element.
PROOF. We first extend $L$ by linearity to $\mathbb{C}[\pi_1(M; y, x)]$. By construction, for any path $\gamma$, the series $L(\gamma)$ starts by one. Therefore, any element in the augmentation ideal of $\mathbb{C}[\pi_1(M; y, x)]$ is sent to an element of the ideal generated by $e_0$ and $e_1$. Thus, it can be extended uniquely to a morphism

$$L : \mathbb{C}[\pi_1(M; y, x)]^\wedge \rightarrow \mathbb{C}[e_0, e_1] = \text{Hom}(\mathcal{H}, \mathbb{C}).$$

That this yields an isomorphism is simply a reformulation of Theorem 3.367. It is enough to check properties i) to iii) on paths. All of them follow from Theorem 3.355.

We start proving i) using Theorem 3.358 i).

$$L(\gamma^{-1}) = \sum_\alpha \langle \omega_\alpha, \gamma^{-1} \rangle^{\text{reg}} e_\alpha = \sum_\alpha \langle S(\omega_\alpha), \gamma \rangle^{\text{reg}} e_\alpha = \sum_\alpha \langle \omega_\alpha, \gamma \rangle^{\text{reg}} S^\vee(e_\alpha) = S^\vee(L(\gamma)).$$

We next prove ii) using 3.358 ii)

$$L(\gamma_1\gamma_2) = \sum_\alpha \langle \omega_\alpha, \gamma_1\gamma_2 \rangle^{\text{reg}} e_\alpha = \sum_\alpha \langle \Delta\omega_\alpha, \gamma_1 \otimes \gamma_2 \rangle^{\text{reg}} e_\alpha = \sum_{\alpha',\alpha''} \langle \omega_{\alpha'}, \omega_{\alpha''}, \gamma_1 \otimes \gamma_2 \rangle^{\text{reg}} e_{\alpha'} e_{\alpha''} = L(\gamma_1) L(\gamma_2).$$

Finally we prove iii) using 3.358 iii).

$$\nabla^\vee(L(\gamma)) = \sum_\alpha \langle \omega_\alpha, \gamma \rangle^{\text{reg}} \nabla^\vee e_\alpha = \sum_\alpha \langle \omega_\alpha, \gamma \rangle^{\text{reg}} \sum_{\alpha',\alpha''} \langle \omega_{\alpha'}, \omega_{\alpha''}, \gamma \rangle^{\text{reg}} e_{\alpha'} \otimes e_{\alpha''} = \sum_{\alpha',\alpha''} \langle \omega_{\alpha'}, \gamma \rangle^{\text{reg}} \langle \omega_{\alpha''}, \gamma \rangle^{\text{reg}} e_{\alpha'} \otimes e_{\alpha''} = L(\gamma) \otimes L(\gamma).$$

This concludes the proof. \(\blacksquare\)

EXAMPLE 3.384. From Theorem 3.383 iii) we deduce that $\Phi(e_0, e_1) = L(dch)$ is a group-like element. In particular, it is the exponential of a primitive element and its inverse as power series is given by its antipode

$$(3.385) \quad L(dch^{-1}) = \Phi(e_0, e_1)^{-1} = S^\vee(\Phi(e_0, e_1)).$$

From examples 3.376 and 3.379 and the compatibility of $L$ with the composition of paths in 3.383 ii) we can compute $L$ on the remaining generators of $\pi_1(M, 0)$ and $\pi_1(M, 1)$.

$$L(\gamma_1) = \Phi(e_0, e_1)^{-1} \exp(2\pi i e_1) \Phi(e_0, e_1),$$
$$L(\gamma'_0) = \Phi(e_0, e_1) \exp(2\pi i e_0) \Phi(e_0, e_1)^{-1}.$$
PROPOSITION 3.386. $L(z)$ satisfies the differential equation

\[
\frac{d}{dz} L(z) = \left( \frac{e_0}{z} + \frac{e_1}{1 - z} \right) L(z).
\]

PROOF. Fix $z \in M$, let $\gamma$ be a path with endpoint $z$ and let $\gamma_\varepsilon(t) = z + t\varepsilon$. To compute the derivative of $L(z)$ we need to evaluate the limit

\[
\lim_{\varepsilon \to 0} \frac{L(\gamma_\varepsilon) - L(\gamma)}{\varepsilon}.
\]

By Theorem 3.383 ii)

\[
L(\gamma_\varepsilon) - L(\gamma) = (L(\gamma_\varepsilon) - 1)L(\gamma).
\]

Moreover,

\[
L(\gamma_\varepsilon) - 1 = \int_{\gamma_\varepsilon}^{reg} \omega_0 e_0 + \int_{\gamma_\varepsilon}^{reg} \omega_1 e_1 + O(\varepsilon^2).
\]

Since

\[
\lim_{\varepsilon \to 0} \frac{1}{\varepsilon} \int_{\gamma_\varepsilon} \omega_0 = \frac{1}{z} \quad \text{and} \quad \lim_{\varepsilon \to 0} \frac{1}{\varepsilon} \int_{\gamma_\varepsilon} \omega_1 = \frac{1}{1 - z},
\]

we conclude

\[
\frac{d}{dz} L(z) = \left( \frac{e_0}{z} + \frac{e_1}{1 - z} \right) L(z).
\]

Finishing the proof. □

3.9.8. The monodromy of $L$. The second property we want to derive is an explicit description of the monodromy of $L$ as a multivalued function.

THEOREM 3.388. Let $z \in M$ and $\gamma$ a path from $0$ to $z$. Then

\[
L(\gamma \cdot \gamma_0) = L(\gamma) \exp(2\pi i e_0),
\]

\[
L(\gamma \cdot \gamma_1) = L(\gamma) \Phi(e_0, e_1)^{-1} \exp(2\pi i e_1) \Phi(e_0, e_1).
\]

PROOF. The statement follows immediately from Theorem 3.383 ii) and examples 3.376 and 3.384. □

3.9.9. Further properties of the Drinfeld associator. We next derive the basic properties of Drinfeld associator $\Phi_{KZ}$. Let $\mathfrak{u}_4$ be the universal enveloping algebra of the Lie algebra of the pro-unipotent completion of the pure braid group on 4 strings. It is the algebra of power series in letters $t_{i,j}, 1 \leq i, j \leq 4$ with the relations

\[
t_{i,i} = 0, \quad t_{i,j} = t_{j,i},
\]

\[
[t_{i,j}, t_{i,k} + t_{j,k}] = 0, \quad \text{for } i, j, k \text{ different},
\]

\[
[t_{i,j}, t_{k,l}] = 0, \quad \text{for } i, j, k, l \text{ different}.
\]

THEOREM 3.389 (Drinfeld [Dri90]). The Drinfeld associator satisfies the following relations.

i) Symmetry relation: $\Phi_{KZ}(e_0, e_1) \Phi_{KZ}(e_1, e_0) = 1$.

ii) Hexagon relation: Write $e_\infty = -e_0 - e_1$, then

\[
e^{i\pi e_0} \Phi_{KZ}(e_\infty, e_0) e^{i\pi e_\infty} \Phi_{KZ}(e_1, e_\infty) e^{i\pi e_1} \Phi_{KZ}(e_0, e_1) = 1.
\]
iii) Pentagon relation: For $t_{i,j} \in Ua_4$ we have

$$
\Phi_{KZ}(t_{1,2}, t_{2,3} + t_{2,4}) \Phi_{KZ}(t_{1,3} + t_{2,3}, t_{3,4})
= \Phi_{KZ}(t_{2,3}, t_{3,4}) \Phi_{KZ}(t_{1,2} + t_{1,3}, t_{2,4} + t_{3,4}) \Phi_{KZ}(t_{1,2}, t_{2,3}).
$$

**Proof.** We start proving i). Consider the automorphism of $M$ given by $z \mapsto 1 - z$. This automorphism sends the form $\omega_i$ to $-\omega_{1-i}$ for $i = 0, 1$, and hence it sends $e_0$ to $-e_1$ and $e_1$ to $-e_0$. Moreover, it sends $\text{dch}$ to $\text{dch}^{-1}$. Therefore, we deduce that $L(\text{dch}^{-1}) = \Phi(-e_1, -e_0)$. Therefore,

$$
1 = L(\text{dch}) L(\text{dch}^{-1}) = \Phi(e_0, e_1) \Phi(-e_1, -e_0),
$$

which is equivalent to i).

To prove ii) we need to introduce more tangential points and paths. Let $0^- = (0, -1)$ be the tangent vector $-1$ at $0$ and $1^- = (1, 1)$ be the tangent vector $1$ at $1$. We consider the point $\infty$ with local coordinate $u = 1/z$ and denote $\infty = (\infty, 1)$ the tangent point $1$ at $\infty$ with respect to this coordinate and $\infty^- = (\infty, -1)$. We denote by $\delta_0 \in \pi(M; 0, 0^-)$ the path that starts in $0^-$, gives half a turn around zero in the counterclockwise direction and ends in $0$. Similarly, $\delta_1 \in \pi(M; 1^-, 1)$ is the path that starts in $1$, gives half a turn in the counterclockwise direction and ends in $1^-$. We denote $\delta_\infty \in \pi(M; \infty^-, \infty)$ is the path that starts in $\infty$, gives half a turn in the counterclockwise direction and ends in $\infty^-$. Finally we denote by $\text{dch}_{\infty, 1} \in \pi(M; \infty, 1^-)$ the straight path that starts in $1^-$ and ends in $\infty$ through the real numbers greater than one and by $\text{dch}_{0, \infty} \in \pi(M; 0^-, \infty^-)$ the straight path that starts in $\infty^-$ and ends in $0^-$ through the negative real numbers. All these paths are represented in Figure 21.

![Figure 21. Paths](image)

Clearly, the composition

$$
\delta_0 \cdot \text{dch}_{0, \infty} \cdot \delta_\infty \cdot \text{dch}_{\infty, 1} \cdot \delta_1 \cdot \text{dch}
$$

is homotopically equivalent to the trivial path. Therefore, by Theorem 3.383 ii),

$$
L(\delta_0) L(\text{dch}_{0, \infty}) L(\delta_\infty) L(\text{dch}_{\infty, 1}) L(\delta_1) L(\text{dch}) = 1.
$$

Arguing as in Example 3.376, we can see that

$$
L(\delta_0) = \exp(\pi i e_0).
$$

We now consider the automorphism of $M$ given by $z \mapsto 1/(1 - z)$. This map sends $\delta_0$ to $\delta_1$ and $\delta_1$ to $\delta_\infty$. It also sends $\text{dch}$ to $\text{dch}_{\infty, 1}$ and $\text{dch}_{\infty, 1}$ to $\text{dch}_{0, \infty}$.

Moreover, the pull back by this isomorphism sends the form $\omega_0$ to the form $\omega_1$ and the form $\omega_1$ to the form $-\omega_0 - \omega_1$. Dualizing we deduce that this automorphism
sends $e_0$ to $-e_1$ and $e_1$ to $e_0 - e_1$. We deduce that

$$L(\delta_1) = \exp(-\pi i e_1), \quad L(\delta_\infty) = \exp(\pi i (e_1 - e_0)),$$

$$L(dch_{\infty,1}) = \Phi(-e_1, e_0 - e_1), \quad L(dch_{0,\infty}) = \Phi(e_1 - e_0, -e_0).$$

Thus, equation (3.390) reads

$$e^{i\pi e_0} \Phi(e_1 - e_0, -e_0) e^{i\pi(e_1 - e_0)} \Phi(-e_1, e_0 - e_1) e^{-i\pi e_1} \Phi(e_0, e_1) = 1,$$

which is equivalent to

$$e^{i\pi e_0} \Phi_{KZ}(e_1 - e_0, e_0) e^{i\pi(e_1 - e_0)} \Phi_{KZ}(-e_1, e_1 - e_0) e^{-i\pi e_1} \Phi_{KZ}(e_0, -e_1) = 1.$$

The hexagon relation is obtained by replacing $e_1$ with $-e_1$.

The proof of iii) involves considering a path in the moduli space $M_{0,5}$ which is a complex surface. To write it properly, we would need to discuss tangential base points and local monodromy in higher dimensions, so we will omit it. □

3.9.10. Associators. The name **associator** for $\Phi_{KZ}$ comes from the theory of quantum groups where one seeks for non-commutative deformations of commutative algebras. We sketch briefly the origin of the term associator, the reader is referred to [ES02] for more details.

Let $k$ be a field of characteristic zero and write $K = k[[h]]$ for the ring of formal power series on the indeterminate $h$. Similarly, if $V$ is a vector space over $k$, we write

$$V[[h]] = \left\{ \sum_{n\geq 0} v_n h^n \mid v_n \in V \right\}.$$

Then $K$ and $V[[h]]$ have an $h$-adic valuation, hence an $h$-adic topology and they are complete with respect to this topology.

A $K$-module $H$ is called **topologically free** if it is isomorphic to $V[[h]]$ for some $k$-vector space $V$. In the category of topologically free $K$-modules, the role of the tensor product is played by the completed tensor product $M \hat{\otimes} N$, which is the completion of $M \otimes N$ with respect to the $h$-adic topology.

As we have defined the notion of completed Hopf algebra in the context of duality, there is also a notion of completed bi-algebra and completed Hopf algebra for topologically free vector spaces, where the tensor product is replaced by the completed tensor product.

In certain circumstances, to ask for a coproduct to be coassociative and cocommutative may be too rigid and it is better to allow for some flexibility.

**Definition 3.391.** Let $A$ be an associative (topologically free $K$-)algebra. Let

$$\Delta: A \rightarrow A \hat{\otimes} A, \quad \epsilon: A \rightarrow K$$

be morphisms of $K$-algebras such that

$$(1 \otimes \epsilon) \circ \Delta = (\epsilon \otimes 1) \circ \Delta = 1.$$

Then $A$ is called a (topologically free) quasi-bialgebra if there exists an invertible element $\Phi \in A \hat{\otimes} A \hat{\otimes} A$ satisfying the following properties:

i) quasi-coassociativity

$$\Phi \cdot (\Delta \otimes 1)\Delta(x) \cdot \Phi^{-1} = (1 \otimes \Delta)\Delta(x)$$

for all $x \in A;$
The element \( \Phi \) is called an **associator**. A quasi-bialgebra is called a quasi-Hopf algebra if it is equipped with an algebra antihomomorphism \( S \): \( A \to A \) and elements \( \alpha, \beta \in A \) such that

\[
\nabla(S \otimes \alpha)\Delta(x) = \epsilon(x)\alpha, \quad \nabla(1 \otimes \beta S)\Delta(x) = \epsilon(x)\beta,
\]

\[
\nabla \circ (\nabla \otimes \text{Id})(S \otimes \alpha \otimes \beta S)\Phi = 1, \quad \nabla \circ (\nabla \otimes \text{Id})(1 \otimes \beta S \otimes \alpha)\Phi^{-1} = 1
\]

**Definition 3.392.** Let \( (A, \Delta, \epsilon, \Phi) \) be a quasi-bialgebra. A **quasi-triangular structure** is an invertible element \( R \in A \hat{\otimes} A \) such that:

i) **quasi-cocommutativity**

\[
R \cdot \Delta(x) \cdot R^{-1} = \tau \circ \Delta(x),
\]

for all \( x \in A \), where \( \tau: A \hat{\otimes} A \to A \hat{\otimes} A \) is the map that switches factors;

ii) **hexagon properties**

\[
(\text{Id} \otimes \Delta)R = \sigma_{231}(\Phi^{-1}) \cdot \iota_{13}(R) \cdot \sigma_{213}(\Phi) \cdot \iota_{12}(R) \cdot \sigma_{123}(\Phi^{-1}),
\]

\[
(\Delta \otimes \text{Id})R = \sigma_{321}(\Phi) \cdot \iota_{13}(R) \cdot \sigma_{132}(\Phi^{-1}) \cdot \iota_{23}(R) \cdot \sigma_{123}(\Phi),
\]

where the maps \( \sigma_{ijk}: A \hat{\otimes} A \hat{\otimes} A \to A \hat{\otimes} A \hat{\otimes} A \) are defined as

\[
x_{1} \otimes x_{2} \otimes x_{3} \mapsto x_{i} \otimes x_{j} \otimes x_{k},
\]

while the map \( \iota_{ij}: A \hat{\otimes} A \to A \hat{\otimes} A \hat{\otimes} A \) sends the element \( x \otimes y \) to the element of the triple tensor product with \( x \) in the position \( i \), \( y \) in the position \( j \) and \( 1 \) in the remaining position.

The Drinfeld associator \( \Phi_{KZ} \in \mathbb{R}\langle e_0, e_1 \rangle \) is not an associator in the sense of Definition 3.391, but, as the next proposition shows, it is a device that allows us to construct associators for the universal enveloping algebra of a Lie algebra. This result follows from Theorem 3.389.

**Proposition 3.393.** Let \( L \) be a finite-dimensional Lie algebra over \( \mathbb{C} \) and \( U(L) \) its universal enveloping algebra with its Hopf algebra structure as in Section 3.2.11. We extend \( \Delta \) to \( H = U(L)[[h]] \) by \( k[[h]] \) linearity. In particular \( \Delta(h) = h \otimes 1 = 1 \otimes h \). Let \( \Omega \in S^2(L) \subset L \otimes L \) be a symmetric invariant element. Then \( \Phi = \Phi_{KZ}(h_{12}(\Omega), h_{23}(\Omega)) \) is an associator of \( H \) and \( \exp(h\Omega/2) \) is a quasi-triangular structure of \( (H, \Phi) \).

In fact, any power series \( \Phi \in k\langle e_0, e_1 \rangle \) satisfying Theorem 3.389 is called a **Lie associator** over \( k \) and they satisfy Proposition 3.393. The series \( \Phi_{KZ} \) is an explicit example of a Lie associator defined over \( \mathbb{R} \). From the existence of \( \Phi_{KZ} \) one can deduce the existence of a Lie associator defined over \( \mathbb{Q} \), although there is no explicit example.

The existence of Lie associators over \( \mathbb{Q} \) and a variant of the Tannakian formalism (see Section 4.1.4) adapted to topologically free algebras, are used to prove that, if \( L \) is a finite-dimensional Lie algebra over \( k \), then the universal enveloping algebra \( U(L) \) admits a functorial non-trivial quantization. Again we refer to [ES02] for details.
3.9.11. The associator relations and the extended double shuffle relations. We close this section by quoting

**Theorem 3.394** (Furusho [Fur10], [Fur11]).

i) Let \((\zeta^s(\alpha))_\alpha\) be a collection of real numbers, one for each binary sequence. Denote by \(\zeta^s: S^0 \rightarrow \mathbb{R}\) the map obtained from these numbers by linearity. If the power series
\[
\sum_\alpha (-1)^\alpha \zeta^s(\alpha)e_\alpha
\]
is group-like and satisfies the associator relations of Theorem 3.389, then \((\mathbb{R}, \zeta^s)\) satisfies the extended double shuffle relations (Definition 1.199).

ii) Let \(\varphi \in \mathbb{R}\langle e_0, e_1 \rangle\) be a group-like element with the coefficient of \(e_0 e_1\) equal to \(-\zeta^s(2) = -\pi^2 / 6\). If \(\varphi\) satisfies the pentagon relation 3.389, then it satisfies the symmetry relation 3.389 and the hexagon relation 3.389.

***

**Exercise 3.395.** Compute explicitly the terms up to degree 5 of the Drinfeld associator \(\Phi_{KZ}(e_0, e_1)\). Show that, with the exception of the unit in degree 0, they can be all written as commutators.

**Exercise 3.396.** In this exercise, we show how Theorem 3.388 encodes the monodromy of multiple polylogarithms in one variable. We start with \(\text{Li}_3\), which is the coefficient of \(e_0 e_0 e_1\) in \(L\). Let \(z \in \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\}\) and let \(\gamma\) be a path from 0 to \(z\).

i) Find the coefficient of \(e_0 e_0 e_1\) in \(L(\gamma \cdot \gamma_0)\) and \(L(\gamma \cdot \gamma_1)\). The resulting expressions give the monodromy of \(\text{Li}_3\).

ii) Compute the monodromy through \(\gamma_0\) and \(\gamma_1\) of the functions
\[
L_0 = 1, \quad L_0, \quad L_1, \quad L_{0001}, \quad L_{01001}.
\]

3.10. The fundamental groupoid of \(\mathbb{P}^1 \setminus \{0, 1, \infty\}\). We continue studying the manifold \(M = \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\}\), but we now view it as the set of complex points of the variety \(X = \mathbb{P}^1_\mathbb{Q} \setminus \{0, 1, \infty\}\) defined over \(\mathbb{Q}\). Recall from Example 2.260 that the dg-algebra \(A^*\) computes the algebraic de Rham cohomology of \(X\).

3.10.1. Summary of structures. For convenience and to fix notation, we start by summarizing some results of the previous sections.

**Summary 3.397.** Let \(x, y, z \in \{0, 1\} \cup X(\mathbb{Q})\) be base points, tangential or not. We have at our disposal the following structures.

**Betti side:** An affine pro-algebraic scheme over \(\mathbb{Q}\)
\[
y\Pi_B^x = \pi_1(\mathbb{P}^1_\mathbb{Q} \setminus \{0, 1, \infty\}; y, x)^{un},
\]
a pro-\(\mathbb{Q}\)-vector space
\[
yU_B^x = \mathbb{Q}[\pi_1(\mathbb{P}^1_\mathbb{Q} \setminus \{0, 1, \infty\}; y, x)]^\wedge,
\]
the subspace of primitive elements
\[
yL_B^x = \{x \in yU_B^x | \nabla^\vee x = 1 \otimes x + x \otimes 1\},
\]
and an ind-\(\mathbb{Q}\)-algebra
\[
yA_B^x = O(y\Pi_B^x) = (yU_B^x)^\vee.
\]
De Rham side: An affine pro-algebraic scheme over \( \mathbb{Q} \)
\[
y \Pi_x^{dR} = \text{Spec}(\mathcal{F}),
\]
a pro-\( \mathbb{Q} \)-vector space
\[
y U_x^{dR} = \mathbb{Q}\langle e_0, e_1 \rangle,
\]
the subspace of primitive elements
\[
y U_x^{dR} = \{ x \in y U_x^{dR} \mid \nabla^\vee x = 1 \otimes x + x \otimes 1 \},
\]
and an ind-\( \mathbb{Q} \)-algebra
\[
y A_x^{dR} = \mathcal{F}.
\]
Comparison: Comparison isomorphisms
\[
\text{comp}^\Pi_{dR,B}: y \Pi_x^{dR} \times_y \mathbb{C} \tilde{} y \Pi_x^{dR} \times_y \mathbb{C},
\]
\[
\text{comp}^U_{dR,B}: y U_x^{dR} \otimes_y \mathbb{C} \tilde{} y U_x^{dR} \otimes_y \mathbb{C},
\]
\[
\text{comp}^L_{dR,B}: y U_x^{dR} \otimes_y \mathbb{C} \tilde{} y U_x^{dR} \otimes_y \mathbb{C},
\]
\[
\text{comp}^{A,B}_{dR}: y A_x^{dR} \otimes_y \mathbb{C} \tilde{} y A_x^{dR} \otimes_y \mathbb{C}.
\]
All the comparison isomorphisms \( \text{comp}^\bullet_{dR,B} \) are given by the regularized iterated integrals. For instance,
\[
\text{comp}^U_{dR,B}: y U_x^B \longrightarrow y U_x^{dR}
\]
agrees with the map \( L \) of Theorem 3.383.

Additional structures: For \( ? = B, dR \), the pro-algebraic schemes come together with morphisms
\[
\pi^\Pi y \times y \Pi_x^{dR} \longrightarrow z \Pi_x^{dR}
\]
induced from the composition of paths on the Betti side and the coproduct of \( \mathcal{F} \) on the de Rham side. These maps turn \( x \Pi_x^{dR} \) into a pro-unipotent group scheme and \( y \Pi_x^{dR} \) into a right \( x \Pi_x^{dR} \)-torsor and a left \( y \Pi_y \)-torsor.

Therefore, the pro-\( \mathbb{Q} \)-vector spaces come equipped with the following structures:

i) a composition of paths
\[
\Delta^\vee: z U_y^2 \otimes y U_x^2 \longrightarrow z U_x^2;
\]

ii) unit
\[
\eta^\vee: \mathbb{Q} \longrightarrow x U_x^2;
\]

iii) a completed coproduct
\[
\nabla^\vee: y U_x^2 \longrightarrow y U_x^2 \otimes_y U_x^2;
\]

iv) counit
\[
\epsilon^\vee: y U_x^2 \longrightarrow \mathbb{Q};
\]

v) a dual antipode
\[
S^\vee: y U_x^2 \longrightarrow x U_y^2.
\]

And the ind-algebras \( y A_x^{dR} \) come equipped with the dual structures. There additional structures are compatible with all the comparison isomorphisms.

\( ^{2} \text{Recall that } y \Pi_x^B \text{ and } y \Pi_x^{dR} \text{ are affine schemes over } \mathbb{Q}. \text{ Below, the notation } \times_y \mathbb{C} \text{ is a shorthand for } \times_{\text{Spec}(\mathbb{Q})} \text{Spec}(\mathbb{C}). \)
Mixed Hodge structures: Extending the construction of Section 3.7.2 to tangential base points as done in Section 3.8.9, we obtain that the spaces $y U^B_{\mathcal{A}}$ and $y A^B_{\mathcal{A}}$ come equipped with a weight filtration $W$ and the spaces $y U^{dR}_{\mathcal{A}}$ and $y A^{dR}_{\mathcal{A}}$ with a weight filtration $W$ and a Hodge filtration $F$ in such a way that

\[
y^A_{\mathcal{A}} H = ((y A^B_{\mathcal{A}}, W), (y A_{\mathcal{A}}^{dR}, W, F), \text{comp}_{B,dR})\]

is in ind-MHS($\mathbb{Q}$) and

\[
y^U_{\mathcal{A}} H = ((y U^B_{\mathcal{A}}, W), (y U^{dR}_{\mathcal{A}}, W, F), \text{comp}_{dR,B})\]

is in pro-MHS($\mathbb{Q}$).

The filtrations in $y U^B_{\mathcal{A}}$ induce a weight filtration on $y L^B_{\mathcal{A}}$ and weight and Hodge filtrations on $y L^{dR}_{\mathcal{A}}$, so that

\[
y^C_{\mathcal{A}} H = ((y L^B_{\mathcal{A}}, W), (y L^{dR}_{\mathcal{A}}, W, F), \text{comp}_{dR,B})^{-1}\]

is also in pro-MHS($\mathbb{Q}$).

Moreover, it is easy to check that all the previous structures of $y^A_{\mathcal{A}} H$ are morphisms of ind-MHS($\mathbb{Q}$) and the corresponding structures of $y^U_{\mathcal{A}} H$ are morphisms of pro-MHS($\mathbb{Q}$).

Remark 3.399. Observe that the de Rham side on Summary 3.397 is independent of the base points. In fact, there is a canonical de Rham path $y^{1dR}_{\mathcal{A}}$ in $y \Pi^{dR}_{\mathcal{A}}$ (it is the unit element in the affine group scheme $\text{Spec}(\mathcal{H})$ and corresponds to the kernel of the counit $\varepsilon: \mathcal{H} \to \mathbb{Q}$). Therefore, for base points $x$, $y$, and $z$, there are canonical isomorphisms

\[
y \Pi^{dR}_{x} \rightarrow y \Pi^{dR}_{y} \quad \gamma \rightarrow \gamma \cdot y^{1dR}_{x}\]

\[
y \Pi^{dR}_{y} \rightarrow y \Pi^{dR}_{z} \quad \gamma \rightarrow \gamma \cdot y^{1dR}_{z}\]

Since the pro-algebraic scheme $y \Pi^{dR}_{x}$ is independent of the base points, we will suppress them from the notation and we will write $\Pi^{dR} = \text{Spec}(\mathcal{H})$.

For future reference, we detail the structure of the ind-mixed Hodge structure on $y^A_{\mathcal{A}} H$. This result follows directly from Proposition 3.336 and its proof.

Proposition 3.400. The ind-mixed Hodge structure $y^A_{\mathcal{A}} H$ is of Hodge–Tate type. Moreover, the associated grading (Lemma 2.216) on

\[
y^A_{\mathcal{A}}^{dR} = \mathcal{H} = \mathbb{Q} \langle x_0, x_1 \rangle\]

is the multiplicative grading that assigns degree 1 to the elements $x_0$ and $x_1$ and degree 0 to the constants.

Variant 3.401. The same structures are available for other varieties. For instance, everything can be easily generalized to any variety of the form $X' = \mathbb{P}^1 \setminus S$ for $S \subset \mathbb{P}^1(\mathbb{Q})$ a finite set. In this case we will use the notation $y \Pi(X')_{\mathcal{A}}^{B}$ for the pro-algebraic scheme in the Betti side and similar notation for the other structures.
In the sequel, we will only need the case $X' = \mathbb{G}_m$. In this particular case we have

$$
\begin{align*}
y \Pi(\mathbb{G}_m)^{dR}_x &= A^1_0 = \mathbb{G}_a \\
y A(\mathbb{G}_m)^{dR}_x &= \mathbb{Q}[x_0] \\
y U(\mathbb{G}_m)^{dR}_x &= \mathbb{Q}[c_0] \\
y \mathcal{L}(\mathbb{G}_m)^{dR}_x &= \mathbb{Q}c_0
\end{align*}
$$

and the map

$$
\text{comp}^{U'}_{dR,B} : y U(\mathbb{G}_m)^B_x \longrightarrow y U(\mathbb{G}_m)^{dR}_x
$$

will also be denoted by $L$.

3.10.2. The fundamental groupoid and the local monodromy. From now on, we focus our attention on the pro-unipotent group picture $\Pi^y_x$. The reader will have no difficulty writing the analogous statements for $U^y, \mathcal{L}^y$ and $A^y$.

**Definition 3.402.** The diagram consisting of the four schemes

$$
y \Pi^y_x, \quad x, y \in \{0, 1\}
$$

with the composition of paths will be called the **tangential fundamental groupoid** of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$. It is represented schematically in Figure 22.

![Figure 22. The fundamental groupoid](image)

To the tangential fundamental groupoid we want to add the **local monodromy** around 0 and 1.

We start with the local monodromy around 0 in the de Rham side. There is a morphism of Hopf algebras $\mathfrak{F} \rightarrow \mathbb{Q}[x]$ that sends any word containing $x_1$ to zero, and $x_0 n x_0$ to $x^n/n!$. We can see this as a map

$$
o A^{dR}_0 \longrightarrow o A(\mathbb{G}_m)^{dR}_0
$$

that induces maps

$$
\mathbb{G}_a = o \Pi(\mathbb{G}_m)^{dR}_0 \longrightarrow o \Pi^0_{0R}, \quad \text{and} \quad o U(\mathbb{G}_m)^{dR}_0 \longrightarrow o U^{dR}_0.
$$

The local monodromy around 0 in the Betti side is obtained topologically as follows. Let $\Delta^*$ be a small punctured disc around zero in $\mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\}$. The local monodromy is the composition of the inverse of the isomorphism

$$
\pi_1(\Delta^*, 0)^{un} \longrightarrow \pi_1(\mathbb{G}_m, 0)^{un} = \mathbb{G}_a
$$
with the natural map
\[ \pi_1(\Delta^*, 0)^{un} \longrightarrow \pi_1(\mathbb{P}^1 \setminus \{0, 1, \infty\}, 0)^{un}. \]

Similarly, the de Rham side of the local monodromy around 1 is induced by the map of Hopf algebras \( \mathcal{H} \rightarrow \mathbb{Q}[x] \) that sends any word containing \( x_0 \) to zero, and \( x_1 \ldots x_n \) to \( x^n/n! \). While the Betti side is obtained from a small punctured disc around 1.

The local monodromy maps are morphisms of ind-MHS(\( \mathbb{Q} \)) in the case of \( A \) and morphism of pro-MHS(\( \mathbb{Q} \)) in the case of \( U \). This means that the pair of maps
\[
0^A_{0}^{dR} \longrightarrow 0^A(\mathbb{G}_m)^{dR}_{0} \quad 0^A_{0}^{B} \longrightarrow 0^A(\mathbb{G}_m)^{B}_{0}
\]
is a morphism of ind-MHS(\( \mathbb{Q} \))
\[
0^{A}^{H}_{0} \longrightarrow 0^{A}(\mathbb{G}_m)^{H}_{0},
\]
while the pair of maps
\[
0^U(\mathbb{G}_m)^{dR}_{0} \longrightarrow 0^U_{0}^{dR} \quad 0^U(\mathbb{G}_m)^{B}_{0} \longrightarrow 0^U_{0}^{B}
\]
is a morphism of pro-MHS(\( \mathbb{Q} \))
\[
0^{U}(\mathbb{G}_m)^{H}_{0} \longrightarrow 0^{U}_{0}^{H},
\]
and the same is true for the local monodromy maps around 1.

**Definition 3.403.** We will denote by \( D^{dR} \) the diagram consisting of the four schemes \( Y^\Pi^d_{x, y} \), \( x, y \in \{0, 1\} \), the morphisms given by the composition of paths, the scheme \( \mathbb{G}_a \) and the two local monodromies
\[
\mathbb{G}_a \longrightarrow 0^\Pi^d_{0}, \quad \mathbb{G}_a \longrightarrow 1^\Pi^d_{1}. 
\]
Similarly, we write \( D^{dR}_A \) and \( D^{dR}_U \) for the corresponding diagram for the vector spaces \( U \) and the algebras \( A \) together with all the additional structures discussed in Summary 3.397. That is, the unit, counit, product, completed coproduct and dual antipode for \( U \) and the dual structures for \( A \). Similarly, we will denote \( D^{B}_U \) for the corresponding diagrams on the Betti side. Finally we will denote \( D^{H}_{U} \) for the pair of diagrams \( D^{B}_U \) and \( D^{dR}_U \) together as a diagram of pro-MHS(\( \mathbb{Q} \)).

We will see in chapter 4.5 that the diagram \( D^{H}_{U} \) is “motivic”.

### 3.10.3. The automorphisms of \( D^{dR} \).

We denote by \( \text{Aut}(D^{dR}) \) the group of automorphisms of \( D^{dR} \) in the following sense: to give an element of \( \text{Aut}(D^{dR}) \) amounts to giving an automorphism of pro-algebraic schemes of each \( Y^\Pi^d_{x, y} \) and an automorphism of \( \mathbb{G}_a \) that are compatible with the composition of paths (3.398) and the local monodromy maps. The group \( \text{Aut}(D^{dR}) \) is a pro-algebraic group.

Similarly, we denote by \( \text{Aut}(D^{dR}_U) \) the automorphisms of the diagram \( D^{dR}_U \) compatible with all the structures. Since the diagrams \( D^{dR} \) and \( D^{dR}_U \) determine each other, there is a canonical identification between \( \text{Aut}(D^{dR}_U) \) and \( \text{Aut}(D^{dR}) \). Hence we will work only with the latter. We denote by \( \text{Aut}^0(D^{dR}) \) the subgroup of \( \text{Aut}(D^{dR}) \) that acts as the identity on \( \mathbb{G}_a \). There is an exact sequence
\[
0 \longrightarrow \text{Aut}^0(D^{dR}) \longrightarrow \text{Aut}(D^{dR}) \longrightarrow \mathbb{G}_m \longrightarrow 0.
\]
Using the tools from the next sections, one can show that the group \( \text{Aut}^0(D^{dR}) \) is pro-unipotent (Exercise 3.424).
Lemma 3.404. There is an isomorphism of schemes
\[ \text{Aut}^0(D^{dR}) \rightarrow \mathcal{O}_{\Pi_0}^{dR} \]
\[ f \mapsto \gamma_f, \]
where \( \gamma_f \) is determined by the equation
\[ f(1_0^{dR}) = 1_0^{dR} \cdot \gamma_f. \]

**Proof.** Recall that the dual of \( \mathcal{H} \), that agrees with the completed universal enveloping algebra of \( \text{Lie}(\mathcal{O}_{\Pi_0}^{dR}) \), is the algebra \( \mathbb{Q}[e_0,e_1] \). Let \( R \) be a \( \mathbb{Q} \)-algebra. The elements of \( \mathcal{O}_{\Pi_0}^{dR}(R) \) are the group-like elements of \( R[e_0,e_1] \). Moreover, we have identities
\[ \mathcal{O}_{\Pi_0}^{dR}(R) = \mathcal{O}_{\Pi_0}^{dR}(R), \]
\[ \mathcal{O}_{\Pi_1}^{dR}(R) = \mathcal{O}_{\Pi_0}^{dR}(R) \cdot \mathcal{O}_{1}^{dR}, \]
\[ \mathcal{O}_{\Pi_0}^{dR}(R) = \mathcal{O}_{1}^{dR} \cdot \mathcal{O}_{\Pi_0}^{dR}(R) \cdot \mathcal{O}_{1}^{dR}. \]

Let \( f \in \text{Aut}^0(D^{dR})(R) \). Since \( f \) is the identity on \( \mathbb{G}_a \), we deduce the equalities
\[ f(\exp(e_0)) = \exp(e_0), \]
\[ f(1_0^{dR} \cdot \exp(e_1) \cdot 0_1^{dR}) = 1_0^{dR} \cdot \exp(e_1) \cdot 0_1^{dR}. \]
We also have \( f_0^{dR}(R) = \mathcal{O}_{0_0}^{dR} \) and \( 0_1^{dR} \cdot 1_0^{dR} = 0_1^{dR} \). Therefore, the fact that \( f \) is compatible with the composition of paths implies that it is determined by the image of \( 1_0^{dR} \). We write
\[ f(1_0^{dR}) = 1_0^{dR} \cdot \gamma_f \]
for an element \( \gamma_f \in \mathcal{O}_{\Pi_0}^{dR}(R) \subset R[e_0,e_1] \).

Conversely, let \( \gamma \in \mathcal{O}_{\Pi_0}^{dR}(R) = \text{Spec}(\mathcal{H})(R) \). It is a group-like element of the algebra \( R[e_0,e_1] \). To give an element of \( \text{Aut}(\mathcal{O}_{\Pi_0}^{dR})(R) \) is equivalent to give a continuous automorphism of \( R[e_0,e_1] \) that is compatible with the completed coproduct and the antipode. We define
\[ f_\gamma(e_0) = e_0, \quad f_\gamma(e_1) = \gamma^{-1} \cdot e_1 \cdot \gamma. \]
This determines a continuous automorphism of \( R[e_0,e_1] \). To show that it is compatible with the completed coproduct, it is enough to check it for the generator \( e_1 \).

On the one hand,
\[ f_\gamma(\nabla^\vee(e_1)) = f_\gamma(1 \otimes e_1 + e_1 \otimes 1) \]
\[ = 1 \otimes (\gamma^{-1} \cdot e_1 \cdot \gamma) + (\gamma^{-1} \cdot e_1 \cdot \gamma) \otimes 1. \]
On the other hand, using that \( \gamma \) is group-like,
\[ \nabla^\vee(f_\gamma(e_1)) = \nabla^\vee(\gamma^{-1} \cdot e_1 \cdot \gamma) \]
\[ = \gamma^{-1} \otimes \gamma^{-1} \cdot (1 \otimes e_1 + e_1 \otimes 1) \cdot \gamma \otimes \gamma \]
\[ = 1 \otimes (\gamma^{-1} \cdot e_1 \cdot \gamma) + (\gamma^{-1} \cdot e_1 \cdot \gamma) \otimes 1. \]
The fact that \( f_\gamma \) is compatible with the dual antipode follows from the fact that, by Lemma 3.228, since \( \gamma \) is group-like, then \( S^\vee(\gamma) = \gamma^{-1} \).

To sum up, \( f_\gamma \) determines an element of \( \text{Aut}(\mathcal{O}_{\Pi_0}^{dR})(R) \), still denoted by \( f_\gamma \).

Writing
\[ f_\gamma(1_0^{dR}) = 1_0^{dR} \cdot \gamma, \quad f_\gamma(0_1^{dR}) = \gamma^{-1} \cdot 0_1^{dR}. \]
and using the identities (3.405), we obtain \( R \)-automorphisms of the schemes \( \Pi^dR \) for \( x, y \in \{0, 1\} \). By construction, these automorphisms are compatible with the composition of paths. Moreover, they are compatible with the identity automorphism of \( G_a \) through any of the two local monodromies. They thus define an element \( f_\gamma \in \text{Aut}^0(D^dR)(R) \).

Clearly, the assignments \( f \mapsto \gamma f \) and \( \gamma \mapsto f_\gamma \) are inverse to each other, and this concludes the proof of the lemma. \( \square \)

3.10.4. A new product structure. The isomorphism of schemes of Lemma 3.404 is not a morphism of groups. Therefore, it induces a new group structure on \( \text{Spec}(\mathcal{O}) \).

**Definition 3.407.** We denote by \( (\Pi, \circ) \) the scheme \( \Pi = \text{Spec}(\mathcal{O}) \) with the product structure induced by the isomorphism of Lemma 3.404.

Since, as schemes \( \Pi = \Pi^dR = \Pi^dR_0 \) but with a different product structure, we obtain a new Lie bracket on the Lie algebra of \( \Pi \) which is still the set of Lie-like elements of \( \mathcal{Q} \langle e_0, e_1 \rangle \) that is called the *Ihara bracket* and a new coproduct on \( \mathcal{O} = \mathcal{Q} \langle x_0, x_1 \rangle \) that is called the *Goncharov coproduct*. We now make all these structures explicit.

We start by computing the new product \( \circ \) of \( \Pi \). This product is determined by the equation

\[
\gamma \circ \mu = \gamma \cdot \langle \gamma \rangle_0(\mu).
\]

Given a group-like element \( \gamma \), we write \( \langle \gamma \rangle_0 \) for the restriction of \( f_\gamma \) to \( \Pi^dR_0 \), as well as for the corresponding continuous automorphism of \( \mathcal{Q} \langle e_0, e_1 \rangle \). According to equation (3.406), it is given by

\[
\langle \gamma \rangle_0(e_0) = e_0, \quad \langle \gamma \rangle_0(e_1) = \gamma^{-1} \cdot e_1 \cdot \gamma.
\]

Since \( f_\gamma \) is compatible with the composition of paths, then

\[
f_\gamma(f_\mu(1^dR_0)) = f_\gamma(1^dR_0 \cdot \mu) = f_\gamma(1^dR_0) \cdot f_\gamma(\mu) = 1^dR_0 \cdot \gamma \cdot \langle \gamma \rangle_0(\mu),
\]

and hence

\[
\gamma \circ \mu = \gamma \cdot \langle \gamma \rangle_0(\mu).
\]

3.10.5. *The Ihara bracket.* We now compute the new bracket induced on the set of primitive elements of \( \mathcal{Q} \langle e_0, e_1 \rangle \). Recall the notion of derivation from Definition 2.64. Given a primitive element \( x \in \mathcal{Q} \langle e_0, e_1 \rangle \), consider the derivation

\[
\partial_x : \mathcal{Q} \langle e_0, e_1 \rangle \longrightarrow \mathcal{Q} \langle e_0, e_1 \rangle
y \mapsto \partial_x(y) = \frac{d}{dt} \left( (\exp(tx)) y \right) \bigg|_{t=0}.
\]

Explicitly, this derivation is determined by

\[
\partial_x e_0 = 0, \quad \partial_x e_1 = -x \cdot e_1 + e_1 \cdot x
\]

and the continuity of the map \( \partial_x \), which allows for its computation term by term. Let \( x \) and \( y \) be primitive elements of \( \mathcal{Q} \langle e_0, e_1 \rangle \). We denote by

\[
[x, y] = x \cdot y - y \cdot x
\]
the Lie bracket corresponding to the composition of paths. The Lie bracket induced by $\circ$ will be denoted by $\{x, y\}$. It is determined by the equality
\[
\{x, y\} = \frac{d}{du} \frac{d}{dv} \left( \exp(ux) \circ \exp(vy) \circ \exp(-ux) \circ \exp(-vy) \right) \bigg|_{u=v=0}
\]
Explicitly, it is given by the formula
\begin{equation}
\{x, y\} = [x, y] + \partial_x y - \partial_y x.
\end{equation}

3.10.6. The Goncharov coproduct. We now turn to the computation of the coproduct on the algebra $H$.\(^{(3.411)}\)

Following Notation 3.372, if $\alpha$ is a binary sequence, we will write $x_\alpha \in \mathcal{H}$ for the corresponding word in the alphabet $\{x_0, x_1\}$, and $e_\alpha \in \mathcal{H}^\vee = \mathbb{Q}\langle e_0, e_1 \rangle$ for the corresponding word in the alphabet $\{e_0, e_1\}$. As a function $x_\alpha \in \mathcal{H} = \mathcal{O}(\Pi)$, the word $x_\alpha$ sends a group-like element of $\mathbb{Q}\langle e_0, e_1 \rangle$ to the coefficient of the word $e_\alpha$.

Recall that, by Lemma 3.228, the dual antipode of a group-like element $\gamma$ is given by $S^\vee(\gamma) = \gamma^{-1}$, while for a word $w = e_{\varepsilon_1} \ldots e_{\varepsilon_n}$ the dual antipode is given in Example 3.71 by
\[
S^\vee(w) = w^* = (-1)^{n} e_{\varepsilon_n} \ldots e_{\varepsilon_1}.
\]
We deduce that, if $\gamma = \sum_{w} \gamma_w w$ is a group-like element, then
\begin{equation}
\gamma^{-1} = \sum_{w} \gamma_w w^*.
\end{equation}

The Goncharov coproduct, denoted by $\Delta^\Gamma$, is the coproduct induced in $\mathcal{H}$ by the product $\circ$ and is determined by the equation
\begin{equation}
\Delta^\Gamma(x)(\gamma \otimes \mu) = x(\gamma \circ \mu) = x(\gamma \cdot \langle \gamma \rangle_0(\mu)).
\end{equation}

Note that the product $\circ$ can be defined, for a group-like element $\gamma$ and an arbitrary element $e \in \mathbb{Q}\langle e_0, e_1 \rangle$ by
\begin{equation}
\gamma \circ e = \gamma \cdot \langle \gamma \rangle_0(e).
\end{equation}

This product is linear in the variable $e$. Using the explicit description (3.408) we see that, for a word $w$ in the alphabet $\{e_0, e_1\}$, the product $\gamma \circ w$ is described as follows:

i) if the word $w$ starts with $e_0$ add $\gamma$ at the beginning, while if the word starts with $e_1$ add nothing at the beginning;

ii) if the word ends with $e_1$ add $\gamma$ at the end, while if the word ends with $e_0$ add nothing at the end;

iii) between $e_0$ and $e_1$ insert $\gamma^{-1}$ and between $e_1$ and $e_0$ insert $\gamma$;

iv) between two consecutive occurrences of $e_0$ or two consecutive occurrences of $e_1$ insert nothing.

For instance,
\[
\gamma \circ (e_0 e_0 e_1 e_0 e_1 e_1) = \gamma e_0 e_0 \gamma^{-1} e_1 \gamma e_0 \gamma^{-1} e_1 e_1 \gamma.
\]

To give a more compact description of this product, we introduce the notation
\[
\gamma_0 = \gamma, \quad 0 \gamma_1 = \gamma^{-1}, \quad 0 \gamma_0 = 1, \quad 1 \gamma_1 = 1.
\]

For a binary sequence $\alpha = (\varepsilon_1, \ldots, \varepsilon_n)$, we have
\begin{equation}
\gamma \circ e_\alpha = 1 \gamma_{\varepsilon_1} \cdot e_{\varepsilon_1} \cdot e_{\varepsilon_2} \cdot e_{\varepsilon_3} \cdot \ldots \cdot e_{\varepsilon_n} \cdot e_{\varepsilon_n} \gamma_0.
\end{equation}
Given the shape (3.415) of the product \( \circ \) and the inversion formula (3.412), for any binary sequence \( \alpha \), we introduce the following symbols:

\[
\begin{align*}
I(1; \alpha; 0) &= x_\alpha, \\
I(0; \alpha; 1) &= x_\alpha^*, \\
I(0; \alpha; 0) &= I(1; \alpha; 1) = 1, \text{ if } \alpha = \emptyset, \\
I(0; \alpha; 0) &= I(1; \alpha; 1) = 0, \text{ if } \alpha \neq \emptyset.
\end{align*}
\]

All of them are elements of \( H \), and hence functions on \( \Pi \). Then, for a binary sequence \( \alpha \), a group-like element \( \gamma \in \Pi(\mathbb{Q}) \) and elements \( \varepsilon, \varepsilon' \in \{0, 1\} \), we have the duality

\[
(3.417) \quad x_\alpha(\varepsilon'; \alpha; \varepsilon) = I(\varepsilon'; \alpha; \varepsilon)(\gamma).
\]

Armed with this notation, we can compute Goncharov’s coproduct. Let \( \alpha \) be a binary sequence and \( \gamma, \mu \) group-like elements of \( \mathbb{Q} \langle e_0, e_1 \rangle \). Write \( \mu = \sum_w \mu_w w \). Then, by equation (3.413),

\[
(\Delta^\Gamma x_\alpha)(\gamma \otimes \mu) = x_\alpha(\gamma \circ \mu)
= x_\alpha\left( \sum_w \mu_w (\gamma \circ w) \right)
= x_\alpha\left[ \sum_w \mu_w (1_{\gamma_{e_1}(w)} \cdot e_{\varepsilon_1(w)} \cdot \ldots \cdot e_{\varepsilon_{\text{wt}(w)}(w)} \cdot \gamma_0) \right],
\]

where \( \text{wt}(w) \) denotes the weight of \( w \) as in Definition 1.131, and \( \varepsilon_i(w) \) is defined to be 0 or 1 depending whether the \( i \)-th letter appearing in \( w \) is \( e_0 \) or \( e_1 \). Let us write \( \alpha = \varepsilon_1 \cdots \varepsilon_n \) and set \( \varepsilon_0 = 1 \) and \( \varepsilon_{n+1} = 0 \).

We need to compute the coefficient of the word \( e_\alpha \) in the above bracketed expression. We will get a contribution for each subword of \( e_\alpha \) corresponding to a binary subsequence \( \varepsilon_{i_1} \cdots \varepsilon_{i_k} \) of \( \alpha \). It is easy to see that the coefficient we are looking for is given by:

\[
\sum_{0 = i_0 < i_1 < \ldots < i_k < i_{k+1} = n+1} I(\varepsilon_0; \varepsilon_{i_1} \cdots \varepsilon_{i_k}; \varepsilon_{n+1})(\mu) \prod_{p=0}^{k} I(\varepsilon_{i_p}; \varepsilon_{i_p+1} \cdots \varepsilon_{i_{p+1} - 1}; \varepsilon_{i_{p+1}})(\gamma).
\]

The upshot of these computations is the following result, which was first obtained by Goncharov [Gon05, Thm. 1.2].

**Proposition 3.418.** Let \( \varepsilon_0 \cdots \varepsilon_{n+1} \) be a binary sequence. By transport of structure, the isomorphism of Lemma 3.404 induces the coproduct

\[
\Delta^\Gamma I(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_n; \varepsilon_{n+1}) = 
\sum_{0 = i_0 < i_1 < \ldots < i_k < i_{k+1} = n+1} \prod_{p=0}^{k} I(\varepsilon_{i_p}; \varepsilon_{i_p+1} \cdots \varepsilon_{i_{p+1} - 1}; \varepsilon_{i_{p+1}}) \otimes I(\varepsilon_0; \varepsilon_{i_1} \cdots \varepsilon_{i_k}; \varepsilon_{n+1})
\]

on the Hoffman algebra \( \mathcal{H} \).

**Proof.** The case \( \varepsilon_0 = 1 \) and \( \varepsilon_{n+1} = 0 \) was settled above. The other cases follow immediately from (3.416). \[\square\]
Example 3.419. If $n = 1$, the formula specializes to
\[
\Delta^\Gamma I(\varepsilon_0; \varepsilon_1; \varepsilon_2) = I(\varepsilon_0; \varepsilon_1; \varepsilon_2) \otimes I(\varepsilon_0; \varepsilon_2) + I(\varepsilon_0; \varepsilon_1)I(\varepsilon_1; \varepsilon_2) \otimes I(\varepsilon_0; \varepsilon_1; \varepsilon_2)
\]
Indeed, $I(\varepsilon'; \varepsilon)$ is always equal to 1 regardless of the values of $\varepsilon$ and $\varepsilon'$.

Example 3.420. If $n = 2$, we get contributions from $k = 0, 1, 2$. As before, the term indexed by $k = 0$ corresponds to the choice of the empty subsequence and gives the value $I(\varepsilon_0; \varepsilon_1\varepsilon_2; \varepsilon_3) \otimes 1$, whereas $k = 2$ represents the choice of the whole sequence and contributes with $1 \otimes I(\varepsilon_0; \varepsilon_1\varepsilon_2; \varepsilon_3)$. For $k = 1$ we obtain two terms, corresponding to $i_1 = 1$ and $i_1 = 2$. In both cases, the product contains only one non-trivial factor ($p = 1$ if $i_1 = 1$ and $p = 0$ if $i_1 = 2$). Putting everything together,
\[
\Delta^\Gamma I(\varepsilon_0; \varepsilon_1\varepsilon_2; \varepsilon_3) = I(\varepsilon_0; \varepsilon_1\varepsilon_2; \varepsilon_3) \otimes 1
+ I(\varepsilon_1; \varepsilon_2; \varepsilon_3) \otimes I(\varepsilon_0; \varepsilon_1; \varepsilon_3)
+ I(\varepsilon_0; \varepsilon_1; \varepsilon_2) \otimes I(\varepsilon_0; \varepsilon_2; \varepsilon_3)
+ 1 \otimes I(\varepsilon_0; \varepsilon_1\varepsilon_2; \varepsilon_3).
\]
(3.421)

Specializing formula (3.421) to the cases $(1; 1, 0, 0)$ and $(1; 0, 1, 0)$, we get
\[
\Delta^\Gamma(x_0x_1) = x_0x_1 \otimes 1 + x_0 \otimes x_1 + x_1 \otimes x_0 + 1 \otimes x_0x_1,
\]
\[
\Delta^\Gamma(x_1x_0) = x_1x_0 \otimes 1 + 1 \otimes x_1x_0.
\]
Just for fun, let us verify the compatibility with shuffle product. On the one hand,
\[
\Delta^\Gamma(x_0 \shuffle x_1)
= \Delta^\Gamma(x_0x_1 + x_1x_0)
= (x_0x_1 + x_1x_0) \otimes 1 + 1 \otimes (x_0x_1 + x_1x_0) + x_0 \otimes x_1 + x_1 \otimes x_0.
\]
On the other hand,
\[
(\Delta^\Gamma x_1) \shuffle (\Delta^\Gamma x_2)
= (1 \otimes x_0 + x_0 \otimes 1) \shuffle (1 \otimes x_1 + x_1 \otimes 1)
= 1 \otimes (x_0 \shuffle x_1) + x_0 \otimes x_1 + x_0 \otimes x_1 + (x_0 \shuffle x_1) \otimes 1,
\]
and we see that the expressions are equal.

As the previous examples show, the formula for Goncharov’s coproduct in Proposition 3.418 contains many trivial factors. Later in Chapter 5 we will give a linearization which is more suitable for computation.

***


Exercise 3.423. Calculate the number of terms appearing in Goncharov’s coproduct.

Exercise 3.424. The goal of this exercise is to prove that the group $\text{Aut}^0(D_{\text{DR}})$ is pro-unipotent.
i) Let $\circ$ denote the product on $\mathcal{H}^\vee = \mathbb{Q}\langle e_0, e_1 \rangle$ induced by the Goncharov coproduct on $\mathcal{H}$. Prove the inequality
\[
\text{length}(a \circ b) \geq \text{length}(a) + \text{length}(b).
\]
ii) Let $C^i$ be the conilpotency filtration of the algebra $\mathcal{H}$. Prove that $C^i$ contains all the monomials of length less than $i$.

iii) Use Proposition 3.153 to conclude that $\text{Aut}^0(D_{\text{dR}})$ is pro-unipotent.

Exercise 3.425. Prove that the derivation $\partial_x$ from (3.410) is continuous, with respect to the natural topology on $\mathbb{Q}\langle e_0, e_1 \rangle$. 
4. Mixed Tate motives

The ultimate goal of this chapter is to give a precise meaning to the statement that the diagram $D^H_U$ from Definition 3.403 has motivic origin. This will keep us busy for a while. We start with the definition of tannakian category in Section 4.1. This notion is an abstraction of the properties of the category of $k$-linear representations of a group together with the forgetful functor to vector spaces. The main theorem of the theory is then that each tannakian category is indeed the category of representations of an affine group scheme. This is very useful in cases where this is not obvious a priori, for it allows one to see objects as representations and translate categorical properties into properties of the group. We give some examples. One of Grothendieck’s motivations to develop the theory of tannakian categories was to study motives, which were envisioned by him as a universal cohomology theory for algebraic varieties. Ideally, a category of motives should be a tannakian category equipped with a Betti realization functor in which Hom groups are obtained from algebraic cycles. In Section 4.2, we sketch the construction of Voevodsky’s triangulated category of motives, which is a candidate for the derived category of motives. We explain how to compute Hom groups in this category in terms of K-theory and how the Hodge realization to the derived category of mixed Hodge structures works. It is expected that there exists a $t$-structure on $\text{DM}(k)$ whose heart yields the sought after category of motives. As we explain in Section 4.3, at the time of writing, it is only known how to do that when $k$ is a number field and $\text{DM}(k)$ is replaced by the subcategory consisting of iterated extensions of the simplest objects $\mathbb{Q}(n)$. This yields the abelian category of mixed Tate motives over $k$. The construction relies on Borel’s computation of the $K$-theory of number fields. We introduce the $t$-structure constructed by Levine and prove that the Hodge realization functor is fully faithful. The rest of the chapter deals with $k = \mathbb{Q}$. For certain purposes, the category $\text{MT}(\mathbb{Q})$ is still too big. In Section 4.4, we introduce a subcategory $\text{MT}(\mathbb{Z})$ of mixed Tate motives over $\mathbb{Z}$, which has the advantage that all extension groups are finite-dimensional. It is a tannakian category endowed with two fiber functors Betti and de Rham. We determine the structure of the associated tannakian group: it is a semidirect product of $\mathbb{G}_m$ and a pro-unipotent group whose graded Lie algebra is free with one generator in each negative odd degree $\leq -3$. We also explain the torsor of motivic periods. In Section 4.5, we construct after Deligne a Goncharov a pro-mixed Tate motive over $\mathbb{Z}$ that contains all multiple zeta values among its periods and whose Hodge realization is the fundamental groupoid of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$ from Chapter 3. As a pro-object of the category $\text{MT}(\mathbb{Z})$, this motivic fundamental groupoid is acted upon by the tannakian fundamental group. The structure of this representation will yield the additional structures that are used in the only proofs known so far of Theorem A and Theorem B about multiple zeta values. A remarkable side effect is that this object generates the whole category.

4.1. Tannakian formalism. The link between mixed Tate motives and multiple zeta values is made through the group of symmetries of mixed Tate motives. To make this idea precise we need the formalism of tannakian categories that we summarize in this section.
The Galois group of a field extension is one of the basic tools in arithmetic and one of its more studied objects. In topology, the fundamental group of a topological space is the analogue of the absolute Galois group of a field and is one of the basic invariants of a topological space. Fueled by the utility of the Galois and fundamental groups it is natural to seek for analogues in other situations. The tannakian formalism is the basic tool to define analogues of the Galois group in many algebro-geometric situations. The origin of this formalism is Pontryagin duality, according to which a locally compact abelian group is characterized by its character group, and the Tannaka-Krein duality that states that we can recover a compact Lie group from the category of its continuous finite-dimensional real representations. Grothendieck extended the Tannaka-Krein duality to affine algebraic groups. Saavedra-Rivano [SR72] encoded the properties of the category of finite-dimensional linear representations of an algebraic group in the concept of a tannakian category. Thus, by construction, the category of finite-dimensional linear representations of an algebraic group is a tannakian category. The fundamental result of the theory of tannakian categories is the converse: every tannakian category is isomorphic to the category of finite-dimensional linear representations of a pro-algebraic group.

Note that the formalism of tannakian categories is tailored to the study of affine group schemes. Thus, we will not recover the “true” fundamental group of a topological space nor the Galois group of a field extension with this formalism, but only its so called pro-algebraic envelope.

We will follow the exposition in [DM82], to which the reader is referred for further details. Throughout this section we fix a field $k$ (of any characteristic), that will play the role of field of coefficients.

4.1.1. Tensor categories. The definition of tannakian category gathers the characteristic properties of finite-dimensional $k$-linear representations of affine group schemes, as introduced in Section 3.2.13. First of all, since morphisms between $k$-linear representations form a vector space, we need the concept of $k$-linear category.

**Definition 4.1.** A $k$-linear category $C$ is an additive category in which the groups $\text{Hom}_C(X, Y)$ are $k$-vector spaces for all objects $X, Y \in \text{Ob}(C)$ and the composition maps are bilinear.

The tensor product of two representations is again a representation. Therefore, a tannakian category should have a tensor product, which is a bilinear functor with some additional properties. Recall that the product category $C \times C$ has objects the pairs of objects of $C$ and morphisms

$$\text{Hom}_{C \times C}((X, Y), (X', Y')) = \text{Hom}_C(X, X') \times \text{Hom}_C(X', Y').$$

for all objects $X, Y, X', Y' \in \text{Ob}(C)$. A functor $F: C \times C \rightarrow C$ is said to be bilinear if

$$\text{Hom}_C(X, X') \rightarrow \text{Hom}_C(X', Y') \rightarrow \text{Hom}_C(F(X, Y), F(X', Y'))$$

is a bilinear map of $k$-vector spaces.

**Definition 4.2.** Let $C$ be a $k$-linear category, together with a bilinear functor

$$\otimes: C \times C \rightarrow C.$$

i) An associativity constraint for $(C, \otimes)$ is a natural transformation

$$\phi = \phi_{\cdot, \cdot, \cdot}: (\cdot \otimes (\cdot \otimes \cdot)) \rightarrow ((\cdot \otimes \cdot) \otimes \cdot)$$

such that the following two conditions hold:
a) For all $X, Y, Z \in \text{Ob}(\mathcal{C})$, the map $\phi_{X,Y,Z}$ is an isomorphism.

b) (Pentagon axiom) For all $X, Y, Z, T \in \text{Ob}(\mathcal{C})$, the following diagram commutes:

\[
\begin{array}{ccc}
X \otimes (Y \otimes (Z \otimes T)) & \xrightarrow{\phi_{X,Y,Z,T}} & (X \otimes Y) \otimes (Z \otimes T) \\
\downarrow & & \downarrow \\
X \otimes ((Y \otimes Z) \otimes T) & \xrightarrow{\phi_{X,Y,Z,T} \otimes \text{Id}} & ((X \otimes Y) \otimes Z) \otimes T
\end{array}
\]

ii) A commutativity constraint is a natural transformation

\[\psi = \psi_{\ast, \ast} : \ast \otimes \ast \longrightarrow \ast \otimes \ast\]

such that, for all objects $X, Y \in \text{Ob}(\mathcal{C})$, the map $\psi_{X,Y}$ is an isomorphism, and the composition

\[\psi_{Y,X} \circ \psi_{X,Y} : X \otimes Y \longrightarrow X \otimes Y\]

is equal to the identity.

iii) An associativity and a commutativity constraint are said to be compatible with each other if, for all objects $X, Y, Z \in \text{Ob}(\mathcal{C})$, the following diagram commutes (hexagon axiom):

\[
\begin{array}{ccc}
X \otimes (Y \otimes Z) & \xrightarrow{\phi_{X,Y,Z}} & (X \otimes Y) \otimes Z \\
\downarrow & & \downarrow \\
X \otimes (Z \otimes Y) & \xrightarrow{\phi_{X,Z,Y}} & Z \otimes (X \otimes Y)
\end{array}
\]

iv) Finally, we say that a pair $(U, u)$ consisting of an object $U$ of $\mathcal{C}$ and an isomorphism $u : U \rightarrow U \otimes U$ is an identity object if the functors

\[X \mapsto U \otimes X \text{ and } X \mapsto X \otimes U\]

are equivalences of categories.

We now have all the ingredients to define tensor categories, which are one of the underlying structures of tannakian categories.

**Definition 4.3.** A $k$-linear tensor category is a tuple $(\mathcal{C}, \otimes, \phi, \psi)$ consisting of a $k$-linear category $\mathcal{C}$, a bilinear functor $\otimes : \mathcal{C} \times \mathcal{C} \rightarrow \mathcal{C}$, and compatible associativity and commutativity constraints $\phi$ and $\psi$, such that $\mathcal{C}$ contains an identity object.

The constraints $\phi$ and $\psi$ are usually omitted from the notation, and one simply writes a $k$-linear tensor category by $(\mathcal{C}, \otimes)$. 
Remark 4.4. Let \((U, u)\) be a unit object. For each object \(X\) of \(C\), there are canonical isomorphisms
\[
\alpha^U_X : X \xrightarrow{\sim} X \otimes U \quad \text{and} \quad \beta^U_X : U \otimes X \xrightarrow{\sim} X
\]
that are functorial on \(X\). Indeed, since \(X \mapsto X \otimes U\) is an equivalence of categories, the map \(\text{Hom}(X, X \otimes U) \to \text{Hom}(X \otimes U, X \otimes U \otimes U)\) is a bijection, and one defines \(\alpha^U_X\) as the preimage of \(\text{Id}_X \otimes u\). Similarly, \(\beta^U_X\) is the preimage of \(u^{-1} \otimes \text{Id}_X\) under the bijection \(\text{Hom}(U \otimes X, X) \to \text{Hom}(U \otimes U \otimes X, U \otimes X)\).

It follows that two identity objects of \(C\) are canonically isomorphic: given identity objects \((U, u)\) and \((U', u')\), the morphism \(\beta^U_{U'} \circ \alpha^{U'}_U : U \to U\) is an isomorphism, and is the unique morphism \(f : U \to U'\) making the diagram
\[
\begin{array}{ccc}
U & \xrightarrow{f} & U' \\
\downarrow u & & \downarrow u' \\
U \otimes U & \xrightarrow{f \otimes f} & U' \otimes U'
\end{array}
\]
From now on, we will fix an identity object and denote it by \((1, e)\).

Definition 4.5. An object \(L\) in \(C\) is called invertible if the functor \(X \mapsto L \otimes X\) is an equivalence of categories.

One easily shows that an object \(L\) is invertible if and only if there exists an object \(L'\) such that \(L \otimes L' \simeq 1\). Then \(L'\) is also invertible.

4.1.2. Rigid categories. The set of \(k\)-linear maps between two representations is again a representation and, in particular, a representation on a vector space induces a representation on the dual vector space. Thus, a tannakian category should contain internal Hom’s and duals.

Let \((C, \otimes)\) be a tensor category and let \(X, Y \in \text{Ob}(C)\) be two objects. We say that the functor \(T \mapsto \text{Hom}(T \otimes X, Y)\) is representable if there exist an object \(Z \in \text{Ob}(C)\) such that there are functorial isomorphisms
\[
(4.6) \quad \text{Hom}(T, Z) \longrightarrow \text{Hom}(T \otimes X, Y)
\]
for all \(T \in \text{Ob}(C)\). If this is the case, we denote \(Z\) by \(\text{Hom}(X, Y)\) and we call it internal Hom between the objects \(X\) and \(Y\). Note that any two such objects \(Z\) are related by a unique compatible isomorphism.

Taking \(T = \text{Hom}(X, Y)\) in (4.6), the image of the identity \(\text{Id}_{\text{Hom}(X, Y)}\) is a morphism which will be denoted by
\[
\text{ev}_{X, Y} : \text{Hom}(X, Y) \otimes X \longrightarrow Y.
\]

The dual of an object \(X\) is defined as \(X^\vee = \text{Hom}(X, 1)\). If \(X^\vee\) and \((X^\vee)^\vee\) exist, there is a natural morphism \(X \mapsto (X^\vee)^\vee\). We say that \(X\) is reflexive if this morphism is an isomorphism.

Example 4.7. In the category of groups, \(\mathbb{Z}/2\) is not reflexive since its dual is the trivial group. In the category of vector spaces, finite-dimensional vector spaces are reflexive, whereas infinite-dimensional ones are not.

Definition 4.8. A \(k\)-linear tensor category is said to be rigid if
i) \(\text{Hom}(X, Y)\) exists for all \(X, Y \in \text{Ob}(C)\);
for all $X_1, X_2, Y_1, Y_2 \in \text{Ob}(C)$, the natural morphism

$$\text{Hom}(X_1, Y_1) \otimes \text{Hom}(X_2, Y_2) \to \text{Hom}(X_1 \otimes X_2, Y_1 \otimes Y_2)$$

is an isomorphism;

iii) all objects of $C$ are reflexive.

4.1.3. **Neutral tannakian categories.** The category of finite-dimensional $k$-linear representations $\text{Rep}_k(G)$ of an algebraic group $G$ over $k$ has other relevant properties. First, it is an abelian category. Second, the one-dimensional representation given by the vector space $k$ with trivial $G$-action is an identity object $1$ that satisfies $\text{End}(1) = k$. Finally, the forgetful functor from $\text{Rep}_k(G)$ to the category of finite-dimensional vector spaces $\text{Vec}_k$ that consists in forgetting the action of $G$ is exact, faithful and compatible with the tensor structure on both categories. These will turn out to be all the necessary ingredients to identify the categories of finite-dimensional representations of algebraic groups.

**Definition 4.9.** A neutral tannakian category over $k$ is a rigid $k$-linear abelian tensor category $C$ such that $\text{End}(1) = k$ and there exists an exact faithful $k$-linear tensor functor $\omega: C \to \text{Vec}_k$. Any such functor is called a fiber functor.

Since we shall never consider non-neutral tannakian categories in the sequel, we will just refer to them as “tannakian categories”.

**Examples 4.10.**

i) The category $\text{Vec}_k$ of finite-dimensional vector spaces over $k$, together with the identity functor, is a tannakian category.

ii) Let $\text{GrVec}_k$ be the category of finite-dimensional graded vector spaces over $k$. Its objects are finite-dimensional $k$-vector spaces $V$ equipped with a direct sum decomposition $V = \bigoplus_{n \in \mathbb{Z}} V_n$, and the morphisms are $k$-linear maps $f: V \to W$ that are compatible with the grading in that $f(V_n) \subseteq W_n$ for all $n \in \mathbb{Z}$. The tensor structure comes from the tensor product of vector spaces, graded by

$$(V \otimes W)_n = \bigoplus_{i+j=n} V_i \otimes W_j.$$

The forgetful functor $\omega: \text{GrVec}_k \to \text{Vec}_k$ sending $(V, (V_n)_{n \in \mathbb{Z}})$ to $V$ makes $\text{GrVec}_k$ into a tannakian category.

iii) Let $G$ be any abstract group and let $\text{Rep}_k(G)$ denote the category of finite-dimensional $k$-linear representations of $G$. Let

$$\omega: \text{Rep}_k(G) \to \text{Vec}_k$$

be the functor that forgets the action of $G$. Then $\text{Rep}_k(G)$ is a tannakian category over $k$ and $\omega$ is a fiber functor.

iv) Let $\text{MHS}(\mathbb{Q})$ be the category of mixed Hodge structures over $\mathbb{Q}$ and let $\omega_{\text{B}}$ and $\omega_{\text{dR}}$ the forgetful functors of Definition 2.206. Then $\text{MHS}(\mathbb{Q})$ is a tannakian category over $\mathbb{Q}$ and both of the functors, $\omega_{\text{B}}$ and $\omega_{\text{dR}}$, are fiber functors.

v) Let $M$ be a path-connected, locally path-connected and locally simply connected topological space. The category $\text{Loc}_k(M)$ of local systems
of finite-dimensional $k$-vector spaces is a tannakian category. For each point $x \in M$, the functor

$$\omega_x : \text{Loc}_k(M) \longrightarrow \text{Vec}_k$$

$$V \longmapsto V_x$$

that sends a local system $V$ to its fiber at $x$ is a fiber functor.

4.1.4. The fundamental group of a tannakian category. Fix a tannakian category $\mathcal{C}$ over $k$ and a fiber functor $\omega : \mathcal{C} \rightarrow \text{Vec}_k$. We want to associate to it an affine group scheme.

**Definition 4.11.** For every $k$-algebra $R$, let $\text{Aut}^\otimes(\omega)(R)$ denote the set of families $(\lambda_X)_{X \in \text{Ob}(\mathcal{C})}$ of $R$-linear automorphisms

$$\lambda_X : \omega(X) \otimes R \longrightarrow \omega(X) \otimes R$$

such that, for all $X, Y \in \text{Ob}(\mathcal{C})$ and $\alpha \in \text{Hom}_\mathcal{C}(X, Y)$, the following three diagrams are commutative:

$$\begin{array}{c}
\omega(X \otimes Y) \otimes R & \xrightarrow{\lambda_{X \otimes Y}} & \omega(X \otimes Y) \otimes R \\
\downarrow & & \downarrow \\
\omega(X) \otimes \omega(Y) \otimes R & \xrightarrow{\lambda_X \otimes \omega(Y) \otimes R} & \omega(X) \otimes \omega(Y) \otimes R \\
\downarrow & & \downarrow \\
(\omega(X) \otimes R) \otimes_R (\omega(Y) \otimes R) & \xrightarrow{\lambda_X \otimes_R \lambda_Y} & (\omega(X) \otimes R) \otimes_R (\omega(Y) \otimes R)
\end{array}$$

(4.12)

$$\begin{array}{c}
\omega(1) \otimes R & \xrightarrow{\lambda_1} & \omega(1) \otimes R \\
\downarrow & & \downarrow \\
R & \xrightarrow{\text{Id}} & R
\end{array}$$

(4.13)

$$\begin{array}{c}
\omega(X) \otimes R & \xrightarrow{\lambda_X} & \omega(X) \otimes R \\
\downarrow & & \downarrow \\
\omega(\alpha) \otimes \text{Id} & \xrightarrow{\omega(\alpha) \otimes \text{Id}} & \omega(\alpha) \otimes \text{Id}
\end{array}$$

(4.14)

In the above diagrams, all unlabeled tensor products of vector spaces are over $k$ and the unlabeled arrows are the obvious isomorphisms.

We think of $\text{Aut}^\otimes(\omega)(R)$ as the set of automorphisms of $\omega$ with coefficients in $R$. In particular, we define $\text{Aut}^\otimes(\omega) = \text{Aut}^\otimes(\omega)(k)$. This is the group of $k$-linear automorphisms of the functor $\omega$.

The main theorem of the theory of tannakian categories is

**Theorem 4.15 ([DM82, Thm. 2.11]).** Let $\mathcal{C}$ be a tannakian category over $k$, together with a fiber functor $\omega$. Then

i) the functor $R \mapsto \text{Aut}^\otimes(\omega)(R)$ is representable by an affine group scheme over $k$ that we denote $\text{Aut}^\otimes(\omega)$;
ii) for every \( X \in \text{Ob}(\mathcal{C}) \), the group \( \text{Aut}^{\otimes}(\omega) \) acts naturally on \( \omega(X) \) and the functor \( \mathcal{C} \to \text{Rep}_{k}(\text{Aut}^{\otimes}(\omega)) \) sending \( X \) to the vector space \( \omega(X) \) with this action of \( \text{Aut}^{\otimes}(\omega) \) is an equivalence of categories.

**Definition 4.16.** The affine group scheme \( \text{Aut}^{\otimes}(\omega) \) is called the *Tannaka group* of \((\mathcal{C}, \omega)\). Whenever we want to stress the category we are considering, we will write \( \text{Aut}^{\otimes}(\omega) \).

Given a second fiber functor \( \omega' \), the functor from \( k \)-algebras to sets

\[
R \mapsto \text{Iso}^{\otimes}(\omega, \omega')
\]

is representable by an affine scheme which is a right \( \text{Aut}^{\otimes}(\omega) \)-torsor and a left \( \text{Aut}^{\otimes}(\omega') \)-torsor, see [DM82, Thm. 3.2].

4.15. **Matrix coefficients.** Instead of proving Theorem 4.15, we will content ourselves with a description of the Hopf algebra of the Tannaka group using the notion of matrix coefficients from [Del90, §4.7] (see also [Bro17] and compare with the notion of framed objects from [BGSV90]).

**Definition 4.17.** Let \( \mathcal{C} \) be a neutral tannakian category over \( k \), together with fiber functors \( \omega_1 \) and \( \omega_2 \). A *matrix coefficient* in \((\mathcal{C}, \omega_1, \omega_2)\) is a triple

\[
(X, v, f)
\]

consisting of an object \( X \) of \( \mathcal{C} \) and elements

\[
v \in \omega_1(X) \quad \text{and} \quad f \in \omega_2(X)^{\vee} = \text{Hom}(\omega_2(X), k).
\]

Let \( H^{\omega_1, \omega_2} \) be the \( k \)-vector space generated by all matrix coefficients, and let

\[
V^{\omega_1, \omega_2} \subseteq H^{\omega_1, \omega_2}
\]

be the sub-vector space spanned by

**Bilinearity relations:** for matrix coefficients \((X, v_1, f)\) and \((X, v_2, f)\), and scalars \(\lambda, \mu \in k\), the relation

\[
(X, \lambda v_1 + \mu v_2, f) - \lambda(X, v_1, f) - \mu(X, v_2, f) \in V.
\]

Similarly, for matrix coefficients \((X, v, f_1)\) and \((X, v, f_2)\), and \(\lambda, \mu \in k\), the relation

\[
(X, v, \lambda f_1 + \mu f_2) - \lambda(X, v, f_1) - \mu(X, v, f_2) \in V.
\]

**Compatibility relations:** for all objects \( X \) and \( X' \) of \( \mathcal{C} \), every morphism \( \phi \in \text{Hom}_{\mathcal{C}}(X, X') \), and elements \( v \in \omega_1(X) \) and \( f' \in \omega_2(X')^{\vee} \), the relation

\[
(X, v, \omega_2(\phi)^{\vee} f') - (X', \omega_1(\phi)v, f') \in V.
\]

We consider the quotient

\[
A^{\omega_1, \omega_2} = H^{\omega_1, \omega_2} / V^{\omega_1, \omega_2}
\]

and we write \([X, v, f]\) for the class of a matrix coefficient \((X, v, f)\) in \( A^{\omega_1, \omega_2} \). Whenever \( \omega_1 = \omega_2 = \omega \), we will write \( A^\omega \) instead of \( A^{\omega_1, \omega_2} \).

The vector space \( A^{\omega_1, \omega_2} \) is equipped with the following structures:

**Product:** The tensor structure of \( \mathcal{C} \) induces the product

\[
[X, v, f] \cdot [X', v', f'] = [X \otimes X', v \otimes v', f \otimes f'].
\]

The associativity and commutativity constraints together with the compatibility relation imply that this product is associative and commutative.
Unit: Let 1 be an identity object of C. For every fiber functor ω on C, there is a canonical isomorphism ω(1) ∼ k. Let v ∈ ω1(1) and f ∈ ω2(1)∨ be the elements corresponding to 1 ∈ k and to its dual respectively. Then [1, v, f] is a unit for the product.

Coaction: For any fiber functor ω3 on C, there is a map

\[ \Delta: A^{ω_1, ω_3} → A^{ω_1, ω_2} ⊗ A^{ω_2, ω_3} \]

given as follows: for each object X of C, choose a basis \( (e_1, \ldots, e_n) \) of \( ω_2(X) \), let \( (e^*_1, \ldots, e^*_n) \) denote the dual basis, and define

\[ \Delta[X, v, f] = \sum_{j=1}^{n} [X, v, e^*_j] ⊗ [X, e_j, f]. \]  

One checks that (4.18) does not depend on the choice of the basis.

In the case where the fiber functors \( ω_1, ω_2 \) and \( ω_3 \) are equal, say \( ω = ω_1 = ω_2 = ω_3 \), the coaction gives rise to a coproduct

\[ \Delta[X, v, f] = \sum_{j=1}^{n} [X, v, e^*_j] ⊗ [X, e_j, f]. \]

Moreover, for \( ω = ω_1 = ω_2 \), there are two extra structures:

Counit: The counit is the map \( A^ω → k \) given by \( [X, v, f] → f(v) \).

Antipode: The antipode is the map \( S: A^ω → A^ω \) given by

\[ S([X, v, f]) = [X^∨, f, v] \]

under the identifications \( ω(X^∨) ∼ ω(X)^∨ \) and \( ω(X^∨)^∨ ∼ ω(X) \) that allow one to swap \( v \) and \( f \).

It is an easy verification to prove the following result.

**Proposition 4.19.** Together with the above structures, \( A^{ω_1} \) and \( A^{ω_2} \) are commutative Hopf algebras, while \( A^{ω_1, ω_2} \) is a left \( A^{ω_1} \)-Hopf module and a right \( A^{ω_2} \)-Hopf module.

Taking Theorem 4.15 for granted, we can show that \( A = A^ω \) is the Hopf algebra of the Tannaka group \( G = Aut^⊗(ω) \). More precisely,

**Proposition 4.20.** The map \( φ: A → O(G) \) given by

\[ φ([X, v, f])(λ) = f(λ_X(v)) \]

is an isomorphism of Hopf algebras.

**Proof.** We leave to the reader the care to check that \( φ \) is a morphism of Hopf algebras, i.e. that it is compatible with the structures on both sides and we prove that it is injective and surjective.

By Theorem 4.15, the category \( C \) is equivalent to the category \( \text{Rep}_k(G) \) of finite-dimensional \( k \)-representations of \( G \), and we can identify \( ω \) with the forgetful functor \( \text{Rep}_k(G) → \text{Vec}_k \).

We first prove that \( φ \) is surjective. Note that there is a left group action of \( G \) on \( O(G) \) given by

\[ (λh)(μ) = h(μλ). \]
By Lemma 3.117, $\mathcal{O}(G)$ is the union of its finite-dimensional subrepresentations. In other words, given $h \in \mathcal{O}(G)$, there exists a finite-dimensional subrepresentation $(V, \rho)$ of $\mathcal{O}(G)$ containing $h$. It determines an object $X$ of $\mathcal{C}$ such that $h$ belongs to $\omega(X) = V$. Let $f \in V'$ be the element given by $f(u) = u(e)$, where $e$ is the unit of $G$ and $u \in V \subseteq \mathcal{O}(G)$. Then, for each element $\lambda \in G$, we have

$$[X, h, f](\lambda) = f(\lambda h) = (\lambda h)(e) = h(e\lambda) = h(\lambda).$$

Therefore, $\varphi([X, h, f]) = h$ and $\varphi$ is surjective.

We next prove the injectivity of $\varphi$. Assume that $\varphi([X, v, f]) = 0$. We identify $X$ with a finite-dimensional representation $(V, \rho)$ of $G$ such that $v \in V$. Let $V'$ be the simple subrepresentation of $V$ containing $v$. Then $V'$ is generated by elements of the form $\lambda v$ for $\lambda \in G$. Since $\varphi([X, v, f]) = 0$, we deduce that $f|_{V'} = 0$. Let $X'$ be the object of $\mathcal{C}$ corresponding to $(V', \rho)$. By the compatibility relation, the equality

$$[X, v, f] = [X', v, f]|_{V'} = [X', v, 0] = 0$$

holds, thus completing the proof. $\square$

**Example 4.21 (Graded vector spaces).** Consider the tannakian category

$$\mathcal{T} = (\text{GrVec}_k, \omega)$$

of finite-dimensional graded vector spaces from Example 4.10 ii). In this category, every object is a direct sum of one-dimensional objects $k_n$, one for each $n \in \mathbb{Z}$, which satisfy

$$\text{Hom}(k_n, k_m) = \begin{cases} k, & \text{if } n = m, \\ 0, & \text{if } n \neq m, \end{cases} \quad k_n \otimes k_m = k_{n+m}, \quad \omega(k_n) \simeq k.$$

The previous conditions mean that we can identify $k_0$ with the unit. Hence, there is a canonical identification $\omega(k_0)$ with $k$ and also $\omega(k_n)$ with $\omega(k_{-n})^\vee$. Choose a non-zero element $u_1 \in \omega(k_1)$ and write

$$u_n = \begin{cases} u_1^\otimes n, & \text{if } n > 0, \\ 1 \in k, & \text{if } n = 0, \\ u_n^\vee, & \text{if } n < 0. \end{cases}$$

Here, for $n > 0$, $u_n^\vee \in \omega(k_n)^\vee = \omega(k_{-n})$ is the element defined by $u_n^\vee(u_n) = 1$. We extend the notation $u_n^\vee$ also to $n \leq 0$. Then every matrix coefficient in $\mathcal{T}$ can be written as a linear combination of the elements

$$[k_n, u_n, u_n^\vee], \quad n \in \mathbb{Z}.$$

Moreover,

$$[k_n, u_n, u_n^\vee] \cdot [k_m, u_m, u_m^\vee] = [k_{n+m}, u_{n+m}, u_{n+m}^\vee].$$

Thus, if we write $t = [k_1, u_1, u_1^\vee]$, there is an isomorphism of algebras

$$\mathcal{O}(\text{Aut}^\otimes(\omega)) = k[t, t^{-1}].$$

Moreover, the coproduct, the counit and the antipode are given by

$$\Delta t = t \otimes t, \quad \epsilon(t) = \epsilon(t^{-1}) = 1, \quad S(t) = t^{-1}.$$

From Example 3.58 ii), we deduce that $\text{Aut}^\otimes(\omega)$ is the multiplicative group $\mathbb{G}_m$.

It is a general fact that the presence of a grading is related to an action of $\mathbb{G}_m$. Indeed, if a fiber functor $\omega : \mathcal{T} \rightarrow \text{Vec}_k$ factors through graded vector spaces, then there is a morphism of affine group schemes from $\mathbb{G}_m$ to the Tannaka group of $\mathcal{T}$. 
Example 4.22 (Split $\mathbb{R}$-mixed Hodge structures). A split real mixed Hodge structure is a finite-dimensional real vector space $H$ equipped with a bigrading

$$H_{\mathbb{C}} = \bigoplus_{p,q \in \mathbb{Z}} H^{p,q}$$

that is symmetric with respect to complex conjugation:

$$H^{p,q} = H^{q,p}.$$  

Together with morphisms of real vector spaces preserving the given bigradings, these objects form a category $\mathcal{C}$. Let

$$\omega: \mathcal{C} \rightarrow \text{Vec}_\mathbb{R}$$

be the forgetful functor that sends a pair $(H, \{H^{p,q}\})$ to $H$. It is a simple matter of unraveling the definitions to check that $(\mathcal{C}, \omega)$ is a neutral tannakian category over $\mathbb{R}$. In what follows, we determine its Tannaka group.

The subgroup of $\text{GL}_2(\mathbb{R})$ consisting of matrices of the form $\begin{pmatrix} x & y \\ -y & x \end{pmatrix}$ can be identified with the real points of an affine algebraic group $S$ over $\mathbb{R}$ called the Deligne torus. A way to define it is as the Weil restriction $S = \text{Res}_{\mathbb{C}/\mathbb{R}}(\mathbb{G}_m)$, which means that $S$ is the functor mapping an $\mathbb{R}$-algebra $A$ to the group

$$S(A) = \mathbb{G}_m(A \otimes_\mathbb{R} \mathbb{C}) = (A \otimes_\mathbb{R} \mathbb{C})^\times.$$  

The complex points of $S$ consist of those matrices of $\text{GL}_2(\mathbb{C})$ of the form $\begin{pmatrix} x & y \\ -y & x \end{pmatrix}$ and there is an isomorphism

$$S(\mathbb{C}) \rightarrow \mathbb{C}^* \times \mathbb{C}^*$$

$$(x, y) \mapsto (x + iy, x - iy)$$

through which the action of complex conjugation on $S(\mathbb{C})$ corresponds to

$$(\alpha, \beta) \mapsto (\bar{\beta}, \bar{\alpha}).$$  

We claim that the category of split real mixed Hodge structures is equivalent to the category of finite-dimensional real representations of $S$. That is,

$$\text{Aut}^0_S(\omega) = S.$$  

Indeed, if $V$ is such a representation, then $S(\mathbb{C})$ acts on $V_\mathbb{C}$. Since $S(\mathbb{C})$ is the torus $\mathbb{C}^* \times \mathbb{C}^*$, the complex representation $V_\mathbb{C}$ decomposes as a direct sum

$$V_\mathbb{C} = \bigoplus_{p,q} V^{p,q},$$

where $V^{p,q}$ is the eigenspace on which $S(\mathbb{C})$ acts through

$$(\alpha, \beta) \cdot v = \alpha^p \beta^q v.$$  

Since the representation we started with is defined over $\mathbb{R}$, we have

$$(\alpha, \beta) \cdot \bar{v} = \overline{(\alpha, \beta) \cdot v} = \overline{(\beta, \alpha) \cdot v} = \beta^p \bar{\alpha}^q \bar{v} = \alpha^q \beta^p \bar{v}$$

for each $v \in V^{p,q}$, and hence $\overline{V^{p,q}} = V^{q,p}$. This yields a functor

$$\text{Rep}_R(S) \rightarrow \mathcal{C},$$

which is compatible with the forgetful functors on both sides.
Conversely, given a split real mixed Hodge structure \( H \), we define an action of \( S(\mathbb{C}) \) on \( H_{\mathbb{C}} \) by letting \( (\alpha, \beta) \in \mathbb{C}^* \times \mathbb{C}^* \) act on \( H^{p,q} \) as multiplication by \( \alpha^p \beta^q \). The condition (4.23) readily implies that the resulting representation comes from a representation \( S \to \text{GL}(H) \) by extension of scalars, and we obtain in this way a quasi-inverse to the functor (4.24).

4.1.6. Tannakian subcategories. Given an object \( Y \) of a neutral tannakian category \( \mathcal{C} \), we denote by \( \langle Y \rangle \) the full subcategory of \( \mathcal{C} \) that contains \( Y \) and is stable by taking sums, tensor products, dual, and subquotients. Together with the restriction of any fiber functor \( \omega \) on \( \mathcal{C} \), the category \( \langle Y \rangle \) is again a neutral tannakian category. The action of \( G = \text{Aut}_{\mathcal{C}}^{\otimes} \) on the vector space \( \omega(Y) \) induces a map \( G \to \text{GL}(\omega(Y)) \). The following is shown in the proof of [DM82, Prop. 2.8]

**Lemma 4.25.** The image \( G^Y \subset \text{GL}(\omega(Y)) \) of \( G \) by the above map is a closed subgroup of \( \text{GL}(\omega(Y)) \) which agrees with the Tannaka group \( \text{Aut}_{\langle Y \rangle}^{\otimes} \) of the subcategory \( \langle Y \rangle \).

We can order the subcategories of the form \( \langle Y \rangle \) for \( Y \) an object of \( \mathcal{C} \) by inclusion. With this order they form a directed system. If \( \langle Y \rangle \subset \langle Z \rangle \), then \( Y \in \langle Z \rangle \) and \( \langle Z \rangle = \langle Z \oplus Y \rangle \). The injection and projection \( Y \to Z \oplus Y \to Y \) induce a map

\[
\text{Aut}_{\langle Z \rangle}^{\otimes}(\omega) = \text{Aut}_{\langle Z \oplus Y \rangle}^{\otimes}(\omega) \to \text{Aut}_{\langle Y \rangle}^{\otimes}(\omega).
\]

The following lemma exhibits the pro-algebraic nature of \( G \).

**Lemma 4.26.** Let \( (\mathcal{C}, \omega) \) be a neutral tannakian category. Then:

\[
\text{Aut}_{\mathcal{C}}^{\otimes}(\omega) = \lim_{\langle Y \rangle} \text{Aut}_{\langle Y \rangle}^{\otimes}(\omega) = \lim_{\langle Y \rangle} G^Y.
\]

**Proof.** By Lemma 4.25, there is a surjection \( G \to G^Y \) for every object \( Y \) of \( \mathcal{C} \). These surjections are compatible with the maps \( G^Z = G^{Z \oplus Y} \to G^Y \) induced by an inclusion \( \langle Y \rangle \subset \langle Z \rangle \). Therefore, there is a surjection

\[
G \twoheadrightarrow \lim_{\langle Y \rangle} G^Y.
\]

This map is also injective, because if an element of \( G \) is sent to the unit, then it acts trivially on \( \omega(Y) \) for every object \( Y \) and is thus the unit of \( G \). \( \square \)

4.1.7. Tannakian categories and the fundamental group. We next explore what can be recovered from the classical fundamental group of a topological space using the tannakian formalism. This includes the pro-unipotent completion.

Let \( M \) be a Hausdorff, second countable, connected, locally compact and locally contractible topological space as in Theorem A.245. Let \( x_0 \) be a point of \( M \) and \( \pi_1(M, x_0) \) the fundamental group of \( M \) with base point \( x_0 \). By part \( v) \) of Example 4.10, the category \( \text{Loc}_k(M) \) of local systems of finite-dimensional \( k \)-vector spaces over \( M \) is a tannakian category with fiber functor \( \omega_{x_0} \). Given a local system \( V \), the fiber at \( x_0 \) is a \( k \)-vector space with an action of \( \pi_1(M, x_0) \). This yields the so-called monodromy representation

\[
\rho_v : \pi_1(M, x_0) \to \text{GL}(\omega_{x_0}(V)).
\]

From Theorem A.245, we know that \( \text{Loc}_k(M) \) is equivalent to the category of finite-dimensional \( k \)-linear representations of \( \pi_1(M, x_0) \). However, since the fundamental group is not an affine group scheme, it cannot be the Tannaka group of the category.
Loc\textsubscript{k}(M). In fact, as we will see, the Tannaka group Aut\textsuperscript{⊗}(ω\textsubscript{x\textsubscript{0}}) is the pro-algebraic completion of π\textsubscript{1}(M, x\textsubscript{0}).

For shorthand, write Γ = π\textsubscript{1}(M, x\textsubscript{0}). Following Lemma 4.26, we can give the following description of the pro-algebraic completion of Γ. Let Y = (V, ρ) be a k-linear finite-dimensional representation of Γ. The group G\textsuperscript{Y} from Lemma 4.26 is the Zariski closure ρ(Γ)\textsuperscript{Zar} of the image of ρ: Γ → GL(V). Let Y′ = (V′, ρ′) be another representation with ⟨Y′⟩ ⊂ ⟨Y⟩. By Lemma 4.25, there is a restriction map ρ(Γ)\textsuperscript{Zar} → ρ′(Γ)\textsuperscript{Zar}. The pro-algebraic completion is the projective limit

\[ \Gamma_{\text{alg}} = \lim_{\leftarrow} \rho(Γ)\textsuperscript{Zar}, \]

where the limit is taken with respect to the subcategories ⟨(V, ρ)⟩ ordered by inclusion.

Similarly, we can recover the pro-unipotent completion of Γ using the tannakian formalism. A local system is called unipotent if its monodromy representation is unipotent (Definition 3.149). The category of unipotent local systems ULoc\textsubscript{k}(M) on M is again a tannakian category and ω\textsubscript{x\textsubscript{0}} is again a fiber functor. In this case, the Tannaka group Aut\textsuperscript{⊗}(ω\textsubscript{x\textsubscript{0}}) is the pro-unipotent completion of Γ. It admits a similar description as the pro-algebraic completion but restricting to finite-dimensional unipotent representations:

\[ \Gamma_{\text{un}} = \lim_{\leftarrow} \rho(Γ)\textsuperscript{Zar}, \]

where the limit again is taken with respect to the subcategories ⟨(V, ρ)⟩ ordered by inclusion.

⋆ ⋆ ⋆

Exercise 4.27. Prove the equality of matrix coefficients

\[ [X ⊕ Y, u ⊕ v, f ⊕ g] = [X, u, f] + [Y, v, g]. \]

Exercise 4.28. Consider the unit circle S\textsuperscript{1} as a topological space. Its fundamental group π\textsubscript{1}(S\textsuperscript{1}, 1) is isomorphic to Z. Prove that the pro-algebraic completion Z\textsuperscript{alg} is an affine group scheme that is not algebraic, while the pro-unipotent completion is the additive group:

\[ Z_{\text{un}} \simeq \mathbb{G}_a. \]

For the second part, use that giving a unipotent representation of Z is equivalent to giving a finite-dimensional vector space V together with a unipotent endomorphism of V, and the explicit description of the Hopf algebra of the Tannaka group from Proposition 4.20.

Exercise 4.29. Consider the tannakian category Vec\textsubscript{k} with the identity as the fiber functor ω. Prove that Aut\textsuperscript{⊗}(ω) = Spec(k), the trivial group.

Exercise 4.30 (The pro-algebraic completion of a group). Let k be a field and let Γ be an abstract group. In this exercise, we present three equivalent constructions of the pro-algebraic completion of Γ, which is an affine group scheme G = Γ\textsuperscript{alg} over k together with a group morphism Γ → G(k).
i) Let $C$ be the category of finite-dimensional $k$-linear representations of $\Gamma$. Equipped with the forgetful functor, it is a tannakian category. Let $G$ be its Tannaka group. A $k$-point of $G$ is thus a collection $(\lambda_V)_{V \in \text{Ob}(C)}$ of automorphisms $\lambda_V : V \to V$ satisfying the constraints of Definition 4.11. To each element $\gamma \in \Gamma$ one associates the collection of automorphisms $\lambda^\gamma = (\lambda^\gamma_V)_{V \in \text{Ob}(C)}$ defined as $\lambda^\gamma_V(v) = \lambda \cdot \gamma$. This yields the map $\Gamma \to G(k)$.

ii) Consider the collection of pairs $(H, \varphi_H)$ consisting of an affine group scheme $H$ over $k$ and a group morphism $\varphi_H : \Gamma \to H(k)$ with Zariski dense image. We define a partial order by setting $(H, \varphi_H) \leq (H', \varphi_H')$ whenever there exists a morphism $f : H \to H'$ such that the induced map on $k$-points commutes with $\varphi_H$ and $\varphi_H'$. We define the pro-algebraic completion $G$ as the projective limit $G = \varprojlim_{(H, \varphi_H)} H$.

iii) The pro-algebraic completion $G$ is an affine group scheme over $k$ with a group morphism $\varphi : \Gamma \to G(k)$ such that, for any affine group scheme $H$ over $k$ and any group morphism $\varphi_H : \Gamma \to H(k)$, there exists a unique morphism $f : G \to H$ satisfying $f \circ \varphi = \varphi_H$.

Prove that the three constructions give the same pro-algebraic group.

Exercise 4.31. Let $C$ be a tannakian category with fiber functor $\omega$. Show that the action of $\text{Aut}^\otimes_{\mathcal{C}}(\omega)$ on the objects of $C$ extends in a unique way to the objects of $\text{Pro}(C)$ and $\text{Ind}(C)$.

4.2. Voevodsky’s category of motives. The interested reader is referred to the book [And04] and the references therein.

4.2.1. A universal cohomology. Different cohomology theories have been proved useful in the study of algebraic varieties. For instance, as we saw in Chapter 2, to any variety $X$ over a subfield $k$ of $\mathbb{C}$, it is attached the Betti cohomology $H^*_B(X) = H^*(X(\mathbb{C}), \mathbb{Q})$, which is a finite-dimensional graded $\mathbb{Q}$-vector space. If, in addition, $X$ is smooth, one has also at disposal the de Rham cohomology $H^*_dR(X) = H^*(X, \Omega^*_X)$, which is a finite-dimensional graded $k$-vector space. Recall from Theorem 2.149 that de Rham and Betti cohomology are related by the period isomorphism

\begin{equation}
H^*_dR(X) \otimes_k \mathbb{C} \cong H^*_B(X) \otimes_{\mathbb{Q}} \mathbb{C}.
\end{equation}

Another important example is $\ell$-adic cohomology defined, for a variety $X$ over a field $k$ of arbitrary characteristic $p$, a choice of a separable closure $\bar{k}$ of $k$, and a prime number $\ell$ different from $p$, by

$\bar{H}^*_\ell(X) = \varprojlim H^*_\ell(X, \mathbb{Z}_\ell/n) \otimes_{\mathbb{Z}_\ell} \mathbb{Q}_\ell$.

When $\bar{k}$ is embeddable into $\mathbb{C}$, Artin proved that there is a canonical isomorphism

\begin{equation}
H^*_\ell(X) \cong H^*_B(X) \otimes_{\mathbb{Q}} \mathbb{Q}_\ell.
\end{equation}

All the cohomology theories we have mentioned satisfy similar properties, such as homotopy invariance, Poincaré duality, Künneth formulas, Mayer-Vietoris exact
sequences etc. A fundamental feature is that the corresponding vector spaces usually come together with extra structures. We have already seen that Betti cohomology can be provided with a mixed Hodge structure. Similarly, ℓ-adic cohomology carries a continuous $\mathbb{Q}_\ell$-linear action of the Galois group $\text{Gal}(\overline{k}/k)$.

The similarities between different cohomology theories, as well as the existence of comparison isomorphisms such as (4.32) or (4.33), led Grothendieck to postulate the existence of a universal cohomology theory which factors all the others: this should be the motive of the variety. Since its introduction by Grothendieck, the theory of motives has inspired a wealth of research but, although we have advanced a lot in our understanding, many fundamental questions remain still unanswered.

Restricting to the case of smooth proper varieties, Grothendieck constructed a category of pure motives over a field $k$ with some of the desired properties. However, in order to prove that it has all of them, he stated a set of conjectures, the standard conjectures, that have proved to be very difficult and seem to be still out of reach. Nevertheless some of the sought properties of the category of pure motives, like the fact that the category of motives up to numerical equivalence is semi-simple [Jan92], have been proved without the use of the standard conjectures.

The terminology “pure” comes from the fact that for any smooth proper variety, its $n$-th cohomology group always has certain properties that are encoded in the statement “$H^n(X)$ is of pure weight $n$”. For instance, if $X$ is a smooth proper complex variety, the group $H^B_n(X,\mathbb{C})$ has a Hodge decomposition

$$H^B_n(X) \otimes_{\mathbb{Q}} \mathbb{C} \simeq \bigoplus_{p+q=n} H^{p,q}(X).$$

The fact that only factors with $p+q = n$ appear means that its Hodge structure is pure of weight $n$. For varieties over a finite field, the corresponding purity is reflected by the fact that the eigenvalues of the action of Frobenius on étale cohomology have absolute value $q^{n/2}$.

Using resolution of singularities, we can express the cohomology of a singular non-necessarily proper variety in terms of the cohomology of smooth proper varieties, but in this expression cohomologies of different degrees get mixed. As we have seen in Section 2.6.2 this gives rise to a mixed Hodge structure in the cohomology of $X$. Thus, the motive of a smooth proper variety should be pure while the motive of a singular or non-proper variety should be mixed. Since Grothendieck, there has been a great effort to develop a theory of mixed motives.

Abstractly we can think of a cohomology theory in the following way. Fix a field $k$, denote by $\text{Var}_k$ the category of varieties over $k$, and let $\mathcal{A}$ be an abelian category (or more precisely a tannakian category). Denote by $\mathcal{D}\mathcal{A}$ the derived category of $\mathcal{A}$. A cohomology theory (with values in $\mathcal{A}$) is a contravariant functor

$$H: \text{Var}_k \rightarrow \mathcal{D}\mathcal{A}$$

satisfying certain properties. We can recover the “cohomology groups” of $X$ from $H(X)$ using the $t$-structure:

$$H^n(X) = \bigcap_{t < n} \bigcup_{t \geq n} H(X) \in \mathcal{A}.$$

Voevodsky was able to define a triangulated category $\mathcal{D}\text{M}_{gm}(k)$, which is a candidate for the derived category of mixed motives over $k$. The main missing
piece is a suitable “motivic” $t$-structure. Recently, Beilinson [Bei12] showed that, when $k$ has characteristic zero, the existence of such motivic $t$-structure implies the standard conjectures. Conversely, Hanamura proved in [Han99] that, over any field $k$, the conjunction of the standard conjectures and conjectures by Murre and Beilinson-Soulé implies the existence of the motivic $t$-structure. Thus, we are back to Grothendieck insight that to have a full theory of motives we need to prove the standard conjectures.

### 4.2.2. The derived category of mixed motives

Let $k$ be a field. In what follows, we give a sketch of Voevodsky’s construction of a derived category of mixed motives over $k$ with rational coefficients, which will be denoted by $\mathsf{DM}(k) = \mathsf{DM}_{\text{sm}}(k)_\mathbb{Q}$.

For more details we refer the reader to the original paper [Voe00], the lecture notes [MVW06] or part II of the introductory book [And04].

We start with the category $\mathsf{Sm}(k)$ of smooth varieties over $k$. This category is not additive, for it does not make sense to “sum” two morphisms of schemes. The first step of the construction will be to enlarge the set of morphisms through the notion of finite correspondence.

### 4.2.3. First step: the category of finite correspondences

**Definition 4.34.** Let $X$ and $Y$ be objects of $\mathsf{Sm}(k)$. A finite correspondence from $X$ to $Y$ is a $\mathbb{Z}$-linear combination of integral closed subschemes $W \subseteq X \times Y$ such that the projection $W \to X$ is finite and surjective over a connected component of $X$.

Finite correspondences form an abelian subgroup of the group of algebraic cycles $\mathcal{Z}^{\dim Y}(X \times Y)$, which will be denoted by $\mathcal{C}(X, Y)$.

**Example 4.35.** The graph $\Gamma_f \subseteq X \times Y$ of a morphism of schemes $f : X \to Y$ is a finite correspondence. In general, we can think of finite correspondences as multivalued maps on a connected component of $X$.

Given $X, Y, Z \in \mathsf{Sm}(k)$, we will denote by $p_{XY}, p_{XZ}$ and $p_{YZ}$ the projections from $X \times Y \times Z$ to $X \times Y$, $X \times Z$ and $Y \times Z$ respectively:

\[
\begin{array}{ccc}
X \times Y \times Z & X \times Y & X \times Z \\
p_{XY} & p_{YZ} & p_{XZ} \\
\downarrow & \downarrow & \downarrow \\
X \times Y & Y \times Z & X \times Z
\end{array}
\]

**Lemma 4.36.** Let $X, Y, Z$ be objects in $\mathsf{Sm}(k)$. Given finite correspondences $W \in \mathcal{C}(X, Y)$ and $W' \in \mathcal{C}(Y, Z)$, the cycles $p_{XY}^*(W)$ and $p_{YZ}^*(W')$ intersect properly on $X \times Y \times Z$. Moreover, the projection of the cycle $(p_{XZ})_* (p_{XY}^* \alpha \cdot p_{YZ}^* \beta)$ is finite over $X$ and surjective over a connected component.

Thanks to the above lemma, we can define a composition of morphisms as follows

\[
\circ : \mathcal{C}(X, Y) \times \mathcal{C}(Y, Z) \longrightarrow \mathcal{C}(X, Z)
\]

\[
(\alpha, \beta) \longmapsto \alpha \circ \beta = (p_{XZ})_* (p_{XY}^* \alpha \cdot p_{YZ}^* \beta).
\]

The category $\mathsf{SmCor}(k)$ has the same objects as $\mathsf{Sm}(k)$, but the morphisms are given by finite correspondences with $\mathbb{Q}$-coefficients:

\[
\text{Hom}_{\mathsf{SmCor}(k)}(X, Y) = \mathcal{C}(X, Y) \otimes_{\mathbb{Z}} \mathbb{Q}.
\]
There is a functor $\text{Sm}(k) \to \text{SmCor}(k)$ that is the identity on objects and sends a map $f : X \to Y$ to its graph $\Gamma_f$. By Exercise 4.62, the composition of maps is compatible with the composition (4.37) of finite correspondences. We denote by $[X]$ the image in $\text{SmCor}(k)$ of a smooth variety $X$.

The direct sum in $\text{SmCor}(k)$ is given by the disjoint union of varieties. This category is also equipped with the tensor product $[X] \otimes [Y] = [X \times_k Y]$.

The category $\text{SmCor}(k)$ is additive.

4.2.4. Second step: A triangulated category with homotopy invariance and Mayer-Vietoris. The second step is similar to the construction of the derived category of an abelian category. We start with the category $C^b(\text{SmCor}(k))$ of bounded chain complexes in $\text{SmCor}(k)$. The objects are diagrams

$$\cdots \to [X_n] \xrightarrow{\partial_n} [X_{n-1}] \to \cdots,$$

where $X_i$ is in $\text{Sm}(k)$ and $\partial_n \in c(X_n, X_{n-1}) \otimes \mathbb{Q}$ are finite correspondences such that $\partial_{n-1} \circ \partial_n = 0$. Then we define the homotopy category $K^b(\text{SmCor}(k))$ as the one having the same objects as $C^b(\text{SmCor}(k))$, and morphisms given by homotopy classes of morphisms of complexes. It is a triangulated category as explained in Section A.3.2.

Two examples of objects of $K^b(\text{SmCor}(k))$ are:

**$A^1$-homotopy complex:** for any $X$ in $\text{Sm}(k)$, the complex

$$[X \times A^1] \xrightarrow{i_{pr}} [X]$$

placed in degrees 1 and 0 as the indices show. In the future we will use such kind of indices to indicate the degree.

**Mayer-Vietoris complex:** for any smooth scheme $X$ in $\text{Sm}(k)$ and any open cover $X = U \cup V$, the complex

$$[U \cap V] \xrightarrow{i_{U \cap V,U} + i_{U \cap V,V}} [U] \oplus [V] \xrightarrow{i_{U, X} - i_{V, X}} [X],$$

where the arrows $i_{U, X}, i_{V, X}, i_{U \cap V, U}$ and $i_{U \cap V, V}$ are the obvious inclusions.

We want to force the homotopy invariance and the Mayer-Vietoris property, which mean that the above two complexes should become acyclic. To this end, we take the quotient of $K^b(\text{SmCor}(k))$ by the thick triangulated subcategory generated by all homotopy classes of morphisms of complexes. This quotient has the structure of a triangulated category.

4.2.5. Third step: The pseudo-abelian envelope. The next step is to take the pseudo-abelian envelope of the quotient obtained in the previous step.

Recall the construction of the pseudo-abelian envelope

**Definition 4.38.** Let $\mathcal{C}$ be an additive category. The pseudo-abelian envelope $\mathcal{C}_{pa}$ of $\mathcal{C}$ is the category with

- **objects:** $(X, p)$ where $X$ is an object of $\mathcal{C}$ and $p \in \text{Hom}_\mathcal{C}(X, X)$ is an idempotent, that is, $p^2 = p$.
- **morphisms:** $\text{Hom}_{\mathcal{C}_{pa}}((X, p), (Y, q)) \subseteq \text{Hom}_\mathcal{C}(X, Y)$ is the subgroup of those $f$ such that $f = q \circ f \circ p$. 

There is a fully faithful functor $\mathcal{C} \rightarrow \mathcal{C}_{pa}$ sending $X$ to $(X, \text{Id})$. Passing to the pseudo-abelian envelope allows us to consider the kernel of each idempotent $p: X \rightarrow X$ as a subobject of $X$. This will be crucial when we want to talk about “pieces of the cohomology”.

**Definition 4.39.** The category $\text{DM}_{gm}^{\text{eff}}(k)$ is defined as the pseudo-abelian envelope of the category obtained in the previous step.

**Remark 4.40.** By a result of Balmer and Schlichting [BS01], if $\mathcal{T}$ is a triangulated category, its pseudo-abelian envelope $\mathcal{T}_{pa}$ has a unique structure of triangulated category such that the functor $\mathcal{T} \rightarrow \mathcal{T}_{pa}$ is triangulated. Thus, $\text{DM}_{gm}^{\text{eff}}(k)$ is still a triangulated category.

We have a functor $M: \text{Sm}(k) \rightarrow \text{DM}_{gm}^{\text{eff}}(k)$ sending $X$ to $[X]$, regarded as a complex concentrated in degree zero. The category $\text{DM}_{gm}^{\text{eff}}(k)$ is also equipped with a tensor product that is characterized by the property

$$M(X) \otimes M(Y) = M(X \times Y).$$

The unit object is the motive of the base field, which will be denoted by $Q(0) = M(\text{Spec}(k))$.

Note also that there is a functor

$$C^b(\text{SmCor}(k)_{pa}) \rightarrow \text{DM}_{gm}^{\text{eff}}(k)$$

from the category of bounded complexes in the pseudo-abelian envelope of $\text{SmCor}(k)$ to the category of effective motives $\text{DM}_{gm}^{\text{eff}}(k)$.

**4.2.6. Fourth step: inversion of the Tate motive.**

Given $X$ in $\text{Sm}(k)$, let $X \rightarrow \text{Spec}(k)$ denote the structure morphism. We can think of it as the complex:

$$[X] \rightarrow [\text{Spec}(k)].$$

**Definition 4.43.** The reduced motive of $X$ is the object $\widetilde{M}(X)$ of $\text{DM}_{gm}^{\text{eff}}(k)$ determined by the complex (4.42).

When $X$ has a $k$-rational point, the motive of $X$ decomposes as a direct sum $M(X) = Q(0) \oplus \widetilde{M}(X)$, and this decomposition is independent of the choice of the point (see Exercise 4.63).

**Definition 4.44.** The Tate motive $Q(1)$ is $M(\mathbb{P}^1_k)[-2]$. For each integer $n \geq 0$, one defines $Q(n)$ as $Q(1)^{\otimes n}$.

The last step of the construction of $\text{DM}(k)$, necessary to obtain a rigid tensor category, is to formally invert the motive $Q(1)$. By this we mean the following: an object of the new category $\text{DM}(k)$ is a pair $(M, m)$, where $M$ is an object of $\text{DM}_{gm}^{\text{eff}}(k)$ and $m \in \mathbb{Z}$. Morphisms are given by

$$\text{Hom}_{\text{DM}(k)}((M, m), (N, n)) = \lim_{r \rightarrow \infty} \text{Hom}_{\text{DM}_{gm}^{\text{eff}}(k)}(M \otimes Q(m + r), N \otimes Q(n + r)).$$

The resulting category has the following property:

**Theorem 4.45 (Voevodsky).** The category $\text{DM}(k)$ is a rigid tensor $\mathbb{Q}$-linear triangulated category.
**Proof.** See [MVW06, Thm. 20.17]. □

4.2.7. **Properties of DM(k).** All the usual machinery to compute the homology of algebraic varieties is still available in the derived category of motives:

**K"unneth:** \( M(X \times Y) = M(X) \otimes M(Y) \).

**\( \mathbb{A}^1 \)-homotopy invariance:** The projection map \( X \times \mathbb{A}^1 \rightarrow X \) induces an isomorphism

\[
M(X \times \mathbb{A}^1) = M(X).
\]

**Mayer-Vietoris:** For \( X = U \cup V \) as before, there is a distinguished triangle

\[
M(U \cap V) \rightarrow M(U) \oplus M(V) \rightarrow M(X) \rightarrow M(U \cap V)[1].
\]

**Gysin:** If \( Z \subseteq X \) is a smooth closed subscheme of codimension \( c \) of a smooth scheme \( X \), then there is a distinguished triangle

\[
M(X \setminus Z) \rightarrow M(X) \rightarrow M(Z)(c)[2c] \rightarrow M(X \setminus Z)[1].
\]

**Blow-up:** Let \( Z \subseteq X \) be a smooth closed subscheme of a smooth scheme, \( \text{Bl}_Z X \) the blow-up of \( X \) along \( Z \), and \( E \) the exceptional divisor. Then there is a distinguished triangle

\[
M(E) \rightarrow M(\text{Bl}_Z X) \oplus M(Z) \rightarrow M(X) \rightarrow M(E)[1].
\]

Moreover, if \( Z \) has codimension \( c \) in \( Z \), the triangle yields a canonical isomorphism

\[
M(\text{Bl}_Z X) = M(X) \oplus \bigoplus_{i=1}^{c-1} M(Z)(i)[2i].
\]

**Duality:** There is a duality \( A \mapsto A^\vee \) that, for \( X \) smooth and proper of dimension \( d \), satisfies

\[
M(X)^\vee = M(X)(-d)[-2d].
\]

**Adjunction:** The duality and tensor product are related by the adjunction formulas

\[
\text{Hom}(A \otimes B^\vee, C) = \text{Hom}(A, C \otimes B),
\]

\[
\text{Hom}(A \otimes B, C) = \text{Hom}(B, A^\vee \otimes C).
\]

**Remark 4.46.** We observe that the functor from \( \text{Sm}(k) \) to \( \text{DM}(k) \) is covariant, thus is a “homological” functor in contrast to the contravariant functor chosen by Grothendieck for pure motives that was cohomological.

**Example 4.47 (Motive of projective space).** Let us combine some of the above properties to prove that the motive of projective space \( \mathbb{P}^n \) is equal to

\[
M(\mathbb{P}^n) = \mathbb{Q}(0) \oplus \mathbb{Q}(1)[2] \oplus \cdots \oplus \mathbb{Q}(n)[2n]
\]

for each \( n \geq 0 \). This equality is to be compared with the computation of the Hodge structure on the cohomology of \( \mathbb{P}^n \) (Example 2.200), but keeping in mind that \( M(\mathbb{P}^n) \) is the universal homology of \( \mathbb{P}^n \) rather than its cohomology.

We proceed by induction on \( n \), the cases \( n = 0 \) and \( n = 1 \) being reduced to the definitions of \( \mathbb{Q}(0) \) and \( \mathbb{Q}(1) \). For \( n \geq 2 \), choosing a closed immersion \( \mathbb{P}^{n-1} \subseteq \mathbb{P}^n \) with complement \( \mathbb{P}^n \setminus \mathbb{P}^{n-1} = \mathbb{A}^n \), we get the Gysin distinguished triangle

\[
M(\mathbb{A}^n) \rightarrow M(\mathbb{P}^n) \rightarrow M(\mathbb{P}^{n-1})(1)[2] \rightarrow M(\mathbb{A}^n)[1].
\]
Note that the structure morphism $\mathbb{A}^n \to \text{Spec}(k)$ induces an isomorphism
\[ M(\mathbb{A}^n) \cong M(\text{Spec}(k)) = \mathbb{Q}(0), \]
as one can prove by repeatedly applying the $\mathbb{A}^1$-homotopy invariance. Factorising that structure morphism as $\mathbb{A}^n \to \mathbb{P}^n \to \text{Spec}(k)$, we also see that the composition
\[ M(\mathbb{A}^n) \to M(\mathbb{P}^n) \to M(\text{Spec}(k)) = M(\mathbb{A}^n) \]
is the identity map $\mathbb{Q}(0) \to \mathbb{Q}(0)$. Thus, the triangle (4.48) is split (Definition A.54 and Proposition A.55) and
\[ M(\mathbb{P}^n) = \mathbb{Q}(0) \oplus M(\mathbb{P}^{n-1})(1)[2]. \]
The result then follows by induction.

**Remark 4.49.** To understand the different roles of the twist and the shift, it is instructive to compare the reduced motives of $\mathbb{P}^1$ and $\mathbb{G}_m$. In the first case,
\[ \widehat{M}(\mathbb{P}^1) = \mathbb{Q}(1)[2] \]
by the definition of the right-hand side. In the second case, the Mayer-Vietoris triangle for the open cover $\mathbb{P}^1 = U \cup V$, with $U = \mathbb{P}^1 \setminus \{0\}$ and $V = \mathbb{P}^1 \setminus \{\infty\}$ reads
\[ M(\mathbb{G}_m) \to \mathbb{Q}(0) \oplus \mathbb{Q}(0) \to \mathbb{Q}(0) \oplus \mathbb{Q}(1)[2] \to M(\mathbb{G}_m)[1]. \]
From the octahedron axiom (see the version in Remark A.51), we deduce a distinguished triangle
\[ M(\mathbb{G}_m) \to \mathbb{Q}(0) \to \mathbb{Q}(1)[2] \to M(\mathbb{G}_m)[1]. \]
Using the discussion in Example 4.47, one can see that the middle arrow in the previous triangle is zero, from which it follows that $M(\mathbb{G}_m) = \mathbb{Q}(0) \oplus \mathbb{Q}(1)[1]$, thus
\[ \widehat{M}(\mathbb{G}_m) = \mathbb{Q}(1)[1]. \]
This can be compared with the fact that, for any of the classical cohomology theories, the groups $H^1(\mathbb{G}_m)$ and $H^2(\mathbb{P}^1)$ are isomorphic, but they lie in different degree. In particular, the Hodge structure $H^2(\mathbb{P}^1)$ is pure of weight 2 and Hodge type $(1,1)$. The same is true for $H^1(\mathbb{G}_m)$, but, since this last group lies in degree one, we consider it as a mixed Hodge structure.

**Example 4.51 (Relative motive).** Let $\iota: Z \to X$ be a closed immersion of smooth schemes. We define the relative motive as
\[ M(X, Z) = M([Z \to X]), \]
where $X$ sits in degree zero. In Exercise 4.64 you will see that there is a distinguished triangle
\[ M(Z) \to M(X) \to M(X, Z) \to M(Z)[1]. \]

**Example 4.52 (Motive of a union of smooth closed subschemes in good position).** Let $X$ be a smooth scheme and $Y_0, Y_1, \ldots, Y_n$ be a collection of smooth closed subschemes of $X$ such that, for each $I \subset \{0, \ldots, n\}$ the intersection
\[ Y_I = \bigcap_{i \in I} Y_i \]
is smooth. A variant of the construction in Section 3.6.2 allows us to define the motive of $Y = \bigcup Y_i$. Consider the complex
\[
C_Y = \begin{bmatrix}
0 & \bigoplus_{|I|=n+1} Y_I & \bigoplus_{|I|=n} Y_I & \cdots & \bigoplus_{|I|=1} Y_I & 0
\end{bmatrix},
\]
where the piece $\bigoplus_{|I|=k} Y_I$ sits in degree $k$ and with differentials as in Section 3.6.2. Then we define $M(Y) = M(C_Y)[-1]$.

The relative motive $M(X, Y)$ is defined as the motive of the complex
\[
C_{X,Y} = \begin{bmatrix}
0 & \bigoplus_{|I|=n+1} Y_I & \bigoplus_{|I|=n} Y_I & \cdots & \bigoplus_{|I|=1} Y_I & X & 0
\end{bmatrix}.
\]
By Exercise 4.64 there is a distinguished triangle
\[
(4.53) \quad M(Y) \to M(X) \to M(X, Y) \to M(Y)[1].
\]

4.2.8. Motivic cohomology. Voevodsky also computed some morphism groups in the category $\mathbf{DM}(k)$. In particular, he defined:

**Definition 4.54.** The **motivic cohomology** of $X$ is
\[
H^n_{\mathcal{M}}(X, \mathbb{Q}(p)) = \text{Hom}_{\mathbf{DM}(k)}(M(X), \mathbb{Q}(p)[n]).
\]

Before stating the next result we have to make a short digression into algebraic $K$-theory. For more details on algebraic $K$-theory see for instance [Wei13] and the references therein.

**Remark 4.55.** To every smooth variety $X$ over $k$, Quillen [Qui73] has associated a graded ring
\[
K_*(X) = \bigoplus_{n \geq 0} K_n(X).
\]
There is a family $\psi^l$, $l \geq 0$, of functorial ring endomorphisms of $K_*(X)$ called the **Adams operations**. They satisfy the relations $\psi^l \circ \psi^m = \psi^{lm}$. In particular the Adams operations commute among themselves. These operations allow us to decompose the $K$-groups into a direct sum. More concretely, we write
\[
(K_n(X) \otimes_{\mathbb{Z}} \mathbb{Q})^{(p)}
\]
for the maximal subspace of $K_n(X) \otimes_{\mathbb{Z}} \mathbb{Q}$ where $\psi^l - l^p \text{Id}$ is nilpotent. The subspaces $(K_n(X) \otimes_{\mathbb{Z}} \mathbb{Q})^{(p)}$ are called the eigenspaces for the Adams operations. Then there is a decomposition
\[
K_n(X) \otimes_{\mathbb{Z}} \mathbb{Q} = \bigoplus_{p \geq 0}(K_n(X) \otimes_{\mathbb{Z}} \mathbb{Q})^{(p)}.
\]
In this book we will only need the case $X = \text{Spec}(k)$.

The eigenspaces for the Adams operations inside algebraic $K$-theory, can be seen as a universal cohomology theory with coefficients in $\mathbb{Q}$ that has characteristic classes for vector bundles. In fact, using Bloch’s formula relating higher Chow groups and $K$-theory ([Voe02], [Blo86], [Lev94]) Voevodsky proves

**Theorem 4.56.** Given a smooth variety $X$ over $k$, there is an isomorphism
\[
H^n_{\mathcal{M}}(X, \mathbb{Q}(p)) = (K_{2p-n}(X) \otimes_{\mathbb{Z}} \mathbb{Q})^{(p)}.
\]
4.2.9. The normalization of a cosimplicial scheme. To every variety \( X \), not necessarily smooth, defined over a field \( k \), there is attached a motive \( M(X) \) in Voevodsky’s derived category of mixed motives \( \mathbf{DM}(k) \). Using tools from homological algebra, one can construct more general motives, for instance the motive of a cosimplicial variety.

Recall that in Section A.8.2 we defined the normalized complex associated with a cosimplicial object in an abelian category. It turns out that it is enough to work in a pseudo-abelian category.

**Lemma 4.57.** Let \( X^\bullet \) be a cosimplicial object of the category \( \text{Sm}(k) \). Given integers \( m > n \geq 0 \), the following endomorphism in \( \text{SmCor}(k) \) is idempotent:

\[
p_n = (1 - \delta^0 \sigma^0)(1 - \delta^1 \sigma^1) \cdots (1 - \delta^n \sigma^n) : [X^m] \to [X^m].
\]

**Proof.** We argue by induction on \( n \). For \( n = 0 \), note that the relation \( \sigma^0 \delta^0 = \text{Id} \) implies that \( \delta^0 \sigma^0 \) is an idempotent, and hence the same holds for \( 1 - \delta^0 \sigma^0 \). Let us now assume that \( p_{n-1} \) is idempotent. We next observe that for \( i = 0, \ldots, n - 1 \), the face \( \sigma^n \) commutes with \( \delta^i \sigma^i \). Indeed, by relations (c) and (b) in (A.166),

\[
\sigma^n(\delta^i \sigma^i) = \delta^i \sigma^{n-1} \sigma^i = (\delta^i \sigma^i) \sigma^n.
\]

Moreover, relation (d) in (A.166) implies \( \sigma^n(1 - \delta^0 \sigma^0) = 0 \). These two equations together imply

(4.58) \[
\sigma^n(1 - \delta^0 \sigma^0) \cdots (1 - \delta^n \sigma^n) = 0.
\]

We now compute, using equation (4.58), and the induction hypothesis,

\[
p_n^2 = \frac{(1 - \delta^0 \sigma^0) \cdots (1 - \delta^{n-1} \sigma^{n-1})(1 - \delta^n \sigma^n)}{p_{n-1}}
\]

\[
= p_{n-1}^2 (1 - \delta^n \sigma^n) = p_{n-1}(1 - \delta^n \sigma^n) = p_n,
\]

as we wanted to show. \( \square \)

Since \( p_n \) is idempotent, \( \text{Im}(p_n) \) is an object of the pseudo-abelian envelope of \( \text{SmCor}(k) \). By convention, we write \( p_{-1} = \text{Id} \).

**Definition 4.59.** Let \( X^\bullet \) be a cosimplicial object in \( \text{Sm}(k) \). The normalization of \( X^\bullet \) is the complex in \( \text{SmCor}(k)_{pa} \) given by

\[
\mathcal{N}(X^\bullet)^n = \text{Im}(p_{n-1} : [X^n] \to [X^n]),
\]

together with the differential

\[
d = \sum_{i=0}^{n+1} (-1)^i \delta^i : \mathcal{N}(X^\bullet)^n \to \mathcal{N}(X^\bullet)^{n+1}.
\]

If the cosimplicial object \( X^\bullet \) is not bounded, then in general, the complex \( \mathcal{N}(X^\bullet) \) is not bounded. To obtain a bounded complex, we consider the \( \text{b\'et\'e} \) truncation \( \sigma_{\leq N}\mathcal{N}(X^\bullet) \), that is,

\[
\sigma_{\leq N}\mathcal{N}(X^\bullet)^n = \begin{cases} 
\mathcal{N}(X^\bullet)^n, & \text{if } n \leq N, \\
0, & \text{if } n > N.
\end{cases}
\]
This is now an element of $C^b(\text{SmCor}(k)_{\text{pa}})$. For each $N \geq 0$, applying the functor (4.41), we obtain a motive $[\sigma_{\leq N}\mathcal{N}(X^*)]$.

Clearly, given integers $M \geq N \geq 0$, there is a morphism of complexes $\sigma_{\leq M}\mathcal{N}(X^*) \to \sigma_{\leq N}\mathcal{N}(X^*)$.

The system $([\sigma_{\leq N}\mathcal{N}(X^*)])_{N \geq 0}$ is a pro-object in $\text{DM}(k)$.

**Remark 4.60.** The advantage of using Lemma 4.57 is that it provides us with an explicit idempotent cutting out the normalized complex from the cochain complex. However, we could have also constructed it directly by abstract means, as we now explain\(^3\). Recall that a category is said to be **preadditive** if the morphism sets are abelian groups and the composition of maps is bilinear. Given a preadditive category $\mathcal{A}$, let $\text{Ab}(\mathcal{A})$ denote the category of presheaves of abelian groups on $\mathcal{A}$, by which we simply mean additive contravariant functors from $\mathcal{A}$ to the category $\text{Ab}$ of abelian groups. Then $\text{Ab}(\mathcal{A})$ is an abelian category, and the Yoneda lemma ensures that the natural functor $h: \mathcal{A} \to \text{Ab}(\mathcal{A})$ which sends $X$ to $\text{Hom}(-, X)$ is fully faithful. Assume now that $\mathcal{A}$ is pseudoabelian. If $Y'$ is a direct factor of an object of the form $h(X)$, then projecting to the complement one gets an idempotent $p$ of $h(X)$ such that $Y' = \text{Ker}(p)$. By full-faithfulness, we can see $p$ as an idempotent of $X$, and the object $Y = \text{Ker}(p)$ in $\mathcal{A}$, determined up to unique isomorphism, satisfies $h(Y) = Y'$. If $X^*$ is a cosimplicial object in $\mathcal{A}$, the associated cochain complex $CX^*$ is a complex in $\mathcal{A}$ whose formation commutes with the functor $h$, in the sense that $h(CX^*) = C^*(h(X^*))$. Since $\text{Ab}(\mathcal{A})$ is abelian, the normalized complex $\mathcal{N}^*(h(X^*))$, as introduced in Section A.8.2, is a direct factor of $C^*(h(X^*))$. Proceeding as above, one gets a complex (up to unique isomorphism) $N X^*$ such that $h(N X^*) = \mathcal{N}^*(h(X^*))$.

**4.2.10. Hodge realization.** From now on, we assume that $k$ has characteristic zero and comes with an embedding $k \to \mathbb{C}$. We end this section recalling the existence of the Hodge realization functor.

**Theorem 4.61.** There is a covariant functor of $\mathbb{Q}$-linear rigid tensor triangulated categories

$$R^H: \text{DM}(k) \to D^b(\text{MHS}(k)).$$

The proof of this theorem is sketched in [DG05, §1.5]. The main difficulty is the covariance of the de Rham complex for finite correspondences. A more detailed version of the argument is exposed in [Bou09].

We now give a sketch of the construction of the Hodge realization functor in the case of the motive $[\sigma_{\leq N}\mathcal{N}(X^*)]$ from the previous section. Let $X^*$ be a cosimplicial object in $\text{Sm}(k)$. Assume that there is an embedding

$$j_*: X^* \to X^n$$

of cosimplicial smooth varieties over $k$ such that, for each $n$, the variety $\overline{X^n}$ is smooth and proper and $D^n = \overline{X^n} \setminus X^n$ is a simple normal crossing divisor. The Hodge realization of $[\sigma_{\leq N}\mathcal{N}(X^*)]$ is constructed as follows.

\[^3\text{We thank J. Ayoub for pointing this argument to us.}\]
To each pair \( X^n \) and \( D^n \) we have associated in Definition 2.255 a mixed Hodge complex \( A^H_X(\log D^n) \). Varying \( n \) we obtain a simplicial mixed Hodge complex \( A^H_X(\log D^\bullet) \). Taking the normalization in the category of mixed Hodge complex we obtain a dg-mixed Hodge complex \( N_A^H_X(\log D^\bullet) \). The \( \hat{\text{bête}} \) truncation \( \sigma_{\leq N} N_A^H_X(\log D^\bullet) \) is still a dg-mixed Hodge complex. By Proposition 2.242 \( \text{Tot} (\sigma_{\leq N} N_A^H_X(\log D^\bullet)) \) is a mixed Hodge complex. Then \([\text{Be}86,\text{Thm}\, 3.4]\) implies that

\[
\text{Tot} (\sigma_{\leq N} N_A^H_X(\log D^\bullet))
\]

determines an element of \( D^b(MHS(k)) \). This element agrees with \( RH ([\sigma_{\leq N} NX^\bullet]) \).

\[\star \star \star\]

**Exercise 4.62.** Prove that the composition of the finite correspondences given by the graphs of two morphisms of algebraic varieties \( f: X \to Y \) and \( g: Y \to Z \), as defined in (4.37), is the graph of \( g \circ f: X \to Z \).

**Exercise 4.63.** Let \( X \) be a smooth variety over \( k \), together with a \( k \)-point \( x: \text{Spec}(k) \to X \). Consider the composition \( p: X \to \text{Spec}(k) \to X \).

i) Show that \( p \) is a projector and that the class of \((X, 1 - p)\) agrees with the reduced motive \( \tilde{M}(X) \) from Definition 4.43. Thus, there is a direct sum decomposition

\[
M(X) = \mathbb{Q}(0) \oplus \tilde{M}(X),
\]

that does not depend on the choice of the point \( x \).

ii) Show that there is an isomorphism \( \tilde{M}(X) \simeq M(X, x) \).

**Exercise 4.64.** Let

\[
C = [0 \to X_n \to X_{n-1} \to \cdots \to X_0 \to 0]
\]

be a complex in \( \text{SmCor}(k) \) and write \( C' \) for its truncation

\[
C' = [0 \to X_n \to X_{n-1} \to \cdots \to X_1 \to 0]
\]

Show that there is a distinguished triangle

\[
M(X_0) \to M(C) \to M(C') \to M(X_0)[1]
\]

in \( \text{DM}(k) \). Conclude that, if \( \iota: Z \to X \) is a closed immersion of smooth schemes, then there is a distinguished triangle

\[
M(Z) \to M(X) \to M(X, Z) \to M(Z)[1].
\]

**4.3. Mixed Tate motives.** As was mentioned in the previous section, it is not known how to construct a motivic \( t \)-structure on \( \text{DM}(k) \) that gives rise to the sought-after abelian category of mixed motives. However, when \( k \) is a number field, one can extract from \( \text{DM}(k) \) an abelian category of mixed Tate motives with similar properties to mixed Hodge Tate structures. The keystone is Borel’s computation of the \( K \)-theory of number fields.
4.3.1. The derived category of mixed Tate motives. The motives $\mathbb{Q}(n)$ are the simplest non-trivial objects of the category $\text{DM}(k)$. It is thus reasonable to figure out what can be built starting from them.

**Definition 4.65.** The derived category of mixed Tate motives over $k$ is the smallest triangulated subcategory $\text{DMT}(k)$ of $\text{DM}(k)$ that is stable under extensions and contains the objects $\mathbb{Q}(n)$ for all $n \in \mathbb{Z}$.

Being stable under extensions means that, for any distinguished triangle

$$A \to B \to C \to A[1]$$

in $\text{DM}(k)$, if two objects among $A, B, C$ lie in $\text{DMT}(k)$, then so does the third.

**Example 4.66.** Let $C = \mathbb{P}^1 \setminus S$ be the complement of a non-empty finite set of $k$-points in $\mathbb{P}^1$. The associated Gysin distinguished triangle reads

$$M(C) \to M(\mathbb{P}^1) \to M(S)(1)[2] \to M(C)[1].$$

Since the motives $M(\mathbb{P}^1) = \mathbb{Q}(0) \oplus \mathbb{Q}(1)[2]$ and $M(S) = \mathbb{Q}(0)_{|S}$ belong to $\text{DMT}(k)$, so does the motive $M(C)$.

Thanks to the comparison between motivic cohomology and $K$-theory (Theorem 4.56), the extension groups of simple objects in the category $\text{DMT}(k)$ are given by

$$\text{Ext}^i(\mathbb{Q}(n), \mathbb{Q}(m)) = \text{Hom}_{\text{DM}(k)}(M(\text{Spec}(k)), \mathbb{Q}(m-n)[i]) = (K_{2(m-n)-i}(k) \otimes \mathbb{Q})^{(m-n)}.$$ 

Recall that $(K_{2(m-n)-i}(k) \otimes \mathbb{Q})^{(m-n)}$ denote the eigenspace with respect to the Adams operations (Remark 4.55).

The $K$-theory groups of general fields are still largely unknown, but, when $k$ is a number field, Borel computed their ranks:

**Theorem 4.67 (Borel, [Bor74]).** Let $k$ be a number field with $r_1$ real embeddings and $2r_2$ complex embeddings. Then:

$$(K_{2(m-n)-i}(k) \otimes \mathbb{Q})^{(m-n)} = \begin{cases} 
\mathbb{Q}, & \text{if } i = 0 \text{ and } m - n = 0, \\
 k^\times \otimes \mathbb{Z} \mathbb{Q}, & \text{if } i = 1 \text{ and } m - n = 1, \\
 \mathbb{Q}^{r_1+r_2}, & \text{if } i = 1 \text{ and } m - n \geq 3 \text{ is odd,} \\
 \mathbb{Q}^{r_2}, & \text{if } i = 1 \text{ and } m - n \geq 2 \text{ is even,} \\
 0, & \text{otherwise.}
\end{cases}$$

The important information we should get from this is

i) the only non-zero groups $\text{Ext}^i$ occur for $i = 0, 1$;

ii) $\text{Ext}^0(\mathbb{Q}(n), \mathbb{Q}(m)) = \text{Hom}(\mathbb{Q}(n), \mathbb{Q}(m)) = 0$ unless $m = n$, for which it is equal to $\mathbb{Q}$;

iii) if $\text{Ext}^1(\mathbb{Q}(n), \mathbb{Q}(m)) \neq 0$, then $m > n$;

iv) the only infinite-dimensional group is $\text{Ext}^1(\mathbb{Q}(n), \mathbb{Q}(n+1))$. 

In particular, when $k = \mathbb{Q}$, we have $r_1 = 1$ and $r_2 = 0$, so

$$\text{Ext}^1_{\text{DMT}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n)) = \begin{cases} \mathbb{Q}^\times \otimes_{\mathbb{Z}} \mathbb{Q}, & \text{if } n = 1, \\ \mathbb{Q}, & \text{if } n \geq 3 \text{ is odd}, \\ 0, & \text{otherwise}. \end{cases}$$

This and the fact that $\text{Ext}^i_{\text{DMT}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n)) = 0$ for $i \geq 2$ will determine the structure of the category of mixed Tate motives over $\mathbb{Q}$.

**Example 4.68 (Kummer motives).** In view of the isomorphism

$$\text{Ext}^1_{\text{DMT}(k)}(\mathbb{Q}(0), \mathbb{Q}(1)) = k^\times \otimes_{\mathbb{Z}} \mathbb{Q},$$

there are plenty of non-trivial extensions of $\mathbb{Q}(0)$ by $\mathbb{Q}(1)$ in the category $\text{DMT}(k)$. They are all rational linear combinations of Kummer motives.

**Definition 4.69.** For each $t \in k^\times$, the Kummer motive $K^\text{Mot}_t$ is the class in $\text{DMT}(k)$ of the complex in $\text{SmCor}(k)$ given by

$$\text{Spec}(k) \oplus \text{Spec}(k) \xrightarrow{f_t} \mathbb{G}_m,$$

where the finite correspondence $f_t$ is defined by the cycle $[[*_1, t]] - [[*_2, 1]].$

By formula (4.50) and Exercise 4.63 ii), the motive $\mathbb{Q}(1)$ can be represented by the complex

$$\text{Spec}(k) \xrightarrow{1} \mathbb{G}_m.$$

Therefore, we obtain a commutative diagram

$$\begin{array}{c}
\mathbb{Q}(0) \xrightarrow{1} M(\mathbb{G}_m) \xrightarrow{0} \mathbb{Q}(0)[1] \\
\downarrow \quad \downarrow \quad \downarrow \\
\mathbb{Q}(0) \oplus \mathbb{Q}(0) \xrightarrow{M(\mathbb{G}_m)} \mathbb{Q}(1)[1] \xrightarrow{0} \mathbb{Q}(0)[1] \\
\downarrow \quad \downarrow \quad \downarrow \\
\mathbb{Q}(0) \oplus \mathbb{Q}(0) \xrightarrow{M(\mathbb{G}_m)} K^\text{Mot}_t[1] \xrightarrow{0} (\mathbb{Q}(0) \oplus \mathbb{Q}(0))[1],
\end{array}$$

where the rows are distinguished triangles. By axiom $\text{T3}$ of triangulated categories, there is a map $\mathbb{Q}(1) \to K^\text{Mot}_t$. Using a variant of the construction of Remark A.51, the octahedron axiom implies that this map can be extended to a distinguished triangle

$$\mathbb{Q}(1) \to K^\text{Mot}_t \to \mathbb{Q}(0) \xrightarrow{g_t} \mathbb{Q}(1)[1].$$

Hence, $K^\text{Mot}_t$ is an extension of $\mathbb{Q}(0)$ by $\mathbb{Q}(1)$. For $t = 1$, the Kummer motive $K^\text{Mot}_1$ is the trivial extension of $\mathbb{Q}(0)$ by $\mathbb{Q}(1)$. Indeed, the map $g_t$ is given by the commutative diagram

$$\begin{array}{c}
\mathbb{Q}(0) \\
\downarrow \\
\mathbb{Q}(0) \xrightarrow{t^1} M(\mathbb{G}_m) \xrightarrow{g_t} \mathbb{Q}(1)[1],
\end{array}$$

where the bottom row is a distinguished triangle. Since the composition of two consecutive arrows in a distinguished triangle is zero (Remark A.50), when $t = 1$, we obtain $g_1 = 0$. By Proposition A.55, the motive $K^\text{Mot}_1$ is a trivial extension.

The Hodge realization of the Kummer motive is the Kummer mixed Hodge structure of Example 2.237, see also Exercise 4.89.
Another case where $K$-theory is well understood is that of finite fields, which was completely computed by Quillen in [Qui72, Thm. 8], shortly after he introduced the definition of higher algebraic $K$-theory:

**Theorem 4.70** (Quillen, [Qui72]). Let $\mathbb{F}_q$ be a finite field with $q$ elements. The $K$-theory groups of $\mathbb{F}_q$ are equal to

$$K_i(\mathbb{F}_q) = \begin{cases} \mathbb{Z}, & \text{if } i = 0, \\ \mathbb{Z}/(q^{n} - 1), & \text{if } i = 2n - 1, \\ 0, & \text{otherwise.} \end{cases}$$

**Conjecture 4.71** (Beilinson-Soulé vanishing). If $k$ is a field, then $K_n(k)_Q^{(r)}$ vanishes for all $n > 2r$.

An immediate corollary of Borel and Quillen’s theorems is:

**Corollary 4.72.** The Beilinson-Soulé vanishing conjecture holds when $k$ is either a number field or a finite field.

4.3.2. A $t$-structure on mixed Tate motives (after Levine). In [Lev93], Levine has shown that, when the field $k$ satisfies the Beilinson-Soulé vanishing conjecture, the derived category of mixed Tate motives has a $t$-structure that allows us to define an abelian category of mixed Tate motives. We sketch here his construction. For more details and proofs of the different results the reader is referred to [Lev93].

For each pair of integers $a$ and $b$, let us denote by $T_{[a,b]}$ the strictly full triangulated subcategory of $\text{DMT}(k)$ generated by the objects $\mathbb{Q}(n)$ for $a < -2n < b$. We denote $T_{[a,a]}$ simply by $T_a$, and we extend the definition to cover the cases $a = -\infty$ or $b = \infty$ as well. In particular, $T_{(-\infty,\infty)}$ coincides with the whole $\text{DMT}(k)$.

**Lemma 4.73.** Let $a < b < c$ be integers (the cases $a = -\infty$ and $c = \infty$ are also allowed). Then $(T_{[a,b-1]}, T_{[b,c]})$ is a $t$-structure on $T_{[a,c]}$.

In particular, the pair $(T_{(-\infty,b)}, T_{[b+1,\infty)})$ provides a $t$-structure on $\text{DMT}(k)$ for each integer $b$. Let us emphasize that this is not the $t$-structure we are looking for, since its heart is reduced to zero. However, it will allow us to define a weight structure.

The truncation functors for the $t$-structure $(T_{(-\infty,b)}, T_{[b+1,\infty)})$ on $\text{DMT}(k)$ will be denoted by

$$W_{\leq b} : \text{DMT}(k) \longrightarrow T_{(-\infty,b]}$$

$$W_{> b} : \text{DMT}(k) \longrightarrow T_{[b+1,\infty)}.$$ 

The reason for the subindex or superindex is that one will give an increasing filtration, whereas the other will give a decreasing filtration.

Let $W_{> b}$ denote $W_{> b}^{-1}$ and define

$$\text{Gr}^{W}_b(M) = W_{> b}W_{\leq b}(M).$$

For each even integer $a$, let $T_{a}^{\leq 0}$ (resp. $T_{a}^{> 0}$) be the full subcategory of $T_a$ generated by $\mathbb{Q}(-a/2)[n]$ for $n \leq 0$ (resp. $n \geq 0$). Finally, let $T_{[a,b]}^{\leq 0}$ (resp. $T_{[a,b]}^{> 0}$) be the full subcategory of $T_{[a,b]}$ generated by the objects $M$ such that $\text{Gr}^{W}_c(M)$ belongs to $T_{c}^{\leq 0}$ (resp. $T_{c}^{> 0}$) for all $a \leq c \leq b$. 

Theorem 4.74 (Levine, [Lev93]). Assume that the field $k$ satisfies the Beilinson-Soulé conjecture. Then the pair of strictly full subcategories
\[(\mathcal{T}^{\leq 0}_{(-\infty,\infty)}, \mathcal{T}^{\geq 0}_{(-\infty,\infty)})\]
forms a non-degenerate $t$-structure on $\text{DMT}(k)$.

Definition 4.75. The category $\text{MT}(k)$ of mixed Tate motives over $k$ is the heart of the $t$-structure of Theorem 4.74.

The category $\text{MT}(k)$ has the following properties:

i) It is a neutral tannakian category generated under extensions by the objects $\mathbb{Q}(n)$ for $n \in \mathbb{Z}$.

ii) Each object $M$ of $\text{MT}(k)$ has an increasing weight filtration $W$ with graded pieces
\[\text{Gr}^{W}_{-2n} M \simeq \mathbb{Q}(n)^{\oplus k_n}, \quad \text{Gr}^{W}_{-2n+1} = 0\]
for some natural numbers $k_n$.

iii) A fiber functor is given by
\[(4.76) \quad \omega(M) = \bigoplus_n \text{Hom}(\mathbb{Q}(n), \text{Gr}^{W}_{-2n} M).\]

Moreover, Wildeshaus [Wil09, Thm. 1.3] proved that there exists a canonical equivalence of categories
\[(4.77) \quad F : D^b(\text{MT}(k)) \rightarrow \text{DMT}(k).\]
The functor $F$ is $t$-exact, induces the identity on the heart $\text{MT}(k)$, and has the property that the composition with the cohomology functor $H^0$ associated with the $t$-structure as in (A.115) coincides with the canonical cohomology functor
\[D^b(\text{MT}(k)) \rightarrow \text{MT}(k).\]

In view of Remark A.113, the main difficulty does not lie in proving that the two categories are equivalent but in constructing a functor between them.

4.3.3. Examples. If the motive of a variety $X$ is of mixed Tate type, i.e. belongs to $\text{DMT}(k)$, then decomposing the dual of $M(X)$ by means of Levine’s $t$-structure we obtain the cohomology motives
\[h^i(X) = t_{\leq 0} t_{\geq 0}(M(X)^{\vee}[i]) \in \text{MT}(k).\]
Thus, we can isolate the different cohomological degrees, something we do not know how to do for general motives.

Example 4.78. By Example 4.47, the motive of the projective space $M(\mathbb{P}^n_k)$ is of mixed Tate type and one has
\[h^i(\mathbb{P}^n_k) = \begin{cases} \mathbb{Q}(-m), & \text{if } i = 2m \text{ and } 0 \leq m \leq n, \\ 0, & \text{otherwise}. \end{cases}\]

Using the properties of $\text{DMT}(k)$ such as the homotopy invariance or the long exact sequence associated with a closed immersion, we can show that certain motives are mixed Tate. For instance, if a variety $X$ possesses a stratification such that the motive of each locally closed stratum is mixed Tate, then the whole $M(X)$ is a mixed Tate motive.
Example 4.79 (Motives of \(M_{0,n}\)). Let \(n \geq 3\) be an integer. Recall the moduli spaces \(M_{0,n}\) from Section 2.5.2. In this example, we show that the motive \(M(M_{0,n})\) belongs to \(\text{DMT}(\mathbb{Q})\) by mimicking the proof of Proposition 2.285. We proceed by induction on \(n\). The result holds for \(n = 3\), since \(M_{0,3} = \text{Spec}(k)\), and for \(n = 4\) since \(M_{0,4} = \mathbb{P}^1 \setminus \{0,1,\infty\}\) and we saw in Example 4.66 that the motive of a punctured projective line belongs to \(\text{DMT}(\mathbb{Q})\). For \(n \geq 5\), we write

\[
M_{0,n} \simeq X \setminus Z, \quad X = M_{0,4} \times M_{0,n-1}, \quad Z = \bigcup_{i=2}^{n-3} M_{0,i}.
\]

By the K"unneth formula and the induction hypothesis, the motives \(M(X)\) and \(M(Z)\) belong to \(\text{DMT}(\mathbb{Q})\). Besides, the Gysin triangle reads

\[
M(M_{0,n}) \longrightarrow M(X) \longrightarrow M(Z)(1)[2] \longrightarrow M(M_{0,n})[1]
\]

and since \(M(X)\) and \(M(Z)(1)[2]\) belong to \(\text{DMT}(\mathbb{Q})\), so does \(M(M_{0,n})\).

Example 4.80. Let \(L = L_1 \cup \cdots \cup L_{n_1}\) and \(M = M_1 \cup \cdots \cup M_{n_2}\) be two collections of linear subspaces of the projective space \(\mathbb{P}^n_k\). We consider the motive

\[
\mathcal{M} = M(\mathbb{P}^n_k \setminus L, M \setminus (M \cap L)) \in \text{DM}(k).
\]

defined in Example 4.52. We want to see that it belongs to \(\text{DMT}(k)\). If one of the \(L_i\) or \(M_j\) is equal to \(\mathbb{P}^n_k\) we obtain the zero motive. So we may assume that the linear subspaces are proper. If \(n = 0\), then \(\mathbb{P}^n_k = \text{Spec}(k)\) and \(L = M = \emptyset\). In this case \(\mathcal{M} = M(\text{Spec}(k)) \in \text{DMT}(k)\). Assume now that \(n > 0\) and \(n_2 = 0\). If also \(n_1 = 0\), then \(\mathcal{M} = M(\mathbb{P}^n_k) \in \text{DMT}(k)\). If \(n_1 > 0\), write \(L = L_1 \cup \cdots \cup L_{n_1-1}\). By the Gysin property in 4.2.7 there is a distinguished triangle in \(\text{DM}(k)\)

\[
M(\mathbb{P}^n_k \setminus L) \longrightarrow M(\mathbb{P}^n_k \setminus L') \longrightarrow M(L_{n_1} \setminus L_{n_1} \cap L')(c)[2c] \longrightarrow M(\mathbb{P}^n_k \setminus L)[1],
\]

where \(c\) is the codimension of \(L_{n_1}\) in \(\mathbb{P}^n_k\). By induction (both on \(n\) and \(n_1\)) the motives \(M(\mathbb{P}^n_k \setminus L')\) and \(M(L_{n_1} \setminus L_{n_1} \cap L')\) belong to \(\text{DMT}(k)\). Since this last category is closed under extensions, it also contains the motive \(M(\mathbb{P}^n_k \setminus L)\).

Using the previous case, Exercise 4.64 and the fact that \(\text{DMT}(k)\) is closed under extensions, we deduce that \(M(M \setminus L) \in \text{DMT}(k)\). By the distinguished triangle (4.53) the motive \(M(\mathbb{P}^n_k \setminus L, M \setminus (M \cap L))\) also belongs to \(\text{DMT}(k)\).

Applying now the t-structure of \(\text{DMT}(k)\), for each \(r \in \mathbb{Z}\), we obtain a motive

\[
h^r(\mathbb{P}^n_k \setminus L, M \setminus (M \cap L))\]

that belongs to \(\text{MT}(k)\).

4.3.4. Realizations. Recall the category \(\text{MHTS}(\mathbb{Q})\) of mixed Hodge Tate structures over \(\mathbb{Q}\) from Definition 2.214. The functor \(R^\text{HT}\) of Theorem 4.61 restricts to a functor

\[
\text{DMT}(\mathbb{Q}) \longrightarrow D^b(\text{MHTS}(\mathbb{Q})).
\]

As explained in Example A.106, the category appearing on the right-hand side has a canonical t-structure. We have also defined a t-structure on \(\text{DMT}(\mathbb{Q})\). In fact, this t-structure has the property that any realization functor is t-exact in the sense of Definition A.103, and hence restricts to a functor on the hearts. This applies in particular to \(R^\text{HT}\), so we obtain a functor from \(\text{MT}(\mathbb{Q})\) to \(\text{MHTS}(\mathbb{Q})\). Taking into account that the Hodge realization of a mixed Tate motive is a mixed Hodge Tate structure, we actually get a functor

\[
R^\text{HT}: \text{MT}(\mathbb{Q}) \longrightarrow \text{MHTS}(\mathbb{Q})
\]
which respects the weight filtrations.

It is important to keep in mind that the category $\text{MHTS}(\mathbb{Q})$ is much bigger than $\text{MT}(\mathbb{Q})$. For instance compare the set of extensions of $\mathbb{Q}(m)$ and $\mathbb{Q}(n)$ in the category $\text{MHTS}(\mathbb{Q})$ given by Theorem 2.235, that is uncountable, with the set of extensions in $\text{MT}(\mathbb{Q})$ given by Theorem 4.67, that is countable. Thus, it is important to know which mixed Hodge structures come from geometry. This leads to the precise meaning to the word “motivic” when speaking about a mixed Hodge Tate structure:

**Definition 4.82.** We say that a mixed Hodge Tate structure over $\mathbb{Q}$ is *motivic* if it lies in the essential image of the functor $R^H$. The same definition applies to pro-mixed Hodge Tate structures. More generally, we say that a diagram of pro-mixed Hodge Tate structures is motivic if it is isomorphic to the image by the functor $R^H$ of a diagram of pro-mixed Tate motives.

Even if $\text{MHTS}(\mathbb{Q})$ is much bigger than $\text{MT}(\mathbb{Q})$, the realization functor between them is fully faithful and stable by subobjects. This is a very useful result to prove that many mixed Hodge structures have motivic origin. We should mention that to determine whether the Hodge realization functor from the hypothetical category of mixed motives is fully faithful (i.e. bijective on Hom sets) would be an extremely difficult problem. For instance, if the realization functor restricted to the category of pure motives is fully faithful, then the Hodge conjecture holds. That we can prove it for $\text{MT}(\mathbb{Q})$ relies again on Borel’s results about the $K$-theory of number fields.

**Proposition 4.83 (Deligne-Goncharov).** The realization functor (4.81) is fully faithful and its essential image is stable under subobjects.

**Proof.** The key point of the argument is that the realization functor $R^H$ determines injections

$$\text{Ext}^1_{\text{MT}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n)) \to \text{Ext}^1_{\text{MHS}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n))$$

into the extension groups which were computed in Theorem 2.235. For $n = 1$, this follows from the injectivity of

$$\log : \mathbb{Q}^\times \otimes \mathbb{Z} \to \mathbb{C}/2\pi i \mathbb{Q}.$$ 

For $n > 1$, the injectivity follows by interpreting $\text{Ext}^1_{\text{MT}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n))$ as a part of the motivic cohomology of $\text{Spec}(\mathbb{Q})$, which can be computed using $K$-theory:

$$\text{Ext}^1_{\text{MT}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n)) = H^1_{\text{M}}(\text{Spec}(\mathbb{Q}), \mathbb{Q}(n)) = K_{2n-1}(\mathbb{Q}) \otimes \mathbb{Q},$$

then interpreting $\text{Ext}^1_{\text{MHS}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n))$ as Deligne cohomology groups:

$$\text{Ext}^1_{\text{MHS}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n)) = H^1_{\text{D}}(\text{Spec}(\mathbb{Q}), \mathbb{Q}(n)).$$

Under this interpretation, the realization map (4.84) should correspond to the Borel regulator map mentioned in Digression 1.13, which is known to be injective by the work of Borel.

Consider now the fiber functors $\omega_{\text{dR}}$ on $\text{MHS}(\mathbb{Q})$ (Definition 2.206) and $\omega$ on $\text{MT}(\mathbb{Q})$ (4.76). These fiber functors are compatible and induce maps at the level of Tannaka groups

$$C_{\omega_{\text{dR}}}^H = \text{Aut}^\otimes_{\text{MHS}(\mathbb{Q})}(\omega_{\text{dR}}) \to \text{Aut}^\otimes_{\text{MT}(\mathbb{Q})}(\omega) = G_\omega.$$
By the tannakian dictionary, the functor $R^H$ is fully faithful if and only if the morphism (4.85) is surjective.

To show this we argue as follows: both $G_H^\text{HdR}$ and $G_\omega$ can be written as the semidirect product of $G_m$ and a pro-unipotent group.

$$G_H^\text{HdR} = U_{\text{HdR}} \rtimes G_m, \quad G_\omega = U_\omega \rtimes G_m.$$ Then the injectivity of (4.84) implies the surjectivity of (4.85) (see the proof of Theorem 4.128 for the precise relationship between the Ext groups and the Lie algebra of $U_\omega$).

\[ \square \]

**Example 4.86.** Let $n > 0$ be an even integer and $H$ a mixed Hodge structure over $\mathbb{Q}$ that is an extension of $\mathbb{Q}(0)$ by $\mathbb{Q}(n)$. If this extension is non-trivial then it is not motivic over $\mathbb{Q}$, in the sense that it cannot be the Hodge realization of a motive over $\mathbb{Q}$. Indeed, assume that there is a mixed Tate motive over $\mathbb{Q}$ whose Hodge realization is $H$. Since the realization functor is fully faithful, from the exact sequence

$$0 \to \mathbb{Q}(n) \to H \to \mathbb{Q}(0) \to 0$$

corresponds an exact sequence of mixed Tate motives

$$0 \to \mathbb{Q}(n) \to M \to \mathbb{Q}(0) \to 0.$$ Since $\text{Ext}^1_{\text{DMT}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(n)) = 0$ this extension is split. Hence the sequence of mixed Hodge structures is also split.

Of course, there exist motivic non-trivial extensions of $\mathbb{Q}(0)$ by $\mathbb{Q}(n)$ defined over number fields that are not totally real.

\[ \star \star \star \]

**Exercise 4.87.** Prove that the pair of subcategories $(T^{\leq 0}, T^{\geq 0})$ of Example A.106 forms indeed a $t$-structure.

**Exercise 4.88.** Let $\text{Gr}(d, n)$ be the Grassmanian scheme of $d$-planes in $k^n$. Show that $M(\text{Gr}(d, n))$ belongs to $\text{DMT}(k)$.

**Exercise 4.89.** Prove that the Kummer motive $K^\text{Mot}$ of Example 4.68 belongs to $\text{MT}(k)$.

**4.4. Mixed Tate motives over $\mathbb{Z}$.** From now on, we specialize further to the case $k = \mathbb{Q}$. The category $\text{MT}(\mathbb{Q})$ is still too big for our purposes since the extension group

$$\text{Ext}^1_{\text{MT}(\mathbb{Q})}(\mathbb{Q}(0), \mathbb{Q}(1)) \simeq \mathbb{Q}^\times \otimes_{\mathbb{Z}} \mathbb{Q} \simeq \bigoplus_{p \text{ prime}} \mathbb{Q}$$

is infinite-dimensional. To remedy this, Goncharov [Gon01, §3] introduced a subcategory of “mixed Tate motives over $\mathbb{Z}$”.

**4.4.1. Definition and basic properties.**

**Definition 4.90.** A motive $M$ in $\text{MT}(\mathbb{Q})$ is said to be everywhere unramified if, given any integer $n$, there is no subquotient $E$ of $M$ which fits into a non-split extension $0 \to \mathbb{Q}(n+1) \to E \to \mathbb{Q}(n) \to 0$. The full subcategory $\text{MT}(\mathbb{Z})$ of $\text{MT}(\mathbb{Q})$ consisting of everywhere unramified motives is called the category of mixed Tate motives over $\mathbb{Z}$. 
To a motive $M$ over $\mathbb{Q}$ and a prime number $\ell$, we can associate the $\ell$-adic realization of $M$. For instance, to the motive corresponding to a smooth variety $X$ over $\mathbb{Q}$ we associate the dual of the $\ell$-adic cohomology $H^\ell_{\text{ét}}(X_{\overline{\mathbb{Q}}}, \mathbb{Q}_\ell)$. The $\ell$-adic realization is a $\mathbb{Q}_\ell$-vector space, together with a continuous action of $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$.

Let $p$ be a prime number distinct from $\ell$. The choice of an algebraic closure $\overline{\mathbb{Q}}_p$ of $\mathbb{Q}_p$ and a field embedding $\mathbb{Q}_p \hookrightarrow \overline{\mathbb{Q}}_p$ allows one to see the Galois group $\text{Gal}(\overline{\mathbb{Q}}_p/\mathbb{Q}_p)$ as a subgroup of $\text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q})$. By restriction, we obtain a representation of $\text{Gal}(\overline{\mathbb{Q}}_p/\mathbb{Q}_p)$.

Recall that the Galois group of the maximal unramified extension $\mathbb{Q}_p \subset \mathbb{Q}_{ur} \subset \overline{\mathbb{Q}}_p$ is isomorphic to $\text{Gal}(\mathbb{F}_p/\mathbb{F}_p)$. The inertia subgroup $I_p$ is defined by

$$1 \longrightarrow I_p \longrightarrow \text{Gal}(\overline{\mathbb{Q}}_p/\mathbb{Q}_p) \longrightarrow \text{Gal}(\mathbb{F}_p/\mathbb{F}_p) \longrightarrow 1.$$

**Definition 4.91.** Let $\rho: \text{Gal}(\overline{\mathbb{Q}}/\mathbb{Q}) \rightarrow \text{GL}(V)$ be an $\ell$-adic representation, and let $p$ be a prime number distinct from $\ell$. We say that $\rho$ is unramified at $p$ if its restriction to the inertia subgroup $I_p \subseteq \text{Gal}(\overline{\mathbb{Q}}_p/\mathbb{Q}_p)$ is trivial.

We have at our disposal the following criterion to decide whether a mixed Tate motive over $\mathbb{Q}$ belongs to $\text{MT}(\mathbb{Z})$.

**Proposition 4.92 (Deligne-Goncharov).** A mixed Tate motive $M$ over $\mathbb{Q}$ belongs to $\text{MT}(\mathbb{Z})$ if and only if, for each prime number $p$, there exists a prime $\ell \neq p$ such that the $\ell$-adic realization $\omega_{\ell}(M)$ is unramified at $p$.

**Proof.** See [DG05, Prop. 1.8].

**Example 4.93.** Let $K^\text{Mot}_t$ be the Kummer motive associated with a non-zero rational number $t \in \mathbb{Q}^\times$ as in Example 4.68. For each prime $\ell$, the $\ell$-adic realization of $K^\text{Mot}_t$ is the extension

$$0 \longrightarrow \mathbb{Q}_\ell(1) \longrightarrow K^\ell_t \longrightarrow \mathbb{Q}_\ell(0) \longrightarrow 0$$

corresponding to the $\mathbb{Q}_\ell(1)$-torsor given by the projective limit of $\ell^n$-th roots of unity of $t$. This is unramified everywhere if and only if $t \in \mathbb{Z}^\times$. Thus, taking into account that $\mathbb{Z}^\times \otimes_{\mathbb{Z}} \mathbb{Q} = 0$, the only Kummer motive that belongs to $\text{MT}(\mathbb{Z})$ is the trivial one $K^\text{Mot}_1$. This solves the problem of the extension groups being infinite-dimensional.

The main properties of the category $\text{MT}(\mathbb{Z})$ are summarized in the following theorem:

**Theorem 4.94.**

i) $\text{MT}(\mathbb{Z})$ is a tannakian category generated by the objects $\mathbb{Q}(n)$ for all integers $n \in \mathbb{Z}$.

ii) Each object $M$ of $\text{MT}(\mathbb{Z})$ has a canonical increasing weight filtration $W$ indexed by even integers, and such that

$$\text{Gr}^W_{2n} M \simeq \mathbb{Q}(-n)^{\oplus k_n}$$

for some integers $k_n \geq 0$.

iii) The extension groups in the category $\text{MT}(\mathbb{Z})$ are given by

$$\text{Ext}^i_{\text{MT}(\mathbb{Z})}(\mathbb{Q}(n), \mathbb{Q}(m)) = \begin{cases} \mathbb{Q}, & \text{if } i = 0 \text{ and } m - n = 0, \\ \mathbb{Q}, & \text{if } i = 1 \text{ and } m - n \geq 3 \text{ is odd}, \\ 0, & \text{otherwise}. \end{cases}$$
Hence, they are all of them finite-dimensional.

Since \( \text{MT}(\mathbb{Z}) \subset \text{MT}(\mathbb{Q}) \) is stable under subobjects, we immediately deduce from Proposition 4.83:

**Corollary 4.95.** The realization functor

\[
R: \text{MT}(\mathbb{Z}) \rightarrow \text{MHTS}(\mathbb{Q})
\]

is fully faithful with essential image stable under subobjects.

### 4.4.2. Fiber functors

In this section, we introduce various fiber functors on the category of mixed Tate motives over \( \mathbb{Z} \). We will then compute the corresponding Tannaka groups in the next section.

The first fiber functor (see Exercise 4.133) is defined using the weight structure on \( \text{MT}(\mathbb{Z}) \) given by part ii) of Theorem 4.94. Namely, we write

\[
\omega_n(M) = \text{Hom}_{\text{MT}(\mathbb{Z})}(\mathbb{Q}(-n), \text{Gr}_2^W(M))
\]

for each object \( M \) of \( \text{MT}(\mathbb{Z}) \) and each integer \( n \in \mathbb{Z} \), and we define a functor

\[
\omega: \text{MT}(\mathbb{Z}) \rightarrow \text{Vec}_\mathbb{Q}
\]

\[
M \mapsto \omega(M) = \bigoplus_n \omega_n(M).
\]

Observe that \( \omega \) factors through the category of graded \( \mathbb{Q} \)-vector spaces.

From the Hodge realization of a motive we obtain two more fiber functors. The de Rham fiber functor, denoted by \( \omega_{dR} \), is the de Rham part of the Hodge structure. For a motive \( M \in \text{MT}(\mathbb{Z}) \), the vector space \( \omega_{dR}(M) \) comes equipped with two filtrations, the decreasing Hodge filtration \( F \), and the increasing weight filtration \( W \). Since \( (\omega_{dR}(M), F, W) \) is part of a mixed Hodge structure of Tate type, these filtrations are opposed in the sense that, if we write

\[
\omega_{dR}(M)_n = F^n \omega_{dR}(M) \cap W_{2n} \omega_{dR}(M),
\]

Lemma 2.216 implies the existence of functorial isomorphisms

\[
\omega_{dR}(M) = \bigoplus_n \omega_{dR}(M)_n,
\]

\[
F^p \omega_{dR}(M) = \bigoplus_{m \geq p} \omega_{dR}(M)_m,
\]

\[
W_{2n} \omega_{dR}(M) = \bigoplus_{m \leq n} \omega_{dR}(M)_m.
\]

Thus, the de Rham fiber functor \( \omega_{dR} \) also factors through the category of graded vector spaces.

**Lemma 4.97.** The de Rham fiber functor \( \omega_{dR} \) is canonically isomorphic to the fiber functor \( \omega \).

**Proof.** By Exercise 2.219, there is a canonical isomorphism

\[
\omega_{dR}(M)_n \simeq \text{Hom}_{\text{MHTS}}(\mathbb{Q}(-n), \text{Gr}_n^W(R^H(M))).
\]

The fully-faithfulness of the Hodge realization functor (Corollary 4.95) then implies the existence of a canonical isomorphism \( \omega_n(M) \simeq \omega_{dR}(M)_n \).
There is also a Betti fiber functor $\omega_B$ given by the Betti part of the Hodge realization. The rational vector space $\omega_B$ is provided with a weight filtration $W$, but not a Hodge filtration. Note that $\omega_B$ does not factor canonically through the category of graded vector spaces. Finally, there is a comparison isomorphism

$$\text{comp}_{B,\text{dR}} : \omega_{\text{dR}} \otimes_{\mathbb{Q}} \mathbb{C} \longrightarrow \omega_B \otimes_{\mathbb{Q}} \mathbb{C}.$$  

**Example 4.99.** In this example, we compute explicitly the de Rham realization, the Betti realization, and the comparison isomorphism for the motive $\mathbb{Q}(1)$. We begin with the smooth variety

$$X = \mathbb{P}^1_{\mathbb{Q}} \setminus \{0, \infty\} = A^1_{\mathbb{Q}} \setminus \{0\} = \mathbb{G}_{m,\mathbb{Q}} = \text{Spec}(\mathbb{Q}[x, x^{-1}]),$$

which by Remark 4.49 has motive

$$M(X) = \mathbb{Q}(0) \oplus \mathbb{Q}(1)[1].$$

Therefore,

$$t_0(M(X)[-i]) = \begin{cases} \mathbb{Q}(i), & \text{if } i = 0, 1, \\ 0, & \text{otherwise}. \end{cases}$$

We work on the compactification $X \subset \mathbb{P}^1_{\mathbb{Q}}$. Explicitly, the complex of differential forms on $\mathbb{P}^1_{\mathbb{Q}}$ with logarithmic poles along $\{0, \infty\}$ is given as follows:

i) $\Omega^0_{\mathbb{P}^1_{\mathbb{Q}}} (\log \{0, \infty\}) \simeq O_{\mathbb{P}^1_{\mathbb{Q}}}$ is the sheaf of regular functions on $\mathbb{P}^1_{\mathbb{Q}}$.

ii) $\Omega^1_{\mathbb{P}^1_{\mathbb{Q}}} (\log \{0, \infty\})$ is the $O_{\mathbb{P}^1_{\mathbb{Q}}}$-module generated by the differential form $dx/x = -dx^{-1}/x^{-1}$. Thus, as a sheaf, is isomorphic to $O_{\mathbb{P}^1_{\mathbb{Q}}}$.

Although $\mathbb{P}^1_{\mathbb{Q}}$ is not affine, since

$$H^i(\mathbb{P}^1_{\mathbb{Q}}, O_{\mathbb{P}^1_{\mathbb{Q}}}) = 0, \quad \text{for } i > 0,$$

there is no need to search for a resolution of the complex $\Omega^*_p \log \{0, \infty\}$ and we can use directly the complex of global sections to compute de Rham cohomology. We have

$$\Gamma(\mathbb{P}^1_{\mathbb{Q}}, \Omega^0_{\mathbb{P}^1_{\mathbb{Q}}} (\log \{0, \infty\})) = \mathbb{Q}[x, x^{-1}],$$

$$\Gamma(\mathbb{P}^1_{\mathbb{Q}}, \Omega^1_{\mathbb{P}^1_{\mathbb{Q}}} (\log \{0, \infty\})) = \mathbb{Q}[x, x^{-1}] \frac{dx}{x}.$$ 

The differential map is given by $dx^n = nx^{n-1}$. Hence,

$$H^0_{\text{dR}}(X) = \mathbb{Q}, \quad H^1_{\text{dR}}(X) = \mathbb{Q} \frac{dx}{x}.$$ 

Therefore

$$\omega_{\text{dR}}(\mathbb{Q}(1)) = \left(\mathbb{Q} \frac{dx}{x}\right)^\vee.$$

Thus, $\omega_{\text{dR}}(\mathbb{Q}(1))$ is a one-dimensional vector space and we have identified a generator $(dx/x)^\vee$.

The Betti realization is given by the singular homology of the space of complex points. Thus,

$$\omega_B(\mathbb{Q}(1)) = H_1(\mathbb{C} \setminus \{0\}, \mathbb{Q})$$

This is again a rational vector space of dimension 1. A generator of it is given by the unit circle traveled in the counterclockwise direction, that we denote $\gamma$. 


The comparison isomorphism is obtained from the integration of differential forms along singular chains. Since
\[ \int_{\gamma} \frac{dx}{x} = 2\pi i \]
we deduce that \( \text{comp}_{dR,B}(\gamma) = (dx/x)^\vee \otimes (2\pi i) \).

4.4.3. Tannaka groups of \( \mathbf{MT}(\mathbb{Z}) \). We now turn to the description of the affine group schemes associated with the various fiber functors on the category of mixed Tate motives over \( \mathbb{Z} \).

**Notation 4.100.** The following notation will be used throughout:
\begin{align}
G_{dR} &= \text{Aut}^\otimes(\omega) = \text{Aut}^\otimes(\omega_{dR}), \\
G_B &= \text{Aut}^\otimes(\omega_B), \\
P_{B,dR} &= \text{Iso}^\otimes(\omega_{dR}, \omega_B), \\
P_{dR,B} &= \text{Iso}^\otimes(\omega_B, \omega_{dR}).
\end{align}
Observe that \( \text{comp}_{B,dR} \) (resp. \( \text{comp}_{dR,B} \)) is a complex point of \( P_{B,dR} \) (resp. \( P_{dR,B} \)). Since the spaces \( P_{B,dR} \) and \( P_{dR,B} \) have a complex point, they also have a \( \mathbb{Q}_2 \)-point. This implies that they are both \( G_{dR} \)-torsors.

In what follows, we will use the subscript \( dR/B \) for properties which are common to \( G_{dR} \) and \( G_B \).

**Lemma 4.105.** The groups \( G_{dR/B} \) fit into an exact sequence
\[ 1 \rightarrow U_{dR/B} \rightarrow G_{dR/B} \rightarrow \mathbb{G}_m \rightarrow 1, \]
where \( U_{dR/B} \) is a pro-unipotent group.

**Proof.** Recall that the category \( \mathbf{MT}(\mathbb{Z}) \) contains the object \( \mathbb{Q}(-1) \). Since \( \omega_{dR/B}(\mathbb{Q}(-1)) \) is a one-dimensional \( \mathbb{Q} \)-vector space, we obtain a morphism
\[ t_{dR/B} : G_{dR/B} \rightarrow \text{GL}(\omega_{dR/B}(\mathbb{Q}(-1))) = \mathbb{G}_m. \]

We define \( U_{dR/B} \) as the kernel of this morphism.

Since the action of \( G_{dR/B} \) is compatible with the tensor product, an element \( g \in G_{dR/B} \) acts on \( \omega_{dR/B}(\mathbb{Q}(-n)) \) as \( t_{dR/B}(g)^n \). Since the weight filtration is a filtration in the category of motives, \( G_{dR/B} \) respects the weight filtration. This means that, if \( g \in G_{dR/B} \) and \( X \in \text{Ob}(\mathbf{MT}(\mathbb{Z})) \), the action of \( g \) in \( \omega_{dR/B}(X) \) sends \( W_{2n}\omega_{dR/B}(X) = \omega_{dR/B}(W_{2n}X) \) to \( W_{2n}\omega_{dR/B}(X) \). Therefore, it acts on \( \text{Gr}_{2n}^W \omega_{dR/B}(X) \). Since \( \text{Gr}_{2n}^W \omega_{dR/B}(X) \) is a sum of copies of \( \omega_{dR/B}(\mathbb{Q}(-n)) \), \( g \) acts on \( \text{Gr}_{2n}^W \omega_{dR/B}(X) \) as \( t_{dR/B}(g)^n \) and the action of an element \( u \in U_{dR/B} \) on the same space is trivial. This implies that \( U_{dR/B} \) is a pro-unipotent group, that is, a projective limit of unipotent affine algebraic groups.

At this level, an advantage of using the de Rham fiber functor \( \omega = \omega_{dR} \) instead of the Betti fiber functor \( \omega_{B} \) is that the exact sequence (4.106) admits a canonical splitting, as the following lemma shows.

**Lemma 4.108.** There exists a canonical section \( \tau : \mathbb{G}_m \rightarrow G_{dR} \) that induces an action of \( \mathbb{G}_m \) on \( U_{dR} \), hence a semi-direct product decomposition
\[ G_{dR} = U_{dR} \rtimes \mathbb{G}_m. \]
Proof. The existence of the canonical section comes from the fact that the functor \( \omega = \omega_{\text{dR}} \) factors through the category of graded vector spaces. Hence, it decomposes as \( \omega = \bigoplus \omega_n \). Given \( t \in \mathbb{G}_m \), define \( \tau(t) \in G_{\text{dR}} \) as the element that acts as multiplication by \( t^n \) on \( \omega_n \). This defines a section \( \tau : \mathbb{G}_m \to G_{\text{dR}} \) of \( t_{\text{dR}} \). Hence \( G_{\text{dR}} \) is a semidirect product. \( \square \)

**Lemma 4.109.** The action of \( \mathbb{G}_m \) over \( U_{\text{dR}} \) is compatible with the structure of pro-unipotent group. Therefore, \( U_{\text{dR}} \) is a graded pro-unipotent group.

Proof. Recall how the pro-algebraic structure of \( G_{\text{dR}} \) is defined (see Lemma 4.26). For every \( Y \in \text{MT}(\mathbb{Z}) \) we consider the tensor category \( \langle Y \rangle \) generated by \( Y \). Then \( G_{\text{dR}}^Y = \text{Aut}_{\langle Y \rangle} (\omega_{\text{dR}}) \) is a closed subgroup of \( \text{GL}(\omega_{\text{dR}}(Y)) \), hence algebraic and \( G_{\text{dR}} = \lim_{\leftarrow} G_{\text{dR}}^Y. \)

Since the elements of the form \( Y \oplus \mathbb{Q}(1) \) are a cofinal system, we can also write \( G_{\text{dR}} = \lim_{\leftarrow} G_{\text{dR}}^{Y \oplus \mathbb{Q}(1)}. \)

The functor \( \omega_{\text{dR}} \) restricted to \( \langle Y \oplus \mathbb{Q}(1) \rangle \) also factors through the category of graded vector spaces. From this we deduce the existence of two commutative diagrams (with the horizontal arrows to the right or to the left)

\[
\begin{array}{ccc}
G_{\text{dR}} & \longrightarrow & \mathbb{G}_m \\
\downarrow & & \downarrow \\
G_{\text{dR}}^{Y \oplus \mathbb{Q}(1)} & \longrightarrow & \mathbb{G}_m.
\end{array}
\]

Writing \( U_{\text{dR}}^{Y \oplus \mathbb{Q}(1)} = \text{Ker}(G_{\text{dR}}^{Y \oplus \mathbb{Q}(1)} \to \mathbb{G}_m) \) we obtain that \( U_{\text{dR}} = \lim_{\leftarrow} U_{\text{dR}}^{Y \oplus \mathbb{Q}(1)}, \)

every \( U_{\text{dR}}^{Y \oplus \mathbb{Q}(1)} \) is unipotent and that the action of \( \mathbb{G}_m \) on \( U_{\text{dR}} \) comes from compatible actions on each \( U_{\text{dR}}^{Y \oplus \mathbb{Q}(1)}. \)

**Corollary 4.110.** Any \( G_{\text{dR}} \)-torsor defined over \( \mathbb{Q} \) is trivial.

Proof. The key ingredient is the vanishing of the Galois cohomology groups \( H^1(\mathbb{Q}, \mathbb{G}_m) = H^1(\mathbb{Q}, \mathbb{G}_a) = 0. \)

See for instance [Wat79, § 18.2] or [Ser94, Chap. II, § 1.2, Prop. 1]. It follows that, for any unipotent group \( U \) or any group \( G \) that is an extension of \( \mathbb{G}_m \) by \( U \), the Galois cohomology groups are also trivial \( H^1(\mathbb{Q}, U) = H^1(\mathbb{Q}, G) = 0. \)

Now, the group \( G_{\text{dR}} \) can be written as \( G_{\text{dR}} = \lim_{\leftarrow} G_{\text{dR}}^N \), where each \( G_{\text{dR}}^N \) is an extension of \( \mathbb{G}_m \) by a unipotent group and all transition maps are surjective. By Mittag-Leffler we deduce that \( H^1(\mathbb{Q}, G_{\text{dR}}) = \lim_{\leftarrow} H^1(\mathbb{Q}, G_{\text{dR}}^N) = 0, \)
which implies that any $G_{\text{dr}}$-torsor defined over $\mathbb{Q}$ is trivial. \hfill \Box

The corollary has the following important consequence, which will be exploited in the next chapter.

**Proposition 4.111.** There exists an element $a \in G_{\text{dr}}(\mathbb{C})$ such that the isomorphism of functors $\text{comp}_{B, \text{dr}} \circ a$ from $\omega_{\text{dr}} \otimes \mathbb{C}$ to $\omega_B \otimes \mathbb{C}$ sends $\omega_{\text{dr}}$ to $\omega_B$. In other words, for every motive $M$ of $\text{MT}(\mathbb{Z})$, the linear map

$$(\text{comp}_{B, \text{dr}} \circ a)_M : \omega_{\text{dr}}(M) \otimes \mathbb{C} \rightarrow \omega_B(M) \otimes \mathbb{C}$$

satisfies

$$(4.112) \quad \omega_B(M) = (\text{comp}_{B, \text{dr}} \circ a)_M(\omega_{\text{dr}}(M)) \subset \omega_B(M) \otimes \mathbb{C}.$$  

Moreover, $a$ can be chosen of the form $a = u_0 \cdot \tau(2\pi i)^{-1}$ with $u_0 \in U_{\text{dr}}(\mathbb{R})$ and $\tau$ the canonical section from Lemma 4.108.

**Proof.** We follow [Del89, § 8.10]. Recall from (4.103) that

$$P_{B, \text{dr}} = \text{Iso}^{\circ}(\omega_{\text{dr}}, \omega_B)$$

is a $G_{\text{dr}}$-torsor defined over $\mathbb{Q}$. By Corollary 4.110, this torsor is already trivial over $\mathbb{Q}$. Therefore, it has a rational point, and hence there exists an isomorphism of fiber functors $\alpha : \omega_{\text{dr}} \to \omega_B$. Define

$$(4.113) \quad a = \text{comp}_{B, \text{dr}} \circ \alpha.$$

By construction, $a$ is an element of $G_{\text{dr}}(\mathbb{C})$ and $\text{comp}_{B, \text{dr}} \circ a = \alpha$, from which the equality (4.112) follows. Note also that any other element of $G_{\text{dr}}(\mathbb{C})$ satisfying this property is of the form $a\gamma$ for some $\gamma \in G_{\text{dr}}(\mathbb{Q})$.

Let us now turn to the assertion that $a$ can be chosen of the form $u_0 \cdot \tau(2\pi i)^{-1}$ for some $u_0 \in U_{\text{dr}}(\mathbb{R})$. This uses in a crucial way the compatibility between the comparison isomorphism and complex conjugation explained in Proposition 2.167. In fact, the morphism $\rho$ in that proposition can be extended to motives to define an automorphism of the functor $\omega_B$. Hence we obtain a rational point $\rho \in G_B(\mathbb{Q})$.

The compatibility of complex conjugation with the comparison isomorphism in our context says that the diagram of fiber functors

$$\begin{array}{ccc}
\omega_{\text{dr}} & \xrightarrow{\alpha} & \omega_B \\
\downarrow{\rho} & & \downarrow{\rho \otimes c} \\
\omega_{\text{dr}} & \xrightarrow{\alpha} & \omega_B \\
\end{array}$$

$$\begin{array}{ccc}
\omega_B \otimes \mathbb{C} & \xrightarrow{\text{comp}} & \omega_{\text{dr}} \otimes \mathbb{C} \\
\downarrow{\text{Id} \otimes c} & & \downarrow{\text{Id} \otimes c} \\
\omega_B \otimes \mathbb{C} & \xrightarrow{\text{comp}} & \omega_{\text{dr}} \otimes \mathbb{C} \\
\end{array}$$

is commutative, where $c$ is complex conjugation on the coefficients. The complex conjugate of $a$ is $\overline{a} = \text{Id} \otimes c \circ a$. Define $x = a^{-1} \overline{a}$. By the commutativity of the diagram, $x = \alpha^{-1} \rho \alpha$. Thus, $x$ belongs to $G_{\text{dr}}(\mathbb{Q})$ and has order two.

Let us apply (4.113) to the motive $\mathbb{Q}(-1)$. Since

$$\text{comp}_{B, \text{dr}} : \omega_B(\mathbb{Q}(-1)) \rightarrow \omega_{\text{dr}}(\mathbb{Q}(-1))$$

is multiplication by $(2\pi i)^{-1}$ by Example 4.99 and $\alpha|_{\mathbb{Q}(1)} : \omega_{\text{dr}}(\mathbb{Q}(1)) \rightarrow \omega_B(\mathbb{Q}(1))$ is an invertible map of one-dimensional $\mathbb{Q}$-vector spaces, it follows that $\tau_{\text{dr}}(a) \in$
\(G_m(\mathbb{C})\) lies in \((2\pi i)^{-1}\mathbb{Q}^\times\), where \(t_{\text{dR}}: G_{\text{dR}} \to G_m\) is the map introduced in Lemma 4.105.

Which implies that \(t_{\text{dR}}(a^{-1}\pi) = -1\). Since \(\tau\) is a section of \(t_{\text{dR}}\) defined over \(\mathbb{Q}\), up to replacing \(a\) with \(a\gamma\) for some \(\gamma \in G_{\text{dR}}(\mathbb{Q})\), we can assume that

\[
a^{-1}\pi = \tau(-1).
\]

Any other element satisfying both (4.112) and (4.114) is of the form \(a\gamma\) for some \(\gamma \in G_{\text{dR}}(\mathbb{Q})\) such that \(\gamma^{-1}\tau(-1)\gamma = \tau(-1)\). In particular, any \(\gamma \in \tau(\mathbb{Q}^\times)\) works.

It remains to show that \(u_0 \in U_{\text{dR}}(\mathbb{R})\). By (4.114),

\[
\tau(2\pi i)u_0^{-1}\overline{\tau}(-2\pi i)^{-1} = \tau(-1),
\]

and writing \(\tau(-1) = \tau(2\pi i)\tau(-2\pi i)^{-1}\) one gets \(u_0 = \overline{u_0}\). \(\square\)

4.4.4. The period map and the period conjecture. Recall from the previous sections that \(P_{\text{dR},B}\) denotes the scheme of tensor isomorphisms between \(\omega_B\) and \(\omega_{\text{dR}}\), which has the structure of a pro-algebraic variety over \(\mathbb{Q}\). The ring of regular functions \(O(P_{\text{dR},B})\) forms an ind-object in the category of \(\mathbb{Q}\)-algebras of finite type.

**Definition 4.115.** The period map is the ring morphism

\[
\text{per}: O(P_{\text{dR},B}) \longrightarrow \mathbb{C}
\]

given by evaluation at the point \(\text{comp}_{\text{dR},B}:\)

\[
\text{per}(f) = f(\text{comp}_{\text{dR},B}).
\]

Similarly, evaluation at the point \(\text{comp}_{B,\text{dR}}\) yields a period map

\[
O(P_{B,\text{dR}}) \longrightarrow \mathbb{C}
\]

The following is a variant of Grothendieck’s period conjecture for the category of mixed Tate motives over \(\mathbb{Z}\) (cf. also [And04, §25.2]).

**Conjecture 4.117** (Grothendieck). The point \(\text{comp}_{\text{dR},B}\) is generic.

To give a meaning to the word “generic”, we observe that the torsor \(P_{B,\text{dR}}\) can be written as the projective system of the torsors \(P_{B,\text{dR}}^Y\) for the different mixed Tate motives \(Y\), in analogy with Lemma 4.26. Generic then means that, for every quotient \(P_{B,\text{dR}} \twoheadrightarrow P_{B,\text{dR}}^Y\) the image \(\text{comp}_{B,\text{dR}}^Y\) of the point \(\text{comp}_{B,\text{dR}}\) in \(P_{B,\text{dR}}^Y\) is not contained in any proper subvariety defined over \(\mathbb{Q}\). Therefore \(\text{comp}_{B,\text{dR}}\) is generic if and only if, for every mixed Tate motive, the period map

\[
\text{per} = \text{ev}_{\text{comp}_{B,\text{dR}}^Y}: O(P_{B,\text{dR}}^Y) \longrightarrow \mathbb{C}
\]

is injective. Moreover, if \(\text{comp}_{B,\text{dR}}\) is generic, then the transcendence degree of the residue field of \(\text{comp}_{B,\text{dR}}^Y\) is equal to the dimension of \(P_{B,\text{dR}}^Y\).

From the previous discussion, we see that Grothendieck’s period conjecture for mixed Tate motives is equivalent to the following:

**Conjecture 4.118.** The period map (4.116) is injective.
4.4.5. Lie algebras. Through the tannakian formalism, the fiber functor $\omega_{\text{dR}}$ produces an equivalence of categories between $\text{MT}(\mathbb{Z})$ and the category of finite-dimensional representations of $G_{\text{dR}}$. We can now apply the theory of graded Lie algebras explained in Section 3.3.8 to the semi-direct product decomposition $G_{\text{dR}} = U_{\text{dR}} \rtimes \mathbb{G}_m$. By Lemma 4.109, the group $U_{\text{dR}}$ is a graded pro-unipotent group (Definition 3.204). Let $u_{\text{dR}}$ be the Lie algebra of $U_{\text{dR}}$ and $u_{\text{dR}}^{\text{gr}}$ the associated graded Lie algebra as in Definition 3.206. We want to derive from Theorem 4.94 a structure theorem for the Lie algebras $u_{\text{dR}}$ and $u_{\text{dR}}^{\text{gr}}$. To this end, we need to extract some finiteness consequences from Theorem 4.94 that will allow us to use the full force of the theory of graded Lie algebras.

**Lemma 4.119.** The Lie algebra $u_{\text{dR}}^{\text{gr}}$ is negatively graded. That is,

$$
\bigoplus_{n \geq 0} (u_{\text{dR}}^{\text{gr}})_n = 0.
$$

**Proof.** The proof goes in several steps. First we write $U_{\text{dR}} = \lim_{\leftarrow} U_{\alpha}$ with the groups $U_{\alpha}$ unipotent, with all the structural maps $U \to U_{\alpha}$ surjective (Exercise 3.144) and with an action of $\mathbb{G}_m$ on each $U_{\alpha}$ compatible with the action of $\mathbb{G}_m$ on $U_{\text{dR}}$ (Lemma 4.109). For each $\alpha$ we denote by $u_{\alpha}$ the Lie algebra of $U_{\alpha}$. It is finite-dimensional and nilpotent.

The second step is to show, for each finite-dimensional nilpotent Lie algebra $u_{\alpha}$, the implication

$$(4.120) \quad \bigoplus_{n \geq 0} (u_{\alpha})_n \neq 0 \implies \bigoplus_{n \geq 0} (u_{\alpha}/[u_{\alpha}, u_{\alpha}])_n \neq 0.$$ 

Indeed, if the right hand side of implication (4.120) is not satisfied, then

$$\bigoplus_{n \geq 0} (u_{\alpha})_n \subset [u_{\alpha}, u_{\alpha}].$$

Since a bracket of non-negative degree between homogeneous elements should contain at least one non-negative element we deduce

$$\bigoplus_{n \geq 0} (u_{\alpha})_n \subset \left[ u_{\alpha}, \bigoplus_{n \geq 0} (u_{\alpha})_n \right].$$

The nilpotency of $u_{\alpha}$ implies that, in this case $\bigoplus_{n \geq 0} (u_{\alpha})_n = 0$ proving the implication (4.120).

Let now $L_{\mathbb{Q}}(-n)$ denote the abelian graded $\mathbb{Q}$-Lie algebra, equal to $\mathbb{Q}$ in degree $n$. The third step is the observation that if $(u_{\alpha}/[u_{\alpha}, u_{\alpha}])_n \neq 0$ then one can construct a surjective homomorphism of graded Lie algebras $u_{\alpha} \to L_{\mathbb{Q}}(-n)$.

The fourth step is the computation

$$(4.121) \quad \text{Ext}^1_{\text{Rep}_{\mathbb{G}_m}(L_{\mathbb{Q}}(-n))}(\mathbb{Q}(n), \mathbb{Q}) \neq 0.$$ 

See Definition 3.209 for the notation $\text{Rep}_{\mathbb{G}_m}(L_{\mathbb{Q}}(-n))$. To prove (4.121) we consider the graded vector space $E = \mathbb{Q}v_0 \oplus \mathbb{Q}v_{-n}$ with $v_0$ in degree zero and $v_{-n}$ in degree $-n$. Denote by $a_n$ a generator of $L_{\mathbb{Q}}(-n)$ sitting in degree $n$. The graded action of $L_{\mathbb{Q}}(-n)$ on $E$ determined by $a_nv_{-n} = v_0$ turns $E$ into a graded representation.
of $L_Q(-n)$. It is easy to check that this representation is a non-trivial element of $\text{Ext}^1_{\text{Rep}_{dR}}(L_Q(-n))(Q(n), Q)$.

Finally, assume that there is an integer $n \geq 0$ such that $(u^\text{gr}_{\text{dR}})_n \neq 0$. Then there is an $\alpha$ such that $(u^\text{gr}_{\text{dR}})_n \neq 0$. By the second and third steps in the proof, there is an $n' \geq 0$ and a surjective graded Lie algebra homomorphism $u_\alpha \to L_Q(-n')$. Since the map

$$\text{Ext}^1_{\text{Rep}_{dR}}(L_Q(-n'))(Q(n'), Q) \rightarrow \text{Ext}^1_{\text{Rep}_{dR}}(u_\alpha)(Q(n'), Q)$$

is injective, by the fourth step before, we obtain

$$\text{Ext}^1_{\text{Rep}_{dR}}(u_\alpha)(Q(n'), Q) = \text{Ext}^1_{\text{Rep}_{dR}}(u_n)(Q(n'), Q) \neq 0.$$ 

Since the map $U_{\text{dR}} \to U_\alpha$ is surjective, the map

$$\text{Ext}^1_{\text{Rep}_{dR}}(u_n)(Q(n'), Q) \rightarrow \text{Ext}^1_{\text{Rep}_{dR}}(u_{\text{dR}})(Q(n'), Q) = \text{Ext}^1_{\text{Rep}(G_{\text{dR}})}(Q(n'), Q)$$

is also injective. So $\text{Ext}^1_{\text{Rep}(G_{\text{dR}})}(Q(n'), Q) \neq 0$, which contradicts Theorem 4.94. Thus for all $n \geq 0$, $(u^\text{gr}_{\text{dR}})_n = \{0\}$.

**Lemma 4.122.** The finiteness condition

$$\dim(u^\text{gr}_{\text{dR}})_n < \infty$$

holds for all $n < 0$.

**Proof.** The technique is similar to the one in the proof of Lemma 4.119. Assume that there is an $n < 0$ such that $\dim(u^\text{gr}_{\text{dR}})_n = \infty$. Let $n_0$ be the maximum of all the $n$ such that $\dim(u^\text{gr}_{\text{dR}})_n = \infty$. Then $\dim(u^\text{gr}_{\text{dR}}/[u^\text{gr}_{\text{dR}}, u^\text{gr}_{\text{dR}}])_{n_0} = \infty$. This implies that we can construct a linearly independent infinite family of graded Lie algebra homomorphism $\omega_i: u^\text{gr}_{\text{dR}} \to L_Q(-n_0)$, $i \geq 0$. Arguing as in the proof of Lemma 4.119, we can construct a linearly independent infinite family of extensions in $\text{Ext}^1_{\text{Rep}(G_{\text{dR}})}(Q(n_0), Q)$, which contradicts the fact that this $Q$-vector space is finite-dimensional.

**Corollary 4.123.** The graded Lie algebra $\mathcal{O}(U_{\text{dR}})$ is connected and satisfies

$$\dim(\mathcal{O}(U_{\text{dR}})) < \infty$$

for all $n \geq 0$.

**Proof.** The ideal $I \subset \mathcal{O}(U_{\text{dR}})$ corresponds to the unit $e \in U_{\text{dR}}$ is homogeneous and there is a decomposition as $Q$-vector spaces $\mathcal{O}(U_{\text{dR}}) = Q \oplus I$ with $Q$ in degree zero. So it is enough to show that $I$ has only positive degrees. There is an inductive limit presentation

$$(4.124) \quad \mathcal{O}(U_{\text{dR}}) = \lim_{\alpha}(\mathcal{O}(U_\alpha))$$

Let $I_\alpha \subset \mathcal{O}(U_\alpha)$ be the restriction of $I$ to $\mathcal{O}(U_\alpha)$. It is still a homogeneous ideal. As a consequence of the proof of Lemma 4.119, the condition $(u_\alpha)_n = 0$ holds for all $n \geq 0$. From this we deduce that

$$(I_\alpha/I^2_\alpha)_n = 0$$

for all $n \leq 0$. Since $\mathcal{O}(U_\alpha)$ is finitely generated, this implies that $(I_\alpha)_n = 0$ for all $n \leq 0$. From the fact that the inductive limit is compatible with the grading we deduce that $I_\alpha = 0$ for all $n \leq 0$ and $\mathcal{O}(U_{\text{dR}})$ is connected.

By Lemma 4.122, $\dim(I/I^2)_n < \infty$ for all $n > 0$. Since the grading of $I$ is positive, this implies that $\dim I_\alpha < \infty$ for all $n > 0$ concluding the proof of the lemma.
After Corollary 4.123, Theorem 3.210 implies that
\[ \text{Rep}(G_{\text{dR}}) = \text{Rep}_{G_m}(u_{\text{gR}}). \]

Let \( \text{GrMod}^{fd}_{U(u_{\text{gR}})} \) be the category of left \( U(u_{\text{gR}}) \)-modules that are finite-dimensional as \( \mathbb{Q} \)-vector spaces. Then there is a natural equivalence of categories
\[ \text{Rep}_{G_m}(u_{\text{gR}}) = \text{GrMod}^{fd}_{U(u_{\text{gR}})}. \]

Let \( \text{GrMod}^{fg}_{U(u_{\text{gR}})} \) be the category of finitely generated left \( U(u_{\text{gR}}) \)-modules.

**Lemma 4.125.** There is an equality of groups of Yoneda extensions
\[ \text{Ext}^i_{\text{GrMod}^{fd}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}) = \text{Ext}^i_{\text{GrMod}^{fg}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}). \]

**Proof.** There is a canonical morphism
\[ (4.126) \quad \text{Ext}^i_{\text{GrMod}^{fd}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}) \longrightarrow \text{Ext}^i_{\text{GrMod}^{fg}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}). \]

We first show that this map is surjective. Let \( \xi \in \text{Ext}^i_{\text{GrMod}^{fg}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}) \) be an extension. Thus
\[ \xi: \quad 0 \longrightarrow \mathbb{Q} \longrightarrow E_1 \longrightarrow \cdots \longrightarrow E_i \longrightarrow Q(n) \longrightarrow 0 \]
For any graded left \( U(u_{\text{gR}}) \)-module \( E \) we write
\[ F_n E = \bigoplus_{n' \leq n} E_{n'}. \]

Since \( U(u_{\text{gR}}) \) is non-positively graded, \( F_n E \) is a submodule of \( E \). Let \( a = \max(-n, 0) \) and \( b = \min(-n, 0) \). Then there is a diagram of equivalences of Yoneda extensions
\[ F_a \xi \quad \xrightarrow{F_b \xi} \quad \xi. \]

Since each \( E_i \) is finitely generated and \( U(u_{\text{gR}}) \) is finite-dimensional for each \( n \), the extension \( F_a \xi/F_b \xi \) belongs to \( \text{Ext}^i_{\text{GrMod}^{fd}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}) \), showing that the morphism \((4.126)\) is surjective.

The proof of the injectivity of the map \((4.126)\) follows the same principle. The trivial extension is
\[ \xi_0: \quad 0 \longrightarrow \mathbb{Q} \longrightarrow \mathbb{Q} \longrightarrow 0 \ldots \longrightarrow \mathbb{Q}(n) \longrightarrow 0 \]
with the obvious variants for \( i = 1, 2 \). An extension \( \xi \in \text{Ext}^i_{\text{GrMod}^{fg}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}) \) is sent to zero in \( \text{Ext}^i_{\text{GrMod}^{fg}_{U(u_{\text{gR}})}}(Q(n), \mathbb{Q}) \) if there exists an extension \( \xi_1 \) of finitely generated left \( U(u_{\text{gR}}) \)-modules and a diagram of equivalences
\[ \xi_1 \]

\[ \xrightarrow{\xi_0} \quad \xrightarrow{\xi}. \]
Now $F_a \xi_1 / F_b \xi_1$ is an extension of finite-dimensional modules and the diagram of equivalences

$$
\begin{array}{ccc}
F_a \xi_1 / F_b \xi_1 & \xrightarrow{\xi_0} & \xi
\end{array}
$$

shows that $\xi$ was already equivalent to the trivial extension. \qed

Since the category $\text{GrMod}^{\text{fg}}_{U(u_{\text{dR}})}$ has enough projectives. The Yoneda extension groups can be computed using projective resolutions and, by Theorem A.279

$$\text{Ext}^{i}_{\text{GrMod}_{U(u_{\text{dR}})}}(\mathbb{Q}(n), \mathbb{Q}) = \text{Ext}^{i}_{\text{GrMod}_{U(u_{\text{dR}})}}(\mathbb{Q}(n), \mathbb{Q}) = H^i(K^*(u_{\text{dR}})_n).$$

Combining with the previous equalities we obtain

$$(4.127) \quad \text{Ext}^{i}_{\text{Rep}(G_{\eta})}(\mathbb{Q}(n), \mathbb{Q}) = H^i(K^*(u_{\text{dR}})_n).$$

4.4.6. The structure of $u_{\text{gr}}^{\text{gr}}$. The main result of this section is the following:

**Theorem 4.128.** The graded Lie algebra $u_{\text{gr}}^{\text{gr}}$ is free with one generator in each negative odd degree $n \leq -3$, and $u_{\text{dR}}$ is the completion of $u_{\text{dR}}^{\text{gr}}$ with respect to the grading.

**Proof.** Applying (4.127), Proposition A.278 and Theorem 4.94 we deduce that $H_1(K^*(u_{\text{dR}}))_n$ is one dimensional for $n \leq -3$ odd, and is zero otherwise, and that $H_2(K^*(u_{\text{dR}}))$ is zero. Then Proposition A.280 implies that $u_{\text{dR}}^{\text{gr}}$ is free with one generator in each odd degree $n \leq -3$. The second statement is consequence of Lemma 3.207 and Corollary 4.123. \qed

**Remark 4.129.**

i) The grading on $u_{\text{dR}}^{\text{gr}}$ that we consider is the one coming from the action of $\mathbb{G}_m$, where $t$ acts as $t$ on $\mathbb{Q}(-1)$. This is the opposite of the grading used in [DG05] and [Del13] but agrees with the grading used in [And04] or [Bro12].

ii) Consider the abelianization

$$(u_{\text{dR}}^{\text{gr}})^{\text{ab}} = u_{\text{dR}}^{\text{gr}} / [u_{\text{dR}}^{\text{gr}}, u_{\text{dR}}^{\text{gr}}],$$

which is a graded vector space. The proof of Theorem 4.128 yields a canonical identification

$$(u_{\text{dR}}^{\text{gr}})^{\text{ab}} = (\text{Ext}^1_{\text{MT}(\mathbb{Z})}(\mathbb{Q}(0), \mathbb{Q}(n)))^\vee.$$ 

Moreover, $u_{\text{dR}}^{\text{gr}}$ is isomorphic to the free Lie algebra generated by $(u_{\text{dR}}^{\text{gr}})^{\text{ab}}$. Nevertheless, there is no canonical section from $(u_{\text{dR}}^{\text{gr}})^{\text{ab}}$ to $u_{\text{dR}}^{\text{gr}}$, and hence no canonical isomorphism between $u_{\text{dR}}^{\text{gr}}$ and the free Lie algebra generated by $(u_{\text{dR}}^{\text{gr}})^{\text{ab}}$.

iii) Note also that $u_{\text{dR}}$ and $u_{\text{dR}}^{\text{gr}}$ are not isomorphic. In fact, $u_{\text{dR}}$ is the completion of $u_{\text{dR}}^{\text{gr}}$ with respect to the grading, which implies that $u_{\text{dR}}$ is not a free Lie algebra.
4.4.7. The Hilbert–Poincaré series. From Theorem 4.128, we deduce that the universal enveloping algebra \( \mathcal{U}(u_{\text{gr}}^{\text{et}}) \) of \( u_{\text{gr}}^{\text{et}} \) is the free associative graded algebra with one generator in each odd degree \( \leq -3 \). The algebra of regular functions \( \mathcal{O}(U_{\text{dr}}) \) is also graded and is the dual of the completed universal enveloping algebra \( \mathcal{U}(u_{\text{gr}}^{\text{et}}) \) in the graded sense (therefore, it is positively graded). We have an identity of Hilbert–Poincaré series

\[
H_{\mathcal{O}(U_{\text{dr}})}(t) = \sum_{n \geq 0} \dim \mathcal{O}(U_{\text{dr}})_n t^n = \sum_{n \leq 0} \dim \mathcal{U}(u_{\text{gr}}^{\text{et}})_n t^{-n} = H_{\mathcal{U}(u_{\text{gr}}^{\text{et}})}(t^{-1}).
\]

Since \( \mathcal{U}(u_{\text{gr}}^{\text{et}}) \) is the free associative graded algebra with one generator in each odd degree \( n \leq -3 \), the latter Hilbert–Poincaré series is equal to

\[
H_{\mathcal{U}(u_{\text{gr}}^{\text{et}})}(t^{-1}) = \frac{1}{1 - t^3 - t^5 - t^7 - \cdots} = \sum_{k \geq 0} (t^3 + t^5 + t^7 + \cdots)^k,
\]

as can be seen easily because the number of words of degree \( n \) made with the letters \( a_3, a_5, a_7, \ldots \) with \( a_r \) in degree \( r \) is exactly the coefficient of \( t^n \) in the above series. (Compare this with Lemma 1.77, where we computed the Hilbert–Poincaré series of a free commutative algebra.) Therefore, we obtain

\[
(4.130) \quad H_{\mathcal{O}(U_{\text{dr}})}(t) = \frac{1}{1 - t^2 - t^3} = \frac{1 - t^2}{1 - t^2 - t^3}.
\]

Let us now, somehow artificially, introduce the algebra

\[
(4.131) \quad \mathcal{H}^{\text{MT}} = \mathcal{O}(U_{\text{dr}}) \otimes_{\mathbb{Q}} \mathbb{Q}[f_2],
\]

where \( f_2 \) is in degree 2. Note that \( \mathcal{H}^{\text{MT}} \) is isomorphic to the space of functions on \( U_{\text{dr}} \times \mathbb{A}^1 \). Therefore, it can be seen as a relative of \( \mathcal{O}(G_{\text{dr}}) = \mathcal{O}(U_{\text{dr}} \times \mathbb{G}_m) \) of "just the right size". From (4.130) we immediately deduce:

\[\text{Lemma 4.132. The Hilbert–Poincaré series of } \mathcal{H}^{\text{MT}} \text{ is given by} \]

\[
H_{\mathcal{H}^{\text{MT}}}(t) = \frac{1}{1 - t^2 - t^3} = \sum_{k \geq 0} d_k t^k,
\]

where the integers \( d_k \) are the same as in Zagier's Conjecture 1.71.

Following Deligne, Goncharov, and Terasoma, in order to prove the upper bound \( \dim \mathcal{Z}_k \leq d_k \) of Theorem A, we will construct in Chapter 5 a \( \mathbb{Q} \)-algebra \( \mathcal{H} \), which injects into \( \mathcal{H}^{\text{MT}} \), and comes together with a surjective graded map \( \mathcal{H} \to \bigoplus \mathcal{Z}_k \). This will imply immediately the bound. The reason we have changed the grading of \( \mathcal{O}(U_{\text{dr}}) \) is precisely to make this map compatible with the degree. We have already seen that multiple zeta values appear as periods of the pro-unipotent completion of the fundamental group of \( \mathbb{P}_1^\mathbb{Q} \setminus \{0, 1, \infty\} \). The motivic interpretation of this pro-unipotent completion will give the link between \( \mathcal{H} \) and \( \bigoplus \mathcal{Z}_k \). We discuss this interpretation in the next section.

\[\text{***}\]

Exercise 4.133. Use Theorem 4.94 to prove that the functor \( \omega \) is a fibre functor.

Exercise 4.134. In this exercise, we study the dimensions of the graded pieces of the Lie algebra \( u_{\text{gr}}^{\text{et}} \).
i) Compute \( \dim u_{dR}^n \) for \( n \leq 15 \).

ii) Deduce that there are many possible sections of the map \( u_{dR}^{\text{gr}} \to (u_{dR}^{\text{gr}})^{ab} \).

In particular, there is no canonical choice.

iii) Prove that the dimensions are given by the formula

\[
\dim u_{dR}^n = \sum_{d|n} \mu(d) \sum_{s_3, s_5, \ldots \in \mathbb{Z}_{\geq 0}} \frac{(s_3 + s_5 + \cdots - 1)!}{s_3! s_5! \cdots},
\]

where \( \mu(d) \) denotes the Möbius function.

Exercise 4.135. In this exercise, we compare the representations of \( G_{dR} \) and \( U_{dR} \) using the functors of induction and restriction of representations. We will denote by \( \text{Rep}_\infty^\mathbb{Q}(U_{dR}) \) the category of possibly infinite-dimensional representations of \( U_{dR} \). From the inclusion \( U_{dR} \to G_{dR} \) we get a functor \( \text{Res}_{G_{dR}}^{U_{dR}} \) from the category of representations of \( G_{dR} \) to the category of representations of \( U_{dR} \) that simply consists in restricting the action. This functor admits a left adjoint functor denoted by \( \text{Ind}_{U_{dR}}^{G_{dR}} \). By definition of left adjoint functor, there is a natural bijection

\[
\text{Hom}_{\text{Rep}_\infty^\mathbb{Q}(U_{dR})}(R, \text{Res}_{U_{dR}}^{G_{dR}}(S)) = \text{Hom}_{\text{Rep}_\infty^\mathbb{Q}(G_{dR})}(\text{Ind}_{U_{dR}}^{G_{dR}}(R), S).
\]

for all representations \( R \) of \( U_{dR} \) and \( S \) of \( G_{dR} \).

i) Prove the equality

\[
\text{Res}_{U_{dR}}^{G_{dR}}(\mathbb{Q}) = \mathbb{Q}, \quad \text{and} \quad \text{Ind}_{U_{dR}}^{G_{dR}}(\mathbb{Q}) = \prod_{n \in \mathbb{Z}} \mathbb{Q}(n).
\]

ii) Prove that, in this case the adjoint property can be extended to the groups of extensions. Namely, there is a natural bijection

\[
\text{Ext}_{\text{Rep}_\infty^\mathbb{Q}(U_{dR})}^i(\mathbb{Q}, \text{Res}_{U_{dR}}^{G_{dR}}(\mathbb{Q})) = \text{Ext}_{\text{Rep}_\infty^\mathbb{Q}(G_{dR})}^i(\text{Ind}_{U_{dR}}^{G_{dR}}(\mathbb{Q}), \mathbb{Q}).
\]

4.5. The motivic fundamental groupoid of \( \mathbb{P}^1 \setminus \{0, 1, \infty\} \). We continue considering the algebraic variety

\[
X = \mathbb{P}^1 \setminus \{0, 1, \infty\}
\]

over \( \mathbb{Q} \) and the complex manifold

\[
M = X(\mathbb{C}) = \mathbb{P}^1(\mathbb{C}) \setminus \{0, 1, \infty\}.
\]

As in Section 3.10, we set:

- \( \mathbf{0} \) is the tangential base point \((0, 1)\), \text{i.e.} the tangent vector 1 at 0,
- \( \mathbf{1} \) is the tangential base point \((1, -1)\), \text{i.e.} the tangent vector \(-1\) at 1.

Let \( x, y \in X(\mathbb{Q}) \cup \{0, 1\} \) be rational or tangential base points. The aim of this section is to explain that the pro-unipotent completion of the torsor of paths from \( x \) to \( y \), as well as the extra structures given by composition of paths and local monodromy, are motivic in the sense of Definition 4.82. In fact, we want to add to Summary 3.397 a motivic side whose Betti and de Rham realizations give the Betti and de Rham sides of that summary. To exhibit the motivic nature of the affine group schemes and torsors in that summary, it seems necessary to use the language of algebraic geometry over a tannakian category [Del89, §6]. In order to avoid this language, we will only consider the motivic analogues of \( \mathcal{U}_\bullet^? \) and \( \mathcal{L}_\bullet^? \).
4.5.1. **The pro-mixed Tate motive** $U_x^{\text{Mot}}$. We start with the case of two rational base points $x, y \in X(\mathbb{Q}) \subseteq M$. Recall the cosimplicial manifold $y M^\bullet_x$ from Construction 3.272. As we already used in Section 3.7.1, when endowing the fundamental group with a mixed Hodge structure over $\mathbb{Q}$, all the maps involved in $y M^\bullet_x$ are algebraic and, the points $x, y$ being rational, defined over $\mathbb{Q}$. We will denote by $y X^\bullet_x$ the corresponding cosimplicial object in the category $\text{Sm}(\mathbb{Q})$.

As explained in Section 4.2.9, to $y X^\bullet_x$ one associates a family of motives

$$\{[\sigma \leq N N y X^\bullet_x]\}_{N \geq 0}.$$

By construction, given integers $M \geq N \geq 0$, there is a morphism

$$\sigma \leq M N y X^\bullet_x \rightarrow \sigma \leq N N y X^\bullet_x$$

making $\{[\sigma \leq N N y X^\bullet_x]\}_{N \geq 0}$ into a projective system of motives.

**Lemma 4.136.** The object $[\sigma \leq N N y X^\bullet_x]$ belongs to $\text{DMT}(\mathbb{Q})$.

**Proof.** Exercise 4.164. □

We can therefore consider its cohomology with respect to the $t$-structure of $\text{DMT}(\mathbb{Q})$.

**Definition 4.137.** For each $N \geq 0$, we define a mixed Tate motive

$$y U_x^{\text{Mot}, N} = H_0([\sigma \leq N N y X^\bullet_x]) \in \text{MT}(\mathbb{Q}).$$

As $N$ varies, these motives fit into a pro-mixed Tate motive $y U_x^{\text{Mot}}$.

We also consider the constant cosimplicial variety $\text{Spec}(\mathbb{Q})^\bullet$ given by $\text{Spec}(\mathbb{Q})$ in all degrees, with coface and codegeneracy maps all equal to the identity. Applying the previous construction to $\text{Spec}(\mathbb{Q})^\bullet$, one easily finds (Exercise 4.165) that, for all $N \geq 0$,

$$H_0([\sigma \leq N N \text{Spec}(\mathbb{Q})^\bullet]) = \mathbb{Q}(0).$$

4.5.2. **The structures of** $y U_x^{\text{Mot}}$. We next introduce some extra structures carried by $y U_x^{\text{Mot}}$: the unit and counit, the completed coproduct, the composition of paths and the antipode. The idea is to give a geometric analogue of the constructions in the reduced bar complex of a connected dg-algebra (see Definition 3.248), in such a way that they are compatible with the isomorphism from Lemma 3.275.

We start with the unit and counit. Each point $x \in X(\mathbb{Q})$ determines a morphism of cosimplicial varieties

$$\eta^Y_x : \text{Spec}(\mathbb{Q})^\bullet \longrightarrow x X^\bullet_x$$

which sends $\text{Spec}(\mathbb{Q})^n = \text{Spec}(\mathbb{Q})$ to the point $(x, \ldots, x) \in x X^n_x$. Besides, we have for each pair of points $x, y \in X(\mathbb{Q})$ a map of cosimplicial varieties

$$\epsilon^Y_{xy} : y X^\bullet_x \longrightarrow \text{Spec}(\mathbb{Q})^\bullet$$

given by the structural map in all degrees. These induce morphisms

$$\eta^Y_x : \mathbb{Q}(0) \longrightarrow x U_x^{\text{Mot}},$$
$$\epsilon^Y_{xy} : y U_x^{\text{Mot}} \longrightarrow \mathbb{Q}(0),$$

which are called *unit* and *counit* respectively.
Remark 4.140. To understand the notation we will use in the following constructions, recall from 4.2.3 that the direct sum in the category $\text{SmCor}(\mathbb{Q})$ corresponds to the disjoint union of varieties, whereas the tensor product is given by the cartesian product of varieties. Note also that the description we will give of morphisms should be understood as correspondences. For instance, the map for the antipode below is the cycle in $X^n \times X^n$ given by $(-1)^{\frac{n(n+1)}{2}} \Gamma$, where $\Gamma$ is the graph of the map $(x_1, \ldots, x_n) \mapsto (x_n, \ldots, x_1)$.

For any rational points $x, y \in X(\mathbb{Q})$, consider the unbounded complex $C^\ast(yX_x^\ast)$ in the category $\text{SmCor}(\mathbb{Q})$ given by

$$C^n(yX_x^\ast) = y^X_x,$$

together with the differential

$$d = \sum_{i=0}^{n+1} (-1)^i \delta^i: C^n(yX_x^\ast) \longrightarrow C^{n+1}(yX_x^\ast).$$

We consider the morphism

$$[X]^\otimes n \longrightarrow \bigoplus_{p+q=n} [X]^\otimes p \otimes [X]^\otimes q$$

in $\text{SmCor}(\mathbb{Q})$ that sends the point $(x_1, \ldots, x_n)$ to

$$\sum_{p+q=n} \sum_{\sigma \in \mathfrak{S}(p,q)} (-1)^{\sigma} (x_{\sigma(1)}, \ldots, x_{\sigma(p)}) \otimes (x_{\sigma(p+1)}, \ldots, x_{\sigma(n)}),$$

where $(-1)^{\sigma}$ is the sign of the permutation $\sigma$.

Remark 4.142. Notice that what appears in this product is the permutation $\sigma$ instead of $\sigma^{-1}$ as in Proposition 1.158 or Definition 3.248. This is due to the contravariant nature of differential forms.

One can check that this map induces a morphism of complexes

$$\nabla^\vee: C^\ast(yX_x^\ast) \longrightarrow C^\ast(yX_x^\ast) \otimes C^\ast(yX_x^\ast).$$

Now, for points $x, y, z \in X(\mathbb{Q})$, and integers $p, q \geq 0$, we consider the map

$$[X]^\otimes p \otimes [X]^\otimes q \longrightarrow [X]^\otimes (p+q)$$

given by

$$\sum_{p+q=n} \sum_{\sigma \in \mathfrak{S}(p,q)} (-1)^{\sigma} (x_{\sigma(1)}, \ldots, x_{\sigma(p)}) \otimes (z_{\sigma(p+1)}, \ldots, z_{\sigma(n)}),$$

where $(-1)^{\sigma}$ is the sign of the permutation $\sigma$.

The next step is to induce morphisms at the level of the normalized complexes $N(yX_x^\ast)$. For this, one needs to check that the chain morphisms commute with the projector $p_n$ of Lemma 4.57 and take care of the truncations. The precise statement is the following lemma whose proof is elementary.
**Lemma 4.145.** Let $N, M \geq 0$ be integers.

i) If $N \geq 2M$, the map $\nabla^\vee$ induces a morphism of complexes

$$\nabla^\vee: \sigma_{\leq N} \mathcal{N}(yX^*_y) \to \sigma_{\leq M} \mathcal{N}(yX^*_y).$$

ii) If $N \geq M$, the map $\Delta^\vee$ induces a morphism of complexes

$$\Delta^\vee: \sigma_{\leq N} \mathcal{N}(zX^*_z) \otimes \sigma_{\leq N} \mathcal{N}(yX^*_y) \to \sigma_{\leq M} \mathcal{N}(zX^*_z).$$

iii) If $N \geq M$, the map $S^\vee$ induces a morphism of complexes

$$S^\vee: \sigma_{\leq N} \mathcal{N}(yX^*_y) \to \sigma_{\leq M} \mathcal{N}(zX^*_z).$$

Moreover, when $N$ and $M$ vary within the above constraints, the three morphisms yield maps of projective systems.

As a consequence of Lemma 4.145 we obtain the following result.

**Proposition 4.146.** Given any three points $x, y, z \in X(\mathbb{Q})$, there are morphisms of pro-mixed Tate motives

i) a composition of paths

$$\Delta^\vee: z \mathcal{U}^\text{Mot}_y \otimes y \mathcal{U}^\text{Mot}_x \to z \mathcal{U}^\text{Mot}_z;$$

ii) a unit

$$\eta^\vee_z: \mathbb{Q}(0) \to z \mathcal{U}^\text{Mot}_z;$$

iii) a completed coproduct

$$\nabla^\vee: y \mathcal{U}^\text{Mot}_x \to y \mathcal{U}^\text{Mot}_x \otimes y \mathcal{U}^\text{Mot}_x;$$

iv) a counit

$$\epsilon^\vee: y \mathcal{U}^\text{Mot}_x \to \mathbb{Q}(0);$$

v) a dual antipode

$$S^\vee: y \mathcal{U}^\text{Mot}_x \to x \mathcal{U}^\text{Mot}_y.$$
As we have seen in Proposition 2.263, the differential graded algebra \( A^* \) allows us to compute the de Rham cohomology of \( \mathbb{P}_Q^1 \setminus \{0, 1, \infty\} \) with its weight and Hodge filtration. We have seen also in Section 3.7.2 that it can be used to compute the de Rham side of \( U_H^• ∗ \).

We will now use this algebra to compute the de Rham side of \( R^H(\text{Mot}_x) \).

Consider the variety \((\mathbb{P}_1 Q)^n\) and the divisor \(D_n\) consisting of all points with one coordinate equal to 0, 1 or \(\infty\). This is a simple normal crossing divisor. Then, for every pair of rational points \(x, y \in X(\mathbb{Q})\), the \(n\)-th component of the cosimplicial scheme \(y X^n_x\) is given by

\[
y X^n_x = (\mathbb{P}_Q^1)^n \setminus D_n.
\]

Let \( (E^n_{\mathbb{P}_1(\mathbb{C})} (\log D_n), F, W) \) be the de Rham algebra of complex-valued smooth differential forms on \((\mathbb{P}_1(\mathbb{C}))^n\) with logarithmic poles along \(D_n\) with its Hodge and weight filtration (see Section 2.8.3). We now denote

\[
A^*(y X^n_x) = A^* \otimes \cdots \otimes A^*.
\]

The Hodge and weight filtrations of \( A^* \) induce Hodge and weight filtrations on \( A^*(y X^n_x) \).

For all rational points \(x, y \in X(\mathbb{Q})\) and integer \(n \geq 0\), there is an inclusion

\[
A^*(y X^n_x) \rightarrow E^n_{\mathbb{P}_1(\mathbb{C})} (\log D_n)
\]

given by

\[
1 \otimes \cdots \otimes \omega_{\varepsilon_i} \otimes \cdots \otimes 1 \mapsto \omega_{\varepsilon_i} (t_i),
\]

where \(\varepsilon_i = 0, 1\), the 1-form \(\omega_{\varepsilon_i}\) is in the position \(i\) and \(t_i\) is the \(i\)-th coordinate of \(A^n_C \subset (\mathbb{P}_C^1)^n\). From the fact that

\[
A^* \otimes \mathbb{C} \rightarrow E^n_{\mathbb{P}_1(\mathbb{C})} (\log D_n)
\]

is a bifiltered quasi-isomorphism (see the end of Example 2.260) we deduce that the map

\[
A^*(y X^n_x) \otimes \mathbb{C} \rightarrow E^n_{\mathbb{P}_1(\mathbb{C})} (\log D_n)
\]

is also a bifiltered quasi-isomorphism. Thus, \( A^*(y X^n_x) \) determine the Hodge and weight filtration of the de Rham cohomology of \(y X^n_x\), even with its \(\mathbb{Q}\)-structure. The important point to note now, that is easy to check, is that the previous inclusions are functorial with respect to any morphism involved in the structures of \(y X^n_x\).

More precisely, the following holds:

**Lemma 4.148.** The family of inclusions

\[(4.149)\quad A^*(y X^n_x) \rightarrow E^n_{\mathbb{P}_1(\mathbb{C})} (\log D_n),\]

for \(x, y \in X(\mathbb{Q})\) and \(n \geq 0\) is functorial with respect to

i) the coface and codegeneracy maps of the cosimplicial schemes \(y X^n_x\);

ii) the maps (4.138) and (4.139), where we identify \(\text{Spec}(\mathbb{Q})\) with \(y X^n_0\) through the structure map of \(\mathbb{Q}\)-schemes;

iii) the maps (4.141), (4.143) and (4.144) that will induce the product, the coproduct and the antipode.

Moreover, each map in the family is a filtered quasi-isomorphism.
Proof. The fact that each map in the family is a quasi-isomorphism has already been discussed. To be precise of the meaning of functoriality in this lemma we spell out the case of a coface, being all the other maps treated in a similar way. Consider the coface 
\[ \delta^0 : yX^n_x \longrightarrow yX^{n+1}_x \]
given by \( \delta^0(x_1, \ldots, x_n) = (y, x_1, \ldots, x_n) \). Then there is a diagram 
\[ \begin{CD}
A^\ast(yX^{n+1}_x) @>>> E^\ast_{p_1(C), n+1}(\log D_{n+1}),
\end{CD} \]
\[ \begin{CD}
A^\ast(yX^n_x) @>>> E^\ast_{p_1(C), n}(\log D_n).
\end{CD} \]
The statement of the lemma means that there is a unique morphism, also denoted by \((\delta^0)^\ast\), 
\[ A^\ast(yX^{n+1}_x) \longrightarrow A^\ast(yX^n_x) \]
completing the diagram to a commutative square. By the fact that the horizontal arrows are injective the unicity is clear and we have to show the existence. The needed map is obviously given by 
\[ (\delta^0)^\ast(a_1 \otimes \cdots \otimes a_{n+1}) = \varepsilon(a_1)a_2 \otimes \cdots \otimes a_{n+1}, \]
where \(\varepsilon\) is the augmentation of \(A^\ast\) given by (3.335). All the remaining maps are defined in a similar way. The compatibility of all the morphisms with the composition of maps is just a consequence of the injectivity of the morphisms (4.149). \(\square\)

The main consequence of Lemma 4.148 is that to compute the de Rham realization functor as explained in Section 4.2.10 we can use the algebras \(A^\ast(yX^n_x)\) and we deduce that 
\[ R^\text{dR}(U^\text{Mot}_y) \cdot \vdash = \lim_{\to} \mathcal{H}^0 \left( \text{Tot} \sigma \subseteq N \mathcal{A}^\ast(yM^n_x) \right). \]

By Lemma 3.275, there is a canonical isomorphism 
\[ \text{Tot} \mathcal{N} A^\ast_x \cong B^\ast(A^\ast). \]
Taking the truncation, the cohomological functor \(H^0\) and the inductive limit we deduce that 
\[ R^\text{dR}(U^\text{Mot}_x) \cdot \vdash = yA^\text{dR}_x. \]
By duality we get 
\[ R^\text{dR}(U^\text{Mot}_x) = yU^\text{dR}_x. \]
The next step is to check the compatibility with the structures on both sides. This is the content of next lemma.

Lemma 4.150. The morphism \(\psi\) of Lemma 3.275 is compatible with the shuffle product, the coproduct and the antipode.

Proof. Since the different structures do not depend on the rational points \(x, y\) we omit them from the notation. We begin by proving the compatibility with the shuffle product. For non-negative integers \(p, q, r, s\), the map (4.141) induces a map 
\[ \nabla : A^\ast(X^p) \otimes A^\ast(X^q) \longrightarrow A^{r+s}(X^{p+q}) \]
given by 
\[ \nabla ((\omega_1(x_1) \wedge \cdots \wedge \omega_p(x_p)) \otimes (\omega_{p+1}(x_{p+1}) \wedge \cdots \wedge \omega_{p+q}(x_{p+q}))) = \sum_{\sigma \in \Omega(p,q)} (-1)^s (-1)^p s_1(\omega_1(x_{\sigma(1)}) \wedge \cdots \wedge \omega_{p+q}(x_{\sigma(p+q)})) \]

The sign \((-1)^s\) comes from the definition of the map (4.141), while the sign \((-1)^p s_1\) comes from the fact that we have to swap the simplicial degree \(p\) with the differential degree \(s\). We now compute 
\[ \nabla(\psi([\omega_1|\ldots|\omega_p] \otimes \psi([\omega_{p+1}|\ldots|\omega_{p+q}])) = \sum_{\sigma \in \Omega(p,q)} (-1)^{\sum_{i=1}^{p+q} i \deg(\omega_i)} (-1)^s \omega_1(x_{\sigma(1)}) \wedge \cdots \wedge \omega_{p+q}(x_{\sigma(p+q)}). \]

In this equality we have used that 
\[ \sum_{i=1}^{p+q} i \deg(\omega_i) + \sum_{j=1}^q j \deg(\omega_{p+j}) + p \sum_{j=1}^q \deg(\omega_{p+j}) = \sum_{i=1}^{p+q} i \deg(\omega_i). \]

We also compute 
\[ \psi(\nabla([\omega_1|\ldots|\omega_p] \otimes [\omega_{p+1}|\ldots|\omega_{p+q}])) = \sum_{\sigma \in \Omega(p,q)} \eta(\sigma)(-1)^{\sum_{i=1}^{p+q} i \deg(\omega_{\sigma^{-1}(i)})} \omega_{\sigma^{-1}(1)}(x_1) \wedge \cdots \wedge \omega_{\sigma^{-1}(p+q)}(x_{p+q}), \]

where \(\eta(\sigma)\) is the sign determined by equation (3.243). In order to see that the signs in both expressions agree we introduce formal variables \(a_1 \ldots a_{p+q}\) of degree \(-1\), and put \(a = a_1 \wedge \cdots \wedge a_{p+q}\). Then, on the one hand, 
\[ \eta(\sigma)(-1)^{\sum_{i=1}^{p+q} i \deg(\omega_{\sigma^{-1}(i)})} \omega_{\sigma^{-1}(1)}(x_1) \wedge \cdots \wedge \omega_{\sigma^{-1}(p+q)}(x_{p+q}) \wedge a = \eta(\sigma)a_1 \wedge \omega_{\sigma^{-1}(1)}(x_1) \wedge \cdots \wedge a_{p+q} \wedge \omega_{\sigma^{-1}(p+q)}(x_{p+q}) = a_1 \wedge \omega_1(x_{\sigma(1)}) \wedge \cdots \wedge a_{p+q} \wedge \omega_{p+q}(x_{\sigma(p+q)}), \]

while, on the other hand, 
\[ (-1)^{\sum_{i=1}^{p+q} i \deg(\omega_i)} (-1)^s \omega_1(x_{\sigma(1)}) \wedge \cdots \wedge \omega_{p+q}(x_{\sigma(p+q)}) \wedge a = (-1)^{\sum_{i=1}^{p+q} i \deg(\omega_i)} \omega_1(x_{\sigma(1)}) \wedge \cdots \wedge \omega_{p+q}(x_{\sigma(p+q)}) \wedge a_1 \wedge \cdots \wedge a_{p+q} = a_1 \wedge \omega_1(x_{\sigma(1)}) \wedge \cdots \wedge a_{p+q} \wedge \omega_{p+q}(x_{\sigma(p+q)}), \]

proving the compatibility with the shuffle product.

We next prove the compatibility with the coproduct. The maps (4.143) induce morphisms 
\[ \Delta: A(X^n) \longrightarrow \bigoplus_{r+s=t} \bigoplus_{p+q=n} A^r(X^p) \otimes A^s(X^q) \]

given by 
\[ \Delta(\omega_1(x_1) \wedge \cdots \wedge \omega_n(x_n)) = \sum_{p=0}^n (-1)^p \sum_{i=p+1}^n \deg(\omega_i) \omega_1(x_1) \wedge \cdots \wedge \omega_p(x_p) \otimes \omega_{p+1}(x_{p+1}) \wedge \cdots \wedge \omega_n(x_n), \]
where the sign comes again from the fact that we are swapping a simplicial degree with a differential degree. Then $\Delta \circ \psi = \psi \circ \Delta$ is easily checked using equation (4.151).

Finally, the map (4.144) induces a morphisms

$$S: A^\ast(X^n) \rightarrow A^\ast(X^n)$$

given by

$$S(\omega_1(x_1) \wedge \cdots \wedge \omega_n(x_n)) = (-1)^{\frac{n(n+1)}{2}} \omega_1(x_n) \wedge \cdots \wedge \omega_n(x_1).$$

The proof of the compatibility of the antipode $S$ with the map $\psi$ follows the same method as the previous compatibilities. □

As a consequence of this lemma we know that the de Rham realization $R^{dR}(U Mot_X)$ agrees with $= y U^{dR}_x$ including all the structures.

To conclude, the fact that $R^B(y U Mot_X) = y U^{B}_x$ follows from Theorem 3.307, Lemma 3.289, Proposition A.178 and the description of the Betti realization functor in Section 4.2.10. □

4.5.4. The case of tangential base points. We next have to consider the case of tangential base points and prove that the space of paths with tangential base points is also motivic.

We start with the particular case of $\mathbb{G}_m = \mathbb{P}^1 \setminus \{0, \infty\}$ and the tangential base point $0 = (0, 1)$. Recall that in Variant 3.401 we have stated that the method used to study $\mathbb{P}^1 \setminus \{0, 1, \infty\}$ can be used to study $\mathbb{G}_m$. In this case the dg-algebra we use is $A(\mathbb{G}_m) = \mathbb{Q} \oplus \mathbb{Q} \omega_0$ and we obtain that $y U^{dR}(\mathbb{G}_m)_x = \mathbb{Q}[\epsilon_0]$

**Proposition 4.152.** There is an isomorphism

$$\varrho U(\mathbb{G}_m)_0^H \xrightarrow{\sim} \imath U(\mathbb{G}_m)_1^H.$$  

Moreover, if $x \in \mathbb{G}_m(\mathbb{Q})$, then there is an isomorphism

$$\varrho U(\mathbb{G}_m)_x^H \xrightarrow{\sim} \imath U(\mathbb{G}_m)_x^H.$$  

**Proof.** We only prove the second statement. The proof of the first one is similar. We define the de Rham component of the sought isomorphism as the identity. Clearly it is compatible with the Hodge and the weight filtrations. This is justified because as was the case of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$, the de Rham side is independent of the base points.

We have introduced the straight path $dch$ between 0 and 1, given by $dch(t) = t$ for $t \in [0, 1]$. We define the Betti part of the isomorphism as the map induced by the composition of paths which sends a path $\gamma \in \pi_1(\mathbb{G}_m; 0, x)$ to the path $dch \cdot \gamma \in \pi_1(\mathbb{G}_m; 1, x)$. We need to prove that both isomorphisms are compatible with the comparison isomorphism. The comparison map $\text{comp} = \text{comp}_{dR,B}$ is given by the iterated integral map

$$\text{comp}(\gamma) = \sum_{n \geq 0} \epsilon_0^n \int_{\gamma} \omega_0.$$

and satisfies $\text{comp}(\gamma \cdot \gamma') = \text{comp}(\gamma) \cdot \text{comp}(\gamma')$. Thus, we only need to check that $\text{comp}(dch) = 1$. This last equality follows by taking the limit $z \to 1$ in Example 3.374.
That the Betti part of the isomorphism is compatible with the weight filtration is now a consequence of the fact that the de Rham side is.

From the proposition we immediately deduce:

**Corollary 4.153.** The pro-mixed Hodge structures \( \mathcal{O}U(\mathbb{G}_m)_H \) and \( \mathcal{O}U(\mathbb{G}_m)_0 \) are motivic (i.e. they are in the essential image of \( R^H \)).

The next lemma describes the structure of \( \mathcal{O}U(\mathbb{G}_m)_H \).

**Lemma 4.154.** The pro-mixed Hodge structure \( \mathcal{O}U(\mathbb{G}_m)_H \) is split and agrees with \( \bigoplus_{n \geq 0} \mathbb{Q}(n) \).

In particular, \( \mathcal{O}L(\mathbb{G}_m)_0 = \mathbb{Q}(1) \).

**Proof.** Let \( f_n \) and \( b_n \) be generators of \( \mathbb{Q}(n)_{\text{dR}} \) and \( \mathbb{Q}(n)_{\text{B}} \) respectively; they satisfy \( \text{comp}(b_n) = (2\pi i)^n f_n \). Let \( \gamma_0 \) be the generator of \( \pi_1(\mathbb{G}_m, 0) \) introduced in Section 3.9.1. By Example 3.376, we know that \( \text{comp}_{\text{dR,B}}(\gamma_0) = \exp(2\pi i c_0) \).

Consider the power series
\[
\log(\gamma_0) = \log(1 + (\gamma_0 - 1)) \in \mathbb{Q}[\pi_1(\mathbb{G}_m, 0)]^\wedge.
\]

For each \( n \), we define a map
\[
\phi_n : \mathbb{Q}(n) \to \mathcal{O}U(\mathbb{G}_m)_0
\]
which sends \( f_n \) to \( e_0^n \in \mathbb{Q}(e_0) \) and \( b_n \) to \( \log(\gamma_0)^n \in \mathbb{Q}[\pi_1(\mathbb{G}_m, 0)]^\wedge \). This map is compatible with the comparison isomorphism:
\[
\text{comp}_{\text{dR,B}}(\phi_n(b_n)) = \text{comp}_{\text{dR,B}}(\log(\gamma_0)^n) = (2\pi i)^e_0^n \in \mathbb{Q}[\pi_1(\mathbb{G}_m, 0)]^\wedge,
\]
\[
\text{comp}_{\text{dR,B}}(\log(\gamma_0)^n) = \phi_n(\text{comp}_{\text{dR,B}}(b_n)).
\]

Moreover, taking into account that
\[
\log(\gamma_0) \in J^n \mathbb{Q}[\pi_1(\mathbb{G}_m, 0)]^\wedge = W_{-2n} \mathbb{Q}[\pi_1(\mathbb{G}_m, 0)]^\wedge
\]
and \( e_0^n \in F^{-n} \cap W_{-2n} \mathbb{Q}(e_0) \), the map (4.155) is a morphism of mixed Hodge structures. The maps \( \phi_n \) induce the sought isomorphism of pro-mixed Hodge structures. The second statement follows immediately from the first one.

We next reduce the question of showing that the mixed Hodge structure of the universal enveloping algebra is motivic to the question that the one of the Lie algebra is motivic.

**Lemma 4.156.** Let \( x \) and \( y \) be two base points of \( M \) (tangential or not). Then the pro-mixed Hodge structure \( yU^H_x \) is motivic if and only if the structure \( yL^H_x \) is.

**Proof.** Since \( yL^H_x \) is a sub-mixed Hodge structure of \( yU^H_x \), by Proposition 4.83, if \( yU^H_x \) is motivic, then \( yL^H_x \) is also motivic.

Conversely, assume that \( yL^H_x \) is motivic. Recall that \( yL^H_x \) is a projective limit
\[
yL^H_x = \lim_{N} yL^H_{x}/(yL^H_{x})_{\geq N + 1}.
\]

By Proposition 4.83, each quotient in this limit is motivic. Since
\[
yA^H_x = \lim_{N} \text{Sym}^*(yL^H_{x}/(yL^H_{x})_{\geq N + 1})^\wedge,
\]
we deduce that $y^AH_x$ is also motivic. By duality, we conclude that $yU^H_x$ is also motivic. \hfill \Box

Now let $x \in X(\mathbb{Q}) = \mathbb{P}^1(\mathbb{Q}) \setminus \{0, 1, \infty\}$ be a rational point and $0$ the tangential base point $(0, 1)$. By Lemma 4.156, to show that $\alpha U^H_x$ is motivic, it is enough to show that $\alpha \mathcal{L}^H_x$ is. To show that $\alpha \mathcal{L}^H_x$ is motivic, we will embed it in a mixed Hodge structure that we know is motivic. Once this is proved, that $\alpha U^H_x$ is motivic follows from the symmetry of $X$ that sends $x$ to $1 - x$.

Let $f \colon X \to \mathbb{G}_m$ be the natural inclusion. Then $f$ induces a morphism of mixed Hodge structures

\begin{equation}
\varphi_1 \colon \alpha \mathcal{L}^H_x \longrightarrow \alpha \mathcal{L}(\mathbb{G}_m)^H_x.
\end{equation}

The map $f$ also induces a local monodromy map

\begin{equation}
\varphi^* \colon \alpha U(\mathbb{G}_m)^H_0 \longrightarrow \alpha U^H_0.
\end{equation}

Consider the composition of morphisms of mixed Hodge structures

\begin{equation}
\alpha U^H_x \otimes \alpha U(\mathbb{G}_m)^H_0 \xrightarrow{\varphi \otimes \text{Id}} \alpha U^H_x \otimes \alpha U(\mathbb{G}_m)^H_0 \xrightarrow{S \otimes \text{Id} \otimes \text{Id}} \alpha U^H_0 \otimes \alpha U(\mathbb{G}_m)^H_0 \longrightarrow \alpha U^H_0,
\end{equation}

where the last morphism is induced by the composition of paths

\begin{equation}
\gamma_1 \otimes \gamma_2 \otimes \gamma_3 \mapsto \gamma_1 \cdot f^*(\gamma_3) \cdot \gamma_2.
\end{equation}

Restricting to Lie type elements we obtain a map

\begin{equation}
\varphi_2 \colon \alpha \mathcal{L}^H_x \longrightarrow \mathcal{L}^H_x(-1).
\end{equation}

**Lemma 4.160.** The following morphism of pro-mixed Hodge structures is injective:

\begin{equation}
\varphi_1 + \varphi_2 \colon \alpha \mathcal{L}^H_x \longrightarrow \alpha \mathcal{L}(\mathbb{G}_m)^H_x \oplus \mathcal{L}^H_x(-1).
\end{equation}

**Proof.** It is enough to check the injectivity on the de Rham side. Let $\mathcal{L}$ be the free Lie algebra with generators $e_0$ and $e_1$ on degree $-1$. Let $\hat{\mathcal{L}}$ be the completion of $\mathcal{L}$ with respect to this grading. Then we have $\alpha \mathcal{L}_{\hat{\mathcal{L}}} = \hat{\mathcal{L}}$ and $\alpha \mathcal{L}(\mathbb{G}_m)^H_\hat{\mathcal{L}} = \mathbb{Q} e_0$. Clearly, the map $\varphi_1$ is the projection to the $e_0$ component. By construction, the map (4.158), is given by $a \otimes e_0 \mapsto [e_0, a]$. Therefore, the map $\varphi_2 : \hat{\mathcal{L}} \to \mathcal{L}$ is given by $a \mapsto [e_0, a]$. Denote by $\varphi'_2 : \mathcal{L} \to \mathcal{L}$ the map given by the same formula. By [Reu93, Thm. 2.10] the kernel of the map $\varphi'_2$ is $\mathbb{Q} e_0$. It is an easy exercise on projective limits to show that this implies that the kernel of $\varphi_2$ is also $\mathbb{Q} e_0$. Since $\varphi_1$ does not vanish on the kernel of $\varphi_2$ we deduce the lemma. \hfill \Box

Combining Proposition 4.152 and Theorem 4.147 we know that the pro-mixed Hodge structure $\alpha \mathcal{L}(\mathbb{G}_m)^H_x \oplus \mathcal{L}^H_x(-1)$ is motivic. By Proposition 4.83, we deduce that $\alpha \mathcal{L}^H_x$ is motivic and by Lemma 4.156 that $\alpha U^H_x$ is motivic.

We now have to consider the case of two tangential base points. Let $x, y \in \{0, 1\}$ two tangential base points of $X$. Let $z \in X(\mathbb{Q}) = \mathbb{P}^1(\mathbb{Q}) \setminus \{0, 1, \infty\}$ be a rational point. The composition of paths gives us a surjection

\begin{equation}
yU^H_x \otimes zU^H_x \longrightarrow yU^H_x.
\end{equation}
Since we already know that the structures on the left-hand side are motivic, we deduce that $yU^H_x$ is also motivic. Once we know that, for all $x, y \in \{0, 1\}$, the mixed Hodge structure $yU^H_x$ is motivic, the realization functor $R^H$ being fully faithful, any morphism among them is also motivic. Therefore, the composition of paths, the completed coproduct, the antipode, the unit and the counit, and the local monodromy maps are motivic.

4.5.5. The main theorem and some consequences. From the previous discussion we deduce

**Theorem 4.161** (Deligne-Goncharov [DG05]). For each pair of tangential base points $x, y \in \{0, 1\}$ of $X$, there is a pro-mixed Tate motive $yU^\text{Mot}_x$ whose Hodge realization is isomorphic to $yU^H_x$. By the fully faithfulness of the realization functor, $yU^\text{Mot}_x$ is unique up to unique isomorphism. Moreover, the unit and the counit, the composition of paths, the completed coproduct, the antipode, and the local monodromy maps are motivic.

In fact we can do even more

**Theorem 4.162** (Deligne-Goncharov [DG05]). For each pair of tangential base points $x, y \in \{0, 1\}$, the pro-mixed Tate motive $yU^\text{Mot}_x$ is a pro-object in the category $\text{MT}(\mathbb{Z})$. The motive $\mathcal{O}U(\mathbb{G}_m)^0$ belongs to $\text{MT}(\mathbb{Z})$.

**Proof.** The proof of this theorem relies on showing that the $\ell$-adic realizations of these motives are unramified (see [DG05, Prop. 4.17]) and using Proposition 4.92. □

**Corollary 4.163.** The diagram $D^\text{H}_U$ of Definition 3.403 is motivic and defined over $\mathbb{Z}$.

The importance of this result is that it connects a very abstract and non-explicit group $G_{\text{dR}} = \text{Aut}^\circ(\omega_{\text{dR}})$, but with known structure (see sections 4.4.3 and 4.4.5), with a very concrete combinatorial group $\text{Aut}(D^\text{dR}_U)$ (see Section 3.10.3). The group $G_{\text{dR}}$ is the group of symmetries of the category $\text{MT}(\mathbb{Z})$ and the fiber functor $\omega_{\text{dR}}$. Therefore it acts on the de Rham realization of every motive defined over $\mathbb{Z}$. By Exercise 4.31 it acts on the de Rham realization of any pro-mixed motive defined over $\mathbb{Z}$ or even of any diagram of pro-motives defined over $\mathbb{Z}$. By Theorem 4.162, the group $G_{\text{dR}}$ acts on the diagram $D^\text{dR}_U$ and we obtain a group homomorphism

$$G_{\text{dR}} \longrightarrow \text{Aut}(D^\text{dR}_U) = \text{Aut}(D^\text{dR}).$$

The subgroup $U_{\text{dR}} \subset G_{\text{dR}}$ acts trivially on the motive $\mathbb{Q}(1)$, which implies that its image acts trivially on $\mathcal{O}L(\mathbb{G}_m)^{\text{dR}}$, and hence on $\mathcal{O}U(\mathbb{G}_m)^{\text{dR}}$. Therefore the image of $U_{\text{dR}}$ is contained in $\text{Aut}^0(D^\text{dR})$ and we obtain a commutative diagram

$$\begin{array}{ccc}
0 & \longrightarrow & U_{\text{dR}} & \longrightarrow & G_{\text{dR}} & \longrightarrow & \mathbb{G}_m & \longrightarrow & 0 \\
& & \downarrow & & \downarrow & & & & \\
0 & \longrightarrow & \text{Aut}^0(D^\text{dR}) & \longrightarrow & \text{Aut}(D^\text{dR}) & \longrightarrow & \mathbb{G}_m & \longrightarrow & 0
\end{array}$$

The next chapter will be mainly devoted to extract consequences of this diagram.

***
Exercise 4.164. Use that $[X]$ belongs to $DMT(Q)$ and the fact that $DMT(Q)$ is closed under products and extensions to prove by induction that $[\sigma_{\leq N} N_y X^\bullet]$ belongs to $DMT(Q)$.

Exercise 4.165. Show that the complex $N \text{Spec}(Q)^\bullet$ in $C(\text{SmCor}(Q)_{pa})$ is isomorphic to the complex $\text{Spec}(Q)$ concentrated in degree zero, and deduce that

$$H_0(\sigma_{\leq N} N \text{Spec}(Q)^\bullet) = Q(0)$$

holds for all $N \geq 0$. 
5. Motivic multiple zeta values  
(after Brown, Deligne, and Goncharov)

The end is nigh! In this final chapter, we pull together all the techniques developed so far to prove Theorem A and Theorem B from the preface. The strategy is to upgrade multiple zeta values, which are real numbers, to motivic multiple zeta values, which are functions on a certain subscheme of the de Rham fundamental groupoid of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$. As such, they carry an action of the motivic fundamental group $G_{\text{dR}}$ of the category of mixed Tate motives $\mathbf{MT}(\mathbb{Z})$ that will be a powerful tool for understanding the relations among them, in the same way that usual Galois theory is for algebraic numbers. More precisely, there is a scheme $\Pi_{\text{dR}}$ defined over $\mathbb{Q}$ whose algebra of functions is the Hoffman algebra $\mathcal{H}$ and that contains a real point $\text{dch}_{\text{dR}}$, the de Rham counterpart of the straight path from 0 to 1. Evaluation at this point yields a map from $\mathcal{H}$ to multiple zeta values that agrees with the shuffle regularization. Every closed subscheme of $\Pi_{\text{dR}}$ that is defined over $\mathbb{Q}$ and contains the point $\text{dch}_{\text{dR}}$ gives rise to an ideal of rational polynomial relations between multiple zeta values. Hence, the problem of finding all of them amounts to finding the smallest such subscheme. A natural candidate from the point of view of the theory of motives is the closure $Y$ of the $G_{\text{dR}}$-orbit of $\text{dch}_{\text{dR}}$. According to the period conjecture, it should be the smallest one. Motivic multiple zeta values are functions on $Y$.

Theorem A is proved in Section 5.1. We begin by summarizing the main properties of the category $\mathbf{MT}(\mathbb{Z})$ and the graded algebra $\mathcal{H}^{\mathbf{MT}}$ that were established in the last chapter. To relate the known dimensions of the graded pieces of $\mathcal{H}^{\mathbf{MT}}$ to multiple zeta values, we perform a close study of the algebra $\mathcal{H} = \mathcal{O}(Y)$. By construction, $\mathcal{H}$ surjects onto the algebra $\mathbb{Z}$ of multiple zeta values. Besides, using the geometric of $Y$ we will show that $\mathcal{H}$ injects into $\mathcal{H}^{\mathbf{MT}}$. The upper bound in Theorem A follows from the combination of these results. In Section 5.2, we define motivic multiple zeta values $\zeta^m(s_1, \ldots, s_\ell)$ as certain elements of $\mathcal{H}$, and we recast Goncharov’s coproduct on iterated integrals as a formula for the action of $G_{\text{dR}}$ on these elements. Working modulo products gives a simpler expression to work with, the so-called infinitesimal coaction. The main result of this section is that simple motivic multiple zeta values $\zeta^m(n)$ span the kernel of this infinitesimal coaction. Using this result, we prove in Section 5.3 that the motivic multiple zeta values of the form $\zeta^m(2, \ldots, 2, 3, 2, \ldots, 2)$ are rational linear combinations of products of $\zeta^m(2n+1)$ and $\zeta^m(2, \ldots, 2)$. The computation of the actual coefficients is due to Zagier. Interestingly, the existence of such a relation among motivic zeta values is predicted by the infinitesimal coaction, but its precise shape can only be obtained working with numbers and is lifted to a motivic relation afterwards. In Section 5.4, we start analyzing the subspace $\mathcal{H}^{2,3} \subset \mathcal{H}$ spanned by motivic multiple zeta values with exponents $s_i \in \{2, 3\}$. A basic tool is the so-called level filtration by the number of 3s and a level lowering operator defined in terms of the infinitesimal coaction. This will be used in Section 5.5 to prove by induction that the generators of $\mathcal{H}^{2,3}$ are linearly independent and that $\mathcal{H}^{2,3}$ is equal to the whole $\mathcal{H}$. Theorem B follows at once. At the end of the chapter, we state some remarkable consequences of both theorems, among which are the fact that periods of mixed Tate motives over $\mathbb{Z}$ are $\mathbb{Q}(2\pi i)^{-1}$-linear combinations of multiple zeta values, and that Zagier’s conjecture implies the algebraic independence of $\pi$, $\zeta(3)$, $\zeta(5)$, \ldots
5.1. The upper bound. In this section, we prove Theorem A. That is, we establish the upper bound $d_k$ for the dimension of the $\mathbb{Q}$-vector space $\mathcal{Z}_k$ generated by multiple zeta values of weight $k$.

5.1.1. Setting. Recall from Section 4.4 that the category $\mathbf{MT}(\mathbb{Z})$ of mixed Tate motives over $\mathbb{Z}$ has as simple objects the Tate motives $\mathbb{Q}(n)$, one for each $n \in \mathbb{Z}$. They satisfy the tensor relation

$$\mathbb{Q}(n+m) = \mathbb{Q}(n) \otimes \mathbb{Q}(m).$$

The structure of the category is determined by the extension groups

$$\text{Ext}^1_{\mathbf{MT}(\mathbb{Z})}(\mathbb{Q}(0), \mathbb{Q}(n)) \simeq \begin{cases} \mathbb{Q}, & \text{if } n \geq 3 \text{ is odd,} \\ 0, & \text{otherwise,} \end{cases}$$

and the vanishing of all higher extension groups:

$$\text{Ext}^i_{\mathbf{MT}(\mathbb{Z})}(\mathbb{Q}(0), \mathbb{Q}(n)) = 0 \quad \text{for} \quad i \geq 2.$$ 

The fiber functor

$$\omega : \mathbf{MT}(\mathbb{Z}) \rightarrow \text{Vec}_\mathbb{Q}$$

from (4.96) makes $\mathbf{MT}(\mathbb{Z})$ into a tannakian category. Namely, $\mathbf{MT}(\mathbb{Z})$ is equivalent to the category of representations of the pro-algebraic $\mathbb{Q}$-group $G_{\text{dR}} = \text{Aut}_{\otimes}(\omega)$.

We already determined the structure of $G_{\text{dR}}$ using the computation of the extension groups (Lemma 4.108). It is a semidirect product

$$G_{\text{dR}} \simeq U_{\text{dR}} \rtimes \mathbb{G}_m,$$

where $U_{\text{dR}}$ is a pro-unipotent affine group scheme over $\mathbb{Q}$. The action of $\mathbb{G}_m$ on $U_{\text{dR}}$ induces an action of $\mathbb{G}_m$ on the Lie algebra

$$u_{\text{dR}} = \text{Lie}(U_{\text{dR}}),$$

and the associated graded Lie algebra $u_{\text{dR}}^\text{gr} \subset u_{\text{dR}}$ is non-canonically isomorphic to the free Lie algebra with one generator in each odd degree $\leq -3$ (Theorem 4.128). The whole Lie algebra $u_{\text{dR}}$ is the completion of $u_{\text{dR}}^\text{gr}$.

Besides, in Section 3.10 we introduced the algebraic group $\text{Aut}(D^{\text{dR}})$ of symmetries of the de Rham fundamental groupoid of $\mathbb{P}^1 \setminus \{0, 1, \infty\}$ and its pro-unipotent part $\text{Aut}^0(D^{\text{dR}})$. Among other things, this fundamental groupoid consists of the pro-algebraic scheme $\Pi_0^{\text{dR}} = \text{Spec}(\mathcal{H})$, where $\mathcal{H} = (\mathbb{Q}(x_0, x_1), \mu)$ is the Hoffman algebra. It is thought of as the de Rham counterpart of the space of paths from 0 to 1. We showed in Lemma 3.404 that there is an isomorphism of $\mathbb{Q}$-schemes

$$\text{Aut}^0(D^{\text{dR}}) \simeq \Pi_0^{\text{dR}}.$$ 

This led us to define (Definition 3.407) a pro-algebraic group $(\Pi, \circ)$ with underlying scheme $\Pi_0^{\text{dR}}$ and multiplication induced by the composition $\circ$ in $\text{Aut}(D^{\text{dR}})$. Recall from Remark 3.399 the canonical de Rham path $1_0^{\text{dR}} \in \Pi_0^{\text{dR}}(\mathbb{Q})$, corresponding to the counit map $\mathcal{H} \rightarrow \mathbb{Q}$. The group $(\Pi, \circ)$ acts on $\Pi_0^{\text{dR}}$, and the map

$$\Pi \rightarrow 1_0^{\text{dR}}$$

$$v \mapsto v(1_0^{\text{dR}})$$

is an isomorphism of schemes. Thus, $1_0^{\text{dR}}$ is a trivial torsor under $(\Pi, \circ)$.
As explained at the end of last chapter, it follows from Theorem 4.161 that there exists a commutative diagram of morphisms of affine group schemes

\[
\begin{array}{ccccccccc}
0 & \rightarrow & U_{\text{dR}} & \rightarrow & G_{\text{dR}} & \rightarrow & G_m & \rightarrow & 0 \\
\downarrow & & \downarrow & & \downarrow & & \downarrow & & \\
0 & \rightarrow & \Pi & \rightarrow & \text{Aut}(D^{\text{dR}}) & \rightarrow & G_m & \rightarrow & 0.
\end{array}
\]

We shall denote the first vertical arrow by

\[
I: U_{\text{dR}} \rightarrow \Pi.
\]

In particular, the group \(G_{\text{dR}}\) acts on the pro-scheme \(1\Pi_0^{\text{dR}}\). The action of the subgroup \(U_{\text{dR}}\) factors through the map \(I\) and the action of \(\Pi\) on \(1\Pi_0^{\text{dR}}\) discussed above. Recall that the decomposition (5.2) is induced by a canonical section \(\tau: G_m \rightarrow G_{\text{dR}}\).

For each \(z \in G_m(\mathbb{C}) = \mathbb{C}^*\), the element \(\tau(z)\) acts on the graded piece

\[
\omega_n(1\Pi_0^{\text{dR}}) = G^{W}_n 1\Pi_0^{\text{dR}}
\]

by multiplication by \(z^n\).

The image \(I(U_{\text{dR}})\) of \(U_{\text{dR}}\) is a closed subgroup of \(\Pi\). We introduce the notation

\[
A^{\text{MT}} = \mathcal{O}(U_{\text{dR}}), \quad A = \mathcal{O}(I(U_{\text{dR}})).
\]

Note that there is an injective morphism of Hopf algebras \(A \hookrightarrow A^{\text{MT}}\).

In (4.131) we introduced the algebra

\[
\mathcal{H}^{\text{MT}} = A^{\text{MT}} \otimes_{\mathbb{Q}} \mathbb{Q}[f_2].
\]

It is a Hopf module over \(A^{\text{MT}}\), with \(f_2\) in degree two, and by Lemma 4.132 its Hilbert-Poincaré series is given by

\[
H_{\mathcal{H}^{\text{MT}}}(t) = \sum_{k \geq 0} d_k t^k.
\]

### 5.1.2. The algebra of motivic multiple zeta values.

Recall that the affine ring of \(1\Pi_0^{\text{dR}}\) is equal to the Hoffman algebra (Example 3.62)

\[
\mathcal{O}(1\Pi_0^{\text{dR}}) = \mathbb{Q}(x_0, x_1) = \mathcal{H},
\]

with the grading induced by \(\deg(x_0) = \deg(x_1) = 1\) (see Proposition 3.400). The dual of \(\mathcal{H}\) is the completed Hopf algebra \(\mathbb{Q}\langle e_0, e_1 \rangle\) from Example 3.71, with the grading determined by \(\deg(e_0) = \deg(e_1) = -1\). For any \(\mathbb{Q}\)-algebra \(R\), the set of \(R\)-points \(1\Pi_0^{\text{dR}}(R)\) is identified with the set of group-like elements of \(R\langle e_0, e_1 \rangle\).

From now on, we will let \(\text{dch}^{\text{dR}}\) denote the image by

\[
\text{comp}_{dR,B}: 1\Pi_0^{B}(\mathbb{C}) \rightarrow 1\Pi_0^{\text{dR}}(\mathbb{C})
\]

of the straight path \(\text{dch} \in 1\Pi_0^{B}(\mathbb{Q})\) from \(0\) to \(1\). This is nothing other than what was previously denoted by

\[
L(\text{dch}) = \sum_{\alpha} \zeta_{\omega}(x_\alpha)e_\alpha
\]

in (3.380). Since all regularized multiple zeta values \(\zeta_{\omega}(x_\alpha)\) are real numbers, \(\text{dch}^{\text{dR}}\) is actually a real point of \(1\Pi_0^{\text{dR}}\).
Evaluating an element \( f \in \mathcal{O}(\Pi_0^{\text{dR}}) \) at the point \( \text{dch}^{\text{dR}} \) yields the map
\[
\text{dch}: \mathcal{O}(\Pi_0^{\text{dR}}) \rightarrow \mathbb{R}
\]
\[
f \mapsto f(\text{dch}^{\text{dR}}).
\]

Seen as a function on \( \Pi_0^{\text{dR}} \), a word \( w \) in the alphabet \( x_0, x_1 \) takes the value
\[
w(\text{dch}^{\text{dR}}) = \zeta(w)
\]
at the point \( \text{dch}^{\text{dR}} \in \Pi_0^{\text{dR}}(\mathbb{R}) \). Thus, by Corollary 1.184, we obtain a surjective map from \( \mathcal{O}(\Pi_0^{\text{dR}}) \) to the algebra \( \mathcal{Z} \) of multiple zeta values.

**Remark 5.7.** The map \( \mathcal{O}(\Pi_0^{\text{dR}}) \rightarrow \mathcal{Z} \) is very far from being injective, as all relations between multiple zeta values belong to the kernel. As a result, the algebra \( \mathcal{O}(\mathbb{G}_m) \) is equal to \( \mathbb{Q}[x, x^{-1}] \), with \( x \) sitting in degree 1.

Using the semi-direct product decomposition (5.2), we derive an isomorphism
\[
\mathcal{O}(\mathbb{G}_m) \simeq A^{\text{MT}} \otimes_{\mathbb{Q}} \mathbb{Q}[x, x^{-1}].
\]
The presence of \( x^{-1} \), which has degree \(-1\), implies that the dimension of each graded piece of \( \mathcal{O}(\mathbb{G}_m) \) is infinite, and therefore this algebra is still not useful for our purposes. Thinking of \( x \) as \( 2\pi i \) and of \( f_2 \) as \( \zeta(2) \) suggests identifying \( f_2 \) with \( -x^2/24 \), and this will yield an injective map \( \mathcal{H}^{\text{MT}} \rightarrow \mathcal{O}(\mathbb{G}_m) \). The strategy to prove Theorem A consists then in showing that the evaluation map (5.6) factors through \( \mathcal{H}^{\text{MT}} \). This can be done in an ad hoc way or we can use a nice geometric interpretation due to Brown.

Following Brown [Bro12, § 2.3], we define a closed subscheme \( \mathcal{Y} \subseteq \Pi_0^{\text{dR}} \) as the Zariski closure of the orbit of \( \text{dch}^{\text{dR}} \) under the action of \( \mathbb{G}_m^{\text{dR}} \):
\[
(5.8) \quad \mathcal{Y} = \mathbb{G}_m^{\text{dR}} \cdot \text{dch}^{\text{dR}}.
\]

**Lemma 5.9.** The subscheme \( \mathcal{Y} \) is defined over \( \mathbb{Q} \).

**Proof.** To see that \( \mathcal{Y} \) is defined over \( \mathbb{Q} \) we give another interpretation of it. Recall that \( \mathcal{P}_{\mathbb{R},\mathbb{B}} \) is the \( \mathbb{G}_m^{\text{dR}} \)-torsor of isomorphisms between the fiber functors \( \omega_{\mathbb{B}} \) and \( \omega_{\mathbb{R}} \). Thus, there is a morphism of affine \( \mathbb{Q} \)-schemes
\[
\mathcal{P}_{\mathbb{R},\mathbb{B}} \times \Pi_0^{\mathbb{B}} \rightarrow \Pi_0^{\text{dR}}.
\]
The point \( \text{dch} \in \Pi_0^{\mathbb{B}}(\mathbb{Q}) \) induces a \( \mathbb{G}_m^{\text{dR}} \)-equivariant map
\[
\text{dch}: \mathcal{P}_{\mathbb{R},\mathbb{B}} \rightarrow \Pi_0^{\text{dR}},
\]
which sends \( \text{comp}_{\mathbb{R},\mathbb{B}} \) to \( \text{dch}^{\text{dR}} \). Hence, its image is the \( \mathbb{G}_m^{\text{dR}} \)-orbit of \( \text{dch}^{\text{dR}} \). It follows that \( \mathcal{Y} \) is the Zariski closure of the image of the map \( \text{dch} \). The point \( \text{dch} \) being rational, we deduce that \( \mathcal{Y} \) is defined over \( \mathbb{Q} \). \( \square \)

**Definition 5.10.** We call **algebra of motivic zeta values** the \( \mathbb{Q} \)-algebra
\[
\mathcal{H} = \mathcal{O}(\mathcal{Y})
\]
of regular functions on the scheme \( \mathcal{Y} \).

In Definition 5.33 below, we will write down a set of generators of \( \mathcal{H} \) called **motivic multiple zeta values**. For the time being, we note the properties of \( \mathcal{H} \) that are relevant for the proof of Theorem A.
• The action of $U_{dR}$ on $\Pi_{0}^{dR}$ induces an action of $U_{dR}$ on $Y$ that factors through $I(U_{dR})$. Therefore, there is a coaction

$\Delta: H \rightarrow A \otimes_{Q} H$

making $H$ into a Hopf comodule over $A$.

• The action of $G_{m}$ on $Y$ induces a grading $H = \bigoplus_{k \geq 0} H_{k}$.

Since $Y$ contains $dch_{dR}$, the map (5.6) factors through $H$ and gives rise to a so-called period map

$\text{per}: H \rightarrow \mathbb{R}.$

Since the map (5.6) surjects onto $Z$, the image of $\text{per}$ is also $Z$.

• Moreover, since the action of $G_{m}$ on $Y$ is compatible with its action on $\Pi_{0}^{dR}$, and since the grading that this action induces on $O(\Pi_{dR})$ agrees with the natural grading of $Q<x_{0}, x_{1}>$, we deduce the equality $\text{per}(H_{k}) = Z_{k}$. 

REMARK 5.13. The map (5.12) is called the period map because it is compatible with the period map from Definition 4.115. In fact, taking the equality $dch(\text{comp}_{dR}, B) = dch^{dR}$ into account, there is a commutative diagram

(5.14) $O(Y) \xrightarrow{dch^{*}} O(P_{dR}, B).$

REMARK 5.15. We can interpret $H$ as follows. Let $\mathcal{I} \subset Q<x_{0}, x_{1}>$ be the ideal of functions vanishing on $dch^{dR}$, i.e. the ideal of all rational relations among multiple zeta values. The ideal $J_{MT}$ defining $Y$ inside $\Pi_{0}^{dR}$ is the ideal of motivic relations between multiple zeta values, that is, those explained by geometry. We will see that $J_{MT} \subseteq \mathcal{I}$ implies the upper bound for the dimension of the space of multiple zeta values, while Zagier’s conjecture is equivalent to the equality $J_{MT} = \mathcal{I}$, that is, that every rational relation among multiple zeta values comes from geometry. In this vein, Zagier’s conjecture is equivalent to saying that $Y$ is the smallest subvariety of $\Pi_{0}^{dR}$ that is defined over $\mathbb{Q}$ and contains $dch^{dR}$.

The strategy to prove Theorem A is now to derive the inequality $\dim H_{k} \leq d_{k}$ from the existence of an injection $H \hookrightarrow H^{MT}$. This injection will come from the study of the geometry of $Y$. Theorem B, to be proved later, will actually imply the equality $\dim H_{k} = d_{k}$, and hence that the algebras $H$ and $H^{MT}$ are isomorphic.

5.1.3. The structure of $Y$.

LEMMA 5.16. There exists an element $\gamma \in \Pi(\mathbb{Q})$ such that the equality

(5.17) $dch^{dR} = (I(u_{0}) \circ \tau(2\pi i)^{-1}(\gamma))(1^{dR})$

holds. Moreover, for any $\gamma$ satisfying (5.17), one has $\tau(-1)(\gamma) = \gamma$. In other words, $\gamma$ only contains monomials of even degree.
PROOF. Recall from Proposition 4.111 that there exists an element
\begin{equation}
(5.18) \quad a = u_0 \cdot \tau(2\pi i)^{-1} \in U_{\text{dir}}(R) \tau(2\pi i)^{-1} \subset G_{\text{dir}}(C)
\end{equation}
such that the equality \( \text{comp}_{\text{dir}, B}(\omega_B(M)) = a(\omega_{\text{dir}}(M)) \) of subspaces of \( \omega_{\text{dir}}(M) \otimes C \) holds for all mixed Tate motives \( M \) in \( \text{MT}(Z) \). In particular, there exists an element \( \gamma' \in \Pi^R_0(Q) \) with
\[
\text{dch}^{\text{dir}}(\gamma') = \text{comp}_{\text{dir}, B}(\text{dch}) = a(\gamma').
\]
Let \( \gamma \in \Pi(Q) \) be such that \( \gamma' = \gamma(1_{1^0}^{\text{dir}}) \). Then
\[
\text{dch}^{\text{dir}} = (u_0 \cdot \tau(2\pi i)^{-1})(\gamma')
\]
\[
= I(u_0)(\tau(2\pi i)^{-1}(\gamma(1_{1^0}^{\text{dir}})))
\]
\[
= (I(u_0) \circ \tau(2\pi i)^{-1} \circ \gamma)(1_{1^0}^{\text{dir}})
\]
\[
= (I(u_0) \circ \tau(2\pi i)^{-1}(\gamma))(1_{1^0}^{\text{dir}}).
\]
To get the last equality, we use the identity
\[
\tau(2\pi i)^{-1} \circ \gamma = \tau(2\pi i)^{-1}(\gamma) \circ \tau(2\pi i)^{-1},
\]
where the action on the right-hand side is the one induced by the grading, along with the fact that, being the unit of the graded Hopf algebra \( H \), the element \( 1_{1^0}^{\text{dir}} \) has degree zero. This finishes the proof of (5.17).

We now turn to the second statement. Since both \( \text{dch} \) and \( u_0 \) are real, it follows from (5.17) that \( \tau(2\pi i)^{-1}(\gamma) \) is real as well. Writing \( \gamma = \sum c_w w \in Q\langle e_0, e_1 \rangle \), an element \( z \in C^\times \) acts through
\[
\tau(z)^{-1}(\gamma) = \sum c_w z^{\text{deg}(w)} w.
\]
Since \( \tau(2\pi i)^{-1}(\gamma) \) is real, it follows that \( c_w = 0 \) for every word \( w \) of odd degree. \( \Box \)

As in the proof of the lemma, we write \( \gamma = \sum c_w w \in Q\langle e_0, e_1 \rangle \). Since \( \gamma \) only contains monomials of even degree, the map \( G_m \to \Pi \) given by \( t \mapsto \tau(t) \) only depends on \( t^2 \). Indeed, if one defines a map \( \rho: G_m \to \Pi \) by
\begin{equation}
(5.19) \quad \rho(t) = \sum t^{\text{deg}(w) - 2} c_w w
\end{equation}
one has \( \tau(t)^{-1}(\gamma) = \rho(t^2) \). Observe that \( \rho \) extends to \( A^1 \) with \( \rho(0) = 1 \).

**Theorem 5.20.** The morphism of schemes
\[
\psi: I(U_{\text{dir}}) \times A^1 \longrightarrow \Pi
\]
\[
(u, t) \quad \mapsto u \circ \rho(t)
\]
induces an isomorphism \( I(U_{\text{dir}}) \times A^1 \simeq \mathcal{Y} \) given by \( (u, t) \mapsto \psi(u, t)(1_{1^0}^{\text{dir}}) \).

**Proof.** Recall that the graded Lie algebra \( u_{\text{dir}}^\text{gr} \) is negatively graded and is zero in degree > \(-3\) by Theorem 4.128. Thus, any element \( u \in I(U_{\text{dir}}) \) can be written as
\[
u = 1 + \sum_{\text{deg}(w) \leq -3} u_w w.
\]
Therefore, the coefficients of the monomial \( c_0 e_1 \) in \( \rho(t) \) and \( u \circ \rho(t) \) agree. Let us compute the former. Recall that
\[
\text{dch}^{\text{dir}} = 1 + \zeta(2) c_0 e_1 + \text{higher degree}.
\]
Taking the equality $\text{dch}^{\text{dR}} = (u \circ \tau(2\pi i)^{-1}(\gamma))(1 \cdot 0)$ from Lemma 5.16 into account, one has $(2\pi i)^2 c_{e_2 e_1} = \zeta(2)$, which yields the value $c_{e_2 e_1} = -1/24$ by Euler’s formula. The coefficient of $e_0 e_1$ in $\rho(t)$ is thus equal to $-t/24$.

This leads naturally to consider the maps
\[
c: \Pi \longrightarrow \mathbb{A}^1 \quad 
x \longmapsto -24 \cdot \text{coefficient of } e_0 e_1 \text{ in } x.
\]
\[
\varphi: \Pi \longrightarrow \Pi \quad 
x \longmapsto x \circ \rho(c(x))^{-1}.
\]
By the previous discussion, we have $c(\psi(u, t)) = t$. Therefore
\[
\varphi(\psi(u, t)) = \psi(u, t) \circ \rho(c(\psi(u, t)))^{-1} = u \circ \rho(t) \circ \rho(t)^{-1} = u.
\]
In particular, the morphism $\psi$ is injective.

Observe that $x \in \Pi$ is in the image of $\psi$ if and only if $\varphi(x)$ belongs to $I(U_{\text{dR}})$. Therefore, $\text{Im } \psi = \varphi^{-1}(I(U_{\text{dR}}))$. Since $I(U_{\text{dR}})$ is closed in $\Pi$, the same holds for $\text{Im } \psi$. By Lemma 5.16, $(\text{Im } \psi)(1 \cdot 0)$ contains $G_{\text{dR}} \cdot \text{dch}^{\text{dR}}$ as an open dense subset, so it has to be equal to its closure $\mathcal{Y}$. Write $\mathcal{Y}$ for the preimage of $\mathcal{Y}$ in $\Pi$. To conclude, we note that the map $\mathcal{Y}' \rightarrow I(U_{\text{dR}}) \times \mathbb{A}^1$ given by $x \mapsto (\varphi(x), c(x))$ is an inverse of $\psi$.

**Corollary 5.21.** The isomorphism $I(U_{\text{dR}}) \times \mathbb{A}^1 \simeq \mathcal{Y}$ from Theorem 5.20 induces an isomorphism of graded algebras
\[
\mathcal{H} \simeq \mathcal{A} \otimes_{\mathbb{Q}} \mathbb{Q}[t],
\]
where $t$ sits in degree two. This isomorphism induces an injection $\mathcal{H} \hookrightarrow \mathcal{H}^{\text{MT}}$ that sends $t$ to $-24 f_2$. Moreover, if we provide $\mathbb{Q}[t]$ with the trivial $\mathcal{A}$-comodule structure, then this isomorphism is compatible with the structure of $\mathcal{A}$-comodules on both sides.

**Proof.** That it is an isomorphism of algebras follows from the duality between affine schemes and algebras of functions. To see that it is a graded isomorphism, we need to show that the map $\psi$ from Theorem 5.20 is $\mathbb{G}_m$-equivariant provided that one makes $\lambda \in \mathbb{G}_m$ act on $\mathbb{A}^1$ by $t \mapsto \lambda^2 t$. On the one hand, formula (5.19) gives $\rho(\lambda^2 t) = \tau(\lambda)(\rho(t))$. On the other hand, using Proposition 4.108, we get
\[
\tau(\lambda)(u \circ \rho(t)) = \tau(\lambda)(u) \circ \tau(\lambda)(\rho(t)),
\]
from which the first statement of the theorem follows. If we endow $\mathbb{A}^1$ with the trivial $I(U_{\text{dR}})$ action, then the map $\psi$ becomes $I(U_{\text{dR}})$ equivariant, from which the second statement follows.

**5.1.4. Proof of Theorem A.** Since the map (5.12) is surjective and respects the weight, it suffices to prove the inequality $\dim \mathcal{H}_k \leq d_k$ for each $k \geq 2$. But Corollary 5.21 and Lemma 4.132 yield
\[
\dim \mathcal{H}_k \leq \dim(\mathcal{H}^{\text{MT}})_k = d_k,
\]
which is what we wanted to show.

**5.2. Motivic multiple zeta values and the motivic coaction.** In this section, we define some elements of the algebra $\mathcal{H}$ called *motivic multiple zeta values*. Exploiting the coaction (5.11), we can find many relations among them. Through the period map, they will yield relations among multiple zeta values.
5.2.1. The structure of \( A^{\mathcal{MT}} \). Recall that the Lie algebra \( \mathfrak{u}_{dR} = \text{Lie}(U_{dR}) \) is isomorphic to the completion of the free Lie algebra with one generator sitting in each odd degree \( \leq -3 \). Its dual is hence positively graded. From this, it follows that \( A^{\mathcal{MT}} = \mathcal{O}(U_{dR}) \) is non-canonically isomorphic to the graded Hopf algebra
\begin{equation}
\mathcal{U}' = \mathbb{Q}\langle f_3, f_5, f_7, \ldots \rangle
\end{equation}
of non-commutative words in symbols \( f_{2i+1} \), one for each \( i \geq 1 \), in degree \( 2i + 1 \), with product given by the shuffle and coproduct by the deconcatenation
\begin{equation}
\Delta(f_{i_1}f_{i_2} \cdots f_{i_r}) = \sum_{k=0}^r f_{i_1} \cdots f_{i_k} \otimes f_{i_k+1} \cdots f_{i_r}.
\end{equation}

We introduce the commutative graded algebra
\begin{equation}
\mathcal{U} = \mathcal{U}' \otimes_{\mathbb{Q}} \mathbb{Q}[f_2] = \mathcal{U}[f_2],
\end{equation}
with \( f_2 \) in degree 2. For each integer \( N \geq 0 \), let \( \mathcal{U}_N \subset \mathcal{U} \) denote the subspace consisting of elements of degree \( N \) of \( \mathcal{U} \) \( (\text{e.g. the subspace of homogeneous polynomials of degree } N \text{ in } f_2, f_3, \ldots) \). The coproduct (5.23) on \( \mathcal{U}' \) extends to a coaction
\begin{equation}
\Delta: \mathcal{U} \rightarrow \mathcal{U}' \otimes_{\mathbb{Q}} \mathcal{U}
\end{equation}
by setting \( \Delta f_2 = 1 \otimes f_2 \). This coaction turns \( \mathcal{U} \) into an \( \mathcal{U}' \)-comodule. Clearly, \( \mathcal{H}^{\mathcal{MT}} \) is non-canonically isomorphic to \( \mathcal{U} \).

For later use, it is also convenient to introduce the elements \( f_4, f_6, \ldots \in \mathcal{U} \) defined, for each integer \( n \geq 2 \), by the formula
\begin{equation}
f_{2n} = b_n f_2^n, \quad b_n = (-1)^{n-1} \frac{24^n}{2(2n)!} B_{2n}.
\end{equation}
By Euler’s Theorem 1.3, the equality \( \zeta(2n) = b_n \zeta(2)^n \) holds.

The Hopf algebra \( \mathcal{U}' \) and the comodule \( \mathcal{U} \) are useful for explicit computations. We will later fix a convenient isomorphism
\begin{equation}
\phi: \mathcal{H}^{\mathcal{MT}} \rightarrow \mathcal{U}
\end{equation}
satisfying certain normalization requirements.

For compatibility with the theory of multiple zeta values, the grading in \( \mathcal{U}, \mathcal{U}' \), \( \mathcal{H} \) and the other algebras will be called the *weight*. We first present the computational tools we will use at the level of \( \mathcal{U}' \). As in Definition 3.85, the Lie coalgebra associated with \( \mathcal{U}' \) is the quotient
\[ L = U'_{>0}/(U'_{>0})^2. \]
From the canonical decomposition \( \mathcal{U}' = \mathbb{Q} \oplus U'_{>0} \), we get a projection \( q: \mathcal{U}' \rightarrow L \). The Lie coalgebra \( L \) inherits a grading from \( \mathcal{U}' \). Let \( L_N \subset L \) be the subspace of weight \( N \) and \( p_N: L \rightarrow L_N \) the projection. For \( r \geq 1 \), we define a map
\begin{equation}
D_{2r+1}: \mathcal{U} \rightarrow L_{2r+1} \otimes_{\mathbb{Q}} \mathcal{U}
\end{equation}
as the composition
\[ \mathcal{U} \xrightarrow{\Delta} \mathcal{U}' \otimes_{\mathbb{Q}} \mathcal{U} \xrightarrow{q \otimes \text{id}} L \otimes_{\mathbb{Q}} \mathcal{U} \xrightarrow{p_{2r+1} \otimes \text{id}} L_{2r+1} \otimes_{\mathbb{Q}} \mathcal{U}, \]
where \( \Delta \) is the coaction (5.25). We will see in Exercise 5.51 that the maps \( D_{2r+1} \) are derivations. We put
\begin{equation}
D_{<N}: \mathcal{U} \rightarrow \bigoplus_{3 \leq 2r+1 < N} L_{2r+1} \otimes_{\mathbb{Q}} \mathcal{U}, \quad D_{<N} = \bigoplus_{3 \leq 2r+1 < N} D_{2r+1}
\end{equation}
Lemma 5.30. For each integer \( N \geq 2 \), the following equality holds:
\[
(\text{Ker } D_{<N}) \cap U_N = \mathbb{Q} f_N.
\]

Proof. We first show that \( f_N \) belongs to \( \text{Ker } D_{<N} \). When \( N \) is even, we already have \( \Delta f_N - 1 \otimes f_N = 0 \). If \( N \) is odd and \( 2r + 1 < N \), then
\[
D_{2r+1} f_N = p_{2r+1} (q(f_N)) \otimes 1 = 0.
\]
Thus, \( f_N \in \text{Ker } D_{<N} \). Conversely, an element \( \xi \in U_N \) can be uniquely written as
\[
\xi = \alpha f_N + \sum_{3 \leq 2r+1 < N, 0 \leq 2j \leq N - 2r - 1} f_{2r+1} v_{r,j} \cdot f_2^j
\]
with \( v_{r,j} \in U_{N - 2r - 1 - 2j} \) and \( \alpha \in \mathbb{Q} \). Writing \( v_r = \sum_j v_{r,j} \cdot f_2^j \) and using the explicit expression of the coaction (5.25), we see that
\[
D_{2r+1} \xi = f_{2r+1} \otimes v_r + \text{other terms},
\]
where none of the monomials of \( U_{2r+1} \) that appear in the extra terms is \( f_{2r+1} \). Thus, \( D_{2r+1} \xi = 0 \) implies \( v_r = 0 \). In consequence if \( \xi \in \text{Ker } D_{<N} \), then \( \xi = \alpha f_N \).

5.2.2. Motivic multiple zeta values. Let \( \alpha \) be a binary sequence. Recall from formula (3.416) at the end of Chapter 3 the function on \( \Pi \) denoted by
\[
I(1; \alpha; 0) = x_\alpha.
\]
We now let \( I^m(1; \alpha; 0) \) denote the restriction of this function to \( Y \), that is, the projection to the quotient
\[
I^m(1; \alpha; 0) \in \mathcal{H} = \mathcal{O}(\Pi)/\mathcal{J}^{MT}.
\]
Following formulas (3.416), for later use, we set
\[
I^m(0; \alpha; 1) = x_\alpha^*|_Y,
\]
where \( x_\alpha^* = S^\vee(x_\alpha) \) and
\[
I^m(0; \alpha; 0) = I^m(1; \alpha; 1) = \begin{cases} 1, & \text{if } \alpha = \emptyset, \\ 0, & \text{if } \alpha \neq \emptyset. \end{cases}
\]
The symbols \( I^m \) are called motivic iterated integrals.

We now list some useful properties of the motivic iterated integrals.

Lemma 5.32.

i) If \( N \geq 1 \) and \( \varepsilon_1 = \cdots = \varepsilon_N \), then \( I^m(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_N; \varepsilon_{N+1}) = 0 \).

ii) Reflection formula
\[
I^m(1; \varepsilon_1 \cdots \varepsilon_N; 0) = (-1)^N I^m(0; \varepsilon_N \cdots \varepsilon_1; 1) = I^m(1; 1 - \varepsilon_N \cdots 1 - \varepsilon_1; 0)
\]

Proof. Property ii) follows from Theorem 3.355 i) and the change of variables \( z \mapsto 1 - z \) on \( \mathbb{P}^1 \setminus \{0, 1, \infty\} \), which reverses the path \( \text{dch} \).

We prove property i). Since \( I^m(0; \alpha; 0) = I^m(1; \alpha; 1) = 0 \) for a non-empty binary sequence \( \alpha \) and, by ii), \( I^m(0; \varepsilon^{\{N\}}; 1) = (-1)^N I^m(1; \varepsilon^{\{N\}}; 0) \), it suffices to show that \( I^m(1; \varepsilon^{\{N\}}; 0) = 0 \). For this, we use the identity
\[
I^m(1; \varepsilon^{\{N\}}; 0) = \frac{1}{N!} I^m(1; \varepsilon; 0)^N
\]
and the fact that $I^m(1; \varepsilon; 0) = 0$ since the algebra $\mathcal{H}$ has no elements in degree one.

**Definition 5.33.** Let $s = (s_1, \ldots, s_r)$ be a positive multi-index. The motivic multiple zeta value $\zeta^m(s)$ is the element of $\mathcal{H}$ defined as

$$\zeta^m(s) = I^m(1; 0^{(s_1-1)}1 \cdots 0^{(s_r-1)}1; 0).$$

The binary sequence $(0^{(s_1-1)}, 1, \cdots, 0^{(s_r-1)}, 1)$ is called the binary sequence associated with $s$ and is denoted in Definition 1.131 as $bs(s)$.

The period map $\text{per}: \mathcal{H} \to \mathbb{R}$ from (5.12) satisfies

$$\text{per}(\zeta^m(s)) = \zeta_{\text{w}}(s).$$

In other words, the motivic multiple zeta value $\zeta^m(s)$ is a function on the variety $\mathcal{Y}$, and the regularized multiple zeta value $\zeta_{\text{w}}(s)$ is the result of evaluating this function at the point $\text{dch}^{\text{dR}} \in \mathcal{Y}$.

**Remark 5.34 (Comparison with Brown’s notation).** Due to the different convention on the definition of multiple zeta values and iterated integrals, there is a discrepancy between the symbols used here and the symbols used in [Bro12]. To ease comparison we summarize it in this remark. Letting

$$\zeta^m_B(s_1, \ldots, s_r), \quad I^m_B(\varepsilon_0 : \varepsilon_1, \ldots, \varepsilon_n : \varepsilon_{n+1}), \quad \text{and} \quad \zeta_B(s_1, \ldots, s_r)$$

denote the motivic multiple zeta values, motivic iterated integrals and multiple zeta values used in [Bro12], the following relations hold:

$$\zeta^m_B(s_1, \ldots, s_r) = \zeta^m(s_r, \ldots, s_1),$$

$$I^m_B(\varepsilon_0 : \varepsilon_1, \ldots, \varepsilon_n : \varepsilon_{n+1}) = I^m(\varepsilon_{n+1} : \varepsilon_n, \ldots, \varepsilon_1 : \varepsilon_0),$$

$$\zeta_B(s_1, \ldots, s_r) = \zeta(s_r, \ldots, s_1).$$

The map $\text{per}$ is the same in [Bro12] and in this book because it is the evaluation morphism at a point. The relation between motivic multiple zeta values and motivic iterated integrals in [Bro12] is given by

$$\zeta^m_B(s_1, \ldots, s_r) = I^m_B(0 : 10^{(s_1-1)} \cdots 10^{(s_r-1)} : 1),$$

while here is given by

$$\zeta^m(s_1, \ldots, s_r) = I^m(1 : 0^{(s_1-1)}1 \cdots 0^{(s_r-1)}1 : 0).$$

Both equations are compatible via the change of notation.

If $s$ is admissible, the function $\zeta^m(s)$ is non-zero since its value at $\text{dch}^{\text{dR}}$ is the non-zero real number $\zeta(s)$. In particular, $\zeta^m(2) \neq 0$. In fact, $\zeta^m(2)$ is the function on $\mathcal{Y}$ that sends an element $g$ of $\mathcal{Y}(\mathbb{Q}) \subset \mathbb{Q}[e_0, e_1]$ to the coefficient of $e_0 e_1$ in $g$.

It follows that $\zeta^m(2)$ is sent to $-t/24$ under the isomorphism $\mathcal{H} \to \mathcal{A} \otimes \mathbb{Q}[t]$ of Corollary 5.21, and hence to the element $f_2$ under the injection $\mathcal{H} \to \mathcal{H}^{\text{MHT}}$ of the same corollary.

**Remark 5.35.** The fact that $\zeta^m(2)$ is not zero is an important difference between Brown’s and Goncharov’s approaches to motivic multiple zeta values. Recall the inclusion $U_{\text{dR}} \subset G_{\text{dR}}$ and the elements $1_{\text{dR}} \in \Pi(\mathbb{Q})$ and $\text{dch}^{\text{dR}} \in \Pi(\mathbb{C})$. Goncharov works with the orbit of $1_{\text{dR}}$ under $U_{\text{dR}}$:

$$\mathcal{X} = U_{\text{dR}} \cdot 1_{\text{dR}} \subset \Pi.$$
As a variety, \( X \) is isomorphic to \( I(U_{dR}) \). Hence, its ring of functions \( \mathcal{O}(X) \) is isomorphic to \( A \). However, Brown works with the variety \( Y \) defined as the closure of the orbit of \( dch^{dR} \) under \( G_{dR} \)

\[
Y = G_{dR} \cdot dch^{dR} \simeq I(U_{dR}) \times \mathbb{A}^1.
\]

Since the leading term of \( dch^{dR} \) is \( 1_{dR} \), we deduce the equality

\[
\lim_{t \to 0} \tau(t) dch^{dR} = 1_{dR}.
\]

This implies that \( 1_{dR} \in Y \) and therefore \( X \subset Y \). Since the action of \( U_{dR} \) on the factor \( \mathbb{A}^1 \) is trivial, we can identify \( X \) with the subscheme \( I(U_{dR}) \times \{0\} \) of \( I(U_{dR}) \times \mathbb{A}^1 \). In other words, the inclusion \( X \hookrightarrow Y \) is given by the algebra morphism

\[
\pi: H \rightarrow H/\zeta^m(2)H = A.
\]

### 5.2.3. The motivic coaction.

We shall now give an explicit description of the coaction (5.11). Following Remark 5.35, there is an isomorphism \( I(U_{dR}) \simeq X \subset \Pi \) and the action of \( I(U_{dR}) \) on \( Y \) fits into the commutative diagram

\[
\begin{array}{ccc}
X \times Y & \longrightarrow & Y \\
\downarrow & & \downarrow \\
\Pi \times \Pi & \longrightarrow & \Pi,
\end{array}
\]

where the vertical arrows are the inclusions and the lower horizontal arrow is the group law on \( \Pi \). Passing to functions, we get the commutative diagram

\[
\begin{array}{ccc}
A \otimes H & \xrightarrow{\Delta} & H \\
\uparrow \hspace{1cm} & & \uparrow \\
\mathcal{O}(\Pi) \otimes \mathcal{O}(\Pi) & \xrightarrow{\Delta^f} & \mathcal{O}(\Pi)
\end{array}
\]

where the lower horizontal arrow is the Goncharov coproduct (Proposition 3.418). Therefore, the coaction (5.11) is given by the formula

\[
\Delta^m(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_N; \varepsilon_{N+1}) = \\
\sum_{0 < i_1 < \cdots < i_k < N+1} \pi \left( \prod_{p=0}^{k} I^m(\varepsilon_{i_p}; \varepsilon_{i_p+1} \cdots \varepsilon_{i_{p+1}-1}; \varepsilon_{i_{p+1}}) \right) \otimes I^m(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_{i_k}; \varepsilon_{N+1}),
\]

where \( \pi: H \rightarrow A \) denotes the projection (5.36) and we set \( i_0 = 0 \) and \( i_{k+1} = N+1 \).

**Lemma 5.38.** For each integer \( N \geq 2 \), the following equality holds:

\[
\Delta \zeta^m(N) = 1 \otimes \zeta^m(N) + \pi(\zeta^m(N)) \otimes 1.
\]

**Proof.** The equality \( \zeta^m(N) = I^m(1; 0^{(N-1)} 1; 0) \) holds by Definition 5.33. Using part i) of Lemma 5.32, we see that the only non-vanishing terms in the coaction formula (5.37) correspond to the indices

\[
k = 0, \ i_0 = 0, \ i_1 = N + 1 \quad \text{and} \quad k = N, \ i_j = j, \ j = 0, \ldots, N + 1.
\]

The first choice yields the term \( \pi(\zeta^m(N)) \otimes 1 \), and the second one \( 1 \otimes \zeta^m(N) \), thus proving the result. \( \Box \)
The formula (5.37) is rather complicated, so we will use an infinitesimal version of it, which is the analogue of the derivations $D_{2r+1}$ for the algebra of motivic multiple zeta values $\mathcal{H}$. For this, we consider the Lie coalgebra

$$\mathcal{L} = A_{>0} / (A_{>0})^2,$$

which inherits a grading from $A$. For each integer $n \geq 1$, let $\mathcal{L}_n \subset \mathcal{L}$ be the subspace of degree $n$ and let $p_n : \mathcal{L} \to \mathcal{L}_n$ be the projection. Since $A$ is graded, the projection from $A_{>0}$ to $\mathcal{L}$ extends to a map $q : A \to \mathcal{L}$.

**Definition 5.39.** For each integer $r \geq 1$, we define a map

$$(5.40)\quad D_{2r+1} : \mathcal{H} \to \mathcal{L}_{2r+1} \otimes \mathcal{H}$$

as the composition

$$\mathcal{H} \xrightarrow{\Delta} A \otimes \mathcal{H} \xrightarrow{q \otimes \text{Id}} \mathcal{L} \otimes \mathcal{H} \xrightarrow{p_{2r+1} \otimes \text{Id}} \mathcal{L}_{2r+1} \otimes \mathcal{H}.$$

We put

$$(5.41)\quad D_{<N} = \bigoplus_{3 \leq 2r+1 < N} D_{2r+1}.$$

For each $n \geq 1$, consider the map

$$\varpi_n = p_n \circ q \circ \pi : \mathcal{H} \to \mathcal{L}_n.$$

Note that $\varpi_1$ is identically zero. The projection $\varpi_n$ kills $\zeta^m(2)$, all products, and all motivic multiple zeta values of weight different from $n$. For example, Lemma 5.38 gives

$$(5.42)\quad D_{2r+1} \zeta^m(N) = \varpi_{2r+1}(\zeta^m(N)) \otimes 1,$$

which vanishes for $N \neq 2r+1$.

**Proposition 5.43.** Let $N \geq 2$ be an integer. For each odd integer $n < N$, the action of $D_n$ is given by

$$(5.44)\quad D_n I^m(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_N; \varepsilon_{N+1}) = \sum_{p=0}^{N-n} \varpi_n (I^m(\varepsilon_p; \varepsilon_{p+1} \cdots \varepsilon_{p+n}; \varepsilon_{p+n+1})) \otimes I^m(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_p, \varepsilon_{p+n+1}, \ldots, \varepsilon_N; \varepsilon_{N+1}).$$

**Proof.** The projection $q$ kills all decomposable elements of $A_{>0}$ and the projection $p_n$ kills all elements of degree different from $n$. Taking into account that

$$I^m(\varepsilon; \alpha; \varepsilon') = 1, \text{ if } \alpha = \emptyset, \text{ while }$$

$$I^m(\varepsilon; \alpha; \varepsilon') \in A_{>0}, \text{ if } \alpha \neq \emptyset,$$

it follows that in the sum that runs over partitions

$$0 = i_0 < i_1 < \cdots < i_k < i_{k+1} = N + 1$$

only the terms having exactly one gap of length $n$ can be non-zero. This gives the desired formula. \qed
5.2.4. **The kernel of** $D_{<N}$. A crucial ingredient in the proof of Brown’s theorem is the explicit knowledge of the kernel of the infinitesimal coaction $D_{<N}$ from (5.41) that is provided by the following theorem:

**Theorem 5.45.** For each integer $N \geq 2$, the following equality holds:

$$\text{Ker } D_{<N} \cap H_N = Q\zeta^m(N).$$

This is the analogue of the result we obtained in Lemma 5.30 for the Hopf algebra $U'$ from (5.22) and its comodule $U$ from (5.24), and the strategy of the proof will be to reduce to this case by choosing an appropriate isomorphism.

**Lemma 5.46.** There exists an isomorphism of Hopf algebras $\phi : A^{MT} \rightarrow U'$ that extends to an isomorphism of Hopf comodules $\phi : H^{MT} \rightarrow U$ sending $\zeta^m(N)$ to $f_N$ for all $N \geq 2$.

**Proof.** Recall from Section 5.2.1 that the Hopf algebras $A^{MT}$ and $U'$ are non-canonically isomorphic. Starting from any isomorphism of Hopf algebras

$$\phi_0 : A^{MT} \rightarrow U',$$

we obtain an isomorphism of Hopf comodules $\phi_0 : H^{MT} \rightarrow U$ by sending $f_2$ to $f_2$. We will still denote by $\phi_0$ the restriction of this map to $H \subset H^{MT}$, as well as the map $L \rightarrow L$ induced by the composition $A \mapsto A^{MT} \xrightarrow{\phi_0} U'$. The diagram

$$\begin{array}{ccc}
H & \xrightarrow{\phi_0} & U \\
D_{2r+1} \downarrow & & \downarrow D_{2r+1} \\
L_{2r+1} \otimes H & \xrightarrow{\phi_0 \otimes \phi_0} & L_{2r+1} \otimes U
\end{array}$$

(5.47)

commutes by construction. Moreover, $\phi_0$ sends $\zeta^m(2)$ to $f_2$ by the discussion before Remark 5.35. It then follows from Lemma 5.38 that $D_{<N}\zeta^m(N) = 0$. By the commutativity of the diagram (5.47) we deduce that $D_{<N}\phi_0(\zeta^m(N)) = 0$. By Lemma 5.30, there exists a non-zero rational number $\alpha_N \in \mathbb{Q}^\times$ satisfying

$$\phi_0(\zeta^m(N)) = \alpha_N f_N.$$

For $N = 2r$ even, we get

$$\phi_0(\zeta^m(2r)) = \alpha_{2r} f_{2r} = \alpha_{2r} b_r f_2^r = \phi_0(\alpha_{2r} b_r \zeta^m(2)^r),$$

where $b_r$ is the rational number from (5.26). By the injectivity of $\phi_0$ we deduce that $\zeta^m(2r) = \alpha_{2r} b_r \zeta^m(2)^r$. Taking the period map we see that $\alpha_{2r} = 1$.

Since $U'$ is the Hopf algebra of non-commutative words in $f_3, f_5, \ldots$, given any family of non-zero rational numbers $(\alpha_{2r+1})_{r \geq 1}$, the $\mathbb{Q}$-linear automorphism $\psi$ of $U'$ determined by

$$f_i \cdots f_i \mapsto (\alpha_i \cdots \alpha_i)^{-1} f_i \cdots f_i$$

is an automorphism of Hopf algebras that sends $f_{2r+1}$ to $\alpha_{2r+1}^{-1} f_{2r+1}$. Therefore, the automorphism $\phi = \psi \circ \phi_0$ sends $\zeta^m(N)$ to $f_N$ for all $N \geq 2$, as wanted. □

**Remark 5.48.** As a byproduct of the proof, we see that the relation from Euler’s theorem $\zeta(2r) = \beta_r \zeta(2)^r$ lifts to a relation

$$\zeta^m(2r) = b_r \zeta^m(2)^r$$

between motivic multiple zeta values.
Proof of Theorem 5.45. After choosing a normalized isomorphism $\phi$ as in Lemma 5.46, the result follows from the combination of Lemma 5.30 and the commutativity of diagram (5.47).

The theorem has the following useful corollary:

Corollary 5.50. Let $N \geq 2$ be an integer and $a^m$ an element of $H_N$. Assume that $D_{<N}(a^m) = 0$ and $\text{per}(a^m) = \alpha \zeta(N)$ for some rational number $\alpha$. Then

$$a^m = \alpha \zeta^m(N).$$

Proof. Since $a^m \in \text{Ker } D_{<N} \cap H_N$, Theorem 5.45 gives the existence of a rational number $\beta$ such that $a^m = \beta \zeta^m(N)$. Applying the period map, one gets $\beta \zeta(N) = \text{per}(a^m) = \alpha \zeta(N)$, and hence $\beta = \alpha$.

The importance of this corollary is that it allows one to lift relations between classical multiple zeta values to their motivic counterparts. This will be exploited in the next sections (for a first application, see Exercise 5.53).

⋆ ⋆ ⋆

Exercise 5.51. Show that the maps $D_{2r+1}: U \rightarrow L_{2r+1} \otimes Q U$ from (5.28) are derivations, that is, they satisfy

$$D_{2r+1}(\xi_1 \xi_2) = (1 \otimes \xi_1)D_{2r+1}(\xi_2) + (1 \otimes \xi_2)D_{2r+1}(\xi_1)$$

for all $\xi_1, \xi_2 \in U$. The same holds for the maps $D_{2r+1}: H \rightarrow L_{2r+1} \otimes Q H$ introduced in Definition 5.39.

Exercise 5.52 (Linear independence of $\zeta^m(2,3)$ and $\zeta^m(3,2)$). In this exercise, we prove the linear independence of the motivic multiple zeta values $\zeta^m(2,3)$ and $\zeta^m(3,2)$ by exploiting the derivation $D_3$. Since $H_5$ has dimension at most $d_5 = 2$ by Theorem A, it will follow that they form a basis. This is the first non-trivial case of Brown’s theorem.

i) Prove the equalities $I^m(1; 010; 0) = -2\zeta^m(3)$ and $I^m(0; 100; 1) = -\zeta^m(3)$.

ii) Use the general formula (5.44) for the action of the derivation $D_3$ and the identities from part i) of the exercise to compute

$$D_3 \zeta^m(2,3) = -2\varpi_3(\zeta^m(3)) \otimes \zeta^m(2),$$

$$D_3 \zeta^m(3,2) = 3\varpi_3(\zeta^m(3)) \otimes \zeta^m(2).$$

iii) Now assume that the equality $\zeta^m(2,3) = \lambda \zeta^m(3,2)$ holds for some rational number $\lambda$. By part ii), this number is necessarily $\lambda = -2/3$. Upon application of the period map, this contradicts the positivity of multiple zeta values.

Exercise 5.53 (Brown’s proof in weight 5). The trick from the previous exercise cannot be generalized to higher weight. Here we present an alternative argument which can be seen as a toy case of Brown’s proof.

i) Prove the equality $D_3(\zeta^m(3) \zeta^m(2)) = \varpi_3(\zeta^m(3)) \otimes \zeta^m(2)$. Together with the computations in Exercise 5.52 and Theorem 5.45, this formula implies that there exist rational numbers $\alpha, \beta \in \mathbb{Q}$ such that

$$\zeta^m(2,3) + 2\zeta^m(3) \zeta^m(2) = \alpha \zeta^m(5),$$

$$\zeta^m(3,2) - 3\zeta^m(3) \zeta^m(2) = \beta \zeta^m(5).$$
ii) By virtue of Corollary 5.50, the stuffle product and the first identity in (1.67), deduce that $\alpha = 9/2$ and $\beta = -11/2$. In particular, the stuffle relation lifts to motivic zeta values:

\begin{equation}
\zeta^m(3)\zeta^m(2) = \zeta^m(2, 3) + \zeta^m(3, 2) + \zeta^m(5).
\end{equation}

iii) Let $\text{gr}_F^H H_{5}^{2,3} \subset H_{5}$ be the subspace spanned by $\zeta^m(2, 3)$ and $\zeta^m(3, 2)$ (the reason for this notation will become apparent later). We define a linear map $(f, g) : \text{gr}_F^H H_{5}^{2,3} \rightarrow \mathbb{Q}$ by requiring

\begin{align*}
D_3(a) &= f(a)\varpi_3(\zeta^m(3)) \otimes \zeta^m(2), \\
D_5(a) &= g(a)\varpi_5(\zeta^m(5)) \otimes 1
\end{align*}

for all $a \in \text{gr}_F^H H_{5}^{2,3}$. Use parts i) and ii) to show that this map has rank two, and hence $\zeta^m(2, 3)$ and $\zeta^m(3, 2)$ form a basis of $H_{5}$.

### 5.3. A family of motivic multiple zeta values and Zagier’s theorem.

In this section, we study certain relations involving motivic multiple zeta values with only 2s as entries or with one entry equal to 3 and the remaining entries equal to 2. The key result is Theorem 5.80. Although the existence of a linear relation of the shape (5.66) is predicted by the motivic coaction, the computation of its actual coefficients relies on a theorem of Zagier about multiple zeta values. Finally, we study the 2-adic properties of the leading coefficient of the linear relation (5.66).

#### 5.3.1. Certain relations among motivic multiple zeta values.

From now on, we follow notation 1.152 to identify the set of words in the alphabet \{1, 2, \ldots\} with the set of positive multi-indices. For instance, we make the identification

the word $2^a 3^b \longleftrightarrow$ the multi-index $(2, \ldots, 2, 3, 2, \ldots, 2)$. 

**Lemma 5.55.** For each $n \geq 1$, the following equality holds:

\begin{equation}
\zeta^m(2^n) = \frac{6^n}{(2n + 1)!} \zeta^m(2)^n.
\end{equation}

**Proof.** Recall that the left-hand side of the equality is defined as

\begin{equation}
\zeta^m(2^n) = I^m(1; 01^{r-1}0; 0).
\end{equation}

We first observe the vanishing

\begin{equation}
D_{2r+1} \zeta^m(2^n) = 0
\end{equation}

for all $3 \leq 2r + 1 < 2n$. Indeed, in formula (5.44) every sequence of the form $\varepsilon_p, \ldots, \varepsilon_{p+2r+2}$ starts and ends with the same value, and the corresponding motivic iterated integral is zero by (5.31) Hence, $\zeta^m(2^n)$ belongs to $\text{Ker} D_{<2n}$. By Theorem 5.45 and equation (5.49), we deduce that $\zeta^m(2^n)$ is a rational multiple of $\zeta^m(2)^n$. To get the precise multiple we use the period map and Example 1.28. □

In order to simplify notation, we write

\begin{equation}
\zeta^m_\mathbf{s}(s) = I^m(1; 0^{(s_1-1)}1 \cdots 0^{(s_r-1)}10; 0)
\end{equation}

for $s = (s_1, \ldots, s_r)$. 

LEMMA 5.57. For \( n \geq 1 \), the following equalities hold:

\[
\zeta^{m}(2^{(n)}) = -2\sum_{i=0}^{n-1} \zeta^m(2^{(i)}32^{(n-i-1)}),
\]

\[
\zeta^{m}(2^{(n)}) = 2\sum_{i=1}^{n} (-1)^i\zeta^m(2i+1)\zeta^m(2^{(n-i)}).
\]

Proof. Recall from (5.31) that \( I^m(1; 0; 1) = 0 \). Since the multiplication in \( \mathcal{H} \) is given by the shuffle product, we have

\[
0 = I^m(1; 01; .01; 1)I^m(1; 0; 1) = \zeta^{m}(2^{(n)}) + 2\sum_{i=0}^{n-1} \zeta^m(2^{(i)}32^{(n-i-1)}),
\]

from which the identity (5.58) follows.

To prove equation (5.59), we first show the equality of multiple zeta values

\[
-\sum_{i=0}^{n-1} \zeta(2^{(i)}32^{(n-i-1)}) = \sum_{i=1}^{n} (-1)^i\zeta(2i+1)\zeta(2^{(n-i)})
\]

using the stuffle product. Indeed, the equalities

\[
\zeta_k(3)\zeta(2^{(n-1)}) = \sum_{i=0}^{n-1} \zeta(2^{(i)}32^{(n-1-i)}) + \sum_{i=0}^{n-2} \zeta(2^{(i)}52^{(n-2-i)})
\]

\[
\zeta_k(5)\zeta(2^{(n-2)}) = \sum_{i=0}^{n-2} \zeta(2^{(i)}52^{(n-2-i)}) + \sum_{i=0}^{n-3} \zeta(2^{(i)}72^{(n-3-i)})
\]

\[\vdots\]

\[
\zeta(2n-1)\zeta(2) = \zeta(2n-1, 2) + \zeta(2, 2n-1) + \zeta(2n+1)
\]

\[
\zeta(2n+1) = \zeta(2n+1)
\]

hold by Exercise 1.45, and taking the alternate sum of these equalities we obtain equation (5.60).

We now prove equation (5.59) by induction on \( n \). The case \( n = 1 \) is given by (5.58) and the case \( n = 2 \) follows from the identity (5.54) in Exercise 5.53. Besides, the equality

\[
D_{2r+1}\zeta^{m}(2^{(n)}) = \varpi_{2r+1}(\zeta^{m}(2^{(r)})) \otimes \zeta^{m}(2^{(n-r)})
\]

holds for all \( 3 \leq 2r + 1 < 2n \) (Exercise 5.89). By the induction hypothesis and the fact that \( \varpi_{2r+1} \) kills products, we then get

\[
D_{2r+1}\zeta^{m}(2^{(n)}) = 2(-1)^r \varpi_{2r+1}(\zeta^{m}(2r+1)) \otimes \zeta^{m}(2^{(n-r)}).
\]

Moreover, using the fact that \( D_{2r+1} \) is a derivation (Exercise 5.51) and equations (5.42) and (5.56) we get

\[
D_{2r+1}(\zeta^{m}(2i+1)\zeta^{m}(2^{(n-i)})) = \begin{cases} 
\varpi_{2r+1}(\zeta^{m}(2r+1)) \otimes \zeta^{m}(2^{(n-r)}), & \text{if } r = i, \\
0, & \text{if } r \neq i.
\end{cases}
\]

Therefore, if \( \Theta \) denotes the difference of the left-hand side and the right-hand side terms of equation (5.59), then

\[
D_{2r+1}\Theta = 0
\]
for all $3 \leq 2r+1 < 2n$. Hence, by Theorem 5.45, $\Theta$ is a multiple of $\zeta^m(2n+1)$, and formula (5.59) follows from Corollary 5.50 and equations (5.60) and (5.58).

Given integers $r$ and $s$, we let $\mathbb{I}(r \geq s)$ denote the indicator function

$$\mathbb{I}(r \geq s) = \begin{cases} 1, & \text{if } r \geq s, \\ 0, & \text{otherwise.} \end{cases}$$

**Lemma 5.63.** Let $a, b \geq 0$ be integers. For each $1 \leq r \leq a+b$, the equality

$$D_{2r+1} \zeta^m(2b^{[a]}) = \varpi_{2r+1}(\xi_{a,b}^r) \otimes \zeta^m(2^{(a+b+1-r)})$$

holds, where $\xi_{a,b}^r \in \mathcal{H}$ is the element given by

$$\xi_{a,b}^r = \sum_{\alpha \leq a, \beta \leq b, \alpha + \beta = r - 1} \xi^m(2^{(\beta)}32^{(\alpha)}) - \sum_{\alpha \leq a, \beta \leq b, \alpha + \beta = r - 1} \xi^m(2^{(\alpha)}32^{(\beta)})$$

$$+ \left( \mathbb{I}(b \geq r) - \mathbb{I}(a \geq r) \right) \zeta^m(2^r).$$

**Proof.** To prove the result it is enough to check which non-zero terms appear in formula (5.44) for the coaction. These terms are given by consecutive subsequences of $2r+1$ entries and can be of the following types:

i) Subsequences containing 001 and starting with 1; these contribute to the first sum.

ii) Subsequences containing 001 and starting with 0; after applying the reflection formula of Lemma 5.32, these contribute to the second sum.

iii) When $b \geq r$ there is exactly one sequence ending with 00; this gives the term $\mathbb{I}(b \geq r)\zeta^m(2^r)$.

iv) When $a \geq r$ there is exactly one sequence starting with 00; after applying the reflection formula we obtain the term $-\mathbb{I}(a \geq r)\zeta^m(2^r)$.

Using equation (5.31), it is easy to check that all the other subsequences do not contribute to the result. 

**Proposition 5.65.** Given $a, b \geq 0$, write $n = a + b + 1$. There exists a unique $n$-tuple of rational numbers $(\gamma_{a,b}^r)_{r=1}^{n}$ such that

$$\zeta^m(2^{(b)}32^{(a)}) = \sum_{r=1}^{n} \gamma_{a,b}^r \zeta^m(2r+1) \zeta^m(2^{(n-r)}).$$

**Proof.** We argue by induction on $n$. The case $n = 1$ is obvious, with $\gamma_{0,0}^1 = 1$. Assume that the result holds for all integers smaller than $n$. In particular, all the numbers $\gamma_{a,b}^r$ are defined for $a + b + 1 < n$. Now let $a$ and $b$ satisfy $a + b + 1 = n$ and recall the element $\xi_{a,b}^r$ from (5.64). For each $r < n$, we define $\gamma_{a,b}^r$ as the unique rational number satisfying

$$\xi_{a,b}^r \equiv \gamma_{a,b}^r \zeta^m(2r+1) \mod \text{products},$$

which exists by the induction hypothesis and equation (5.59). Therefore, the projection of $\xi_{a,b}^r$ to $L_{2r+1}$ is given by

$$\varpi_{2r+1}(\xi_{a,b}^r) = \gamma_{a,b}^r \varpi_{2r+1}(\zeta^m(2r+1)).$$
and from Lemma 5.63 we find
\begin{equation}
D_{2r+1} \zeta^m(2^{(b)}32^{(a)}) = \gamma_{a,b} \zeta^{m}(2r+1) \otimes \zeta^m(2^{(n-r)}).
\end{equation}
Using equation (5.62), we deduce that the element
\begin{equation}
\zeta^m(2^{(b)}32^{(a)}) - \sum_{r=1}^{n-1} \gamma_{a,b} \zeta^m(2r+1) \zeta^m(2^{(n-r)})
\end{equation}
belongs to the kernel of the derivation $D_{<2n+1}$. By Theorem 5.45, it is a rational multiple of $\zeta^m(2n+1)$ and we define the remaining $\gamma_{a,b}^n$ as this rational factor. □

We have here a remarkable example of both the strength and the limits of the motivic formalism. Applying the period map (5.12), the motivic identity (5.66) implies that the same holds for usual multiple zeta values, something which would have been difficult to predict working only with numbers, where the coaction is invisible. However, the motivic formalism alone does not allow us to compute the precise value of the constants $\gamma_{a,b}$. For this one needs to prove the corresponding identity of numbers first. In fact, for given $a, b, n$ with $a+b+1 = n$ the numbers $\gamma_{a,b}^r$ for $r < n$ are determined by induction but the last term $\gamma_{a,b}^n$ can only be determined by the corresponding equality of numbers. Zagier [Zag12] has been able to prove an equality with the desired shape between multiple zeta values. To prove that Zagier’s equation is motivic we will need to show that the coefficients in Zagier’s equation are compatible with the induction process in the proof of Proposition 5.65.

5.3.2. Zagier’s theorem. Define, for each $a, b, r \geq 0$, rational numbers
\begin{equation}
A_{a,b}^r = \left( \frac{2r}{2a+2} \right), \quad B_{a,b}^r = (1 - 2^{-2r}) \left( \frac{2r}{2b+1} \right).
\end{equation}
As in the previous paragraph, we set $n = a + b + 1$.

**Theorem 5.71** (Zagier, [Zag12]). The following equality holds:
\begin{equation}
\zeta(2^{(b)}32^{(a)}) = 2 \sum_{r=1}^{n} (-1)^r \left( A_{a,b}^r - B_{a,b}^r \right) \zeta(2r+1) \zeta(2^{(n-r)}).
\end{equation}

**Sketch of proof.** Let $\hat{H}(a, b)$ denote the right-hand side of (5.72). The strategy of the proof consists in showing that the generating series
\[
F(x, y) = \sum_{a, b \geq 0} (-1)^{a+b+1} \zeta(2^{(b)}32^{(a)})x^{2a+2}y^{2b+1},
\]
\[
\hat{F}(x, y) = \sum_{a, b \geq 0} (-1)^{a+b+1} \hat{H}(a, b)x^{2a+2}y^{2b+1}
\]
are equal. Using a similar technique to that of Example 1.28 (see Exercise 5.91), the first series is seen to be equal to
\begin{equation}
F(x, y) = \frac{\sin \pi y}{\pi} \frac{\partial}{\partial z} \left. 3F_2 \left( \frac{x, -x, z}{1+y, 1-y} \right) \right|_{z=0},
\end{equation}
where the second factor involves the hypergeometric function
\[
3F_2 \left( \frac{a_1, a_2, a_3}{b_1, b_2} \left| t \right. \right) = \sum_{n=0}^{\infty} \frac{(a_1)_n(a_2)_n(a_3)_n}{(b_1)_n(b_2)_n} \frac{t^n}{n!}
\]
(in this formula, \((\alpha)_n = \alpha(\alpha+1) \cdots (\alpha+n-1)\) is the so-called Pochhammer symbol).

It follows from the bound

\[ 0 < \zeta(2b)32^{(a)} < \frac{1}{a+1} \zeta(2^{(n)}) = \frac{1}{a+1} \frac{\pi^n}{(2n)!} \quad (n = a + b + 1) \]

that the series \(F(x, y)\) converges absolutely for all \(x, y \in \mathbb{C}\) (and hence defines a holomorphic function on \(\mathbb{C} \times \mathbb{C}\)) and satisfies the bound

\[ \max_{|x|, |y| \leq M} |F(x, y)| = O(e^{\pi M} \log M), \quad M \rightarrow \infty. \]

The expression for the second generating series is more involved: \(\hat{F}(x, y)\) is an integral linear combination of fourteen terms of the form

\[ \psi\left(1 + \frac{u}{2}\right) \frac{\sin \pi v}{2\pi}, \quad u \in \{\pm x, \pm y, \pm 2x, \pm 2y\}, \quad v \in \{x, y\}, \]

where \(\psi(s) = \Gamma'(s)/\Gamma(s)\) is the digamma function (see Exercise 5.92). Using this explicit expression and standard properties of \(\psi(s)\), one sees that \(\hat{F}(x, y)\) is also a holomorphic function on \(\mathbb{C} \times \mathbb{C}\) satisfying

\[ \max_{|x|, |y| \leq M} |\hat{F}(x, y)| = O(e^{\pi M} \log M), \quad M \rightarrow \infty. \]

At this point, Zagier observes that the expressions for the functions \(F(x, y)\) and \(\hat{F}(x, y)\) allow him to prove that they are equal for certain values of \(x\) and \(y\). Namely, it is not hard to prove that

\[ F(x, x) = \hat{F}(x, x), \quad x \in \mathbb{C}. \]

Much trickier is the equality

\[ F(x, n) = \hat{F}(x, n), \quad x \in \mathbb{C}, \quad n \in \mathbb{Z}, \]

from \([Zag12, Prop.6]\). One is then led to the question of whether the partial information provided by (5.76) and (5.77) suffices to derive the equality of the functions. It turns out that the growth conditions (5.74) and (5.75) do the trick. Indeed, we can invoke the following result proved in \([Boa54, Cor.9.4.2]\).

**Theorem 5.78.** Let \(f: \mathbb{C} \rightarrow \mathbb{C}\) be an entire function that vanishes at all integers and satisfies the estimate \(f(z) = O(e^{\pi|z|} \log |z|)\) for \(|z| \rightarrow +\infty\). Then \(f\) is a constant multiple of \(\sin(\pi z)\).

Together with the estimates (5.74) and (5.75) and the equalities (5.77), this theorem implies the existence of a function \(c: \mathbb{C} \rightarrow \mathbb{C}\) satisfying

\[ F(x, y) - \hat{F}(x, y) = c(x) \sin \pi y. \]

The equality (5.76) implies the vanishing \(c(x) = 0\) for all \(x \in \mathbb{C} \setminus \mathbb{Z}\), and hence the equality \(F(x, y) = \hat{F}(x, y)\) for all \(x, y \in \mathbb{C}\) since these are holomorphic functions. □

**Remark 5.79.** After the original proof of Zagier’s theorem, Z. H. Li in \([Li13]\) has shown directly the equality \(F(x, y) = \hat{F}(x, y)\) using the transformation relations of hypergeometric functions \(_3F_2\) that involve the gamma function. It is also worth mentioning that Terasoma \([Ter13]\) showed that the relation (5.72) holds for any associator.
5.3.3. Lifting Zagier’s theorem to a motivic identity. The first non-trivial case of Zagier’s theorem are the identities
\[ \zeta(2,3) = -2\zeta(3)\zeta(2) + \frac{9}{2}\zeta(5), \]
\[ \zeta(3,2) = 3\zeta(3)\zeta(2) - \frac{11}{2}\zeta(5). \]
In Exercise 5.53, we show that they lift to motivic equalities.

**Theorem 5.80.** For \( a, b \geq 0 \) and \( 1 \leq r \leq a+b+1 \), the numbers \( \gamma_{a,b}^r \) from the statement of Proposition 5.65 are equal to
\[ (5.81) \quad \gamma_{a,b}^r = (-1)^r 2 \left( A_{a,b}^r - B_{a,b}^r \right). \]
In other words, writing \( n = a + b + 1 \), the identity
\[ (5.82) \quad \zeta_m(2^{(b)} 32^{(a)}) = 2 \sum_{r=1}^{n} (-1)^r \left( A_{a,b}^r - B_{a,b}^r \right) \zeta_m(2r+1) \zeta_m(2^{(n-r)}) \]
of motivic multiple zeta values holds.

**Proof.** We first note that, for any \( a, b \geq 0 \) and \( 1 \leq r \leq a+b+1 \), the following identities are satisfied:
\[ (5.83) \quad A_{a,b}^r = \sum_{\alpha \leq a, \beta \leq b} A_{\alpha,\beta}^r - \sum_{\alpha \leq a, \beta \leq b} A_{\beta,\alpha}^r + \|_r(b \geq r) - \|_r(a \geq r), \]
\[ (5.84) \quad B_{a,b}^r = \sum_{\alpha \leq a, \beta \leq b} B_{\alpha,\beta}^r - \sum_{\alpha \leq a, \beta \leq b} B_{\beta,\alpha}^r. \]
This can be proved using that \( A_{a,b}^r \) does not depend on \( b \), that \( B_{a,b}^r \) does not depend on \( a \), and the symmetries \( A_{\alpha,\beta}^{\alpha+\beta+1} = A_{\beta,\alpha}^{\beta-1,\alpha+1} \) and \( B_{\alpha,\beta}^{\alpha+\beta+1} = B_{\beta,\alpha}^{\beta,\alpha} \). For instance, the second equality is clear because by symmetry each term of the second sum cancels one term of the first sum; the only remaining term in the first sum is \( B_{r-1-a,b}^r \) that agrees with \( B_{a,b}^r \) because it is independent of \( a \). To prove the first identity we may distinguish different cases according to whether \( a \) and \( b \) are bigger than or equal to \( r \) or not. For instance, if \( a < r \) and \( b \geq r \), the term \( A_{a,b}^r \) is different from zero. In these cases, both sums range from \( (\alpha, \beta) = (a, r - 1 - a) \) to \((0, r - 1)\). By the symmetry of the \( A \)'s all terms cancel except \( A_{a-1,r-r-1-a}^r \) from the first sum, that agrees with \( A_{a,b}^r \) and \(-A_{r-1,0}^r = -1 \) that cancels with \( \|_r(b \geq r) \). The remaining cases are similar.

We now prove the theorem by induction on \( n = a + b + 1 \). For \( n = 1 \), the right-hand side of \((5.81)\) is equal to 1, which is also the value \( \gamma_{0,0}^1 \), as we noted in the proof of Proposition 5.65. So we assume that equation \((5.81)\) is true for all \( a', b' \) with \( a' + b' < n - 1 \) and all \( 1 \leq r' \leq a' + b' + 1 \) and we fix \( a, b \) with \( a + b + 1 = n \). We compute \( D_{2r+1} \zeta_m(2^{(b)} 32^{(a)}) \) in two ways and compare the results. The first way is equation \((5.68)\), while the second is to apply Lemma 5.63, then use Lemma 5.57 to get rid of the terms \( \zeta_m(2^{(r)}) \) and apply equation \((5.67)\) to the terms \( \varpi_{2r+1}(\zeta_m(2^{(r)})) \). Comparing both results we obtain
\[ \gamma_{a,b}^r = \sum_{\alpha \leq a, \beta \leq b} \gamma_{\alpha,\beta}^r - \sum_{\alpha \leq a, \beta \leq b} \gamma_{\beta,\alpha}^r + 2(-1)^r (\|_r(b \geq r) - \|_r(a \geq r)). \]
Using the induction hypothesis and the identities (5.83) and (5.84), we deduce the equality (5.81) for \(1 \leq r \leq a + b\).

To treat the remaining case \(r = a + b + 1\), set

\[
\Theta = \zeta^m(2^{(b)}32^{(a)}) - 2 \sum_{r=1}^{a+b} (-1)^r \left(A_{a,b}^r - B_{a,b}^r\right) \zeta^m(2r + 1)\zeta^m(2^{(n-r)}),
\]

which is a motivic zeta value of weight \(2a + 2b + 3\). The identities we already proved and equation (5.66) yield \(D_{c2a+2b+3}(\Theta) = 0\). By Zagier’s Theorem 5.71, we obtain \(\text{per}(\Theta) = 0\). Finally, Corollary 5.50 implies \(\Theta = 0\), thus proving the result. \(\square\)

### 5.3.4. The coefficients \(c_s\)

Among the coefficients \(\gamma_{a,b}^r\), the leading one \(\gamma_{a,b}^{a+b+1}\) will play a special role, so we single it out.

**Definition 5.85.** Let \(s = 2^{(b)}32^{(a)}\) be a word in the alphabet \(2, 3\) with only one 3 and all the remaining entries equal to 2. We set

\[
c_s = \gamma_{a,b}^{a+b+1}.
\]

We will also write

\[
c_{12(n)} = 2(-1)^n.
\]

With this notation, Lemma 5.57 and Proposition 5.65 imply the following:

**Corollary 5.86.** For integers \(n, a, b \geq 0\) with \(n = a + b + 1\), the following equalities hold:

\[
\begin{align*}
&\text{i)} \quad \varpi_{2n+1}\left(\zeta^m(2^{(n)})\right) = c_{12(n)}\zeta^m(2n + 1), \\
&\text{ii)} \quad \varpi_{2n+1}\left(\zeta^m(2^{(b)}32^{(a)})\right) = c_{2^{(b)}32^{(a)}}\zeta^m(2n + 1).
\end{align*}
\]

Moreover, the following equality holds:

\[
(5.87) \quad c_{12(n)} = -2 \sum_{i=0}^{n-1} c_{2^{(i)}32^{(n-i-1)}}.
\]

Recall that, given a prime number \(p\), the \(p\)-adic valuation of a non-zero rational number \(x\) is the only integer \(v_p(x)\) such that \(x\) can be written as \(x = p^{v_p(x)}a/b\) with \(a\) and \(b\) relatively prime to \(p\). We also set \(v_p(0) = \infty\). As a consequence of Theorem 5.80, the coefficients \(c_w\) have the following 2-adic properties.

**Lemma 5.88.** Let \(s\) be a word of the form \(s = 2^{(b)}32^{(a)}\), denote by \(s^r\) the word written in reverse order, i.e. \(s^r = 2^{(a)}32^{(b)}\) and set \(n = a + b + 1\). Then

\[
\begin{align*}
&\text{i)} \quad c_s \in \mathbb{Z}\left[\frac{1}{2}\right], \\
&\text{ii)} \quad c_s - c_{s^r} \text{ is an even integer}, \\
&\text{iii)} \quad v_2(c_{2^{(i)}32^{(n-i-1)}}) = v_2(c_{2^{(n-i)}}) \leq v_2(c_s) \leq 0.
\end{align*}
\]

**Proof.** Recall the formula

\[
c_s = (-1)^n 2(A_{a,b}^n - B_{a,b}^n)
\]

from Theorem 5.80. Since \(A_{a,b}^n\) is an integer and \(B_{a,b}^n\) belongs to \(\mathbb{Z}\left[\frac{1}{2}\right]\), the first claim follows.

Property ii) is obtained from the symmetry \(B_{a,b}^n = B_{b,a}^n\). Indeed,

\[
c_s - c_{s^r} = (-1)^n 2[A_{a,b}^n - A_{b,a}^n] \in 2\mathbb{Z}.
\]
To prove iii), we first observe that
\[ v_2(2^{-2n}(2n)!) < 2n, \]
and hence
\[ v_2(2^{-2n}(2n)!) < 0. \]
Using the triangle inequality, it follows that
\[ v_2(c_a) = v_2(2 \cdot 2^{-2n}(2n)!) = 1 + v_2(2^{-2n}(2n)!) \leq 0. \]
For the remaining inequality, we write
\[ \binom{2n}{b+1} = \frac{2n}{2b + 1} \binom{2n-1}{2b}. \]
Therefore,
\[ v_2(c_a) = 2 - 2n + v_2(n) + v_2(2^{(2n-1)}). \]
Since \( v_2(2^{(2n-1)}) \geq 0 \), the right-hand side attains its minimum for \( b = n - 1 \) and \( b = 0 \), which correspond to the cases \( s = 2^{(n-1)}3 \) and \( s = 2^{(n-1)} \).

\[ \Box \]

Exercise 5.89. Prove equation (5.61).

Exercise 5.90. Show that one may replace the multiple zeta value \( \zeta(2^{(n-r)}) \) with either \( \zeta(2n-2r) \) or \( \zeta(2)^{n-r} \) in the right-hand side of Zagier’s theorem 5.71 without losing the rationality of the coefficients \( \gamma^r_{a,b} \).

Exercise 5.91. The goal of this exercise is to prove equation (5.73) in the sketch of proof of Zagier’s theorem.

i) Prove that the equalities
\[ \prod_{0 < k < m} \left( 1 - \frac{x^2}{k^2} \right) = \sum_{j=0}^{m-1} \sum_{0 < k_1 < \ldots < k_j < m} \frac{(-1)^j x^{2j}}{k_1^2 \ldots k_j^2} \]
\[ \prod_{\ell > m} \left( 1 - \frac{y^2}{\ell^2} \right) = \sum_{j \geq 0} \sum_{m < \ell_1 < \ldots < \ell_j} \frac{(-1)^j y^{2j}}{\ell_1^2 \ldots \ell_j^2} \]
hold for each integer \( m \geq 1 \). Deduce that the first generating series in the proof is given by
\[ F(x, y) = -x^2 y \sum_{m \geq 1} \prod_{0 < k < m} \left( 1 - \frac{x^2}{k^2} \right) \cdot \frac{1}{m^3} \cdot \prod_{\ell > m} \left( 1 - \frac{y^2}{\ell^2} \right). \]

ii) Prove the equality
\[ -x^2 \prod_{0 < k < m} \left( 1 - \frac{x^2}{k^2} \right) = \frac{(-x)_m(x)_m}{(m-1)!^2}, \]
where \((x)_m\) stands for the Pochhammer symbol. Similarly, prove
\[ \frac{y}{m^2} \prod_{\ell > m} \left( 1 - \frac{y^2}{\ell^2} \right) = \frac{\sin \pi y}{\pi} \cdot \frac{(m-1)!^2}{(1-y)_m(1+y)_m} \]
using the product expansion of \( \sin(\pi y)/\pi \). Conclude that
\[ F(x, y) = \frac{\sin \pi y}{\pi} \sum_{m \geq 1} \frac{1}{m} \frac{(-x)_m(x)_m}{(1-y)_m(1+y)_m}. \]
iii) Prove equation (5.73).

Exercise 5.92. Consider the meromorphic functions

\[ A(z) = \sum_{n=1}^{\infty} \frac{z^2}{n(n^2 - z^2)}, \quad B(z) = \sum_{n=1}^{\infty} \frac{(-1)^{n-1}z^2}{n(n^2 - z^2)} \]

defined on the complex plane, with simple poles at all non-zero integers.

i) Prove the equality \( B(z) = A(z) - A(z/2) \).

ii) Prove the equalities of formal power series

\[ A(z) = \sum_{r=1}^{\infty} \zeta(2r+1)z^{2r}, \quad B(z) = \sum_{r=1}^{\infty} (1 - 2^{-2r})\zeta(2r+1)z^{2r}. \]

(The right-hand sides of both equalities only converge for \(|z| < 1\). This is the reason to work with \( A(z) \) and \( B(z) \) instead.)

iii) Use the Taylor expansion of the logarithm of \( \Gamma(1+z) \) and \( \Gamma(1+z) \) from Exercise 1.19 to get the equality

\[ A(z) = \psi(1) - \frac{1}{2}(\psi(1+z) + \psi(1-z)) \]

iv) Using Example 1.28, the binomial theorem, and the above results, derive the expression

\[ \hat{F}(x, y) = \frac{\sin \pi y}{\pi} [A(x + y) + A(x - y) - 2A(y)] - \frac{\sin \pi x}{\pi} [B(x + y) - B(x - y)] \]

for the second generating series in the proof of Zagier’s theorem.

5.4. The subspaces \( \mathcal{H}^{2,3} \). In this section, we begin the study of the subspaces \( \hat{\mathcal{H}}^{2,3} \subset \mathcal{H} \) and \( \mathcal{H}^{2,3} \subset \mathcal{H} \) spanned by admissible words containing only 2s and 3s and by motivic multiple zeta values with only 2s and 3s as entries respectively. Clearly, there is a surjective map \( \hat{\mathcal{H}}^{2,3} \to \mathcal{H}^{2,3} \). A key step to prove Theorem B in the next section is to show that this map is an isomorphism. As a preparation of the stage, we define a level filtration on both spaces by counting the number of 3s and, using the infinitesimal coaction, a level lowering operators that sends an element of level \( \ell \) and weight \( N \) to a linear combination of elements of level \( \ell - 1 \) and smaller weight. The operators for \( \hat{\mathcal{H}}^{2,3} \) and \( \mathcal{H}^{2,3} \) are compatible. Finally, we exhibit some explicit bases of the source and the target of the level lowering operator that will help us to prove, in the next section, that it is an isomorphism.

5.4.1. The level filtration.

Definition 5.93. We denote by \( \hat{\mathcal{H}}^{2,3} \subset \mathcal{O}(\Pi) = \mathcal{H} \) the subspace generated by the functions \( I(1; \alpha; 0) \), where \( \alpha \) is the binary sequence associated with an admissible multi-index containing only 2 and 3 as entries, and by \( \mathcal{H}^{2,3} \subset \mathcal{H} \) the image of \( \hat{\mathcal{H}}^{2,3} \) under the restriction map

\[ \text{res}: \mathcal{O}(\Pi) \to \mathcal{H}. \]

Clearly, \( \mathcal{H}^{2,3} \) is the \( \mathbb{Q} \)-vector space spanned by the motivic multiple zeta values

\[ \zeta^m(s_1, \ldots, s_r) \text{ with } s_i \in \{2, 3\}. \]
We filter \( \widetilde{H}^{2,3} \) by the number of entries equal to 3 in the admissible multi-index. Precisely, for each integer \( \ell \geq 0 \), consider
\[
F_\ell \widetilde{H}^{2,3} = (I(1; bs(s); 0) \mid s \text{ contains } \leq \ell \text{ entries equal to } 3)_Q.
\]
This defines an increasing level filtration
\[
0 \subseteq F_0 \widetilde{H}^{2,3} \subseteq F_1 \widetilde{H}^{2,3} \subseteq \cdots
\]
We deduce an increasing filtration on \( H^{2,3} \) with
\[
F_\ell H^{2,3} = \langle \zeta^m(s_1, \ldots, s_r) \in H^{2,3} \mid \text{number of } s_i = 3 \leq \ell \rangle_Q.
\]
The associated graded pieces \( \text{gr} F_\ell H^{2,3} = \frac{F_\ell H^{2,3}}{F_{\ell - 1} H^{2,3}} \) are spanned by the projections of motivic multiple zeta values with exactly \( \ell \) entries equal to 3, which will be denoted in the same way. In particular,
\[
\text{gr}_0 F_0 H^{2,3} = \langle \zeta^m(2 \{n\}) \mid n \geq 1 \rangle_Q,
\]
\[
\text{gr}_1 F_1 H^{2,3} = \langle \zeta^m(2^a 3^b) \mid a, b \geq 0 \rangle_Q.
\]
Note that these are precisely the two families of motivic multiple zeta values that we studied in the previous section.

**Remark 5.94.** The \( \mathbb{Q} \)-vector space \( \text{gr} F_\ell H^{2,3} \) is non-zero if and only if the weight \( N \) and the level \( \ell \) have the same parity and \( N \geq 3 \ell \). When this is the case, writing \( N = 2m + 3\ell \), the dimensions are given by
\[
\dim_{\mathbb{Q}} \text{gr} F_\ell H^{2,3} = \binom{m + \ell}{\ell},
\]
hence the inequality
\[
(5.95) \quad \dim_{\mathbb{Q}} \text{gr} F_\ell H^{2,3} \leq \binom{m + \ell}{\ell}
\]
because we do not know yet that the generators of \( \text{gr} F_\ell H^{2,3} \) discussed previously are linearly independent. Indeed, in Theorem 5.111 we will see that this is the case and that the inequality \((5.95)\) turns out to be an equality.

5.4.2. The level lowering operator. Recall that in Section 3.10.6 we introduced Goncharov’s coproduct as a morphism
\[
(5.96) \quad \Delta^\Gamma : \mathcal{O}(\Pi) \longrightarrow \mathcal{O}(\Pi) \otimes_{\mathbb{Q}} \mathcal{O}(\Pi).
\]
From this we obtained the motivic coaction \((5.11)\)
\[
\Delta : \mathcal{H} \longrightarrow \mathcal{A} \otimes_{\mathbb{Q}} \mathcal{H}
\]
that we have been using in the last pages. In what follows, we will also use an intermediate version
\[
(5.97) \quad \Delta : \mathcal{O}(\Pi) \longrightarrow \mathcal{A} \otimes \mathcal{O}(\Pi)
\]
which is simply obtained from \((5.96)\) via the projection \( \mathcal{O}(\Pi) \rightarrow \mathcal{A} \) (recall that this corresponds to restricting a function on \( \Pi \) to the subvariety \( X \) of Remark 5.35). This is nothing else but the coaction associated with the action of \( I(U_{\text{dir}}) \) on \( \Pi \). As in Definition 5.39, there are maps
\[
D_{2r+1} : \mathcal{O}(\Pi) \longrightarrow \mathcal{L}_{2r+1} \otimes \mathcal{O}(\Pi).
\]
Following the proof of Proposition 5.43 we see that, for all odd integers \( n < N \), the analogue of (5.44) also holds:

\[
D_n I(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_N; \varepsilon_{N+1}) =
\sum_{p=0}^{N-n} \varpi_n \left( \frac{I^m(\varepsilon_p; \varepsilon_{p+1} \cdots \varepsilon_{p+n}; \varepsilon_{p+n+1})}{\otimes I(\varepsilon_0; \varepsilon_1 \cdots \varepsilon_p, \varepsilon_{p+n+1}, \ldots, \varepsilon_N; \varepsilon_{N+1})} \right).
\]

We now study how the filtered subspace \( H^{2,3} \subset O(\Pi) \) behaves with respect to the coaction and its infinitesimal version.

**Lemma 5.99.** The subspace \( H^{2,3} \) is stable under the coaction (5.97). That is, the subspace \( \Delta(H^{2,3}) \) of \( A \otimes O(\Pi) \) is contained in \( A \otimes Q H^{2,3} \), so that (5.97) restricts to a coaction

\[
\Delta: H^{2,3} \longrightarrow A \otimes Q H^{2,3}.
\]

**Proof.** Let \( I(1; \alpha; 0) \) be an element of \( H^{2,3} \). Then \( \alpha \) is a binary sequence obtained by successive concatenation of the subsequences 01 and 001. From the explicit formula for the coaction (5.37) and the fact that the iterated integrals \( I(\varepsilon; \alpha'; \varepsilon') \) vanish for \( \varepsilon = \varepsilon' \) and \( \alpha' \neq 0 \), we deduce that each non-trivial term appearing in \( \Delta I(1; \alpha; 0) \) has, in the right-hand side of the coaction, a factor of the form \( I(1; \beta; 0) \), where \( \beta \) is again a concatenation of the subsequences 01 and 001.

**Remark 5.100.** In [Del13, §6.3], the above result is rephrased by saying that the subspace \( H^{2,3} \) is “motivic”, thus invariant under the action of \( U_{dR} \).

From this we immediately deduce:

**Corollary 5.101.** For each \( r \geq 1 \), the derivation \( D_{2r+1} \) restricts to a map

\[
D_{2r+1}: H^{2,3} \longrightarrow L_{2r+1} \otimes Q H^{2,3}.
\]

In fact, more is true:

**Lemma 5.102.** For each \( r \geq 1 \), the derivation \( D_{2r+1} \) is compatible with the level filtration, in the sense that it induces a map

\[
D_{2r+1}: F_{\ell} H^{2,3} \longrightarrow L_{2r+1} \otimes Q F_{\ell-1} H^{2,3}.
\]

**Proof.** Given a word \( s \) in the alphabet \( \{2, 3\} \) of level \( \ell \), the binary sequence \( bs(s) \) contains at most \( \ell \) subsequences 00. Any subsequence of odd length of \( (1; bs(s); 0) \) that begins and ends with the same symbol will be killed by \( I^m \) and will not contribute to \( D_{2r+1} \). Otherwise it must contain at least a subsequence 00. Thus, the complementary quotient sequence will contain at most \( \ell - 1 \) subsequences 00. Hence will have level at most \( \ell - 1 \).

The above lemma yields a map

\[
g_{F_{\ell}} D_{2r+1}: g_{F_{\ell}} H^{2,3} \longrightarrow L_{2r+1} \otimes g_{F_{\ell-1}} H^{2,3}.
\]

**Lemma 5.104.** For all \( r, \ell \geq 1 \), there is an inclusion

\[
g_{F_{\ell}} D_{2r+1}(g_{F_{\ell}} H^{2,3}) \subseteq Q \varpi_{2r+1}(\zeta^m(2r + 1)) \otimes Q g_{F_{\ell-1}} H^{2,3}.
\]
Proof. Let $\mathbf{s}$ be a word in the alphabet $\{2, 3\}$ of level $\ell$, and let $I^m(1; \text{bs}(\mathbf{s}); 0)$ be the corresponding motivic iterated integral. From the definition of $D_{2r+1}$, we have

$$gr^F_{\ell} D_{2r+1}(\zeta^m(\mathbf{s})) = \sum_\gamma \varpi_{2r+1}(I^m(\gamma)) \otimes \zeta^m(\mathbf{s}_\gamma),$$

where the sum runs over all subsequences $\gamma$ of $(1; \text{bs}(\mathbf{s}); 0)$ of length $2r+1$, and $\mathbf{s}_\gamma$ is obtained by removing the internal part of $\gamma$.

If $\gamma$ contains more than one subsequence $00$, then $\mathbf{s}_\gamma$ has level $\ell - 1$, and hence does not contribute. If $\gamma$ begins and ends in the same symbol, then $I^m(\gamma)$ is zero. One checks that $I^m(\gamma)$ can be of four remaining types:

i) $I^m(1; 01\ldots 01001\ldots 01; 0) = \zeta^m(2^\beta 32^{\alpha})$,

ii) $I^m(0; 10\ldots 1001\ldots 10; 1) = -\zeta^m(2^\beta 32^{\alpha})$,

iii) $I^m(1; 01\ldots 10; 0) = \zeta^m_{\ell}(2^r)$,

iv) $I^m(0; 01\ldots 10; 1) = -\zeta^m_{\ell}(2^r)$.

By Corollary 5.86, $\varpi_{2r+1}(I^m(\gamma))$ belongs to $Q\zeta^m(2r + 1)$ in all cases. □

The above lemma justifies the following definition:

**Definition 5.106.** For all $N, \ell \geq 1$, the **level lowering operator** $\partial_{N, \ell}$ is the $Q$-linear map

$$\partial_{N, \ell} : gr^F_{\ell} H^2,3_N \longrightarrow \bigoplus_{3 \leq 2r+1 \leq N} gr^F_{\ell-1} H^2,3_{N-2r-1}$$

obtained by first applying

$$\bigoplus_{3 \leq 2r+1 \leq N} gr^F_{\ell} D_{2r+1} |_{gr^F_{\ell} H^2,3_N}$$

and then sending $\varpi_{2r+1}(\zeta^m(2r + 1))$ to 1.

The same construction gives rise to operators

$$\partial_{N, \ell} : gr^F_{\ell} H^2,3_N \longrightarrow \bigoplus_{3 \leq 2r+1 \leq N} gr^F_{\ell-1} H^2,3_{N-2r-1}$$

that fit in the commutative diagrams

5.4.3. **A pair of bases.** We next describe bases of the source and the target of the map (5.107). For $\ell \geq 1$ and $N \geq 3$, we define

$B_{N, \ell} = \text{set of words in the alphabet } \{2, 3\} \text{ of weight } N \text{ and level } \ell$.

$B'_{N, \ell} = \text{set of words in the alphabet } \{2, 3\} \text{ of weight } \leq N - 3 \text{ and level } \ell - 1$

(this includes the empty word if $\ell = 1$).
Clearly, $B_{N,\ell}$ gives a basis $B_{N,\ell}^E$ of $\mathbb{F}_q \overline{\mathcal{H}}_{N,2,3}$, while $B'_{N,\ell}$ determines a basis $B'_{N,\ell}$ of $\bigoplus_{3 \leq 2r+1 \leq N} \mathbb{F}_q \overline{\mathcal{H}}_{N-2r-1,2,3}$. Write $N = 3\ell + 2m$, so $m$ is the number of entries equal to 2 in an element of $B_{N,\ell}$. Then

$$|B_{N,\ell}| = \binom{\ell + m}{\ell},$$

$$|B'_{N,\ell}| = \sum_{m'=0}^m \binom{\ell - 1 + m'}{\ell - 1}.$$ 

From the identity of binomial coefficients

$$\binom{\ell + m}{\ell} = \sum_{m'=0}^m \binom{\ell - 1 + m'}{\ell - 1},$$

we deduce the equality $|B_{N,\ell}| = |B'_{N,\ell}|$.

We provide $B_{N,\ell}$ with the lexicographic order for the ordering $2 < 3$ and $B'_{N,\ell}$ with the order $s \leq s'$ if and only if $\text{wt}(s) < \text{wt}(s')$ or $\text{wt}(s) = \text{wt}(s')$ and $s$ is smaller than or equal to $s'$ in the lexicographic order.

**Lemma 5.110.** The map $B'_{N,\ell} \to B_{N,\ell}$ that sends an element $s \in B'_{N,\ell}$ to $2^{(r-1)}3s \in B_{N,\ell}$, where $2r = N - 1 - \text{wt}(s)$ is an order-preserving bijection.

**Proof.** Denote by $v$ the map in the statement. Let $s, s' \in B'_{N,\ell}$ and write $2r = N - 1 - \text{wt}(s)$ and $2r' = N - 1 - \text{wt}(s')$. If $\text{wt}(s) < \text{wt}(s')$, then $r > r'$, and hence $v(s) = 2^{(r-1)}3s < 2^{(r'-1)}3s' = v(s')$. If $\text{wt}(s) = \text{wt}(s')$ but $s$ is smaller than $s'$ in the lexicographic order, then $v(s) = 2^{(r-1)}3s < 2^{(r'-1)}3s' = v(s')$. Therefore, $v$ is injective and order-preserving. Since the sets $B'_{N,\ell}$ and $B_{N,\ell}$ have the same cardinality, $v$ is a bijection. \qed

### 5.5. Brown’s theorem.

In this final section, we prove Brown’s theorem and deduce some consequences concerning the structure of mixed Tate motives over $\mathbb{Z}$ and their periods.

#### 5.5.1. Statement.

Our goal is to prove the following result:

**Theorem 5.111 (Brown).** The set of elements

$$\{\zeta^m(s_1, \ldots, s_r) \mid s_i \in \{2, 3\}\}$$

forms a basis of the $\mathbb{Q}$-vector space of motivic multiple zeta values.

Before going into the proof, let us mention the immediate corollary:

**Corollary 5.112 (Theorem B).** Every multiple zeta value is a $\mathbb{Q}$-linear combination of multiple zeta values with only 2 and 3 as entries.

**Proof.** Apply the period map (5.12). \qed

**Remark 5.113.**

i) The proof does not give an algorithm to compute such a linear combination.

ii) The missing information to deduce that such multiple zeta values furnish a basis, as it is conjectured, is to know that all relations among multiple zeta values have motivic origin.
5.5.2. **Strategy of the proof.** The key point to prove Theorem 5.111 is the following lemma.

**Lemma 5.114.** For all $N, \ell \geq 1$, the level lowering operator $\tilde{\partial}_{N, \ell}$ is an isomorphism of $\mathbb{Q}$-vector spaces.

We show how to deduce Theorem 5.111 from Lemma 5.114. The first step is the following:

**Lemma 5.115.** The map $\tilde{H}^{2,3}_N \to H^{2,3}_N$ is an isomorphism.

**Proof.** We first prove by induction on the level that, for every weight $N$ and level $\ell$, the restriction map $gr^F_{\ell} \tilde{H}^{2,3}_N \to gr^F_H^{2,3}$ is an isomorphism.

The initial step is $\ell = 0$. If $N = 2r$ is even, the space $gr^F_0 \tilde{H}^{2,3}_N$ is one-dimensional generated by the symbol $I(1; bs(2^r); 0)$ while the space $gr^F_0 H^{2,3}_N$ is generated by $\zeta^m(2^r) \neq 0$. Thus, the restriction map

\[
gr^F_0 \tilde{H}^{2,3}_N \to gr^F_0 H^{2,3}_N
\]

is an isomorphism. If $N$ is odd, then both spaces are zero and therefore the map (5.116) is also an isomorphism.

We now consider the commutative diagram (5.109). By definition, the left vertical arrow is an epimorphism. By the induction hypothesis, the right vertical map is an isomorphism and by Lemma 5.114 the upper horizontal map is injective. Hence the left vertical arrow is an isomorphism.

Once we now that all the restriction maps $gr^F_{\ell} \tilde{H}^{2,3}_N \to gr^F_H^{2,3}$ are isomorphisms, we deduce that the restriction map $\tilde{H}^{2,3}_N \to H^{2,3}_N$ is an isomorphism by using the fact that the filtration by the level is bounded and the five lemma (see Exercise A.157).

By equation (1.72), the dimension of $\tilde{H}^{2,3}_N$ is $d_N$. By Lemma 5.115, $d_N$ is also the dimension of $H^{2,3}_N$. Hence, the elements $\zeta^m(s_1, \ldots, s_r)$ of weight $N$ with $s_i \in \{2, 3\}$ form a basis of $H^{2,3}_N$. We have injections

$H^{2,3}_N \subset H_N \hookrightarrow H^{MT}_N$.

Since now we know that the dimensions of the left and right vector spaces are the same we deduce that the three spaces are isomorphic, and hence Theorem 5.111 holds.

5.5.3. **Proof of Lemma 5.114.** The proof is based on the study of the 2-adic valuation of the coefficients of the matrix of $\tilde{\partial}_{N, \ell}$ with respect to the bases introduced in Section 5.4.3. We shall use the following lemma:

**Lemma 5.117.** Let $A = (a_{ij})_{i,j}$ be a square matrix of size $n$ with rational coefficients. Assume that there exists a prime number $p$ such that the following conditions hold:

i) $v_p(a_{ij}) \geq 1$ for all $i > j$,

ii) $v_p(a_{ii}) = \min_j \{v_p(a_{ij})\} \leq 0$ for all $i$.

Then $A$ is invertible.

**Proof.** Consider the matrix $A'$ obtained by multiplying the $i$-th row of $A$ by $p^{-v_p(a_{ii})}$. By condition ii), the $p$-adic valuation of the coefficients of $A'$ is non-negative, so we can reduce modulo $p$. Since we still have $v_p(a'_{ij}) \geq 1$ for $i > j$ but
now \( v_p(a''_i) = 0 \), the reduction is upper triangular with non-zero elements in the diagonal. It follows that the determinant of \( A' \), and hence the determinant of \( A \), is non-zero. \( \square \)

We next see that, up to terms with even coefficients, the map \( \partial_{N,\ell} \) acts by deconcatenation.

**Proposition 5.118.** Let \( s \) be a word in the alphabet \( \{2, 3\} \) of weight \( N \) and level \( \ell \). Then
\[
\partial_{N,\ell} I(1; \bs(s); 0)) = \sum_{\deg_3 u = 1} c_u I(1; \bs(v); 0)
+ \text{terms with } 2\mathbb{Z} \text{ coefficients},
\]
where \( \deg_3 u \) is the number of entries equal to 3 in the word \( u \) and \( c_u \) is the coefficient introduced in Definition 5.85.

**Proof.** Following the proof of Lemma 5.104, there are four types of terms in \( \partial_{N,\ell} I(1; \bs(s); 0)) \). We start with types iii) and iv). Since \( c_{12^{(n)}} = 2(-1)^n \), these terms contribute with even coefficients. Besides, almost all terms of types i) and ii) can be grouped in pairs. Indeed, choose four positions as follows
\[
I(\ldots, a b, 01, \ldots, a b, 0, \ldots, 010, \ldots)
\]
that is, \( a \) and \( b \) (resp. \( c \) and \( d \)) are consecutive, \( a \) (resp. \( d \)) contains a 0 and \( b \) (resp. \( c \)) contains a 1. Combining Lemma 5.32 ii) and Lemma 5.88 ii), the sum of the contributions of the subsequences \( ac \) and \( bd \) has again coefficients in \( 2\mathbb{Z} \). The only terms that cannot be paired this way are the leftmost subsequences appearing in the sum of the statement. \( \square \)

**Corollary 5.119.** With respect to the bases \( B_{N,\ell} \) and \( B'_{N,\ell} \), ordered as in Section 5.4.3, the matrix \( M_{N,\ell} \) of the operator \( \partial_{N,\ell} \) satisfies the assumptions of Lemma 5.117 for the prime \( p = 2 \).

**Proof.** Let \( \upsilon \) be a word with only 2 and 3 as entries, of weight \( \leq N - 3 \) and level \( \ell - 1 \). Put \( 2r = N - 1 - \wt(\upsilon) \) and \( s = 2^{(r-1)}3\upsilon \). Then \( s \) is the multi-index corresponding to \( \upsilon \) under the order-preserving bijection from Lemma 5.110. Consider any admissible multi-index with only 2 and 3 as entries, of weight \( N \) and level \( \ell \) that can be written as \( \upsilon \) with \( \deg_3 u = 1 \). If \( s \neq \upsilon \), then the number of occurrences of 2 before the first 3 in \( u \) is smaller than \( r \), hence the inequality \( \upsilon \upsilon > s \). By Proposition 5.118, this implies that any term in \( M_{N,\ell} \) that is not an even integer is above the diagonal. Moreover, by the same proposition and the statement iii) of Lemma 5.88, the coefficient of \( \upsilon \) in \( \partial_{N,\ell} s \) sitting at the diagonal of \( M_{N,\ell} \) has 2-adic valuation smaller than or equal to zero and it realizes the minimum of this valuation within its row. Therefore, the assumptions of Lemma 5.117 are satisfied. \( \square \)

Clearly, Lemma 5.114 is a consequence of Corollary 5.119 and Lemma 5.117, thus finishing the proof of Theorem 5.111.

5.5.4. **Some consequences of Brown’s theorem.** We conclude this chapter with some corollaries of Brown’s theorem.

**Corollary 5.120.** The map \( U_{\text{dR}} \to I(U_{\text{dR}}) \) from (5.4) is a group isomorphism.
As a consequence, both the morphism of Tannaka groups is an isomorphism follows from Corollary 5.120. The finite-dimensional pieces of the motivic fundamental groupoid of every mixed Tate motive over \( \mathbb{Z} \) schemes. Therefore, this inclusion is an equivalence of tannakian categories, so that induced by the inclusion of \( \text{MT} \) ring of periods of mixed Tate motives over \( \mathbb{Z} \) where \( \text{MT} \).

We want to show that the injective map \( H \), also surjective. In Corollary 5.21 we proved that this map extends to an injection \( \text{MT} \) fiber functor \( H \) of \( U \) objects of Brown’s theorem, we saw that the graded pieces of \( H \) are isomorphic to those of \( H \), hence the algebras are isomorphic. □

Let \( \text{MT}'(\mathbb{Z}) \) be the full tannakian subcategory of \( \text{MT}(\mathbb{Z}) \) generated by the objects \( xU_{y}^{\text{Mot}}.N \) for \( N > 0 \) and \( x, y \in \{0, 1\} \) and let \( \omega_{\text{dr}} \) be the restriction of the fiber functor \( \omega_{\text{dr}} \) to \( \text{MT}'(\mathbb{Z}) \).

**Corollary 5.121.** The map

\[
\text{Aut}_{\text{MT}(\mathbb{Z})}^{\otimes}(\omega_{\text{dr}}) \to \text{Aut}_{\text{MT}'(\mathbb{Z})}^{\otimes}(\omega'_{\text{dr}})
\]

induced by the inclusion of \( \text{MT}'(\mathbb{Z}) \) in \( \text{MT}(\mathbb{Z}) \) is an isomorphism of affine group schemes. Therefore, this inclusion is an equivalence of tannakian categories, so that every mixed Tate motive over \( \mathbb{Z} \) is a subquotient of a tensor construction on one of the finite-dimensional pieces of the motivic fundamental groupoid of \( \mathbb{P}^1 \setminus \{0, 1, \infty\} \).

**Proof.** The Tannaka group \( \text{Aut}_{\text{MT}}^{\otimes}(\omega_{\text{dr}}) \) is \( I(U_{\text{dr}}) \times \mathbb{G}_{m} \). Thus, the fact that the morphism of Tannaka groups is an isomorphism follows from Corollary 5.120. As a consequence, both \( \text{MT}(\mathbb{Z}) \) and \( \text{MT}'(\mathbb{Z}) \) are equivalent to the category of finite-dimensional representations of \( G_{\text{dr}} \).

**Corollary 5.122.** The periods of every mixed Tate motive over \( \mathbb{Z} \) are linear combinations with \( \mathbb{Q}[\frac{1}{2\pi i}] \)-coefficients of multiple zeta values. In other words, the ring of periods of mixed Tate motives over \( \mathbb{Z} \) is \( \mathbb{Z}[\frac{1}{2\pi i}] \).

**Proof.** Recall the canonical section \( \tau: \mathbb{G}_{m} \to G_{\text{dr}} \) from Lemma 4.108, the element \( a \in G_{\text{dr}}(\mathbb{C}) \) from Proposition 4.111, and the isomorphism \( \psi: I(U_{\text{dr}}) \times \mathbb{A}^{1} \to \mathcal{V} \) from Theorem 5.20. Consider the diagram

\[
\begin{array}{ccc}
U_{\text{dr}} \times \mathbb{G}_{m} & \xrightarrow{f_{1}} & G_{\text{dr}} & \xrightarrow{f_{2}} & P_{\text{dr,B}} \\
g_{1} & & & & g_{2} \\
U_{\text{dr}} \times \mathbb{A}^{1} & \xrightarrow{f_{3}} & \mathcal{V}
\end{array}
\]

where

\[
\begin{align*}
f_{1}(u, s) &= u \cdot \tau(s)^{-1}, \quad g_{1}(u, s) = (u, s^{2}) \\
f_{2}(g) &= g \cdot a^{-1} \cdot \text{comp}_{\text{dr,B}} \\
g_{2}(p) &= p \cdot \text{dch}, \quad f_{3}(u, t) = \psi(I(u), t)(1_{10}).
\end{align*}
\]

This diagram is commutative by the definition of \( \psi \) and Lemma 5.16. The upper horizontal arrows are clearly isomorphisms and the lower horizontal arrow is an isomorphism by Theorem 5.20 and Corollary 5.120.

Recall from (5.18) that \( a \) can be written as \( a = u_{0} \cdot \tau(2\pi i)^{-1} \) for some \( u_{0} \in U_{\text{dr}}(\mathbb{R}) \). Then \( f_{1}(u_{0}, 2\pi i) = a \). Clearly

\[
\begin{align*}
f_{2}(a) &= \text{comp}_{\text{dr,B}}, \quad g_{2}(\text{comp}_{\text{dr,B}}) = \text{dch}_{\text{dr}}, \quad g_{1}(u_{0}, 2\pi i) = (u_{0}, (2\pi i)^{2}).
\end{align*}
\]

By the commutativity of the diagram \( f_{3}(u_{0}, (2\pi i)^{2}) = \text{dch}_{\text{dr}} \). All the morphisms on the diagram are defined over \( \mathbb{Q} \).
The algebra of periods of $MT(Z)$ is
\[ ev_{\text{comp}_{dR,B}}(O(P_{dR,B})) = ev_{(u_0,2\pi i)}(O(U_{dR} \times G_m)). \]
The algebra of multiple zeta values is
\[ ev_{\text{deh}}(O(Y)) = ev_{(u_0,(2\pi i)^2)}(O(U_{dR} \times A^1)). \]
Finally, the result follows from the fact that $g_1$ induces an isomorphism
\[ O(U_{dR} \times G_m) \cong O(U_{dR} \times A^1)[s^{-1}], \]
where $s$ is the coordinate of $G_m$, so that $s(u_0, 2\pi i) = 2\pi i$ holds.
\[ \square \]

**Corollary 5.123.** Zagier’s conjecture \[1.71\] implies that the numbers $\pi$, $\zeta(3)$, $\zeta(5)$, \ldots are algebraically independent over $\mathbb{Q}$.

**Proof.** The key ingredient is a structure theorem for Hopf algebras due to Milnor and Moore [MM65] (see [Car07, Thm. 8.1.3] and its proof).

If $V$ is a vector space over a field of characteristic zero, then the symmetric algebra $\text{Sym}(V)$ is the quotient of the tensor algebra $T(V) = \bigoplus_{n \geq 0} V^\otimes n$ by the bilaterial ideal generated by the elements of the form $x \otimes y - y \otimes x$. This is a commutative algebra. Moreover, if $S \subset V$ is a basis of $S$ then $\text{Sym}(V)$ is the free commutative algebra generated by $S$. In other words $\text{Sym}(V)$ is the polynomial algebra in a basis of $V$. If $V$ is graded with strictly positive degrees then $\text{Sym}(V)$ has a structure of a connected graded algebra.

**Theorem 5.124 (Milnor–Moore).** Let $k$ be a field of characteristic zero and let $A = \bigoplus_{n \geq 0} A_n$ be a graded connected Hopf algebra over $k$ with commutative multiplication, such that $A_n$ is finite-dimensional for all $n$. Then, as graded algebra, $A$ is the symmetric algebra
\[ A = \text{Sym}[A_{>0}/(A_{>0})^2]. \]

We will use the theorem through the following straightforward consequence.

**Claim:** if $x_1, x_2, \ldots$ are elements of $A_{>0}$ whose classes in the quotient $A_{>0}/(A_{>0})^2$ are linearly independent, then $x_1, x_2, \ldots$ are algebraically independent.

Let us apply this to the Hopf algebra $A = O(U_{dR})$ and the motivic zeta values $\zeta^m(3), \zeta^m(5), \ldots$. These elements lie in different degrees and their images in the quotient $L = A_{>0}/(A_{>0})^2$ are non-zero, so they are linearly independent. By the previous claim, $\zeta^m(3), \zeta^m(5), \ldots$ are algebraically independent in $A$. Since $H = A[\zeta^m(2)]$, we deduce that the motivic zeta values $\zeta^m(2), \zeta^m(3), \zeta^m(5), \ldots$ are algebraically independent in $H$. Now, if one assumes Zagier’s conjecture, the period map per: $H \to \mathbb{Z}$ is an isomorphism. Since $\text{per}(\zeta^m(n)) = \zeta(n)$ and $\zeta(2) = \frac{\pi^2}{6}$, it follows that the numbers $\pi, \zeta(3), \zeta(5), \ldots$ are algebraically independent over $\mathbb{Q}$.

**Corollary 5.125.** Zagier’s conjecture \[1.71\] is equivalent to Grothendieck’s period conjecture for mixed Tate motives \[4.118\].

**Proof.** Zagier’s conjecture is equivalent to the injectivity of the map per: $H \to \mathbb{C}$. Since $O(P_{dR,B}) = H[s^{-1}]$ with $s^2 = -24\zeta^m(2)$, this is equivalent to the injectivity of the period map per: $O(P_{dR,B}) \to \mathbb{C}$, which is precisely the content of Conjecture \[4.118\].

\[ \square \]
Appendix A. Some results from homological algebra

In this appendix, we gather a number of notions and results from category theory, homological algebra, and sheaf theory that are used through the main text. We assume that the reader is familiar with the notions of category, functor, and natural transformation between functors. Unless otherwise specified, by a functor we mean a covariant functor. A category is called small if its objects and morphisms form a set. All the categories we will work with are essentially small, in the sense that they are equivalent to small categories. In order to avoid set-theoretic issues, we will always replace such categories with small equivalent ones. Some standard references for the material we cover without proof are the books by Kashiwara and Schapira [KS06], Gelfand and Manin [GM03], and Weibel [Wei94].

A.1. Abelian categories, complexes, and cohomology.

A.1.1. The definition of abelian category.

**Definition A.1.** An *abelian* category is a category $\mathcal{A}$ whose morphisms

$$\text{Hom}_{\mathcal{A}}(X,Y)$$

are endowed, for all objects $X, Y \in \text{Ob}(\mathcal{A})$, with the structure of an abelian group (in particular, with a group law $+$ that we call *addition* and a zero morphism $0$) such that the following conditions hold:

i) Composition of morphisms is distributive with respect to addition:

$$f \circ (g + h) = f \circ g + f \circ h,$$

$$g + h \circ f = g \circ f + h \circ g.$$

ii) There exists a *zero object*, that is, an object $0 \in \text{Ob}(\mathcal{A})$ such that there exists a unique morphism $0 \to X$ and a unique morphism $X \to 0$ for every object $X \in \text{Ob}(\mathcal{A})$. The zero morphism $0 \in \text{Hom}_{\mathcal{A}}(X,Y)$ is nothing but the composition $X \to 0 \to Y$.

iii) Given objects $X, Y \in \text{Ob}(\mathcal{A})$, there exists a *direct sum* object (also known as a *coproduct*, see Exercise A.33), *i.e.* an object

$$X \oplus Y \in \text{Ob}(\mathcal{A})$$

together with morphisms

$$X \to X \oplus Y \leftarrow Y$$

satisfying the following universal property: for each object $Z \in \text{Ob}(\mathcal{A})$ with morphisms $X \to Z$ and $Y \to Z$, there exists a unique morphism

$$X \oplus Y \to Z$$

such that the diagram below commutes:

$$\begin{array}{ccc}
X & \longrightarrow & X \oplus Y \\
\downarrow & & \downarrow \\
Y & \leftarrow & Y.
\end{array}$$

**Definition A.2.** Let $\mathcal{A}$ and $\mathcal{B}$ be additive categories. A functor $F : \mathcal{A} \to \mathcal{B}$ is called *additive* if it sends a zero object of $\mathcal{A}$ to a zero object of $\mathcal{B}$ and, for all objects $X, Y \in \text{Ob}(\mathcal{A})$, the morphism

$$F(X) \oplus F(Y) \to F(X \oplus Y)$$
given by the universal property of the direct sum applied to the objects \(F(X), F(Y),\) and \(F(X \oplus Y)\) of \(B\) is an isomorphism.

An equivalent definition of additive functors is presented in Exercise A.34.

**Definition A.3.** Let \(f: X \to Y\) be a morphism in an additive category \(A.\)

i) A *kernel* of \(f\) is a pair consisting of an object \(\text{Ker}(f) \in \text{Ob}(A)\) and a morphism \(\iota: \text{Ker}(f) \to X\) that satisfies \(f \circ \iota = 0\) and is universal for this property: for each morphism \(g: Z \to X\) with \(f \circ g = 0\), there is a unique morphism \(\varphi: Z \to \text{Ker}(f)\) making the following diagram commutative:

\[
\begin{array}{ccc}
Z & \xrightarrow{g} & X \\
\downarrow{\varphi} & & \downarrow{\iota} \\
\text{Ker}(f) & & \\
\end{array}
\]

ii) A *cokernel* of \(f\) is a pair consisting of an object \(\text{Coker}(f) \in \text{Ob}(A)\) and a morphism \(p: Y \to \text{Coker}(f)\) that satisfies \(p \circ f = 0\) and is universal for this property: for each morphism \(g: Y \to Z\) with \(g \circ f = 0\), there is a unique morphism \(\varphi: \text{Coker}(f) \to Z\) making the following diagram commutative:

\[
\begin{array}{ccc}
Y & \xrightarrow{g} & Z \\
\downarrow{p} & & \downarrow{\varphi} \\
\text{Coker}(f) & & \\
\end{array}
\]

These notions are dual to each other (Exercise A.35). The kernel and the cokernel of a morphism may or may not exist, as Exercise A.36 illustrates. Whenever they do, \(\text{Ker}(f)\) and \(\text{Coker}(f)\) are not unique but unique up to a unique isomorphism, as is the case for all objects defined by means of a universal property. In practice, we will identify all possible choices through the unique isomorphisms and pretend that \(\text{Ker}(f)\) and \(\text{Coker}(f)\) are unique. For simplicity, \(\text{Ker}(f)\) and \(\text{Coker}(f)\) will denote both the objects and the morphisms to \(X\) and from \(Y\) respectively.

**Definition A.4.** Let \(f: X \to Y\) be a morphism in an additive category \(A.\)

Whenever they exist, the *image* and the *coimage* of \(f\) are defined as

\[\text{Im}(f) = \text{Ker}(\text{Coker}(f)), \quad \text{Coim}(f) = \text{Coker}(\text{Ker}(f)).\]

Thanks to the universal property of the kernel and the cokernel, there is a canonical morphism (Exercise A.37)

\[\text{Coim}(f) \longrightarrow \text{Im}(f)\]

**Definition A.5.** An *abelian* is an additive category \(A.\) satisfying the following two conditions:

i) Every morphism \(f\) in \(A\) has a kernel and a cokernel. Therefore, every morphism has an image and a coimage.

ii) For every morphism \(f\) in \(A\), the map \(\text{Coim}(f) \to \text{Im}(f)\) is an isomorphism.

See Exercise A.156 for a typical example of an additive category that has all kernels and cokernels but is not abelian since condition ii) fails.
A.1.2. **Categories of modules.** The category $\text{Mod}_R$ of left modules over a ring $R$ is abelian. Conversely, the following result allows us to work in any small abelian category as if it were the category of modules over a ring. It is particularly useful for performing “diagram chasing” or similar operations that require picking elements of the objects of the category.

**Theorem A.6 (Freyd–Mitchell).** Let $\mathcal{A}$ be a small abelian category. There exists a ring $R$ and an exact and fully faithful functor from $\mathcal{A}$ to the category of left $R$-modules. In particular, $\mathcal{A}$ can be viewed as a full subcategory of $\text{Mod}_R$.

Recall that a functor $F: \mathcal{A} \to \mathcal{B}$ is **fully faithful** if the map $\text{Hom}_A(X, Y) \to \text{Hom}_B(F(X), F(Y))$ is bijective for all objects $X$ and $Y$ of $\mathcal{A}$. While a subcategory $\mathcal{A}$ of a category $\mathcal{B}$ is called **full** if the inclusion functor is fully faithful.

The notion of exact functor will be introduced in Definition A.15 below. A proof of the Freyd–Mitchell theorem can be found, for example, in [Wei94, Thm. 1.6.1].

A.1.3. **Subobjects and quotients.** Let $\mathcal{A}$ be a category. A morphism $f: X \to Y$ in $\mathcal{A}$ is called a **monomorphism** if the equality $f \circ g = f \circ h$ implies $g = h$ for all morphisms $g, h: Z \to X$, and an **epimorphism** if the equality $g \circ f = h \circ f$ implies $g = h$ for all $g, h: Y \to Z$. Note that kernels are monomorphisms and cokernels are epimorphisms (Exercise A.38). In the category of sets, monomorphisms and epimorphisms are injective and surjective maps respectively. However, this intuition fails for other categories. For example, the inclusion $\mathbb{Z} \to \mathbb{Q}$ in the category of rings or the inclusion of a dense open subset in the category of topological spaces are epimorphisms. See Exercise A.39 for an example of a non-injective monomorphism.

Let $X$ be an object of $\mathcal{A}$. A **subobject** of $X$ is an object $Y$ of $\mathcal{A}$ equipped with a monomorphism $Y \to X$ and a **quotient** of $X$ is an object $Z$ of $\mathcal{A}$ equipped with an epimorphism $X \to Z$. Usually, we will denote subobjects simply by $Y \subset X$. If the category $\mathcal{A}$ is abelian, then to each subobject $Y \subset X$ corresponds a quotient object $X/Y$ defined as the cokernel of the monomorphism $Y \to X$.

A.1.4. **Complexes and cohomology.**

**Definition A.7.** Let $\mathcal{A}$ be an additive category.

i) A **cochain complex** (or simply a complex) $A = (A^*, d^*)$ is a sequence of objects $A^n$ of $\mathcal{A}$ and morphisms

$$
\cdots \rightarrow A^{n-1} \xrightarrow{d^{n-1}} A^n \xrightarrow{d^n} A^{n+1} \rightarrow \cdots
$$

called **differentials** such that the equality

(A.8) $d^n \circ d^{n-1} = 0$

holds for all $n \in \mathbb{Z}$.

ii) A **morphism of cochain complexes** $f: (A^*, d^*) \to (B^*, d^*)$ is a sequence of maps $f^n: A^n \to B^n$ commuting with the differential, i.e. satisfying

$$
f^n \circ d^{n-1} = d^{n-1} \circ f^{n-1}
$$
for each $n \in \mathbb{Z}$. We picture it as follows:

\[ \cdots \xrightarrow{f^{n-1}} A^{n-1} \xrightarrow{d^{n-1}} A^n \xrightarrow{f^n} A^{n+1} \xrightarrow{d^n} A^{n+2} \xrightarrow{f^{n+1}} A^{n+3} \cdots \]

\[ \cdots \xrightarrow{f^{n-1}} B^{n-1} \xrightarrow{d^{n-1}} B^n \xrightarrow{f^n} B^{n+1} \xrightarrow{d^n} B^{n+2} \xrightarrow{f^{n+1}} B^{n+3} \cdots \]

iii) For a cochain complex $A = (A^*, d^*)$ and an integer $r$, the \textit{shifted} complex


is the cochain complex with

\[ A[r]^n = A^{n+r} \quad \text{and} \quad d[r]^n = (-1)^r d^n. \]

(One reason why changing the sign of the differential is necessary will be explained when discussing the cone in Definition A.17 below.)

iv) A cochain complex is called \textit{bounded} if there exists an integer $M$ such that $A^n = 0$ holds for all $|n| \geq M$. Similarly, one defines the notion of \textit{bounded below} and \textit{bounded above} cochain complex.

v) The notion of \textit{chain complex} in an additive category is dual to the notion of cochain complex; that is, the differential $d$ lowers the degree instead of increasing it. Therefore, a chain complex $(A_*, d_*)$ is a sequence of objects $A_n$ of $\mathcal{A}$ and morphisms

\[ \cdots \xrightarrow{d_{n+1}} A_{n+1} \xrightarrow{d_n} A_n \xrightarrow{d_{n-1}} A_{n-1} \xrightarrow{d_{n-2}} \cdots \]

also called \textit{differentials} such that the equality

\[ d_n \circ d_{n+1} = 0 \]

holds for all $n \in \mathbb{Z}$. A \textit{morphism of chain complexes} $f : (A_*, d_*) \rightarrow (B_*, d_*)$ is a sequence of maps $f_n : A_n \rightarrow B_n$ satisfying $f_{n-1} \circ d_n = d_{n} \circ f_n$.

vi) A chain complex $(A_*, d_*)$ may be turned into a cochain complex $(A^*, d^*)$ by setting

\[ A^n = A_{-n} \quad \text{and} \quad d^n = d_{-n}. \]

The position of the index will usually be enough to indicate that we have performed this operation. If needed, “raising the index” will be denoted by $r$, so that the first equality in (A.9) becomes $r(A)^n = A_{-n}$.

vii) For a chain complex $A = (A_*, d_*)$ and an integer $r$, the shifted complex


is the chain complex with

\[ A[r]^n = A_{n-r} \quad \text{and} \quad d[r]^n = (-1)^r d^n. \]

Hence, the raising and the shift operators are related by the equality

\[ r(A[r]) = r(A)[r]. \]

Since we will mainly use cochain complexes, we will often simply call them “complexes”. It is also convenient to think of a complex as a graded object

\[ A^* = \bigoplus_{n \in \mathbb{Z}} A^n \]
in the category $\mathcal{A}$ together with a morphism $d: A^* \to A^*$ that is homogeneous of degree one, \textit{i.e.} maps the subobject $A^n$ to the subobject $A^{n+1}$ for all $n \in \mathbb{Z}$. With this convention, the morphisms

$$d^n: A^n \to A^{n+1}$$

are the restrictions of $d$ to the various $A^n$, and condition (A.8) simply reads $d \circ d = 0$. For this to make sense, we need to assume either that the complex $A^*$ is bounded or that the abelian category admits infinite sums. That is, given a sequence $(X_n)_{n \in \mathbb{Z}}$ of objects of $\mathcal{A}$, there exists an object $\bigoplus_{n \in \mathbb{Z}} X_n$ of $\mathcal{A}$ with morphisms $f_i: X_i \to \bigoplus_{n \in \mathbb{Z}} X_n$ for all $i \in \mathbb{Z}$ such that, for each object $Z$ with morphisms $g_i: X_i \to Z$, there is a unique morphism $h: \bigoplus_{n \in \mathbb{Z}} X_n \to Z$ satisfying $h \circ f_i = g_i$.

**Remark A.10.** If $\mathcal{A}$ is an abelian category, condition (A.8) can be rephrased by saying that the morphism $\text{Im}(d^{n-1}) \to A^n$ factors uniquely through $\text{Ker}(d^n) \to A^n$ for each integer $n$. That is, there exists a unique morphism $\varphi_n$ making the diagram

$$\begin{array}{ccc}
\text{Im}(d^{n-1}) & \longrightarrow & A^n \\
\varphi_n \downarrow & & \downarrow \\
\text{Ker}(d^n) & & 
\end{array}$$

commutative. Moreover, $\text{Ker}(\varphi_n)$ is a zero object (use Exercise A.40).

**Definition A.11.** Let $\mathcal{A}$ be an abelian category and let $A = (A^*, d)$ be a cochain complex in $\mathcal{A}$. For each $n \in \mathbb{Z}$, the cohomology in degree $n$ of $A$ is the object

$$H^n(A) = \text{Coker}(\varphi_n).$$

If the category $\mathcal{A}$ admits infinite sums or the complex $A$ is bounded, the \textit{total cohomology} of $A$ is defined as the graded object

$$H^*(A) = \bigoplus_{n \in \mathbb{Z}} H^n(A).$$

The \textit{homology} of a chain complex is defined similarly.

**Example A.12.** Let $\mathcal{A} = \textbf{Mod}_R$ be the abelian category of modules over a ring $R$. Let $A = (A^*, d)$ be a complex. Then the maps $\varphi_n$ are the inclusions of the submodule $\text{Im}(d^n)$ of $\text{Ker}(d^n)$ and the cohomology objects are the quotient modules

$$H^n(A) = \text{Ker}(d^n)/\text{Im}(d^n).$$

This setting (with $R = \mathbb{Z}$ or a field) will be mostly sufficient for our purposes.

Formation of cohomology is functorial: a morphism of complexes $f: A^* \to B^*$ induces a morphism of cohomology objects

$$H(f): H^*(A^*) \longrightarrow H^*(B^*)$$

that satisfies $H(\text{Id}) = \text{Id}$ and $H(f \circ g) = H(f) \circ H(g)$ for composable morphisms $f$ and $g$. In other words, the assignment $A \mapsto H^*(A)$ defines a functor from the category of complexes of $\mathcal{A}$ to $\mathcal{A}$.

**Definition A.13.** A morphism of complexes $f$ is called a \textit{quasi-isomorphism} if the induced morphism on cohomology objects $H(f)$ is an isomorphism.
By construction, the cohomology in degree $n$ of the shifted complex $A[r]$ is the cohomology in degree $n + r$ of $A$:

$$H^n(A[r]) = H^{n+r}(A).$$

A.1.5. **Exact sequences and exact functors.**

**Definition A.14.** Let $A$ be an abelian category. An **exact sequence** is a complex $A = (A^i, d)$ with vanishing cohomology. In other words, $A$ is an exact sequence if the maps $\varphi_n : \text{Im}(d^{i-1}) \to \text{Ker}(d^i)$ are isomorphisms for all $n$. A **short exact sequence** is an exact sequence in which all but three consecutive terms are zero.

**Definition A.15.** Let $A$ and $B$ be abelian categories and let $F : A \to B$ be an **additive functor**. We say that $F$ is **exact** if the sequence

$$0 \longrightarrow F(A) \longrightarrow F(B) \longrightarrow F(C) \longrightarrow 0$$

in $B$ is exact for every short exact sequence $0 \to A \to B \to C \to 0$ in $A$.

Many widely used functors are not exact because either $F(A) \to F(B)$ fails to be a monomorphism or $F(B) \to F(C)$ fails to be an epimorphism. This motivates the introduction of the following weaker definitions:

**Definition A.16.** The functor $F : A \to B$ is **right exact** (resp. **left exact**) if, for all short exact sequences as above, the following sequence is exact:

$$F(A) \longrightarrow F(B) \longrightarrow F(C) \longrightarrow 0 \quad (\text{resp. } 0 \longrightarrow F(A) \longrightarrow F(B) \longrightarrow F(C)).$$

There are analogous definitions for contravariant functors.

A.1.6. **The cone of a morphism of complexes.** Another important tool of homological algebra is the cone of a morphism of complexes. For the sake of readability, we define it by picking elements of the objects in the complexes (recall that this is justified by the Freyd–Mitchell theorem). The zealous reader will have no trouble in replacing all morphisms below with their abstract definitions.

**Definition A.17.** Let $A$ be an additive category and let $f : A^* \to B^*$ be a morphism of complexes in $A$. The cone of $f$ is the complex defined as

$$\text{cone}(f)^n = A^{n+1} \oplus B^n,$$

together with the differential

$$d(a, b) = (-da, db + f(a)).$$

By construction, the cone is equipped with two morphisms of complexes

\begin{align*}
\text{b} : B^* &\longrightarrow \text{cone}(f), \quad b(b) = (0, b) \\
\text{a} : \text{cone}(f) &\longrightarrow A[1]^*, \quad a(a, b) = a,
\end{align*}

(A.18)

that induce a long exact sequence of cohomology objects

\begin{align*}
\cdots \longrightarrow H^n(A^*) &\xrightarrow{H(f)} H^n(B^*) \xrightarrow{H(b)} H^n(\text{cone}(f)) \xrightarrow{H(a)} H^{n+1}(A^*) \longrightarrow \cdots \\
\text{taking the equality } H^n(A[1]^*) = H^{n+1}(A^*) \text{ into account.}
\end{align*}

(A.19)

**Remark A.20.** Dually, the cone of a morphism of chain complexes $f : A_* \to B_*$ is defined as follows. The raising operator from Definition A.7 vi) yields a morphism of cochain complexes $r(f) : r(A) \to r(B)$, and $\text{cone}(f)$ is determined by the equality

$$r(\text{cone}(f)) = \text{cone}(r(f)).$$

(A.21)
Concretely, \( \text{cone}(f) \) is the chain complex given by
\[
\text{cone}(f)_n = A_{n-1} \oplus B_n \quad \text{and} \quad d(a, b) = (-da, f(a) + db).
\]
It is also equipped with two morphisms of chain complexes
\[
\begin{align*}
\text{(A.22)} \quad b &: B_* \to \text{cone}(f), \quad b(b) = (0, b), \\
a &: \text{cone}(f) \to A[-1]*, \quad a(a, b) = a,
\end{align*}
\]
which induce a long exact sequence of homology objects
\[
\text{(A.23)} \quad \cdots \to H_n(A_*) \xrightarrow{H(f)} H_n(B_*) \xrightarrow{H(b)} H_n(\text{cone}(f)) \xrightarrow{H(a)} H_{n-1}(A_*) \to \cdots
\]

**Remark A.24.** A choice of sign in the differential of the cone is needed for the equality \( d \circ d = 0 \) to hold. With the current choice, which is the most standard, \( a \) is only a morphism of complexes if the differential of \( A[1]^* \) carries a minus sign. With the choice \( d(a, b) = (da, -db + f(a)) \), the map \( b \) would not be a morphism of complexes. Finally, the choice \( d(a, b) = (da, db + (-1)^n f(a)) \), would make both \( a \) and \( b \) morphisms of complexes without changing the sign in the shifted complex.

**A.1.7. Double complexes.**

**Definition A.25.** Let \( \mathcal{A} \) be an additive category. A **double complex**
\[
C = (C^{*,*}, d^{\text{hor}}, d^{\text{ver}})
\]
is a collection of objects \( C^{p,q} \) of \( \mathcal{A} \), one for each \( (p, q) \in \mathbb{Z}^2 \), and morphisms
\[
d^{\text{hor}}: C^{p,q} \to C^{p+1,q}, \quad d^{\text{ver}}: C^{p,q} \to C^{p,q+1}
\]
called the **horizontal** and the **vertical** differentials satisfying
\[
(d^{\text{hor}})^2 = 0, \quad (d^{\text{ver}})^2 = 0, \quad d^{\text{hor}} \circ d^{\text{ver}} = d^{\text{ver}} \circ d^{\text{hor}}.
\]
In other words, \((C^{*,q}, d^{\text{hor}})\) and \((C^{p,*}, d^{\text{ver}})\) are cochain complexes for each fixed \( p \) and \( q \), and all the diagrams
\[
\begin{array}{c}
C^{p+1,q} \xrightarrow{d^{\text{hor}}} C^{p+1,q+1} \\
\bigg\downarrow \quad d^{\text{ver}} \quad \bigg\downarrow \\
C^{p,q} \xrightarrow{d^{\text{hor}}} C^{p,q+1}
\end{array}
\]
commute. We say that \( C \) is **bounded** if there exists an integer \( M \) such that \( C^{p,q} = 0 \) for all \( |p|, |q| \geq M \), with the obvious variants for bounded below and above complexes.

Associated with a bounded below double complex \( C \) as above is a usual cochain complex \((\text{Tot}(C), d)\) called the **total complex** and defined as
\[
\text{Tot}^n(C) = \bigoplus_{p+q=n} C^{p,q}
\]
in degree \( n \), with differential
\[
dx = d^{\text{hor}}x + (-1)^pd^{\text{ver}}x \quad \text{for} \quad x \in C^{p,q}.
\]
Note that, for the condition \( d^2 = 0 \) to hold and give rise to a complex, one needs to change the sign of either the vertical or the horizontal differential in the double complex; this choice is arbitrary and varies from one reference to another.
Example A.26. A morphism of complexes \( f: A^* \rightarrow B^* \) can be viewed as a double complex \( C \) with non-trivial terms
\[
C^{p,q} = A^p \quad \text{and} \quad C^{1,q} = B^q,
\]
and differentials \( d^{\text{hor}} = f \) and \( d^{\text{ver}} = 0 \). Its total complex \( \text{Tot}(f) \) is then given by
\[
\text{Tot}(f)^n = A^n \oplus B^{n-1}, \quad d(a, b) = (da, -db + f(a)).
\]
Comparing with Definition A.17 of the cone of a morphism, one finds
\[
\text{cone}(f) = \text{Tot}(-f)[1].
\]

Example A.27. The tensor product of complexes is another instance of a total complex associated with a double complex. Assume that the additive category \( A \) is equipped with a tensor product, that is, a bilinear functor \( \otimes: A \times A \rightarrow A \). This is the case, for example, for the category of \( R \)-modules. The tensor product of bounded below complexes \( A = (A^*, d_A) \) and \( B = (B^*, d_B) \) in \( A \) is defined as the complex \( A \otimes B \) with degree \( n \) terms
\[
(A \otimes B)^n = \bigoplus_{p+q=n} A^p \otimes B^q
\]
and differential given on the \( A^p \otimes B^q \) component by
\[
d_{A \otimes B} = d_A \otimes \text{Id}_B + (-1)^p \text{Id}_A \otimes d_B.
\]
This is the total complex associated with the double complex
\[
C^{p,q} = A^p \otimes B^q
\]
with horizontal differential \( d^{\text{hor}} = d_A \otimes \text{Id}_B \) and vertical differential \( d^{\text{ver}} = \text{Id}_A \otimes d_B \).

A.1.8. Cohomological functors. Let \( A \) be an abelian category. The category of complexes of \( A \), denoted by \( C(A) \), the category of bounded below complexes, denoted by \( C^+(A) \), and the category of bounded complexes, denoted by \( C^b(A) \), are abelian categories in turn. In particular, the notion of exact sequence of complexes makes sense. The cohomology functors
\[
H^n: C(A) \rightarrow A \quad (n \in \mathbb{Z})
\]
satisfy the property that, for every short exact sequence of complexes
\[
(A.28) \quad 0 \rightarrow A \rightarrow B \rightarrow C \rightarrow 0,
\]
there are morphisms \( \partial^n: H^n(C) \rightarrow H^{n+1}(A) \) such that the sequence
\[
(A.29) \quad \cdots \rightarrow H^n(A) \rightarrow H^n(B) \rightarrow H^n(C) \xrightarrow{\partial^n} H^{n+1}(A) \rightarrow H^{n+1}(B) \rightarrow \cdots
\]
is exact. Indeed, assuming that \( \mathcal{A} \) is a category of modules, we may define \( \partial^n \) by a diagram chase in

\[
\begin{array}{ccccccccc}
A^{n+2} & \rightarrow & B^{n+2} \\
\uparrow & & \uparrow \\
0 & \rightarrow & A^{n+1} & \rightarrow & B^{n+1} & \rightarrow & C^{n+1} & \rightarrow & 0 \\
\uparrow & & \uparrow & & \uparrow & & \uparrow & & \uparrow \\
0 & \rightarrow & A^n & \rightarrow & B^n & \rightarrow & C^n & \rightarrow & 0 \\
\uparrow & & \uparrow & & \uparrow & & \uparrow & & \uparrow \\
B^{n-1} & \rightarrow & C^{n-1} 
\end{array}
\]

Let \( c \in C^n \) be an element satisfying \( d^n c = 0 \). Since the map \( B^n \rightarrow C^n \) is surjective and the right square in the middle commutes, \( c \) is the image of an element \( b \in B^n \) such that \( d^n b \) maps to 0 in \( C^{n+1} \). By exactness of the second row, \( d^n b \) is the image of a unique \( a \in A^{n+1} \), which satisfies \( d^{n+1} a = 0 \) since the left upper square commutes and \( d^{n+1} \circ d^n = 0 \). Moreover, different choices of \( b \) give rise to elements \( a \) that differ by an element in the image of \( d^n \). Finally, if \( c \) is of the form \( d^{n-1} c' \) for some \( c' \in C^{n-1} \), then writing \( c' \) as the image of some \( b' \in B^{n-1} \) and using the commutativity of the right lower square, one finds that \( d^n b \), and hence \( a \), vanishes. All in all, the assignment \( c \mapsto a \) is a well defined map \( \partial^n : H^n(C) \rightarrow H^{n+1}(A) \) that by design makes the sequence (A.29) exact.

This property leads to the definition of cohomological \( \delta \)-functors and is the inspiration for the definition of derived functors (see Section A.4).

**Definition A.30.** A cohomological \( \delta \)-functor from an abelian category \( \mathcal{A} \) to an abelian category \( \mathcal{B} \) is the data of

i) a sequence of additive functors \( F^n : \mathcal{A} \rightarrow \mathcal{B} \) indexed by \( n \in \mathbb{Z} \);

ii) for each short exact sequence (A.28) in \( \mathcal{A} \), connection morphisms

\[
\partial^n : F^n(C) \rightarrow F^{n+1}(A);
\]

subject to the conditions:

i) the following sequence is exact:

\[
\cdots \rightarrow F^n(A) \rightarrow F^n(B) \rightarrow F^n(C) \xrightarrow{\partial^n} F^{n+1}(A) \rightarrow F^{n+1}(B) \rightarrow \cdots
\]

ii) for every morphism of short exact sequences

\[
\begin{array}{ccccccccc}
0 & \rightarrow & A^{n+1} & \rightarrow & B^{n+1} & \rightarrow & C^{n+1} & \rightarrow & 0 \\
\uparrow & & \uparrow & & \uparrow & & \uparrow & & \uparrow \\
0 & \rightarrow & A^n & \rightarrow & B^n & \rightarrow & C^n & \rightarrow & 0 \\
\uparrow & & \uparrow & & \uparrow & & \uparrow & & \uparrow \\
0 & \rightarrow & A^{n-1} & \rightarrow & B^{n-1} & \rightarrow & C^{n-1} & \rightarrow & 0
\end{array}
\]
the following diagram commutes:

\[
\begin{array}{c}
F^n(C) \xrightarrow{\partial^n} F^{n+1}(A) \\
\downarrow \\
F^n(C') \xrightarrow{\partial^n} F^{n+1}(A').
\end{array}
\]

In Definition A.56 below, we will introduce the notions of triangulated and cohomological functor in the setting of triangulated categories. The relation with cohomological \(\delta\)-functors is explained in Exercise A.74.

Remark A.31. Given any collection of signs \(\varepsilon_n \in \{-1, 1\}\), if \((F^n, \partial^n)_{n \in \mathbb{Z}}\) is a cohomological \(\delta\)-functor, then \((F^n, \varepsilon_n \partial^n)_{n \in \mathbb{Z}}\) is also a cohomological \(\delta\)-functor. This ambiguity of signs of connection morphisms in the definition of a cohomological \(\delta\)-functor is already visible in the construction of \(\partial^n\) by diagram chasing.

***

Exercise A.32. Let \(\mathcal{A}\) be an additive category. Show that \(\text{Hom}_{\mathcal{A}}(X, X)\) is endowed with a ring structure for each object \(X \in \text{Ob}(\mathcal{A})\).

Exercise A.33. Let \(\mathcal{A}\) be a category. A product of objects \(X, Y \in \text{Ob}(\mathcal{A})\) is an object \(X \times Y \in \text{Ob}(\mathcal{A})\) endowed with morphisms

\[
X \leftarrow X \times Y \rightarrow Y
\]

such that, for each object \(Z \in \text{Ob}(\mathcal{A})\) with morphisms \(Z \rightarrow X\) and \(Z \rightarrow Y\), there exist a unique morphism \(Z \rightarrow X \times Y\) making the diagram

\[
\begin{array}{ccc}
X & \xleftarrow{\delta} & X \times Y \\
\downarrow & & \downarrow \\
Z & \rightarrow & Y
\end{array}
\]

commutative. Show that the product \(X \times Y\) exists in every additive category \(\mathcal{A}\), and is equal to the direct sum \(X \oplus Y\). Conclude that, in an additive category, finite products exist and they agree with finite direct sums. (Since the notion of direct sum objects in Definition A.1 iii) is dual to the above, \(X \oplus Y\) is also called a coproduct in the categorial sense.)

Exercise A.34. Let \(F\): \(\mathcal{A} \rightarrow \mathcal{B}\) be a functor between additive categories. Prove that \(F\) is additive if and only if, for all objects \(X, Y \in \text{Ob}(\mathcal{A})\), the map

\[
F: \text{Hom}_{\mathcal{A}}(X, Y) \rightarrow \text{Hom}_{\mathcal{B}}(F(X), F(Y))
\]

is a group homomorphism. [Hint: the sum \(f + g\) of morphisms \(f, g \in \text{Hom}_{\mathcal{A}}(X, Y)\) is given by the composition

\[
X \rightarrow X \oplus X \xrightarrow{(f \ 0)} Y \oplus Y \rightarrow Y,
\]

where the diagonal \(X \rightarrow X \oplus X\) and the codiagonal \(Y \oplus Y \rightarrow Y\) are the maps obtained from the universal property of the product and the coproduct.]
Exercise A.35. Given an additive category \( \mathcal{A} \), let \( \mathcal{A}^{\text{op}} \) denote the opposite category, which has the same objects as \( \mathcal{A} \) but reversed morphisms

\[
\text{Hom}_{\mathcal{A}^{\text{op}}}(X, Y) = \text{Hom}_{\mathcal{A}}(Y, X)
\]

for all objects \( X, Y \in \text{Ob}(\mathcal{A}) \). Prove that \( \mathcal{A}^{\text{op}} \) is an additive category and that a cokernel for \( f : X \to Y \) in \( \mathcal{A} \) is a kernel for the corresponding morphism from \( Y \) to \( X \) in \( \mathcal{A}^{\text{op}} \), and vice versa.

Exercise A.36. Let \( \mathcal{A} \) be the category whose objects are pairs \((V, W)\) of vector spaces of the same dimension and whose morphisms are pairs of linear maps. Show that \( \mathcal{A} \) is an additive category in which some morphisms do not have a kernel. This is a toy example of the category of vector bundles on a topological space (in this case consisting of two points), which is typically not abelian by contrast with the category of coherent sheaves.

Exercise A.37. Let \( \mathcal{A} \) be an additive category and let \( f \) be a morphism in \( \mathcal{A} \). Assume that the image \( \text{Im}(f) \) and the coimage \( \text{Coim}(f) \) exist. Show that there is a canonical morphism

\[
\text{Coim}(f) \to \text{Im}(f).
\]

Exercise A.38. Let \( \mathcal{A} \) be an additive category and \( f : X \to Y \) a morphism in \( \mathcal{A} \) that has a kernel and a cokernel.

i) Prove that \( \text{Ker}(f) \to X \) is a monomorphism and \( Y \to \text{Coker}(f) \) is an epimorphism.

ii) Show that \( f \) is a monomorphism if and only if \( \text{Ker}(f) \) is a zero object and an epimorphism if and only if \( \text{Coker}(f) \) is a zero object.

Exercise A.39. Prove that the projection map \( \mathbb{Q} \to \mathbb{Q}/\mathbb{Z} \) is a monomorphism in the category of abelian divisible groups, i.e. those groups \( G \) such that, for each element \( x \in G \) and each integer \( n \geq 1 \), there exists \( y \in G \) satisfying \( ny = x \).

Exercise A.40. Let \( \mathcal{A} \) be an additive category and \( f \) a morphism in \( \mathcal{A} \). Prove that, if \( \text{Ker}(f) \) exists, then \( \text{Ker}(\text{Ker}(f)) \) exists and is a zero object of \( \mathcal{A} \). Similarly, if \( \text{Coker}(f) \) exists, then \( \text{Coker}(\text{Coker}(f)) \) exists and is a zero object.

Exercise A.41. Let \( \mathcal{A} \) be an abelian category and \( X \) an object of \( \mathcal{A} \). Show that \( \text{Hom}_{\mathcal{A}}(X, -) \) is a left exact functor from \( \mathcal{A} \) to the category of abelian groups.

A.2. Yoneda extensions.

A.2.1. Definition.

Definition A.42. Let \( \mathcal{A} \) be an abelian category, let \( A \) and \( B \) be objects of \( \mathcal{A} \), and \( n \geq 1 \) an integer. An extension of degree \( n \) of \( A \) by \( B \) is an exact sequence

\[
E : \quad 0 \to B \to C_{n-1} \to \cdots \to C_0 \to A \to 0.
\]

Given extensions of the same degree \( E \) and \( E' \), we say that \( E \) is equivalent to \( E' \) if there exists a commutative diagram

\[
\begin{array}{ccc}
0 & \to & B \\
\downarrow & & \downarrow \\
C_{n-1} & \to & C_0 \\
\downarrow & & \downarrow \\
\cdots & \to & \cdots \\
\downarrow & & \downarrow \\
A & \to & 0
\end{array}
\]

\[
\begin{array}{ccc}
0 & \to & B \\
\downarrow & & \downarrow \\
C'_{n-1} & \to & C'_0 \\
\downarrow & & \downarrow \\
\cdots & \to & \cdots \\
\downarrow & & \downarrow \\
A & \to & 0
\end{array}
\]
For $n = 1$, this notion agrees with that from Definition 2.226 in the particular case of mixed Hodge structures. In contrast to that case, the binary relation defined by the existence of the above diagram is not symmetric for $n \geq 2$. We consider instead the equivalence relation generated by such relations, which means that we force symmetry and transitivity by adding the missing relations.

**Definition A.43.** For $n \geq 1$, we denote by $\text{Ext}^n_A(A, B)$ the set of equivalence classes of degree $n$ extensions of $A$ by $B$. To unify notation, we also set

$$\text{Ext}^0_A(A, B) = \text{Hom}_A(A, B)$$

and $\text{Ext}^n_A(A, B) = 0$ for all $n < 0$.

**A.2.2. Some properties of Yoneda extensions.**

The **Baer sum**. The sets $\text{Ext}^n_A(A, B)$ are endowed with a group structure. We first describe it for $n = 1$. Let

$$E: 0 \to B \xrightarrow{\iota} C_{n-1} \to \cdots \to C_0 \xrightarrow{\pi} A \to 0$$

$$E': 0 \to B \xrightarrow{\iota'} C'_{n-1} \to \cdots \to C'_0 \xrightarrow{\pi'} A \to 0$$

be degree $n$ extensions of $A$ by $B$. The pull-back of $C_0$ and $C'_0$ over $A$ is the object

$$C''_0 = \text{Ker} \left( C_0 \oplus C'_0 \xrightarrow{\phi} A \right), \quad \phi(c, c') = \pi'(c') - \pi(c).$$

By construction, $\pi$ and $\pi'$ agree on $C''_0$, hence a well defined morphism

$$\pi'': C''_0 \to A, \quad \pi''(c, c') = \pi(c) = \pi'(c').$$

Dually, the push-out of $C_{n-1}$ and $C'_{n-1}$ under $B$ is the object

$$C''_{n-1} = \text{Coker} \left( B \xrightarrow{\psi} C_{n-1} \oplus C'_{n-1} \right), \quad \psi(b) = (\iota(b), -\iota'(b)).$$

By construction, the maps $b \mapsto (\iota(b), 0)$ and $b \mapsto (0, \iota'(b))$ from $B$ to $C_{n-1} \oplus C'_{n-1}$ induce the same map

$$\iota'': B \to C''_{n-1}.$$

**Definition A.44.** For $n \geq 2$, the **Baer sum** of the degree $n$ extensions $E$ and $E'$ is the degree $n$ extension given by

$$0 \to B \to C''_{n-1} \to C_{n-2} \oplus C'_{n-2} \to \cdots \to C_1 \oplus C'_1 \to C'_0 \to A \to 0.$$
With the Baer sum the equivalence class sets $\text{Ext}^n_A(A, B)$ form a group (Exercise A.47).

**Functoriality:** Formation of extensions is functorial. This means that, given objects $A$, $B$, and $B'$, a morphism $f : B \to B'$, and an extension

$$E : 0 \to B \xrightarrow{d_n} C_{n-1} \xrightarrow{d_{n-1}} \cdots \xrightarrow{d_1} C_0 \xrightarrow{d_0} A \to 0,$$

one constructs an extension $\text{Ext}^n_A(A, f)(E) \in \text{Ext}^n_A(A, B')$ as follows.

First define $C'_{n-1}$ as the pushout of $C_{n-1}$ and $B'$ under $B$. Then there are maps $f_{n-1} : C_{n-1} \to C'_{n-1}$ and $d'_n : B' \to C'_{n-1}$. For notational convenience write $C_n = B$, $C'_n = B'$ and $f_n = f$. Assume that we have defined the groups $C'_n, \ldots, C'_k$ and the maps $f_i, i = n, \ldots, k$ and $d'_i, i = n, \ldots, k + 1$, where $1 \leq k \leq n - 1$. Then the group $C'_{k-1}$ is defined as

$$C'_{k-1} = \text{Coker}(\psi : C'_{k+1} \oplus C_k \to C'_k \oplus C_{k-1}),$$

where the map $\psi$ is given by

$$\psi(c', c) = (d'_{k+1}(c') + f_k(c), -d_k(c)).$$

There are induced maps $f_{k-1} : C_{k-1} \to C'_{k-1}$ and $d'_k : C'_k \to C'_{k-1}$. Using the universal property of the cokernel, one proves that there is a map $d'_0 : C'_0 \to A$. The resulting sequence

$$0 \to B' \xrightarrow{d'_0} C'_{n-1} \xrightarrow{d'_{n-1}} \cdots \xrightarrow{d'_1} C'_0 \xrightarrow{d'_0} A' \to 0,$$

is exact and defines the extension $E' = \text{Ext}^n_A(A, f)(E) \in \text{Ext}^n(A, B')$.

Let $0 \to B_1 \to B_2 \to B_3 \to 0$ be a short exact sequence. There is a map

$$\partial^0 : \text{Hom}_A(A, B_3) \to \text{Ext}^1_A(A, B_1)$$

sending a morphism $f$ to the sequence $0 \to B_1 \to E \to A \to 0$, where $E$ is the pullback of $B_2$ and $A$ over $B_3$. There are also maps $\partial^n : \text{Ext}^n_A(A, B_3) \to \text{Ext}^{n+1}_A(A, B_1)$ that send the extension

$$0 \to B_3 \xrightarrow{d_n} C_{n-1} \xrightarrow{d_{n-1}} \cdots \xrightarrow{d_1} C_0 \xrightarrow{d_0} A \to 0,$$

to the extension

$$0 \to B_1 \xrightarrow{d_n} C_{n-1} \xrightarrow{d_{n-1}} \cdots \xrightarrow{d_1} C_0 \xrightarrow{d_0} A \to 0.$$

In Exercise A.48 you will prove that the extension groups together with the connecting morphisms defined above form a cohomological $\delta$-functor (Definition A.30).

**A vanishing criterion:**

**Lemma A.46.** Let $A$ be an abelian category. Assume that there exists an integer $n_0 \geq 0$ such that, for all objects $A$ in $A$, the functor $\text{Ext}^{n_0}_A(A, -)$ is right exact. Then $\text{Ext}^n_A(A, B) = 0$ for all objects $A, B$ in $A$ and all integers $n > n_0$.

**Proof.** It is enough to prove that, if the functor $\text{Ext}^n_A(A, -)$ is right exact for all objects $A$, then $\text{Ext}^{n+1}_A(A, B) = 0$ for all objects $A, B$, because the functor zero is right exact and we proceed by induction. We start with the case $n = 0$. Assume that $\text{Ext}^0_A(A, -) = \text{Hom}_A(A, -)$ is right exact for all $A$ and let $0 \to B \to E \xrightarrow{\pi} A \to 0$ be an extension. Since $\text{Hom}_A(A, -)$ is right exact, there exists a map $f : A \to E$ such that $\pi \circ f = \text{Id}_A$. This means that the extension is split and we conclude that $\text{Ext}^1_A(A, B) = 0$. 
Let now $n \geq 1$ and assume that $\text{Ext}_{A}^{n}(A, -)$ is right exact. Let

$$E: 0 \to B \xrightarrow{d_{n+1}} C_{n} \xrightarrow{d_{n}} \cdots \xrightarrow{d_{1}} C_{0} \xrightarrow{d_{0}} A \to 0,$$

be an extension in $\text{Ext}_{A}^{n+1}(A, B)$. Let $C = \text{Coker}(d_{n+1})$ and consider the exact sequence

$$0 \to B \to C_{n} \to C \to 0$$

and the extension

$$E': 0 \to C \xrightarrow{d_{n}} C_{n-1} \xrightarrow{d_{n-1}} \cdots \xrightarrow{d_{1}} C_{0} \xrightarrow{d_{0}} A \to 0,$$

then $E' \in \text{Ext}_{A}^{n}(A, C)$ and $E = \partial^{n}(E')$. Since $\text{Ext}_{A}^{n}(A, -)$ is right exact, one necessarily has $\partial^{n}(E') = 0$, and hence $E = 0$. □

⋆ ⋆ ⋆

Exercise A.47. Show that the Baer sum is well defined on equivalence classes, and hence induces group structure on $\text{Ext}_{A}^{n}(A, B)$ for each $n \geq 1$.

Exercise A.48. Let $\mathcal{A}$ be an abelian category. Prove that, for every object $A$ of $\mathcal{A}$, the functors $\text{Ext}_{\mathcal{A}}^{n}(A, -)$ together with the connection morphisms $\partial^{n}$ defined before Lemma A.46 form a cohomological $\delta$-functor.

A.3. Triangulated and derived categories.

A.3.1. The definition of a triangulated category.

Definition A.49 (Verdier). A triangulated category $\mathcal{T}$ is an additive category, together with the following extra data:

i) A self-equivalence of categories

$$[1]: \mathcal{T} \to \mathcal{T}$$

$$X \mapsto X[1].$$

We denote by $f[1]$ the image of a morphism $f$ by this functor. Once the self-equivalence $[1]$ is given, we call triangles all sequences of the form

$$X \xrightarrow{u} Y \xrightarrow{v} Z \xrightarrow{w} X[1].$$

A morphism of triangles is a commutative diagram

$$\begin{array}{ccc}
X & \xrightarrow{u} & Y \\
\downarrow & & \downarrow \\
X' & \xrightarrow{u'} & Y'
\end{array}$$

$$\begin{array}{ccc}
Y & \xrightarrow{v} & Z \\
\downarrow & & \downarrow \\
Y' & \xrightarrow{v'} & Z'
\end{array}$$

$$\begin{array}{ccc}
Z & \xrightarrow{w} & X \\
\downarrow & & \downarrow \\
Z' & \xrightarrow{w'} & X'[1]
\end{array}.$$

We will use the convention that arrows decorated with $[1]$ such as $A \xrightarrow{[1]} B$ represent morphisms $A \to B[1]$.

ii) A class of triangles called distinguished triangles.

These data are required to satisfy the following axioms:

(T1): i) For any $X \in \text{Ob}(\mathcal{T})$, the following triangle is distinguished:

$$X \xrightarrow{\text{Id}} X \to 0 \to X[1].$$

ii) Any triangle isomorphic to a distinguished one is distinguished.
iii) Any morphism $X \overset{u}{\to} Y$ can be completed to a distinguished triangle

$$X \overset{u}{\to} Y \overset{v}{\to} Z \overset{w}{\to} X[1].$$

(T2): The triangle $X \overset{u}{\to} Y \overset{v}{\to} Z \overset{w}{\to} X[1]$ is distinguished if and only if the triangle $Y \overset{v}{\to} Z \overset{w}{\to} X[1] \overset{-u[1]}{\longrightarrow} Y[1]$ is distinguished.

(T3): Given distinguished triangles

$$X \overset{u}{\to} Y \overset{v}{\to} Z \overset{w}{\to} X[1], \quad X' \overset{u'}{\to} Y' \overset{v'}{\to} Z' \overset{w'}{\to} X'[1],$$

and morphisms $f: X \to X'$ and $g: Y \to Y'$ such that $g \circ u = u' \circ f$, there exists a (not necessarily unique) morphism $h: Z \to Z'$ such that

$$X \overset{u}{\to} Y \overset{v}{\to} Z \overset{w}{\to} X[1]$$

$$\downarrow f \downarrow g \downarrow h \downarrow f[1]$$

$$X' \overset{u'}{\to} Y' \overset{v'}{\to} Z' \overset{w'}{\to} X'[1]$$

is a morphism of triangles.

(T4): (Octahedron axiom) Given a diagram of solid arrows

if the three triangles

$$X \overset{u}{\to} Y \overset{j}{\to} Z' \overset{k}{\to} X[1]$$

$$Y \overset{v}{\to} Z \overset{\ell}{\to} X' \overset{i}{\to} Y[1]$$

$$X \overset{\circ u}{\to} Z \overset{m}{\to} Y' \overset{n}{\to} X[1]$$

are distinguished, there exist dashed arrows $f: Z' \to Y'$ and $g: Y' \to X'$ as above such that the triangle

$$Z' \overset{f}{\to} Y' \overset{g}{\to} X' \overset{j[1]|i}{\to} Z'[1]$$
is distinguished and the following equalities hold:
\[ k = n \circ f, \quad \ell = g \circ m, \]
\[ m \circ v = f \circ j, \quad u[1] \circ n = i \circ g. \]

**Remark A.50.** The first basic property of distinguished triangles is that the composition of two consecutive maps is zero. That is, let \( \mathcal{T} \) be a triangulated category and let
\[
X \xrightarrow{u} Y \xrightarrow{v} Z \xrightarrow{w} X[1]
\]
be a distinguished triangle, then
\[ v \circ u = 0, \quad w \circ v = 0, \quad u[1] \circ w = 0. \]
Indeed, by axiom \( \mathbf{T2} \) it is enough to prove \( v \circ u = 0 \). Consider now the diagram
\[
\begin{array}{ccc}
X & \xrightarrow{\text{Id}} & X \\
\downarrow{u} & & \downarrow{v} \\
Y & \xrightarrow{\text{Id}} & Y \\
\downarrow{v} & & \downarrow{w} \\
Z & \xrightarrow{\text{Id}} & Z \\
\downarrow{w} & & \downarrow{X[1]} \\
X[1] & \xrightarrow{\text{Id}} & X[1]
\end{array}
\]
Since, by axiom \( \mathbf{T3} \) the dotted arrow exists, making the diagram commutative, we deduce \( v \circ u = 0 \).

**Remark A.51.** The octahedron axiom can be flattened by repeating some vertices. Namely if in the commutative diagram (without the dotted arrows)
\[
\begin{array}{ccccccc}
X & \xrightarrow{u} & Y & \xrightarrow{v} & Z & \xrightarrow{w} & X[1] \\
\downarrow{u} & & \downarrow{v} & & \downarrow{w} & & \downarrow{X[1]} \\
Y & \xrightarrow{f} & Z & \xrightarrow{m} & X' & \xrightarrow{i} & Y[1] \\
\downarrow{j} & & \downarrow{m} & & \downarrow{j[1]} & & \downarrow{j[1]} \\
Z' & \xrightarrow{g} & Y' & \xrightarrow{j[1]} & X' & \xrightarrow{i} & Z'[1] \\
\downarrow{k} & & \downarrow{g} & & \downarrow{k} & & \downarrow{k} \\
X[1] & \xrightarrow{n} & X[1]
\end{array}
\]
the two long columns and the long row are distinguished triangles, then there exist arrows \( f \) and \( g \), making the whole diagram commutative, the second long row a distinguished triangle and the additional compatibility condition
\[ i \circ g = u[1] \circ n : Y' \rightarrow Y[1] \]
holds.

**Proposition A.52.** Let \( \mathcal{T} \) be a triangulated category and let
\[
X_i \xrightarrow{u_i} Y_i \xrightarrow{v_i} Z_i \xrightarrow{w_i} X_i[1] \quad (i = 1, 2)
\]
be distinguished triangles. The triangle
\[
X_1 \oplus X_2 \xrightarrow{u_1 \oplus w_2} Y_1 \oplus Y_2 \xrightarrow{u_1 \oplus v_2} Z_1 \oplus Z_2 \xrightarrow{w_1 \oplus w_2} X_1[1] \oplus X_2[1]
\]
is distinguished as well.
MULTIPLE ZETA VALUES: FROM NUMBERS TO MOTIVES

See [Nee01, Prop. 1.2.1] for a proof, which is trickier than what one might think. It follows that, for all objects \(X, Z \in \text{Ob}(\mathcal{T})\), the triangle

\[
X \rightarrow X \oplus Z \rightarrow Z \overset{0}{\rightarrow} X[1]
\]

is distinguished.

**Definition A.54.** A triangle is called **split** if it is isomorphic to a triangle of the form (A.53).

**Proposition A.55.** Let \(\mathcal{T}\) be a triangulated category and let

\[
X \overset{u}{\rightarrow} Y \overset{v}{\rightarrow} Z \overset{w}{\rightarrow} X[1]
\]

be a distinguished triangle. The following statements are equivalent.

i) The triangle is split.

ii) The equality \(w = 0\) holds.

iii) There is a map \(s : Z \rightarrow Y\) satisfying \(v \circ s = \text{Id}_Z\).

iv) There is a map \(r : Y \rightarrow X\) satisfying \(r \circ u = \text{Id}_X\).

**Proof.** Clearly, statement i) implies the other three. Assume there is a map \(s : Z \rightarrow Y\) satisfying \(v \circ s = \text{Id}_Z\). Then the equalities \(w = w \circ \text{Id}_Z = w \circ v \circ s = 0\) hold, and hence iii) implies ii). Similarly, iv) implies ii). Therefore, the main content of the proposition is that ii) implies i), which is proved in [Nee01, Cor. 1.2.7]. \(\square\)

**Definition A.56.** Let \(\mathcal{T}\) and \(\mathcal{T}'\) be triangulated categories and let \(\mathcal{A}\) be an abelian category.

i) A **triangulated functor** \(F : \mathcal{T} \rightarrow \mathcal{T}'\) is an additive functor that sends distinguished triangles to distinguished triangles and is compatible with the self-equivalence [1], in that the equalities

\[
F(X[1]) = F(X)[1] \quad \text{and} \quad F(f[1]) = F(f)[1]
\]

hold for each object \(X\) and each morphism \(f\) of \(\mathcal{T}\).

ii) A **cohomological functor** \(H : \mathcal{T} \rightarrow \mathcal{A}\) is an additive functor such that, for each distinguished triangle

\[
X \overset{u}{\rightarrow} Y \overset{v}{\rightarrow} Z \overset{w}{\rightarrow} X[1]
\]

in \(\mathcal{T}\), the sequence

\[
\cdots \rightarrow H(X[n]) \overset{H(u[n])}{\rightarrow} H(Y[n]) \overset{H(v[n])}{\rightarrow} H(Z[n]) \overset{H(w[n])}{\rightarrow} \\
H(X[n + 1]) \overset{H(u[n+1])}{\rightarrow} H(Y[n + 1]) \overset{H(v[n+1])}{\rightarrow} H(Z[n + 1]) \rightarrow \cdots
\]

is exact. (Here, \([n]\) denotes the \(n\)-th iteration of the self-equivalence [1] if \(n \geq 0\) and the \((-n)\)-th iteration of its inverse \([-1]\) if \(n \leq 0\).)

**A.3.2. Example: the homotopy and derived categories.** The first example of a triangulated category is the category of bounded below complexes up to homotopy, whose construction we now sketch. Let \(\mathcal{A}\) be an additive category and let \(\mathcal{C}^+(\mathcal{A})\) be the category of bounded below cochain complexes on \(\mathcal{A}\). Recall the notions of shift of a complex and cone of a morphism of complexes from Section A.1.4.
Definition A.57. Let \( f, g : A^* \to B^* \) be morphisms of complexes. A homotopy between \( f \) and \( g \) is a collection of maps \( s^n : A^n \to B^{n-1} \) such that the equality 
\[
f^n - g^n = d^{n-1} \circ s^n + s^{n+1} \circ d^n
\]
holds for all \( n \). We picture it as follows:

\[
\begin{array}{ccccccccc}
\ldots & \to & A^{n-1} & \to & A^n & \to & A^{n+1} & \to & \ldots \\
& & s^n & & s^{n+1} & & & & \\
\ldots & \to & B^{n-1} & \to & B^n & \to & B^{n+1} & \to & \ldots
\end{array}
\]

If such a homotopy exists, we say that \( f \) and \( g \) are homotopically equivalent.

If the category \( \mathcal{A} \) is abelian, then homotopically equivalent morphisms of complexes induce the same map in cohomology. Indeed, it suffices to prove that \( f - g \) induces the zero map from \( \text{H}^*(A^*) \) to \( \text{H}^*(B^*) \). To see this, let \( [x] \in \text{H}^n(A^*) \) be a cohomology class. Then
\[
[(f^n - g^n)(x)] = [d^{n-1}(s^n(x)) + s^{n+1}(d^n(x))] = [s^{n+1}(d^n(x))] = 0,
\]
since \( d^{n-1}(s^n(x)) \) is a coboundary and \( d^n(x) = 0 \).

Definition A.58. A morphism of complexes \( f : A^* \to B^* \) is called a homotopy equivalence if there exists a morphism of complexes \( g : B^* \to A^* \) such that \( g \circ f \) and \( f \circ g \) are homotopically equivalent to \( \text{Id}_{A^*} \) and \( \text{Id}_{B^*} \), respectively.

This defines an equivalence relation on the set of morphisms of complexes. If the category \( \mathcal{A} \) is abelian, then a homotopy equivalence \( f \) is a quasi-isomorphism since \( \text{H}(f) \) and \( \text{H}(g) \) are inverse to each other.

Definition A.59. Let \( \mathcal{A} \) be an additive category. The homotopy category of \( \mathcal{A} \) is the category \( \mathcal{K}^+(\mathcal{A}) \) whose objects are the same as those of \( \mathcal{C}^+(\mathcal{A}) \) but whose morphisms are equivalence classes with respect to the homotopy equivalence of morphisms in \( \mathcal{C}^+(\mathcal{A}) \). The shift functor
\[
[1] : \mathcal{K}^+(\mathcal{A}) \to \mathcal{K}^+(\mathcal{A})
\]
sends a complex \( A \) to the shifted complex \( A[1] \). A distinguished triangle is a triangle isomorphic to one of the form
\[
A^* \xrightarrow{f} B^* \xrightarrow{b} \text{cone}(f) \xrightarrow{a} A[1]
\]
for some morphism of complexes \( f : A^* \to B^* \) and \( a \) and \( b \) defined as in (A.18). Together with this data, \( \mathcal{K}^+(\mathcal{A}) \) is a triangulated category.

Example A.60. Let \( \mathcal{A} \) be an abelian category. The exactness of the sequence (A.19) shows that the functor
\[
\text{H} : \mathcal{K}^+(\mathcal{A}) \to \mathcal{A}, \quad A^* \mapsto \text{H}^0(A^*)
\]
is a cohomological functor.

Example A.61. Let \( \mathcal{A} \) and \( \mathcal{B} \) be additive categories and let \( F : \mathcal{A} \to \mathcal{B} \) be an additive functor. The functor \( F : \mathcal{K}^+(\mathcal{A}) \to \mathcal{K}^+(\mathcal{B}) \) that sends a complex \( (A^*, d) \) to the complex \( F((A^*, d)) \) with terms \( F((A^*, d))^n = F(A)^n \) with differential \( F(d) \) is a triangulated functor (see Exercise A.73).
The second example, and for our purposes the main one, of a triangulated category is the (bounded) *derived category* of an abelian category $\mathcal{A}$, which is obtained by inverting the quasi-isomorphisms in the homotopy category $\mathcal{K}^+(\mathcal{A})$. The construction is done in two steps. The first step is the construction of the homotopy category $\mathcal{K}^+(\mathcal{A})$ that we have already sketched. In the second step, one constructs $\mathcal{D}^+(\mathcal{A})$ by inverting the quasi-isomorphisms. The objects of $\mathcal{D}^+(\mathcal{A})$ are the same as the objects of $\mathcal{K}^+(\mathcal{A})$ (which are the same as the ones of $\mathcal{C}^+(\mathcal{A})$), while the morphisms between two objects $A^*$ and $B^*$ of $\mathcal{D}^+(\mathcal{A})$ are equivalence classes of diagrams of the form

\[(A.62)\]

where the arrow to the left is a quasi-isomorphism. The diagrams

\[
\begin{align*}
& \quad \approx \quad C_1^* \\
& A^* \quad \approx \quad B^* \\
& \quad \approx \quad C_2^* \\
\end{align*}
\]

and

\[
\begin{align*}
& \quad \approx \quad C_1^* \\
& A^* \quad \approx \quad B^* \\
& \quad \approx \quad C_2^* \\
\end{align*}
\]

are equivalent if there is a diagram of the same type and morphisms $C_3^* \to C_1^*$ and $C_3^* \to C_2^*$ such that the diagram

\[(A.63)\]

is commutative in $\mathcal{K}^+(\mathcal{A})$. This means that all the triangles in (A.63) are commutative *up to homotopy*, although not necessarily commutative.

**Remark A.64.** A reason to define the derived category by inverting quasi-isomorphisms in $\mathcal{K}^+(\mathcal{A})$ rather than directly in $\mathcal{C}^+(\mathcal{A})$ is that this allows for a simple description of the morphisms. Otherwise, morphisms would be given by chains of the form

\[
\begin{align*}
& \quad \approx \quad C_1^* \\
& A^* \quad \approx \quad C_2^* \\
& \quad \approx \quad C_{k-1}^* \\
& \quad \approx \quad B^* \\
\end{align*}
\]

where all the arrows in the left direction are quasi-isomorphisms.

The category $\mathcal{D}^+(\mathcal{A})$ is a triangulated category, with the self equivalence [1] defined by the shift of complexes and the class of distinguished triangles given by those triangles that are isomorphic (in $\mathcal{D}^+(\mathcal{A})$) to one of the form

\[
A^* \xrightarrow{f} B^* \xrightarrow{b} \text{cone}(f) \xrightarrow{a} A[1]^*.
\]
Remark A.65. In contrast with the ambiguity of signs of connection morphisms in Definition A.30, there is no ambiguity of signs in Definition A.56. This implies that the choice of the class of distinguished triangles allows us to fix the sign of many cohomological $\delta$-functors, at least all those coming from a triangulated functor between derived categories. We illustrate the choice of signs with the following example. Let $A$ be an abelian category and $f: A^* \to B^*$ a morphism of complexes such that $f^n: A^n \to B^n$ is a monomorphism for all $n$. As in Exercise A.71, let $C^*$ denote the complex assembling the cokernels of the maps $f^n$, so that there is a short exact sequence of complexes

$$0 \to A^* \to B^* \to C^* \to 0.$$ 

By Exercise A.71, there is an isomorphism

$$\varphi: \text{cone}(f) \sim C^*$$

in the derived category $\mathcal{D}(A)$, and hence the connection morphism

$$\partial^n: H^n(C^*) \to H^{n+1}(A^*)$$

in the associated long exact sequence is given by the composite

$$H^n(C^*) \xrightarrow{H^n(\varphi)^{-1}} H^n(\text{cone}(f)) \to H^n(A[1]^*) = H^{n+1}(A^*).$$

This yields a long exact sequence

(A.66) \[ \cdots \to H^n(A^*) \xrightarrow{f} H^n(B^*) \xrightarrow{b} H^n(C^*) \xrightarrow{a} H^{n+1}(A^*) \to \cdots \]

where $a$ and $b$ denote the maps (A.18) composed with $H^n(\varphi)^{-1}$. Besides, the sign in Axiom (T2) of Definition A.49 implies that the short exact sequence of complexes

$$0 \to B^* \to \text{cone}(f) \to A[1]^* \to 0$$

gives rise to the long exact sequence

(A.67) \[ \cdots \to H^n(B^*) \xrightarrow{b} H^n(C^*) \xrightarrow{a} H^{n+1}(A^*) \xrightarrow{f} H^{n+1}(B^*) \to \cdots . \]

This apparent contradiction in the signs is explained by the fact that the exact sequence (A.67) is isomorphic to (A.66) shifted by 1.

Definition A.68. Let $A$ be an abelian category. The (bounded below) derived category is the category we just described. The localization functor is the functor

$$Q: K^+(A) \to D^+(A)$$

that is the identity on objects and maps a morphism to its equivalence class.

Remark A.69. There is a similar definition of the bounded homotopy category $K^b(A)$ and the bounded derived category $D^b(A)$ that is obtained by replacing bounded below complexes with bounded complexes in what precedes.

The construction of the derived category is an example of a more general process called Verdier localization. Let $\mathcal{T}$ be a triangulated category and let $\mathcal{E}$ be a triangulated subcategory of $\mathcal{T}$.

Proposition A.70. There exists a triangulated category $\mathcal{T}/\mathcal{E}$ that is universal for the following two properties:

i) There exists a triangulated functor $\mathcal{T} \to \mathcal{T}/\mathcal{E}$ that is the identity on objects.
ii) Every object \( X \) of \( E \) is isomorphic to the zero object \( 0 \) in \( T/E \).

For example, the homotopy category \( K^+(A) \) (resp. the derived category \( D^+(A) \)) is obtained from the category of complexes \( C^+(A) \) by taking the Verdier localization with respect to the triangulated subcategory of complexes homotopically equivalent to zero (resp. quasi-isomorphic to zero).

\[ \star \star \star \]

**Exercise A.71.** Let \( A \) be an abelian category and let \( f: A^+ \to B^+ \) be a morphism of complexes in \( A \).

i) Assume that, for each \( n \in \mathbb{Z} \), the map \( f^n: A^n \to B^n \) is a monomorphism. Let \( C^+ \) be the complex with \( C^n = \text{Coker}(f^n) \) and differential induced by that of \( B^+ \). Let \( p: B^+ \to C^+ \) be the projection map. Prove that the map

\[
\text{cone}(f) \xrightarrow{\sim} C^+, \quad (a, b) \mapsto p(b)
\]

is a morphism of complexes, which becomes an isomorphism in \( D(A) \).

ii) Assume that, for each \( n \in \mathbb{Z} \), the map \( f^n: A^n \to B^n \) is an epimorphism. Let \( C^+ \) be the complex with \( C^n = \ker(f^n) \) and differential induced by that of \( A^+ \). Let \( \iota: C^+ \to A^+ \) denote the inclusion map. Prove that

\[
C^+ \xrightarrow{\sim} \text{Tot}(f), \quad c \mapsto (\iota(c), 0)
\]

is a morphism of complexes, which becomes an isomorphism in \( D(A) \).

iii) Assume that \( A \) has the property that every short exact sequence is split (for instance, the category of vector spaces over a field has this property). Show that the previous quasi-isomorphisms are homotopy equivalences. Give an example showing that the assumption on \( A \) is necessary.

**Exercise A.72.** Let \( f: A^+ \to B^+ \) and \( g: A^+ \to C^+ \) be morphisms of complexes in an abelian category \( A \). Show that, if \( g \) is a quasi-isomorphism, then the composition \( B \to B \oplus C \to \text{cone}(f + g) \) is a quasi-isomorphism.

**Exercise A.73.** Let \( F: A \to B \) be an additive functor of abelian categories.

i) If \( (A^+, d) \) is a bounded below complex in \( A \), then \( (F(A^+), F(d)) \) is a bounded below complex in \( B \). Observe that, if \( f \) and \( g \) are homotopically equivalent morphisms in \( A \), then \( F(f) \) and \( F(g) \) are also homotopically equivalent in \( B \). Therefore, \( F \) induces a functor

\[
F: K^+(A) \to K^+(B).
\]

ii) Prove that the induced functor \( F \) is compatible with the shift functor and with the formation of the cone. Conclude that \( F \) is a triangulated functor.

**Exercise A.74.** As we saw in Example A.60, the basic example of a cohomological functor comes from taking cohomology in degree zero. Let \( A \) and \( B \) be abelian categories.

i) Show that the cohomological functor \( H^0 \) from \( K^+(B) \) to \( B \) descends to a cohomological functor \( D^+(B) \to B \).

ii) Let \( F: D^+(A) \to D^+(B) \) be a triangulated functor and define the functors \( F^n: A \to B \) as the composition

\[
A \to D^+(A) \xrightarrow{F} D^+(B) \xrightarrow{[n]} D^+(B) \xrightarrow{H^0} B,
\]
where the first map sends an object in $\mathcal{A}$ to this object seen as a complex concentrated in degree zero. Show that the functors $F^n$ with the appropriate connection morphisms form a cohomological $\delta$-functor.

iii) Let $F : \mathcal{K}^+(\mathcal{A}) \to \mathcal{K}^+(\mathcal{B})$ be a triangulated functor and define the functors $F^n : \mathcal{A} \to \mathcal{B}$ as the composition

$$\mathcal{A} \longrightarrow \mathcal{K}^+(\mathcal{A}) \xrightarrow{F^n} \mathcal{K}^+(\mathcal{B}) \longrightarrow \mathcal{D}^+(\mathcal{B}) \xrightarrow{H^0} \mathcal{B}.$$ 

Show with an example that, in general, the functors $F^n$ do not form a cohomological $\delta$-functor.

A.4. Derived functors. Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories and let $F : \mathcal{A} \to \mathcal{B}$ be an additive functor. We know from Example A.61 that $F$ induces a triangulated functor, also denoted by $F$, between the homotopy categories $\mathcal{K}^+(\mathcal{A})$ and $\mathcal{K}^+(\mathcal{B})$. If $F$ is exact, then this functor sends quasi-isomorphisms to quasi-isomorphisms, and hence gives rise to a functor $\mathcal{D}^+(\mathcal{A}) \to \mathcal{D}^+(\mathcal{B})$ between the derived categories. By contrast, non-exact functors do not extend naively to the derived categories. Whenever it exists, the derived functor $RF$ is the triangulated functor between the derived categories that best approximates $F$.

A.4.1. Definition of derived functors. Recall that $Q : \mathcal{K}^+(\mathcal{A}) \to \mathcal{D}^+(\mathcal{A})$ denotes the localization functor from Definition A.68.

**Definition A.75.** Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories and $F : \mathcal{A} \to \mathcal{B}$ an additive functor. We also denote by $F$ the induced triangulated functor

$$F : \mathcal{K}^+(\mathcal{A}) \longrightarrow \mathcal{K}^+(\mathcal{B})$$

between the corresponding homotopy categories. The **(total) right derived functor** of $F$ is a triangulated functor

$$RF : \mathcal{D}^+(\mathcal{A}) \longrightarrow \mathcal{D}^+(\mathcal{B})$$

together with a natural transformation

$$\xi : Q \circ F \longrightarrow RF \circ Q$$

of functors from $\mathcal{K}^+(\mathcal{A})$ to $\mathcal{D}^+(\mathcal{B})$ that satisfy the following universal property: for each triangulated functor $G : \mathcal{D}^+(\mathcal{A}) \to \mathcal{D}^+(\mathcal{B})$ and each natural transformation $\zeta : Q \circ F \to G \circ Q$, there exists a unique natural transformation $\eta : RF \to G$ satisfying

$$\zeta = (\eta \circ Q) \circ \xi.$$ 

We give more details on what this definition means. Since the functor $Q$ is the identity on objects, we will denote $Q(A)$ simply by $A$. The natural transformation $\xi$ provides, for every object $A$ of $\mathcal{K}^+(\mathcal{A})$, a morphism

$$\xi(A) : F(A) \longrightarrow RF(A)$$

such that, for every morphism $f \in \text{Hom}_{\mathcal{K}^+(\mathcal{A})}(A, B)$, the diagram

$$\begin{array}{ccc}
F(A) & \xrightarrow{F(f)} & F(B) \\
\downarrow{\xi(A)} & & \downarrow{\xi(B)} \\
RF(A) & \xrightarrow{RF(f)} & RF(B)
\end{array}$$
commutes in $\mathcal{D}^+(\mathcal{B})$. If $G$ is a functor as in the definition, provided with a natural transformation $\zeta$, then for every object $A$ of $\mathcal{K}^+(\mathcal{A})$ there is also a morphism
\[ \zeta(A): F(A) \to G(A) \]
such that, for every morphism $f \in \text{Hom}_{\mathcal{K}^+(\mathcal{A})}(A, B)$, the diagram
\[
\begin{array}{ccc}
F(A) & \xrightarrow{F(f)} & F(B) \\
\downarrow{\zeta(A)} & & \downarrow{\zeta(B)} \\
G(A) & \xrightarrow{G(f)} & G(B)
\end{array}
\]
commutes in $\mathcal{D}^+(\mathcal{B})$. The universality of $RF$ means that there exist morphisms
\[ \eta(A): RF(A) \to G(A) \quad \text{for each} \quad A \in \text{Ob}(\mathcal{D}^+(\mathcal{A})) = \text{Ob}(\mathcal{K}^+(\mathcal{A})), \]
such that the equality $\eta(A) \circ \xi(A) = \zeta(A)$ holds. This $\eta$ is a natural transformation: for every morphism $f$ as above the equality $G(f) \circ \eta(A) = \eta(B) \circ RF(f)$ holds.

**Remark A.76.**

i) Similarly, there is a notion of bounded derived functor $RF: \mathcal{D}^b(\mathcal{A}) \to \mathcal{D}^b(\mathcal{B})$.

ii) The definition of right derived functor of a contravariant functor is the same as above, thinking of a contravariant functor as a covariant functor from the opposite category.

iii) The definition of the left derived functor $LF$ is similar, with the direction of the natural transformations $\xi$ and $\eta$ reversed.

From the total right derived functor we define the cohomological derived functors.

**Definition A.77.** Let $F: \mathcal{A} \to \mathcal{B}$ be an additive functor between abelian categories. Denote also by $F: \mathcal{K}^+(\mathcal{A}) \to \mathcal{K}^+(\mathcal{B})$ the extension to the homotopy category. If the total derived functor $RF$ exists, then the cohomological derived functors $R^n F$ are defined, for each $n \in \mathbb{Z}$, as the composition
\[
\mathcal{A} \to \mathcal{D}^+(\mathcal{A}) \xrightarrow{RF} \mathcal{D}^+(\mathcal{B}) \xrightarrow{[n]} \mathcal{D}^+(\mathcal{B}) \xrightarrow{\text{H}^n} \mathcal{B}.
\]
In other words, for each object $A$ of $\mathcal{A}$, the object $R^n F(A)$ of $\mathcal{B}$ is the cohomology in degree $n$ of the complex $RF(A)$.

**A.4.2. Categories with enough injectives.** The standard situation in which one can show the existence of the right derived functor is when $F: \mathcal{A} \to \mathcal{B}$ is a left exact additive functor and the category $\mathcal{A}$ has enough injectives.

**Definition A.78.** Let $\mathcal{A}$ be an abelian category. An object $I$ of $\mathcal{A}$ is called injective if, for each monomorphism $f: A \to B$ and each morphism $\alpha: A \to I$, there exists a morphism $\beta: B \to I$ satisfying $\alpha = \beta \circ f$. In other words, the map
\[ \text{Hom}(B, I) \to \text{Hom}(A, I) \]
given by precomposition with $f$ is surjective.

Injective objects satisfy the following properties:

**Lemma A.79.** Let $\mathcal{A}$ be an abelian category and $I$ an injective object of $\mathcal{A}$.
i) The functor $\text{Hom}(-, I)$ is exact.

ii) Every short exact sequence $0 \to I \to E \to A \to 0$ is split.

iii) For every object $A \in \text{Ob}(\mathcal{A})$ and every integer $n \geq 1$, the Yoneda extension group $\text{Ext}^n(A, I)$ vanishes.

Proof. The first statement is just a reformulation of the definition because $\text{Hom}(-, I)$ is always left exact. Let now

$$0 \to I \to E \to A \to 0$$

be a short exact sequence. By the definition of injective object, there is a morphism $E \to I$ making the diagram

$$\begin{array}{ccc}
0 & \to & I \\
& & \downarrow \\
& & E
\end{array}$$

commutative. This precisely means that the sequence is split.

The third statement follows from the first one and Lemma A.46 or from the second statement using the connection morphism. □

Lemma A.80. Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories and let $F: \mathcal{A} \to \mathcal{B}$ be a functor that has an exact left adjoint functor, i.e. such that there exists an exact functor $G: \mathcal{B} \to \mathcal{A}$ and natural isomorphisms

$$\text{Hom}_\mathcal{A}(G(-), -) \simeq \text{Hom}_\mathcal{B}(-, F(-)).$$

Then $F$ preserves injective objects.

Proof. Let $I$ be an injective object of $\mathcal{A}$ and let $f: A \to B$ be a monomorphism in $\mathcal{B}$. Consider the commutative diagram

$$\begin{array}{ccc}
\text{Hom}_\mathcal{A}(G(B), I) & \longrightarrow & \text{Hom}_\mathcal{A}(G(A), I) \\
\downarrow \cong & & \downarrow \cong \\
\text{Hom}_\mathcal{B}(B, F(I)) & \longrightarrow & \text{Hom}_\mathcal{B}(A, F(I)).
\end{array}$$

Since $G$ is exact, $G(f): G(A) \to G(B)$ is a monomorphism and, the object $I$ being injective, the top horizontal arrow is surjective. Hence, so is the bottom one, which means by definition that $F(I)$ is injective. □

Intuitively, on an abelian category that only contains injective objects any additive functor would be exact, since any short exact sequence would be split and additive functors preserve direct sums. The idea to correct the lack of exactness of a functor is then to replace any object with an injective one.

Definition A.81. An abelian category $\mathcal{A}$ is said to have enough injectives if, for each object $A$ of $\mathcal{A}$, there is an injective object $I$ and a monomorphism $A \to I$.

Example A.82. The injective objects of the category of abelian groups are the divisible abelian groups, i.e. the groups $I$ such that, for each $x \in I$ and each $n \geq 1$, there exists an element $y \in I$ satisfying $ny = x$. For example, the group $I = \mathbb{Q}/\mathbb{Z}$ is
divisible. The category $\text{Mod}_R$ of left modules over a ring $R$ has enough injectives. Indeed, every right $R$-module $N$ is a quotient of the free right $R$-module $R^N = \bigoplus_{m \in N} [m]R$ with basis the elements of $N$. Applying the functor $\text{Hom}_{\text{Ab}}(-, \mathbb{Q}/\mathbb{Z})$, we find that every left $R$-module $M$ embeds into the module $\text{Hom}_{\text{Ab}}(R, I)$, where $I$ is a product of $\mathbb{Q}/\mathbb{Z}$ indexed by the set $\text{Hom}_R(M, \text{Hom}_{\text{Ab}}(M, \mathbb{Q}/\mathbb{Z}))$. By Exercise A.97, the abelian group $I$ is injective. Finally, since the forgetful functor from $\text{Mod}_R$ to $\text{Ab}$ is exact and left adjoint to the functor $\text{Hom}_{\text{Ab}}(R, -)$ from $\text{Ab}$ to $\text{Mod}_R$, it follows from Lemma A.80 that $\text{Hom}_{\text{Ab}}(R, I)$ is an injective left $R$-module.

This example suggests that it might not be possible to find a monomorphism into an injective object if one imposes some finiteness conditions on the objects. Indeed, the subcategory of $\text{Mod}_R$ consisting of finitely generated left $R$-modules does not have enough injectives in general. For example, there are no finitely generated divisible abelian groups.

A.4.3. Existence of derived functors in the presence of enough injectives.

Let $A$ be an abelian category with enough injectives and let $I$ be the full subcategory of $A$ consisting of injective objects of $A$.

**Theorem A.83.** The natural functor

$$K^+(I) \longrightarrow D^+(A)$$

is an equivalence of categories.

This is proved for instance in [GM03, Thm. III.2.21]. The ingredients of the proof are as follows. If $A^*$ is a bounded below cochain complex, then there exists a bounded below complex $I^*$ of injective objects and a quasi-isomorphism $A^* \rightarrow I^*$. Any such complex $I^*$ is called an injective resolution of $A^*$. This implies that the above map is essentially surjective. An arrow $f: A^* \rightarrow B^*$ in $C^+(A)$ can always be completed to a diagram

$$A^* \longrightarrow B^*$$

$$\downarrow \quad \downarrow$$

$$I^*_A \longrightarrow I^*_B,$$

where $I^*_A$ (resp. $I^*_B$) is an injective resolution of $A$ (resp. $B$). Moreover, if $f: A^* \rightarrow I^*$ and $g: A^* \rightarrow J^*$ are two quasi-isomorphisms, then there is a third bounded below complex $K^*$ of injective objects and quasi-isomorphisms $\psi: I^* \rightarrow K^*$, $\phi: J^* \rightarrow K^*$. Finally, if $I^*_A \rightarrow I^*_B$ is a quasi-isomorphism between elements of $K^+(I)$ then it is already an isomorphism. These properties are the ingredients to prove that the map in Theorem A.83 is fully faithful.

**Proposition A.84.** Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories, and let $F: \mathcal{A} \rightarrow \mathcal{B}$ be a left exact functor. Assume that $\mathcal{A}$ has enough injectives. Then the composition

$$D^+(\mathcal{A}) \rightarrow K^+(I) \xrightarrow{F} K^+(\mathcal{B}) \xrightarrow{Q} D^+(\mathcal{B}),$$

where the first arrow is a quasi-inverse of the equivalence of Theorem A.83, satisfies the universal property of Definition A.75, and hence it is the total derived functor of $F$. In concrete terms, $RF$ can be computed as

$$RF(A^*) = F(I^*),$$
where $I^*$ is any injective resolution of $A^*$.

**Proof.** Let $G: D^+(A) \to D^+(B)$ be a functor such that there is a natural transformation $Q \circ F \to G \circ Q$. For any injective resolution $A^* \to I^*$, we obtain a map $RF(A^*) \to G(I^*)$ as the composition

$$RF(A^*) = F(I^*) \to G(I^*) \to G(A^*),$$

where the last map is the result of applying the functor $G$ to the inverse of the isomorphism $A^* \to I^*$ in $D^+(A)$. Then one verifies that this composition is independent of the choice of the resolution and that it provides a natural transformation $RF \to G$ satisfying the required properties. \hfill \square

It follows from Proposition A.84 that the cohomological derived functors $R^nF: A \to B$ of Definition A.77 are given by

$$R^nF(A) = H^n(F(I^*)),\]$$

for any injective resolution $I^*$ of an object $A$ of $A$.

Note that the cohomological derived functors $R^nF: A \to B$ form a cohomological $\delta$-functor in the sense of Definition A.30.

**Lemma A.85.** Let $A$ and $B$ be abelian categories, and let $F: A \to B$ be a left exact functor. Assume that $A$ has enough injectives.

i) For each object $A$ of $A$, the equality $F(A) = R^0F(A)$ holds.

ii) For each injective object $I$, the vanishing $R^nF(I) = 0$ holds for all $n \geq 1$.

**Proof.** Exercise A.96. \hfill \square

**A.4.4. Yoneda extensions and higher derived functors.**

**Example A.86.** Let $A$ be an abelian category with enough injectives. Then the Yoneda extension groups can be also constructed as the higher derived functors of the functor $\text{Hom}$. More precisely, given an object $A \in \text{Ob}(A)$ the functor $\text{Hom}(A, -)$ is left exact (Exercise A.41) and, for any other object $B$, there are functorial isomorphisms

$$\text{Ext}^n(A, B) \cong R^n\text{Hom}(A, B).$$

For ease of notation, we write $R^n\text{Hom}(A, -)(B) = R^n\text{Hom}(A, B)$. This is unambiguous in view of the equality

$$R^n\text{Hom}(A, -)(B) = R^n\text{Hom}(-, B)(A).$$

We prove the claim. By definition and Lemma A.85 i), the equalities

$$\text{Ext}^0(A, B) = \text{Hom}(A, B) = R^0\text{Hom}(A, B)$$

holds, hence the claim for $n = 0$. Assume by induction that there are functorial isomorphisms

$$\text{Ext}^m(A, B) \cong R^m\text{Hom}(A, B)$$

for all $m < n$. Let

$$0 \to B \to I \to C \to 0$$
be a short exact sequence with $I$ injective. By induction, there is a commutative diagram with exact rows
\[
\begin{array}{c}
\Ext^{n-1}(A, I) \longrightarrow \Ext^{n-1}(A, C) \overset{\partial}{\longrightarrow} \Ext^n(A, B) \longrightarrow 0 \\
\mathbb{R}^{n-1}\Hom(A, I) \longrightarrow \mathbb{R}^{n-1}\Hom(A, C) \overset{\partial}{\longrightarrow} \mathbb{R}^n\Hom(A, B) \longrightarrow 0
\end{array}
\]
Since all the vertical arrows are isomorphisms, there is a unique isomorphism $\Ext^n(A, B) \xrightarrow{\sim} \mathbb{R}^n\Hom(A, B)$ making the diagram commutative. It is easy to show that this isomorphism is independent of the chosen exact sequence and is functorial.

In the previous example we have interpreted the Yoneda extension groups as the derived functors of the Hom functor. But there is another interpretation as the Hom functor in the derived category.

**Proposition A.87.** Let $A$ be an abelian category, and let $A$ and $B$ be objects of $A$. We see $A$ and $B$ as objects in $D^+(A)$ concentrated in degree zero. For each $n \geq 0$, there are functorial isomorphisms
\[
\Ext^n(A, B) \xrightarrow{\sim} \Hom_{D^+(A)}(A, B[n]).
\]
**Proof.** We start by constructing the map. Let
\[
E: 0 \longrightarrow B \xrightarrow{i} C_{n-1} \longrightarrow \cdots \longrightarrow C_0 \xrightarrow{\pi} A \longrightarrow 0
\]
be a degree $n$ extension of $A$ by $B$. Let $C^*$ be the complex obtained from $E$ by deleting $A$ and putting $C_i$ in degree $-i$, so that $B$ sits in degree $-n$. The map $C_0 \rightarrow A$ induces a morphisms of complexes $C^* \rightarrow A$, which by the exactness of $E$ is a quasi-isomorphism. The identity of $B$ also defines a morphism of complexes $C^* \rightarrow B[n]$. To the extension $E$ it corresponds the morphism in the derived category
\[
\begin{array}{c}

\begin{tikzpicture}
\node (A) at (0,0) {$A$};
\node (B) at (2,0) {$B[n]$};
\node (C) at (1,1) {$C^*$};
\draw[->] (A) -- (C);
\draw[->] (B) -- (C);
\end{tikzpicture}
\end{array}
\]
(A.88)

Conversely, assume there is a morphism in $\Hom_{D^+(A)}(A, B[n])$ represented by a diagram like (A.88) with $(C^*, d)$ a complex quasi-isomorphic to $A$. We write
\[
\begin{align*}
C_0' &= \ker(d^0: C^0 \rightarrow C^1), \\
C_i' &= C^{-i}, \quad i = 1, \ldots, n-1 \\
B' &= C^{-n} / \text{Im}(d^{n-1}).
\end{align*}
\]
We obtain an extension $E' \in \Ext^n(A, B')$ and a map $B' \rightarrow B$. By the functoriality of Yoneda extensions we deduce an extension $E \in \Ext^n(A, B)$.

The following facts are left as an exercise:

i) Two equivalent extensions give rise to the same morphism in the derived category.

ii) Two representations of the same morphism in the derived category define the same class of extensions.

iii) The two constructions are inverse of each other.
A.4.5. Projective objects. The dual notion of injective object is that of projective object. Most of the discussion in the previous sections explaining how to compute right derived functors using injective objects carries through and allows us to compute left derived functors using projective objects.

Definition A.89. Let $\mathcal{A}$ be an abelian category. An object $P$ of $\mathcal{A}$ is called projective if, for each epimorphism $f : B \to A$ and each morphism $\alpha : P \to A$, there exists a morphism $\beta : P \to B$ satisfying $\alpha = f \circ \beta$. In other words, the map

$$\text{Hom}(P, B) \to \text{Hom}(P, A)$$

given by postcomposition with $f$ is surjective.

The dual of Lemma A.79 is the next result, whose proof is left to the reader.

Lemma A.90. Let $\mathcal{A}$ be an abelian category and $P$ a projective object of $\mathcal{A}$.

i) The functor $\text{Hom}(P, -)$ is exact.

ii) Every short exact sequence $0 \to A \to E \to P \to 0$ is split.

iii) For every object $A \in \text{Ob}(\mathcal{A})$ and every integer $n \geq 1$, the Yoneda extension group $\text{Ext}^n(P, A)$ vanishes.

There is also the notion of having enough projectives.

Definition A.91. An abelian category $\mathcal{A}$ is said to have enough projectives if, for each object $A$ of $\mathcal{A}$, there is a projective object $P$ and an epimorphism $P \to A$.

Example A.92. By Exercise A.99, if $R$ is a ring, then the category $	ext{Mod}_R$ has enough projectives.

Let $\mathcal{A}$ be an abelian category with enough projectives and $\mathcal{P}$ the full subcategory of $\mathcal{A}$ consisting of projective objects. Dually to Theorem A.83, we have:

Theorem A.93. The natural functor

$$\mathcal{K}^+(\mathcal{P}) \to \mathcal{D}^+(\mathcal{A})$$

is an equivalence of categories.

If $A^*$ is a bounded below complex on an abelian category $\mathcal{A}$, a projective resolution of $A^*$ is a bounded complex $P^*$ consisting of projective objects, together with a quasi-isomorphism $P^* \to A^*$. As in the case when the category has enough injectives, the main ingredient of the proof of Theorem A.93 is that, if $\mathcal{A}$ has enough projectives, then projective resolutions always exist. By the dual argument of the proof of Proposition A.84, we then deduce the following.

Corollary A.94. Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories, and let $F : \mathcal{A} \to \mathcal{B}$ be a right exact functor. Assume that $\mathcal{A}$ has enough projectives. Then the total left derived functor $LF$ of $F$ can be computed as

$$LF(A^*) = F(P^*),$$

where $P^*$ is any projective resolution of $A^*$.
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Remark A.95. The data of a contravariant functor \( F: \mathcal{A} \to \mathcal{B} \) is equivalent to the data of a covariant functor \( F^{\text{op}}: \mathcal{A}^{\text{op}} \to \mathcal{B} \). A contravariant functor is left (resp. right) exact if and only if \( F^{\text{op}} \) is. An injective object of \( \mathcal{A} \) is the same as a projective object of \( \mathcal{A}^{\text{op}} \) and vice versa. Therefore the right derived functors of a left exact contravariant functor are computed using projective resolutions, whereas the left derived functors of a right exact contravariant functor are computed using injective resolutions. See Exercise A.100 for an example.

⋆ ⋆ ⋆

Exercise A.96. Prove Lemma A.85.

Exercise A.97. Let \( \mathcal{A} \) be an abelian category that admits arbitrary products and let \((I_\alpha)\) be a family of injective objects of \( \mathcal{A} \). Show that the product \( \prod_\alpha I_\alpha \) is injective as well.

Exercise A.98. Fill the details in the proof of Proposition A.87.

Exercise A.99. Let \( R \) be a ring and let \( \text{Mod}_R \) be the category of left \( R \)-modules. Show that an object \( P \) of \( \text{Mod}_R \) is projective if and only if it is a direct summand of a free \( R \)-module. Conclude that the category \( \text{Mod}_R \) has enough projectives.

Exercise A.100. Let \( \mathcal{A} \) be a category with enough injectives and projectives. For any object \( A \in \mathcal{A} \), the functor \( \text{Hom}_\mathcal{A}(A, -) \) is a left exact covariant functor, while \( \text{Hom}_\mathcal{A}(-, A) \) is a left exact contravariant functor. Therefore, the symbol \( R^n \text{Hom}(A, B) \) may, in principle, be ambiguous. Your task in this exercise is to show that there is no such ambiguity. Prove that there is are canonical isomorphisms

\[
R^n \text{Hom}(-, B)(A) \xrightarrow{\cong} R^n \text{Hom}(A, -)(B),
\]

where the right hand side is computed using an injective resolution of \( B \) and the left a projective resolution of \( A \).

A.5. \textit{t-structures}. There are many natural situations in which we are able to construct a triangulated category but we would like to obtain an abelian category instead. In their work on perverse sheaves \([BBD82]\), Beilinson, Bernstein, and Deligne introduced the notion of \textit{t-structure} as a way of extracting an abelian category from a triangulated category. This is precisely how the abelian category of mixed Tate motives over a number field is constructed in Section 4.3.

A.5.1. \textit{t-structures and their hearts}.

Definition A.101 (Beilinson-Bernstein-Deligne). Let \( \mathcal{T} \) be a triangulated category. A \textit{t-structure} on \( \mathcal{T} \) is a pair of \textit{strictly full} (that is, full and closed under isomorphism) subcategories

\[
(\mathcal{T}^{\leq 0}, \mathcal{T}^{\geq 0})
\]
such that, defining for each integer \( n \) the subcategories

\[
\mathcal{T}^{\leq n} = \mathcal{T}^{\leq 0}[-n], \quad \mathcal{T}^{\geq n} = \mathcal{T}^{\geq 0}[-n]
\]
of \( \mathcal{T} \), the following three conditions hold:

i) \( \mathcal{T}^{\leq -1} \subseteq \mathcal{T}^{\leq 0} \) and \( \mathcal{T}^{\geq 1} \subseteq \mathcal{T}^{\geq 0} \).

ii) (Orthogonality) If \( X \in \mathcal{T}^{\leq 0} \) and \( Y \in \mathcal{T}^{\geq 1} \), then \( \text{Hom}_{\mathcal{T}}(X, Y) = 0 \).
iii) Each object $X$ of $\mathcal{T}$ fits into a distinguished triangle

\[(A.102)\quad Y \rightarrow X \rightarrow Z \rightarrow Y[1]\]

with $Y \in \mathcal{T}^{\leq 0}$ and $Z \in \mathcal{T}^{\geq 1}$.

We say that the $t$-structure is non-degenerate if, in addition to the previous axioms, the intersections $\cap_{n \in \mathbb{Z}} \mathcal{T}^{\leq n}$ and $\cap_{n \in \mathbb{Z}} \mathcal{T}^{\geq n}$ are reduced to zero.

**Definition A.103.** The heart of a $t$-structure is the full subcategory

\[\mathcal{T}^0 = \mathcal{T}^{\leq 0} \cap \mathcal{T}^{\geq 0}.\]

A functor $F: \mathcal{T}_1 \rightarrow \mathcal{T}_2$ of triangulated categories endowed with $t$-structures is said to be $t$-exact whenever $F(\mathcal{T}_1^{\leq 0}) \subseteq \mathcal{T}_2^{\leq 0}$ and $F(\mathcal{T}_1^{\geq 0}) \subseteq \mathcal{T}_2^{\geq 0}$, and hence $F$ restricts to a functor between the hearts.

Note that the objects $Y$ and $Z$ in the triangle (A.102) are not a priori required to be unique. However, this follows from the other axioms:

**Lemma A.104 ([BBD82, Prop. 1.3.3]).** Let $\mathcal{T}$ be a triangulated category endowed with a $t$-structure.

i) The inclusion of $\mathcal{T}^{\leq n}$ into $\mathcal{T}$ admits a right adjoint

\[t_{\leq n}: \mathcal{T} \rightarrow \mathcal{T}^{\leq n}\]

and the inclusion $\mathcal{T}^{\geq n}$ into $\mathcal{T}$ admits a left adjoint

\[t_{\geq n}: \mathcal{T} \rightarrow \mathcal{T}^{\geq n}.\]

ii) For each object $X$ in $\mathcal{T}$, there exists a unique morphism

\[w \in \text{Hom}_\mathcal{T}(t_{\geq 1}X, t_{\leq 0}X[1])\]

such that the following is a distinguished triangle:

\[t_{\leq 0}X \rightarrow X \rightarrow t_{\geq 1}X \xrightarrow{w} t_{\leq 0}X[1].\]

Up to unique isomorphism, this triangle is the only one satisfying condition iii) in Definition A.101.

Moreover, if $a \preceq b$, there is a unique isomorphism

\[(A.105)\quad t_{a\leq b}X \xrightarrow{\sim} t_{b\geq a}X.\]

The standard example of $t$-structure is the following:

**Example A.106.** Let $\mathcal{A}$ be an abelian category. Recall from Section A.3 that the bounded below derived category $D^+(\mathcal{A})$ is a triangulated category. It comes together with a canonical $t$-structure which measures how far a complex is from having its cohomology concentrated in degree zero. Precisely, for each integer $n$, one considers the full subcategories

\[\mathcal{T}^{\leq n} = \{ C^* \in D^b(\mathcal{A}) \mid H^m(C^*) = 0 \text{ for all } m > n \}, \]

\[\mathcal{T}^{\geq n} = \{ C^* \in D^b(\mathcal{A}) \mid H^m(C^*) = 0 \text{ for all } m < n \}.\]

It is easy to check that the pair $(\mathcal{T}^{\leq 0}, \mathcal{T}^{\leq 0})$ satisfies the axioms i) to iii) from Definition A.101. Moreover, this $t$-structure is non-degenerate. To make the functors
from Lemma A.104 explicit, we consider the canonical truncations

\[
(\tau_{\leq n} C)^p = \begin{cases} 
C^p, & \text{if } p < n, \\
\text{Ker}(d), & \text{if } p = n, \\
0, & \text{if } p > n.
\end{cases}
\]

\[
(\tau_{\geq n} C)^p = \begin{cases} 
0, & \text{if } p < n, \\
C^p / \text{Im}(d), & \text{if } p = n, \\
C^p, & \text{if } p > n.
\end{cases}
\]

The canonical truncations are functorial and satisfy

\[
H^p(\tau_{\geq n} C) = \begin{cases} 
H^p(C), & \text{if } p \geq n, \\
0, & \text{if } p > n,
\end{cases}
\]

\[
H^p(\tau_{\leq n} C) = \begin{cases} 
0, & \text{if } p < n, \\
H^p(C), & \text{if } p \geq n.
\end{cases}
\]

In this case, the functors \( t_{\leq n} \) and \( t_{\geq n} \) are given by the canonical truncations, namely

\[ t_{\leq n} C = \tau_{\leq n} C, \quad t_{\geq n} C = \tau_{\geq n} C. \]

It follows that

\[ t_{\leq 0} t_{\geq 0} (C[n]) = H^n(C). \]

Viewing an object of \( A \) as a complex concentrated in degree zero, one gets an equivalence of categories from \( A \) to the heart of this \( t \)-structure on \( D^b(A) \).

We now copy two definitions from [BBD82, §1.2].

**Definition A.107.** Let \( \mathcal{T} \) be a triangulated category and let \( \mathcal{A} \) be a subcategory of \( \mathcal{T} \). Given objects \( X, Y, Z \) of \( \mathcal{T} \), we say that \( Y \) is an extension of \( Z \) by \( X \) if there exists a distinguished triangle

\[ X \rightarrow Y \rightarrow Z \rightarrow X[1]. \]

We say that \( \mathcal{A} \) is stable under extensions if, whenever \( X \) and \( Z \) are objects of \( \mathcal{A} \) and \( Y \) is an extension of \( Z \) by \( X \), then \( Y \) lies in \( \mathcal{A} \) as well.

**Definition A.108.** Let \( \mathcal{T} \) be as above and let \( \mathcal{A} \) be a full abelian subcategory of \( \mathcal{T} \). We say that \( \mathcal{A} \) is admissible if it satisfies the following conditions.

i) Given any two objects \( X, Y \) of \( \mathcal{A} \) and any integer \( i < 0 \),

\[ \text{Hom}_\mathcal{T}(X, Y[i]) = 0. \]

ii) A sequence

\[ 0 \rightarrow B \overset{u}{\rightarrow} C \overset{\nu}{\rightarrow} A \rightarrow 0 \]

is a short exact sequence in \( \mathcal{A} \) if and only if there exists a distinguished triangle in \( \mathcal{T} \)

\[ B \overset{\pi}{\rightarrow} C \overset{\nu}{\rightarrow} A \overset{\omega}{\rightarrow} B[1]. \]

**Remark A.110.** The definition presented in [BBD82, 1.2.5] is apparently weaker than the above Definition A.108, as it only demands that every short exact sequence \( B \rightarrow C \rightarrow A \) can be extended to a distinguished triangle. Nevertheless, it follows from Propositions 1.2.2 and 1.2.4 of loc. cit. that both definitions are equivalent. In [Lev93] the definition of admissible subcategory only includes statement ii) and not condition i). In any case, if a subcategory satisfies A.108 it is also admissible in the sense of [Lev93].
Remark A.111. The fact that \( \mathcal{A} \) is a full subcategory implies that the extension (A.109) to a distinguished triangle is unique. Indeed, it follows from axiom (T3) in the definition of triangulated categories that, given two extensions as in (A.109), the identity maps \( B \to B \) and \( C \to C \) can be completed to a morphism of triangles

\[
\begin{array}{ccc}
B & \to & C \\
\uparrow & & \uparrow \\
B & \to & C
\end{array}
\quad
\begin{array}{ccc}
A & \to & B[1] \\
\downarrow & & \downarrow \\
A & \to & B[1]
\end{array}
\]

in \( \mathcal{T} \). In particular, \( w = w' \circ h \) and uniqueness amounts to proving that \( h \) is the identity. Since \( \mathcal{A} \) is a full subcategory, \( h: A \to A \) is a morphism in \( \mathcal{A} \) such that \( h \circ v = v \). Since \( v \) is an epimorphism, we deduce that \( h = \text{Id}_A \).

The following theorem is proved in [BBD82, Thm. 1.3.6]:

**Theorem A.112 (Beilinson-Bernstein-Deligne).** The heart of a \( t \)-structure on a triangulated category is a full admissible abelian subcategory, stable under extensions.

Remark A.113. It is not true, however, that \( \mathcal{T} \) is equivalent, as triangulated category, to the derived category of the heart of a \( t \)-structure (see Exercise A.118).

Definition A.114. Let \( n \) be an integer. The \( n \)-th cohomology of \( X \in \mathcal{T} \) with respect to the \( t \)-structure is the following object of the heart:

\[
\text{(A.115)} \quad h^n(X) = t_{\leq 0} t_{\geq 0} (X[n]) \in \mathcal{T}^0.
\]

By [BBD82, Thm. 1.3.6], the functor \( h^0 \) is a cohomological functor. Recall from Definition A.56 that this means that a distinguished triangle \( X \to Y \to Z \to X[1] \) induces a long exact sequence

\[
\cdots \to h^n(X) \to h^n(Y) \to h^n(Z) \to h^{n+1}(X) \to \cdots.
\]

A.5.2. **Extensions.** Recall that, in Proposition A.87 we have seen that the extension groups in an abelian category can be interpreted as morphism groups in the derived category. Up to some extent this can be generalized to abelian subcategories of a triangulated category.

Consider a full admissible abelian subcategory \( \mathcal{A} \) of a triangulated category \( \mathcal{T} \). The definition of the map \( \text{Ext}^n(\mathcal{A}, B) \to \text{Hom}_{\mathcal{T}^{+}(\mathcal{A})}(A, B[n]) \) can be adapted to the triangulated category \( \mathcal{T} \).

Let \( 0 \to B \to C \to A \to 0 \) be an extension in \( \mathcal{A} \). By Remark A.111, it extends to a unique distinguished triangle \( B \to C \to A \to B[1] \), yielding a map \( w: A \to B[1] \). Moreover, the same argument shows that two equivalent extensions give rise to the same \( w \). We thus obtain a homomorphism

\[
\varphi_1: \text{Ext}^1_{\mathcal{A}}(A, B) \to \text{Hom}_{\mathcal{T}}(A, B[1]).
\]

More generally, breaking a degree \( n \) extension

\[
0 \to B \to C_{n-1} \to \cdots \to C_0 \to A \to 0
\]

into several short exact sequences gives a morphism \( A \to B[n] \) which only depends on the equivalence class of the extension. For instance, if \( n = 2 \), one associates to
0 \to B \to C_1 \xrightarrow{a} C_0 \xrightarrow{b} A \to 0 \text{ the short exact sequences}

\[
\begin{array}{cccccc}
0 & \longrightarrow & B & \longrightarrow & C_1 & \longrightarrow & \text{Im}(a) & \longrightarrow & 0 \\
\downarrow & & & & & & & & \\
0 & \longrightarrow & \text{Ker}(b) & \longrightarrow & C_0 & \longrightarrow & A & \longrightarrow & 0.
\end{array}
\]

Setting \( D = \text{Im}(a) = \text{Ker}(b) \) and applying \( \varphi_1 \) to the rows of the above diagram, we get maps \( \alpha : D \to B[1] \) and \( \beta : A \to D[1] \). Then we form \( \alpha[1] \circ \beta : A \to B[2] \).

**Proposition A.116.** Let \( T \) be a triangulated category and \( A \) a full admissible abelian subcategory stable under extensions. Then the process we have sketched gives well defined maps

\[ \varphi_n : \text{Ext}^n_A(A, B) \to \text{Hom}_T(A, B[n]), \quad n \geq 0. \]

Moreover \( \varphi_1 \) is an isomorphism and \( \varphi_2 \) is an injection.

**Proof.** See [Lev93, Prop. 1.6]. \( \square \)

***

**Exercise A.117.** Show that the distinguished triangle (A.102) in the definition of \( t \)-structure is uniquely determined by \( X \) up to a unique isomorphism. Thus, it makes sense to write \( Y = X^{\leq 0} \) and \( Z = X^{> 1} \). Moreover, the assignments \( X \mapsto X^{\leq 0} \) and \( X \mapsto X^{> 1} \) determine functors \( t_{\leq 0} \) and \( t_{> 0} \).

**Exercise A.118 (A \( t \)-structure such that the derived category of the heart is not equivalent to the original triangulated category).** Let \( X \) be a connected finite CW-complex and let \( \text{Sh}_\mathbb{Q}(X) \) be the abelian category of sheaves of \( \mathbb{Q} \)-vector spaces on \( X \). Consider the full subcategory

\[ T \subseteq D^b(\text{Sh}_\mathbb{Q}(X)) \]

consisting of complexes of sheaves \( C \) whose cohomology sheaves \( \mathcal{H}^i(C) \) are all constant. Then \( T \) inherits a structure of triangulated category. We define

\[
\begin{align*}
T^{\leq 0} &= \{ C \mid \mathcal{H}^i(C) = 0 \text{ for } i > 0 \}, \\
T^{> 0} &= \{ C \mid \mathcal{H}^i(C) = 0 \text{ for } i < 0 \}.
\end{align*}
\]

i) Show that the pair \((T^{\leq 0}, T^{> 0})\) forms a \( t \)-structure on \( T \) and that its heart is equivalent to the category \( \text{Vec}_\mathbb{Q} \) of finite-dimensional \( \mathbb{Q} \)-vector spaces.

ii) Let \( \underline{\mathbb{Q}}^X \) be the constant sheaf with stalk \( \mathbb{Q} \) on \( X \). Prove the equality

\[ \text{Hom}_T(\underline{\mathbb{Q}}^X, \underline{\mathbb{Q}}^X[n]) = \mathbb{H}^n(X, \mathbb{Q}) \]

for every \( n \geq 0 \). Using the fact that the categories \( D^b(T^0) \) and \( D^b(\text{Vec}_\mathbb{Q}) \) are equivalent, show the vanishing

\[ \text{Hom}_{D^b(T^0)}(\underline{\mathbb{Q}}^X, \underline{\mathbb{Q}}^X[n]) = 0 \]

for each \( n \geq 2 \). Deduce that, as long as there exists some \( n \geq 2 \) such that the cohomology \( \mathbb{H}^n(X, \mathbb{Q}) \) does not vanish, the triangulated category \( T \) is not equivalent to the derived category of the heart of this \( t \)-structure.
Exercise A.119 (Weight structures). Let $\mathcal{T}$ be a triangulated category. After Bondarko [Bon10], a weight structure on $\mathcal{T}$ is a pair of strictly full subcategories $(\mathcal{T}_{w \leq 0}, \mathcal{T}_{w \geq 0})$ such that, defining for each integer $n$ the subcategories $\mathcal{T}_{w \leq n} = \mathcal{T}_{w \leq 0}[n]$, $\mathcal{T}_{w \geq n} = \mathcal{T}_{w \geq 0}[n]$ of $\mathcal{T}$, the following conditions hold:

i) The categories $\mathcal{T}_{w \leq 0}$ and $\mathcal{T}_{w \geq 0}$ are stable under extraction of direct summands.

ii) $\mathcal{T}_{w \leq 0} \subseteq \mathcal{T}_{w \leq 1}$ and $\mathcal{T}_{w \geq 1} \subseteq \mathcal{T}_{w \geq 0}$.

iii) (Orthogonality) If $X \in \mathcal{T}_{w \leq 0}$ and $Y \in \mathcal{T}_{w \geq 1}$, then $\text{Hom}_\mathcal{T}(X, Y) = 0$.

iv) Each object $X$ of $\mathcal{T}$ fits into a distinguished triangle $Y \rightarrow X \rightarrow Z \rightarrow Y[1]$ with $Y \in \mathcal{T}_{w \leq 0}$ and $Z \in \mathcal{T}_{w \geq 1}$.

By analogy with $t$-structures, the heart of a weight structure is the subcategory $\mathcal{T}_{w \leq 0} \cap \mathcal{T}_{w \geq 0}$.

Let $\mathcal{T}$ be the bounded derived category of the abelian category $\text{MHS}$ of mixed Hodge structures. Let $\mathcal{T}_{w \leq 0}$ (resp. $\mathcal{T}_{w \geq 0}$) be the subcategory consisting of complexes $A$ such that the mixed Hodge structure $\text{H}^n(A)$ has weights $\leq n$ (resp. $\geq n$). Show that the pair $(\mathcal{T}_{w \leq 0}, \mathcal{T}_{w \geq 0})$ defines a weight structure and compute its heart.

A.6. Ind and pro-objects in a category. Inductive and projective limits are important operations in category theory. Nevertheless, in many interesting categories such limits may not exist. This is the case of the category of mixed Hodge structures. To remedy this situation, given a category $\mathcal{C}$, one can define categories $\text{Ind}(\mathcal{C})$ and $\text{Pro}(\mathcal{C})$ of inductive and projective systems in $\mathcal{C}$, where inductive or projective limits in $\mathcal{C}$ exist. We give a concise introduction to ind and pro-categories and refer the reader to [KS06, Chap. 6] for more details.

A.6.1. Definitions and first properties. A directed set is a non-empty set $I$ endowed with a partially ordered $\leq$ with the property that, for all elements $a, b \in I$, there exists an element $c$ satisfying $a \leq c$ and $b \leq c$. The notion of filtered category generalizes that of directed set in the following way:

**Definition A.120.** A filtered category $D$ is a category such that

i) There exists at least one object in $D$.

ii) Given objects $a, b \in \text{Ob}(D)$, there exists an object $c$ and morphisms $a \rightarrow c$ and $b \rightarrow c$.

iii) Given morphisms $f_1, f_2: a \rightarrow b$ with the same source and target, there exists a morphism $g: b \rightarrow c$ satisfying $g \circ f_1 = g \circ f_1$.

**Example A.121.** A directed set $I$ gives rise to the filtered category with objects the elements of $I$ and morphisms $\text{Hom}(x, y)$ reduced to a singleton for $x \leq y$ and empty otherwise.

**Definition A.122.** Let $\mathcal{C}$ be a category and let $D$ be a small filtered category.

i) An *inductive system* $X$ in $\mathcal{C}$ indexed by $D$ is a functor $X: D \rightarrow \mathcal{C}$. 


ii) Let $X$ and $Y$ be inductive systems indexed by $D$ and $E$ respectively. A morphism $f$ from $X$ to $Y$ is the data of a functor $f_1: D \to E$ and a natural transformation from $X$ to $Y \circ f_1$.

iii) A projective system $X$ in $C$ indexed by $D$ is a functor $X: D^{\text{op}} \to C$.

iv) If $X$ is a projective system indexed by $D$ and $Y$ is a projective system indexed by $E$, then a morphism $f$ between $X$ and $Y$ is a functor $f_1: D \to E$ and a natural transformation between $X$ and $Y \circ f_1^{\text{op}}$.

An inductive system will be called a directed system if the index category is the category associated with a directed set as in Example A.121.

**Definition A.123.** Let $C$ be a category, $D$ a small filtered category and $X = (X_d)_{d \in D}$ an inductive system indexed by $D$. An inductive limit of this system is a universal solution to the problem: find an object $X_0$ in $C$ together with a morphism of inductive systems $X \to X_0$. Here $X_0$ denotes at the same time the object $X_0$ and the constant inductive system $1 \to X_0$. If $X_0$ is such a universal solution, it is written as

$$X_0 = \lim_{d \in D} X_d.$$

An inductive limit whose index category is a directed set is also called a direct limit.

Let now $X = (X_d)_{d \in D}$ be a projective system. A projective limit of this system in a universal solution to the problem: find an object $X_0$ in $C$ together with a morphism of projective systems $X_0 \to X$. If $X_0$ is such universal solution it is written as

$$X_0 = \lim_{d \in D} X_d.$$

A projective limit whose index category is a directed set is also called an inverse limit.

Inductive limits are also called colimits, while projective limits are also called just limits.

**Remark A.124.** In many cases it is important to know if a functor respects inductive limits. For this it is enough to check if the functor respects direct limits. Similarly, a functor that respects projective limits, also respects projective limits with respect to any small filtered category.

**Definition A.125.** Let $C$ be any category. The ind-category of $C$ is the universal category that “contains” $C$ and is closed under inductive limits. More precisely, is a category $\text{Ind}(C)$ closed under inductive limits, together with a functor $h_I: C \to \text{Ind}(C)$ such that, for any category $A$ closed under inductive limits, with a functor $C \to A$, there exists a unique functor $\text{Ind}(C) \to A$ preserving inductive limits and making the triangle

$$
\begin{array}{ccc}
C & \xrightarrow{h_I} & \text{Ind}(C) \\
& \Downarrow & \\
& A
\end{array}
$$

commutative.

The pro-category of $C$ is a category $\text{Pro}(C)$ closed under projective limits together with a functor $h_P: C \to \text{Pro}(C)$ such that, for any category $A$, closed under
projective limits, with a functor \( C \to A \), there exists a unique functor \( \text{Pro}(C) \to A \) preserving projective limits and making the triangle

\[
\begin{array}{ccc}
C & \xrightarrow{h_P} & \text{Pro}(C) \\
\downarrow & & \downarrow \\
A & & \\
\end{array}
\]

commutative.

We next give a construction of the categories \( \text{Ind}(C) \) and \( \text{Pro}(C) \). For an alternative construction see [KS06, § 6].

**Proposition A.126.** Let \( C \) be a category.

i) The ind-category \( \text{Ind}(C) \) is the category whose objects are inductive systems in \( C \) and whose morphisms are given, for \( X = (X_d)_{d \in D} \) and \( Y = (Y_e)_{e \in E} \), by

\[
\text{Hom}_{\text{Ind}(C)}(X, Y) = \lim_{d \in D} \lim_{e \in E} \text{Hom}_C(X_d, Y_e).
\]

ii) The pro-category \( \text{Pro}(C) \) is the category whose objects are projective systems in \( C \) and whose morphisms are given, for \( X = (X_d)_{d \in D} \) and \( Y = (Y_e)_{e \in E} \), by

\[
\text{Hom}_{\text{Ind}(C)}(X, Y) = \lim_{e \in E} \lim_{d \in D} \text{Hom}_C(X_d, Y_e).
\]

**Remark A.127.** As you will prove in exercise A.141, a morphism of inductive systems in \( C \) induces a morphism in \( \text{Ind}(C) \) and, if they exist, a morphism between the corresponding inductive limits. Moreover, if two morphisms induce the same morphism in \( \text{Ind}(C) \), they also induce the same morphism between inductive limits. Similar result is true for projective systems.

Once we know that the categories \( \text{Ind}(C) \) and \( \text{Pro}(C) \) exist, the first useful property is the following.

**Proposition A.128.** The functors \( h_I \) and \( h_P \) are fully faithful.

**Proof.** Denote by \( C^\wedge \) the category of functors from \( C^{\text{op}} \) to \( \text{Set} \) and by \( C^\vee \) the category of functors from \( C^{\text{op}} \) to \( \text{Set}^{\text{op}} \). There are canonical functors \( h_C : C \to C^\wedge \) and \( k_C : C \to C^\vee \) ([KS06, Def. 1.4.2]). We use now that the category \( C^\wedge \) is closed under inductive limits and the category \( C^\vee \) is closed under projective limits ([KS06, Cor. 2.4.3]). Therefore there are commutative diagrams

\[
\begin{array}{ccc}
C & \xrightarrow{h_I} & \text{Ind}(C) \\
\downarrow & & \downarrow \text{h}_C \\
C^\wedge & & \\
\end{array}, \quad \begin{array}{ccc}
C & \xrightarrow{h_P} & \text{Pro}(C) \\
\downarrow & & \downarrow k_C \\
C^\vee & & \\
\end{array}
\]

Since the functors \( h_C \) and \( k_C \) are fully faithful ([KS06, Cor. 1.4.4]) we deduce that \( h_I \) and \( h_P \) are fully faithful. \( \square \)

**Remark A.129.** In fact, the functors \( \text{Ind}(C) \to C^\wedge \) and \( \text{Pro}(C) \to C^\vee \) are also fully faithful and we can alternatively define \( \text{Ind}(C) \) as a subcategory of \( C^\wedge \) and \( \text{Pro}(C) \) as a subcategory of \( C^\vee \).
One needs to be careful with the fact that the objects in \( \text{Ind}(\mathcal{C}) \) are “formal” limits and not “true” limits; that is, if \( \mathcal{C} \) is already closed under inductive limits, then the functor \( \mathcal{C} \to \text{Ind}(\mathcal{C}) \) does not preserve, in general, inductive limits (see Exercise A.140). In this case, to understand the difference between \( \mathcal{C} \) and \( \text{Ind}(\mathcal{C}) \) is convenient to introduce the notion of compact objects.

**Definition A.130.** Let \( \mathcal{C} \) be a category that admits inductive limits. An object \( X \) of \( \mathcal{C} \) is called **compact** if for every inductive system \( (Y_d)_{d \in D} \) the canonical map

\[
\lim_{d \in D} \text{Hom}(X, Y_d) \to \text{Hom}(X, \lim_{d \in D} Y_d)
\]

is an isomorphism.

Dually, if \( \mathcal{C} \) is a category that admits projective limits, then an object \( X \) of \( \mathcal{C} \) is called **cocompact** if the canonical map

\[
\lim_{d \in D} \text{Hom}(Y_d, X) \to \text{Hom}(\lim_{d \in D} Y_d, X)
\]

is an isomorphism.

The interest of the notion of compact object is the following result, which is proved in [KS06, Cor. 6.3.5].

**Theorem A.131.** Let \( \mathcal{C} \) be a category that admits inductive limits and let \( \mathcal{C}^{\text{cpt}} \) be the full subcategory of compact objects. If every object of \( \mathcal{C} \) is an inductive limit of compact objects, then the composition

\[
\text{Ind}(\mathcal{C}^{\text{cpt}}) \to \text{Ind}(\mathcal{C}) \to \mathcal{C}
\]

is an equivalence of categories. Dually, let \( \mathcal{C} \) be a category that admits projective limits and let \( \mathcal{C}^{\text{ccpt}} \) be the full subcategory of cocompact objects. If every object of \( \mathcal{C} \) is a projective limit of cocompact objects, then the composition

\[
\text{Pro}(\mathcal{C}^{\text{ccpt}}) \to \text{Pro}(\mathcal{C}) \to \mathcal{C}
\]

is an equivalence of categories.

**Example A.132.** In the category \( \text{Vec}_k^{\infty} \) of vector spaces over a field \( k \), the compact objects and the cocompact objects are the finite-dimensional vector spaces. See also Exercise A.142.

A.6.2. **Derived functors via ind-objects.** Passing to the ind-category allows us to construct derived functors even when the original category does not have enough injectives (see, for instance, [Wil00]). In what follows, we explain how this works for the bounded below derived category; a similar construction also applies to the bounded case.

Throughout, \( \mathcal{A} \) denotes a small abelian category. Consider the functor

\[
(-)^+: K^+ (\mathcal{A}) \to \text{Ind}(K^+ (\mathcal{A}))
\]

that with a complex \( C \) associates the complex

\[
C^+ = \lim_{(i, D)} D,
\]

where the inductive limit is taken with respect to the small category in which objects are pairs \( (i, D) \) with \( D \in K^+ (\mathcal{A}) \) and \( i: C \to D \) a quasi-isomorphism, and morphisms from \( (i_1, D_1) \) to \( (i_2, D_2) \) are morphisms \( f: D_1 \to D_2 \) such that the
equality $i_2 = f \circ i_1$ holds in $\mathcal{K}^+(\mathcal{A})$. It follows from the definition that, if $f: E \to C$ is a quasi-isomorphism, then the induced map

$$f^+: E^+ \to C^+$$

is an isomorphism. There is a \textit{tautological} natural transformation $\tau$ from the functor $h_I: \mathcal{K}^+(\mathcal{A}) \to \text{Ind}(\mathcal{K}^+(\mathcal{A}))$ to the functor $(-)^+$. The morphism $\tau_C$ from $h_I(C)$ (the constant system $C$) to $C^+$ is the one induced by the quasi-isomorphism $i$ in the position $(i, D)$. This natural transformation has the property that $\text{Ind}(Q) \circ \tau$ is an isomorphism. Here, $Q$ stands for the localization functor from $\mathcal{K}^+$ to $\mathcal{D}^+$ and $\text{Ind}(Q)$ is the one induced between the ind-categories. In the sequel, we will denote $\text{Ind}(Q)$ simply by $Q$.

An additive functor of abelian categories $F: \mathcal{A} \to \mathcal{B}$ extends to a functor $F: \text{Ind}(\mathcal{K}^+(\mathcal{A})) \to \text{Ind}(\mathcal{K}^+(\mathcal{B}))$.

Since the functor $(-)^+$ inverts quasi-isomorphisms, the composition

$$\mathcal{K}^+(\mathcal{A}) \xrightarrow{(-)^+} \text{Ind}(\mathcal{K}^+(\mathcal{A})) \xrightarrow{F} \text{Ind}(\mathcal{K}^+(\mathcal{B})) \to \text{Ind}(\mathcal{D}^+(\mathcal{B}))$$

factors uniquely through $\mathcal{D}^+(\mathcal{A})$, thus defining a functor

$$RF: \mathcal{D}^+(\mathcal{A}) \to \text{Ind}(\mathcal{D}^+(\mathcal{B}))$$

\textbf{Definition A.133 (Deligne [Del73, Déf. 1.2.1. (iii)]).} The functor $F$ is said to be \textit{right derivable} (in the bounded below derived category) if $RF$ factors through $\mathcal{D}^+(\mathcal{B})$. In this case, the functor

$$RF: \mathcal{D}^+(\mathcal{A}) \to \mathcal{D}^+(\mathcal{B})$$

is called the \textit{total right derived functor}.

\textbf{Remark A.134.} By Proposition A.128, the functor $\mathcal{D}^+(\mathcal{B}) \to \text{Ind}(\mathcal{D}^+(\mathcal{B}))$ is fully faithful. If it exists, the functor $RF: \mathcal{D}^+(\mathcal{A}) \to \mathcal{D}^+(\mathcal{B})$ is hence unique up to a unique isomorphism of functors. As it is customary, we will pretend that it is well defined.

There is also a criterion for existence of the total right derived functor saying that, in order to check that $RF$ factors through a functor to $\mathcal{D}^+(\mathcal{B})$, it suffices to check this property on objects of $\mathcal{A}$ considered as complexes concentrated in degree zero.

\textbf{Proposition A.135 ([Del73, Prop. 1.2.2. (ii)])}. $F$ is right derivable (in the bounded below derived category) if and only if

$$RF(A) \in \text{Ind}(\mathcal{D}^+(\mathcal{B}))$$

lies in $h_I(\mathcal{D}^+(\mathcal{B}))$ for any object $A \in \mathcal{A}$.

The following lemma justifies calling $RF$ the total right derived functor.

\textbf{Lemma A.136.} Let $\mathcal{A}$ and $\mathcal{B}$ be abelian categories. If $F: \mathcal{A} \to \mathcal{B}$ is right derivable as in Definition A.133, then the total right derived functor $RF$ satisfies the universal property of Definition A.75.
Proof. Assume that there is a factorization $RF: \mathcal{D}^+(A) \to \mathcal{D}^+(B)$ as in Definition A.133. We will first show, using the tautological transformation $\tau$ from above, that there is a natural transformation from $Q \circ F$ to $RF \circ Q$. Since $h_I$ is fully faithful, it is enough to construct a natural transformation from $h_I \circ Q \circ F$ to $h_I \circ RF \circ Q$. On the one hand, $h_I$ commutes with any additive functor, and hence $h_I \circ Q \circ F = Q \circ F \circ h_I$. On the other hand, by definition of right derivability, $h_I \circ RF \circ Q = Q \circ F \circ (\cdot)^+$. Therefore, there is a unique natural transformation $\xi: Q \circ F \to RF \circ Q$ satisfying the equality

$$h_I \circ \xi = (Q \circ F) \circ \tau.$$

Assume now that a functor $G: \mathcal{D}^+(A) \to \mathcal{D}^+(B)$ and a natural transformation $\zeta: Q \circ F \to G \circ Q$ are given. We need to construct a natural transformation $\eta: RF \to G$ satisfying

$$\zeta = (\eta \circ Q) \circ \xi. \quad (A.137)$$

We first observe that the natural transformation

$$(G \circ Q) \circ \tau: G \circ Q \circ h_I \to G \circ Q \circ (\cdot)^+$$

is an isomorphism because $Q$ inverts quasi-isomorphisms. Thanks to the identifications $h_I \circ G \circ Q = G \circ Q \circ h_I$ and $h_I \circ RF \circ Q = Q \circ F \circ (\cdot)^+$, we obtain a natural transformation

$$\eta' = (((G \circ Q) \circ \tau)^{-1} \circ (\xi \circ (\cdot)^+): h_I \circ RF \circ Q \to h_I \circ G \circ Q.$$

Using again that $h_I$ is fully faithful, we obtain a natural transformation $\eta'': RF \circ Q \to G \circ Q$. Since $Q$ is a localization functor, this yields a natural transformation $\eta: RF \to G$. We explain this step in more detail. As $Q$ is the identity on objects, for $A \in \mathcal{D}^+(A)$ we define $\eta_A: RF(A) \to G(A)$ as $\eta''_A$. We need to check that, given $f \in \text{Hom}_{\mathcal{D}^+(A)}(A, B)$, the diagram

$$\begin{array}{ccc}
RF(A) & \xrightarrow{RF(f)} & RF(B) \\
\eta_A & \downarrow & \eta_B \\
G(A) & \xrightarrow{G(f)} & G(B)
\end{array} \quad (A.138)$$

commutes. Since morphisms in the derived category are diagrams of the form (A.62), it suffices to check the commutativity of the diagram for morphisms of the form $f = Q(g)$, with $g \in \text{Hom}_{\mathcal{K}^+(A)}(A, B)$, and $f = Q(g)^{-1}$, with $g$ a quasi-isomorphism. In both cases, the commutativity of the diagram (A.138) follows from the commutativity of the corresponding diagram for $g$ and $\eta''$. Finally, it remains to show that $\eta$ is the unique natural transformation satisfying the compatibility condition (A.137). Let now $\eta_0$ be any natural transformation satisfying the compatibility (A.137). We consider the commutative diagram of
Since $h_I$ is fully faithful and $Q$ is a localization functor, $\eta_0$ is univocally determined by $h_I \circ \eta_0 \circ Q$. Since $(G \circ Q) \circ \tau$, and $\xi \circ (-)^+$ are isomorphisms, the natural transformation $h_I \circ \eta_0 \circ Q$ is univocally determined by the diagram. That is,

$$h_I \circ \eta_0 \circ Q = ((G \circ Q) \circ \tau)^{-1} \circ (\xi \circ (-)^+) \circ (\xi \circ (-)^+)^{-1} \circ ((RF \circ Q) \circ \tau).$$

Hence we deduce that $\eta_0$ is unique, which concludes the proof. □

**Example A.139.** Let $k$ be a subfield of $k$. The abelian category $\text{MHS}(k)$ of mixed Hodge structures over $k$ does not have enough injectives. The main reason for this is that, if $H$ is a mixed Hodge structure, then $H_B$ and $H_{dR}$ are finite-dimensional vector spaces (see exercise A.143. We will see in Exercise A.144 that if we consider the functor $\text{Hom}_{\text{MHS}(k)}(H, -)$ to take values in finite-dimensional vector spaces, then it is not right derivable, but if we consider it as taking values in arbitrary vector spaces, then it is right derivable.

***

**Exercise A.140.** In this exercise, we illustrate the fact that, even if a category $\mathcal{C}$ admits inductive limits, $\mathcal{C}$ and $\text{Ind}(\mathcal{C})$ may not be equivalent. Let $\text{Vec}_Q^\infty$ be the category of arbitrary $Q$-vector spaces, not necessarily of finite dimension. Let $V$ be a vector space with a countable basis and write it as

$$V = \lim_{\longrightarrow} W_n$$

with $W_n$ a vector space of dimension $n$. Write also $V_n = V$ for all $n \in \mathbb{N}$. Thus,

$$V = \lim_{\longrightarrow} V_n.$$

Show that the natural map in $\text{Ind}(\text{Vec}_Q^\infty)$

$$(W_n)_{n \in \mathbb{N}} \rightarrow (V_n)_{n \in \mathbb{N}}$$

is not an isomorphism. Conclude that the functor

$$\text{Ind}(\text{Vec}_Q^\infty) \rightarrow \text{Vec}_Q^\infty$$

is not an equivalence of categories.
Exercise A.141. Let \( \mathcal{C} \) be a category.

i) Let \((X_i)_{i \in I}\) and \((Y_j)_{j \in J}\) be inductive systems and \( f \) a morphism of inductive systems. Assume that the inductive limits \( X \) and \( Y \) of the inductive systems exist. Then \( f \) induces a morphism, also denoted \( f \), between \( X \) and \( Y \). Prove that, if \( g \) is an equivalent morphism, then the morphisms induced by \( f \) and \( g \) agree.

ii) Let \((X_i)_{i \in I}\) and \((Y_j)_{j \in J}\) be projective systems and \( f \) a morphism of projective systems. Assume that the projective limits, \( X \) and \( Y \), of the projective systems exist. Then \( f \) induces a morphism, also denoted \( f \), between \( X \) and \( Y \). Prove that, if \( g \) is an equivalent morphism, then the morphisms induced by \( f \) and \( g \) agree.

Exercise A.142. Let \( \text{Vec}_k \) be the category of finite-dimensional vector spaces over \( k \).

i) Prove that, if \( V \) is an ind-vector space, then its dual \( V^\vee \) is a pro-vector space.

ii) If \( f : V \to W \) is a morphism of ind-vector spaces, show that it induces a morphism \( f^\vee \) of pro-vector spaces.

iii) Show that \( \text{Ind}(\text{Vec}_k) \) is equivalent to the category of arbitrary vector spaces \( \text{Vec}_\infty^Q \).

Exercise A.143. Let \( k \) be a subfield of \( \mathbb{C} \). Assume that there is an injective object \( I \in \text{MHS}(k) \) with a monomorphism \( \mathbb{Q}(0) \to I \). For every \( n > 0 \), by considering monomorphisms \( \mathbb{Q}(0) \to E \) with \( E \in \text{Ext}^1_{\text{MHS}(k)}(\mathbb{Q}(-n), \mathbb{Q}(0)) \) a non-split extension, show that \( \text{Gr}^W_{2n} I \neq 0 \). Conclude that \( I \) is not an object of \( \text{MHS}(k) \). Therefore \( \text{MHS}(k) \) does not have enough injectives.

Exercise A.144. Let \( k \) be a subfield of \( \mathbb{C} \) and let \( H \) be a mixed Hodge structure over \( k \). Observe that, for every mixed Hodge structure \( H' \), the abelian group \( \text{Hom}_{\text{MHS}(k)}(H, H') \) has a structure of \( \mathbb{Q} \)-vector space. Moreover, since it is a subspace of \( \text{Hom}_{\text{Vec}_Q}(H_B, H_B') \) it is finite-dimensional. Show that the functor

\[
\text{Hom}_{\text{MHS}(k)}(H, -) : \text{MHS}(k) \to \text{Vec}_Q
\]

is not right derivable, but the functor with the same values

\[
\text{Hom}_{\text{MHS}(k)}(H, -) : \text{MHS}(k) \to \text{Vec}_Q^\infty
\]

is right derivable. Moreover, there is an equality

\[
R^i \text{Hom}_{\text{MHS}(k)}(H, -) = \text{Ext}^i_{\text{MHS}(k)}(H, -).
\]

A.7. Filtrations and spectral sequences.

A.7.1. Basic definitions.

Definition A.145. Let \( \mathcal{A} \) be an abelian category and let \( V \) be an object of \( \mathcal{A} \). A decreasing filtration on \( V \) is a collection of subobjects

\[
V \supseteq \cdots \supseteq F^{p-1}V \supseteq F^pV \supseteq F^{p+1}V \supseteq \cdots \supseteq 0.
\]

This can be seen as a projective system \((F^pV)_p\) or an inductive system \((F^{-p}V)_p\) indexed by the directed set of integers. If the limits exist, we will use the notation

\[
F^\infty V = \lim_{\leftarrow} F^pV, \quad F^{-\infty} V = \lim_{\rightarrow} F^{-p}V.
\]
For instance, if $\mathcal{A}$ is the category of modules over a ring, then 
\[
F^\infty V = \bigcap_p F^p V, \quad F^{-\infty} V = \bigcup_p F^p V.
\]
A filtration is called \textit{separated} if $F^\infty V = 0$ and is called \textit{exhaustive} if $F^{-\infty} V = V$. A decreasing filtration is called \textit{finite} if there are integers $p_1$ and $p_2$ such that $F^{p_1} V = 0$ and $F^{p_2} V = V$. Thus, a finite filtration is separated and exhaustive.

Similarly, an \textit{increasing filtration} on $V$ is a collection of subobjects 
\[
0 \subset \cdots \subset F_{p-1} V \subset F_p V \subset F_{p+1} V \subset \cdots \subset V.
\]
A decreasing filtration $F$ can be made into an increasing filtration by setting 
\[
F_p V = F^{-p} V.
\]

Unless explicitly indicated, all filtrations will be decreasing from now on. We leave to the reader the task of translating from decreasing to increasing filtrations.

If $F$ is a decreasing filtration on an object $V$ and $n \in \mathbb{Z}$, the \textit{shifted} filtration $F[n]$ is defined by 
\[
F[n]^p V = F^{n+p} V.
\]

Let $A = (A^*, d)$ be a cochain complex in $C^+(A)$. A filtration $F$ on $A$ is the data of a filtration $F$ on each $A^n$ that are compatible with the differential in the sense that, for any two integers $n$ and $p$, one has 
\[
d(F^p A^n) \subset F^p A^{n+1}.
\]
A filtered complex is called \textit{strict} if the differential is strict with respect to the filtration. A filtered complex is called \textit{biregular} if, for every $n \in \mathbb{Z}$, the filtration $F$ on the object $A^n$ is finite.

**Definition A.146.** Let $(A, F)$ and $(B, G)$ be filtered complexes. A filtered morphism of complexes $f: A^* \to B^*$ is called a \textit{filtered quasi-isomorphism} if, for every $p$, the induced morphism 
\[
\text{Gr}_F^p A^* \longrightarrow \text{Gr}_G^p B^*
\]
is a quasi-isomorphism.

**Example A.147.** Given a cochain complex $A$, the following biregular filtrations are widely used:

i) The \textit{decreasing bête filtration} $\sigma^{\geq p}$ is given by 
\[
\sigma^{\geq p} A^n = \begin{cases} 
0, & \text{if } n < p, \\
A^n, & \text{if } n \geq p.
\end{cases}
\]
ii) The increasing canonical filtration $\tau_{\leq p}$ is given by
\[
(\tau_{\leq p} A)^n = \begin{cases} 
A^n, & \text{if } n < p, \\
\ker(d), & \text{if } n = p, \\
0, & \text{if } n > p.
\end{cases}
\]

A.7.2. Spectral sequences. A filtration on a complex can be used to construct successive approximations to its cohomology. This process generalizes the long exact sequence associated with a short exact sequence of complexes and will be achieved by means of a tool called spectral sequence.

Let $A$ be an abelian category. For the sake of simplicity, we assume $A$ is the category of modules over a ring, so that we can pick elements of objects of $A$ in the discussion. Let $(A^*, F)$ be a complex in $A$ endowed with a biregular decreasing filtration. For each integer $n$, set $Z_A^n = \ker(d: A^n \to A^{n+1})$. The filtration $F$ induces a filtration
\[
F^p H^n(A) = \text{Im} \left( F^p A^n \cap Z A^n \to Z A^n / d(A^{n-1}) \right)
\]
on cohomology objects. The spectral sequence will allow us to recover the graded object $\text{Gr}^* F H^* (A)$ rather than the total cohomology $H^* (A)$.

The basic idea is to approximate $\text{Gr}^p F H^p (A)$ by first computing the cohomology of the graded complex $\text{Gr}^p A$ and then improving this approximation step by step. The first page of the spectral sequence is the collection of objects
\[
E_1^{p,q} = H^{p+q}(\text{Gr}^p A) = \frac{F^p A^{p+q} \cap d^{-1} (F^{p+1} A^{p+q+1})}{d(F^p A^{p+q}) + F^{p+1} A^{p+q+1}}
\]
for all $(p, q) \in \mathbb{Z}^2$, together with the morphisms
\[
d_1: E_1^{p,q} \to E_1^{p+1,q}
\]
induced by sending the class of $x \in F^p A^{p+q}$ to the class of $dx \in F^{p+1} A^{p+q+1}$ (see Exercise A.162). We picture it as follows:

\[
\begin{array}{ccccccccc}
\vdots & \rightarrow & \bullet & \rightarrow & \bullet & \rightarrow & \bullet & \rightarrow & \bullet \\
\vdots & \rightarrow & \bullet & \rightarrow & E_1^{p,q} & \rightarrow & E_1^{p+1,q} & \rightarrow & \bullet \\
\vdots & \rightarrow & \bullet & \rightarrow & \bullet & \rightarrow & \bullet & \rightarrow & \bullet \\
\end{array}
\]

Figure 23. First page of the spectral sequence

There are two possible sources of inaccuracy in approximating $\text{Gr}^p F H^{p+q}(A)$ by $E_1^{p,q}$. First, we are taking elements $x \in F^p A^{p+q}$ such that $dx$ lies in $F^{p+1} A^{p+q+1}$, while the classes in $\text{Gr}^p F H^{p+q}(A)$ are represented by elements with $dx = 0$. Secondly, we are taking the quotient modulo $d(F^p A^{p+q+1})$, while all coboundaries should be taken into account. Therefore, $\text{Gr}^p F H^{p+q}(A)$ will in general only be a subquotient of $E_1^{p,q}$. The second page of the spectral sequence will be a better
approximation to $\text{Gr}_F^p H^{p+q}(A)$ than the first page. It is defined as the collection of objects

$$E_2^{p,q} = \frac{F^p A^{p+q} \cap d^{-1}(F^{p+2} A^{p+q+1})}{F^p A^{p+q} \cap d(F^{p-1} A^{p+q-1}) + F^{p+1} A^{p+q} \cap d^{-1}(F^{p+2} A^{p+q+1})}$$

for all $(p, q) \in \mathbb{Z}^2$, together with the morphisms

$$d_2: E_2^{p,q} \longrightarrow E_2^{p+2,q-1}$$

induced by $[x] \mapsto [dx]$. We picture it as follows:

![Diagram](image)

**Figure 24.** Second page of the spectral sequence

The errors in the approximation now come from the fact that $d_2 x$ is only required to lie in $F^{p+2} A^{p+q+1}$, rather than being zero, and that we are considering classes modulo $d(F^{p-1} A^{p+q-1})$ instead of all coboundaries. Since $F^{p+2} A^{p+q+1}$ will in general be smaller than $F^{p+1} A^{p+q+1}$ and $F^{p-1} A^{p+q-1}$ bigger than $F^p A^{p+q-1}$, this is a finer approximation to the conditions defining $\text{Gr}_F^p H^{p+q}(A)$. Moreover, there are isomorphisms

$$E_2^{p,q} \simeq \frac{\text{Ker}(d_1: E_1^{p,q} \longrightarrow E_1^{p+1,q})}{\text{Im}(d_1: E_1^{-1,q} \longrightarrow E_1^{p,q})},$$

through which we can identify the second page of the spectral sequence with the cohomology of the first page.

This process can be iterated. Explicitly, for each $r \geq 1$, we define the $r$-th page of the spectral sequence as the collection of objects

$$E_r^{p,q} = \frac{F^p A^{p+q} \cap d^{-1}(F^{p+r} A^{p+q+1})}{F^p A^{p+q} \cap d(F^{p-r+1} A^{p+q-1}) + F^{p+1} A^{p+q} \cap d^{-1}(F^{p+r} A^{p+q+1})}$$

for all $(p, q) \in \mathbb{Z}^2$, together with the differential

$$d_r: E_r^{p,q} \longrightarrow E_r^{p+r,q-r+1}$$

induced by $[x] \mapsto [dx]$. Again, there is an isomorphism

$$E_{r+1}^{p,q} \simeq \frac{\text{Ker}(d_r: E_r^{p,q} \longrightarrow E_r^{p+r,q-r+1})}{\text{Im}(d_r: E_r^{-r,q+r-1} \longrightarrow E_r^{p,q})}$$

This is the outcome of Exercise A.162.
The definition (A.148) makes sense for $r = \infty$ and we obtain

$$E_{\infty}^{p,q} = \frac{F_p \mathcal{A}^{p+q} \cap d^{-1}(\mathcal{A}^{p+q+1})}{F_p \mathcal{A}^{p+q} \cap d(\mathcal{A}^{p+q-1}) + F_{p+1} \mathcal{A}^{p+q} \cap d^{-1}(\mathcal{A}^{p+q+1})}.$$ 

If, for every $n \in \mathbb{Z}$, the filtration $F$ on $A_n$ is separated and exhaustive, then

(A.150) $E_{\infty}^{p,q} = \text{Gr}_F^{p+q}(A).$

**Definition A.151.** Let $(A,F)$ be a filtered complex. We will denote by $E_r^{p,q}$ the elements defined by equation (A.148) and the collection of pages $E_r^{*,*}$ and morphisms $d_r$ will be called the spectral sequence associated with the filtration $F$. If the conditions for equation (A.150) are meet, then we will say that the spectral sequence converges and, for any $r \geq 1$, we will use the notation

$$E_r^{p,q} \rightarrow H^{p+q}(A)$$

to indicate that the spectral sequence converges to the cohomology of $A$. But recall that we only recover the associated graded vector space. If we want to stress the filtration, because the original complex may have more that one filtration, then we will denote the spectral sequence as $E_r^{p,q}$.

If the filtration $F$ is biregular, then for every $p,q \in \mathbb{Z}$ there is an integer $r_0 \geq 1$ such that $E_{r_0}^{p,q} = E_{\infty}^{p,q}$ for all $r \geq r_0$. Therefore, we can compute each $\text{Gr}_F^{p+q}(A)$ with a finite number of steps of the spectral sequence. If there is an $r_0 \geq 1$ that works for all degrees, that is, such that for all $p,q$, the equality $E_{r_0}^{p,q} = E_{\infty}^{p,q}$ holds, we say that the spectral sequence degenerates at the term $E_{r_0}$ or that it degenerates at the $r_0$-th page.

**A.7.3. Degeneracy criteria.** In this section, we discuss several criteria for the degeneration of a spectral sequence.

**Proposition A.152.** Let $(A,F)$ be a filtered complex.

i) If there is an integer $r \geq 1$ such that the page $E_{r}^{*,*}$ is reduced to one row, that is

$$E_r^{p,q} = 0 \text{ for all } q \neq q_0,$$

then the spectral sequence degenerates at the page $E_r^{*,*}$ and there is an identity

$$H^{p+q_0}(A) = E_r^{p,q_0}.$$ 

In this case, we recover the cohomology and not just the associated graded space.

ii) Assume that there is an integer $r_0 \geq 1$ such that the page $E_{r_0}^{*,*}$ is reduced to two rows, that is,

$$E_{r_0}^{p,q} = 0 \text{ for all } q \neq q_0, q_1$$

with $q_0 < q_1$. Write $r = q_1 - q_0 + 1$. Then the spectral sequence degenerates at the page $E_{\max(r_0, r+1)}^{*,*}$, If $r_0 \leq r$, then there is a long exact sequence

$$\cdots \rightarrow H^{p+q_1}(A) \rightarrow E_r^{p,q_1} \xrightarrow{d_r} E_r^{p+r,q_1-r+1} \rightarrow H^{p+q_1+1} \rightarrow E_r^{p+1,q_1} \rightarrow \cdots$$

PROOF. Exercise A.163.
Proposition A.153. Let \((A,F)\) be a biregular filtered complex. If \(d\) is strict with respect to the filtration \(F\) then the spectral sequence \(E_r^{*,*}\) degenerates at the term \(E_1\). In this case, the following holds:

\[
F^pH^n(A) = H^n(F^pA), \quad \text{Gr}_F^pH^n(A) = H^n(\text{Gr}_F^pA).
\]

Proof. Consider the diagram

\[
\begin{array}{ccc}
F^pA^n \cap \ker d & \xrightarrow{f} & E_1^{p,n-p} \\
\downarrow{g} & & \\
F^p\sigma^n \cap d(F^pA^{n-1}) & \xrightarrow{f'} & E_1^{p,n-p}.
\end{array}
\]

If \(x \in F^pA^n\) satisfies that \(dx \in F^{p+1}A^{n+1}\), then by the strictness of \(d\), there is an element \(y \in F^{p+1}A^n\) such that \(dx = dy\). This implies that the map \(f\) in the above diagram is an isomorphism.

If \(x \in F^pA^n\) satisfies that \(x \in \text{Im} \, d\), again by strictness, there is an element \(z \in F^pA^{n-1}\) such that \(x = dz\). This shows that the map \(g\) in the above diagram is an isomorphism.

Since the maps \(f\) and \(g\) are isomorphisms, we deduce that the spectral sequence degenerates at \(E_1\). In particular, being the complex biregular, this implies that

\[
H^n(\text{Gr}_F^pA) = E_1^{p,n-p} = E_1^{\infty,n-p} = \text{Gr}_F^pH^n(A).
\]

The equality \(H^n(F^pA) = F^pH^n(A)\) follows from

\[
dF^pA^{n-1} = dA^{n-1} \cap F^pA^n
\]

that is true by the strictness of \(d\). \(\Box\)

Example A.154. The total complex of a double complex (Definition A.25) comes always equipped with the horizontal bête filtration

\[
\sigma \geq p \, \text{Tot}(A)^n = \bigoplus_{p' \geq p} A^{p',n-p'}.
\]

The corresponding spectral sequence has \(E_1\) term

\[
E_1^{p,q} = H^q(A^{p,*}) \Rightarrow H^{p+q}(A).
\]

Exercise A.156. Let \(k\) be a field and let \(\textbf{FVec}_k\) be the category of filtered \(k\)-vector spaces together with filtered morphisms. This is an additive category.

i) Show that every morphism in \(\textbf{FVec}_k\) has a kernel and a cokernel. More precisely, the kernel of an arrow \(f\) agrees with the kernel computed in \(\textbf{Vec}_k\) together with the induced filtration as a subobject. Similarly, the cokernel agrees with the one computed in \(\textbf{Vec}_k\), together with the induced filtration as a quotient.

ii) Let \(f : (V,F) \to (W,F)\) be a morphism of filtered vector spaces. Show that the arrow \(f\) is strict with respect to \(F\) if and only if the canonical map \(\text{Coim}(f) \to \text{Im}(f)\) is an isomorphism.

iii) Conclude that \(\textbf{FVec}_k\) is not an abelian category.
Exercise A.157. Let \((V, F)\) and \((W, F)\) be objects of an abelian category equipped with a finite increasing filtration. Let \(f: (V, F) \to (W, F)\) be a filtered morphism. Show that, if \(\text{gr}_n^F f: \text{gr}_n^F V \to \text{gr}_n^F W\) is an isomorphism for all \(n\), then \(f\) itself is an isomorphism.

Exercise A.158. Let \(f: (A^*, F) \to (B^*, G)\) be a filtered quasi-isomorphism of complexes. Show that, if the filtrations are biregular, then \(f\) is a quasi-isomorphism. Give an example showing that the biregularity assumption is necessary.

Exercise A.159. Let \(A\) be an abelian category, and let \(f: (A^*, F) \to (B^*, F)\) and \(g: (A^*, F) \to (C^*, F)\) be morphisms of filtered complexes in \(A\). The given filtrations induce a filtration on cone\((f + g)\). Show that, if \(g\) is a filtered quasi-isomorphism then the composition \(B \to B \oplus C \to \text{cone}(f + g)\) is a filtered quasi-isomorphism.

Exercise A.160. Let \(f: (A^*, F) \to (B^*, G)\) be a filtered quasi-isomorphism. Show that \(f\) induces an isomorphism between the spectral sequences of \(F\) and \(G\).

Exercise A.161. Let \(f: F^* \to G^*\) be a morphism of complexes. Show that the following statements are equivalent.

i) \(f\) is a quasi-isomorphism.

ii) \(f\) is a filtered quasi-isomorphism with respect to the increasing canonical filtration \(\tau_\leq\).

iii) \(f\) is a filtered quasi-isomorphism with respect to the decreasing canonical filtration \(\tau_\geq\).

Exercise A.162. Show that, for each \(r \geq 1\), the map \(E_{p,q}^p \to E_{p+r,q-r+1}^p\) given by \([x] \mapsto [dx]\) is well defined and prove equation (A.149).

Exercise A.163. Prove Proposition A.152.

Exercise A.164. In this exercise, we introduce the shifted filtration. Given a filtered complex \((A, F)\), the shifted filtration \(\text{Dec}(F)\) is defined as
\[
\text{Dec}(F)^p A^n = \{ x \in F^{p+n} A^n \mid dx \in F^{p+n+1} A^{n+1} \}.
\]
The notation comes from “filtration décalée” in French.

i) Prove that \((A, \text{Dec}(F))\) is a filtered complex.

ii) Prove that there are isomorphisms compatible with the differentials \(\text{Dec}(F)^p E_{r}^{p,n-p} \to F_{r+1}^{p+n,-p}\).

A.8. Simplicial techniques. A very useful tool in homological algebra is that of simplicial objects. A good reference for simplicial techniques is [GJ09].

A.8.1. Simplicial and cosimplicial objects. We first review the definition of simplicial and cosimplicial objects in a category. Let \(\Delta\) denote the small category whose objects are the finite ordered sets
\[
\Delta_n = \{0, \ldots, n\}, \quad n \geq 0,
\]
and whose morphisms are the non-decreasing maps between the various \(\Delta_n\). Any morphism in \(\Delta\) can be written as a composition of faces \(\delta^i: \Delta_n \to \Delta_{n+1}\), for
\( i = 0, \ldots, n + 1 \), and degeneracies \( \sigma^i : \Delta_{n+1} \to \Delta_n \), for \( i = 0, \ldots, n \), which are defined as follows:

\[
\delta^i(j) = \begin{cases} 
  j, & \text{if } j < i, \\
  j + 1, & \text{if } j \geq i,
\end{cases}
\sigma^i(j) = \begin{cases} 
  j, & \text{if } j \leq i, \\
  j - 1, & \text{if } j > i.
\end{cases}
\]

In other words, the face \( \delta^i \) is the map that skips \( i \), while the degeneracy \( \sigma^i \) is the map that repeats \( i \).

**Definition A.165.** Let \( \mathcal{C} \) be a category. A simplicial (resp. cosimplicial) object in \( \mathcal{C} \) is a functor \( \Delta^{op} \to \mathcal{C} \) (resp. \( \Delta \to \mathcal{C} \)).

Using the above characterization of morphisms in \( \Delta \), simplicial and cosimplicial objects admit a very concrete description. For instance, a cosimplicial object \( X^\bullet \) is a collection \((X^n)_{n \geq 0}\) of objects of \( \mathcal{C} \), each \( X^n \) being the image of \( \Delta_n \) through the functor \( \Delta \to \mathcal{C} \), together with morphisms

\[
\delta^i : X^n \to X^{n+1}, \quad i = 0, \ldots, n + 1
\]
\[
\sigma^i : X^{n+1} \to X^n, \quad i = 0, \ldots, n,
\]
satisfying the commutativity relations

\[
\begin{align*}
(a) \quad & \delta^i \delta^j = \delta^j \delta^i, & \text{for } i < j, \\
(b) \quad & \sigma^j \sigma^i = \sigma^i \sigma^{i+1}, & \text{for } i \leq j, \\
(c) \quad & \sigma^j \delta^i = \delta^j \sigma^i, & \text{for } i < j, \\
(d) \quad & \sigma^i \delta^j = \Id, & \text{for } i = j, j + 1, \\
(e) \quad & \sigma^j \delta^i = \delta^{j-1} \sigma^j, & \text{for } i > j + 1.
\end{align*}
\]

The maps \( \delta^i \) and \( \sigma^i \) are again called faces and degeneracies, and one usually represents these data by a diagram of the form

\[
X^0 \xrightarrow{\delta^0} X^1 \xrightarrow{\delta^1} X^2 \cdots
\]

The description of a simplicial object is the dual one. It is thus given by a collection of objects \((X_n)_{n \geq 0}\), together with morphisms

\[
\delta_i : X_{n+1} \to X_n, \quad i = 0, \ldots, n + 1
\]
\[
\sigma_i : X_n \to X_{n+1}, \quad i = 0, \ldots, n
\]
satisfying the commutativity relations dual to (A.166), that is:

\[
\begin{align*}
(a) \quad & \delta_i \delta_j = \delta_j \delta_i, & \text{for } i < j, \\
(b) \quad & \sigma_i \sigma_j = \sigma_j \sigma_{i+1}, & \text{for } i \leq j, \\
(c) \quad & \delta_i \sigma_j = \sigma_j \delta_i, & \text{for } i < j, \\
(d) \quad & \delta_i \sigma_j = \Id, & \text{for } i = j, j + 1, \\
(e) \quad & \delta_i \sigma_j = \sigma_j \delta_{i-1}, & \text{for } i > j + 1.
\end{align*}
\]

**Remark A.168.** The category \( \Delta \) is equivalent to the category \( \text{FOS} \) of totally ordered non-empty finite sets. We can also view a simplicial object \( X^\bullet \) in \( \mathcal{C} \) as a functor \( \text{FOS}^{op} \to \mathcal{C} \), by sending a totally ordered non-empty finite set \( I \) to the object \( X_I = X_{|I|-1} \), where \( |I| \) denotes the cardinal of \( I \).
Example A.169. Recall from Notation 1.113 that the symbol $\Delta^n$ was already used for the topological simplex

$$\Delta^n = \{(t_1, \ldots, t_n) \in \mathbb{R}^n \mid 1 \leq t_1 \geq \cdots \geq t_n \geq n\}.$$ 

As $n$ varies, the simplices $\Delta^n$ form a cosimplicial object $\Delta^\bullet$ in the category of topological spaces. The faces are given by

$$\delta^i(t_1, \ldots, t_n) = \begin{cases} (1, t_1, \ldots, t_n), & \text{if } i = 0, \\ (t_1, \ldots, t_i, t_{i+1}, \ldots, t_n), & \text{if } i = 1, \ldots, n, \\ (t_1, \ldots, t_n, 0), & \text{if } i = n + 1, \end{cases}$$

and the degeneracies by

$$\sigma^i(t_1, \ldots, t_{n+1}) = (t_1, \ldots, \hat{t}_{i+1}, \ldots, t_n), \quad i = 0, \ldots, n,$$

where the symbol $\hat{t}_{i+1}$ means that the coordinate $t_{i+1}$ is omitted.

What we called the standard simplex in Section 2.1, that is, $\Delta^n_{st} = \{(t_0, \ldots, t_n) \in \mathbb{R}^{n+1} \mid \sum_{i=0}^n t_i = 1, t_i \geq 0, \quad i = 0, \ldots, n\}$ gives a more symmetric representation of the same cosimplicial topological space (see Exercise A.180). The face maps $\delta^i : \Delta^n_{st} \to \Delta^{n+1}_{st}$ are now defined as

$$\delta^i(t_0, \ldots, t_{n+1}) = (t_0, \ldots, \hat{t}_{i-1}, 0, t_i, \ldots, t_n), \quad i = 0, \ldots, n+1,$$

and the degeneracy maps $\sigma^i : \Delta^{n+1}_{st} \to \Delta^n_{st}$ as

$$\sigma^i(t_0, \ldots, t_{n+1}) = (t_0, \ldots, t_i + t_{i+1}, \ldots, t_{n+1}), \quad i = 0, \ldots, n.$$

A.8.2. Simplicial abelian groups and chain complexes. Simplicial and cosimplicial objects in an abelian category are closely related to chain and cochain complexes, as introduced in Section A.1. In this paragraph, we review some constructions making this relation precise. To begin with, we associate a chain complex with a simplicial object in an abelian category.

Definition A.170. Given a simplicial object $X_\bullet$ in an abelian category, the associated chain complex is the complex $CX_\bullet$ with

$$CX_n = X_n, \quad \partial_n = \sum_{i=0}^n (-1)^i \delta_i : CX_n \to CX_{n-1}.$$ 

When there is no need to emphasize the degree, we will denote the differential of this complex simply by $\partial$. We can also consider a smaller complex that, as we will see in the next theorem, has the same homology as $CX_\bullet$.

Definition A.171. Given a simplicial object $X_\bullet$ in an abelian category, the associated normalized chain complex is the subcomplex $NX_\bullet \subset CX_\bullet$ with

$$NX_n = \bigcap_{i=0}^{n-1} \operatorname{Ker} \delta_i.$$ 

The complex of degenerate elements is the subcomplex $DX_\bullet \subset CX_\bullet$ with

$$DX_n = \sum_{i=0}^{n-1} \sigma_i(X_{n-1}).$$
The reader is encouraged to check in Exercise A.181 that $CX_*$ is indeed a complex and that $N X_*$ and $DX_*$ form subcomplexes of $CX_*$. Note that the differential on $N X_n$ is reduced to $\partial_n = (-1)^n \delta_n$.

**Theorem A.172.** Let $X_*$ be a simplicial object in an abelian category. The composition of the inclusion and the quotient maps

$$N X_* \longrightarrow CX_* \longrightarrow CX_*/DX_*$$

is an isomorphism. Moreover, $N X_* \longrightarrow CX_*$ is a quasi-isomorphism.

**Proof.** For each integer $k$, consider the subobjects

$$N_k X_n = \bigcap_{j=0}^{\min(k,n-1)} \ker \delta_j, \quad D_k X_n = \sum_{i=0}^{\min(k,n-1)} \sigma_i(X_{n-1})$$

of $N_k X_n$ and $D_k X_n$ respectively. It follows from the simplicial identities (A.167) that $(N_k X_*, \partial)$ and $(D_k X_*, \partial)$ are subcomplexes of $(CX_*, \partial)$.

We shall prove that, for all $k$ and $n \geq 0$, the composition

(A.173) \[ \begin{array}{ccc} N_k X_n & \longrightarrow & CX_n \\ \downarrow & & \downarrow \\ N_k X_n & \longrightarrow & CX_n/\sigma_k(X_{n-1}) \end{array} \]

of the inclusion and the quotient maps is an isomorphism and that the inclusion

$$N_k X_* \longrightarrow N_{k-1} X_*$$

is a quasi-isomorphism. The theorem results from this, on noting the equalities $N_k X_n = CX_n$ for all $k \leq -1$ and $N_k X_n = N X_n$ and $D_k X_n = DX_n$ for all $k \geq n-1$.

We argue by induction on $k$. The above statements clearly hold for $k \leq -1$, since $N_k X_n = CX_n$ and $D_k X_n = 0$ in that case. We assume that both statements are true for $j < k$ and we prove them for $k$. We first prove that the composition (A.173) is an isomorphism. For $n \leq k$ this follows directly by the induction hypothesis because, in this case, $N_k X_n = N_{k-1} X_n$ and $D_k X_n = D_{k-1} X_n$. Let $x \in N_{k-1} X_n$ with $n \geq k + 1$. Then by the simplicial identities,

$$x - \sigma_k \delta_k x \in N_k X_n.$$

Since $\sigma_k \delta_k x \in D_k X_n$, using the induction hypothesis we conclude

$$CX_n = D_{k-1} X_n + N_{k-1} X_n = D_{k-1} X_n + D_k X_n + N_k X_n = D_k X_n + N_k X_n.$$

Therefore, the composition (A.173) is surjective.

Using again the simplicial identities, it follows that

$$\sigma_k(N_{k-1} X_n) \subset N_{k-1} X_n, \quad \sigma_k(D_{k-1} X_n) \subset D_{k-1} X_n.$$

In particular, $\sigma_k$ induces a map $\sigma_k: X_n/D_{k-1} X_n \rightarrow X_n/D_{k-1} X_n$ and, by the induction hypothesis, there is a commutative diagram

$$\begin{array}{ccc} N_{k-1} X_n & \xrightarrow{\sim} & X_n/D_{k-1} X_n \\ \sigma_k \downarrow & & \sigma_k \\ N_{k-1} X_n & \xrightarrow{\sim} & X_n/D_{k-1} X_n. \end{array}$$

There is a canonical isomorphism

$$\frac{X_n}{D_k X_n} = \frac{X_n}{D_{k-1} X_n + \sigma_k(X_n)} \xrightarrow{\sim} \frac{X_n}{\sigma_k(X_n/D_{k-1} X_n)}.$$
From this isomorphism and the previous commutative diagram, we deduce that, if \( x \in \mathcal{N}_{k-1}X_n \) belongs to \( D_kX_n \), then \( x = \sigma_ky \) with \( y \in \mathcal{N}_{k-1}X_n \).

Let \( x \in \mathcal{N}_kX_n \cap D_kX_n \). By the previous discussion \( x = \sigma_ky \) with \( y \in \mathcal{N}_{k-1}X_n \). Since \( x \in \text{Ker} \delta_k \), then
\[
0 = \delta_kx = \delta_k\sigma_ky = y.
\]
So \( y = 0 \) and, in consequence \( x = 0 \). This shows that \( \mathcal{N}_kX_n \cap D_kX_n = 0 \) and that the composition \((\mathcal{A}.173)\) is injective. It is thus an isomorphism.

Now we prove that the inclusion \( \mathcal{N}_kX_* \to \mathcal{N}_{k-1}X_* \) is a quasi-isomorphism. In fact we will prove more. We prove that it is a homotopy equivalence. Let us denote by \( \iota_k: \mathcal{N}_kX_* \to \mathcal{N}_{k-1}X_* \) the inclusion and by \( \pi_k \) the composition
\[
\mathcal{N}_{k-1}X_* \to X_*/D_{k-1}X_* \simeq \mathcal{N}_kX_*.
\]
One checks that, for \( x \in \mathcal{N}_{k-1}X_n \),
\[
\pi_k \circ \iota_k(x) = x = \text{Id}(x)
\]
\[
\iota_k \circ \pi_k(x) = x, \quad \text{if} \ n \leq k,
\]
\[
\iota_k \circ \pi_k(x) = x - \sigma_k\delta_k(x) \quad \text{if} \ n > k.
\]
We need to show that \( \iota_k \circ \pi_k \) is homotopy equivalent to the identity. For this, let \( s: \mathcal{N}_{k-1}X_* \to \mathcal{N}_{k-1}X_* \) be the map that sends \( x \in \mathcal{N}_{k-1}X_n \) to
\[
s(x) = \begin{cases} 0, & \text{if} \ n < k, \\ (-1)^k\sigma_k(n), & \text{if} \ n \geq k. \end{cases}
\]
Using the simplicial identities it follows that
\[
x - \iota_k \circ \pi_k(x) = (\partial s + s\partial)(x)
\]
showing that \( \mathcal{N}_kX_* \) and \( \mathcal{N}_{k-1}X_* \) are homotopy equivalent and finishing the proof of the theorem. \( \square \)

Example \( \mathcal{A}.174 \). Let \( M \) be a topological space. As in Section 2.1, we denote by \( C_n(M) = C_n(M, \mathbb{Z}) \) the free abelian group generated by all continuous maps \( \sigma: \Delta^n \to M \). The cosimplicial structure of \( \Delta_*^n \) induces a simplicial group structure on \( C_*(M) \). We will denote by \( C_*(M) \) the associated chain complex and by \( \widetilde{C}_*(M) \) the normalized chain complex. As explained in Section 2.1, the complex \( (C_*(M), \partial_*) \) computes the singular homology of \( M \). The same is true for the complex \( (\widetilde{C}_*(M), \partial_*) \).

Similarly, if \( M \) is a differentiable manifold, we will denote by \( S_*(M) \) the chain complex of smooth singular chains and by \( \widetilde{S}_*(M) \) the normalized complex of smooth singular chains.

Dualizing the construction of the chain complex we obtain the definition of the associated cochain complex.

Definition \( \mathcal{A}.175 \). Let \( X^\bullet \) be a cosimplicial object in an abelian category, the associated cochain complex is the complex \( CX^\bullet \) with
\[
CX^n = X^n, \quad d = \sum_{i=0}^{n+1} (-1)^i \delta^i: CX^n \to CX^{n+1},
\]
and the normalized cochain complex is
\[ \mathcal{N}X^n = X^n / \sum_{i=0}^{n-1} \text{Im} \delta^i \simeq \bigcap_{i=0}^{n-1} \text{Ker} \delta^i, \quad d = \sum_{i=0}^{n+1} (-1)^i \delta^i. \]

The statements that \( X^n / \sum_{i=0}^{n-1} \text{Im} \delta^i \) and \( \bigcap_{i=0}^{n-1} \text{Ker} \delta^i \) are isomorphic and that the inclusion \( \mathcal{N}X^* \to CX^* \) is a quasi-isomorphism are dual to the statements in Theorem A.172 and are proved in a similar way.

**Example A.176.** Let \( M \) be a topological space. For any coefficient ring \( R \), the groups
\[ C^n(M, R) = \text{Hom}(C_n(M), R), \]
form a cosimplicial abelian group. We will also denote by \( C^*(M, R) \) the associated cochain complex and by \( C^*(M, R) \) the normalized cochain complex. Similarly, when \( M \) is a differentiable manifold, \( S^*(M, R) \) and \( S^*(M, R) \) will denote the cochain complex of smooth singular cochains and the corresponding normalized complex. The four complexes in this example compute the singular cohomology of \( M \) with coefficients in \( R \).

In the course of the proof of Beilinson’s Theorem 3.307, one needs to associate with a cosimplicial manifold a variant of the normalized cochain complex from Definition A.175. In fact, it is a complex homotopically equivalent to a truncation of the normalized one. For each \( N \geq 0 \) and each simplicial object \( X_\bullet \) in an abelian category, we introduce a new complex \( C_\bullet(\Delta_N, X_\bullet) \). For each \( \emptyset \neq I \subset \Delta_N \), using the convention of Remark A.168, we have the object \( X_I = X_{|I|-1} \). If \( K = \{k_0, \ldots, k_p\} \) with the indices \( k_i \) in increasing order, and \( I = \{k_0, \ldots, \hat{k}_i, \ldots, k_p\} \), we set the sign \( \varepsilon(I, K) = (-1)^i \), which is the same sign appearing in Notation 3.277. We also denote
\[ d_{I,K} = \delta_i : X_K \to X_I. \]
For each \( p \geq 0 \), we define
\[ C_p(\Delta_N, X_\bullet) = \bigoplus_{I \subset \Delta_N \atop |I| = p+1} X_I, \tag{A.177} \]
with differential \( d : C_p(\Delta_N, X_\bullet) \to C_{p-1}(\Delta_N, X_\bullet) \) given by
\[ d = \bigoplus_{I \subset K} \varepsilon(I, K)d_{I,K}. \]

For a chain complex \( C_\bullet \), let \( \sigma_{\leq N} \) denote the \( \text{bête} \) filtration
\[ \sigma_{\leq N} C_n = \begin{cases} C_n, & \text{if } n \leq N, \\ 0, & \text{if } n > N. \end{cases} \]
This filtration is the dual of the \( \text{bête} \) filtration in a cochain complex given in Example A.147.

For a conceptual proof of the following result, see [DG05, Prop. 3.10]. We give an elementary proof similar to the proof of Theorem A.172.

**Proposition A.178.** Given a simplicial object \( X_\bullet \) in an abelian category and an integer \( N \geq 0 \), the complexes \( C_\bullet(\Delta_N, X_\bullet) \) and \( \sigma_{\leq N} \mathcal{N}X_\bullet \) are functorially homotopically equivalent.
PROOF. Let \( \phi: \sigma_{\leq N}NX_\bullet \to C_*(\Delta_N, X_\bullet) \) be the map sending the object \( NX_n \) to \( X_\Delta_n \subset C_0(\Delta_N, X_\bullet) \). This map is a morphism of complexes because for each subset \( J \subset \Delta_n \), with \( |J| = n \), the restriction to \( NX_n \) of the map \( d_{\Delta_n,J} \) vanishes unless \( J = \Delta_n \). The map \( \phi \) is injective and we identify \( \sigma_{\leq N}NX_\bullet \) with its image inside \( C_*(\Delta_N, X_\bullet) \).

We consider the decreasing filtration \( F \) on the complex \( C_*(\Delta_N, X_\bullet) \) defined, for \( I = \{i_0, \ldots, i_k, \ldots \} \) in increasing order, by

\[
F^p X_I = \begin{cases} 
\bigcap_{j=0}^{\min(p,|I|-1)} \ker \delta_j, & \text{if } i_j = j \text{ for } j = 0, \ldots, \min(p,|I|-1), \\
0, & \text{otherwise}.
\end{cases}
\]

The simplicial identities readily show that this filtration is by subcomplexes. Moreover

\[
F^{-1}C_*(\Delta_N, X_\bullet) = C_*(\Delta_N, X_\bullet),
\]

\[
F^NC_*(\Delta_N, X_\bullet) = \sigma_{\leq N}NX_\bullet.
\]

Therefore, it is enough to show, for \( p \geq 0 \), that each inclusion

\[
F^pC_*(\Delta_N, X_\bullet) \rightarrow F^{p-1}C_*(\Delta_N, X_\bullet),
\]

is a homotopy equivalence.

For \( p \geq 0 \), let \( I \subset \Delta_N \) be a subset of the form

\[
(A.179) \quad I = \{0, 1, \ldots, p-1, i_p, \ldots, i_n\}, \quad p < i_p < i_{p+1} < \cdots < i_n.
\]

Write \( I_p = \{0, 1, \ldots, p-1, i_p, \ldots, i_n\} \). There is an increasing map \( \sigma^p: I_p \to I \) that sends \( p \) to \( i_p \) and the other elements to themselves. Being \( X_\bullet \) a simplicial object, there is a map \( \sigma^p: X_I \to X_{I_p} \).

For \( p \geq 0 \) we define the degree one map

\[
s^p: F^{p-1}C_*(\Delta_N, X_\bullet) \rightarrow F^{p-1}C_*(\Delta_N, X_\bullet)
\]

that, in the component \( X_I \) is equal to \((-1)^p\sigma^p: X_I \rightarrow X_{I_p}\) if \( I \) has the shape \((A.179)\) and is zero otherwise.

We look at the map

\[
\psi_p: F^{p-1}C_*(\Delta_N, X_\bullet) \rightarrow F^{p-1}C_*(\Delta_N, X_\bullet)
\]

given as \( \psi_p = \operatorname{Id} - (ds^p + s^p d) \). The simplicial identities imply that,

i) if \( x \in F^pC_*(\Delta_N, X_\bullet) \), then \( \psi_p(x) = x \);

ii) for \( x \in F^{p-1}C_*(\Delta_N, X_\bullet) \), then \( \psi_p(x) \in F^pC_*(\Delta_N, X_\bullet) \).

Thus, \( \psi_p \) induces a morphism of complexes

\[
\psi'_p: F^{p-1}C_*(\Delta_N, X_\bullet) \rightarrow F^pC_*(\Delta_N, X_\bullet)
\]

that, combined with the inclusion in the opposite direction, yields a homotopy equivalence.

Writing \( \psi = \psi'_{n-1} \circ \cdots \circ \psi'_0 \) we obtain a homotopy inverse of the map \( \phi \). Since we have only used the simplicial maps, it is clear that the resulting homotopy equivalence is functorial. \( \square \)

***
Exercise A.180. Show that the maps $\Delta^n \to \Delta^*_n$, $n \geq 0$ given by
$$(t_1, \ldots, t_n) \mapsto (1 - t_1, t_1 - t_2, \ldots, t_{n-1} - t_n, t_n)$$
are homeomorphisms that commute with the face and degeneracy maps from Example A.169.

Exercise A.181. Let $X_\bullet$ be a simplicial object $X_\bullet$ in an abelian category. Use
the simplicial identities (A.167) to prove the following statements.

i) The composition $\partial_n \circ \partial_{n+1}$ is zero. Therefore, $(CX_\ast, \partial)$ is a complex.

ii) Show that $\partial_n$ sends $N X_n$ to $N X_{n-1}$ and, when restricted to $N X_n$ agrees
with $(-1)^n \delta_n$.

iii) Show that $\partial_n$ sends $DX_n$ to $DX_{n-1}$.

Exercise A.182 (The nerve of a category). Let $C$ be a small category. Let $N(C)_0$
denote the set of objects and $N(C)_1$ the set of morphisms. For each $n \geq 2$, define
$N(C)_n$ as the set of $n$-tuples of composable morphisms

\[(A.183) \quad C_0 \xrightarrow{f_1} C_1 \xrightarrow{f_1} \cdots \xrightarrow{f_n} C_n. \]

On the one hand, we have maps
$\delta_i: N(C)_n \to N(C)_{n-1}$ \hspace{1cm} i = 0, \ldots, n,

given by composing at the $i$-th object or removing it whenever $i = 0$ or $n$. In other
words, $\delta_i$ sends an $n$-tuple as in (A.183) to the $(n-1)$-tuple
$C_0 \xrightarrow{f_1} \cdots \xrightarrow{f_{i-1}} C_{i-1} \xrightarrow{f_{i+1} \circ f_i} C_{i+1} \xrightarrow{f_{i+2}} \cdots \xrightarrow{f_n} C_n.$

On the other hand, there are maps
$\sigma_i: N(C)_n \to N(C)_{n+1}$ \hspace{1cm} i = 0, \ldots, n,

obtained by inserting an identity morphism at the $i$-th object, that is,
$C_0 \xrightarrow{f_1} \cdots \xrightarrow{f_i} C_i \xrightarrow{id} C_i \xrightarrow{f_{i+1}} \cdots \xrightarrow{f_n} C_n.$

i) Prove that $N(C)_\bullet$, together with the maps $\delta_i$ as faces and the maps $\sigma_i$ as degeneracies, has the structure of a simplicial set. This construction is
called the nerve of the category $C$.

ii) In particular, identify the simplicial identity which corresponds to the
associativity of the composition of morphisms.

A.9. Sheaf cohomology. This section contains a brief summary of sheaf
cohomology. For more detailed accounts, we refer the reader to [Bre97] or [Ive86].
A.9.1. The definition of sheaf.

Definition A.184. Let $M$ be a topological space. A presheaf of abelian
groups $F$ on $M$ is the data of

- an abelian group $F(U)$ for each open subset $U \subset M$;
- a group homomorphism $\rho_{U,V}: F(V) \to F(U)$ for each inclusion $U \subset V$ of
open subsets;

satisfying the following properties:

i) $\rho_{U,U} = \text{Id}_{F(U)}$ for all open subsets $U$;

ii) $\rho_{U,W} = \rho_{U,V} \circ \rho_{V,W}$ for all open subsets $U \subset V \subset W$. 

The elements of $F(U)$ are called the sections of $F$ on $U$ and the maps $\rho_{U,V}$ are called restriction maps. The notation

$$t \mid_U = \rho_{U,V}(t)$$

is most often used for the restriction of a section $t \in F(V)$. Sometimes, $F(U)$ is also denoted by $\Gamma(U, F)$, especially for $U = M$.

Definition A.185. Let $F$ and $G$ be presheaves of abelian groups on a topological space $M$. A morphism of presheaves $\varphi: F \to G$ is the data of a group homomorphism $\varphi_U: F(U) \to G(U)$ for each open subset $U \subset M$ that is compatible with the restriction maps in that the diagram

$$
\begin{array}{ccc}
F(V) & \xrightarrow{\varphi_V} & G(V) \\
\downarrow{\rho_{U,V}} & & \downarrow{\rho_{U,V}} \\
F(U) & \xrightarrow{\varphi_U} & G(U)
\end{array}
$$

commutes for all open subsets $U \subset V$.

Definition A.186. A presheaf of abelian groups $F$ on $M$ is called a sheaf if it satisfies the following extra conditions:

iii) For each open subset $U \subset M$ and each open cover $U = \bigcup_{i \in I} U_i$, if a section $t \in F(U)$ satisfies $t \mid_{U_i} = 0$ for all $i \in I$, then $t = 0$.

iv) For each open subset $U \subset M$, each open cover $U = \bigcup_{i \in I} U_i$ and each collection of sections $t_i \in F(U_i)$ satisfying

$$t_i \mid_{U_i \cap U_j} = t_j \mid_{U_i \cap U_j}$$

for all $i, j \in I$, there exists a section $t \in F(U)$ satisfying $t \mid_{U_i} = t_i$.

A morphism of sheaves $\varphi: F \to G$ is the same as a morphism of presheaves.

Remark A.187. Properties i) and ii) in the definition of presheaf can be rephrased as follows: let $\text{Op}(M)$ be the category whose objects are the open subsets of $M$ and whose set of morphisms $\text{Hom}(U, V)$ consist of a singleton if $U$ is a subset of $V$ and are empty otherwise; then $F$ is a contravariant functor from $\text{Op}(M)$ to the category $\text{Ab}$ of abelian groups. Property iii) means that the conditions defining $F(U)$ are of local nature, i.e., can be tested on an open neighbourhood of each point. For example, being a closed differential form is a local property, but being exact is not. Property iv) allows one to glue local sections. Moreover, thanks to the locality property, the section $t$ in iv) is unique. In particular, a sheaf $F$ is determined by its sections on a basis of the topology of $M$ and the restriction maps between them. For example, if $M$ is a differentiable manifold, it suffices to work with contractible open subsets (Exercice A.249).

The category $\text{Sh}(M)$ is abelian, so it makes sense to talk about kernels, cokernels, and images of morphisms of sheaves; of complexes of sheaves and their cohomology (in particular, of exact sequences); of injective sheaves, and so on.

In practice, it is often easier to write down a presheaf than a sheaf, as the locality and the gluing property may fail in very natural examples of presheaves. However, there is a canonical procedure to obtain a sheaf starting from a presheaf.
Proposition A.188 (Sheaf associated with a presheaf). Given a presheaf $F$ on a topological space $M$, there exists a sheaf $F^+$ on $M$ and a morphism of presheaves $\theta: F \to F^+$ that is universal for this property: for every morphism of presheaves $f: F \to G$ with target a sheaf $G$, there exists a unique morphism of sheaves $\phi: F^+ \to G$ satisfying $f = \phi \circ \theta$.

This is proved, for instance, in [Har77, Prop.–Def. II 1.2]. We call $F^+$ the sheaf associated with the presheaf $F$ or the sheafification of $F$.

Examples A.189.

i) The constant presheaf $A^o$ is the presheaf with $A^o(U) = A$ for each open subset $U \subset M$ and all restriction maps equal to the identity. This presheaf is rarely a sheaf, because sections on two disjoint open subsets do not glue to a section on the union unless they are equal. The constant sheaf $\underline{A}$ is defined as the sheaf associated with $A^o$; its sections are equal to $\underline{A}(U) = \{\text{locally constant functions } U \to A\}$.

We will also write $\underline{A}_M$ when we want to emphasise the topological space. A sheaf is called constant if it is of the form $\underline{A}$ for some abelian group $A$.

ii) Given a sheaf $F$ on $M$ and an open subset $U \subset M$, the restriction of $F$ to $U$ is the sheaf $F|_U$ on $U$ with sections $F|_U(W) = F(W)$ for each open subset $W \subset U$ and the same restriction maps as those of $F$. A sheaf $F$ is said to be locally constant if each point of $M$ has an open neighbourhood $U$ such that $F|_U$ is a constant sheaf. For example, the holomorphic solutions to a differential equation of the form

$$\frac{d}{dz}^n f + a_{n-1}(z)\frac{d}{dz}^{n-1} f + \cdots + a_0(z)f = 0$$

where $a_i(z)$ are holomorphic functions on a punctured projective line $\mathbb{P}^1 \setminus S$ form a locally constant sheaf on $\mathbb{P}^1 \setminus S$.

iii) Let $A$ be an abelian group and let $x \in M$ be a point. The skyscraper sheaf $\underline{A}_x$ is the sheaf with sections

$$\underline{A}_x(U) = \begin{cases} A, & \text{if } x \in U, \\ 0, & \text{if } x \notin U, \end{cases}$$

and restriction maps $\rho_{U,V}$ equal to the identity if both $U$ and $V$ contain $x$, and zero otherwise.

Definition A.190. Let $F$ be a sheaf on a topological space $M$ and let $x \in M$ be a point. The stalk of $F$ at $x$ is the direct limit

$$F_x = \lim_{\xrightarrow{x \in U}} F(U)$$

over the directed set of open neighbourhoods of $x$ in $M$.

An element of $F_x$ is thus an equivalence class of pairs $(U,t)$, where $U \subset M$ is an open subset containing $x$ and $t \in F(U)$ is a section, with respect to the equivalence relation generated by $(U,t) \sim (W,t|_W)$ for all open neighborhoods $W \subset U$ of $x$. The class of $(U,t)$ in $F_x$ will be denoted by $t_x$. The assignment $t \mapsto t_x$ defines a group homomorphism $F(U) \to F_x$. 


A.9.2. Sheaf cohomology. Let $F$ be a sheaf on a topological space $M$. The elements in the group $F(M) = \Gamma(M, F)$ are called the global sections of $F$. The assignment $F \mapsto \Gamma(M, F)$ gives rise to the global section functor

$$\Gamma : \text{Sh}(M) \to \text{Ab}.$$  

The functor $\Gamma$ is left exact (Definition A.16): for each short exact sequence of sheaves $0 \to F_1 \to F_2 \to F_3 \to 0$, the sequence of abelian groups

$$0 \to \Gamma(M, F_1) \to \Gamma(M, F_2) \to \Gamma(M, F_3)$$

is exact. However, the rightmost map does not need to be surjective, and hence the functor is not exact. For example, let $M$ be a connected Hausdorff topological space and let $x, y \in M$ be two distinct points. The morphism of sheaves $\mathbb{Z}_M \to \mathbb{Z}_x \oplus \mathbb{Z}_y$ that sends a locally constant function to its values at $x$ and $y$ is surjective (check stalk by stalk), but the induced map on global sections $\Gamma(M, \mathbb{Z}_M) \to \Gamma(M, \mathbb{Z}_x \oplus \mathbb{Z}_y)$ is the diagonal map $\mathbb{Z} \to \mathbb{Z} \oplus \mathbb{Z}$, which is not. This observation is the starting point of the definition of sheaf cohomology. Recall the notion of derived functor from Definition A.77 and the criterion for existence given in Proposition A.84. The functor $\Gamma$ is left exact, so in order to apply it it remains to prove the following:

**Lemma A.191.** The category $\text{Sh}(M)$ has enough injectives.

**Proof.** Let $F$ be a sheaf. For each point $x \in M$ and each abelian group $A$, there is a natural isomorphism

$$\text{Hom}_{\text{Ab}}(F_x, A) \simeq \text{Hom}_{\text{Sh}(M)}(F, A_x),$$

which shows that $A_x$ is an injective object of $\text{Sh}(M)$ if $A$ is an injective abelian group. Using that the category $\text{Ab}$ has enough injectives (Example A.82), there exists an injective homomorphism $F_x \to I_x$ into an injective abelian group for each $x$. Thinking of $I_x$ as a skyscraper sheaf supported at $x$, the product $\prod_{x \in M} I_x$ is an injective sheaf by Exercise A.97, and the map $F \to \prod_{x \in M} I_x$ obtained from the natural maps $F_x \to F_x$ is a monomorphism. \hfill \Box

**Definition A.192.** Let $M$ be a topological space and let $F$ be a sheaf on $M$. The cohomology groups of $F$ are the derived functors of the global sections functor:

$$\text{H}^n(M, F) = R^n\Gamma(M, F).$$

Sheaf cohomology can be computed by choosing an injective resolution

$$0 \to F \to I^0 \to I^1 \to I^2 \to \cdots$$

of $F$ (i.e. a long exact sequence where all the $I^i$ are injective sheaves) and considering the cohomology of the complex

$$0 \to \Gamma(M, I^0) \to \Gamma(M, I^1) \to \Gamma(M, I^2) \to \cdots$$

obtained by taking global sections. That is, the equality

$$\text{H}^n(M, F) = \text{H}^n(\Gamma(M, I^*))$$

holds. The resulting groups are independent of the choice of the injective resolution.

Injective resolutions are useful for theoretical purposes, but they may not be the best way to compute cohomology explicitly. For this reason, it is useful to have other more concrete techniques at disposal.

**Definition A.193.** Let $F$ be a sheaf on a topological space $M$. 
i) We say that $F$ is flasque (or flabby) if the restriction maps
\[ \rho_{U,V} : F(V) \rightarrow F(U) \]
are surjective for all open subsets $U \subset V \subset M$.

ii) We say that $F$ is acyclic if the vanishing $H^n(X, F) = 0$ holds for all $n \geq 1$.

An acyclic resolution of a sheaf $F$ is an exact sequence
\[ 0 \rightarrow F \rightarrow A^0 \rightarrow A^1 \rightarrow A^2 \rightarrow \cdots \]
in which all $A^i$ are acyclic sheaves.

**Lemma A.194.** Let $F$ be a sheaf and let $A^*$ be an acyclic resolution of $F$. Then there is a canonical isomorphism
\[ H^n(M, F) \simeq H^n(\Gamma(M, A^*)). \]

**Proof.** Consider the short exact sequence
\[ 0 \rightarrow F \rightarrow A^0 \rightarrow A^0/F \rightarrow 0. \]
Using the acyclicity of $A^0$, we deduce an exact sequence
\[ 0 \rightarrow H^0(F) \rightarrow \Gamma(M, A^0) \rightarrow H^0(A^0/F) \rightarrow H^1(F) \rightarrow 0 \]
and isomorphisms
\[ (A.195) \quad H^n(A^0/F) \simeq H^{n+1}(F) \quad \text{for all} \quad n \geq 1. \]
Besides, the complex
\[ (A.196) \quad 0 \rightarrow A^0/F \rightarrow A^1 \rightarrow A^2 \rightarrow \cdots \]
is an acyclic resolution of $A^0/F$. From this, one easily deduce the equalities
\[ H^0(F) = \ker(\Gamma(M, A^0) \rightarrow H^0(A^0/F)) = \ker(\Gamma(M, A^1) \rightarrow \Gamma(M, A^1)), \]
\[ H^1(F) = \frac{H^0(A^0/F)}{\text{Im}(\Gamma(M, A^0) \rightarrow H(A^0/F))} = \frac{\ker(\Gamma(M, A^1) \rightarrow \Gamma(M, A^2))}{\text{Im}(\Gamma(M, A^0) \rightarrow \Gamma(M, A^1))}. \]
We have thus proved the cases $n = 0$ and $n = 1$ of the lemma. The remaining cases follow inductively from the resolution (A.196) and the isomorphisms (A.195).

A proof of the next result can be found in [Har77, Prop. III 2.5].

**Lemma A.197.** Every flasque sheaf is acyclic.

There is another class of acyclic sheaves called fine sheaves that is very useful in differential geometry. For instance, we used it in the course of the proof of de Rham’s Theorem 2.62 to show that the sheaf of smooth differential forms on a differential manifold is acyclic. An open cover \( \{U_i\}_{i \in I} \) of a topological space $M$ is said to be locally finite if every point $x \in M$ has a neighborhood that intersects only finitely many of the open subsets $U_i$.

**Definition A.198.** Let $M$ be a paracompact Hausdorff space. A sheaf $F$ on $M$ is said to be fine if, for every locally finite open cover \( \{U_i\} \) of $M$, there exists a family of sheaf endomorphisms $h_i : F \rightarrow F$ such that
\[ i) \] the support of $h_i$ is contained in $U_i$, that is, $h_i(F_x) = 0$ holds for all $x$ in some neighborhood of $X \setminus U_i$;
\[ ii) \] the sum $\sum_{i \in I} h_i$, that is well defined because of $i)$ and the fact that the covering is locally finite, is the identity endomorphism.
Such a family is called a partition of unity.

Example A.199. Let $M$ be a differentiable manifold and $\mathcal{E}_M^0$ the sheaf of differentiable functions on $M$. For every locally finite open cover $\{U_i\}_{i \in I}$ of $M$ one can find a family of differentiable functions $f_i: M \to \mathbb{R}_{\geq 0}$ such that

i) $\text{supp}(f_i) \subset U_i$,

ii) $\sum_{i \in I} f_i(x) = 1$ for all $x \in M$.

This family is called a differentiable partition of unity subordinated to the open cover. If a sheaf $F$ is an $\mathcal{E}_M^0$-module, then multiplying by the function $f_i$ provides the endomorphism $h_i$ in Definition A.198. Thus, every $\mathcal{E}_M^0$-module is a fine sheaf. This applies in particular to the sheaves of smooth differential forms $\mathcal{E}_M^p$.

Lemma A.200. Every fine sheaf is acyclic.

Proof. Exercise A.258. □

A.9.3. Godement’s canonical resolution. A sheaf $F$ on a topological space $M$ admits a canonical resolution by flasque sheaves called Godement’s resolution. The construction starts as follows: for each open subset $U$ of $M$, consider the product $Gd^0(F)(U) = \prod_{x \in U} F_x$ of the stalks of $F$ at all points of $U$. Together with the obvious restriction maps, one obtains a presheaf $Gd^0(F)$ on $M$, which is readily seen to be a sheaf.

Lemma A.201. For every sheaf $F$, the sheaf $Gd^0(F)$ is flasque.

Proof. Follows immediately form the definition. □

Moreover, the natural morphism of sheaves $F \to Gd^0(F)$ is injective. Then one defines $Gd^1(F) = Gd^0(Gd^0(F)/F)$. There is an obvious map $\partial: Gd^0(F) \to Gd^1(F)$. Assume now that we have constructed sheaves $Gd^i(F)$ with maps $\partial: Gd^{i-1}(F) \to Gd^i(F)$ for $i < k$ satisfying $\partial \circ \partial = 0$. Then one defines $Gd^k(F) = Gd^0(Gd^{k-1}(F)/\partial Gd^{k-2}(F))$. Clearly, there is a map $\partial: Gd^{k-1}(F) \to Gd^k(F)$ satisfying $\partial(\partial Gd^{k-2}(F)) = 0$.

The following result can be verified directly using the definition.

Lemma A.202. For every sheaf $F$, the sequence

$$0 \longrightarrow F \longrightarrow Gd^0(F) \longrightarrow Gd^1(F) \longrightarrow Gd^2(F) \longrightarrow \ldots$$

is exact.

Definition A.203. Let $F$ be a sheaf. The Godement resolution of $F$ is the complex

$Gd(F): Gd^0(F) \to Gd^1(F) \to Gd^2(F) \to \ldots$

Moreover Godement’s resolution is functorial:

Lemma A.204. If $f: F \to G$ is a morphism of sheaves, there is an induced morphism of sheaves $Gd(f): Gd(F) \to Gd(G)$ satisfying $Gd(f \circ g) = Gd(f) \circ Gd(g)$.

Another important property of Godement’s resolution is its exactness.
Lemma A.205. Godement’s resolution is exact. That is, for each exact sequence

$$0 \rightarrow F \rightarrow G \rightarrow H \rightarrow 0$$

of sheaves on $M$, the sequence

$$0 \rightarrow \text{Gd}^n(F) \rightarrow \text{Gd}^n(G) \rightarrow \text{Gd}^n(H) \rightarrow 0$$

is exact for all $n \geq 0$.

Proof. We argue by induction on $n$, setting $\text{Gd}^{-1}(F) = F$ and $\text{Gd}^{-2}(F) = 0$ for notational convenience. For $n = 0$, it follows from the definition of $\text{Gd}^0(F)$ as the product of stalks that the sequence

$$0 \rightarrow \text{Gd}^0(F)(U) \rightarrow \text{Gd}^0(G)(U) \rightarrow \text{Gd}^0(H)(U) \rightarrow 0$$

is exact for all open subsets $U \subset M$, and hence that the sequence of sheaves

$$0 \rightarrow \text{Gd}^0(F) \rightarrow \text{Gd}^0(G) \rightarrow \text{Gd}^0(H) \rightarrow 0$$

is exact. Assume that the functors $\text{Gd}^{-1}$ and $\text{Gd}^{-2} / \partial \text{Gd}^{-3}$ are exact, and consider the commutative diagram

$$
\begin{array}{ccc}
0 & \rightarrow & 0 \\
\downarrow & & \downarrow \\
(\text{Gd}^{-2} / \partial \text{Gd}^{-3})(F) & \rightarrow & (\text{Gd}^{-2} / \partial \text{Gd}^{-3})(G) \\
\downarrow & & \downarrow \\
\text{Gd}^{-1}(F) & \rightarrow & \text{Gd}^{-1}(G) \\
\downarrow & & \downarrow \\
(\text{Gd}^{-1} / \partial \text{Gd}^{-2})(F) & \rightarrow & (\text{Gd}^{-1} / \partial \text{Gd}^{-2})(G) \\
\downarrow & & \downarrow \\
0 & \rightarrow & 0 \\
\end{array}
$$

In this diagram, all three columns are exact by design. For lack of space, we have omitted the zeros from the beginning and the end of each row. The first two rows are exact by induction hypothesis. It then follows from the nine lemma that the third row is exact as well. Once that we know that the functors $\text{Gd}^0$ and $\text{Gd}^{-1} / \partial \text{Gd}^{-2}$ are exact, exactness of $\text{Gd}^n$ follows from the formula

$$\text{Gd}^n(F) = \text{Gd}^0(\text{Gd}^{-1}(F) / \partial \text{Gd}^{-2}(F)).$$

This concludes the proof. \hfill \square

Thanks to this exactness property, Godement’s resolution of a filtered sheaf is canonically endowed with a filtration.

Definition A.206. Let $F$ be a sheaf and let $W$ be an increasing filtration on $F$. We define the filtration $\text{Gd}(W)$ of $\text{Gd}^*(F)$ as

$$\text{Gd}(W)_n \text{Gd}^p(F) = \text{Gd}^p(W_n F).$$

Note that the exactness of $\text{Gd}^p$ implies that $\text{Gd}^p(W_n F)$ is a sub-sheaf of $\text{Gd}^p(F)$. The definition for decreasing filtrations is similar.
A.9.4. Hypercohomology. We now turn to complexes of sheaves. Let

\[ F^* : \ldots \longrightarrow F^{n-1} \longrightarrow F^n \longrightarrow F^{n+1} \longrightarrow \ldots \]

be a bounded below complex of sheaves on a topological space \( M \). There are two possible meanings for the cohomology of \( F^* \): either the cohomology of the complex viewed as a cochain complex in the abelian category \( \text{Sh}(M) \), in which case the cohomology objects will also be sheaves, or the result of applying the derived functor of global sections to \( F^* \), in which case the resulting objects will be abelian groups. To distinguish between these two, the latter is classically called the hypercohomology of the complex.

A resolution of the complex \( F^* \) consists of a complex \( D^* \) together with a quasi-isomorphism \( F^* \rightarrow D^* \). If all the sheaves \( D^n \) are injective (resp. acyclic), we say that \( D^* \) is an injective (resp. acyclic) resolution.

**Definition A.207.** The hypercohomology groups of \( F^* \) are the cohomological right derived functors of the global sections functor applied to \( F^* \) as an object of \( D^+(\text{Sh}) \). In other words,

\[ \mathbb{H}^n(M, F^*) = R^n\Gamma(F^*). \]

To compute them, we choose any bounded below acyclic resolution \( D^* \) of \( F^* \), then

\[ \mathbb{H}^n(M, F^*) = H^n(\Gamma(M, D^*)). \]

Using the functoriality and the exactness of Godement’s canonical resolution, we can construct a resolution of any bounded below complex of sheaves. Let

\[ \ldots \longrightarrow F^{n-1} \longrightarrow F^n \longrightarrow F^{n+1} \longrightarrow \ldots \]

be a complex of sheaves such that there exists an \( n_0 \in \mathbb{Z} \) with \( F^n = 0 \) for all \( n \leq n_0 \). For each \( n \), let \( Gd(F^n) \) be Godement’s canonical resolution. By functoriality, there are maps

\[ d^{\text{hor}} : Gd^m(F^n) \longrightarrow Gd^m(F^{n+1}), \]

that commute with the resolution maps

\[ d^{\text{ver}} : Gd^m(F^n) \longrightarrow Gd^{m+1}(F^n). \]

**Definition A.208.** Let \( F^* \) be a bounded below complex of sheaves. The Godement resolution of \( F^* \) is the total complex of \( Gd^*(F^*) \). That is, the complex \( Gd(F^*) = \text{Tot}^*(Gd^*(F^*)) \) with

\[ \text{Tot}^n(Gd^*(F^*)) = \bigoplus_{p+q=n} Gd^q(F^p) \]

and differential \( d \) given, for each \( x \in Gd^q(F^p) \), by

\[ dx = d^{\text{hor}} x + (-1)^p d^{\text{ver}} x. \]

There is a map \( F^* \rightarrow Gd(F^*) \) of complexes of sheaves. The exactness of \( Gd \) readily implies that this map is a quasi-isomorphism making \( Gd(F^*) \) into an acyclic resolution of \( F^* \). Thus,

\[ \mathbb{H}^n(M, F^*) = H^n(\Gamma(M, Gd(F^*)�)). \]
Since, thanks to Godement’s resolution, the hypercohomology of a sheaf can be computed as the cohomology of a double complex it comes equipped with the spectral sequence (A.155). The first page of this spectral sequence is
\[ E_1^{p,q} = H^q(M, F_p) \implies H^{p+q}(M, F^*). \]

There is another useful spectral sequence that relates the hypercohomology groups of a complex of sheaves with the cohomology groups of the cohomology sheaves of the complex. Roughly speaking this second spectral sequence is constructed by flipping the indices of Godement’s resolution. Indeed, by the exactness of Godement’s resolution we have that
\[ \ker(d_{\text{hor}}: G^p_d(F^q) \to G^p_d(F^{q+1})) = G^p_d(Ker(d: F^q \to F^{q+1})). \]
\[ H^q_{d_{\text{hor}}}(G^p_d(F^*)) = G^p_d(H^q(F^*)). \]

This together with the fact that the sheaves $G^p_d$ are flasque implies that
\[ H^q_{d_{\text{hor}}}(\Gamma(M, G^p_d(F^*))) = \Gamma(M, G^p_d(H^q(F^*)�). \]

Therefore, if on the complex $\Gamma(M, G_d(F^*))$ we put the filtration by the second degree
\[ ^"F^p\Gamma(M, G_d(F^*)) = \bigoplus_{p' \geq p} \Gamma(M, G^{p'}(F^*)�, \]
we obtain a spectral sequence whose second page is
\[ E_2^{p,q} = H^p(X, H^q(F^*)) \implies H^{p+q}(M, F^*). \]

A.9.5. Higher direct images. Higher direct images are a way to encode how sheaf cohomology varies in families.

**Definition A.211.** Let $f: M \to N$ be a continuous map of topological spaces and let $F$ be a sheaf on $M$. The direct image sheaf $f_*F$ is the sheaf on $N$ whose sections on an open subset $U \subset N$ are given by
\[ (f_*F)(U) = F(f^{-1}(U)), \]
and whose restriction maps for open subsets $U \subset V \subset N$ are those of $F$ for the open subsets $f^{-1}(U) \subset f^{-1}(V) \subset M$.

In fact, the direct image construction (A.212) defines a left exact functor
\[ f_*: \text{Sh}(M) \to \text{Sh}(N). \]

Since the category $\text{Sh}(M)$ has enough injectives, the general constructions of Section A.4 apply to this setting, thus giving rise to a total right derived functor $Rf_*$ and to cohomological $\delta$-functors $R^if_*$ for each integer $i \geq 0$. These cohomological $\delta$-functors are called higher direct images.

**Example A.213.** The cohomology groups of a sheaf are a particular case of higher direct images. Indeed, let $M$ be a topological space and let $F$ be a sheaf on $M$. Let $\ast$ denote the topological space consisting of a single point and let $\pi: M \to \ast$ be the unique map with target $\ast$. Since a sheaf on $\ast$ is simply an abelian group, the categories $\text{Sh}(\ast)$ and $\text{Ab}$ are canonically equivalent. Under this identification, we have:
\[ f_*F = \Gamma(M, F), \quad R^if_*F = H^i(M, F). \]
The stalks of the higher direct image sheaves are related with the cohomology of a small neighborhood of the fiber. For a proof of the next proposition, see for instance [Har77, Prop. III.8.1], together with the fact that the stalks of a presheaf agree with the stalks of the associated sheaf.

**Proposition A.214.** Let \( f : X \to Y \) be a continuous map of topological spaces, let \( F \) be a sheaf on \( X \), and let \( y \in Y \) be a point. The stalk of the higher direct image sheaf \( R^i f_* F \) at \( y \) is given by

\[
(R^i f_* F)_y = \lim_{y \in U} H^i(f^{-1}(U), F),
\]

where the limit runs over all open sets \( U \) of \( Y \) containing \( y \).

Given a continuous map \( f : X \to Y \), the Leray spectral sequence allows us to compute the cohomology of a sheaf \( F \) on \( X \) in terms of the cohomology of its higher direct images sheaves on \( Y \). We will construct this spectral sequence as an application of Godement’s resolution. For this, we first make two preliminary remarks. First, if \( F \) is a flasque (Definition A.193) sheaf on \( X \), then \( f_* F \) is a flasque sheaf on \( Y \). Secondly, if \( F \) is a flasque sheaf on \( X \), then \( R^i f_* F = 0 \) for all \( i > 0 \) by Proposition A.214. This last property is expressed saying that \( F \) is \( f \)-acyclic.

Let \( F \) be a sheaf on \( X \). Recall that \( H^i(X, F) = H^i(R\Gamma(F)) \) and

\[
R\Gamma(F) = \Gamma(X, Gd(F))
\]

because the sheaves of the Godement resolution are flasque. Moreover, using that the flasque sheaves are \( f \)-acyclic

\[
Rf_* F = f_* Gd(F),
\]

and, using that \( f_* \) sends flasque sheaves to flasque sheaves,

\[
R\Gamma(Rf_* F) = \Gamma(Y, f_* Gd(F)) = \Gamma(X, Gd(F)).
\]

This last equation can be written as

\[
\]

Applying the spectral sequence (A.210) to the complex of sheaves \( f_* Gd(F) \), we obtain:

**Proposition A.216.** Let \( f : X \to Y \) be a continuous map and let \( F \) be a sheaf on \( X \). There is a spectral sequence with second page

\[
E_2^{p,q} = H^p(Y, R^q f_* F) \implies H^{p+q}(X, F).
\]

It is called the Leray spectral sequence.

We will also use another compatibility between the Godement’s resolution and direct images that we now explain. Let \( f : X \to Y \) be a continuous map of topological spaces and \( F \) a sheaf on \( X \). Let \( x \in X \) be a point and \( y = f(x) \). Then

\[
(f_* F)_y = \lim_{U \ni y} F(f^{-1}(U)),
\]

\[
F_x = \lim_{V \ni x} F(V).
\]
Since \( y \in U \) implies \( x \in f^{-1}(U) \) we deduce a map \( f_*F_y \to F_x \). Putting together these maps we deduce a morphism of sheaves \( \text{Gd}^0(f_*F) \to f_*\text{Gd}^0(F) \), given, in an open set \( U \subset Y \) by
\[
\text{Gd}^0(f_*F)(U) = \prod_{y \in U} f_*F_y \longrightarrow \prod_{x \in f^{-1}(U)} F_x = f_*\text{Gd}^0(F)(U).
\]

The following result is left as an exercise. It follows easily from the previous construction and the definition of Godement’s resolution.

**Lemma A.217.** The above construction induces a morphism of complexes
\[
\text{Gd}(f_*F) \longrightarrow f_*\text{Gd}(F)
\]
that represents the morphism \( f_*F \to Rf_*F \).

**A.9.6. Inverse images.** Given a continuous map \( f : X \to Y \) and a sheaf \( F \) on \( Y \), there is also a construction of the inverse image of \( F \) as a sheaf on \( X \).

**Definition A.219.** Let \( f : X \to Y \) be a continuous map and \( F \) a sheaf on \( Y \). The inverse image sheaf \( f^{-1}F \) is the sheaf on \( X \) associated with the presheaf
\[
U \longmapsto \lim_{V \supset f(U)} F(V),
\]
where the limit runs over all open subsets \( V \subset Y \) containing \( f(U) \) ordered by inclusion.

**Remark A.220.** If \( \iota : Z \to X \) is the inclusion of either an open or a closed subset \( Z \) of \( X \) and \( F \) is a sheaf on \( X \) we will denote the inverse image \( \iota^{-1}F \) by \( F|_Z \) and call it the restriction of \( F \) to \( Z \).

Although the definition of \( f^{-1}F \) looks more difficult than the definition of the direct image \( f_*F \), this construction behaves better in some respects. For example, the stalks are easier to compute, as we have
\[
(f^{-1}F)_x = F_{f(x)}
\]
for all \( x \in X \). From this it follows that \( f^{-1} : \text{Sh}(Y) \to \text{Sh}(X) \) is an exact functor.

Moreover, the direct image and the inverse image functors are adjoint to each other. This means that, given a continuous map \( f : X \to Y \), a sheaf \( F \) on \( X \), and a sheaf \( G \) on \( Y \), there is a functorial isomorphism
\[
\text{Hom}_{\text{Sh}(X)}(f^{-1}G, F) \xrightarrow{\sim} \text{Hom}_{\text{Sh}(Y)}(G, f_*F).
\]
In particular, the images by (A.221) of the identity maps on \( f^{-1}F \) and \( f_*F \) respectively yield canonical morphisms
\[
G \longrightarrow f_*f^{-1}G, f^{-1}f_*F \longrightarrow F
\]
for each sheaf \( G \) on \( Y \) and each sheaf \( F \) on \( X \) which are called adjunction morphisms. The situation may be pictured as follows:

\[
X \xrightarrow{f} Y \quad \xrightarrow{f_*} \text{Sh}(X) \xrightarrow{f^{-1}} \text{Sh}(Y).
\]
A.9.7. Direct image with proper support. Given a continuous map \( f : M \to N \), there is a second way to obtain a sheaf on \( N \) starting from a sheaf \( F \) on \( M \) which is called the direct image with proper support and denoted by \( f_! F \). These symbols are often read as “\( f \) lower shriek of \( F \)”, as “shriek” is a slang word for “exclamation”.

Before giving the definition of \( f_! \), we recall the notion of support of a section. Let \( M \) be a topological space, \( F \) a sheaf on \( M \), and \( U \subset M \) an open subset.

**Definition A.223.** The support of a section \( s \in F(U) \) is the set
\[
\text{supp}(s) = \{ x \in U \mid s_x \neq 0 \},
\]
where \( s_x \) is the class of \( s \) in the stalk \( F_x \) (Definition A.190).

By definition, the complement \( U \setminus \text{supp}(s) \) of the support of a section \( s \) consists of the points \( y \in U \) such that there is an open subset \( y \in V \subset U \) with \( s|_V = 0 \). It follows that \( \text{supp}(s) \) is a closed subset of \( U \).

We also recall the notion of a proper map between topological spaces.

**Definition A.224.** A continuous map of topological spaces \( f : M \to N \) is called proper if the preimage \( f^{-1}(K) \) of every compact subset \( K \subset N \) is compact.

**Remark A.225.** In algebraic geometry there is also the notion of proper morphism, see for instance [Har77, §II 4]. One has to be careful that for a morphism of algebraic varieties, being proper is not equivalent to the map of subjacent topological spaces being proper. Nevertheless, if \( k \) is a subfield of \( \mathbb{C} \) and \( f : X \to Y \) is a morphism of \( k \)-varieties, then \( f \) is proper in the algebro-geometric sense if and only if \( f^{\text{an}} : X(\mathbb{C}) \to Y(\mathbb{C}) \) is a proper map of topological spaces.

Since the definition of proper we are using is pathological when the spaces are not Hausdorff and locally compact in the remainder of this section we will restrict ourselves to this case.

**Definition A.226.** Let \( f : M \to N \) be a continuous map of locally compact Hausdorff topological spaces and let \( F \) be a sheaf on \( M \). The direct image with proper support \( f_! F \) is the sheaf
\[
U \mapsto \{ s \in F(f^{-1}(U)) \mid \text{the restriction } \text{supp}(s) \to U \text{ is proper} \}.
\]

**Remark A.227.** The fact that \( f_! F \) is a sheaf is proved for instance in [Ive86, VII Proposition 1.2]. Moreover it is clearly a subsheaf of \( f_* F \). The functor \( f_! \) is left exact.

**Remark A.228.** There is also an analogous notion of direct image with proper support in algebraic geometry, but using the algebro-geometric notion of properness. Due to Remark A.225, if \( f : X \to Y \) is a morphism of algebraic varieties, and \( f^{\text{top}} \) is the corresponding map of topological spaces, then, in general, \( f_! \neq f_!^{\text{top}} \). This is in contrast with the functor \( f_* \) that depends only on the underlying topological spaces.

When \( f \) is the inclusion of an open subset into a locally compact Hausdorff space, then \( f_! \) coincides with the extension by zero.

**Lemma A.229.** Let \( N \) be a locally compact Hausdorff space and \( f : M \to N \) be the inclusion of an open subset \( M \) of \( N \), and let \( F \) be a sheaf on \( M \). Then \( f_! F \) is the sheaf on \( N \) associated with the presheaf
\[
U \mapsto \begin{cases} F(U), & \text{if } U \subset M, \\ 0, & \text{otherwise.} \end{cases}
\]
Proof. The proof can be done in the following steps. If \( x \in M \) then \((j!F)_x = F_x\). Indeed, to compute \((j!F)_x\) we can use open sets contained in \( M \). If \( V \subset M \) is an open subset and \( s \in F(V) \) is a section, \( \text{supp}(s) \) is closed in \( V \). By the hypothesis on \( N \), the restriction \( \text{supp}(s) \to V \) is proper.

If \( y \not\in M \) then \((j!F)_y = \{0\}\). Let \( y \in U \) be an open set. Put \( V = U \cap M \) and let \( s \in F(V) \) be a section such that \( \text{supp}(s) \to U \) is proper. Again by the hypothesis on \( N \), this implies that \( \text{supp}(s) \) is closed in \( U \). Hence \( W = U \setminus \text{supp}(s) \) is open, contains \( y \) and \( s|_W = 0 \). So the class of any section with proper support vanishes in \((j!F)_y\).

Let \( F_0 \) be the presheaf in the statement. One readily checks that the stalks of this presheaf are equal to \((F_0)_x = F_x\) if \( x \in M \) and to zero otherwise. Moreover, there is a map \( F_0 \to j!F \).

Summing up, we deduce the existence of a map from the sheaf associated to the presheaf \( F_0 \) to \( j!F \) that is an isomorphism in stalks. Therefore both sheaves are isomorphic. \( \square \)

Remark A.230. The analogue of Lemma A.229 is also valid in the algebraic situation.

The functor \( f! \) allows us to define cohomology with compact support.

Definition A.231. Let \( M \) be a locally compact Hausdorff topological space and \( * \) the topological space consisting of a single point. Let \( \pi : M \to * \) be the unique map from \( M \) to \(*\). The functor of global sections with compact support is \( \Gamma_c(M, F) = \Gamma(*, \pi!F) \) and the cohomology with compact support is the derived functor of \( \Gamma_c \):

\[ H^p_c(M, F) = R^p\Gamma_c(M, F). \]

In the special case where \( f : M \to N \) is the inclusion of an open subset, the direct image with compact support and the inverse image functors are also adjoint: there is a functorial isomorphism

\[ \text{Hom}_{\mathcal{S}(M)}(F, \pi^{-1}G) \cong \text{Hom}_{\mathcal{S}(N)}(f_!F, G). \]

for each sheaf \( F \) on \( M \) and each sheaf \( G \) on \( N \). Observe that the position of \( \pi^{-1} \) in this isomorphism and in (A.221) are different. We say that \( \pi_* \) is a right adjoint of \( \pi^{-1} \), while \( f_! \) is a left adjoint.

As in the case of \( f_* \), considering identity maps in (A.232) yields canonical adjunction morphisms

\[ f_!f^{-1}G \to G, \quad F \to f^{-1}f_!F. \]

The adjunction morphisms (A.222) and (A.233) allow us to interpret cohomology with compact support as relative cohomology. This was used in Section 2.8.5 to introduce a mixed Hodge structure in the groups of cohomology with compact support. The steps for this identification are spelled out in Exercise A.252.

The cohomology with compact supports is contravariant for proper morphisms. Namely, let \( f : N \to M \) be a proper map of locally compact Hausdorff topological spaces. For a sheaf \( F \) in \( M \), there are inverse image maps

\[ H^n_c(M, F) \to H^n_c(N, f^{-1}F). \]
that we now explain. The functoriality of the direct image with compact support implies that

\[(\pi_N)^{-1}f^{-1}F = (\pi_M)^{-1}f_*f^{-1}F,\]

where \(\pi_N\) and \(\pi_M\) are the maps to \(*\). Since \(f\) is proper, \(f_* = f_*\) and there is an
adjunction morphisms \(A.222\)

\[F \rightarrow f_*f^{-1}F = f_*f^{-1}F\]

that gives a map \((\pi_M)^{-1}f : F \rightarrow (\pi_N)^{-1}f^{-1}F\) from which the claimed functoriality follows.

A.9.8. Singular cohomology as cohomology of the constant sheaf. Let \(M\) be a
topological space. For each open subset \(U\) of \(M\), let

\[C_\ast(U) = (C_\ast(U), d_\ast)\]
denote the singular chain complex of \(U\), as introduced in (2.3).

**Definition A.234.** Given an open cover \(\mathcal{U} = (U_i)_{i \in I}\) of \(U\), we say that a
singular chain \(\sum n_i\sigma_j \in C_n(U)\) is subordinated to \(\mathcal{U}\) if each simplex \(\sigma_j : \Delta^n_{\ast i} \to U\)
lands in one of the open subsets \(U_i\).

Singular chains subordinated to a fixed open cover \(\mathcal{U}\) form a subcomplex \(C_\ast^\mathcal{U}(U)\)
and the inclusion

\[C_\ast^\mathcal{U}(U) \hookrightarrow C_\ast(U)\]

induces an isomorphism in homology by barycentric subdivision [Ram05, Chap. 4, Prop. 4.12]. Let now

\[C_\ast(U) = \text{Hom}(C_\ast(U), \mathbb{Z}), \quad \text{and} \quad C_\ast^\mathcal{U}(U) = \text{Hom}(C_\ast^\mathcal{U}(U), \mathbb{Z})\]
denote the complexes of singular cochains and singular cochains subordinated to \(\mathcal{U}\).

The assignment \(U \mapsto C_\ast(U)\) (resp. \(U \mapsto C_\ast^\mathcal{U}(U)\)) defines a complex \(C^\ast\) (resp. \(C^\ast_\mathcal{U}\))
of presheaves of abelian groups on \(M\) such that the natural map \(C^\ast \to C^\ast_\mathcal{U}\) is a
quasi-isomorphism.

The presheaves \(C^n\) are flasque in the sense that the restriction maps \(C^n(U) \to C^n(V)\) are surjective.
Indeed, for a cochain \(\varphi : C_n(V) \to \mathbb{Z}\), a preimage is the cochain \(C_n(U) \to \mathbb{Z}\) that sends a simplex \(\sigma : \Delta^n_{\ast i} \to U\) to \(\varphi(\sigma)\) if it lands in \(V\)
and to zero otherwise. The presheaves \(C^n\) are *not* sheaves but they satisfy the
gluing condition iv) from Definition A.186. Let \(\tilde{C}^n\) denote the associated sheaves.
If one further assumes that all open subsets \(U\) of \(M\) are paracompact\(^4\), then the
natural maps \(C^n(U) \to \tilde{C}^n(U)\) are surjective [Ram05, Chap. 1, Prop. 1.4]. As a
consequence, the sheaves \(\tilde{C}^n\) are also flasque. Indeed, given open subsets \(U \subset V \subset M\), in the commutative diagram

\[
\begin{array}{ccc}
C^n(U) & \longrightarrow & C^n(V) \\
\downarrow & & \downarrow \\
\tilde{C}^n(U) & \longrightarrow & \tilde{C}^n(V)
\end{array}
\]

we already know that the upper horizontal map and the vertical maps are surjective,
and hence so is the lower horizontal map.

\(^4\)Recall that a topological space \(M\) is said to be *paracompact* if it is Hausdorff and every open
cover can be refined to a locally finite cover, that is, given an open cover \(U = (U_i)_{i \in I}\) there exists
an open cover \(\mathcal{V} = (V_j)_{j \in J}\) such that each \(V_j\) is contained in some \(U_i\) and every point \(x \in M\) has
an open neighborhood which only intersects finitely many \(V_j\).
Let now $U$ be an open subset and $\mathcal{U}$ an open cover of $M$. The kernel of the map $C^*(U) \to C^*_\mathcal{U}(U)$ consist of the sections that vanish when restricted to $V \cap U$ for all $V \in \mathcal{U}$. Therefore, any such section is mapped to zero in $\check{C}^*(U)$ by the sheaf condition. Thus, the map $C^*(U) \to \check{C}^*(U)$ factors through a map $C^*_\mathcal{U}(U) \to \check{C}^*(U)$.

Moving $\mathcal{U}$, we obtain a map

\[(A.235) \quad \lim_{\mathcal{U}} C^*_\mathcal{U}(U) \longrightarrow \check{C}^*(U).\]

By the surjectivity of the map $C^*(U) \to \check{C}^*(U)$ we deduce the surjectivity of the map $(A.235)$. Moreover, if a section $s \in C^*(U)$ is mapped to zero in $\check{C}^*(U)$, then it is mapped to zero in all the stalks of points of $U$. Therefore there is an open cover $\mathcal{U}$ of $U$ such that $s$ is mapped to zero in $C^*_\mathcal{U}(U)$. We conclude that the map $(A.235)$ is also injective, hence an isomorphism.

Since all transition maps in $(A.235)$ are surjective, this limit satisfies the Mittag-Leffler condition, and hence

\[H^i(\check{C}^*(U)) = \lim_{\mathcal{U}} H^i(C^*_\mathcal{U}(U)) = H^i(C^*(U)).\]

In other words, the complexes $\check{C}^*(U)$ and $C^*(U)$ are quasi-isomorphic.

Let $Z^0 \to C^0$ be the morphism of presheaves (of abelian groups) that sends $1 \in Z^0(U) = \mathbb{Z}$ to the singular cochain $\left(\sum n_x[x] \mapsto \sum n_x\right)$ and let $\mathbb{Z} \to \check{C}^0$ be the associated morphism of sheaves.

**Theorem A.236.** Let $M$ be a locally contractible topological space in which all open subsets are paracompact (e.g. the underlying topological space of a complex manifold). The map $\mathbb{Z} \to \check{C}^0$ induces an isomorphism between sheaf and singular cohomology of $M$:

\[H^*(M, \mathbb{Z}) \xrightarrow{\sim} H^*(M, \mathbb{Z}).\]

**Proof.** The sheaves $\check{C}^n$ are flasque, and hence acyclic by Lemma A.197. Besides, the sequence of sheaves

\[(A.237) \quad \mathbb{Z} \longrightarrow \check{C}^0 \longrightarrow \check{C}^1 \longrightarrow \cdots\]

is exact. Indeed, each point $x \in M$ has a contractible open neighborhood $U_x$, and it suffices to check exactness after taking sections on such a $U_x$. Since the complex $\check{C}^*(U_x)$ is quasi-isomorphic to $C^*(U_x) = C^*(U_x)$, exactness follows from the fact that $H^i(U_x, \mathbb{Z}) = \mathbb{Z}$ and $H^i(U_x, \mathbb{Z}) = 0$ for all $i > 0$, which is an instance of homotopy invariance of singular cohomology. Hence $(A.237)$ is an acyclic resolution, and $H^*(M, \mathbb{Z})$ is isomorphic to the cohomology of the complex $\check{C}^*(M)$. Using again that $\check{C}^*(M)$ is quasi-isomorphic to $C^*(M)$, the latter agrees with singular cohomology. \(\square\)

**Remark A.238.** The preprint [Sel16] contains a proof of this comparison result without the paracompactness assumption.

**Remark A.239.** If $M$ is a smooth manifold, as it is mentioned in part ii) of Remark 2.10, singular homology and cohomology can be computed also using smooth chains and cochains.

A simplex $\sigma: \Delta^n_{st} \to M$ is called smooth if there exists an open neighbourhood $V$ of $\Delta^n_{st} \subset \mathbb{R}^{n+1}$ and a smooth map $\bar{\sigma}: V \to M$ such that $\sigma = \bar{\sigma}|_{\Delta^n_{st}}$. A chain $\sum_j n_j \sigma_j$ is called smooth if all the simplices $\sigma_j$ are smooth. If $U \subset M$ is an open
subset, we denote by \( C_{sm,n}(U) \subset C_n(U) \) the subspace of smooth chains and by \( S^n(U) = \text{Hom}(C_{sm,n}(U), \mathbb{Z}) \) the space of smooth singular cochains. The boundary maps \( \partial \) send smooth singular chains to smooth singular chains, making \( C_{sm}^\ast(U) \) into a chain complex and defining a differential in \( S^\ast(U) \). The maps

\[
C_{sm}^\ast(U) \longrightarrow C_\ast(U) \text{ and } C_\ast(U) \longrightarrow S^\ast(U)
\]

are quasi-isomorphisms, see e.g. [War83, 5.32] or [Lee13, Thm. 18.7]. Therefore, everything we have done in this section can be repeated for smooth singular cochains. In particular, we obtain a complex of flasque sheaves \( \tilde{S}_\ast \) and, by Theorem A.236, a quasi-isomorphism

\[
\mathbb{Z} \longrightarrow \tilde{S}_\ast.
\]

that gives an isomorphism between the cohomology of the constant sheaf and smooth singular cohomology. In fact, for any ring \( \Lambda \), we will write \( S^\ast(M, \Lambda) = \text{Hom}(C_{sm,n}(M), \Lambda) \) and there are isomorphisms

\[
H^\ast(M, \Lambda) \cong H^\ast(S^\ast(M, \Lambda)).
\]

We will apply this result mainly when \( \Lambda = \mathbb{Q}, \mathbb{R} \).

A.9.9. Coherent sheaves. In this section, we briefly recall the notion of coherent sheaf in algebraic and analytic geometry and some vanishing theorems for higher cohomology groups of coherent sheaves due to Cartan and Serre.

Recall that an algebraic variety \( X \) comes equipped with a sheaf of rings \( \mathcal{O}_X \), the sheaf of regular functions. Similarly, a complex manifold \( X \) is endowed with a sheaf of rings, the sheaf of holomorphic functions that is denoted in the same way \( \mathcal{O}_X \). In both cases, the sheaf \( \mathcal{O}_X \) is called the structure sheaf. This abuse of notation is intentional because we can state similar results in algebraic geometry and in complex geometry with the same words. So from now on \( X \) will be either an algebraic variety or a complex manifold. Once we have the structural sheaf \( \mathcal{O}_X \), we can talk about \( \mathcal{O}_X \)-modules. Among them the ones that are more directly related to geometry are the coherent ones.

**Definition A.240.** Let \( X \) be either an algebraic variety or a complex manifold. A **sheaf of \( \mathcal{O}_X \)-modules** is a sheaf of abelian groups \( F \) on the underlying topological space such that, for every open set \( U \) of \( X \), the abelian group \( F(U) \) carries the structure of an \( \mathcal{O}_U \)-module. Moreover, for each inclusion \( V \subset U \) and sections \( f \in \mathcal{O}_X(U), s \in F(U) \), the relation

\[
(f \cdot s)|_V = f|_V \cdot s|_V
\]

holds. That is, the restriction maps are compatible with the \( \mathcal{O}_X \)-module structures. The basic examples of \( \mathcal{O}_X \)-modules are the sheaf \( \mathcal{O}_X \) itself and the direct sums \( \mathcal{O}_X^I \), for \( I \) a set. A sheaf of \( \mathcal{O}_X \)-modules \( F \) is called **quasi-coherent** if every point has a neighborhood \( U \) such that the restriction \( F|_U \) fits in an exact sequence

\[
\mathcal{O}_U^I \longrightarrow \mathcal{O}_U^J \longrightarrow F|_U \longrightarrow 0,
\]

with \( I \) and \( J \) arbitrary sets. The sheaf \( F \) is called **coherent** if the sets \( I \) and \( J \) can be chosen finite.

In algebraic geometry, a scheme is called **affine** if it is of the form \( \text{Spec}(A) \) for some ring \( A \). If \( X \) is an algebraic variety over a field \( k \), being affine is equivalent to
being a closed subvariety of an affine space $\mathbb{A}^N_k$ over $k$. Similarly, in complex geometry there is the analogous notion of \textit{Stein manifold} (or more generally Stein space). The embedding theorem for Stein manifolds implies that a complex manifold is Stein if and only if it is a closed holomorphic submanifold of an affine space $\mathbb{C}^n$.

The next result is due to Cartan in the case of coherent sheaves over a Stein manifold and to Serre for quasi-coherent sheaves on a Noetherian scheme. For a proof in the algebraic case see [Har77, Thm. III.3.7].

**Theorem A.241.** Let $X$ be a noetherian affine scheme (resp. a Stein complex manifold) and let $F$ be a quasi-coherent (resp. coherent) sheaf of $\mathcal{O}_X$-modules. Then

$$H^i(X, F) = 0 \text{ in all degrees } i \geq 1.$$ 

The previous theorem has also a relative version, that we now explain.

A morphism of schemes $f : X \to Y$ is called \textit{affine} if there is a covering $Y = \bigcup_i U_i$ of $Y$ by affine open subsets such that $f^{-1}(U_i)$ is affine for each $i$. Equivalently, $f$ is affine if the inverse image of any affine open subset of $Y$ is affine.

**Example A.242.** Let $X$ be a scheme and $D$ an effective Cartier divisor of $X$. For instance any effective divisor in a smooth variety. Then the inclusion $j : X \setminus |D| \to X$ is affine. Indeed, since $D$ is Cartier and effective, there is a covering of $X$ by open affine subsets $U_i = \text{Spec}(A_i)$ such that $D|U_i$ is defined by the equation $f_i = 0$, with $f_i \in A_i$. Then $j^{-1}(U_i) = \text{Spec}(A_i[f_i^{-1}])$ is affine.

Note that it is important that $D$ is a divisor. For instance the inclusion $\mathbb{A}^2 \setminus \{(0,0)\} \to \mathbb{A}^2$ is not affine.

Similarly, a morphism of complex manifolds is called \textit{Stein} if the inverse image of every open Stein subset of the target is Stein.

**Theorem A.243.** Let $f : X \to Y$ be an affine morphism of noetherian schemes (resp. a Stein morphism of complex manifolds) and let $F$ be a quasi-coherent (resp. coherent) sheaf of $\mathcal{O}_X$-modules. Then

$$R^i f_* F = 0 \text{ for all } i \geq 1.$$ 

In other words, quasi-coherent (resp. coherent) sheaves are acyclic for the direct image functor $f_*$. 

**Proof.** By Proposition A.214, the stalk of the higher direct image sheaf $R^i f_* F$ at a closed point $y$ of $Y$ is given by

$$(R^i f_* F)_y = \lim_{y \in V} H^i(f^{-1}(U), F).$$

As one can restrict to affine (resp. Stein) neighborhoods of $y$ to compute the limit, the right-hand vanishes for all $i \geq 1$ by Theorem A.241. □

**A.9.10. Local systems as representations of the fundamental group.** In this section, we discuss a class of sheaves on a topological space called \textit{local systems} and we prove that, under some hypothesis, the category they form is equivalent to the category of representations of the fundamental group of the topological space.

**Definition A.244.** A sheaf $F$ on a topological space $M$ is said to be \textit{locally constant} if there exists an open cover $\{U_i\}_{i \in I}$ of $M$ such that all the restrictions $F|_{U_i}$ are constant sheaves as in i) of Examples A.189. A locally constant sheaf is also called a \textit{local system}. 

Theorem A.245. Let $M$ be a Hausdorff, second countable, connected, locally compact and locally contractible topological space. Let $x_0 \in M$ be a point and $V$ a vector space. There is an equivalence of categories between the category of local systems $F$ on $M$ with fiber $F_{x_0} = V$ and the category of representations of $\pi_1(X, x_0)$ on $V$.

Proof. We first show how to construct a local system from a representation of the fundamental group. For every point $x \in M$ we choose once and for all a path $\alpha_x \in \pi(M)_{x_0}$. Thus, $\alpha_x : [0, 1]$ is a piecewise smooth map with $\alpha_x(0) = x_0$ and $\alpha_x(1) = x$. Let $\rho : \pi_1(M, x_0) \to \text{GL}(V)$ be a representation. We define a sheaf $F$ by describing its sections. For every open set $U \subset M$, let $F(U)$ be the vector space of all functions $f : U \to V$ satisfying that, for every pair of points $x, y \in U$ and path $\gamma \in \gamma \mathcal{P}(U)_x$, the relation

$$\rho((\alpha_y^{-1} \cdot \gamma \cdot \alpha_x)) \cdot f(x) = f(y)$$

holds. The fact that $F$ is a sheaf is left as Exercise A.257. We now show that $F$ is locally constant. Since $M$ is assumed to be locally contractible we can cover $M$ with contractible open subsets. Let $U$ be one of these subsets. We show that $F(U) \cong V$. Choose a point $x \in U$ and let $\varphi_x : F(U) \to V$ be the map $f \mapsto f(x)$. The map $\varphi_x$ is injective. Indeed, since $U$ is contractible, it is in particular connected. Therefore, for each $y$ there is a path $\gamma \in \gamma \mathcal{P}(U)_x$, so, if $\varphi_x(f) = f(x) = 0$, then

$$f(y) = \rho((\alpha_y^{-1} \cdot \gamma \cdot \alpha_x)) \cdot f(x) = 0,$$

thus $f = 0$. We now show that $\varphi_x$ is surjective. Let $v \in V$, for every point $y$ choose a path $\gamma_y \in \gamma \mathcal{P}(U)_x$ and define $f_v$ by the rule

$$f_v(y) = \rho((\alpha_y^{-1} \cdot \gamma_y \cdot \alpha_x)) \cdot v.$$  

The resulting function is independent of the choice of paths $\gamma_y$. Since $U$ is contractible, it is in particular simply-connected. Therefore if $\gamma'_y$ is another choice, then $[\gamma_y] = [\gamma'_y] \in \pi(M; y, x)$. Therefore

$$\rho((\alpha_y^{-1} \cdot \gamma'_y \cdot \alpha_x)) = \rho((\alpha_y^{-1} \cdot \gamma_y \cdot \alpha_x)).$$

Then $f_v$ is easily seen to be a section of $F(U)$. Moreover $f_v(x) = v$, showing that $\varphi_x$ is surjective and hence an isomorphism. The same argument can be repeated to show that for each connected open subset $U' \subset U$ the restriction $F(U) \to F(U')$ is an isomorphism showing that $F|_U$ is isomorphic to the constant sheaf.

The next step is to produce a representation of $\pi_1(M, x_0)$ starting with a locally constant sheaf with fiber $F_{x_0} = V$. Let $F$ be such a sheaf. An open subset $U \subset M$ will be called good (for this sheaf) if $U$ is connected and $F|_U$ is isomorphic to the constant sheaf $V$ on $U$. Since $F$ is locally constant, $M$ can be covered by good open subsets. Let $\gamma \in \gamma \mathcal{P}(X)_x$ be a path between two points. Using that $[0, 1]$ is compact, we can choose a finite set of points $0 = t_0 < t_1 < \cdots < t_k < t_{k+1} = 1$ and good open sets $U_j$, $j = 0, \ldots, k$ such that $\gamma([t_j, t_{j+1}]) \subset U_j$. For each $j = 0, \ldots, k$ there is an isomorphism

$$\rho_j : F_{\gamma(t_j)} \to F_{\gamma(t_{j+1})},$$

given as the composition

$$F_{\gamma(t_j)} \xrightarrow{\sim} F(U_j) \xrightarrow{\sim} F_{\gamma(t_j)}.$$
We denote by $\rho_\gamma : F_x \to F_y$ the composition

$$\rho_\gamma = \rho_k \circ \cdots \circ \rho_0.$$  

The fact that $\rho_\gamma$ is independent of the choices follows from two properties:

i) the isomorphism $\rho_j$ does not depend on the choice of the good open set $U'$ containing $\gamma([t_j, t_{j+1}]);$

ii) the composition $\rho_\gamma$ does not change if we add a point $t'_j$ with $t_j < t'_j < t_{j+1}.$

The next step is to show that $\rho_\gamma$ only depends on the homotopy class $[\gamma] \in \pi_1(M; y, x).$ Let $\gamma$ and $\gamma'$ be two paths and $H$ a homotopy between them. We can find points

$$0 = t_0 < t_1 < \cdots < t_k < t_{k+1} = 1, \quad 0 = s_0 < s_1 < \cdots < s_{\ell} < s_{\ell+1} = 1$$

and good open sets $U_{i,j}$ such that $H([t_i, t_{i+1}] \times [s_j, s_{j+1}]) \subset U_{i,j}.$ Then one checks that the square

$$\begin{array}{ccc}
F_{H(t_i,s_j)} & \cong & F_{H(t_i,s_{j+1})} \\
\cong & \quad & \cong \\
F_{H(t_{i+1},s_j)} & \cong & F_{H(t_{i+1},s_{j+1})}
\end{array}$$

is commutative. From this it follows that $\rho_{\gamma'} = \rho_\gamma.$ The map $\rho_\gamma$ is called the parallel transport along $\gamma.$

As a consequence of this construction there is a representation

$$\rho : \pi_1(X, x_0) \to \text{GL}(V)$$

given by $[\gamma] \mapsto \rho_\gamma.$

We leave to the reader to check that the constructions we have described are inverses of each other and are functorial. □

**Remark A.246.** It is clear from the proof of Theorem A.245 that the hypothesis are an overkill, but are satisfied in the examples we are interested in. For instance, instead of asking the topological space to be locally contractible it is enough to ask it to be locally path-connected and semilocally simply-connected. The second condition means that every point has a neighborhood such that every loop in the neighborhood is null-homotopic in the whole space.

**Remark A.247.** The relation between the categories of local systems and that of representations of the fundamental group implies a relation between the cohomology of a local system as a sheaf and group cohomology of its fiber. More precisely, let $M, x_0$ and $V$ be as in Theorem A.245. Write $\Gamma = \pi_1(M, x_0)$ for the fundamental group of $M$ and let $F$ be a local system on $M$ with fiber $V.$ This turns $V$ into a $\Gamma$-module. Then, for all $i \geq 0,$

$$H^i(M, F) = H^i(\Gamma, V),$$

where the left-hand side is sheaf cohomology and the right-hand side is group cohomology.

***
EXERCISE A.248. Prove that a sheaf \( F \) satisfies \( F(\emptyset) = 0 \), while this does not necessarily hold for presheaves.

EXERCISE A.249. Let \( M \) be a topological space and let \( \mathcal{B} \) be a basis of its topology, that is, a collection of open subsets that cover \( M \) and such that, for any two basis elements \( U_1, U_2 \in \mathcal{B} \) and any point \( x \in U_1 \cap U_2 \), there exists a basis element \( U_3 \in \mathcal{B} \) such that \( x \in U_3 \subset U_1 \cap U_2 \). Show that any assignment \( U \mapsto F(U) \), for each \( U \in \mathcal{B} \), satisfying the four conditions in Definition A.186 determines uniquely a sheaf \( F \) on \( M \).

EXERCISE A.250. Let \( M \) be a topological space and let \( \iota : N \to M \) be the inclusion of a closed subspace. Show that, given a sheaf \( F \) on \( N \), the direct image sheaf \( \iota_* F \) from Definition A.211 is the extension by zero of \( F \), that is, the sheaf on \( N \) with stalks \( F_x \) if \( x \in N \) and 0 otherwise. Then prove that \( \iota_* \) is an exact functor, so that the higher direct image sheaves vanish.

EXERCISE A.251. Let \( M \) be a locally compact Hausdorff space and \( j : U \to M \) an open immersion. Prove that the functor \( j! \) is exact.

EXERCISE A.252. Let \( M \) be a compact Hausdorff topological space, \( j : U \to M \) an open immersion and \( i : Z \to M \) the complementary closed immersion. Let \( F \) be a sheaf on \( X \).

i) Prove that there is an exact sequence
\[
0 \to j_! j^{-1} F \to F \to i_* i^{-1} F \to 0.
\]

ii) Prove that, since \( M \) is compact, there is a canonical isomorphism
\[
H^*(M, j_! j^{-1} F) \simeq H^*_c(U, j^{-1} F).
\]

iii) Let \( * \) be the topological space containing a single point and let \( \pi_M, \pi_U \) and \( \pi_Z \) the unique maps from \( M, U \) and \( Z \) to \( * \). Using exercises A.250 and A.251 show that there is a canonical isomorphism
\[
R(\pi_U)_* j^{-1} F \simeq \text{Tot}(R(\pi_M)_* F \to R(\pi_Z)_* i^{-1} F).
\]

iv) Assume that \( M \) and \( Z \) satisfy the hypothesis of Theorem A.236. Particularize the previous result to the case \( F = \mathbb{Z} \) to show that there is a canonical isomorphism
\[
H^*_c(U, \mathbb{Z}) \simeq H^*(M, Z; \mathbb{Z}).
\]

Conclude that there is a long exact sequence
\[
\cdots \to H^*_c(U, \mathbb{Z}) \to H^*(M, \mathbb{Z}) \to H^*(Z, \mathbb{Z}) \to \cdots
\]

v) Generalize the previous result to the case when \( M \) is not necessarily compact. Namely, if \( M \) is a topological Hausdorff space, then there is a long exact sequence
\[
\cdots \to H^*_c(U, \mathbb{Z}) \to H^*_c(M, \mathbb{Z}) \to H^*_c(Z, \mathbb{Z}) \to \cdots
\]

EXERCISE A.253. Let \( M \) be a topological space and let \( A^* \) be a bounded below complex of sheaves of abelian groups. Consider the Godement resolution \( Gd \) from Section A.9.3. Show that there is a natural isomorphism of complexes
\[
Gd(A[k]^*) \to Gd(A^*)[k].
\]
Exercise A.254. Let $F^*$ be a complex of sheaves. We can consider the increasing canonical filtration of $F^*$ and apply Godement’s resolution to it, to obtain the filtered complex $(\text{Gd}(F^*), \text{Gd}(\tau_{\leq})).$ Or we can consider directly the canonical filtration of the total complex $(\text{Tot}^*(\text{Gd}^*(F^*)), \tau_{\leq}).$ In general both filtrations are different. Prove that the identity map gives a filtered quasi-isomorphism $(\text{Tot}^*(\text{Gd}^*(F^*)), \tau_{\leq}) \to (\text{Gd}(F^*), \text{Gd}(\tau_{\leq})).$

Exercise A.255. Let $M = \mathbb{C}^2$ be the complex affine plane and let $j: U \hookrightarrow M$ be the inclusion of the complement of a point. Compute the higher direct image sheaves $R^i j_* \mathbb{Z}.$


Exercise A.257. Let $M$ be a connected locally contractible topological space and let $\rho$ be a representation of its fundamental group. Show that the presheaf $F$ constructed in the proof of Theorem A.245 is a sheaf.

Exercise A.258. Let $F$ be a fine sheaf on a paracompact topological space $M.$ Let $\text{Gd}(F)$ be Godement’s canonical resolution of $F.$ Prove the following statements.

i) Let $\{U_i\}$ be a locally finite covering of $M$ and $h_i$ a partition of unity subordinated to this covering. Prove that the endomorphisms $h_i$ induce endomorphisms, also denoted $h_i,$ of the complex $\text{Gd}(F),$ and these endomorphisms still satisfy that the support of $h_i$ is contained in $U_i.$

ii) Use i) to prove that $H_p(M, F) = 0$ for all $p > 0.$ [Hint: show that, given a global section $s \in \Gamma(M, \text{Gd}^p(M))$ with $ds = 0,$ then a partition of unity allows us to glue together local primitives to obtain a global primitive of $s.$]

Exercise A.259. Let $X = \mathbb{C}^\times$ viewed as a Stein complex manifold and consider the constant sheaf $\mathcal{C}_X.$ Use Theorem A.241 to show that this sheaf does not admit any structure of coherent $\mathcal{O}_X$-module.

A.10. Lie algebra homology and cohomology. In this section, we gather some properties of Lie algebra homology and cohomology following [Wei94, Ch. VII]. Throughout, $k$ denotes a field of characteristic zero.

A.10.1. Lie algebras and Lie modules. We fix a field $k$ of characteristic zero.

Definition A.260. A Lie algebra (over $k$) is a $k$-vector space $L$ together with a bilinear map, called the Lie bracket,

$$[\cdot, \cdot]: L \times L \to L$$

such that the equalities

\begin{align*}
(A.261) \quad [x, y] + [y, x] &= 0 \quad \text{(antisymmetry),} \\
(A.262) \quad [x, [y, z]] + [y, [z, x]] + [z, [x, y]] &= 0 \quad \text{(Jacobi identity)}
\end{align*}

hold for all $x, y, z \in L.$

Definition A.263. Let $L$ be a Lie algebra over $k.$ A left $L$-module is the data of a $k$-vector space $L$ and a bilinear map

$$L \times M \to M$$
such that the equality
\[ [x, y]m = x(ym) - y(xm) \]
holds for all \( x, y \in L \) and all \( m \in M \). A morphism of left \( L \)-modules is a \( k \)-linear map \( f : M \to N \) that satisfies \( f(xm) = xf(m) \) for all \( x \in L \) and all \( m \in M \).

The notion of right \( L \)-module is defined with the obvious modifications.

Note that a left \( L \)-module gives rise to a Lie algebra representation, in the sense of Definition 3.121, and conversely every Lie algebra representation defines a left \( L \)-module structure. Both notions are thus equivalent.

**Example A.264.** Let \( L \) be a Lie algebra and \( M \) a \( k \)-vector space. The trivial Lie module structure on \( M \) is defined by the rule
\[ xm = 0 \quad \text{for all } x \in L \text{ and } m \in M. \]
This gives rise to a functor from the category of \( k \)-vector spaces to the category of left \( L \)-modules, which will be called the trivial \( L \)-module functor.

Recall from Section 3.2.11 that every Lie algebra can be embedded into an associative algebra in such a way that the Lie bracket is given by the commutator.

**Definition A.265.** Let \( L \) be a Lie algebra over \( k \). The universal enveloping algebra is an associative \( k \)-algebra \( U(L) \) along with a morphism of Lie algebras \( \iota_L : L \to U(L) \), that is, a \( k \)-linear map satisfying
\[ \iota([x, y]) = \iota(x)\iota(y) - \iota(y)\iota(x) \]
for all \( x, y \in L \), and that is universal among associative algebras with this property.

It is proved in the aforementioned section that the universal enveloping algebra always exists (see formula (3.93)), that the map \( \iota_L \) is injective (Corollary 3.97) and that the category of left \( L \)-modules is equivalent to the category of left \( U(L) \)-modules (Proposition 3.123).

**A.10.2. Homology and cohomology.** Given a Lie algebra \( L \), there are two functors from the category of \( k \)-vector spaces to the category of left \( L \)-modules that play a role in the definition of Lie algebra homology and cohomology.

**Definition A.266.** Let \( L \) be a Lie algebra and \( M \) a left \( L \)-module.

i) The subspace of invariant elements is defined as
\[ M^L = \{ m \in M \mid xm = 0 \text{ for all } x \in L \}. \]

The assignment \( M \mapsto M^L \) is a functor from the category of left \( L \)-modules to the category of \( k \)-vector spaces. Moreover, if \( k \) is given the trivial left \( L \)-module structure, then the invariants are equal to
\[ (A.267) \quad M^L = \text{Hom}_{U(L)}(k, M). \]

ii) The quotient of coinvariants is defined as
\[ (A.268) \quad M_L = M/LM = k \otimes_{U(L)} M, \]
where \( k \) is given again the trivial left \( L \)-module structure and we use the identification \( k = U(L)/LU(L) \) to derive the second equality.
Remark A.269. The functor $M \mapsto M^L$ is right adjoint to the trivial left $L$-module functor from Example A.264. That is, there is a canonical bijection

$$\text{Hom}_{U(L)}(M, N) = \text{Hom}_k(M, N^L)$$

for all $k$-vector spaces $M$ and all left $L$-modules $N$ (see Exercise A.281). In particular, as all right adjoints, it is a left exact functor.

Similarly, the functor $M \mapsto M^L$ is left adjoint to the trivial left $L$-module functor. That is, there is a canonical bijection

$$\text{Hom}_k(M^L, N) = \text{Hom}_{U(L)}(M, N)$$

for all left $L$-modules $M$ and all $k$-vector spaces $N$. In particular, as all left adjoints, it is a right exact functor.

Being equivalent to the category of left modules for the ring $U(L)$, the category of left $L$-modules has enough injectives (Example A.82) and projectives (REFERENCE). An example of a projective left $L$-module is the universal enveloping algebra $U(L)$ itself with the left $L$-module structure induced by the product in $U(L)$.

Definition A.270. Let $L$ be a Lie algebra over $k$, let $M$ be a left $L$-module, and $i \geq 0$ an integer.

i) The $i$-th cohomology group $H^i(L, M)$ is the $i$-th cohomological right derived functor of the invariants functor $(\cdot)^L$.

ii) The $i$-th homology group $H_i(L, M)$ is the $i$-th cohomological left derived functor of the coinvariants functor $(\cdot)_L$.

Taking the equality (A.267) into account, Lie cohomology can be computed as

$$H^i(L, M) = \text{Ext}^i_k(U(L), M) = \text{Ext}^i_{U(L)}(k, M).$$

Similarly, using the equality (A.268), Lie homology is given by

$$H_i(L, M) = \text{Tor}^i_{U(L)}(k, M).$$

A.10.3. The Chevalley–Eilenberg complex. The main tool to compute homology and cohomology of Lie algebras is the Chevalley–Eilenberg complex.

Definition A.271. Let $L$ be a Lie algebra over $k$. The Chevalley–Eilenberg complex of $L$ is the chain complex of left $U(L)$-modules $(V^\bullet(L), \partial)$ with

$$V_p(L) = U(L) \otimes_k \Lambda^p L$$

in degree $p$ and differential $\partial_p : V_p(L) \to V_{p-1}L$ given by

$$\partial_p(u \otimes x_1 \wedge \cdots \wedge x_p) = \sum_{i=1}^p (-1)^{i+1}ux_i \otimes x_1 \wedge \cdots \wedge \hat{x}_i \wedge \cdots \wedge x_p$$

$$+ \sum_{1 \leq i < j \leq p} (-1)^{i+j}u \otimes [x_i, x_j] \wedge x_1 \wedge \cdots \wedge \hat{x}_i \wedge \cdots \wedge \hat{x}_j \wedge \cdots \wedge x_p$$

for $u \in U(L)$ and $x_i \in L$.

Note that all terms in the Chevalley–Eilenberg complex are free, and hence projective, $U(L)$-modules. Indeed, they are the tensor product of the the free $U(L)$-module $U(L)$ with the $k$-vector space $\Lambda^p L$. 
Theorem A.272. Let $\epsilon : V_0(L) = U(L) \to k$ be the augmentation. Then

$$V_*(L) \xrightarrow{\epsilon} k$$

is a projective resolution of the trivial module $k$ in the category of left $U(L)$-modules.

The proof relies on the Poincaré–Birkhoff–Witt theorem, see [Wei94, Cor. 7.7.3]. Applying the coinvariants functor to the Chevalley-Eilenberg complex, one gets a chain complex of $k$-vector spaces called the Koszul complex.

Definition A.273. Let $L$ be a Lie algebra over $k$. The Koszul complex is the chain complex of $k$-vector spaces $(K^*_L, \partial)$ with

$$K^n_L = \Lambda^n L$$

in degree $p$ and differential

$$\partial_p(x_1 \wedge \cdots \wedge x_p) = \sum_{1 \leq i < j \leq p} (-1)^{i+j} [x_i, x_j] \wedge x_1 \wedge \cdots \wedge \hat{x}_i \wedge \cdots \wedge \hat{x}_j \wedge \cdots \wedge x_p.$$

In particular, the Koszul complex starts as

$$\cdots \to L \wedge L \xrightarrow{[-,-]} L \xrightarrow{0} k.$$

Thanks to Theorem A.272, Lie algebra homology and cohomology with trivial coefficients can be computed using the Koszul complex.

Proposition A.274. Let $L$ be a Lie algebra over $k$. The homology groups $H_*(L, k)$ are the homology of the chain complex $K_*(L)$, and the cohomology groups $H^*(L, k)$ are the cohomology of the cochain complex $\text{Hom}_k(K_*(L), k)$. That is, there canonical isomorphisms

$$H_n(L, k) = H_n(K_*(L)), \quad H^n(L, k) = H^n(\text{Hom}_k(K_*(L), k)).$$

Proof. Since $V_*(L)$ is a projective resolution of $k$ and $H_i(L, k) = \text{Tor}^U_i(L, k)$, while $H^i(L, k) = \text{Ext}^i_{U(L)}(k, k)$ the result follows from the facts

$$K_*(L) = k \otimes U(L) V_*(L),$$

$$\text{Hom}_k(K_*(L), k) = \text{Hom}_{U(L)}(V_*(L), k).$$

□

A.10.4. Homology and cohomology of graded Lie algebras.

Definition A.275. A graded algebra $A$ in an algebra $A$ together with a decomposition

$$A = \bigoplus_{n \in \mathbb{Z}} A_n$$

such that $A_n \cdot A_m \subset A_{n+m}$.

This definition applies to Lie algebras and to associative algebras.

Definition A.276. Let $A$ be an algebra (associative or Lie). A graded $A$-module $M$ is an $A$-module together with a decomposition

$$M = \bigoplus_{n \in \mathbb{Z}} M_n$$

such that $A_n \cdot M_m \subset M_{n+m}$.

The category of graded left $A$-modules will be denoted $\text{GrMod}_A$. 
Example A.277. Let \( n \) be an integer. The graded left \( L \)-module \( k(n) \) is the trivial \( L \)-module \( k \) concentrated in degree \( -n \). If \( M \) is a graded left \( L \)-module, we define \( M(n) = M \otimes_k k(n) \). That is, \( M(n) \) is the same module \( M \) with the decomposition given by \( M(n)_m = M_{n+m} \).

Let \( L \) be a graded Lie algebra. Then, using for instance the Poincaré–Birkhoff–Witt theorem, the associative algebra \( U(L) \) inherits a structure of graded algebra. The categories \( \text{GrMod}_L \) and \( \text{GrMod}_{U(L)} \) are equivalent.

The Chevalley–Eilenberg complex can be seen as a complex of graded left \( U(L) \)-modules. The Koszul complex is a complex of graded \( k \)-vector spaces and since the differential is homogeneous of degree zero, the homology of the Koszul complex is again a graded vector space. More concretely

\[
K_*(L) = \bigoplus_n K_*(L)_n
\]

with

\[
K_i(L)_n = (\Lambda^i L)_n.
\]

Moreover

\[
\partial K_i(L)_n \subset K_{i-1}(L)_n
\]

and

\[
H_i(K_*(L))_n = H_i(K_*(L)_n).
\]

We define the graded dual of the Koszul complex

\[
K^*(L)_n = \text{Hom}_k(K_*(L)_{-n}, k)
\]

and the graded cohomology

\[
H^*(K^*(L)_n).
\]

Proposition A.278. Let \( L \) be a graded Lie algebra. Then, for every \( i, n \),

\[
H^i(K^*(L)_n) = (H_i(K_*(L))_{-n})^\vee.
\]

Proof. Since every \( k \)-vector space is projective. Then the universal coefficients theorem ([Wei13, Thm. 3.6.5]) implies the result. \( \square \)

Theorem A.279. Let \( L \) be a graded Lie algebra. Then

\[
\text{Ext}^i_{\text{GrMod}_{U(L)}}(k(n), k) = H^i(K^*(L)_{-n})
\]

Proof. The category \( \text{GrMod}_{U(L)} \) has enough projectives. In fact, the Chevalley–Eilenberg complex is still a projective resolution \( V_*(L) \rightarrow k \) of the trivial vector bundle in the category \( \text{GrMod}_{U(L)} \). Changing the degree we obtain that \( V_*(L)(n) \) is a projective resolution of \( k(n) \). Then

\[
\text{Ext}^i_{\text{GrMod}_{U(L)}}(k(n), k) = H^i(\text{Hom}_{\text{GrMod}_{U(L)}}(V_*(L)(n), k))
\]

\[
= H^i(\text{Hom}_{\text{GrMod}_k}(K_*(L)(n), k))
\]

\[
= H^i(K_*(L)(n), k)
\]

\[
= H^i(K^*(L)_{-n}),
\]

as we wanted to show. \( \square \)
A.10.5. The structure of a Lie algebra from its homology. In this section, we show one example where the structure of a Lie algebra is determined by its homology. 

Recall that a Lie algebra is called quasi-nilpotent (Definition 3.160) if the lower central series is separated.

Proposition A.280. Let $L = \bigoplus_n L_n$ be a quasi-nilpotent graded Lie algebra over $k$ with $H_1(L, k)$ concentrated in negative degrees and $H_2(L, k) = 0$. Then $L$ is isomorphic to the free algebra generated by $H_1(L, k)$.

Proof. The Koszul complex of $L$ (see A.273 and Proposition A.274) in lower degrees reads

\[ \cdots \rightarrow L \wedge L \wedge L \rightarrow L \wedge L \rightarrow L \rightarrow k, \]

where the last map in the complex is the zero map and the previous to the last is given by the Lie bracket. From this complex we derive the well known identity

\[ H_1(L, k) = L/[L, L]. \]

The map $L \rightarrow H_1(L, k)$ is homogeneous and surjective, thus we can choose a homogeneous section $s: H_1(L, k) \rightarrow L$. In general, this section is non-canonical. Let $\mathfrak{g}$ be the free Lie algebra generated by $H_1(L, k)$. It is also a quasi-nilpotent graded Lie algebra. By the universal property of free Lie algebras, the chosen section defines a graded map, $\mathfrak{g}(s): \mathfrak{g} \rightarrow L$. We will show that this map is an isomorphism.

Let $F_n$ denote the increasing filtration of $L$ and $F_n\mathfrak{g}$ given by the (opposite of the) degree:

\[ F_n L = \bigoplus_{n' \leq -n} L_{n'}, \quad F_n \mathfrak{g} = \bigoplus_{n' \leq -n} \mathfrak{g}_{n'}. \]

We prove by induction on $n \geq 0$ that the map $F_n\mathfrak{g} \rightarrow F_n L$ is surjective. Since $H_1(L, k)$ has only negative degrees, by construction, $F_0\mathfrak{g} = 0$. Since $L$ is graded, we deduce that $F_0 L$ is a Lie subalgebra. Since $H_1(L, k)$ is concentrated in negative degrees, $F_0 L \subset [L, L]$. Since $L$ is a graded Lie algebra, this implies $F_0 L \subset [L, F_0 L]$. Using now that $L$ is quasi-nilpotent, we deduce that $F_0 L = \{0\}$, so we have proven that the case $n = 0$ of the induction process is true.

We now assume that $F_n\mathfrak{g} \rightarrow F_n L$ is surjective for all $n' < n$. Since we can write

\[ F_n L / F_{n-1} L = s \left( H_1(L, k)_n \right) + [L, L]_n, \]

where $H_1(L, k)_n$ and $[L, L]_n$ denote the homogeneous component of degree $n$ of $H_1(L, k)$ and $[L, L]$ respectively. Clearly, $s \left( H_1(L, k)_n \right)$ lies in the image of $\mathfrak{g}(s)$. Since $F_0 L = 0$, every elements of $[L, L]_n$ is a linear combination of products of terms of lower degree. Therefore, the induction hypothesis implies that $[L, L]_n$ also lies in the image of $\mathfrak{g}(s)$. In consequence, the map $F_n\mathfrak{g} \rightarrow F_n L$ is surjective. Since $L$ is graded,

\[ L = \bigoplus_{n \in \mathbb{Z}} L_n = \bigcup_{n \geq 0} F_n L, \]

and we conclude the surjectivity of $\mathfrak{g} \rightarrow L$. 
Let now \( k \subset F \) denote the kernel of the map \( F \to L \). We have a commutative diagram

\[
\begin{array}{cccccc}
\mathfrak{g} \wedge \mathfrak{k} & \to & \mathfrak{k} \\
\uparrow & & \uparrow \\
\mathfrak{g} \wedge \mathfrak{g} \wedge \mathfrak{g} & \to & \mathfrak{g} \wedge \mathfrak{g} & \to & \mathfrak{g} & \to & H_1(L, k) \\
\downarrow & & \downarrow & & \downarrow & & \downarrow \\
L \wedge L \wedge L & \to & L \wedge L & \to & L & \to & H_1(L, k),
\end{array}
\]

where \( \mathfrak{g} \wedge \mathfrak{k} \) is the image of \( \mathfrak{g} \otimes \mathfrak{k} \) in \( \mathfrak{g} \wedge \mathfrak{g} \). The long vertical sequences are exact by definition, and the upper long horizontal sequence is exact because \( \mathfrak{g} \) is the free Lie algebra generated by \( H_1(L, k) \). The lower long sequence is exact because \( H_2(L, k) = 0 \). A diagram chase argument shows that the top horizontal arrow is surjective. From this we deduce

\[ \mathfrak{k} \subset [\mathfrak{k}, \mathfrak{g}] \).

Since \( \mathfrak{g} \) is quasi-nilpotent we conclude that \( \mathfrak{k} = 0 \), thus showing the injectivity of the map \( \mathfrak{g} \to L \).

\[ \square \]

***

Exercise A.281. Let \( L \) be a Lie algebra and \( M \) a left \( L \)-module.

i) Prove that \( M^L \) is the largest sub-\( L \)-module of \( M \) on which \( L \) acts trivially. Deduce that \( M^L \) is right adjoint to the trivial left \( L \)-module functor.

ii) Prove that \( M_L \) is the largest \( L \)-module quotient of \( M \) on which \( L \) acts trivially. Deduce that \( M_L \) is left adjoint to the trivial \( L \)-module functor.

Exercise A.282. Let \( L \) be a Lie algebra and \( M \) a left \( L \)-module. Show that the action \( mx = -xm \) defines a structure of right \( L \)-module on \( M \).

Exercise A.283. Let \( A \) be a graded associative algebra with unit. Let \( \mathcal{C} \) be the category of graded left \( A \)-modules.

i) For \( n \in \mathbb{Z} \), let \( A(n) = A \otimes_k k(n) \). It is the graded \( A \) module with \( A(n)_m = A_{n+m} \). Show that \( A(n) \) is projective in \( \mathcal{C} \).

ii) Conclude that \( \mathcal{C} \) has enough projectives.

Exercise A.284. Find examples showing that all the hypothesis of Proposition A.280 are needed.
References


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\[ \text{Sm}(k) \] the category of smooth varieties over a field \( k \), page 317
\[ s^{(n)} \] the multi-index \((s, \ldots, s)\) of length \( n \), page 26
\[ \text{Tot} \] total complex, page 394
\[ U_{dR} \] the pro-unipotent part of \( G_{dR} \), page 336
\[ \hat{U}(L) \] completed universal enveloping algebra, page 201
\[ U(L) \] universal enveloping algebra, page 199
\[ \text{wt}(s) \] weight of a multi-index, page 22
\[ X^* \] the set of words in the alphabet \( X \), page 37
\[ Z \] the \( \mathbb{Q} \)-algebra of multiple zeta values, page 23
\[ F_{\ell}Z \] the vector subspace of \( Z \) spanned by MZVs of length \( \leq \ell \), page 23
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\[ \zeta(s) \] zeta value, page 15

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