INTRODUCTION TO SPECTRAL SEQUENCES

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1. INTRODUCTION TO THE GENERAL FORMALISM: 5/8/17

Today, Adrian spoke about what a spectral sequence is and where they come from. The next four lectures will be interesting examples, even if today is somewhat dry.

Definition 1.1. A (homological) spectral sequence is the data of

• modules over a ring $E^r_{p,q}$ indexed by $r \geq N$ for some positive $N$ and $p, q \in \mathbb{Z}$, and
• maps $d_r: E^r_{p,q} \to E^r_{p-r,q-1+r}$, called differentials,

subject to the following conditions:

• $d_r^2 = 0$, and
• for all $p, q$, and $r$, $E^{r+1}_{p,q}$ is the homology of the chain complex $(E^r_{p-r,q-1+r}, d_r)$ at $E^r_{p,q}$.

The way in which the differentials affect the grading is pretty opaque, so let’s see what it looks like for small $r$.

\[
\begin{array}{c}
E_0^{p,q} \\
\downarrow d_0 \\
E_0^{p,q-1}
\end{array}
\begin{array}{c}
E_1^{p-1,q} \\
\leftarrow d_1 \\
E_1^{p,q}
\end{array}
\begin{array}{c}
E_2^{p-2,q+1} \\
\leftarrow d_2 \\
E_2^{p,q}
\end{array}

The differentials swing from downward to leftward, and comes closer and closer to pointing northwest.

This is a lot of structure, and one usually visualizes it as a book, with pages $E^r_{\bullet, \bullet}$, and each page is thought of as a lattice with the differentials:

\[
\cdots E^r_{p+1,q-1} \xleftarrow{d_0} E^r_{p+1,q} \xrightarrow{d_1} E^r_{p,q} \xleftarrow{d_2} E^r_{p,q+1} \xrightarrow{d_3} E^r_{p-1,q+1} \cdots
\]

\[
\cdots E^r_{p,q-1} \xleftarrow{d_0} E^r_{p,q} \xrightarrow{d_1} E^r_{p,q+1} \xleftarrow{d_2} E^r_{p-1,q+1} \cdots
\]

\[
\cdots E^r_{p-1,q-1} \xleftarrow{d_0} E^r_{p-1,q} \xrightarrow{d_1} E^r_{p-1,q+1} \xleftarrow{d_2} E^r_{p-2,q+2} \cdots
\]

\[
\cdots \quad \cdots \quad \cdots
\]

1In the general setup, one has to be somewhat agnostic about what these are: in any context where one can do homological algebra, one can define spectral sequences: abelian groups, modules over a ring, objects in an abelian category...
The point of this heavy machinery is that there’s a machine which takes filtered objects and functors satisfying an excision property to spectral sequences, and such pairs arise in many contexts in algebra, topology, and geometry.

**Definition 1.2.** Let \( Z \) denote the **poset category** of the integers, i.e. there’s a unique arrow \( m \to n \) iff \( m \leq n \). Then, a **filtered object** in a category \( C \) is a functor \( X : Z \to C \).

The idea is a topological space \( X \) together with inclusions \( X_i \hookrightarrow X_{i+1} \), such that \( X \) is the union of all of the \( X_i \). More generally, one can let \( X \) be the colimit over \( i \) of \( X(i) \). One example is the CW filtration of a CW complex \( X \), where \( X(n) \) is the \( n \)-skeleton of \( X \).

**Definition 1.3.** Let \( C \) be either \( \text{Top}_* \), the category of pointed topological spaces, or \( \text{Ch}(\text{Mod}_A) \), the category of chain complexes of \( A \)-modules for a ring \( A \).

- Let \( f : X \to Y \) be a \( C \)-morphism, so that we can take its mapping cone \( C_f \) and obtain a sequence \( X \to Y \to C_f \). If we iterate this construction, \( C_{Y \to C_f} \) is weakly equivalent to \( \Sigma X \), and the mapping cone of this is weakly equivalent to \( \Sigma Y \), so we obtain a sequence

\[
X \xrightarrow{f} Y \xrightarrow{C} \Sigma X \xrightarrow{\Sigma f} \Sigma Y \xrightarrow{\Sigma C_f} \ldots
\]

Such a sequence is called a **cofiber sequence**.²

- A **functor satisfying excision** is a covariant or contravariant functor \( C \to \text{Ab} \) taking cofiber sequences to long exact sequences.³

To see why \( C_{Y \to C_f} \simeq \Sigma X \), one can work with particularly nice maps, so that \( Y \to C_f \) is an injection, and its mapping cone crushes \( Y \) to a point, producing \( \Sigma X \). The cofiber \( C_f \) is the topological analogue of the quotient \( Y/X \).

**Example 1.4.** Here are some examples of these functors. First, let \( C = \text{Top}_* \):

1. Covariant functors \( \text{Top}_* \to \text{Ab} \) with excision include homology functors \( H_n \).
2. For covariant functors sending fiber sequences to long exact sequences, we have homotopy groups \( \pi_i \).
3. Contravariant functors with excision include cohomology functors \( H^n \).

For the category of chain complexes, cofiber and fiber sequences are the same thing.

4. Covariant functors include homology and covariant derived functors such as \( \text{Ext}^i(M, -) \) and \( \text{Tor}_i(M, -) \).
5. Contravariant functors include cohomology and contravariant derived functors such as \( \text{Ext}^i(-, M) \).

From here, one can draw picture of the argument for why such a functor defines a spectral sequence:

\[
\text{(Diagram to be made later.)}
\]

From this diagram, one can see how the differentials arise, and they have the grading for the \( E_2 \) page. In particular, given the filtration \( \{X_p\} \) of \( X \), we can let \( E^{2}_{p,q} := H_{p+q}(X_p) \).⁴ Thus the \( E^1 \) page is

\[
\begin{align*}
&\vdots \quad \vdots \\
H_2(X_0) &\xrightarrow{d_1} H_3(X_1) &\xrightarrow{d_1} H_4(X_2) &\leftarrow \cdots \\
H_1(X_0) &\xrightarrow{d_1} H_2(X_1) &\xrightarrow{d_1} H_3(X_2) &\leftarrow \cdots \\
H_0(X_0) &\xrightarrow{d_1} H_1(X_1) &\xrightarrow{d_1} H_2(X_2). &\leftarrow \cdots
\end{align*}
\]

²You may prefer to call this a **cofibre sequence**.
³There’s a version of this for functors taking fibre sequences to long exact sequences, but we won’t need to use it.
⁴Technically, we started only with one functor \( H \), but we can define \( H_{n-1}(X) := H_n(\Sigma X) \) and extend to a family of functors, just as for homology.
The key is explaining how the differentials occur. Let \( h \) be a homology theory, \( X = \{X_i\} \) be a filtration, and \( C_i := X_i/X_{i-1} \) be the cofibers. Then we have a diagram

\[
\begin{align*}
  & h(C_1) \leftarrow h(C_2) \leftarrow h(C_3) \\
  & h(X_0) \longrightarrow h(X_1) \longrightarrow h(X_2) \longrightarrow h(X_3) \longrightarrow \cdots
\end{align*}
\]

Any pair \( \rightarrow, \uparrow \) fits into a long exact sequence with connecting morphism \( \delta: h(C_i) \rightarrow h(\Sigma X_{i-1}) \):

\[
\begin{align*}
  & h(C_1) \leftarrow h(C_2) \leftarrow h(C_3) \\
  & \delta \downarrow \delta \downarrow \delta \downarrow \\
  & h(X_0) \longrightarrow h(X_1) \longrightarrow h(X_2) \longrightarrow h(X_3) \longrightarrow \cdots
\end{align*}
\]

This is how the first differentials arise: take the connecting morphism \( \delta \), then map back \( h(X_{i-1}) \rightarrow h(C_{i-1}) \).

Considering longer sequences of maps after taking homology gives you the higher-order differentials.

What follows was a complicated diagram chase that was hard to live-T\( \varphi \)X.

We had the \( E^1 \) page and differentials, and after taking homology, we get the \( E^2 \) page:

\[
\begin{align*}
  & E_{0,0}^2 \leftarrow E_{1,0}^2 \leftarrow E_{2,0}^2 \\
  & E_{0,1}^2 \leftarrow E_{1,1}^2 \leftarrow E_{2,1}^2 \\
  & E_{0,2}^2 \leftarrow E_{1,2}^2 \leftarrow E_{2,2}^2
\end{align*}
\]

2. The Atiyah-Hirzebruch spectral sequence: 5/9/17

Today, I’m going to talk about the Atiyah-Hirzebruch spectral sequence. Last time, we talked about how to construct a spectral sequence from a filtration of a topological space; today, we’ll black-box that construction and use it to compute some stuff. Namely, we’ll use the CW fibration associated to any CW complex.

Let \( E^* \) be a generalized cohomology theory and \( X \) be a CW complex. The **Atiyah-Hirzebruch spectral sequence** is a spectral sequence

\[
E_2^{p,q} = H^p(X; E^q(\text{pt})) \Longrightarrow E^{p+q}(X).
\]

We’ll explain what all this actually means.

**Convergence.** Sometimes you’re reading a book and it feels like it goes on forever. It’s nice when spectral sequences don’t do that. As an example, we’ll look at a **first-quadrant spectral sequence**, one where \( E_2^{p,q} = 0 \) when \( p < 0 \) or \( q < 0 \). In this setup, if you pick any \( (p,q) \), then after finitely many pages, the differentials are so long that they leave the first quadrant, so you get a sequence \( 0 \rightarrow E_{r,q}^p \rightarrow 0 \), and therefore when you take homology, nothing changes. Thus it makes sense to say what the end of the spectral sequence is.

**Definition 2.1.** Whenever it makes sense, we’ll define the \( E_\infty \)-page of the spectral sequence to be \( E_\infty^{p,q} = E_r^{p,q} \) for \( r \gg 0 \). One says \( E_r^{p,q} \) **converges** or **abuts** to \( E_\infty^{p,q} \).

Typically this is something interesting we want to calculate.

**Definition 2.2.** Let \( A_\bullet \) be a graded abelian group together with an exhaustive filtration \( \{F_p\} \).

- The **associated graded** of the filtration \( \{F_p\} \) is

  \[
  (\text{gr } A)_{p,q} := F_p A_{p+q}/F_{p-1} A_{p+q}.
  \]

- A spectral sequence \( E_r^{p,q} \) **converges (weakly)** to \( A_\bullet \), written \( E_r^{p,q} \Longrightarrow A_\bullet \), if it has an \( E_\infty \) page and the \( E_\infty \) page is the associated graded of \( A_\bullet \).
Remark. There is a notion of conditional convergence, due to Boardman, which essentially means “not always weakly convergent, but converges under hypotheses often met in practice.” Unfortunately, defining this precisely would be a huge digression.

**Generalized cohomology theories.** The Atiyah-Hirzebruch spectral sequence is used to compute things which behave like homology or cohomology, but are slightly different: they satisfy all of the Eilenberg-Steenrod axioms except for the dimension axiom. These generalized cohomology theories have been a huge area of focus in algebraic topology in the last half century.

**Definition 2.3.** A generalized cohomology theory (also extraordinary cohomology theory) is a collection of functors $h^n: \text{Top} \to \text{Ab}$ such that:

- Given a map $f: A \to X$, let $X/A$ denote its cofiber. There is a natural transformation $\delta: h^n(X/A) \to h^{n+1}(A)$ such that the following sequence is long exact:

  $\cdots \to h^n(A) \xrightarrow{h^n(f)} h^n(X) \xrightarrow{\delta} h^n(X/A) \xrightarrow{\delta} h^{n+1}(A) \xrightarrow{} \cdots$

- $h^n$ takes wedge sums to direct sums: if $X = \bigvee_i X_i$, then the natural map

  $$\bigoplus h^n(X_i) \to h^n(X)$$

  is an isomorphism.

The dual notion of a generalized homology theory is the same, except the differentials go in the other direction. This defines a reduced homology theory, i.e. one for spaces with basepoints.

**Example 2.4 (K-theory).** Let $X$ be a compact Hausdorff space. Then, the set of isomorphism classes of complex vector bundles on $X$ is a semiring, so we can take its group completion and obtain a ring $K^0(X)$.

The following theorem is foundational and beautiful.

**Theorem 2.5 (Bott periodicity).** $K^0(\Sigma^2 X) \cong K^0(X)$.

This allows us to promote $K^* + \mathbb{Z}_2$ into a 2-periodic generalized cohomology theory $K^*$, called complex $K$-theory, by setting $K^{2n}(X) = K^0(X)$ and $K^{2n+1}(X) = K^0(\Sigma X)$.\(^5\)

Like cohomology, $K$-theory is multiplicative, i.e. it spits out $\mathbb{Z}$-graded rings. However, $K^i(X)$ is often nonzero for negative $i$.

**Exercise 2.6.** For example, show that as graded abelian groups, $K^*(pt) = \mathbb{Z}[t, t^{-1}]$, where $|t| = 2$.

$K$-theory admits a few variants.

- If you use real vector bundles instead of complex vector bundles, everything still works, but Bott periodicity is 8-fold periodic. Thus we obtain a periodic, multiplicative cohomology theory called real $K$-theory, denoted $KO^*(X)$. Its value on a point is encoded in the Bott song.
- Sometimes it will be simpler to consider a smaller variant where we only keep the negative-degree elements. This is called connective $K$-theory, and is denoted $ku^*$ (for complex $K$-theory) or $ko^*$ (for real $K$-theory). These are also multiplicative.\(^6\)

**Example 2.7 (Bordism).** Let $X$ be a space and define $\Omega^n_0(X)$ to be the set of equivalence classes of maps of $n$-manifolds $M \to X$, where $[f_0: M \to X] \sim [f_1: N \to X]$ if there’s a cobordism $Y: M \to N$ and a map $F: Y \to X$ extending $f_0$ and $f_1$. This is an abelian group under disjoint union, and the collection $\{\Omega^n_0\}$ defines a generalized homology theory called unoriented bordism.\(^7\)

The following theorem was the beginning of differential topology.

**Theorem 2.8 (Thom).** As graded abelian groups, $\Omega^n_0(pt) \cong \mathbb{F}_2[x_2, x_4, x_6, \ldots] = \mathbb{F}_2[x_i \mid i \neq 2^j - 1]$. Moreover, $\Omega^n_0$ is a direct sum of (suspended) ordinary cohomology theories.

There’s a lot of variations, based on whatever flavors of manifolds you consider. Using oriented manifolds produces oriented bordism $\Omega^n_{SO}$, spin manifolds produce spin bordism $\Omega^n_{Spin}$, and so forth. These are not direct sums of ordinary cohomology theories in general.\(^8\)

---

\(^5\)Extending from compact Hausdorff spaces to all of $\text{Top}$ is possible, but then one loses the vector-bundle-theoretic description.

\(^6\)The corresponding cohomology theory is called cobordism.
2.1. The definition. Recall that if \( X \) is a CW complex, it has a CW filtration in which \( X_n \) is the \( n \)-skeleton, the union of all cells of dimension \( \leq n \). Then, \( X_n/X_{n-1} \) is a wedge of \( n \)-spheres indexed by the \( n \)-cells of \( X \). Using this formalism we can define some spectral sequences.

**Definition 2.9.**
- Let \( E_* \) be a generalized homology theory and \( X \) be a CW complex. Then, the CW filtration on \( X \) induces a spectral sequence of homological type that strongly converges, called the Atiyah-Hirzebruch spectral sequence:
  \[
  E^2_{p,q} = H^p(X; E_q(pt)) \Rightarrow E_{p+q}(X).
  \]
- Let \( E^* \) be a generalized cohomology theory and \( X \) be a CW complex. Then, the CW filtration on \( X \) induces a spectral sequence of cohomological type that conditionally converges, called the Atiyah-Hirzebruch spectral sequence:
  \[
  E^2_{p,q} = H^p(X; E^q(pt)) \Rightarrow E_{p+q}(X).
  \]

Calculations.

**Example 2.10.** We’ll use the Atiyah-Hirzebruch spectral sequence to compute \( K^*(\mathbb{CP}^n) \). Recall that
\[
H^p(\mathbb{CP}^k; A) = \begin{cases} A, & p \text{ even} \\ 0, & p \text{ odd}. \end{cases}
\]
Hence
\[
E^2_{p,q} = \begin{cases} \mathbb{Z}, & p, q \text{ even, } 0 \leq p \leq 2k \\ 0, & \text{otherwise}. \end{cases}
\]
Thus all the differentials are zero! So \( E^2_{p,q} \cong E^\infty_{p,q} \). Hence the \( E_\infty \) page has no torsion, and therefore \( K^*(\mathbb{CP}^n) \) is isomorphic to its associated graded.
\[
K^i(\mathbb{CP}^n) = \begin{cases} \mathbb{Z}^{n+1}, & i \text{ even} \\ 0, & \text{otherwise}. \end{cases}
\]

**Exercise 2.11.** Let \( \Sigma \) be a genus-\( g \) orientable closed surface. Compute \( K^*(\Sigma_g) \).

**Exercise 2.12.** What changes when you replace \( K^* \) with \( KO^* \)?

3. THE SERRE SPECTRAL SEQUENCE AND COMPUTATIONS: 5/10/17

Today, Ernie spoke on the Serre spectral sequence and some other topics.

**Multiplicative structures.** So far, everything we’ve done has been graded modules over a ring \( R \), and often \( R = \mathbb{Z} \), so we’re thinking about graded abelian groups. Recall that a **graded \( R \)-module** is an \( R \)-module
\[
M_* = \bigoplus_{i \in \mathbb{Z}} M_i,
\]
If \( x \in M_i \), we say its **degree** is \( i \), and write \( |x| = i \).

Graded modules are great, as they resemble homology of spaces. Cohomology has additional structure in the form of a cup product: if \( x \in H^i(X) \) and \( y \in H^j(X) \), their cup product, denoted \( x \smile y \) or just \( xy \), is a class in \( H^{i+j}(X) \), and \( xy = (-1)^{ij}yx \). This structure is axiomatized as a graded algebra.

**Definition 3.1.** A **graded \( R \)-algebra** \( M_* \) is a graded \( R \)-module together with a **multiplication map** \( \mu : M_* \times M_* \to M_* \) such that
- \( \mu(M_i, M_j) \subseteq M_{i+j} \)
- if \( |x| = i \) and \( |y| = j \), then \( \mu(x, y) = (-1)^{ij}(X) \).

The structure of (a page of) a spectral sequence fits into something called a differential graded module.

**Definition 3.2.**
• A bigraded $R$-module is an $R$-module $M_{*,*}$ admitting a decomposition

$$M_{*,*} = \bigoplus_{i,j \in \mathbb{Z}} M_{i,j}.$$  

The total degree of an $x \in M_{i,j}$, denoted $|x|$, is $i + j$. This degree turns $M_{*,*}$ into a singly graded $R$-module; this grading is called the total grading.

• A differential graded $R$-module is a bigraded $R$-module $M_{*,*}$ together with a map $d: M_{*,*} \to M_{*,*}$ such that $d^2 = 0$ and $d$ shifts the total grading by either $1$ (if $M_{*,*}$ is graded cohomologically) or $-1$ (if it’s graded homologically).

• A differential graded $R$-algebra (DGA) is a differential graded $R$-module $M_{*,*}$ together with a multiplication map making $M_{*,*}$ a graded $R$-algebra with respect to the total grading and such that for all $x, y \in M_{*,*}$,

$$d(xy) = d(x)y + (-1)^{|x|}xd(y).$$

The multiplicative structure in cohomology is very useful: it forces a lot of information, and also can be directly useful, e.g. showing that $\mathbb{C}P^2$ and $S^2 \vee S^4$ aren’t homotopic, even though they have the same homology. Similarly, a multiplicative structure on a spectral sequence will force a lot of differentials, so is an awesome thing to have in your pocket if you want to compute things with spectral sequences.

**Definition 3.3.** A multiplicative spectral sequence is a spectral sequence $E^{p,q}_2 \Rightarrow M_*$ such that the pages $E^{p,q}_2$ are DGAs with respect to the grading and differential from the spectral sequence, $M_*$ is a graded algebra, and the convergence reflects the multiplicative structure.

The Serre spectral sequence.

**Definition 3.4.** A (Serre) fibration $f: E \to X$ of topological spaces is a map such that if $\Delta^n$ denotes the $n$-simplex and one has commuting maps

$$\begin{array}{ccc}
\Delta^n \times \{0\} & \longrightarrow & E \\
\downarrow & & \downarrow f \\
\Delta^n \times [0,1] & \longrightarrow & X,
\end{array}$$

there exists a map $G: \Delta^n \times [0,1] \to E$ that commutes with the maps in the diagram.

We always take $X$ to be path-connected, in which case $f^{-1}(x) \simeq f^{-1}(x')$ for all $x, x' \in X$. This preimage is called the fiber of $f$, and is often denoted $F$; the triple $F \to E \to X$ is called a fiber sequence. We will also assume $X$ is simply connected, which will allow us to obtain stronger results.

**Example 3.5.** Let $M$ be a manifold of dimension $n$. Then, $TM \to M$ is a fibration, and the fiber is $\mathbb{R}^n$.  

**Theorem 3.6** (Serre). Fix a coefficient ring $R$; let $f: E \to X$ be a fibration and $F$ be its fiber. Then, there exists a multiplicative spectral sequence, called the Serre spectral sequence

$$E^{p,q}_2 = H^p(X; H^q(F; R)) \Rightarrow H^{p+q}(E; R).$$

**Proof sketch.** Let $\{X_i\}$ be the CW filtration of $X$, and let $E_i := f^{-1}(X_i)$, which induces an exhaustive filtration $\{E_i\}$ of $E$. Applying $H^q(\cdot; R)$ defines a spectral sequence by the formalism from the first lecture. The multiplicative structure comes from the cup product on $X$.

**Remark.** Let $A$ be a multiplicative generalized cohomology theory (e.g. $K$-theory). Then, we could have applied $A$ instead of $H^q(\cdot; R)$ and obtained a multiplicative spectral sequence

$$E^{p,q}_2 = H^p(X; A^q(F)) \Rightarrow A^{p+q}(E).$$

Letting $A = H^*(\cdot, R)$, we recover the Serre spectral sequence, and letting $E \to X$ be the identity map $X \to X$, which is a fibration, we recover the Atiyah-Hirzebruch spectral sequence. For this reason this spectral sequence is sometimes called the Serre-Atiyah-Hirzebruch spectral sequence.  

6
Example 3.7. Let $PX := \text{Top}_*(I, X)$ denote the path space, i.e. the maps from the unit interval to $X$. Evaluation at 0 defines a map $ev: PX \to X$. The path space is made of spaghetti, hence is contractible: shrink each path from time 1 to time $t$, and let $t \to 0$.

$ev: PX \to X$ is a fibration, and the fiber is $\Omega X$, the space of (based) loops in $X$ (i.e. based maps $S^1 \to X$). Recall that a fiber sequence induces a long exact sequence in homotopy groups:

$$\cdots \to \pi_n(F) \to \pi_n(E) \to \pi_n(X) \to \pi_{n-1}(F) \to \cdots$$

Since $\pi_n(PX) = 0$, this implies $\pi_n(X) \cong \pi_{n-1}(\Omega X)$.

Let’s apply the Serre spectral sequence to this fibration in the case where $R = \mathbb{Q}$ and $X = S^3$. The Serre spectral sequence takes the form

$$E_2^{p,q} = H^p(S^3; H^q(\Omega S^3; \mathbb{Q})) \Rightarrow H^{p+q}(PS^3; \mathbb{Q}).$$

We know the $E_\infty$ page already: it’s 0 unless $p + q = 0$, in which case it’s $\mathbb{Q}$. So we’re going to reverse-engineer the spectral sequence, to use the $E_\infty$ page to compute the $E_2$ page.

We also know $H^*(S^3; \mathbb{Q}) = E_2(X)$, where $|x| = 3$, an exterior algebra in one variable. This is also isomorphic to $\mathbb{Q}[x]/x^2$, so has a $\mathbb{Q}$ in degrees 0 and 3, and is 0 elsewhere.

We know $H^0(\Omega S^3; \mathbb{Q}) = \mathbb{Q}$, so the $E_2$ page looks like

$$
\begin{array}{ccc}
3 & ? & ? \\
2 & ? & ? \\
1 & ? & ? \\
0 & 1 & x \\
\end{array}
$$

with the missing entries equal to 0.

We know that the $(3,0)$ term has to vanish by the $E_\infty$ page, so it either supports a differential (has a nonzero differential mapping out of it) or receives a differential (has a nonzero differential mapping into it). Since this is a first-quadrant spectral sequence, all differentials out of $x$ hit 0, so it has to receive a differential. But on the $E_2$ page, this differential comes from the 0 in position $(1,1)$, so it’s zero, and any differentials in page 4 or above mapping into $x$ come from the fourth quadrant, so there has to be a nonzero differential on the $E_3$ page mapping into $x$, so there’s some $y \in E_2^{0,2}$, which generates a copy of $\mathbb{Q}$, such that $d_3y = x$. There can’t be more than one generator in $E_2^{0,2}$, because then either it would survive to the $E_\infty$ page (which can’t happen), or it gets killed, meaning the difference of it and $y$ is not killed by $d_3$ and hence survives. Oops. Thus, $E_2^{0,2} = H^2(\Omega S^3; \mathbb{Q}) \cong \mathbb{Q}$. Hence we know $E_2^{3,3} = H^3(S^3; \mathbb{Q})$ as well, and the spectral sequence looks like

$$
\begin{array}{ccc}
2 & y & \mathbb{Q} \\
1 & ? & ? \\
0 & 1 & x. \\
\end{array}
$$

We can also immediately determine $E_2^{*,2}$: looking at $E_2^{0,2}$, there are no differentials that hit something nonzero, or map from something nonzero to it. So anything in it survives to the $E_\infty$ page, and hence it must be zero. Thus $H^1(\Omega S^3; \mathbb{Q}) = 0$ and hence $E_2^{1,3} = 0$ too.
The multiplicative structure tells us that the generator of $E_2^{3,2}$ must be $y \cdot x$. Thus, the spectral sequence looks like

\[
\begin{array}{c|ccc}
2 & y & yx \\
1 & d_3 & \\
0 & 1 & x \\
\end{array}
\]

But now $yx$ has to die, and the only way that can happen is if it’s hit by $d_3$ of the $E_0^{0,4}$ term, which turns out to be $y^2$. This is because $d_3 y = x$, so

\[d_3(y^2) = d_3(y)y + (-1)^2yd_3(y) = 2xy.\]

Thus $d_3$ is multiplication by 2. Hence the spectral sequence looks like

\[
\begin{array}{c|cccc}
4 & y^2 & y^2x \\
3 & & y^2x \\
2 & y & yx \\
1 & & \\
0 & 1 & x \\
\end{array}
\]

But now we need $y^2x$ to vanish, and it’s hit by $y^3 \in E_2^{0,6}$ via $d_3$, which is multiplication by 3, and so on. Inductively we can conclude that

\[H^*(\Omega S^3; \mathbb{Q}) \cong \begin{cases} \mathbb{Q}, & n \text{ even} \\ 0, & n \text{ odd} \end{cases} \]
Much of this argument, but not all of it, works with \( \mathbb{Q} \) replaced by \( \mathbb{Z} \). The difference is that multiplication by 2, 3, etc. is not an isomorphism, so we have a sequence of generators \( y_1, y_2, \ldots \):

\[
\begin{array}{c|ccc}
 & 7 & 6 & 5 \\
\hline
0 & 1 & 2 & 3 \\
1 & & & \\
2 & & & y_1 \\
3 & & & y_2 \\
4 & & & y_3 \\
5 & & & y_4 \\
6 & & & y_5 \\
7 & & & y_6 \\
\end{array}
\]

Now we have to figure out the multiplicative structure. We know \( y_2^1 = c_1 y_2 \) for some \( c_1 \in \mathbb{Z} \), so since \( d_3 \) is an isomorphism, let’s compute: we know \( d_3(y_2) = y_1 x \) by construction, and \( d_3(y_2^2) = 2 y_1 x \) for the same reason as over \( \mathbb{Q} \), so \( y_2^2 = 2 y_2 \).

A similar calculation in general shows that \( y_n^1 = n! y_n \), as

\[
d_3(y_n^i) = d_3(y_n y_n^{i-1}) = d_3(y_1) y_n^{i-1} + y_1 (n-1)! d(y_{n-1}) = xy_n^{i-1} + y_1 (n-1)! xy_{n-2} = x(n-1)! y_{n-1} + (n-1) y_{n-1} x(n-1)! = n! x y_{n-1},
\]

but \( d_3(n! y_n) = n! x y_{n-1} \). Hence the ring structure on \( H^*(\Omega S^3) \) is a divided power algebra.

**Definition 3.9.** A divided power algebra on a single generator \( x \) in degree \( k \), denoted \( \Gamma(x) \), is the free algebra generated by \( \{x^i\}_{i \geq 1} \) where \( |x^i| = ki \), subject to the relations

\[
x i x + j = \binom{i + j}{j} x i+j \quad \text{and} \quad x_i = \frac{x^i}{i!}.
\]

Thus \( H^*(\Omega S^3) \cong \Gamma(y) \) with \( |y| = 2 \). \( \star \)

**Exercise 3.10.** The same argument works to compute \( H^*(\Omega S^{2n+1}) \). Work it out for \( H^*(\Omega S^{2n}) \), which behaves differently.

**Example 3.11.** Let \( K(G,n) \) be an Eilenberg-Mac Lane space, i.e. a space with \( \pi_n(K(G,n)) = G \) and all other homotopy groups vanishing. It’s a theorem that these exist for all \( n \) and \( G \) (abelian when \( n \geq 2 \)), and any two choices of a \( K(G,n) \) are homotopy equivalent for given \( G \) and \( n \). For a simple example, \( S^1 \) is a \( K(\mathbb{Z},1) \), and for a less simple example, \( \mathbb{CP}^\infty \) is a \( K(\mathbb{Z},2) \).

Eilenberg-Mac Lane spaces with \( n \geq 3 \) are usually much harder to describe explicitly, but we can use the Serre spectral sequence to compute their cohomology. (3.8) tells us that \( \Omega K(G,n) \) has \( \pi_{n-1}(\Omega K(G,n)) = G \) and all other homotopy groups vanishing, so it’s a model of \( K(G,n-1) \) (here we need \( n > 1 \)). Thus, the path space fibration is a fibration

\[
K(G,n-1) \longrightarrow * \longrightarrow K(G,n).
\]
You can use this to inductively compute $H^*(K(G,n))$, starting from $n = 1$, where $K(G, 1)$ often has a more explicit model.

This is useful for understanding cohomology operations, maps $H^n(\cdot, \mathbb{Z}) \to H^p(\cdot, \mathbb{Z})$, e.g. $x \mapsto x^2$. Since Eilenberg-Mac Lane spaces represent ordinary cohomology, these are parameterized by $[K(\mathbb{Z}, n), K(\mathbb{Z}, p)] = H^p(K(\mathbb{Z}, n))$.

**Example 3.12.** The unitary group $U_n$ acts on $S^{2n-1}$ through the unit sphere embedding $S^{2n-1} \hookrightarrow \mathbb{C}^n$, and this action is transitive. The stabilizer of a point is $U_{n-1}$, so we obtain a fiber sequence

$$U_{n-1} \longrightarrow U_n \longrightarrow S^{2n-1}.$$  

We'll use this to compute the cohomology of $U_n$. When $n = 1$, $U_1 = S^1$, so $H^*(U_1) = E(x_1)$, with $|x_1| = 1$.  

Next let’s consider $n = 2$. $H^*(S^3) = E(x_3)$, where $|x_3| = 3$, so by the Künneth formula, $H^*(U_1, H^*(S^3)) = H^*(S^1) \otimes H^*(S^3) = E(x_1) \otimes E(x_3)$, and this is the $E_2$ page, with multiplicative structure.

Thus, no differentials are supported, so $E_2 = E_\infty = E(x_1, x_3)$. Thus, $H^*(U_2) \cong E_2(x_1, x_3)$. Inductively, considering $S^{2n-1}$ adds one more class $x_{2n-1} \in E_2^{2n-1,0}$ and no differentials can exist, so $E_2 = E_\infty = E(x_1, x_3, x_5, \ldots, x_{2n-1})$, and this is $H^*(U_n)$.

**Example 3.13.** We can apply this computation of the cohomology of $U_n$ to obtain the cohomology of its classifying space $BU_n$. This is the quotient of a contractible space $EU_n$ by a free $U_n$-action (again, it’s a theorem that this exists, and that any two choices are homotopy equivalent). Hence we get a fiber sequence $U_n \to * \to BU_n$.

Once again, the $E_\infty$ page vanishes, and we'll use this to determine the $E_2$ page. We start with column 0, which is $H^*(U_n)$. But $x_1 \in E_2^{0,1}$ must die, and the only differential it can support is $d_2$. Thus, there’s a $y_2 \in E_2^{2,0}$ with $dx_1 = y_2$. Since $|x_1|$ is odd, then the Leibniz rule means $x_1^2 = 0$, and therefore

$$d(x_1 y_2^k) = y_2 y_2^k + (-1)x_1(0) = y_2^{k+1}.$$  

Thus we know part of the $E_2$ page:

Thus $d_2: x_1 y_2 \to y_2^2$ is an isomorphism, then $d_2: x_3 \to 0$, and $x_3$ survives to the $E_3$ page. However, this is the last differential we can use to kill it, so $d_3 x_3$ must be some new element of $E_3^{1,0}$, which we’ll call $y_4$. We

\footnote{This works for any Lie group $G$: we get a sequence $G \to EG \to BG$.}
can also compute that \( d_2(x_1x_3) = y_2x_3 \) using the Leibniz rule, so we have

\[
\begin{array}{cccccc}
 & & & & & \\
 & x_1x_3 & \xrightarrow{d_2} & x_3y_2 & \xrightarrow{d_3} & x_1y_2^2 & \xrightarrow{d_2} & \cdots \\
 & x_1 & \xrightarrow{d_2} & x_1y_2 & \xrightarrow{d_2} & y_4, y_2^2 & \xrightarrow{d_2} & \cdots \\
1 & 0 & 0 & y_2 & 0 & \cdots \\
0 & 1 & 2 & 3 & 4 \\
\end{array}
\]

If we continue this, we inductively get generators \( y_i \in H^{2i}(BU_n) \), and we’ll see that \( d(x_1y_k^i) = y_k^{i+1} \), so there are no relations. Hence \( H^*(BU_n) \cong \mathbb{Z}[y_2, y_4, y_6, \ldots, y_n] \). One application of this is to characteristic classes: \( y_{2m} \) is better known as \( c_m \), the \( m \)th Chern class for complex vector bundles.  

\[\text{Example 3.14.} \] Let \( M \) be a manifold, which we’ll assume to be simply connected. Let \( S(M) \to M \) be the unit sphere bundle inside the tangent bundle.  

This is a spherical fibration, meaning a fibration whose fiber is a sphere. Since the cohomology of a sphere is very simple, the Serre spectral sequence allows us to calculate \( H^*(S(M)) \). 

The fibration is \( S^{n-1} \to S(M) \to M \), so the \( E_2 \) page is a copy of \( H^*(M) \) in row 0 and a copy in row \( n-1 \). One can show that if \( x_{n-1} \in E_2^{n,n-1} \) is the generator, then the first and only supported differential is \( d_n(x_{n-1}) = 
\chi(M) \cdot [M] \). You can use this to compute the \( E_\infty \) page.

4. The Eilenberg-Moore spectral sequence: 5/11/17

Today, Richard Wong spoke on the Eilenberg-Moore spectral sequence, and through it a lot of homological algebra, including the Künneth theorem and derived functors.

Last time, Ernie told us about the Serre spectral sequence, which is associated to a fibration \( F \to E \to B \) and converges strongly if \( B \) is simply connected (so we don’t have to worry about the \( \pi_1(B) \)-action on \( E \)). The Eilenberg-Moore spectral sequence is a generalization.

Let \( F \to E \to B \) be a fibration and \( f : X \to B \) be a fibration. If \( E \times_B X \) denotes the pullback of \( E \to B \) by \( f \), then \( E \times_B X \to X \) is a fibration with fiber \( F \), i.e. we have a diagram of fiber sequences

\[
\begin{array}{ccc}
F & \xrightarrow{f} & F \\
\downarrow & & \downarrow \\
E \times_B X & \xrightarrow{f} & E \\
\downarrow \pi & & \downarrow \pi \\
X & \xrightarrow{f} & X.
\end{array}
\]

There are two versions of the Eilenberg-Moore spectral sequence, one for homology and one for cohomology; they’re very similar, so we’ll only discuss the cohomology one today. If \( R \) is a ring, it will be a spectral sequence that, given \( H^*(E; R), H^*(X; R), H^*(E; R) \), and \( \pi \) and \( f^* \), computes \( H^*(E \times_B X; R) \).

\[\text{Remark.} \] Suppose \( X = B \) and \( f = \text{id} \). Then, the Eilenberg-Moore spectral sequence will reduce to the Serre spectral sequence.

Suppose \( B \) is a point, so the fibration is \( E \to E \to * \), so \( f \) is the crush map. Then (4.1) asks how to compute \( H^*(E \times X; R) \) in terms of \( H^*(X; R) \) and \( H^*(E; R) \). This reduces to a preexisting result in algebraic topology called the Künneth formula.

---

8This requires a choice of a Riemannian metric to construct it, but the resulting bundle does not depend on the choice of metric.
Theorem 4.2 (Künneth). Let \( k \) be a field and \( E \) and \( X \) be topological spaces. Then, there is an isomorphism
\[
H^*(E; k) \otimes_k H^*(X; k) \cong H^*(E \times X; k).
\]

The map can be made explicit: let \( \pi_1: E \times X \to E \) and \( \pi_2: E \times X \to X \) be the projections. By universal property of the coproduct (which is the tensor product for rings), we get a map \( \pi_1^* \otimes \pi_2^*: H^*(E; k) \otimes_k H^*(X; k) \to H^*(E \times X; k) \), and then can push forward along multiplication \( k \otimes k \to k \) to obtain a map \( H^*(E \times X; k \otimes k) \to H^*(E \times X; k) \). In symbols, \( x, y \mapsto \pi_1^*(x) \cdot \pi_2^*(y) \). More generally there’s a Künneth spectral sequence.

The universal coefficient theorem encodes another important piece of homological algebra. If we know \( H_n(X; \mathbb{Z}) \) and want to understand \( H_n(X; A) \) (where \( A \) is an abelian group), we would like it to just be \( H_n(X; \mathbb{Z}) \otimes A \), but this isn’t always true, and fails when \(- \otimes A \) is not exact. So we get a leftover term.

Theorem 4.3 (Universal coefficient theorem). Let \( C_\bullet \) be a chain complex and \( H_n(C_\bullet; A) := H_n(C_\bullet \otimes A) \).

Then, there is a short exact sequence
\[
0 \longrightarrow H_n(C_\bullet) \otimes A \longrightarrow H_n(C_\bullet; A) \longrightarrow \text{Tor}^1(H_{n-1}(C_\bullet), A) \longrightarrow 0.
\]

\( \text{Tor}^n_R(-, A) \) is the \( n \)th derived functor of \(- \otimes R A \). When \( A = \mathbb{Z} \), \( \text{Tor}^n_R\mathbb{Z}, A = 0 \) for \( n > 1 \), and for this reason, \( \text{Tor}^1_R \mathbb{Z} \) is sometimes just denoted \( \text{Tor} \).

Let’s go into this for a little bit. Suppose we have a short exact sequence of \( R \)-modules
\[
0 \longrightarrow X \longrightarrow Y \longrightarrow Z \longrightarrow 0.
\]
If \( A \) is another \( R \)-module, \(- \otimes R A \) is right exact, but in general not left exact, so we only have the sequence
\[
(4.4) \quad X \otimes R A \longrightarrow Y \otimes R A \longrightarrow Z \otimes R A \longrightarrow 0.
\]
We’d like to measure how badly this fails to be left exact, and \( \text{Tor}^n_R \) does this. Specifically, it extends (4.4) into a long exact sequence
\[
\cdots \longrightarrow \text{Tor}^2_R(Z, A) \longrightarrow \text{Tor}^1_R(X, A) \longrightarrow \text{Tor}^1_R(Y, A) \longrightarrow \text{Tor}^1_R(Z, A) \longrightarrow X \otimes R A \longrightarrow Y \otimes R A \longrightarrow Z \otimes R A \longrightarrow 0.
\]
So how can you compute this? The first step is to take a projective resolution, a long exact sequence
\[
\cdots \longrightarrow P_{-2} \longrightarrow P_{-1} \longrightarrow P_0 \longrightarrow X \longrightarrow 0
\]
such that each \( P_i \) is projective.\(^9\) Now, apply \(- \otimes R A \) to get a sequence which is not necessarily exact, but the composition of any two maps is zero:
\[
\cdots \longrightarrow P_{-2} \otimes R A \longrightarrow P_{-1} \otimes R A \longrightarrow P_0 \otimes R A \longrightarrow X \otimes R A \longrightarrow 0.
\]
Call this complex \( P_\bullet \otimes R A \).

Definition 4.5. The \( n \)th Tor group is
\[
\text{Tor}^n_R(X, A) := H_{-n}(P_\bullet \otimes R A).
\]

It’s important to prove that this doesn’t depend on your choice of projective resolution. It’s also possible to resolve \( A \) instead of resolving \( X \), and this produces isomorphic Tor groups.

Remark. Any module over a principal ideal domain has a two-term free resolution, hence also a projective resolution:
\[
0 \longrightarrow F_{-1} \longrightarrow F_0 \longrightarrow A \longrightarrow 0.
\]
Here, \( F_0 \) is free on the generators of \( A \), and \( F_{-1} \) is free on the relations between those generators, with the map encoding this.

Using this, one has a more powerful version of the Künneth theorem.

\(^9\)The category of \( R \)-modules has enough projectives, meaning such a sequence always exists. In more general abelian categories, this isn’t always the case.
Theorem 4.6 (Künneth). Let $R$ be a PID and $X$ and $Y$ be spaces such that $H^*(Y; R)$ is a finitely-generated, free $R$-module. Then, for all $n$, there’s a short exact sequence

$$0 \rightarrow \bigoplus_{i+j=n} H_i(X; R) \otimes_R H_j(Y; R) \rightarrow H_n(X \times Y; R) \rightarrow \bigoplus_{i+j=n-1} \text{Tor}_R^1(H_i(X; R), H_j(Y; R)) \rightarrow 0.$$ 

This is the degeneration of the Eilenberg-Moore spectral sequence for the fibration $Y \rightarrow *$ and a crush map $X \rightarrow *$. The requirement that $R$ be a PID is what gives us the two-term free resolution, so that higher Tor vanishes, allowing the spectral sequence to degenerate.

Theorem 4.7. Given a fibration $F \rightarrow E \rightarrow B$ and a map $f: X \rightarrow B$, such that $B$ is simply connected, then there exists a second-quadrant spectral sequence

$$E_2^{p,q} \cong \text{Tor}_{H^*(B; R)}^p(H^*(X; R), H^*(E; R)) \Rightarrow H^*(E \times_B X; R).$$

This Tor is over a DGA, which is new. Let $\Gamma$ be a DGA and $(M^\bullet, d_M)$ and $(N^\bullet, d_N)$ be $\Gamma$-modules. By a projective resolution we mean a resolution of $M^\bullet$ by projective $\Gamma$-modules

$$\cdots \rightarrow P_{-2}^\bullet \rightarrow P_{-1}^\bullet \rightarrow P_0^\bullet \rightarrow M^\bullet \rightarrow 0,$$

i.e. a double complex

$$\cdots \rightarrow (P_{-2})^2 \rightarrow (P_{-1})^2 \rightarrow (P_0)^2 \rightarrow M^2 \rightarrow 0 \rightarrow \cdots$$

Using this, we can define the total complex or totalization, a singly graded DGA, to be

$$\text{Tot}((P^\bullet)_*) := \bigoplus_{m+n=j} (P_m)^n,$$

with differential

$$\delta_j := \sum_{m+n=j} \delta^0 + (-1)^m d_{P_m}.$$

You can filter this in different ways, as long as you exhaust everything, e.g.

$$F^{-i}_r := \bigoplus_{i+j=r} (P_i)^j.$$ 

Now, we can define the bigraded Tor groups to be

$$\text{Tot}_{-i,j}^\Gamma(M, N) := H^{-i,j}(M \otimes_{\Gamma} \text{Tot}(P^\bullet)).$$

The bar construction. The way we actually calculate this is to use the bar construction. Fix a field $k$ and a DGA $\Gamma$, and assume $\Gamma$ is connected, i.e. the map $\eta: k \rightarrow \Gamma$ is an isomorphism on degree-0 terms. Let $\Gamma$ denote the subalgebra of $\Gamma$ generated by terms of positive degree, $M$ be a right $\Gamma$-module, and $N$ be a left $\Gamma$-module. Then, let

$$B^{-n}(M, \Gamma, N) := M \otimes_k \Gamma \otimes_k \cdots \otimes_k \Gamma \otimes_k N.$$ 

\footnote{More generally, we can allow $B$ such that the action of $\pi_1(B)$ on the fiber is trivial, like in the Serre spectral sequence.}
For a $\gamma \in \Gamma$, let $\gamma := (-1)^{1+\deg(\gamma)}\gamma$. Then, the differential is
\[
\delta(m[\gamma_1 | \cdots | \gamma_n]) := (-1)^{\deg m}(m \cdot \gamma_1[\gamma_2 | \cdots | \gamma_n] + \sum_{i=1}^{n-1}(m[\gamma_1 | \cdots | \gamma_i \gamma_{i+1} | \cdots | \gamma_n]) + m[\gamma_1 | \cdots | \gamma_{n-1}]\gamma_n).
\]
With this differential, $B^\bullet(M, \Gamma, N)$ is a resolution for $M \otimes_\Gamma N$, and so
\[
\Tor^\Gamma_{-}(M, N) = H^i(B^\bullet(M, \Gamma, N)).
\]
Let’s use this to compute something.

Example 4.8. Let $\Gamma = \Lambda(x)$ with $|x| = m$, i.e. an exterior algebra in a single variable. We want to compute $\Tor_{\Lambda(x)}(k, k)$. $B^{-n}(k, \Lambda(x), k) = \Lambda(x)^{\otimes n}$ is free in degree $(-n, mn)$, generated by $[x | \cdots | x]$. You can calculate that the differential is equal to 0, so passing to total degree, the homology is
\[
\Tor_{\Lambda(x)}^{i,j}(k, k) = \begin{cases} 
k, & (i, j) = (r, m-1), \ r \geq 0 
0, & \text{otherwise}.
\end{cases}
\]
Now let’s feed this to the Eilenberg-Moore spectral sequence applied to the pullback
\[
\begin{array}{c}
\Omega S^{n+1} \\
\downarrow \downarrow \\
* \\
\end{array}
\begin{array}{c}
PS^{n+1} \\
\downarrow \\
S^n.
\end{array}
\]

Example 4.9. Another application which is harder with the Serre spectral sequence is to apply this to the fibration $G/H \to BH \to BG$ when $G$ is a Lie group and $H$ is a normal closed subgroup. You can run the Serre spectral sequence here, but have to worry about local coefficients and other things that go bump in the night. In particular, the $E_2$ page is $\Tor_{H^r(S^n, k)}^\bullet(k, k)$, which we just computed.

Another application is to the Bökstedt spectral sequence for computing topological Hochschild homology $THH(R) := R \otimes_{R \otimes k R^e} L R$, where $R$ is a ring spectrum.

5. The Grothendieck spectral sequence: 5/12/17

Today, Richard Hughes spoke about the Grothendieck spectral sequence.

Preliminaries on derived functors. We saw a little of this yesterday, but we’ll need to study derived functors in more detail today.

Let $F: A \to B$ be an additive functor between abelian categories.\footnote{There are several versions of this, e.g. replacing $F$ with a contravariant functor or a right exact functor. The plot is exactly the same, and the proofs don’t change that much.} Recall that $F$ is left exact if it takes every short exact sequence
\[
(5.1) \quad 0 \to A \to B \to C \to 0
\]
to an exact sequence
\[
0 \to FA \to FB \to FC.
\]
If it sends short exact sequences to short exact sequences, it’s called exact. So a natural question to ask is, can we measure the failure of a left exact functor to be exact?

Of course, this is a leading question: the answer is “yes,” through the world of derived functors $R^pF: A \to B$, which are in a precise sense the universal extension of $F$ to an exact functor. In particular, (5.1) is sent to a long exact sequence
\[
0 \to FA \to FB \to FC \to R^1FA \to R^1FB \to R^1FC \to R^2FA \to \cdots
\]
Recall that an object $I \in A$ is injective if $\Hom_A(-, I): A^{op} \to Ab$ is an exact functor.
Definition 5.2. A injective resolution of \( A \in \mathcal{A} \) is a quasi-isomorphism\(^\text{12}\) in \( \text{Ch}(\mathcal{A}) \) (the category of chain complexes in \( \mathcal{A} \)) \( \phi: A \to I^\bullet \), where each \( I^n \) is injective. Here, \( \phi \) is a map of chain complexes, treating \( A \) as concentrated in degree 0.

This is dual to the notion of projective resolution defined yesterday. Another way to say that \( A \to I^\bullet \) is a quasi-isomorphism is to require that
\[
0 \longrightarrow A \longrightarrow I^0 \longrightarrow I^1 \longrightarrow \cdots
\]
is exact.

For \( A \in \mathcal{A} \), choose an injective resolution\(^\text{13}\) \( A \to I^\bullet \), and define the right derived functors of \( F \) to be
\[
R^p F(A) := H^p(F(I^\bullet)).
\]

Though this \( a \, \text{priori} \) depends on the choice of injective resolution, one can show that there is a unique isomorphism between what you get for any choice of two injective resolutions.

Since \( F \) is left exact, (5.3) begins
\[
0 \longrightarrow FA \longrightarrow FI^0 \longrightarrow FI^1 \longrightarrow \cdots
\]
and therefore \( R^0 F(A) \cong FA \).

Definition 5.4. We say that \( A \in \mathcal{A} \) is \( F \)-acyclic if \( R^p F(A) = 0 \) for \( p > 0 \).

For example, yesterday we considered this for \(- \otimes B\); its derived functor is \( \text{Tor}^1(\_, B) \), and acyclic objects for this are called flat.

Remark. The reason we work with arbitrary abelian categories is that the interesting examples will map between different abelian categories, so we can’t just restrict to \( \text{Ab} \) or \( \text{Mod}_R \).

Example 5.5.

(1) Let \( \text{Sh}(X) \) denote the category of sheaves of abelian groups on a space \( X \). The global sections functor \( \Gamma: \text{Sh}(X) \to \text{Ab} \) is left exact, and its right exact functors are sheaf cohomology: \( R^p \Gamma(\mathcal{F}) = H^p(X; \mathcal{F}) \).

(2) Let \( G \) be a group; then, taking invariants defines a left exact functor \( (-)^G: \text{Mod}_G \to \text{Ab} \). The right derived functors are group cohomology: \( R^p (-)^G(M) = H^p(G; M) \). This is a slick way to define group cohomology.

(3) If \( R \) is a commutative ring and \( M \) is an \( R \)-module, \( \text{Hom}_R(M, -): \text{Mod}_R \to \text{Ab} \) is left exact, and its right derived functors are the Ext groups \( \text{Ext}^p_R(M, N) = R^p \text{Hom}_R(M, -)(N) \).

You may have seen some of these, particularly \( R^1 F \), in other contexts: for example, \( \text{Ext}^1(M, N) \) classifies extensions of \( M \) by \( N \), i.e. short exact sequences
\[
0 \longrightarrow M \longrightarrow P \longrightarrow N \longrightarrow 0
\]
up to isomorphism of short exact sequences.

The Grothendieck spectral sequence. We now have all the tools we need to understand what question the Grothendieck spectral sequence answers.

Let \( F: \mathcal{A} \to \mathcal{B} \) and \( G: \mathcal{B} \to \mathcal{C} \) be left exact functors between abelian categories. Assume \( \mathcal{A} \) and \( \mathcal{B} \) have enough injectives and that \( F \) sends injectives to \( G \)-acyclic objects. Then, \( G \circ F \) is left exact, so we want to compute its derived functors in terms of \( R^p F \) and \( R^q G \) (or vice versa).

Theorem 5.6. In this situation, choose an \( A \in \mathcal{A} \); then, there is a first-quadrant spectral sequence, called the Grothendieck spectral sequence
\[
E_2^{p,q} = (R^p G \circ R^q F)(A) \Rightarrow R^{p+q}(G \circ F)(A).
\]

Remark.

\(^{12}\)A quasi-isomorphism of chain complexes is one that induces an isomorphism on homology.

\(^{13}\)You cannot always do this in an arbitrary abelian category. We’re going to assume that you can, i.e. that \( \mathcal{A} \) has enough injectives. This is true for \( \text{Mod}_R \) for any commutative ring \( R \), for example.
where the differentials are all induced by the differential on
This is a (singly graded) cochain complex, so let’s filter it. There are two ways we can do this:

Thus, we can define the total complex

This comes from an
By the tensor-hom adjunction,

so the composition in (5.7) satisfies the Grothendieck spectral sequence.

Corollary 5.8 (Base change for Ext). Let $M$ be an $R$-module. Then, there is a spectral sequence

Example 5.9. Suppose $S$ is a projective $R$-module, so that $\Ext^q_R(S, M) = 0$ for $q > 0$, so the spectral sequence collapses to the identity

Example 5.10. Let $R = \mathbb{Z}$, $S = \mathbb{Z}/n$, and $f$ be projection. Let $M$ be an $n$-torsion-free abelian group and $N$ be a $\mathbb{Z}/n$-module, so that $\Hom(\mathbb{Z}/n, N) = 0$.

Using the fact that $\Ext^2 = 0$, the spectral sequence mostly collapses, and we get another useful identity:

The construction of the Grothendieck spectral sequence.

Proof of Theorem 5.6. Let $C^\bullet \in \text{Ch}(A)$ and assume it has an exhaustive filtration by subcomplexes $F^p C^\bullet \supseteq F^{p+1} C^\bullet$ such that $d(F^p C^n) \subseteq F^p C^{n+1}$. Then, there’s a spectral sequence (the spectral sequence for a filtered complex)

This comes from an $E_0$-page

where the differentials are all induced by the differential on $C^\bullet$, $d: F^p C^{n+q} \to F^p C^{n+q+1}$. The higher differentials end up in further steps along the filtration $F^{p+1} C^{p+q+1}$.

Now, let’s look at the spectral sequence associated to a double complex. Let $C^{\bullet, \bullet}$ be a double complex in $A$, i.e. a bigraded $A$-object together with two differentials $d^h: C^{p, q} \to C^{p+1, q}$ and $d^v: C^{p, q} \to C^{p, q+1}$ which anticommute, i.e.

Thus, we can define the total complex

with differential

This is a (singly graded) cochain complex, so let’s filter it. There are two ways we can do this:

Base change for Ext. This section will also be useful for next week. Let $f: R \to S$ be a ring homomorphism, and choose an $N \in \text{Mod}_S$, so that $f$ realizes $S$ and $N$ as $R$-modules. Then, we have a commutative triangle

By the tensor-hom adjunction,

so the composition in (5.7) satisfies the Grothendieck spectral sequence.

Corollary 5.8 (Base change for Ext). Let $M$ be an $R$-module. Then, there is a spectral sequence

Example 5.9. Suppose $S$ is a projective $R$-module, so that $\Ext^q_R(S, M) = 0$ for $q > 0$, so the spectral sequence collapses to the identity

Example 5.10. Let $R = \mathbb{Z}$, $S = \mathbb{Z}/n$, and $f$ be projection. Let $M$ be an $n$-torsion-free abelian group and $N$ be a $\mathbb{Z}/n$-module, so that $\Hom(\mathbb{Z}/n, N) = 0$.

Using the fact that $\Ext^2 = 0$, the spectral sequence mostly collapses, and we get another useful identity:

The construction of the Grothendieck spectral sequence.

Proof of Theorem 5.6. Let $C^\bullet \in \text{Ch}(A)$ and assume it has an exhaustive filtration by subcomplexes $F^p C^\bullet \supseteq F^{p+1} C^\bullet$ such that $d(F^p C^n) \subseteq F^p C^{n+1}$. Then, there’s a spectral sequence (the spectral sequence for a filtered complex)

This comes from an $E_0$-page

where the differentials are all induced by the differential on $C^\bullet$, $d: F^p C^{n+q} \to F^p C^{n+q+1}$. The higher differentials end up in further steps along the filtration $F^{p+1} C^{p+q+1}$.

Now, let’s look at the spectral sequence associated to a double complex. Let $C^{\bullet, \bullet}$ be a double complex in $A$, i.e. a bigraded $A$-object together with two differentials $d^h: C^{p, q} \to C^{p+1, q}$ and $d^v: C^{p, q} \to C^{p, q+1}$ which anticommute, i.e.

Thus, we can define the total complex

with differential

This is a (singly graded) cochain complex, so let’s filter it. There are two ways we can do this:
We could truncate the columns, putting 0 in any column before the $p$th:

$$(c) F^p \text{ Tot}(C^{\bullet \bullet})^n = \bigoplus_{i+j=n, i \geq p} C^{i,j}.$$ 

We could truncate the rows in the same way:

$$(r) F^q \text{ Tot}(C^{\bullet \bullet})^n = \bigoplus_{i+j=n, j \geq q} C^{i,j}.$$ 

We have a filtered complex, so let’s apply (5.11). For the column filtration, this gives us a spectral sequence whose $E_2$ takes the form

$$(c) E^{p,q}_2 = (c) F^p \text{ Tot}(C^{\bullet \bullet})^{p+q} / (c) F^{p+1} \text{ Tot}(C^{\bullet \bullet})^{p+q} \xrightarrow{d^p} E^{p,q+1}_2.$$ 

Taking homology, we see that

$$(c) E^{1,q}_1 = H^q(C^{p \bullet}, d^p),$$

which we’ll call $H^q_{\text{row}}(C^{p \bullet})$, and

$$(c) E^{2,q}_2 = H^p(H^q_{\text{row}}(C^{p \bullet}, d^p)) = H^p_{\text{col}}(H^q_{\text{row}}(C^{p \bullet})).$$

The same story applies to the row filtration, and we get

$$(r) E^{p,q}_2 = H^p_{\text{col}}(H^q_{\text{row}}(C^{\bullet \bullet})).$$

We could apply (5.11), and assuming some niceness on $C^{\bullet \bullet}$ (which is satisfied in the context of the Grothendieck spectral sequence, as it’s first quadrant), we obtain spectral sequences

$$(5.12a) (c) E^{p,q}_2 = H^p_{\text{col}}(H^q_{\text{row}}(C^{\bullet \bullet})) \implies H^{p+q}(\text{Tot}(C^{\bullet \bullet}))$$

$$(5.12b) (r) E^{p,q}_2 = H^p_{\text{col}}(H^q_{\text{row}}(C^{\bullet \bullet})) \implies H^{p+q}(\text{Tot}(C^{\bullet \bullet})).$$

Now we’ll get the Grothendieck spectral sequence out of this. Let $A \to I^{\bullet}$ be an injective resolution in $A$, so that $F(I^{\bullet}) \in \text{Ch}(B)^-$ (i.e. bounded-below chain complexes). Then, resolve again, obtaining what’s called a (first-quadrant) Cartan-Eilenberg resolution $J^{\bullet \bullet}$, where we want $F(I^{\bullet}) \to J^{\bullet \bullet}$ to induce an injective resolution for each $F(I^p)$. In particular, this means $J^{\bullet \bullet}$ is a double complex of injectives, and induces injective resolutions on coboundaries and cohomology. In particular, $H^q_{\text{col}}(J^{\bullet \bullet})$ is an injective resolution of $R^q F(A) = H^q(F(I^{\bullet})).$

Let’s plug this into (5.12a): we get

$$(c) E^{p,q}_2 = H^p_{\text{col}}(H^q_{\text{row}}(G(J^{\bullet \bullet}))) \implies H^{p+q}(\text{Tot}(G(J^{\bullet \bullet}))),$$

but since $H^q_{\text{row}}(G(J^{\bullet \bullet})) = 0$ unless $q = 0$, the spectral sequence collapses, and we conclude that

$$R^p(G \circ F)(A) \cong H^p(\text{Tot}(G(J^{\bullet \bullet}))).$$

The same story applied to (5.12b) tells us

$$H^p_{\text{row}}(G(H^q_{\text{col}}(J^{\bullet \bullet}))) = R^p G(R^q F(A)),$$

and therefore the spectral sequence takes the form

$$(r) E^{p,q}_2 = (R^p G \circ R^q F)(A) \implies R^{p+q}(G \circ F)(A).$$

We’ve been doing topology all week; now let’s do some geometry.
One consequence of the Grothendieck spectral sequence is a generalization of the Leray-Serre spectral sequence. Let \( f : X \to B \) be a continuous map of topological spaces, and consider the unique maps \( X \to \ast \) and \( B \to \ast \), giving us a commutative diagram

\[
\begin{array}{ccc}
X & \overset{f}{\longrightarrow} & B \\
\downarrow & & \downarrow \\
\ast & & \ast
\end{array}
\]

Thus, we can apply the **sheaf pushforward** to sheaves of abelian groups: \( (f_* \mathcal{F})(U) := \mathcal{F}(f^{-1}(U)) \). We don’t need to sheafify or anything. Sheaves on a point are just abelian groups, and pushing forward to a point is the global sections map. Hence we obtain a commutative diagram

\[
\begin{array}{ccc}
\text{Sh}(X) & \overset{f_*}{\longrightarrow} & \text{Sh}(B) \\
\downarrow \Gamma & & \downarrow \Gamma \\
\text{Ab.} & & \text{Ab.}
\end{array}
\]

(5.13)

Pushforward of sheaves is left exact, because it’s right exact to **pullback** \( f^{-1} : \text{Sh}(B) \to \text{Sh}(X) \). On sufficiently small open sets \( U \subset X \), this is

\[
(f^{-1} \mathcal{G})(U) := \lim_{V \subset f(U)} \mathcal{G}(V).
\]

We can make this construction for all opens, we get a presheaf, and have to sheafify.\(^{14}\)

Suppose we have an injective sheaf\(^{15}\) \( \mathcal{I} \in \text{Sh}(X) \) and a short exact sequence of sheaves on \( B \),

\[
0 \longrightarrow \mathcal{F} \longrightarrow \mathcal{G} \longrightarrow \mathcal{H} \longrightarrow 0.
\]

Since \( f^{-1} \) is exact and \( \text{Hom}_X(-, \mathcal{I}) \) is exact, then the following sequence is exact:

\[
0 \longrightarrow \text{Hom}_X(f^{-1} \mathcal{H}, \mathcal{I}) \longrightarrow \text{Hom}_X(f^{-1} \mathcal{G}, \mathcal{I}) \longrightarrow \text{Hom}_X(f^{-1} \mathcal{F}, \mathcal{I}) \longrightarrow 0,
\]

and therefore by adjunction, the following sequence is short exact:

\[
0 \longrightarrow \text{Hom}_B(\mathcal{H}, f_* \mathcal{I}) \longrightarrow \text{Hom}_B(\mathcal{G}, f_* \mathcal{I}) \longrightarrow \text{Hom}_B(\mathcal{F}, f_* \mathcal{I}) \longrightarrow 0.
\]

Therefore we’re in the situation of the Grothendieck spectral sequence, and can conclude there’s a first-quadrant spectral sequence

\[
E_2^{p,q} = H^p(B, R^q f_* \mathcal{F}) \Longrightarrow H^{p+q}(X, \mathcal{F}).
\]

(5.14)

This is a version of the Leray-Serre spectral sequence: if \( X \to B \) is a fibration with fiber \( F \), then \( R^q f_* \mathcal{F} \) is the sheafification of

\[
U \longmapsto H^q(f^{-1}(U); \mathcal{F}|_{f^{-1}(U)}).
\]

On small enough \( U \), \( f^{-1}(U) \simeq F \), so take \( \mathcal{F} = A \) for an abelian group \( A \), and assume the monodromy of pushforward is trivial (e.g. if \( B \) is simply connected). Thus \( H^q(f^{-1}(U); A) \simeq H^q(F; A) \), so \( R^q f_* \mathcal{F} \) is a constant sheaf values in \( H^q(F; A) \) over \( B \). Thus, (5.14) has the form

\[
E_2^{p,q} = H^p(B; H^q(F; A)) \Longrightarrow H^{p+q}(X; A),
\]

and is the Leray-Serre spectral sequence.

Now the geometry: suppose \( f : X \to B \) is a morphism of Noetherian schemes over a field \( k \) of characteristic 0. Assume \( B \) is normal and \( f \) is faithfully flat (flat and surjective), with geometrically connected fibers. These conditions suffice to show that \( f_* \mathcal{O}_X = \mathcal{O}_B \).

---

\(^{14}\) The usual notation \( f^* \) is usually reserved for pullback of \( \mathcal{O}_X \)-modules: \( f^* \mathcal{F} = f^{-1} \mathcal{F} \otimes \mathcal{O}_X \). This is not always exact: it’s exact precisely when \( f \) is flat.

\(^{15}\) \( \text{Sh}(X) \) has enough injectives; you can see this by mapping discrete spaces into \( X \), and sheaves on discrete spaces have enough injectives because \( \text{Ab} \) does.
Now consider $\mathcal{O}_X^\times$, the group of units of $\mathcal{O}_X$ (which corresponds to $\mathbb{G}_m$). Then,

\[ R^1 f_* \mathcal{O}_X^\times(U) = H^1(f^{-1}(U), \mathcal{O}_X^\times|_{f^{-1}(U)}) = \text{Pic}(f^{-1}(U)) \]

\[ H^1(X; \mathcal{O}_X^\times) = \text{Pic}(X) \]

\[ H^1(B; \mathcal{O}_B^\times) = \text{Pic}(B). \]

The Grothendieck spectral sequence in the form (5.14) takes the form

\[ E^{p,q}_2 = H^p(B; R^q f_* \mathcal{O}_X^\times) \Rightarrow H^{p+q}(X; \mathcal{O}_X^\times). \]

So $H^1(B; \mathcal{O}_B^\times) = \text{Pic} B$ and $H^0(B; R^1 f_* \mathcal{O}_X^\times)$ together approximate $H^1(X; \mathcal{O}_X^\times) = \text{Pic} X$; thus $R^1 f_* \mathcal{O}_X^\times$ is sometimes called the relative Picard sheaf.

**Exercise 5.15.** Given a first-quadrant spectral sequence converging to $M^\bullet$, there’s a five-term exact sequence

\[ 0 \longrightarrow E^{1,0}_2 \longrightarrow M^1 \longrightarrow E^{0,1}_2 \longrightarrow E^{2,0}_2 \longrightarrow M^2. \]

In our case, this sequence is

\[ 0 \longrightarrow \text{Pic}(B) \longrightarrow \text{Pic}(X) \longrightarrow H^0(B; R^1 f_* \mathcal{O}_X^\times) \longrightarrow H^2(B; \mathcal{O}_B^\times) \longrightarrow H^2(X; \mathcal{O}_X^\times). \]

Thus, the obstruction to taking a family of line bundles on the base and producing a line bundle on $X$ live in $H^2(B; \mathcal{O}_B^\times)$. There’s a geometric incarnation of what these obstructions look like, and they’re $\mathcal{O}_B^\times$-gerbes.