MATH 662 SPRING 2025
BRIEF COURSE NOTES

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These notes will include some, but not all, of the material from class. Proofs of theorems and examples are more likely to appear in class than in these notes. The appendix includes some supplementary topics that may not be covered in class.

Throughout, R will be a ring with $1 \neq 0$. Each R-module M is assumed to be *unital*, i.e. the multiplicative identity 1 of R acts as the identity map on M. We will work with both left and right modules, and where this distinction is essential, it will be specified which one.

1. Complexes

A *complex* $C_\bullet$ (or $(C_\bullet, d_\bullet)$ or (C, d)) of R-modules is a sequence of R-modules and R-module homomorphisms (called *differentials*),

$$C_\bullet : \qquad \cdots \longrightarrow C_2 \xrightarrow{d_2} C_1 \xrightarrow{d_1} C_0 \xrightarrow{d_0} C_{-1} \xrightarrow{d_{-1}} C_{-2} \longrightarrow \cdots$$

for which $d_{n-1}d_n = 0$ for all $n \in \mathbb{Z}$. The *degree* $|x|$ of an element x of C_n is n. Under this terminology, each of the differentials d_n has degree -1 as a map.

For each degree n, we define R-submodules and a subquotient of C_n as follows.

$$\begin{aligned} Z_n(C_\bullet) &= \operatorname{Ker}(d_n) \qquad \text{(the } n\text{-}\textit{cycles}) \\ B_n(C_\bullet) &= \operatorname{Im}(d_{n+1}) \qquad \text{(the } n\text{-}\textit{boundaries}) \\ H_n(C_\bullet) &= Z_n(C_\bullet)/B_n(C_\bullet) \qquad \text{(the } n\textit{th homology}) \end{aligned}$$

We say that two n-cycles x and y are *homologous* if $x - y$ is an n-boundary, that is, $x - y \in B_n$. We collect all the homology modules together and write

$$\mathrm{H}_*(C_\bullet) = \bigoplus_{n \in \mathbb{Z}} \mathrm{H}_n(C_\bullet),$$

the *homology* of $C_\bullet$ (or of C, omitting the subscript for simplicity of notation). It is common to identify C with the R-module $\oplus_{n\in\mathbb{Z}} C_n$, and d with the endomorphism of this direct sum that is just d_n on each C_n as identified canonically with an R-submodule of this direct sum.

Some further terminology (that is not used universally or consistently in the literature): A *chain complex* is a complex for which $C_n = 0$ for $n < 0$. A *cochain complex* is a complex for which $C_n = 0$ for $n > 0$. These two terms are also used more generally in the literature to refer to complexes as we have defined them here.

We may wish to index complexes differently, replacing n by $-n$ in $C_\bullet$ above, with the maps still oriented as shown. Then the indexing in the above diagram is

visually the same as the ordering of integers on a number line. A cochain complex then has differential of degree +1; the index is often then written as a superscript:

$$C^\bullet : \qquad 0 \longrightarrow C^0 \xrightarrow{d_0} C^1 \xrightarrow{d_1} C^2 \xrightarrow{d_2} \cdots$$

With this indexing, elements in the kernel of d_n are called the *n-cocycles*, and elements in the image of d_{n-1} are called the *n-coboundaries*. Two n-cocycles are called *cohomologous* if their difference is an n-coboundary. Similar to the above, we set

$$\mathrm{H}^n(C^\bullet) = \mathrm{Ker}(d_n)/\,\mathrm{Im}(d_{n-1})$$

and $\mathrm{H}^*(C^\bullet) = \oplus_{n\geq 0}\,\mathrm{H}^n(C^\bullet)$, the *cohomology* of the cochain complex $C^\bullet$.

A complex $C_\bullet$ is called *acyclic*, or *exact*, if $\mathrm{H}_n(C_\bullet) = 0$ for all n. A *short exact sequence* is an exact complex of the form $0 \to U \to V \to W \to 0$.

Let (C, d) and (C', d') be complexes. A *chain map* $f_\bullet : C_\bullet \to C'_\bullet$ is a collection of R-module homomorphisms $f_n : C_n \to C'_n$ for which $f_{n-1}d_n = d'_n f_n$ for each $n \in \mathbb{Z}$. That is, the following diagram commutes:

$$\begin{tikzcd}
\cdots \arrow[r] & C_1 \arrow[r, "d_1"] \arrow[d, "f_1"] & C_0 \arrow[r, "d_0"] \arrow[d, "f_0"] & C_{-1} \arrow[r] \arrow[d, "f_{-1}"] & \cdots \\
\cdots \arrow[r] & C'_1 \arrow[r, "d'_1"] & C'_0 \arrow[r, "d'_0"] & C'_{-1} \arrow[r] & \cdots
\end{tikzcd}$$

It can be checked that a chain map induces a map on homology. A chain map is called a *quasi-isomorphism* if this induced map is an isomorphism on homology.

We say that two chain maps $f_\bullet, g_\bullet : C_\bullet \to C'_\bullet$ are *chain homotopic* if there exist R-module homomorphisms $s_n : C_n \to C'_{n+1}$ such that

$$f_n - g_n = s_{n-1}d_n + d'_{n+1}s_n \tag{1.1}$$

for all n. The collection $s_\bullet$ of homomorphisms is called a *homotopy* for $f_\bullet - g_\bullet$. It can be checked that chain homotopy is an equivalence relation, and that two chain homotopic maps induce the same maps on homology. As a special case, when $g_\bullet$ is the zero map, we call $s_\bullet$ a *chain contraction* of $f_\bullet$. A chain contraction of the identity map on $C_\bullet$, if it exists, is sometimes called a *contracting homotopy*, and in this case, it can be checked that $C_\bullet$ is acyclic. (In fact, for this last consequence, it is not needed that the functions s_n are R-module homomorphisms, only that there are such functions (of sets, or of abelian groups, for example) satisfying equation (1.1).)

2. Projective and injective resolutions

We call an R-module P *projective* if for every surjective R-module homomorphism $f : U \to V$ and R-module homomorphism $g : P \to V$, there exists an R-module homomorphism $h : P \to U$ such that $fh = g$:

$$\begin{tikzcd}
 & P \arrow[dl, dashed, "h"'] \arrow[d, "g"] & \\
U \arrow[r, "f"] & V \arrow[r] & 0
\end{tikzcd} \tag{2.1}$$

There are other equivalent definitions of projective module. For example, an R-module is projective if, and only if, it is a direct summand of a free module (i.e. $R^{\oplus I}$ for some indexing set I).

Let M be an R-module. A *projective resolution* of M is a chain complex $P_\bullet$ consisting of projective R-modules P_n $(n \geq 0)$ for which $\mathrm{H}_0(P_\bullet) \cong M$ and $\mathrm{H}_n(P_\bullet) = 0$ for all $n \neq 0$. As a consequence, $P_\bullet$ is quasi-isomorphic to the complex that is M concentrated in degree 0 and 0 elsewhere:

$$\begin{tikzcd}
\cdots \arrow[r] & P_2 \arrow[r] \arrow[d] & P_1 \arrow[r] \arrow[d] & P_0 \arrow[r] \arrow[d, "\varepsilon"] & 0 \arrow[r] \arrow[d] & \cdots \\
\cdots \arrow[r] & 0 \arrow[r] & 0 \arrow[r] & M \arrow[r] & 0 \arrow[r] & \cdots
\end{tikzcd}$$

Another consequence of the definition is that the following sequence is exact:

$$\cdots \xrightarrow{d_2} P_1 \xrightarrow{d_1} P_0 \xrightarrow{\varepsilon} M \longrightarrow 0. \tag{2.2}$$

(In some texts, (2.2) is called a projective resolution of M.) The complex (2.2) is sometimes called the *augmented complex* of $P_\bullet$. This augmented complex may be abbreviated $P_\bullet \xrightarrow{\varepsilon} M$. The complex $P_\bullet$ (without the M) is sometimes called the *truncated complex* of (2.2).

Projective resolutions of R-modules always exist: Every R-module M is a homomorphic image of a projective R-module, for example, the free module on a set of generators of M. One may use this fact to build a projective resolution as follows. Let P_0 be a projective R-module mapping surjectively to M via an R-module homomorphism ε. Let $K_1 = \mathrm{Ker}(\varepsilon)$. In turn, K_1 is a homomorphic image of some projective R-module P_1 via some R-module homomorphism $\varepsilon_1 : P_1 \to K_1$. Denote by i_1 the inclusion map $i_1 : K_1 \to P_0$ and set $d_1 = i_1\varepsilon_1$. Let $K_2 = \mathrm{Ker}(d_1)$ and continue. Visually, we have:

$$\begin{tikzcd}
\cdots \arrow[r] & P_2 \arrow[rr, "d_2"] \arrow[dr, "\varepsilon_2"'] & & P_1 \arrow[rr, "d_1"] \arrow[dr, "\varepsilon_1"'] & & P_0 \arrow[r, "\varepsilon"] & M \arrow[r] & 0 \\
& & K_2 \arrow[ur, "i_2"'] & & K_1 \arrow[ur, "i_1"'] & & &
\end{tikzcd} \tag{2.3}$$

The R-module K_i is called an *ith syzygy module* of M. This module depends on some choices. However, it is unique up to an equivalence relation, as stated in Lemma 2.5 below. We will first need Schanuel's Lemma:

Lemma 2.4 (Schanuel's Lemma)**.** *Let*

$$0 \to K \to P \xrightarrow{\varepsilon} M \to 0 \quad \textit{and} \quad 0 \to K' \to P' \xrightarrow{\varepsilon'} M \to 0$$

be two short exact sequences of R-modules with P, P' projective. Then $K \oplus P' \cong K' \oplus P$.

A proof is given in class, using the pullback of ε and ε'. For definition of pullback, see the appendix.

The next lemma is a consequence of Schanuel's Lemma via a mathematical induction argument.

Lemma 2.5. *Let K_i and K_i' be two ith syzygy modules of the R-module M. There are projective R-modules P, P' such that $K_i \oplus P \cong K_i' \oplus P'$.*

A proof is given in class.

Remark 2.6. There is another way to state Lemma 2.5: Call two R-modules U and V *equivalent* if there exist projective R-modules P, P' for which $U \oplus P \cong V \oplus P'$ as R-modules. This can be shown to be an equivalence relation. The conclusion of Lemma 2.5 is that K_i and K_i' are equivalent under this equivalence relation.

The next theorem implies a relation among projective resolutions themselves.

Theorem 2.7 (Comparison Theorem). *Let $(P_\bullet, d_\bullet)$ and $(Q_\bullet, d_\bullet')$ be chain complexes of R-modules with $M = \mathrm{H}_0(P_\bullet)$, $N = \mathrm{H}_0(Q_\bullet)$, and let $\varepsilon : P_0 \to M$ and $\varepsilon' : Q_0 \to N$ be corresponding augmentation maps. Assume that P_i is projective for each i and that the augmented complex $\cdots \to Q_1 \to Q_0 \to N \to 0$ is exact. If $f : M \to N$ is an R-module homomorphism, then there is a chain map $f_\bullet : P_\bullet \to Q_\bullet$ for which $f\varepsilon = \varepsilon' f_0$, that is, the following diagram commutes:*

$$\begin{tikzcd}
\cdots \arrow[r] & P_2 \arrow[r, "d_2"] \arrow[d, dashed, "f_2"] & P_1 \arrow[r, "d_1"] \arrow[d, dashed, "f_1"] & P_0 \arrow[r, "\varepsilon"] \arrow[d, dashed, "f_0"] & M \arrow[r] \arrow[d, "f"] & 0 \\
\cdots \arrow[r] & Q_2 \arrow[r, "d_2'"] & Q_1 \arrow[r, "d_1'"] & Q_0 \arrow[r, "\varepsilon'"] & N \arrow[r] & 0
\end{tikzcd}$$

The chain map $f_\bullet$ is unique up to chain homotopy.

Proof. A proof of existence of chain map $f_\bullet$ was given in class in the special case that both $P_\bullet$ and $Q_\bullet$ are projective resolutions. It can be checked that the "same" proof applies under these slightly more general hypotheses.

Proof of uniqueness up to chain homotopy: Let $g_\bullet : P_\bullet \to Q_\bullet$ be another chain map lifting $f : M \to N$, so that $f\varepsilon = \varepsilon' g_0$ and $d_n' g_n = g_{n-1} d_n$ for all $n \geq 1$. First note that as $\varepsilon'(f_0 - g_0) = f\varepsilon - f\varepsilon = 0$, we have

$$\mathrm{Im}(f_0 - g_0) \subseteq \mathrm{Ker}(\varepsilon') = \mathrm{Im}(d_1').$$

Since P_0 is projective, there exists a map $s_0 : P_0 \to Q_1$:

$$\begin{tikzcd}
 & P_0 \arrow[dl, dashed, "s_0"'] \arrow[d, "f_0 - g_0"] & \\
Q_1 \arrow[r, "d_1'"] & \mathrm{Im}(d_1') \arrow[r] & 0
\end{tikzcd} \tag{2.8}$$

Setting $s_{-1} \equiv 0$, we now have $f_0 - g_0 = d_1' s_0 = d_1' s_0 + s_{-1}\varepsilon$.

Next we claim that $\mathrm{Im}(f_1 - g_1 - s_0 d_1) \subseteq \mathrm{Im}(d_2')$. To see this, first compute the composition:

$$d_1'(f_1 - g_1 - s_0 d_1) = f_0 d_1 - g_0 d_1 - d_1' s_0 d_1 = (f_0 - g_0) d_1 - d_1' s_0 d_1 = d_1' s_0 d_1 - d_1' s_0 d_1 = 0.$$

It follows that $\mathrm{Im}(f_1 - g_1 - s_0 d_1) \subseteq \mathrm{Ker}(d_1') = \mathrm{Im}(d_2')$. Since P_1 is projective, there is consequently a map $s_1 : P_1 \to Q_2$:

$$\begin{tikzcd}
 & P_1 \arrow[dl, dashed, "s_1"'] \arrow[d, "f_1 - g_1 - s_0 d_1"] & \\
Q_2 \arrow[r, "d_2'"] & \mathrm{Im}(d_2') \arrow[r] & 0
\end{tikzcd} \tag{2.9}$$

So $f_1 - g_1 - s_0 d_1 = d_2' s_1$, that is $f_1 - g_1 = s_0 d_1 + d_2' s_1$.

Continuing in this manner, we see that for each n, there exists a map $s_n : P_n \to Q_n$ with $f_n - g_n = s_{n-1} d_n + d_{n+1}' s_n$. That is, the two chain maps $f_\bullet$ and $g_\bullet$ are chain homotopic. $\square$

As a consequence of the Comparison Theorem, if $P_\bullet, Q_\bullet$ are projective resolutions of M, N, respectively, then there is a chain map $f_\bullet : P_\bullet \to Q_\bullet$ *lifting* the R-module homomorphism $f : M \to N$.

We will also work with injective resolutions. An R-module I is called *injective* if for every injective R-module homomorphism $f : V \to U$ and R-module homomorphism $g : V \to I$, there is an R-module homomorphism $h : U \to I$ for which $hf = g$:

$$\begin{tikzcd} & I & \\ U \arrow[ur, dashed, "h"] & V \arrow[l, "f"'] \arrow[u, "g"'] & 0 \arrow[l] \end{tikzcd} \tag{2.10}$$

An *injective resolution* of an R-module M is a cochain complex $(I_\bullet, d_\bullet)$ consisting of injective R-modules I_n $(n \leq 0)$ for which $\mathrm{H}_0(I_\bullet) \cong M$ and $\mathrm{H}_n(I_\bullet) = 0$ for all $n \neq 0$. That is, $M \cong \mathrm{Ker}(d_0)$, and the following sequence is exact:

$$0 \longrightarrow M \xrightarrow{\iota} I_0 \xrightarrow{d_0} I_1 \xrightarrow{d_1} \cdots, \tag{2.11}$$

where ι is an isomorphism from M to $\mathrm{Ker}(d_0)$ followed by inclusion into I_0. The complex (2.11) is sometimes called the *augmented complex* of $I_\bullet$. It may also itself be called an injective resolution of M. The complex $I_\bullet$ is sometimes called the *truncated complex* of (2.11).

Injective resolutions of R-modules always exist: Baer's Theorem states that every R-module can be embedded into an injective R-module. (See e.g. [2] or Hungerford for a proof of Baer's Theorem.) An injective resolution can thus be built similarly (and in reverse order) to the construction of a projective resolution above. Specifically, let $L_1 = \mathrm{Coker}(\iota) = I_0/\mathrm{Im}(\iota)$. Let $\pi_0 : I_0 \to L_1$ be the quotient map. Embed L_1 into an injective module I_1 via an R-module homomorphism $\iota_1 : L_1 \to I_1$. Let $\delta_0 = \iota_1\pi_0$. Continue by letting $L_2 = \mathrm{Coker}(\iota_1) = \mathrm{Coker}(\delta_0)$, then embed L_2 into an injective module I_2, and so on.

$$\begin{tikzcd} 0 \arrow[r] & M \arrow[r, "\iota"] & I_0 \arrow[rr, "\delta_0"] \arrow[dr, "\pi_0"'] & & I_1 \arrow[rr, "\delta_1"] \arrow[dr, "\pi_1"'] & & I_2 \arrow[r] & \cdots \\ & & & L_1 \arrow[ur, "\iota_1"'] & & L_2 \arrow[ur, "\iota_2"'] & & \end{tikzcd} \tag{2.12}$$

The module L_1 will be unique up to injective direct summands, due to a dual version of Schanuel's Lemma that may be checked: If $0 \to N \to I \to L \to 0$ and $0 \to N \to I' \to L' \to 0$ are exact sequences with I, I' injective, then there is an isomorphism $L \oplus I' \cong L' \oplus I$.

There is a version of Theorem 2.7 for injective resolutions. See for example [3, Comparison Theorem 2.7].

Other types of resolutions may be defined similarly, for example, flat resolutions. (See Remark 3.3 below for a definition of *flat*.)

3. Ext and Tor

In this section we will define Ext and Tor.

Ext. Let M and N be R-modules. Let $P_\bullet \xrightarrow{\varepsilon} M$ be a projective resolution of M. Apply $\mathrm{Hom}_R(-,N)$ to the (truncated) complex $\cdots \xrightarrow{d_2} P_1 \xrightarrow{d_1} P_0 \to 0$ to obtain a sequence of abelian groups (in reverse order for visual appeal):

$$0 \longrightarrow \mathrm{Hom}_R(P_0,N) \xrightarrow{d_1^*} \mathrm{Hom}_R(P_1,N) \xrightarrow{d_2^*} \cdots \tag{3.1}$$

Here the abelian group homomorphism d_i^* is that induced by d_i, i.e. $d_i^*(f) = fd_i$ for all $f \in \mathrm{Hom}_R(P_{i-1},N)$ and all $i > 0$. For convenience, we define $d_0^* = 0$.

Note that $d_{i+1}^* d_i^* = 0$ since $d_i d_{i+1} = 0$, so the above sequence (3.1) is in fact a (cochain) complex of abelian groups (that is, $\mathbb{Z}$-modules). If R is commutative, it is a complex of R-modules. If R is an algebra over a field k (that is, a ring that is also a vector space with multiplication bilinear), it is a complex of k-vector spaces. Define $\mathrm{Ext}_R^n(M,N)$ to be the cohomology of this cochain complex:

$$\mathrm{Ext}_R^n(M,N) = \mathrm{H}^n(\mathrm{Hom}_R(P_\bullet,N)) = \mathrm{Ker}(d_{n+1}^*)/\,\mathrm{Im}(d_n^*)$$

for $n \geq 0$, and

$$\mathrm{Ext}_R^*(M,N) = \bigoplus_{n\geq 0} \mathrm{Ext}_R^n(M,N).$$

It can be checked that, by the Comparison Theorem (Theorem 2.7), up to isomorphism of abelian groups, $\mathrm{Ext}_R^*(M,N)$ does not depend on choice of projective resolution of M. In degree 0, we have

$$\mathrm{Ext}_R^0(M,N) \cong \mathrm{Hom}_R(M,N).$$

Note that by construction, if M is itself projective, then $\mathrm{Ext}_R^n(M,N) = 0$ for all $n > 0$.

We may alternatively define $\mathrm{Ext}_R^n(M,N)$ by first taking an injective resolution of N, instead of a projective resolution of M: Take $N \xrightarrow{\iota} I_\bullet$ to be an injective resolution of N. Apply $\mathrm{Hom}_R(M,-)$ to the (truncated) sequence $0 \to I_0 \xrightarrow{d_0} I_1 \xrightarrow{d_1} \cdots$ to obtain:

$$0 \longrightarrow \mathrm{Hom}_R(M,I_0) \xrightarrow{(d_0)_*} \mathrm{Hom}_R(M,I_1) \xrightarrow{(d_1)_*} \cdots \tag{3.2}$$

with $(d_i)_*(f) = d_i f$ for all i and $f \in \mathrm{Hom}_R(M,I_i)$. Set $(d_{-1})_* = 0$. It can be checked that $(d_{i+1})_*(d_i)_* = 0$ for all $i \geq -1$. Thus the sequence (3.2) is a (cochain) complex of abelian groups. It can be shown that

$$\mathrm{Ext}_R^n(M,N) \cong \mathrm{H}^n(\mathrm{Hom}_R(M,I_\bullet)) = \mathrm{Ker}((d_n)_*)/\,\mathrm{Im}((d_{n-1})_*).$$

(A proof of the above isomorphism will at least be outlined in class at some point.) If N is an injective R-module, it now follows that $\mathrm{Ext}_R^n(M,N) = 0$ for all $n > 0$.

Tor. Let M be a right R-module and let N be a left R-module. Let $P_\bullet \to M$ be a (right R-module) projective resolution of M. Apply $- \otimes_R N$ to the (truncated) complex $P_\bullet$ to obtain a sequence of abelian groups (i.e. $\mathbb{Z}$-modules):

$$\cdots \longrightarrow P_2 \otimes_R N \xrightarrow{d_2 \otimes 1_N} P_1 \otimes_R N \xrightarrow{d_1 \otimes 1_N} P_0 \otimes_R N \longrightarrow 0.$$

Here 1_N denotes the identity map on N. (In order to reduce notational clutter, we suppress the subscript R on the tensor symbol $\otimes$, just for maps and elements, when it is clear from context that the subscript on the tensor symbol $\otimes$ should be R.) Set $d_0 = 0$. The above is a chain complex. We define $\mathrm{Tor}_n^R(M, N)$ to be its homology:

$$\mathrm{Tor}_n^R(M, N) = \mathrm{H}_n(P_\bullet \otimes_R N) = \mathrm{Ker}(d_n \otimes 1)/\,\mathrm{Im}(d_{n+1} \otimes 1)$$

for $n \geq 0$, and

$$\mathrm{Tor}_*^R(M, N) = \bigoplus_{n \geq 0} \mathrm{Tor}_n^R(M, N).$$

It can be checked that, by the Comparison Theorem (Theorem 2.7), $\mathrm{Tor}_n^R(M, N)$ does not depend on choice of projective resolution of M. It may be checked that

$$\mathrm{Tor}_0^R(M, N) \cong M \otimes_R N.$$

We may alternatively define $\mathrm{Tor}_n^R(M, N)$ via a (left R-module) projective resolution of N: Let $Q_\bullet \to N$ be a projective resolution of N. Apply $M \otimes_R -$ to $Q_\bullet$ to obtain a sequence

$$\cdots \longrightarrow M \otimes_R Q_2 \xrightarrow{1_M \otimes d_2} M \otimes_R Q_1 \xrightarrow{1_M \otimes d_1} M \otimes_R Q_0 \longrightarrow 0.$$

It can be proven that $\mathrm{Tor}_n^R(M, N) \cong \mathrm{H}_n(M \otimes_R Q_\bullet)$. *(Details to be discussed in class at some point.)*

Remark 3.3. We call a left R-module F *flat* if for every short exact sequence of right R-modules $0 \to U \to V \to W \to 0$, the induced sequence of abelian groups $0 \to U \otimes_R F \to V \otimes_R F \to W \otimes_R F \to 0$ is exact. (There is a similar definition of flatness for right R-modules.) It may be checked that every projective module is flat. As a direct consequence of this definition, combined with the definition and balancing of Tor, if either M or N is flat as an R-module, then $\mathrm{Tor}_n^R(M, N) = 0$ for all $n > 0$.

4. Long exact sequences for Ext and Tor

We first state the Snake Lemma, which has many uses. Here, we will use it to construct long exact sequences for Ext and Tor.

Lemma 4.1 (Snake Lemma)**.** *Suppose there is a commuting diagram of R-modules and R-module homomorphisms with exact rows:*

$$\begin{tikzcd}
 & U' \arrow[r] \arrow[d, "f"] & V' \arrow[r, "p"] \arrow[d, "g"] & W' \arrow[r] \arrow[d, "h"] & 0 \\
0 \arrow[r] & U \arrow[r, "i"] & V \arrow[r] & W &
\end{tikzcd}$$

Then there is an exact sequence

$$\mathrm{Ker}(f) \to \mathrm{Ker}(g) \to \mathrm{Ker}(h) \xrightarrow{\partial} \mathrm{Coker}(f) \to \mathrm{Coker}(g) \to \mathrm{Coker}(h)$$

where $\partial(w') = i^{-1}gp^{-1}(w')$ *for all* $w' \in \mathrm{Ker}(h)$.[1] *If the map* $U' \to V'$ *is injective, then the map* $\mathrm{Ker}(f) \to \mathrm{Ker}(g)$ *is injective, and if* $V \to W$ *is surjective, then* $\mathrm{Coker}(g) \to \mathrm{Coker}(h)$ *is surjective.*

This lemma is often illustrated as follows, hence the name.

$$\begin{tikzcd}
 & \mathrm{Ker}(f) \arrow[r, dashed] \arrow[d] & \mathrm{Ker}(g) \arrow[r, dashed] \arrow[d] & \mathrm{Ker}(h) \arrow[d] \arrow[dddll, dashed, bend left] & \\
 & U' \arrow[r] \arrow[d, "f"] & V' \arrow[r, "p"] \arrow[d, "g"] & W' \arrow[r] \arrow[d, "h"] & 0 \\
0 \arrow[r] & U \arrow[r, "i"] \arrow[d] & V \arrow[r] \arrow[d] & W \arrow[d] & \\
 & \mathrm{Coker}(f) \arrow[r, dashed] & \mathrm{Coker}(g) \arrow[r, dashed] & \mathrm{Coker}(h) &
\end{tikzcd}$$

One consequence of the Snake Lemma (Lemma 4.1) is the following theorem that will be used to obtain long exact sequences for Tor and Ext. We define a *short exact sequence of complexes* to be a sequence

$$0 \to U_\bullet \xrightarrow{f_\bullet} V_\bullet \xrightarrow{g_\bullet} W_\bullet \to 0$$

where $f_\bullet$, $g_\bullet$ are chain maps and f_i is injective, g_i is surjective, and $\mathrm{Im}(f_i) = \mathrm{Ker}(g_i)$ for each i.

Theorem 4.2. *Let* $0 \to U_\bullet \xrightarrow{f_\bullet} V_\bullet \xrightarrow{g_\bullet} W_\bullet \to 0$ *be a short exact sequence of complexes. There are abelian group homomorphisms* $\partial_n : \mathrm{H}_n(W_\bullet) \to \mathrm{H}_{n-1}(U_\bullet)$ *for each* n *such that*

$$\cdots \longrightarrow \mathrm{H}_{n+1}(W) \xrightarrow{\partial_{n+1}} \mathrm{H}_n(U) \xrightarrow{\overline{f}_n} \mathrm{H}_n(V) \xrightarrow{\overline{g}_n} \mathrm{H}_n(W) \xrightarrow{\partial_n} \cdots$$

is an exact sequence. (Here, $\overline{f}_n, \overline{g}_n$ *denote the maps induced by* f_n, g_n*.)*

We call the homomorphisms ∂_n in the theorem *connecting homomorphisms.*

The next lemma will also be used in constructing long exact sequences for Ext and Tor. It is called the Horseshoe Lemma due to the shape of the given diagram.

Lemma 4.3 (Horseshoe Lemma)**.** *Supppose there is a short exact sequence of* R*-modules and* R*-module homomorphisms* $0 \to U' \to U \to U'' \to 0$*. Let* $P'_\bullet \to U'$*,*

[1]Caution: This is abuse of notation. The R-module homomorphisms p, i are not assumed to be isomorphisms. Instead, by $p^{-1}(w')$ we mean any element in the inverse image of w' under p, and similarly for i^{-1}, which is then followed by canonical projection to $\mathrm{Coker}(f)$. It can be checked that this element in $\mathrm{Coker}(f)$ does not depend on these choices.

$P''_\bullet \to U''$ be projective resolutions of U' and U'' as in the diagram:

$$\begin{tikzcd}
 & & & 0 \arrow[d] & \\
\cdots \arrow[r] & P'_1 \arrow[r] & P'_0 \arrow[r] & U' \arrow[r] \arrow[d] & 0 \\
 & & & U \arrow[d] & \\
\cdots \arrow[r] & P''_1 \arrow[r] & P''_0 \arrow[r] & U'' \arrow[r] \arrow[d] & 0 \\
 & & & 0 &
\end{tikzcd}$$

For each n, let $P_n = P'_n \oplus P''_n$. Then there are differentials d_i for which

$$\cdots \to P_1 \xrightarrow{d_1} P_0 \to U \to 0$$

is a projective resolution of U. Furthermore, the right column lifts to an exact sequence of complexes $0 \to P'_\bullet \xrightarrow{\iota_\bullet} P_\bullet \xrightarrow{\pi_\bullet} P''_\bullet \to 0$ for which $\iota_\bullet, \pi_\bullet$ are the canonical inclusion and projection maps.

Now we may use Theorem 4.2 and the Horseshoe Lemma (Lemma 4.3) to obtain the following four long exact sequences.

Theorem 4.4 (First long exact sequence for Ext)**.** *Suppose U is an R-module and $0 \to V' \to V \to V'' \to 0$ is a short exact sequence of R-modules. Then there is an exact sequence*

$$0 \to \mathrm{Hom}_R(U, V') \longrightarrow \mathrm{Hom}_R(U, V) \longrightarrow \mathrm{Hom}_R(U, V'') \longrightarrow$$

$$\mathrm{Ext}^1_R(U, V') \longrightarrow \mathrm{Ext}^1_R(U, V) \longrightarrow \mathrm{Ext}^1_R(U, V'') \longrightarrow \mathrm{Ext}^2_R(U, V') \cdots$$

Theorem 4.5 (Second long exact sequence for Ext)**.** *Suppose V is an R-module and $0 \to U' \to U \to U'' \to 0$ is a short exact sequence of R-modules. Then there is an exact sequence*

$$0 \to \mathrm{Hom}_R(U'', V) \longrightarrow \mathrm{Hom}_R(U, V) \longrightarrow \mathrm{Hom}_R(U', V) \longrightarrow$$

$$\mathrm{Ext}^1_R(U'', V) \longrightarrow \mathrm{Ext}^1_R(U, V) \longrightarrow \mathrm{Ext}^1_R(U', V) \longrightarrow \mathrm{Ext}^2_R(U'', V) \cdots$$

Theorem 4.6 (First long exact sequence for Tor)**.** *Suppose V is a left R-module and $0 \to U' \to U \to U'' \to 0$ is an exact sequence of right R-modules. Then there*

is an exact sequence

$$\cdots \longrightarrow \mathrm{Tor}_2^R(U'', V) \longrightarrow \mathrm{Tor}_1^R(U', V) \longrightarrow \mathrm{Tor}_1^R(U, V) \longrightarrow$$

$$\mathrm{Tor}_1^R(U'', V) \longrightarrow U' \otimes_R V \longrightarrow U \otimes_R V \longrightarrow U'' \otimes_R V \longrightarrow 0.$$

Theorem 4.7 (Second long exact sequence for Tor)**.** *Suppose U is a right R-module and $0 \to V' \to V \to V'' \to 0$ is an exact sequence of left R-modules. Then there is an exact sequence*

$$\cdots \longrightarrow \mathrm{Tor}_2^R(U, V'') \longrightarrow \mathrm{Tor}_1^R(U, V') \longrightarrow \mathrm{Tor}_1^R(U, V) \longrightarrow$$

$$\mathrm{Tor}_1^R(U, V'') \longrightarrow U \otimes_R V' \longrightarrow U \otimes_R V \longrightarrow U \otimes_R V'' \longrightarrow 0.$$

5. Homological dimensions and Hilbert's Syzygy Theorem

In this section, we will define the homological dimensions termed projective dimension and global dimension, focusing first on the special cases of rings and modules for which these are either 0 or 1. We will then develop some preliminary results leading to a proof of Hilbert's Syzygy Theorem that gives the global dimension of a polynomial ring.

We will begin with semisimple rings and modules. An R-module M is *semisimple* if it is isomorphic to a direct sum of (possibly infinitely many) simple R-modules. (Recall a *simple* R-module is one having no proper nonzero R-submodules.) The ring R is called *semisimple* if the R-module R itself (under either left or right multiplication) is a semisimple R-module.

A classification of semsimple rings is given by the following theorem.

Theorem 5.1 (Wedderburn-Artin Theorem)**.** *Every semisimple ring is isomorphic to a finite direct product of matrix rings over division rings.*

The following proposition gives several equivalent conditions for a ring to be semisimple.

Proposition 5.2. *The following are equivalent for a ring R.*

(i) *R is semisimple.*
(ii) *Every R-module is semisimple.*
(iii) *Every R-module is projective.*
(iv) *Every R-module is injective.*

We will turn to nonsemisimple rings next, and start by proving a theorem that is sometimes termed *dimension shifting*. It gives an isomorphism between Ext groups in different homological degrees by replacing a module with one of its syzygy modules (thus shifting degree, or dimension, of the Ext group).

For each R-module M and $i \geq 1$, denote by $\Omega^i M$ an ith syzygy module of M. (The statements of theorems to follow will not depend on the choice of $\Omega^i M$.)

Theorem 5.3 (Dimension shifting)**.** *Let M and N be R-modules. There is an isomorphism of abelian groups for all $n \geq 2$,*

$$\mathrm{Ext}^n_R(M,N) \quad \cong \quad \mathrm{Ext}^1_R(\Omega^{n-1}M,N).$$

Proof. This is by construction of diagram (2.3) and definition of Ext. Alternatively, one may apply the second long exact sequence for Ext to the short exact sequence $0 \to \Omega^1 M \to P_0 \to M \to 0$ and N to obtain isomorphisms $\mathrm{Ext}^n_R(M,N) \cong \mathrm{Ext}^{n-1}_R(\Omega^1 M,N)$. Then note $\Omega^i(\Omega^1 M)$ is isomorphic to $\Omega^{i+1}M$ up to projective direct summands, and use induction. □

Let V be a left R-module. The *projective dimension* $\mathrm{pd}_R(V)$ is the smallest integer n for which there exists a projective resolution of V of the form

$$0 \to P_n \to \cdots \to P_1 \to P_0 \to V \to 0.$$

If no such n exists, we write $\mathrm{pd}_R(V) = \infty$. By its definition, we see that the projective dimension $\mathrm{pd}_R(M)$ of M is also the smallest integer n for which some nth syzygy module $\Omega^n M$ of M is projective. (Note this does not depend on choice of syzygy module since any two are isomorphic up to projective direct summands as seen earlier.)

The *left global dimension* of R is

$$\mathrm{gldim}(R) = \sup\{\mathrm{pd}_R(V) \mid V \text{ is a left } R\text{-module}\}.$$

(This is also sometimes denoted $\mathrm{lgldim}(R)$ to distinguish it from the similarly defined right global dimension, which can be different.) Note that R is semisimple if, and only if, $\mathrm{gldim}(R) = 0$.

A ring R is called (left) *hereditary* if every left R-submodule of every free left R-module is projective.

Proposition 5.4. $\mathrm{gldim}(R) = 1$ *if, and only if, R is hereditary and not semisimple.*

By dimension shifting and the definition of projective dimension, we find the following.

Lemma 5.5. *Let A be a left R-module and d be a nonnegative integer. The following are equivalent:*

(i) $\mathrm{pd}_R(A) \leq d$.
(ii) $\mathrm{Ext}^n_R(A,B) = 0$ *for all $n > d$ and all left R-modules B.*
(iii) $\mathrm{Ext}^{d+1}_R(A,B) = 0$ *for all left R-modules B.*

As a consequence,

$$\mathrm{pd}_R(M) = \sup\{j \mid \mathrm{Ext}^j_R(M,N) \neq 0 \text{ for some } R\text{-module } N\}. \tag{5.6}$$

The next lemma gives a comparison of projective dimensions among modules in a short exact sequence.

Lemma 5.7. *Let $0 \to A \to B \to C \to 0$ be a short exact sequence of left R-modules. Then*

$$\mathrm{pd}_R(B) \leq \max\{\mathrm{pd}_R(A), \mathrm{pd}_R(C)\}.$$

If the inequality is strict, then $\mathrm{pd}_R(C) = \mathrm{pd}_R(A) + 1$.

The next two theorems and corollary compare projective dimensions of modules for two rings related to each other in the specified ways.

Theorem 5.8 (First Change of Rings Theorem)**.** *Let x be a central nonzerodivisor in R and let $\overline{R} = R/(x)$. If A is a left $\overline{R}$-module with $\mathrm{pd}_{\overline{R}}(A)$ finite, then*

$$\mathrm{pd}_R(A) = \mathrm{pd}_{\overline{R}}(A) + 1.$$

Theorem 5.9 (Second Change of Rings Theorem)**.** *Let x be a central nonzerodivisor in a ring R, and let $\overline{R} = R/(x)$. If A is a left R-module and $\mathrm{Tor}_1^R(\overline{R}, A) = 0$, then*

$$\mathrm{pd}_R(A) \geq \mathrm{pd}_{\overline{R}}(A/xA).$$

Corollary 5.10. *Let S be a ring, $R = S[x]$, and M a left S-module. Then*

$$\mathrm{pd}_R(R \otimes_S M) = \mathrm{pd}_S(M).$$

We are now ready for Hilbert's Syzygy Theorem.

Theorem 5.11 (Hilbert's Syzygy Theorem)**.** *Let k be a field. Then*

$$\mathrm{gldim}\,(k[x_1, \ldots, x_n]) = n.$$

Thus the nth syzygy module of every $k[x_1, \ldots, x_n]$-module is projective.

6. Categories, functors, derived functors

Everything we have done so far in the course, other than results for specific types of rings and modules, can be done more generally for categories having some good properties (specifically, additive or abelian categories). We will start by summarizing the needed ideas from category theory. Then we will define derived functors, showing that Ext and Tor are specific instances of derived functors.

Recall that a *category* $\mathcal{C}$ consists of a collection of *objects* $\mathrm{Obj}(\mathcal{C})$ and sets of *morphisms* $\mathrm{Hom}_{\mathcal{C}}(A, B)$ for all objects A, B of $\mathcal{C}$, satisfying the following: For each object A in $\mathcal{C}$, there is an *identity morphism* $1_A \in \mathrm{Hom}_{\mathcal{C}}(A, A)$. There is a binary operation, called *composition*, $\circ : \mathrm{Hom}_{\mathcal{C}}(A, B) \times \mathrm{Hom}_{\mathcal{C}}(B, C) \to \mathrm{Hom}_{\mathcal{C}}(A, C)$ for all objects A, B, C of $\mathcal{C}$, for which

$$(hg)f = h(gf) \quad \text{and} \quad 1_B f = f 1_A$$

for all $f \in \mathrm{Hom}_{\mathcal{C}}(A, B)$, $g \in \mathrm{Hom}_{\mathcal{C}}(B, C)$, $h \in \mathrm{Hom}_{\mathcal{C}}(C, D)$ and all objects A, B, C, D of $\mathcal{C}$. (In the above, for simplicity, we have written gf in place of $g \circ f$ to denote composition of morphisms.)

A morphism $f \in \mathrm{Hom}_{\mathcal{C}}(A, B)$ is called an *isomorphism* if there exists a morphism $g \in \mathrm{Hom}_{\mathcal{C}}(B, A)$ for which $gf = 1_A$ and $fg = 1_B$.

Examples of categories include those of modules for a ring R: Let R-Mod (respectively, R-mod) denote the category of all left R-modules (respectively, all finitely generated left R-modules). The objects are the modules, the morphisms are module homomorphisms (including the identity homomorphism for each module), and composition is function composition. Similarly, let Mod-R (respectively, mod-R) denote the category of right R-modules (respectively, all finitely generated right R-modules). It is common to simplify the notation $\mathrm{Hom}_{R\text{-Mod}}$ (respectively, $\mathrm{Hom}_{R\text{-mod}}$, $\mathrm{Hom}_{\text{Mod-}R}$, $\mathrm{Hom}_{\text{mod-}R}$) and write just Hom_R in all these cases; it should always be clear from context which is meant.

Let $\mathcal{C}$ and $\mathcal{D}$ be categories. A *functor* $F : \mathcal{C} \to \mathcal{D}$ is an assignment of an object $F(A)$ of $\mathcal{D}$ to each object A of $\mathcal{C}$, and a morphism $F(f) \in \mathrm{Hom}_{\mathcal{D}}(F(A), F(B))$ to each morphism $f \in \mathrm{Hom}_{\mathcal{C}}(A, B)$ for each pair of objects A, B of $\mathcal{C}$ such that

the following holds: $F(1_A) = 1_{F(A)}$ for all A and $F(g \circ f) = F(g) \circ F(f)$ for all morphisms f, g that it is possible to compose. One example of a functor is the identity functor $1_{\mathcal{C}} : \mathcal{C} \to \mathcal{C}$ given by $1_{\mathcal{C}}(A) = A$ and $1_{\mathcal{C}}(f) = f$ for all objects A and morphisms f of $\mathcal{C}$.

To be more precise, the above in fact defines a *covariant functor*. Similarly, a *contravariant functor* $F : \mathcal{C} \to \mathcal{D}$ is an assignment to each object A of $\mathcal{C}$ an object $F(A)$ of $\mathcal{D}$ and to each morphism $f \in \mathrm{Hom}_{\mathcal{C}}(A, B)$ a morphism $F(f) \in \mathrm{Hom}_{\mathcal{D}}(F(B), F(A))$ for which $F(1_A) = 1_{F(A)}$ and $F(g \circ f) = F(f) \circ F(g)$ for all morphisms f, g that can be composed.

Let $\mathcal{C}$ and $\mathcal{D}$ be categories, and let $F : \mathcal{C} \to \mathcal{D}$ and $G : \mathcal{C} \to \mathcal{D}$ be functors. A *natural transformation* $\eta : F \to G$ is an assignment of a morphism $\eta_A : F(A) \to G(A)$ to each object A of $\mathcal{C}$ for which the following holds: $G(f) \circ \eta_A = \eta_B \circ F(f)$ for all objects A, B of $\mathcal{C}$ and morphisms $f \in \mathrm{Hom}_{\mathcal{C}}(A, B)$. That is, the following diagram commutes:

$$\begin{tikzcd} F(A) \arrow[r, "F(f)"] \arrow[d, "\eta_A"'] & F(B) \arrow[d, "\eta_B"] \\ G(A) \arrow[r, "G(f)"] & G(B) \end{tikzcd}$$

We say that η is a *natural isomorphism* if η_A is an isomorphism for each object A. In this case, we write $F \cong G$.

Remark 6.1. Often in the literature, the term "natural" is used in this technical sense.

We say that two categories $\mathcal{C}$ and $\mathcal{D}$ are *equivalent* if there are functors $F : \mathcal{C} \to D$, $G : \mathcal{D} \to \mathcal{C}$ and natural isomorphisms $FG \cong 1_{\mathcal{D}}$ and $GF \cong 1_{\mathcal{C}}$.

Example 6.2. Let k be a field and $M_2(k)$ be the ring of 2×2-matrices over k. Each of these two rings is semisimple, with a unique simple module up to isomorphism. This leads to a category equivalence between their module categories (sending the unique simple object of one to the unique simple object of the other). When two rings have equivalent categories of modules, as in this example, the rings are called *Morita equivalent*.

Next we define adjoint functors. Let $\mathcal{C}$, $\mathcal{D}$ be categories and let $F : \mathcal{C} \to \mathcal{D}$ and $G : \mathcal{D} \to \mathcal{C}$ be functors. We say that F is *left adjoint* to G, and that G is *right adjoint* to F if there exist natural isomorphisms

$$\mathrm{Hom}_{\mathcal{D}}(F(X), Y) \xrightarrow{\sim} \mathrm{Hom}_{\mathcal{C}}(X, G(Y))$$

for each object X of $\mathcal{C}$ and Y of $\mathcal{D}$.

Standard examples of adjoint functors are given by induction and coinduction of modules: Let R be a ring with a subring $S \subseteq R$. Let N be an S-module. The corresponding *induced* (also called *tensor induced*) R-module is $R \otimes_S N$ as an abelian group, with R-module structure given by multiplication on the left tensor factor R. The corresponding *coinduced* R-module is $\mathrm{Hom}_S(R, N)$ as an abelian group with R-module structure given by

$$(r \cdot f)(x) = f(xr)$$

for all $r, x \in R$ and $f \in \mathrm{Hom}_S(R, N)$. The following lemma states that these are left and right adjoint functors of restriction of modules from R to S:

Lemma 6.3 (Nakayama relations)**.** *Let R be a ring with a subring $S \subseteq R$. Let M be an R-module and N an S-module. There are isomorphisms of abelian groups:*

$$\begin{aligned} \mathrm{Hom}_S(N, M) &\cong \mathrm{Hom}_R(R \otimes_S N, M), \\ \mathrm{Hom}_S(M, N) &\cong \mathrm{Hom}_R(M, \mathrm{Hom}_S(R, N)). \end{aligned}$$

That is, induction is left adjoint to restriction from R to S, and coinduction is right adjoint to restriction from R to S.

The above Lemma 6.3 may be used to prove:

Lemma 6.4 (Eckmann-Shapiro Lemma)**.** *Let R be a ring with a subring $S \subseteq R$ for which R is projective as a right S-module under multiplication. Let M be an R-module and N an S-module. Then there are isomorphisms of abelian groups:*

$$\begin{aligned} \mathrm{Ext}^n_S(N, M) &\cong \mathrm{Ext}^n_R(R \otimes_S N, M), \\ \mathrm{Ext}^n_S(M, N) &\cong \mathrm{Ext}^n_R(M, \mathrm{Hom}_S(R, N)). \end{aligned}$$

We define additive and abelian categories next; these are categories that have enough structure for homological algebra. Categories of modules for rings will be examples. There are some other definitions we need to make first.

A *zero object* of a category $\mathcal{C}$ is an object Z for which $|\mathrm{Hom}_{\mathcal{C}}(Z, X)| = 1$ and $|\mathrm{Hom}_{\mathcal{C}}(X, Z)| = 1$ for all objects X of $\mathcal{C}$ (we also say that Z is both an *initial* and a *terminal* object). Such a zero object Z is often denoted 0.

We recall next the notions of product and coproduct: Let $\{A_i\}_{i \in I}$ be a set of objects A_i of $\mathcal{C}$ indexed by some set I. A *product* $\prod_{i \in I} A_i$ is an object A and a collection of morphisms $\pi_i \in \mathrm{Hom}_{\mathcal{C}}(A, A_i)$ for all $i \in I$ for which the following universal property holds: If B is an object of $\mathcal{C}$ and $\psi_i \in \mathrm{Hom}_{\mathcal{C}}(B, A_i)$ for all $i \in I$, then there exists a unique morphism $\theta \in \mathrm{Hom}_{\mathcal{C}}(B, A)$ such that the following diagram commutes for all $i \in I$:

$$\begin{tikzcd} & A \arrow[d, "\pi_i"] \\ B \arrow[ur, "\theta"] \arrow[r, "\psi_i"'] & A_i \end{tikzcd}$$

A *coproduct* $\coprod_{i \in I} A_i$ is an object A and a collection of morphisms $\iota_i \in \mathrm{Hom}_{\mathcal{C}}(A_i, A)$ for which the following universal property holds: If B is an object of $\mathcal{C}$ and $\phi_i \in \mathrm{Hom}_{\mathcal{C}}(A_i, B)$ for all $i \in I$, then there is a unique $\tau \in \mathrm{Hom}_{\mathcal{C}}(A, B)$ such that the following diagram commutes for all $i \in I$:

$$\begin{tikzcd} A \arrow[dr, "\tau"] & \\ A_i \arrow[u, "\iota_i"] \arrow[r, "\phi_i"'] & B \end{tikzcd}$$

As examples, in categories of modules, product is direct product and coproduct is direct sum.

A category $\mathcal{C}$ is called *additive* if $\mathrm{Hom}_{\mathcal{C}}(A, B)$ is an abelian group (i.e. $\mathbb{Z}$-module) for each pair of objects A, B in $\mathcal{C}$, composition of morphisms is $\mathbb{Z}$-bilinear, and $\mathcal{C}$ has a zero object, finite products and coproducts. Let $\mathcal{C}$ and $\mathcal{D}$ be two additive categories. A functor $F : \mathcal{C} \to \mathcal{D}$ is *additive* if F induces homomorphisms of

abelian groups $\mathrm{Hom}_{\mathcal{C}}(A,B) \to \mathrm{Hom}_{\mathcal{D}}(F(A),F(B))$ for all objects A,B of $\mathcal{C}$. By [1, Proposition II.9.5], this is equivalent to preserving products of two objects.

We next define kernels and cokernels for morphisms in additive categories, by way of universal properties. A slight difference in comparison with modules for a ring is that these are defined not just as objects but as pairs of objects and morphisms: Let $\mathcal{C}$ be an additive category and consider a morphism $f \in \mathrm{Hom}_{\mathcal{C}}(A,B)$ for objects A,B of $\mathcal{C}$. A *kernel* of f is an object K in $\mathcal{C}$ and a morphism $j \in \mathrm{Hom}_{\mathcal{C}}(K,A)$ such that $fj = 0$, and whenever C is an object and $g \in \mathrm{Hom}_{\mathcal{C}}(C,A)$ satisfies $fg = 0$, there is a unique $\overline{g} \in \mathrm{Hom}_{\mathcal{C}}(C,K)$ such that $j\overline{g} = g$. That is, the following diagram commutes:

$$\begin{tikzcd} K \arrow[r, "j"] & A \arrow[r, "f"] & B \\ & C \arrow[ul, "\overline{g}"] \arrow[u, "g"'] & \end{tikzcd}$$

A *cokernel* of f is an object D in $\mathcal{C}$ and a morphism $p \in \mathrm{Hom}_{\mathcal{C}}(B,D)$ such that $pf = 0$, and whenever C is an object and $g \in \mathrm{Hom}_{\mathcal{C}}(B,C)$ satisfies $gf = 0$, there is a unique $\overline{g} \in \mathrm{Hom}_{\mathcal{C}}(D,C)$ such that $\overline{g}p = g$. That is, the following diagram commutes:

$$\begin{tikzcd} A \arrow[r, "f"] & B \arrow[r, "p"] \arrow[d, "g"'] & D \arrow[dl, "\overline{g}"] \\ & C & \end{tikzcd}$$

It may be checked that kernels and cokernels are unique up to isomorphism (of the objects), and also that they can be realized as pullbacks and pushouts, respectively. When all is clear from context, sometimes by kernel or cokernel, it is common to refer to just the object, and other times to just the morphism.

We define monomorphism and epimorphism next. Let $\mathcal{C}$ be a category. Let A,B be objects of $\mathcal{C}$ and $f \in \mathrm{Hom}_{\mathcal{C}}(A,B)$. We call f a *monomorphism* if whenever C is an object of $\mathcal{C}$ and $g,h \in \mathrm{Hom}_{\mathcal{C}}(C,A)$, if $fg = fh$ then $g = h$. We call f an *epimorphism* if whenever C is an object of $\mathcal{C}$ and $g,h \in \mathrm{Hom}_{\mathcal{C}}(B,C)$, if $gf = hg$ then $g = h$.

A category $\mathcal{C}$ is called *abelian* if it is additive, every morphism has both a kernel and a cokernel, every monomorphism is a kernel, and every epimorphism is a cokernel. Examples include categories of R-modules for a ring R.

Remark 6.5. As a consequence of the Freyd-Mitchell Embedding Theorem, your every day abelian category will in fact be equivalent to a subcategory of a category of modules for some ring.

Next we define exact sequences in an abelian category $\mathcal{C}$: A sequence

$$A \xrightarrow{f} B \xrightarrow{g} C$$

of objects A,B,C and morphisms f,g in $\mathcal{C}$ is called *exact* if f is a kernel of g and g is a cokernel of f. We may define projective and injective objects of $\mathcal{C}$ via diagrams (2.1) and (2.10) just as in the case of a category of modules over a ring. We may similarly define projective and injective resolutions, however they do not always exist. When they do exist, homological constructions can be carried out in $\mathcal{C}$ just as for modules in the previous sections.

Let $\mathcal{C}$ and $\mathcal{D}$ be abelian categories. A covariant functor $F : \mathcal{C} \to \mathcal{D}$ is called *left exact* (respectively, *right exact*) if for every exact sequence $0 \to A \to B \to C$ (respectively, $A \to B \to C \to 0$), the sequence

$$0 \to F(A) \to F(B) \to F(C)$$

is exact (respectively, $F(A) \to F(B) \to F(C) \to 0$ is exact). For example, letting $\mathcal{C}$ be the category of modules for a ring R, $\mathcal{D}$ the category of abelian groups, and M an R-module, the functor $\mathrm{Hom}_R(M, -)$ is left exact. A contravariant functor $F : \mathcal{C} \to \mathcal{D}$ is called *left exact* (respectively, *right exact*) if for every exact sequence $A \to B \to C \to 0$ (respectively, $0 \to A \to B \to C$), the sequence

$$0 \to F(C) \to F(B) \to F(A)$$

is exact (respectively, $F(C) \to F(B) \to F(A) \to 0$ is exact). For example, $\mathrm{Hom}_R(-, M)$ is left exact. In either case, we say that F is *exact* if it is both left and right exact.

Let $\mathcal{C}$ and $\mathcal{D}$ be abelian categories and $F : \mathcal{C} \to \mathcal{D}$ an additive (covariant) functor. Assume $\mathcal{C}$ *has enough projectives*, that is, assume that for each object A of $\mathcal{C}$, there is an epimorphism from a projective object in $\mathcal{C}$ to A. For each object A in $\mathcal{C}$, choose a projective resolution $(P_\bullet, d_\bullet)$ of A, which exists since $\mathcal{C}$ has enough projectives. Apply the functor F to obtain the complex $F(P_\bullet)$:

$$F(P_\bullet): \qquad \cdots \longrightarrow F(P_2) \xrightarrow{F(d_2)} F(P_1) \xrightarrow{F(d_1)} F(P_0) \longrightarrow 0.$$

The *left derived functor* of F is defined to be $L_\bullet F$ where $L_n F(A) = \mathrm{H}_n(F(P_\bullet))$. In the case that F is right exact, it follows from the definition that $L_0 F(A) \cong F(A)$. (The adjective "left" here indicates the objects are on the left with 0 at the end.)

We now show that Tor is an example of left derived functor: Let R be a ring, $\mathcal{C} = \text{Mod-}R$, $\mathcal{D} = \mathbb{Z}\text{-Mod}$, B an object of R-Mod, and F the functor $- \otimes_R B$. Then

$$L_n F(A) \cong \mathrm{Tor}_n^R(A, B).$$

Next assume $\mathcal{D}$ *has enough injectives*, that is, assume that for each object A of $\mathcal{C}$, there is a monomorphism from A to an injective object. For each object B in $\mathcal{C}$, choose an injective resolution $(I_\bullet, d_\bullet)$ of B. Apply the functor F to obtain the complex $F(I_\bullet)$:

$$F(I_\bullet): \qquad 0 \longrightarrow F(I_0) \longrightarrow F(I_1) \longrightarrow F(I_2) \longrightarrow \cdots$$

The *right derived functor* of F is defined to be $R^\bullet F$ where $R^n F(B) = \mathrm{H}^n(F(I_\bullet))$. If F is left exact, it follows from the definition that $R^0 F(B) \cong F(B)$. (The adjective "right" here indicates the objects are on the right with 0 at the beginning.)

As an example, let R be a ring, $\mathcal{C} = R$-Mod, $\mathcal{D} = \mathbb{Z}$-Mod, A an object of $\mathcal{C}$, and $F(B) = \mathrm{Hom}_R(A, B)$. Then

$$R^n F(B) \cong \mathrm{Ext}_R^n(A, B).$$

Similarly we may define derived functors of contravariant functors, using a projective resolution for a right derived functor, and an injective resolution for a left derived functor.

Appendix A. Supplementary definitions and constructions

Items in this appendix may not be presented in class, but may still be useful.

Pushout and pullback. Let A, B, Y be (left or right) R-modules. Let $\alpha : Y \to A$, $\beta : Y \to B$ be R-module homomorphisms. A *pushout* of α, β is an R-module X together with R-module homomorphisms $\phi : A \to X$, $\psi : B \to X$ for which the following holds: $\phi\alpha = \psi\beta$ and for any R-module Z and R-homomorphisms $\tilde{\phi} : A \to Z$, $\tilde{\psi} : B \to Z$ for which $\tilde{\phi}\alpha = \tilde{\psi}\beta$, there is a unique R-module homomorphism $\eta : X \to Z$ such that $\tilde{\phi} = \eta\phi$, $\tilde{\psi} = \eta\psi$:

$$\begin{tikzcd}
Y \arrow[r, "\alpha"] \arrow[d, "\beta"'] & A \arrow[d, "\phi"'] \arrow[ddr, "\tilde{\phi}"] & \\
B \arrow[r, "\psi"] \arrow[drr, "\tilde{\psi}"'] & X \arrow[dr, dotted, "\eta"] & \\
& & Z
\end{tikzcd}$$

This is unique up to isomorphism (by applying the definition two ways to a pair of pushouts X, X'). In fact we may take

$$X = A \oplus B / \{(-\alpha(y), \beta(y)) \mid y \in Y\} \tag{A.1}$$

and ϕ, ψ the maps induced by inclusion into $A \oplus B$ followed by the quotient map.

Let A, B, X be R-modules. Let $\phi : A \to X$, $\psi : B \to X$ be R-module homomorphisms. A *pullback* of ϕ, ψ is an R-module Y together with R-module homomorphisms $\alpha : Y \to A$, $\beta : Y \to B$ for which the following holds: $\phi\alpha = \psi\beta$ and for any R-module W and R-module homomorphisms $\tilde{\alpha} : W \to A$, $\tilde{\beta} : W \to B$ for which $\phi\tilde{\alpha} = \psi\tilde{\beta}$, there is a unique R-module homomorphism $\eta : W \to Y$ such that $\tilde{\alpha} = \alpha\eta$, $\tilde{\beta} = \beta\eta$.

$$\begin{tikzcd}
W \arrow[dr, dotted, "\eta"] \arrow[drr, "\tilde{\alpha}"] \arrow[ddr, "\tilde{\beta}"'] & & \\
& Y \arrow[r, "\alpha"'] \arrow[d, "\beta"] & A \arrow[d, "\phi"'] \\
& B \arrow[r, "\psi"] & X
\end{tikzcd}$$

This is unique up to isomorphism (by applying the definition two ways to a pair Y, Y' of pullbacks). In fact we may take

$$Y = \{(a, b) \in A \oplus B \mid \phi(a) = \psi(b)\}$$

and α, β the maps induced by projection from $A \oplus B$.

Extension interpretation of Ext. The abelian groups $\mathrm{Ext}^n_R(M, N)$ have an interpretation in terms of exact sequences, or extensions, as follows. An *n-extension* of M by N is an exact sequence of R-modules and R-module homomorphisms:

$$\mathbf{f} : \qquad 0 \longrightarrow N \longrightarrow U_{n-1} \longrightarrow \cdots \longrightarrow U_1 \longrightarrow U_0 \longrightarrow M \longrightarrow 0.$$

Suppose $\mathbf{g}$ is another n-extension of M by N. A *morphism* of extensions from $\mathbf{f}$ to $\mathbf{g}$ is a chain map that is the identity map on each of M and N:

$$\begin{tikzcd}
0 \arrow[r] & N \arrow[r] \arrow[d, "1_N"] & U_{n-1} \arrow[r] \arrow[d, "\phi_{n-1}"] & \cdots \arrow[r] & U_1 \arrow[r] \arrow[d, "\phi_1"] & U_0 \arrow[r] \arrow[d, "\phi_0"] & M \arrow[r] \arrow[d, "1_M"] & 0 \\
0 \arrow[r] & N \arrow[r] & V_{n-1} \arrow[r] & \cdots \arrow[r] & V_1 \arrow[r] & V_0 \arrow[r] & M \arrow[r] & 0
\end{tikzcd}$$

Morphisms of n-extensions generate an equivalence relation. The set of equivalence classes of n-extensions becomes an abelian group under a binary operation termed the Baer sum. The n-extension $\mathbf{f}$ above has additive inverse represented by the sequence with the same modules, the map $U_0 \to M$ replaced by its additive inverse, and all other maps the same. As an abelian group, $\mathrm{Ext}^n_R(M,N)$ is isomorphic to this group of equivalence classes of n-extensions of M by N. We give the one-to-one correspondence on elements of these two groups below. We leave the proof that it is an isomorphism of abelian groups as a very lengthy exercise.

Let $\mathbf{f}$ be the n-extension of M by N given above. We wish to associate an element of $\mathrm{Ext}^n_R(M,N)$ to $\mathbf{f}$. With this goal, let $P_\bullet \to M$ be a projective resolution of M. By the Comparison Theorem (Theorem 2.7), there is a chain map $\hat{f}_\bullet$:

$$\begin{tikzcd}
P_{n+1} \arrow[r, "d_{n+1}"] \arrow[d] & P_n \arrow[r, "d_n"] \arrow[d, "\hat{f}_n"] & P_{n-1} \arrow[r] \arrow[d, "\hat{f}_{n-1}"] & \cdots \arrow[r] & P_1 \arrow[r, "d_1"] \arrow[d, "\hat{f}_1"] & P_0 \arrow[r, "\varepsilon"] \arrow[d, "\hat{f}_0"] & M \arrow[r] \arrow[d, "1"] & 0 \\
0 \arrow[r] & N \arrow[r] & U_{n-1} \arrow[r] & \cdots \arrow[r] & U_1 \arrow[r] & U_0 \arrow[r] & M \arrow[r] & 0
\end{tikzcd}$$

Note that by construction, $\hat{f}_n \in \mathrm{Hom}_R(P_n, N)$ and $\hat{f}_n d_{n+1} = 0$. That is, $\hat{f}_n$ is a cocycle. Write $f = \hat{f}_n$. By the Comparison Theorem again, $\hat{f}_\bullet$ is unique up to chain homotopy. It follows that the corresponding element of $\mathrm{Ext}^n_R(M,N)$ does not depend on the choice of $\hat{f}_\bullet$. We have thus given a map from equivalence classes of n-extensions of M by N to $\mathrm{Ext}^n_R(M,N)$.

Now let $f \in \mathrm{Hom}_R(P_n, N)$ represent an element in $\mathrm{Ext}^n_R(M,N)$, that is, $f d_{n+1} = 0$. We will construct an n-extension $\mathbf{f}$ of M by N from f. Let X be a pushout of $P_n \xrightarrow{d_n} P_{n-1}$ and $P_n \xrightarrow{f} N$. As described above, we may take

$$X = (P_{n-1} \oplus N)/\{(-d_n(x), f(x)) \mid x \in P_n\}.$$

It may be checked that the following diagram commutes:

$$\begin{tikzcd}
P_{n+1} \arrow[r, "d_{n+1}"] \arrow[d] & P_n \arrow[r, "d_n"] \arrow[d, "f"] & P_{n-1} \arrow[r, "d_{n-1}"] \arrow[d, "\binom{1}{0}"] & P_{n-2} \arrow[r] \arrow[d, "1"] & \cdots \arrow[r] & P_0 \arrow[r, "\varepsilon"] \arrow[d, "1"] & M \arrow[r] \arrow[d, "1"] & 0 \\
0 \arrow[r] & N \arrow[r, "\binom{0}{1}"] & X \arrow[r, "(d_{n-1},0)"] & P_{n-2} \arrow[r, "d_{n-2}"] & \cdots \arrow[r] & P_0 \arrow[r, "\varepsilon"] & M \arrow[r] & 0
\end{tikzcd}$$

(Equivalently, P_n may be replaced by the syzygy module $K_n = \mathrm{Ker}(d_{n-1})$ in the pushout diagram.) It may be checked that the lower sequence is an n-extension of M by N, and that any other map in $\mathrm{Hom}_R(P_n, N)$ representing the same element of $\mathrm{Ext}^n_R(M,N)$ yields an n-extension equivalent to this one. We have thus given a map from $\mathrm{Ext}^n_R(M,N)$ to the set of equivalence classes of n-extensions of M by N.

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