M4P63 Algebra IV

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$$
\begin{tikzcd}
 & 0 \arrow[d] & \vdots \arrow[dd] & 0 \arrow[d] & \vdots \arrow[dd] & 0 \arrow[d] & \vdots \arrow[dd] & & \\
0 \arrow[r] & \operatorname{Ker} d_n^A \arrow[rr] \arrow[dr] & & \operatorname{Ker} d_n^B \arrow[rr] \arrow[dr] & & \operatorname{Ker} d_n^C \arrow[dr] \arrow[dddddll, bend left=60] & & & \\
 & 0 \arrow[r] & A_{n+1} \arrow[rr, "f_{n+1}"] \arrow[ddd, "d_n^A"'] & & B_{n+1} \arrow[rr, "g_{n+1}"] \arrow[ddd, "d_n^B"'] & & C_{n+1} \arrow[r] \arrow[ddd, "d_n^C"'] & 0 & \\
 & 0 \arrow[d] & & 0 \arrow[d] & & 0 \arrow[d] & & & \\
0 \arrow[r] & \operatorname{Ker} d_{n-1}^A \arrow[rr] \arrow[dr] & & \operatorname{Ker} d_{n-1}^B \arrow[rr] \arrow[dr] & & \operatorname{Ker} d_{n-1}^C \arrow[dr] \arrow[dddddll, bend left=60] & & & \\
 & 0 \arrow[r] & A_n \arrow[rr, "f_n"'] \arrow[dr] \arrow[ddd, "d_{n-1}^A"] & & B_n \arrow[rr, "g_n"] \arrow[dr] \arrow[ddd, "d_{n-1}^B"] & & C_n \arrow[r] \arrow[dr] \arrow[ddd, "d_{n-1}^C"] & 0 & \\
 & & & \operatorname{Coker} d_n^A \arrow[rr] \arrow[d] & & \operatorname{Coker} d_n^B \arrow[rr] \arrow[d] & & \operatorname{Coker} d_n^C \arrow[r] \arrow[d] & 0 \\
 & & & 0 & & 0 & & 0 & \\
 & 0 \arrow[r] & A_{n-1} \arrow[rr, "f_{n-1}"'] \arrow[dr] \arrow[dd] & & B_{n-1} \arrow[rr, "g_{n-1}"'] \arrow[dr] \arrow[dd] & & C_{n-1} \arrow[r] \arrow[dr] \arrow[dd] & 0 & \\
 & & & \operatorname{Coker} d_{n-1}^A \arrow[rr] \arrow[d] & & \operatorname{Coker} d_{n-1}^B \arrow[rr] \arrow[d] & & \operatorname{Coker} d_{n-1}^C \arrow[r] \arrow[d] & 0 \\
 & & \vdots & 0 & \vdots & 0 & \vdots & 0 &
\end{tikzcd}
$$

Syllabus

Exact sequences. Hom and tensor product. Projective and free modules. Injective and divisible modules. Torsion-free and flat modules. Projective and injective resolutions. Chain and cochain complexes. Homology and cohomology. Derived functors. Tor and torsion. Ext and extensions. Global dimension.

Contents

1 Modules over a ring

Lecture 1 Friday 10/01/20

Let R be an **associative ring with unity**, that is an abelian group written additively with a multiplication which is associative but not necessarily commutative, with an identity 1 and distributive laws $a(b+c) = ab + ac$ and $(a+b)c = ac + bc$. Then

$$R^* = \{r \in R \mid \exists s \in R,\ rs = 1 = sr\}$$

is the unit group of R. If $R^* = R \setminus \{0\}$ then R is a **division ring**, or a **skew field**. In the case that R is commutative, R is a **field**.

Example.

- Fields $\mathbb{C}$, $\mathbb{R}$, $\mathbb{Q}$, and $\mathbb{F}_q$, the field with $q = p^a$ elements with p a prime and $a \geq 1$.
- Skew fields $\mathbb{H} = \{a + bi + cj + dk \mid a, b, c, d \in \mathbb{R}\}$ where $i^2 = j^2 = k^2 = ijk = -1$.
- Other rings are polynomial rings $k[x]$ for k a field, more generally $k[x_1, \dots, x_p]$, and $\mathrm{Mat}_n\, k$, the $n \times n$ matrices with entries from k, a field.

1.1 Modules over rings

Definition 1.1. Let R be a ring. A **left R-module** is an abelian group M, written additively, together with a function $* : R \times M \to M$ satisfying

$$r*(m_1 + m_2) = r*m_1 + r*m_2, \qquad (r_1 + r_2)*m = r_1*m + r_2*m, \qquad (r_1 r_2)*m = r_1*(r_2 * m), \qquad 1*m = m.$$

We write rm for $r * m$.

Example.

- R is itself a left R-module, with $*$ as ring multiplication. More generally, let I be a left ideal of R, so I is an additive subgroup, and $rI \leq I$ for all $r \in R$. Then I is an R-module with $*$ as ring multiplication.
- Let k be a field. Then any vector space over k is a k-module, and vice versa.
- Any abelian group is a $\mathbb{Z}$-module, with $*$ defined by $na = a + \dots + a$ for $n \in \mathbb{Z}^+$ and $a \in A$, and $(-n)a = -(na)$.
- Let k be a field. Let k^n be column vectors. Then k^n is a left $\mathrm{Mat}_n\, k$-module, with $*$ as the usual matrix-vector multiplication.
- Let $M \in \mathrm{Mat}_n\, k$. Then we can define a left $k[x]$-module structure on k^* by letting x act as M on k^*. So $\left(x^2 + 3x - 2\right) * v = M^2 v + 3Mv - 2v$.
- Let G be a group. Any representation of G over the field k is a left module for $k[G]$, the **group algebra**, a vector space over k with elements of G as a basis, with multiplication derived from that of G.

Definition 1.2. A **right R-module** is defined similarly, with the R-multiplication on the right, so M an abelian group under $+$, and a map $M \times R \to M$ satisfying

$$(m_1 + m_2)*r = m_1*r + m_2*r, \qquad m*(r_1 + r_2) = m*r_1 + m*r_2, \qquad m*(r_1 r_2) = (m * r_1)*r_2, \qquad m*1 = m.$$

Left and right modules are not quite the same. If we amend this definition by putting the ring multiplication on the left, the third axiom becomes $(r_1 r_2)m = r_2(r_1 m)$. But in a left module, we have $(r_1 r_2)m = r_1(r_2 m)$.

Definition 1.3. Let R be a ring. The **opposite ring** R^{op} is R with a redefined multiplication $r *_{R^{\mathrm{op}}} s = s *_R r$.

It is easy to see that a left R-module is the same as a right R^{op}-module and vice versa. If R is commutative then $R = R^{\mathrm{op}}$.

Exercise. Show that $\mathrm{Mat}_n\, k \cong \mathrm{Mat}_n\, k^{\mathrm{op}}$.

Except where otherwise stated, R-modules are assumed to be left R-modules.

1.2 Homomorphisms and submodules

Definition 1.4. Let M_1 and M_2 be R-modules. A map $f : M_1 \to M_2$ is an R**-module homomorphism** if

- f is a group homomorphism, with respect to the $+$ operation, and
- $f(rm) = rf(m)$, for $r \in R$ and $m \in M$.

If f is bijective, then it is an R**-module isomorphism**.

Definition 1.5. An additive subgroup $L \leq M$ is a **submodule** if $rL \leq L$ for $r \in R$. In this case we automatically get an R-module structure on the quotient M/L with multiplication given by $r(m+L) = rm + L$.

Theorem 1.6 (First isomorphism theorem)**.** *Let $f : M_1 \to M_2$ be an R-module homomorphism. Then*

$$\operatorname{Im} f \leq M_2, \qquad \operatorname{Ker} f \leq M_1, \qquad \operatorname{Im} f \cong M / \operatorname{Ker} f.$$

The other isomorphism theorems have R-module versions too.

1.3 Direct products and direct sums

Lecture 2 Monday 13/01/20

Let S be a set. We have a collection of R-modules $(M_s)_S$ indexed by S.

Definition 1.7. The **direct product** is

$$\prod_{s \in S} M_s = \{(m_s)_S \mid m_s \in M_s\},$$

with coordinate-wise addition and R-multiplication, so

$$(m_s)_S + (n_s)_S = (m_s + n_s)_S, \qquad r(m_s)_S = (rm_s)_S.$$

If $M_s = M$ for all $s \in S$, then we write M^S for $\prod_{s \in S} M_s$.

Definition 1.8. The **direct sum** is

$$\bigoplus_{s \in S} M_s = \{(m_s)_S \mid \text{all but finitely many coordinates } m_s \text{ are zero}\} \leq \prod_{s \in S} M_s.$$

If S is finite then the direct product and the direct sum are equal.

Example. Let $M = \mathbb{Z}_2$, as a $\mathbb{Z}$-module, and let $S = \mathbb{N}$. Then $\bigoplus_{s \in \mathbb{N}} \mathbb{Z}_2$ is a countable $\mathbb{Z}$-module but $\prod_{s \in \mathbb{N}} \mathbb{Z}_2 = \mathbb{Z}_2^{\mathbb{N}}$ is uncountable.

When $|S| = 2$, generally we write $M_1 \oplus M_2$ for the direct sum or product. There are natural injective maps

$$\begin{array}{cccc} \iota_A & : & A & \longrightarrow & A \oplus B \\ & & a & \longmapsto & (a, 0) \end{array}, \qquad \begin{array}{cccc} \iota_B & : & B & \longrightarrow & A \oplus B \\ & & b & \longmapsto & (0, b) \end{array},$$

and surjective maps

$$\begin{array}{cccc} \pi_A & : & A \oplus B & \longrightarrow & A \\ & & (a, b) & \longmapsto & a \end{array}, \qquad \begin{array}{cccc} \pi_B & : & A \oplus B & \longrightarrow & B \\ & & (a, b) & \longmapsto & b \end{array}.$$

1.4 Exact sequences

Definition 1.9. Suppose we have a sequence of R-modules

$$\dots \xrightarrow{f_{n-1}} M_n \xrightarrow{f_n} M_{n+1} \xrightarrow{f_{n+1}} \dots,$$

with maps $f_n : M_n \to M_{n+1}$. Say the sequence is **exact at** M_n if

$$\operatorname{Im} f_{n-1} = \operatorname{Ker} f_n.$$

The sequence is **exact** if it is exact everywhere. A **short exact sequence** is an exact sequence

$$0 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 0.$$

Note. α is injective and β is surjective.

The first isomorphism theorem implies that $B/\operatorname{Im}\alpha \cong C$, where $\operatorname{Im}\alpha \cong A$. An easy case is

$$B \cong A \oplus C,$$

with $\operatorname{Im}\alpha = \operatorname{Im}\iota_A = A \oplus 0$ and $\operatorname{Im}\beta = \operatorname{Im}\pi_\beta = C$. We say that the short exact sequence **splits** in this case.

Example. A non-split short exact sequence of $\mathbb{Z}$-modules, or abelian groups, is

$$0 \to \mathbb{Z}/2\mathbb{Z} \to \mathbb{Z}/4\mathbb{Z} \to \mathbb{Z}/2\mathbb{Z} \to 0.$$

Proposition 1.10. *A short exact sequence*

$$0 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 0$$

is split if and only if there exists an R-module homomorphism $\sigma : C \to B$ such that $\beta \circ \sigma = \mathrm{id}_C$.

Such a σ is called a **section** of β.

Proof.

$\implies$ Suppose that the short exact sequence is split. So assume $B = A \oplus C$, with $\alpha = \iota_A$ and $\beta = \pi_C$. Now ι_C is a section for β.

$\impliedby$ For the converse, suppose that σ is a section for β. We want $f : A \oplus C \xrightarrow{\sim} B$ such that $f \circ \iota_A = \alpha$ and $\beta \circ f = \pi_C$, so

$$\begin{tikzcd} & & A \oplus C \arrow[d, "f"] \arrow[dr, "\pi_C"] & & \\ 0 \arrow[r] & A \arrow[ur, "\iota_A"] \arrow[dr, "\alpha"'] & & C \arrow[r] & 0 \\ & & B \arrow[ur, "\beta"'] & & \end{tikzcd} .$$

Define

$$\begin{array}{cccc} f & : & A \times C & \longrightarrow & B \\ & & (a, c) & \longmapsto & \alpha(a) + \sigma(c) \end{array} .$$

Need to check the following.

- f is an R-module homomorphism. [1]
- f is injective. Suppose $f(a, c) = 0$. Then $\alpha(a) + \sigma(c) = 0$. Now $\alpha(a) \in \operatorname{Im}\alpha = \operatorname{Ker}\beta$, so $\beta(\alpha(a) + \sigma(c)) = \beta(\sigma(c)) = c$. Since $\alpha(a) + \sigma(c) = 0$, we have $c = 0$. Hence $\alpha(a) = 0$, and so $a = 0$ since α is injective. We have shown that f is injective.
- f is surjective. Let $b \in B$. Let $c = \beta(b)$. We have $(\beta \circ \sigma)(c) = c = \beta(b)$, so $b - \sigma(c) \in \operatorname{Ker}\beta = \operatorname{Im}\alpha$. So there exists $a \in A$ with $\alpha(a) = b - \sigma(c)$. Then $b = \alpha(a) + \sigma(c) = f(a, c)$.
- $f \circ \iota_A = \alpha$ and $\beta \circ f = \pi_C$. Immediate from the construction of f.

$\square$

Proposition 1.11. *The short exact sequence*

$$0 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 0$$

is split if and only if there exists $\rho : B \to A$ such that $\rho \circ \alpha = \mathrm{id}_A$.

Such a ρ is a **retraction** of α.

Proof.

$\implies$ Once again, if the short exact sequence is split then the existence of ρ is clear.

$\impliedby$ Suppose that ρ is a retraction for α. We define $f : B \xrightarrow{\sim} A \oplus C$ such that $f \circ \alpha = \iota_A$ and $\pi_C \circ f = \beta$. Do this by

$$\begin{array}{cccc} g & : & B & \longrightarrow & A \oplus C \\ & & b & \longmapsto & (\rho(a), \beta(c)) \end{array} .$$

$\square$

[1] Exercise

2 Projective and injective modules

2.1 Projective modules

Lecture 3 Tuesday 14/01/20

Definition 2.1. An R-module M is **projective** if any surjective map $\beta : B \to M$ has a section. In other words, any short exact sequence

$$0 \to A \to B \to M \to 0$$

splits.

Example. The R-module R is projective. Let

$$0 \to A \to B \xrightarrow{\beta} R \to 0$$

be a short exact sequence. Since β is surjective, there exists $b \in B$ such that $\beta(b) = 1$. Now for all $r \in R$, $\beta(rb) = r$. Now define

$$\begin{array}{cccccc} \sigma & : & R & \longrightarrow & B \\ & & r & \longmapsto & rb \end{array}.$$

Then σ is a section for β.

Proposition 2.2. *An R-module M is projective if and only if whenever $\beta : B \to C$ is surjective, and $f : M \to C$, there exists $g : M \to B$ such that $f = \beta \circ g$, so*

$$\begin{tikzcd} & & & M \arrow[dl, dashed, "g"'] \arrow[d, "f"] & \\ 0 \arrow[r] & A \arrow[r] & B \arrow[r, "\beta"'] & C \arrow[r] & 0 \end{tikzcd}.$$

Such a g is called a **lift** of f.

Proof.

$\Longleftarrow$ Suppose that whenever $\beta : B \to C$ is surjective and $f : M \to C$ then there exists $g : M \to B$ with $f = \beta \circ g$. Suppose $\beta : B \to M$ is a surjective map. Define $f : M \to M$ to be id_M. Then there exists $g : M \to B$ such that $f = \beta \circ g$, so $\mathrm{id}_M = \beta \circ g$. So g is a section for β, and so M is projective.

$\Longrightarrow$ For the converse, suppose $\beta : B \to C$ is surjective, and $f : M \to C$. We construct a module X to complete a commuting square

$$\begin{tikzcd} X \arrow[r, "\epsilon"] \arrow[d, "\delta"'] & M \arrow[d, "f"] \\ B \arrow[r, "\beta"'] & C \end{tikzcd}.$$

Let X be the submodule of $B \oplus M$ defined by

$$X = \{(b, m) \mid \beta(b) = f(m)\}.$$

The maps δ and ϵ are just π_B and π_M respectively, in their restrictions to X. It is clear that $X \le B \oplus M$, and that the square above commutes. Now suppose that M is projective. Since β is surjective, we see that for all $m \in M$ there exists $b \in B$ with $\beta(b) = f(m)$. It follows that $\epsilon : X \to M$ is surjective. So ϵ has a section $\sigma : M \to X$. Define $g = \delta \circ \sigma : M \to B$, so

$$\begin{tikzcd} X \arrow[r, bend left, "\epsilon"] \arrow[d, "\delta"'] & M \arrow[l, dashed, bend left, "\sigma"] \arrow[d, "f"] \arrow[dl, dashed, "g"] \\ B \arrow[r, "\beta"'] & C \end{tikzcd}.$$

Since $\beta \circ \delta = f \circ \epsilon$, we have

$$(\beta \circ g)(m) = (\beta \circ \delta \circ \sigma)(m) = (f \circ \epsilon \circ \sigma)(m) = (f \circ \mathrm{id}_M)(m) = f(m), \qquad m \in M.$$

So $\beta \circ g = f$ as required.

$\square$

Such an X is the **pullback** of β and f, and there is a short exact sequence

$$0 \to A \to X \to M \to 0.$$

2.2 Free modules

Definition 2.3. An R-module M is **free** if M is a direct sum of copies of R, so

$$M = \bigoplus_{s \in S} R.$$

A **basis** for a module M is a set T of elements such that every element $m \in M$ has a unique expression as

$$m = \sum_{i=1}^{m} r_i t_i, \qquad r_i \in R, \qquad t_i \in T.$$

If $M = \bigoplus_{s \in S} R$, then M has a basis consisting of elements with exactly one coordinate one, and the rest zero. On the other hand, if M has a basis T then it is straightforward to show that $M \cong \bigoplus_{t \in T} R$.

Proposition 2.4. *Let F be a free R-module with basis T. Let M be some R-module, and let $\psi : T \to M$ be a set map. Then ψ extends uniquely to an R-module homomorphism $\psi : F \to M$.*

Proof. Each element of F has a unique expression as $\sum_i r_i t_i$ for $r_i \in R$ and $t_i \in T$. Now define

$$\begin{array}{cccc} \psi & : & F & \longrightarrow & M \\ & & \sum_i r_i t_i & \longmapsto & \sum_i r_i \psi(t_i) \end{array}.$$

It is easy to check that this respects $+$ and R-multiplication. □

Proposition 2.5. *A module M is projective if and only if there exists N such that $M \oplus N$ is free, so projective modules are direct summands of free modules.*

Proof.

$\implies$ Suppose M is projective. Let F be the free module with basis $\{b_m \mid m \in M\}$. Now the map $b_m \mapsto m$ extends to an R-module homomorphism $F \to M$, which is clearly surjective. Then if $K = \operatorname{Ker} \psi$, we have a short exact sequence

$$0 \to K \to F \xrightarrow{\psi} M \to 0.$$

Since M is projective, there is a section σ for ψ, and so the short exact sequence splits, and $F \cong K \oplus M$. Lecture 4 Friday 17/01/20

$\impliedby$ Suppose that $M \oplus N = F$, a free module with basis T. Suppose $\beta : B \to C$ is surjective, and that $f : M \to C$. Note that $f \circ \pi_M : F \to C$. For each $t \in T$, let $b_t \in B$ be such that $\beta(b_t) = (f \circ \pi_M)(t)$. The set map

$$\begin{array}{ccc} T & \longrightarrow & B \\ t & \longmapsto & b_t \end{array}$$

extends to a homomorphism $\widehat{g} : F \to B$. Now define $g : M \to B$ by $g = \widehat{g} \circ \iota_M$. We need to show $f = \beta \circ g$. Take $m \in M$. Then $\iota_M(m) = (m, 0) \in F$ can be written as $\sum_i r_i t_i$, where $t_i \in T$ and $r_i \in R$. Applying π_M, $m = \sum_i r_i m_{t_i}$. Then

$$g(m) = (\widehat{g} \circ \iota_M)(m) = \widehat{g}\left(\sum_i r_i t_i\right) = \sum_i r_i b_{t_i}.$$

So

$$(\beta \circ g)(m) = \beta\left(\sum_i r_i b_{t_i}\right) = \sum_i r_i \beta(b_{t_i}) = \sum_i r_i f(m_{t_i}) = f\left(\sum_i r_i m_{t_i}\right) = f(m).$$

Hence $\beta \circ g = f$. So M is projective.

□

2.3 Injective modules

Definition 2.6. Let M be an R-module. Then M is **injective** if whenever $\alpha : M \to B$ is an injective map, it has a retraction $\rho : B \to M$, so $\rho \circ \alpha = \mathrm{id}_M$. Equivalently, every short exact sequence

$$0 \to M \to B \to C \to 0$$

splits.

Example. Let k be a field. Then k-modules are vector spaces. Every k-module is injective. Suppose M and N are k-vector spaces and $\alpha : M \to N$ is a injective map. Then $\operatorname{Im} \alpha$ is a submodule, or subspace, of N. Take a basis for $\operatorname{Im} \alpha$, and extend to a basis for N. The basis vectors not in $\operatorname{Im} \alpha$ form a basis for a complementary subspace U, so $N = \operatorname{Im} \alpha \oplus U$. Now $\pi_{\operatorname{Im} \alpha}$ is surjective, and $\alpha : M \to \operatorname{Im} \alpha$ is an isomorphism. This gives a retraction $N \to M$.

If R is a general ring, the module R need not be injective.

Example. Let $R = \mathbb{Z}$. Then R-modules are abelian groups. There exists an injective $\alpha : \mathbb{Z} \to \mathbb{Q}$. But $\mathbb{Z}$ is not a quotient of $\mathbb{Q}$, [2] so no retraction exists for α.

Proposition 2.7. *An R-module M is injective if and only if whenever $\alpha : A \to B$ is injective, and $f : A \to M$, there exists $g : B \to M$ such that $f = g \circ \alpha$.*

Proof.

$\Longleftarrow$ Suppose that whenever $\alpha : A \to B$ is injective, and $f : A \to M$, there exists $g : B \to M$ such that $f = g \circ \alpha$. Suppose that $\alpha : M \to B$ is injective. We have a map $M \to M$, namely id_M. There exists $g : B \to M$ such that $\mathrm{id}_M = g \circ \alpha$. So g is a retraction for α, and so M is injective.

$\Longrightarrow$ For the converse, suppose $\alpha : A \to B$ is injective, and M is an injective module, with $f : A \to M$. We define a module Y completing a square

$$\begin{tikzcd} A \arrow[r, "\alpha"] \arrow[d, "f"'] & B \arrow[d, "\delta"] \\ M \arrow[r, "\epsilon"'] & Y \end{tikzcd},$$

with $\epsilon \circ f = \delta \circ \alpha$. Let Y be a quotient of $B \oplus M$, by the kernel

$$K = \{(\alpha(a), -f(a)) \mid a \in A\}.$$

Let $\gamma : B \oplus M \to (B \oplus M)/K$ be the canonical quotient map. Then we define $\delta = \gamma \circ \iota_B$ and $\epsilon = \gamma \circ \iota_M$. By construction, we have

$$\begin{aligned} (\epsilon \circ f)(a) &= (\gamma \circ \iota_M \circ f)(a) = \gamma(0, f(a)) = (0, f(a)) + K \\ &= (\alpha(a), 0) + K = \gamma(\alpha(a), 0) = (\gamma \circ \iota_B \circ \alpha)(a) = (\delta \circ \alpha)(a). \end{aligned}$$

Hence $\epsilon \circ f = \delta \circ \alpha$. Claim that ϵ is injective. Suppose $\epsilon(m) = 0$. Then $\iota_M(m) \in K$, so $(0, m) = (\alpha(a), -f(a))$ for some $a \in A$. But $\alpha(a) = 0$ implies that $a = 0$, and so $m = -f(0) = 0$. Since M is injective, ϵ has a retraction $\rho : Y \to M$. Define $g : B \to M$ by $g = \rho \circ \delta$, so

$$\begin{tikzcd} A \arrow[r, "\alpha"] \arrow[d, "f"'] & B \arrow[d, "\delta"] \arrow[dl, dashed, "g"'] \\ M \arrow[r, bend right, "\epsilon"'] & Y \arrow[l, dashed, "\rho"'] \end{tikzcd},$$

We know that $(\epsilon \circ f)(a) = (\delta \circ \alpha)(a)$ for all $a \in A$. So

$$f(a) = (\mathrm{id}_M \circ f)(a) = (\rho \circ \epsilon \circ f)(a) = (\rho \circ \delta \circ \alpha)(a) = (g \circ \alpha)(a),$$

so $f = g \circ \alpha$ as required.

$\square$

[2] Exercise

We know that projectives are direct summands of free modules. We might hope for a dual version of this for injective modules. But there is no straightforward way of doing this. Lecture 5 Monday 20/01/20

Proposition 2.8 (Baer's criterion for injectivity)**.** *Let M be an R-module. Then M is injective if and only if every R-module map $f : I \to M$, where I is a left ideal of R, has the form $f(x) = xm$ for some $m \in M$. Equivalently, every map $I \to M$ extends to a map $R \to M$.*

Why are these two conditions equivalent? If $f(x) = xm$ for $x \in I$, then we can extend f to R by $f(r) = rm$. Conversely, suppose that $f : I \to M$ extends to $f^+ : R \to M$. Let $m = f^+(1)$. Then for all $r \in R$, $f^+(r) = rm$, and so $f(x) = xm$ for $x \in I$. The proof requires Zorn's lemma.

Lemma 2.9 (Zorn's lemma)**.** *Let X be a non-empty set, partially ordered by $\le$. If every chain, or totally ordered subset, in X has an upper bound in X, then X has a maximal element.*

Proof.

$\Longleftarrow$ Suppose $\alpha : A \to B$, where α is injective. Suppose $f : A \to M$. We want to show there exists $g : B \to M$ such that $f = g \circ \alpha$. We have $\operatorname{Im} \alpha \le B$. Define

$$X = \{(L, h) \mid \operatorname{Im} \alpha \le L \le B,\ h : L \to M,\ f = h \circ \alpha\}.$$

Note that $X \ne \emptyset$ since $\left(\operatorname{Im} \alpha, f \circ \alpha^{-1}\right)$ is in it. Define $\le$ on X by $(L_1, h_1) \le (L_2, h_2)$ if $L_1 \le L_2$ and h_2 extends h_1, so $h_2|_{L_1} = h_1$. Suppose $\{(L_s, h_s) \mid s \in S\}$ is a chain in X. Set $L = \bigcup_{s \in S} L_s$. Then $\operatorname{Im} \alpha \le L \le B$. Define

$$\begin{array}{cccc} h & : & L & \longrightarrow & M \\ & & l & \longmapsto & h_s(l) \end{array}, \qquad l \in L_s.$$

This does not depend on the choice of s. Then (L, h) is an upper bound for the chain $\{(L_s, h_s) \mid s \in S\}$. Hence X has a maximal element, (L_0, h_0). We want to show that $L_0 = B$. Then we may set $g = h_0$. Suppose that $L_0 \ne B$. Let $b \in B \setminus L_0$. Note that $Rb \le B$. Consider

$$L_0 + Rb = \{l + rb \mid l \in L_0,\ r \in R\} \le B.$$

We would like to extend h_0 to h_0^+ by specifying an image for $h_0^+(b)$. The problem is that $Rb \cap L_0$ may not be $\{0\}$, and if $rb \in L_0$ then we require $rh_0^+(b) = h_0(rb)$, otherwise h_0^+ will not be well-defined. Note that $I = \{r \in R \mid rb \in L_0\}$ is a left ideal for R. Suppose that M has the condition from Baer's criterion, so every map $I \to M$ has the form $x \mapsto xm$ for some $m \in M$. Note that $\{xb \mid x \in I\}$ is a submodule of L_0. Define

$$\begin{array}{cccc} \delta & : & I & \longrightarrow & M \\ & & x & \longmapsto & h_0(xb) \end{array}.$$

This is an R-module homomorphism. So $\delta(x) = xm$ for some $m \in M$. Hence $h_0(xb) = xm$ for all $x \in I$. So we can safely define $h_0^+(b) = m$. Now $\left(L_0 + Rb, h_0^+\right) \in X$, and $(L_0, h_0) < \left(L_0 + Rb, h_0^+\right)$, which contradicts the maximality of (L_0, h_0). Hence $L_0 = B$, and we are done.

$\Longrightarrow$ The converse is left as an exercise. [3]

$\square$

Example.

- Suppose R is a field. Then the only ideals of R are zero and R. Any map $0 \to M$, for M an R-module, can be extended to the zero map $R \to M$. Hence any R-module is injective.
- Let $\mathbb{Z}$ be a module for itself. The ideals of $\mathbb{Z}$ are $k\mathbb{Z}$ for $k \in \mathbb{Z}$. Define
$$\begin{array}{cccc} f & : & k\mathbb{Z} & \longrightarrow & \mathbb{Z} \\ & & km & \longmapsto & m \end{array}.$$
If $k \ne 0, \pm 1$, then $f(k) = 1$, and so $f(x) \ne xm$ for $m \in \mathbb{Z}$, since one is not divisible by k in $\mathbb{Z}$. So Baer's criterion fails, and $\mathbb{Z}$ is not injective. We already knew that $\mathbb{Z} \to \mathbb{Q}$ has no retraction.
- $\mathbb{Q}$ is injective as a $\mathbb{Z}$-module. Suppose we have a map $f : k\mathbb{Z} \to \mathbb{Q}$. Let $q = f(k)$. Then $f(kt) = qt = (q/k)\,kt$. So $f(x) = x(q/k)$ for all x, so $\mathbb{Q}$ satisfies Baer's criterion.

[3] Exercise

3 Hom and tensor products

3.1 Hom

Lecture 6 Tuesday 21/01/20

Let A and B be two R-modules.

Definition 3.1. Define

$$\mathrm{Hom}_R(A,B) = \{R\text{-module homomorphisms } A \to B\}.$$

We can define a natural addition on $\mathrm{Hom}_R(A,B)$ by defining $f_1 + f_2$ by

$$(f_1+f_2)(a) = f_1(a) + f_2(b), \qquad f_1, f_2 \in \mathrm{Hom}_R(A,B).$$

This gives $\mathrm{Hom}_R(A,B)$ the structure of an abelian group. Why does $\mathrm{Hom}_R(A,B)$ not carry an R-module structure in general? The only obvious candidate for rf is

$$(rf)(a) = rf(a) = f(ra), \qquad r \in R, \qquad f \in \mathrm{Hom}_R(A,B).$$

Now suppose $s \in R$. We have $(rf)(sa) = rf(sa) = rsf(a)$. But for rf to be a homomorphism, we would need $(rf)(sa) = s(rf)(a) = srf(a)$. If R is non-commutative, then rs may not be sr, and so rf is not an R-module homomorphism in general. Clearly, however, if R is commutative then rf is an R-module homomorphism, and $\mathrm{Hom}_R(A,B)$ has an R-module structure. The following are observations.

Proposition 3.2. *Suppose $A, A_1, A_2, B, B_1, B_2, M$ are R-modules, and $\alpha : A \to B$.*

- $\mathrm{Hom}_R(A_1 \oplus A_2, B) \cong \mathrm{Hom}_R(A_1, B) \oplus \mathrm{Hom}_R(A_2, B)$.
- $\mathrm{Hom}_R(A, B_1 \oplus B_2) \cong \mathrm{Hom}_R(A, B_1) \oplus \mathrm{Hom}_R(A, B_2)$.
- *Then we can define*

$$\begin{array}{cccccc} \alpha_* & : & \mathrm{Hom}_R(M,A) & \longrightarrow & \mathrm{Hom}_R(M,B) \\ & & f & \longmapsto & \alpha \circ f \end{array}, \qquad f : M \to A.$$

- *We can also define*

$$\begin{array}{cccccc} \alpha^* & : & \mathrm{Hom}_R(B,M) & \longrightarrow & \mathrm{Hom}_R(A,M) \\ & & g & \longmapsto & g \circ \alpha \end{array}, \qquad g : B \to M.$$

Thus Hom is a bifunctor between the category of R-modules and the category of abelian groups, additive in both arguments, covariant in the second argument and contravariant in the first argument.

- Bi means Hom takes two arguments.
- Functor means that homomorphisms between R-modules turn into abelian group homomorphisms.
- Covariant means the homomorphism goes in the same direction.
- Contravariant means the direction gets reversed.
- Additive in both arguments means Hom respects direct sums.

Proposition 3.3. *Suppose $\alpha : A \to B$ is surjective. Then $\alpha^* : \mathrm{Hom}_R(B,M) \to \mathrm{Hom}_R(A,M)$ is injective.*

Proof. Suppose $f_1, f_2 : B \to M$ are such that $\alpha^*(f_1) = \alpha^*(f_2)$. Then $f_1 \circ \alpha = f_2 \circ \alpha$, so $(f_1 \circ \alpha)(a) = (f_2 \circ \alpha)(a)$ for all $a \in A$. Let $b \in B$. Then $b = \alpha(a)$ for some a, since α is surjective, so $f_1(b) = (f_1 \circ \alpha)(a) = (f_2 \circ \alpha)(a) = f_2(b)$, so $f_1 = f_2$. ☐

Proposition 3.4. *Suppose $\alpha : A \to B$ is injective. Then $\alpha_* : \mathrm{Hom}_R(M,A) \to \mathrm{Hom}_R(M,B)$ is injective.*

Proof. Suppose $f_1, f_2 : M \to A$, and $\alpha_*(f_1) = \alpha_*(f_2)$. Then $\alpha \circ f_1 = \alpha \circ f_2$, so $(\alpha \circ f_1)(m) = (\alpha \circ f_2)(m)$ for all $m \in M$. But α is injective, so this implies $f_1(m) = f_2(m)$ for all $m \in M$. ☐

Proposition 3.5. *Suppose*
$$0 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 0$$
is a short exact sequence of R-modules. Then we have an exact sequence
$$0 \to \mathrm{Hom}_R(C, M) \xrightarrow{\beta^*} \mathrm{Hom}_R(B, M) \xrightarrow{\alpha^*} \mathrm{Hom}_R(A, M).$$

Proof. This is exact at $\mathrm{Hom}_R(C, M)$, since β^* is injective. Claim that the sequence is also exact at $\mathrm{Hom}_R(B, M)$, so it is an exact sequence. It is not necessarily a short exact sequence since α^* is not generally surjective. Let $g : B \to M$. We have
$$g \in \mathrm{Ker}\,\alpha^* \iff \alpha^*(g) = 0 \iff g \circ \alpha = 0 \iff g(\alpha(A)) = 0 \iff \mathrm{Im}\,\alpha \le \mathrm{Ker}\,g \iff \mathrm{Ker}\,\beta \le \mathrm{Ker}\,g,$$
Then $g \in \mathrm{Ker}\,\alpha^*$ if and only if for all $b_1, b_2 \in B$, $\beta(b_1) = \beta(b_2)$ implies that $g(b_1) = g(b_2)$, which is if and only if the map defined by
$$\begin{array}{cccc} f & : & C & \longrightarrow & M \\ & & c & \longmapsto & g(b) \end{array}, \qquad \beta(b) = c$$
is well-defined, since β is surjective, and f is an R-module homomorphism. Thus
$$g \in \mathrm{Ker}\,\alpha^* \qquad \iff \qquad \exists f \in \mathrm{Hom}_R(C, M),\ \beta^*(f) = g \qquad \iff \qquad g \in \mathrm{Im}\,\beta^*.$$
Hence $\mathrm{Ker}\,\alpha^* = \mathrm{Im}\,\beta^*$. So the sequence is exact at $\mathrm{Hom}_R(B, M)$. $\square$

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Example. These examples show that $\alpha : A \to B$ is injective does not imply $\alpha^* : \mathrm{Hom}_R(B, M) \to \mathrm{Hom}_R(A, M)$ is surjective.

- The inclusion $\alpha : \mathbb{Z} \to \mathbb{Q}$ is a $\mathbb{Z}$-module homomorphism. Let $M = \mathbb{Z}$. Then we get $\alpha^* : \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Q}, \mathbb{Z}) \to \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}, \mathbb{Z})$. Then α is injective, but α^* is not surjective. Why is this? In fact $\mathrm{Hom}_{\mathbb{Z}}(\mathbb{Q}, \mathbb{Z}) = 0$. Suppose
$$\begin{array}{cccc} f & : & \mathbb{Q} & \longrightarrow & \mathbb{Z} \\ & & 1 & \longmapsto & k \ne 0 \end{array}.$$
Suppose $p \nmid k$. Then there is no possible image for $1/p \in \mathbb{Q}$, since we would require $pf(1/p) = f(1) = k$. But $\mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}, \mathbb{Z}) \cong \mathbb{Z}$, so α^* is not surjective.

- Let $\alpha : k\mathbb{Z} \to \mathbb{Z}$ be the inclusion, so α is injective and not surjective. Let $M = \mathbb{Z}$. So we get $\alpha^* : \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}, \mathbb{Z}) \to \mathrm{Hom}_{\mathbb{Z}}(k\mathbb{Z}, \mathbb{Z})$. Suppose that $g \in \mathrm{Im}\,\alpha^*$. Then $g = f \circ \alpha$, where $f : \mathbb{Z} \to \mathbb{Z}$. Then $g(k) = f(k) = kf(1)$, so $\mathrm{Im}\,g \le k\mathbb{Z}$. But there exists $g \in \mathrm{Hom}_{\mathbb{Z}}(k\mathbb{Z}, \mathbb{Z})$ such that $g(k) = 1$. So this $g \notin \mathrm{Im}\,\alpha^*$, so α^* is not surjective.

Proposition 3.6. *Let*
$$0 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 0$$
be exact. Then
$$0 \to \mathrm{Hom}_R(M, A) \xrightarrow{\alpha_*} \mathrm{Hom}_R(M, B) \xrightarrow{\beta_*} \mathrm{Hom}_R(M, C)$$
is exact.

Proof. We already know that α injective implies that α_* is injective, so the sequence is exact at $\mathrm{Hom}_R(M, A)$. We show that $\mathrm{Ker}\,\beta_* = \mathrm{Im}\,\alpha_*$. Suppose $g \in \mathrm{Hom}_R(M, B)$. Then
$$g \in \mathrm{Ker}\,\beta_* \qquad \iff \qquad (\beta \circ g)(M) = 0 \qquad \iff \qquad \mathrm{Im}\,g \le \mathrm{Ker}\,\beta \qquad \iff \qquad \mathrm{Im}\,g \le \mathrm{Im}\,\alpha.$$
Note there exists $\alpha^{-1} : \mathrm{Im}\,\alpha \to A$. If $\mathrm{Im}\,g \le \mathrm{Im}\,\alpha$, then $\alpha^{-1} \circ g : M \to A$. If $f = \alpha^{-1} \circ g$, then $\alpha \circ f = g$, so $g \in \mathrm{Im}\,\alpha_*$. Conversely, if $g \in \mathrm{Im}\,\alpha_*$, then $g = \alpha \circ f$ for some $f \in \mathrm{Hom}_R(M, A)$ and so $\mathrm{Im}\,g \le \mathrm{Im}\,\alpha$. So
$$g \in \mathrm{Ker}\,\beta_* \qquad \iff \qquad \mathrm{Im}\,g \le \mathrm{Im}\,\alpha \qquad \iff \qquad g \in \mathrm{Im}\,\alpha_*.$$
Hence $\mathrm{Ker}\,\beta_* = \mathrm{Im}\,\alpha_*$. So the sequence is exact at $\mathrm{Hom}_R(M, B)$. $\square$

Example. These examples show that $\beta : B \to C$ is surjective does not imply $\beta_* : \mathrm{Hom}_R(M, B) \to \mathrm{Hom}_R(M, C)$ is surjective.

- Let
$$\begin{array}{cccc} \beta & : & \sum_{q \in \mathbb{Q}} \mathbb{Z} & \longrightarrow & \mathbb{Q} \\ & & e_q & \longmapsto & q \end{array}.$$
In general $\beta : \sum_{m \in M} R \to M$ defined by mapping the basis vector e_m to m, is a surjective homomorphism, so β is surjective. Let $M = \mathbb{Q}$. So we get $\beta_* : \mathrm{Hom}_{\mathbb{Z}}\left(\mathbb{Q}, \sum_{q \in \mathbb{Q}} \mathbb{Z}\right) \to \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Q}, \mathbb{Q})$. Claim that $\mathrm{Hom}_{\mathbb{Z}}\left(\mathbb{Q}, \sum_{q \in \mathbb{Q}} \mathbb{Z}\right)$ is trivial. Suppose $f : \mathbb{Q} \to \sum_{q \in \mathbb{Q}} \mathbb{Z}$ is not zero. Suppose $f(q_0) \neq 0$. Then there exist $q_1, \dots, q_t \in \mathbb{Q}$ and $a_1, \dots, a_t \in \mathbb{Z}$ such that $f(q_0) = \sum_{i=1}^t a_i e_{q_i}$. Now the projection of $\sum_{q \in \mathbb{Q}} \mathbb{Z}$ onto $\mathbb{Z} e_{q_1}$ is a non-trivial $\mathbb{Z}$-module homomorphism. But $\mathbb{Z} e_{q_1} \cong \mathbb{Z}$, and so no non-trivial map $\mathbb{Q} \to \mathbb{Z} e_{q_1}$ exists. But $\mathrm{Hom}_{\mathbb{Z}}(\mathbb{Q}, \mathbb{Q})$ is not trivial, so β_* is not surjective.

- Let
$$0 \to \mathbb{Z}_2 \to \mathbb{Z}_4 \to \mathbb{Z}_2 \to 0$$
be a short exact sequence of $\mathbb{Z}$-modules. Then we have
$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_2, \mathbb{Z}_2) & \xrightarrow{\alpha_*} & \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_2, \mathbb{Z}_4) & \xrightarrow{\beta_*} & \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_2, \mathbb{Z}_2) \\ & & \wr\Vert & & \wr\Vert & & \wr\Vert \\ & & \mathbb{Z}_2 & & \mathbb{Z}_2 & & \mathbb{Z}_2 \end{array}.$$
But there is no short exact sequence of abelian groups
$$0 \to \mathbb{Z}_2 \to \mathbb{Z}_2 \to \mathbb{Z}_2 \to 0,$$
and so β_* cannot be surjective.

Proposition 3.7. *Let M be an R-module. Then M is injective if and only if for every injective map $\alpha : A \to B$, we get $\alpha^* : \mathrm{Hom}_R(B, M) \to \mathrm{Hom}_R(A, M)$ is surjective.*

Proof. M is injective if and only if for all injective $\alpha : A \to B$, for all $f \in \mathrm{Hom}_R(A, M)$, there exists $g \in \mathrm{Hom}_R(B, M)$ such that $f = g \circ \alpha$, so $f = \alpha^*(g)$. This is if and only if for all injective $\alpha : A \to B$, $f \in \mathrm{Im}\,\alpha^*$ for all $f \in \mathrm{Hom}_R(A, M)$, which is if and only if α^* is surjective. ☐

Proposition 3.8. *Let M be an R-module. Then M is projective if and only if whenever $\beta : B \to C$ is surjective, the map $\beta_* : \mathrm{Hom}_R(M, B) \to \mathrm{Hom}_R(M, C)$ is surjective.*

Proof. M is projective if and only if whenever $\beta : B \to C$ is surjective, and $f \in \mathrm{Hom}_R(M, C)$, there exists $g \in \mathrm{Hom}_R(M, B)$ such that $f = \beta \circ g$. This is if and only if whenever $\beta : B \to C$ is surjective, and $f \in \mathrm{Hom}_R(M, C)$, then $f \in \mathrm{Im}\,\beta_*$, which is if and only if β_* is surjective. ☐

3.2 The snake lemma

Lecture 8 Monday 27/01/20

Let $\alpha : A \to B$ be an R-module homomorphism. The **cokernel** of α is $B / \mathrm{Im}\,\alpha$, written $\mathrm{Coker}\,\alpha$. The sequence
$$0 \to \mathrm{Ker}\,\alpha \to A \xrightarrow{\alpha} B \to \mathrm{Coker}\,\alpha \to 0$$
is exact.

Lemma 3.9 (The snake lemma)**.** *Suppose we have a commutative diagram*
$$\begin{tikzcd} & A \arrow[r, "\alpha"] \arrow[d, "f"] & B \arrow[r, "\beta"] \arrow[d, "g"] & C \arrow[r] \arrow[d, "h"] & 0 \\ 0 \arrow[r] & X \arrow[r, "\phi"'] & Y \arrow[r, "\psi"'] & Z & \end{tikzcd},$$
where the rows are exact. Then we obtain an exact sequence
$$\mathrm{Ker}\,f \xrightarrow{\alpha} \mathrm{Ker}\,g \xrightarrow{\beta} \mathrm{Ker}\,h \xrightarrow{\delta} \mathrm{Coker}\,f \xrightarrow{\overline{\phi}} \mathrm{Coker}\,g \xrightarrow{\overline{\psi}} \mathrm{Coker}\,h.$$

Proof.

- The maps $\alpha : \operatorname{Ker} f \to \operatorname{Ker} g$ and $\beta : \operatorname{Ker} g \to \operatorname{Ker} h$ are obtained simply by restricting α and β respectively. Observe that if $a \in \operatorname{Ker} f$ then $f(a) = 0$, so $(\phi \circ f)(a) = 0$. But $\phi \circ f = g \circ \alpha$, and so $(g \circ \alpha)(a) = 0$, so $\alpha(a) \in \operatorname{Ker} g$, which is what we wanted.
- The maps $\overline{\phi} : \operatorname{Coker} f \to \operatorname{Coker} g$ and $\overline{\psi} : \operatorname{Coker} g \to \operatorname{Coker} h$ are induced from ϕ and ψ by

$$\overline{\phi}(x + \operatorname{Im} f) = \phi(x) + \operatorname{Im} g, \qquad \overline{\psi}(y + \operatorname{Im} g) = \psi(g) + \operatorname{Im} h.$$

  Check that these maps make sense. Suppose $x_1 + \operatorname{Im} f = x_2 + \operatorname{Im} f$. Then $x_1 - x_2 \in \operatorname{Im} f$, so there exists $a \in A$ such that $f(a) = x_1 - x_2$. Now

$$\phi(x_1) - \phi(x_2) = \phi(x_1 - x_2) = (\phi \circ f)(a) = (g \circ \alpha)(a) \in \operatorname{Im} g.$$

  So $\phi(x_1) + \operatorname{Im} g = \phi(x_2) + \operatorname{Im} g$. So $\overline{\phi}$ is well-defined, and $\overline{\psi}$ is shown to be well-defined by a similar argument.
- How is the **connecting homomorphism** δ defined? Since β is surjective, for all $c \in C$, there exists $b \in B$ with $\beta(b) = c$. Suppose $c \in \operatorname{Ker} h$. Then $(h \circ \beta)(b) = 0$, so $(\psi \circ g)(b) = 0$. Hence $g(b) \in \operatorname{Ker} \psi = \operatorname{Im} \phi$. Define

$$\delta(c) = x + \operatorname{Im} f, \qquad \phi(x) = g(b), \qquad \beta(b) = c.$$

  Check this is well-defined. Suppose b_1, b_2, x_1, x_2 are such that $\phi(x_1) = g(b_1)$ and $\phi(x_2) = g(b_2)$, and $\beta(b_1) = \beta(b_2) = c$. We have $b_1 - b_2 \in \operatorname{Ker} \beta = \operatorname{Im} \alpha$. So $b_1 - b_2 = \alpha(a)$ for some $a \in A$. Then

$$(\phi \circ f)(a) = (g \circ \alpha)(a) = g(b_1 - b_2) = g(b_1) - g(b_2) = \phi(x_1) - \phi(x_2) = \phi(x_1 - x_2).$$

  But ϕ is injective, and so $f(a) = x_1 - x_2$, and so $x_1 + \operatorname{Im} f = x_2 + \operatorname{Im} f$. So δ is well-defined.

Exactness of the sequence is an exercise, on problem sheet. □

3.3 Tensor products

Definition 3.10. Let M be a left R-module, and let L be a right R-module. The **tensor product** $L \otimes_R M$ is an abelian group generated as an abelian group by a set of **pure tensors**

$$\{l \otimes m \mid l \in L,\ m \in M\},$$

subject to the relations

$$l_1 \otimes m + l_2 \otimes m = (l_1 + l_2) \otimes m, \qquad l_1, l_2 \in L, \qquad m \in M,$$
$$l \otimes m_1 + l \otimes m_2 = l \otimes (m_1 + m_2), \qquad l \in L, \qquad m_1, m_2 \in M,$$
$$(lr) \otimes m = l \otimes (rm), \qquad l \in L, \qquad m \in M, \qquad r \in R.$$

The following are observations.

- In general, not every element of $L \otimes_R M$ is a pure tensor. A general element of $L \otimes_R M$ is a $\mathbb{Z}$-linear combination of pure tensors.
- If R is commutative, L can be a left module, since left and right modules are the same. Also, in this case, $L \otimes_R M$ has an R-module structure, by $r(l \otimes m) = rl \otimes m$.
- Suppose that S is a set of generators for L, as an abelian group, and T is a set of generators for M, as an abelian group. Then a smaller generating set for $L \otimes_R M$ is $\{s \otimes t \mid s \in S,\ t \in T\}$. This is because if

$$l = \sum_{i=1}^{p} a_i s_i, \qquad m = \sum_{i=1}^{q} b_j t_j, \qquad s_i \in S, \qquad t_i \in T, \qquad a_i, b_i \in \mathbb{Z},$$

  then, from the relations,

$$l \otimes m = \sum_{i=1}^{p} \sum_{j=1}^{q} a_i b_j (s_i \otimes t_j).$$

Example. Tensor products can be counter intuitive, such as $\mathbb{Z}_2 \otimes_{\mathbb{Z}} \mathbb{Z}_3 = 0$. Why? Observe that for $x \in \mathbb{Z}_2$, $x3 = 3x = x$. So for all $x \in \mathbb{Z}_2$ and $y \in \mathbb{Z}_3$,

$$x \otimes y = x3 \otimes y = x \otimes 3y = x \otimes 0 = x \otimes y - x \otimes y = 0.$$

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Theorem 3.11 (Universal property of tensor products). *Let A be a right R-module and B a left R-module. Let C be an abelian group. Let $f : A \times B \to C$ be a map, not necessarily a homomorphism, which is $\mathbb{Z}$-linear in both arguments, so*

$$f(a_1 + a_2, b) = f(a_1, b) + f(a_2, b), \qquad a_1, a_2 \in A, \qquad b \in B,$$

$$f(a, b_1 + b_2) = f(a, b_1) + f(a, b_2), \qquad a \in A, \qquad b_1, b_2 \in B,$$

and such that

$$f(ar, b) = f(a, rb), \qquad a \in A, \qquad b \in B, \qquad r \in R.$$

Then there is a unique homomorphism

$$\begin{array}{rccc} g & : & A \otimes_R B & \longrightarrow & C \\ & & a \otimes b & \longmapsto & f(a, b) \end{array}.$$

Proof. In formal group theoretic terms, the tensor product $A \otimes_R B$ is a quotient F/K, where F is the free abelian group on the set of pure tensors $a \otimes b$, and K is the subgroup of F generated by elements of the form

$$(a_1 + a_2) \otimes b - a_1 \otimes b - a_2 \otimes b, \qquad a \otimes (b_1 + b_2) - a \otimes b_1 - a \otimes b_2, \qquad ar \otimes b - a \otimes rb.$$

The universal property of free abelian groups states that if F is free abelian on a set S, then any set map $S \to C$, for C an abelian group, extends uniquely to a homomorphism $F \to C$. In the situation under discussion, we have a map

$$g' : \{a \otimes b \mid a \in A,\ b \in B\} \to C.$$

So g' extends uniquely to a homomorphism $F \to C$. The conditions stipulated on f guarantee that $g'(K) = 0$. So g' induces a map $g : F/K \to C$, which is what we want, since $F/K = A \otimes_R B$. This establishes the existence of g. Since the images of the pure tensors under g are specified, it is clear that g is unique. □

Corollary 3.12.

1. *Let M be a left R-module. Then $R \otimes_R M \cong M$, via the map*

$$\begin{array}{rcccc} f & : & M & \longrightarrow & R \otimes_R M \\ & & m & \longmapsto & 1 \otimes m \end{array}.$$

2. *Let M be a right R-module. Then $M \otimes_R R \cong M$.*

Proof.

1. It is clear that f is a homomorphism of abelian groups. Now $r \otimes m = 1 \otimes rm$, so $R \otimes_R M$ is generated by $\{1 \otimes m \mid m \in M\}$, so f is surjective. For injectivity of f, we need the universal property. Define a bilinear map

$$\begin{array}{ccc} R \times M & \longrightarrow & M \\ (r, m) & \longmapsto & rm \end{array}.$$

   This induces a homomorphism

$$\begin{array}{rcccc} g & : & R \otimes_R M & \longrightarrow & M \\ & & r \otimes m & \longmapsto & rm \end{array}.$$

   It is easy to check that g is an inverse for f, so f is bijective.

2. By the same argument as 1.

□

Corollary 3.13. *Let A and B be right R-modules, and let C be a left R-module.*

1. $(A \oplus B) \otimes_R C \cong (A \otimes_R C) \oplus (B \otimes_R C)$, *via the map*

$$f \quad : \quad \begin{array}{rcl} (A \oplus B) \otimes_R C & \longrightarrow & (A \otimes_R C) \oplus (B \otimes_R C) \\ (a, b) \otimes c & \longmapsto & (a \otimes c, b \otimes c) \end{array}.$$

2. $A \otimes_R (B \oplus C) \cong (A \otimes_R B) \oplus (A \otimes_R C)$.

Proof.

1. Take a bilinear map, that is $\mathbb{Z}$-bilinear in both arguments, and respecting R-multiplication,

$$\begin{array}{rcl} A \oplus B \times C & \longrightarrow & (A \otimes_R C) \oplus (B \otimes_R C) \\ ((a, b), c) & \longmapsto & (a \otimes c, b \otimes c) \end{array}.$$

This induces a homomorphism $f : (A \oplus B) \otimes_R C \to (A \otimes_R C) \oplus (B \otimes_R C)$ with the description as given above. Now take the bilinear map given by

$$\begin{array}{rcl} A \times C & \longrightarrow & (A \oplus B) \otimes_R C \\ (a, c) & \longmapsto & (a, 0) \otimes c \end{array}.$$

This induces a homomorphism $g_1 : A \otimes_R C \to (A \oplus B) \otimes_R C$. Similarly, we get a homomorphism $g_2 : B \otimes_R C \to (A \oplus B) \otimes_R C$. Now define

$$g = g_1 \oplus g_2 \quad : \quad \begin{array}{rcl} (A \otimes_R C) \oplus (B \otimes_R C) & \longrightarrow & (A \oplus B) \otimes_R C \\ (x, y) & \longmapsto & g_1(x) + g_2(y) \end{array}.$$

It is easy to check that f and g are mutually inverse, so both isomorphisms.

2. Similarly.

$\square$

Corollary 3.14. *Let A be an abelian group. Then*

1. $\mathbb{Z}_n \otimes_{\mathbb{Z}} A \cong A/nA$, *and*

2. $A \otimes_{\mathbb{Z}} \mathbb{Z}_n \cong A/nA$.

Proof.

1. Define a map by

$$f \quad : \quad \begin{array}{rcl} A & \longrightarrow & \mathbb{Z}_n \otimes_{\mathbb{Z}} A \\ a & \longmapsto & 1 \otimes a \end{array}.$$

Suppose $a_0 \in A$ such that $a_0 = na$ for some a. Then $f(a_0) = 1 \otimes a_0 = 1 \otimes na = n \otimes a = 0$ so $nA \leq \operatorname{Ker} f$. So f induces a map

$$\overline{f} : A/nA \to \mathbb{Z}_n \otimes_{\mathbb{Z}} A.$$

Notice that the pure tensor $k \otimes a$ is equal to $1 \otimes ka$, so $\mathbb{Z}_n \otimes_{\mathbb{Z}} A$ is generated by $\{1 \otimes a \mid a \in A\}$. So $\overline{f}$ is surjective. For injectivity, use the universal property. We have a bilinear map

$$g \quad : \quad \begin{array}{rcl} \mathbb{Z}_n \times A & \longrightarrow & A/nA \\ (k, a) & \longmapsto & ka + nA \end{array}.$$

This is well-defined and bilinear. So extends to a homomorphism

$$\overline{g} : \mathbb{Z}_n \otimes_{\mathbb{Z}} A \to A/nA.$$

It is easy to check that $\overline{g} \circ \overline{f} = \mathrm{id}_{A/nA}$, so $\overline{f}$ is injective.

2. Similarly.

$\square$

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Proposition 3.15. *Let $\alpha : A \to B$ be a homomorphism of right R-modules. Let M be a left R-module. There is a unique abelian group homomorphism*

$$\begin{array}{cccc} \alpha' & : & A \otimes_R M & \longrightarrow & B \otimes_R M \\ & & a \otimes m & \longmapsto & \alpha(a) \otimes m \end{array}, \qquad a \in A, \qquad m \in M.$$

Proof. The set map defined by

$$\begin{array}{cccc} f & : & A \times M & \longrightarrow & B \otimes_R M \\ & & (a, m) & \longmapsto & \alpha(a) \otimes m \end{array}$$

is linear in both arguments, and we have

$$f(ar, m) = \alpha(ar) \otimes m = \alpha(a) r \otimes m = \alpha(a) \otimes rm = f(a, rm).$$

Now by the universal property of tensor products, f gives rise to a unique homomorphism $\alpha' : A \otimes_R M \to B \otimes_R M$ with the properties claimed. □

Proposition 3.16. *Suppose $\alpha : A \to B$ is surjective. Then $\alpha' : A \otimes_R M \to B \otimes_R M$ is surjective.*

Proof. Since α is surjective, every pure tensor $b \otimes m \in B \otimes_R M$ is equal to $\alpha(a) \otimes m$ for some $a \in A$. So $b \otimes m = \alpha'(a \otimes m) \in \operatorname{Im} \alpha'$. Since $B \otimes_R M$ is generated by its pure tensors, α' is surjective. □

An observation is that it is not true that $A \to B$ is injective implies $A \otimes_R M \to B \otimes_R M$ is injective.

Example. Let

$$\begin{array}{cccc} \alpha & : & \mathbb{Z}_2 & \longrightarrow & \mathbb{Z}_4 \\ & & 1 & \longmapsto & 2 \end{array},$$

which is injective. Consider

$$\begin{array}{cccc} \alpha' & : & \mathbb{Z}_2 \otimes_{\mathbb{Z}} \mathbb{Z}_2 \cong \mathbb{Z}_2 & \longrightarrow & \mathbb{Z}_4 \otimes_{\mathbb{Z}} \mathbb{Z}_2 \\ & & 1 \otimes 1 & \longmapsto & 2 \otimes 1 = 1 \otimes 2 = 0 \end{array}.$$

So α' is the zero map, which is not injective.

Proposition 3.17. *Let*

$$0 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 0$$

be a short exact sequence of right R-modules. Then the sequence

$$A \otimes_R M \xrightarrow{\alpha'} B \otimes_R M \xrightarrow{\beta'} C \otimes_R M \to 0$$

is exact.

Proof. Since β' is surjective, the sequence is exact at $C \otimes_R M$. We show it is exact at $B \otimes_R M$. Since β is surjective, for every $c \in C$, there exists $f(c) \in B$ such that $\beta(f(c)) = c$. Here f is a set map $C \to B$, which is not uniquely defined in general. Suppose that $\beta(b) = c$. Then $b - f(c) \in \operatorname{Ker} \beta = \operatorname{Im} \alpha$, so $f(c) + \operatorname{Im} \alpha = b + \operatorname{Im} \alpha$. Define a set map by

$$\begin{array}{cccc} g & : & C \times M & \longrightarrow & (B \otimes_R M) / \operatorname{Im} \alpha' \\ & & (c, m) & \longmapsto & f(c) \otimes m + \operatorname{Im} \alpha' \end{array}.$$

Note that if $\beta(b) = c$, then $b \otimes m - f(c) \otimes m = \alpha(a) \otimes m \in \operatorname{Im} \alpha'$ for some $a \in A$. We can check that g is linear in both arguments. For example, for the first argument, we have $g(c_1 + c_2, m) = f(c_1 + c_2) \otimes m + \operatorname{Im} \alpha'$. Now $\beta(f(c_1 + c_2)) = c_1 + c_2 = \beta(f(c_1)) + \beta(f(c_2)) = \beta(f(c_1) + f(c_2))$ so

$$g(c_1 + c_2, m) = (f(c_1) + f(c_2)) \otimes m + \operatorname{Im} \alpha' = f(c_1) \otimes m + f(c_2) \otimes m + \operatorname{Im} \alpha' = g(c_1, m) + g(c_2, m).$$

Also, we have $g(cr, m) = f(cr) \otimes m + \operatorname{Im} \alpha'$. But $\beta(f(cr)) = cr = \beta(f(c) r)$, so $f(cr) \otimes m + \operatorname{Im} \alpha' = f(c) r \otimes m + \operatorname{Im} \alpha'$. So

$$g(cr, m) = f(c) r \otimes m + \operatorname{Im} \alpha' = f(c) \otimes rm + \operatorname{Im} \alpha' = g(c, rm).$$

By the universal property, there is a unique homomorphism

$$\begin{array}{rccl} \psi & : & C \otimes_R M & \longrightarrow & (B \otimes_R M) / \operatorname{Im} \alpha' \\ & & c \otimes m & \longmapsto & f(c) \otimes m + \operatorname{Im} \alpha' \end{array}.$$

Next observe that $(\beta' \circ \alpha')(a \otimes m) = (\beta \circ \alpha)(a) \otimes m = 0$, since $\operatorname{Im} \alpha = \operatorname{Ker} \beta$. Since $A \otimes_R M$ is generated by pure tensors, we have $\beta' \circ \alpha' = 0$. So $\operatorname{Im} \alpha' \le \operatorname{Ker} \beta'$. Hence β' induces a map

$$\phi : (B \otimes_R M) / \operatorname{Im} \alpha' \to C \otimes_R M.$$

It is easy to check that ϕ and ψ are mutually inverse, and so both are isomorphisms. In particular ϕ is injective, and so $\operatorname{Im} \alpha' = \operatorname{Ker} \beta'$ as required. $\square$

3.4 Flat modules

Definition 3.18. A left R-module M is **flat** if $A \to B$ is injective implies that $A \otimes_R M \to B \otimes_R M$ is injective.

If M is flat then any short exact sequence of right R-modules

$$0 \to A \to B \to C \to 0$$

corresponds to a short exact sequence of abelian groups

$$0 \to A \otimes_R M \to B \otimes_R M \to C \otimes_R M \to 0.$$

Proposition 3.19. *Every projective module is flat.*

This follows from two lemmas.

Lemma 3.20. *$P \oplus Q$ is flat if and only if P and Q are both flat.*

Proof. Recall there is a canonical isomorphism

$$A \otimes_R (P \oplus Q) \cong (A \otimes_R P) \oplus (A \otimes_R Q).$$

Suppose $\alpha : A \to B$ is injective. Then $\alpha' : A \otimes_R (P \oplus Q) \to B \otimes_R (P \oplus Q)$ corresponds to

$$\begin{array}{rccl} \overline{\alpha'} & : & (A \otimes_R P) \oplus (A \otimes_R Q) & \longrightarrow & (B \otimes_R P) \oplus (B \otimes_R Q) \\ & & (a \otimes p, 0) & \longmapsto & (\alpha(a) \otimes p, 0) \\ & & (0, a \otimes q) & \longmapsto & (0, \alpha(a) \otimes q) \end{array}.$$

It is clear from this that $\overline{\alpha'}$ is injective if and only if $A \otimes_R P \to B \otimes_R P$ and $A \otimes_R Q \to B \otimes_R Q$ are injective, and Lemma 3.20 follows immediately. $\square$

Lemma 3.21. *Every free R-module is flat.*

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Proof. We know $(A \oplus B) \otimes_R C \cong (A \otimes_R C) \oplus (B \otimes_R C)$. Similarly,

$$\left(\bigoplus_{s \in S} A_s \right) \otimes_R C \cong \bigoplus_{s \in S} (A_s \otimes_R C).$$

So Lemma 3.20 generalises, so $\bigoplus_{s \in S} A_s$ is flat if and only if all of the A_s is flat for $s \in S$. Let F be free. Then $F = \bigoplus_{s \in S} R$, and so F is flat if and only if R is flat. But for any R-module in A, we have $A \otimes_R R \cong A$, so

$$\begin{tikzcd} A \arrow[r, "\alpha"] \arrow[d, phantom, "\cong" rotate=90] & B \arrow[d, phantom, "\cong" rotate=90] \\ A \otimes_R R \arrow[r, dashed, "\alpha'"'] & B \otimes_R R \end{tikzcd},$$

and it is easy to check that R is flat. $\square$

Proof of Proposition 3.19. Lemma 3.20 and Lemma 3.21 imply Proposition 3.19, since a projective module is a direct summand of a free module. $\square$

4 Modules over a PID

There exist flat modules which are not projective. We will show that $\mathbb{Q}$ as a module for $\mathbb{Z}$ is flat, and it is easy to see it is not projective. To do this we will study the case of modules over a PID. Recall that R is an **integral domain** if R is commutative and $rs = 0$ implies that $r = 0$ or $s = 0$ for $r, s \in R$. An integral domain is a **PID** if every ideal is $\langle a \rangle = \{ra \mid r \in R\}$ for some $a \in R$.

Example. The ring $\mathbb{Z}$ is an example of a PID.

4.1 Free and projective modules

Proposition 4.1. *Let R be a PID. Then every projective R-module is free. Equivalently, every summand of a free module is free.*

In fact we will show that any submodule of a free module is free. Moreover, if $F_1 \leq F_2$, where F_1 and F_2 are free, and if B_1 and B_2 are bases for F_1 and F_2 respectively, then $|B_1| \leq |B_2|$. In particular, if $M \leq R^n$, then $M \cong R^m$ for some $m \leq n$. For this, we will need the well-ordering theorem.

Theorem 4.2 (Well-ordering theorem)**.** *Let X be a set. There exists a well-order $\leq$ on X, that is a total order such that every non-empty subset of X has a least element.*

Corollary 4.3 (Transfinite induction)**.** *Let X be a non-empty set well-ordered by $\leq$. Let x_0 be the least element of X. Let $S \subseteq X$. If $x_0 \in S$, and $s < t$ implies $s \in S$ implies that $t \in S$, then $S = X$.*

Proof. Let $F = \bigoplus_{s \in S} R$. Let $\leq$ be a well-order on S. For $s \in S$, let π_s be the projection map $F \to R$ onto the s-coordinate. Let e_s be the element of F with one in coordinate s, and zero elsewhere. Suppose $U \leq F$ is an R-submodule of F. Define R_t to be the submodule of F generated by $\{e_s \mid s \leq t\}$, so

$$R_t = \mathrm{sp}\,\{e_s \mid s \leq t\}.$$

So if $t_1 \leq t_2$ then $R_{t_1} \leq R_{t_2}$. Let

$$U_t = U \cap R_t.$$

So $t_1 < t_2$ implies that $U_{t_1} \leq U_{t_2}$. Consider $\pi_s(U_s)$. This is an ideal of R. Hence there exists $a_s \in R$ such that $\pi_s(U_s) = \langle a_s \rangle$, since R is a PID. For each s, let $u_s \in U_s$ be such that $\pi_s(u_s) = a_s$. In cases where $a_s = 0$, assume $u_s = 0$. Let

$$B = \{u_s \mid s \in S,\ u_s \neq 0\}.$$

- Claim that B generates U. We will actually prove that $B_t = \{u_s \mid s \leq t\}$ generates U_t, using transfinite induction. If s_0 is the least element of S, it is easy to see that $B_{s_0} = \{u_{s_0}\}$ generates U_{s_0}. Suppose B_t generates U_t for all $t < t_0$. Let $u \in U_{t_0}$. Then $\pi_{t_0}(u) = ra_{t_0}$. Hence $\pi_{t_0}(u - ru_{t_0}) = 0$. So $u - ru_{t_0}$ has zero in the t_0-coordinate, so $u - ru_{t_0} \in \mathrm{sp}\,\{e_s \mid s < t_0\}$. Clearly $u - ru_{t_0} \in U$. We have $u - ru_{t_0} = \sum_{i=1}^{q} r_i e_{s_i}$, where $s_i < t_0$, and $s_1 < \dots < s_q$. Then

  $$u - ru_{t_0} \in U \cap R_{s_q} = U_{s_q} = \mathrm{sp}\,B_{s_q},$$

  by the inductive hypothesis. Hence $u \in \mathrm{sp}\left(B_{s_q} \cup \{u_{t_0}\}\right) \subseteq \mathrm{sp}\,B_{t_0}$. Hence B_{t_0} generates U_{t_0}, as required.

- Next we show the linear independence of B. Suppose we have a linear combination of elements of B equal to zero. Say $\sum_{i=1}^{k} r_i u_{s_i} = 0$. Assume $s_1 < \dots < s_k$. We have

  $$\pi_{s_k}\left(\sum_{i=1}^{k} r_i u_{s_i}\right) = \sum_{i=1}^{k} r_i \pi_{s_k}(u_{s_i}).$$

  Now $u_{s_i} \in U_{s_i} \subseteq R_{s_i}$, and so $\pi_{s_k}(u_{s_i}) = 0$ if $s_i < s_k$. Hence $r_k \pi_{s_k}(u_{s_k}) = 0$, so $r_k a_{s_k} = 0$. But $a_{s_k} \neq 0$, and R is an integral domain. So $r_k = 0$. It follows easily that $r_i = 0$ for all i, so B is linearly independent.

We have shown that B is a basis for U. Hence U is free. Since the elements of B are indexed by a subset of S, we have $|B| \leq |S|$. □

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4.2 Injective and divisible modules

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Definition 4.4. Let R be an integral domain, and M an R-module. Let $m \in M$. Say that m is **infinitely divisible** if for all $r \in R \setminus \{0\}$ there exists $l \in M$ such that $rl = m$.

Proposition 4.5. *The divisible elements of M form a submodule* $\mathrm{D}(M)$.

Proof. Easy. ☐

Definition 4.6. If $\mathrm{D}(M) = M$, then M is **divisible**.

Proposition 4.7. *Let R be an integral domain. Then if an R-module M is injective then it is divisible.*

Proof. Recall that for an integral domain R, and $a \in R \setminus \{0\}$, the map

$$\begin{array}{cccc} f & : & R & \longrightarrow & \langle a \rangle \\ & & r & \longmapsto & ra \end{array}$$

is an isomorphism. Suppose M is an injective R-module. Let

$$\begin{array}{cccc} g & : & R & \longrightarrow & M \\ & & 1 & \longmapsto & m \end{array}.$$

Then $g \circ f^{-1}$ is a homomorphism $\langle a \rangle \to M$, and $\left(g \circ f^{-1}\right)(a) = g(1) = m$. Now by Baer's criterion, there is a map $h : R \to M$ extending $g \circ f^{-1}$. Now $ah(1) = h(a) = \left(g \circ f^{-1}\right)(a) = m$. Hence there exists $l \in M$ such that $al = m$. So m is a divisible element, and so M is divisible. ☐

Proposition 4.8. *Let R be a PID. If M is a divisible R-module then M is injective.*

So divisible equals injective when R is a PID.

Proof. We use Baer's criterion. Let I be an ideal of R, and $f : I \to M$ an R-module homomorphism. Since R is a PID, $I = \langle a \rangle$ for some $a \in R$. Suppose $f(a) = m$. If $a = 0$ there is nothing to prove, since the zero map $R \to M$ extends f. So assume $a \neq 0$. Since m is divisible, there exists $l \in M$ with $al = m$. Now the map given by

$$\begin{array}{ccc} R & \longrightarrow & M \\ 1 & \longmapsto & l \end{array}$$

extends f. So Baer's criterion is satisfied, and so M is injective. ☐

4.3 Flat and torsion-free modules

Definition 4.9. Let R be an integral domain. Let M be an R-module. Say that $m \in M$ is a **torsion element** if there exists $r \in R \setminus \{0\}$ such that $rm = 0$.

Proposition 4.10. *The torsion elements of M form a submodule* $\mathrm{T}(M)$.

Proof. Easy, using the fact that integral domains are commutative. ☐

Definition 4.11. If $\mathrm{T}(M) = 0$, then M is **torsion-free**. If $\mathrm{T}(M) = M$, then M is a **torsion module**.

Proposition 4.12. *Let R be an integral domain. Let M be a flat R-module. Then M is torsion-free.*

Proof. Let $a \in R \setminus \{0\}$. Then

$$\begin{array}{cccc} f & : & R & \longrightarrow & R \\ & & 1 & \longmapsto & a \end{array}$$

is an injective R-module homomorphism. Suppose that M is flat. Then the map

$$\begin{array}{cccc} g & : & R \otimes_R M & \longrightarrow & R \otimes_R M \\ & & r \otimes m & \longmapsto & ra \otimes m = r \otimes am \end{array}$$

is injective. But $R \otimes_R M$ is canonically isomorphic to M, under which the map g corresponds to $m \mapsto am$. Since g is injective, we have $am \neq 0$ for $m \neq 0$. Hence m is not a torsion element, if $m \neq 0$, and so M is torsion-free. ☐

We now build up to the following.

Proposition 4.13. *Let R be a PID. If M is a torsion-free R-module then M is flat.*

The following is the strategy. We want to prove that whenever $\alpha : A \to B$ is injective, so is $\alpha' : A \otimes_R M \to B \otimes_R M$, where M is torsion-free.

1. Prove this in the case that B is free, and A is a submodule of B, and α is the inclusion map, by
   - first reducing the problem to the case that A and B are finitely generated, so $B \cong \mathbb{R}^n$, and
   - then using induction on the rank n of B.
2. Show the general case follows from 1.

Lemma 4.14. *Let R be a PID, let $I = \langle a \rangle$ be an ideal of R, and let M be a torsion-free R-module. Then $g : I \otimes_R M \to R \otimes_R M$ is injective.*

Proof. The homomorphism given by

$$\begin{array}{ccc} R & \longrightarrow & I \\ r & \longmapsto & ra \end{array}$$

gives a map $f : R \otimes_R M \to I \otimes_R M$. Now $g \circ f$ is a map

$$\begin{array}{ccc} R \otimes_R M & \longrightarrow & R \otimes_R M \\ r & \longmapsto & ra \end{array}.$$

Now f is surjective, and $g \circ f$ is injective, since R is an integral domain. But this implies that g is injective, as required. $\square$

Lemma 4.15. *Let A be a right R-module. Let M be a left R-module. Suppose $\sum_{i=1}^{t} (a_i \otimes m_i) = 0$ in $A \otimes_R M$. There exists a finitely generated submodule $A_0 \leq A$ such that $a_i \in A_0$ for all i, and $\sum_{i=1}^{t} (a_i \otimes m_i) = 0$ in $A_0 \otimes_R M$.*

Proof. Recall that

$$A \otimes_R M = \mathrm{F}_{\mathrm{ab}} (A \times M) / K,$$

where K is generated by certain relators. If $\sum_{i=1}^{t} (a_i \otimes m_i) = 0$ in $A \otimes_R M$, then in $\mathrm{F}_{\mathrm{ab}} (A \times M)$, we have $\sum_{i=1}^{t} (a_i \otimes m_i) \in K$. So there exist relators $s_1, \dots, s_q$, or their negations, such that

$$\sum_{i=1}^{t} (a_i \otimes m_i) = \sum_{i=1}^{q} s_i.$$

Only finitely many elements of A are involved in the relators $s_1, \dots, s_q$. Let A_0 be generated by these together with $a_1, \dots, a_t$. Then certainly $a_i \in A_0$ for all i. And $\sum_{i=1}^{t} (a_i \otimes m_i) = \sum_{i=1}^{q} s_i$ in $\mathrm{F}_{\mathrm{ab}} (A_0 \times M)$ so $\sum_{i=1}^{t} (a_i \otimes m_i) = 0$ in $A_0 \otimes_R M$. Clearly A_0 is finitely generated. $\square$

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Lemma 4.16. *Let $F = \mathrm{F}(S) = \bigoplus_{s \in S} R$. Let U be a finitely generated submodule of F. Then there exists a finite $T \subseteq S$ such that $U \leq \mathrm{F}(T)$, and for any M, the map $\mathrm{F}(T) \otimes_R M \to \mathrm{F}(S) \otimes_R M$ is injective.*

Proof. Let $u_1, \dots, u_q$ be generators for U. Every u_i is an R-linear combination of elements of S. Since each of these linear combinations mentions only finitely many elements of S, there is a finite subset $T \subseteq S$ such that every u_i is an R-linear combination of elements of T. So $U \leq \mathrm{F}(T)$. We have

$$\mathrm{F}(S) = \mathrm{F}(T) \oplus \mathrm{F}(S \setminus T),$$

and so

$$\mathrm{F}(S) \otimes_R M \cong (\mathrm{F}(T) \otimes_R M) \oplus (\mathrm{F}(S \setminus T) \otimes_R M).$$

It follows that the natural map $\mathrm{F}(T) \otimes_R M \to \mathrm{F}(S) \otimes_R M$ is injective. $\square$

Lemma 4.15 and Lemma 4.16 tell us that if F is free and $U \leq F$, and if M is an R-module, if $U \otimes_R M \to F \otimes_R M$ is not injective, then there exists a finitely generated $U_0 < U$ and a finite rank free submodule $F_0 < F$ such that $U_0 \otimes_R M \to F_0 \otimes_R M$ is not injective.

Lemma 4.17. *Let R be a PID. Let F be free, and $U \leq F$. Let M be torsion-free. Then $U \otimes_R M \to F \otimes_R M$ is injective.*

Proof. We assume that $F = R^n$. We do this by induction on n.

Base case. Let $n = 1$. So F is R, and U is an ideal of R. By Lemma 4.14, $U \otimes_R M \to F \otimes_R M$ is injective in this case.

Inductive hypothesis. $U \leq F = R^{n-1}$ implies that $U \otimes_R M \to F \otimes_R M$ is injective.

Inductive step. Assume $U \leq F = R^n$. Write $R^n = R \oplus R^{n-1}$. So we have a short exact sequence

$$0 \to R \to R^n \to R^{n-1} \to 0.$$

We also have a short exact sequence

$$0 \to U_1 \to U \to \pi_{R^{n-1}}(U) \to 0,$$

where $U_1 = U \cap \left(R \oplus 0^{n-1}\right)$. Identifying R with $R \oplus 0^{n-1}$, we get a commuting diagram

$$\begin{tikzcd} 0 \arrow[r] & U_1 \arrow[r] \arrow[d] & U \arrow[r] \arrow[d] & \pi_{R^{n-1}}(U) \arrow[r] \arrow[d] & 0 \\ 0 \arrow[r] & R \arrow[r] & R^n \arrow[r] & R^{n-1} \arrow[r] & 0 \end{tikzcd},$$

where the vertical maps are inclusions, and the rows are exact. Tensoring everything with M, we get a new commuting diagram

$$\begin{tikzcd} & U_1 \otimes_R M \arrow[r] \arrow[d, "f"] & U \otimes_R M \arrow[r] \arrow[d, "g"] & \pi_{R^{n-1}}(U) \otimes_R M \arrow[r] \arrow[d, "h"] & 0 \\ 0 \arrow[r] & R \otimes_R M \arrow[r] & R^n \otimes_R M \arrow[r] & R^{n-1} \otimes_R M \arrow[r] & 0 \end{tikzcd}.$$

The initial zero in the bottom row comes from the fact that

$$0 \to R \to R^n \to R^{n-1} \to 0$$

is split, since $R^n = R \oplus R^{n-1}$, and so

$$R^n \otimes_R M \cong (R \otimes_R M) \oplus \left(R^{n-1} \otimes_R M\right).$$

Now f is injective by Lemma 4.14, and h is injective by the inductive hypothesis. The snake lemma tells us that the sequence

$$\operatorname{Ker} f \to \operatorname{Ker} g \to \operatorname{Ker} h$$

is exact at $\operatorname{Ker} g$. So

$$0 \to \operatorname{Ker} g \to 0$$

is exact, and so $\operatorname{Ker} g = 0$. So g is injective, and this completes the induction.

$\square$

Proof of Proposition 4.13. Prove that if $\alpha : A \to B$ is injective, and M is torsion-free, over a PID R, then $\alpha' : A \otimes_R M \to B \otimes_R M$ is injective. There exists a free module F such that B is quotient of F. So there is a short exact sequence

$$0 \to K \to F \xrightarrow{\delta} B \to 0.$$

Now $A \cong \alpha A = \operatorname{Im} \alpha$. Let F_A be the δ-preimage of αA. Then $K < F_A$, and we have another short exact sequence

$$0 \to K \to F_A \to \alpha A \to 0.$$

We have a commuting diagram

$$\begin{tikzcd} & & F_A \arrow[r] \arrow[dd, hook] & \alpha A \arrow[r] \arrow[dd, hook] & 0 \\ 0 \arrow[r] & K \arrow[ur] \arrow[dr] & & & \\ & & F \arrow[r] & B \arrow[r] & 0 \end{tikzcd} .$$

Tensoring with M,

$$\begin{tikzcd} & F_A \otimes_R M \arrow[r, "\gamma"] \arrow[dd, "f"] & \alpha A \otimes_R M \arrow[r] \arrow[dd, "g"] & 0 \\ K \otimes_R M \arrow[ur, "\beta"] \arrow[dr, "\delta"'] & & & \\ & F \otimes_R M \arrow[r, "\epsilon"'] & B \otimes_R M \arrow[r] & 0 \end{tikzcd}$$

is commuting, and exact along rows. Let $u \in \operatorname{Ker} g \leq \alpha A \otimes_R M \cong A \otimes_R M$. Since γ is surjective, there is $w \in F_A \otimes_R M$ with $\gamma(w) = u$. So $(g \circ \gamma)(w) = 0$. So $(\epsilon \circ f)(w) = 0$. So $f(w) \in \operatorname{Ker} \epsilon = \operatorname{Im} \delta$, so $f(w) = \delta(k)$ for $k \in K \otimes_R M$. Since f is injective, by Lemma 4.17, we get $w = \beta(k) \in \operatorname{Im} \beta$. So $w \in \operatorname{Ker} \gamma$, so $u = 0$. Hence g is injective, as required. $\square$

We have shown that if R is a PID, and if M is torsion-free, then M is flat.

4.4 Modules over PIDs

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For an R-module M

$$\text{free} \implies \text{projective} \implies \text{flat} \implies \text{torsion-free}, \qquad \text{injective} \implies \text{divisible}.$$

Over a PID

$$\text{free} \iff \text{projective} \implies \text{flat} \iff \text{torsion-free}, \qquad \text{injective} \iff \text{divisible}.$$

Do we have projective if and only if flat, over a general ring, or over a PID? The answer is no.

Example. The $\mathbb{Z}$-module $\mathbb{Q}$ is torsion-free, so flat. Is $\mathbb{Q}$ projective? Is $\mathbb{Q}$ free, since $\mathbb{Z}$ is a PID? Consider a free $\mathbb{Z}$-module $F = \bigoplus_{s \in S} \mathbb{Z}$. Let $s_0 \in S$. Then let

$$x = (x_s)_{s \in S} = \begin{cases} 1 & s = s_0 \\ 0 & \text{otherwise} \end{cases} \in F.$$

It is clear there are no $y \in F$ such that $2y = x$. So x is not a divisible element of F. Indeed, $\mathrm{D}(F) = \{0\}$. But $\mathrm{D}(\mathbb{Q}) = \mathbb{Q}$. Hence $\mathbb{Q} \ncong F$. So $\mathbb{Q}$ is an example of a flat module which is not projective.

5 Projective and injective resolutions

Definition 5.1. Let M be an R-module. A **resolution**, or **left resolution**, for M is a sequence of R-modules $A_0, A_1, A_2, \dots$, with homomorphisms $d : A_{i+1} \to A_i$, and also a homomorphism $A_0 \to M$, such that

$$\dots \xrightarrow{d} A_2 \xrightarrow{d} A_1 \xrightarrow{d} A_0 \to M \to 0$$

is an exact sequence, where d is the **differential**. If all of the modules A_i have a property $\mathcal{P}$, we call this a **$\mathcal{P}$-resolution**.

So we can talk about free resolutions, projective resolutions, flat resolutions. We do not use the term injective resolution in this context.

Definition 5.2. A **right resolution**, or **coresolution**, for M is a sequence of R-modules $A^0, A^1, A^2, \dots$, with homomorphisms $d : A^i \to A^{i+1}$, and $M \to A^0$, such that

$$0 \to M \to A^0 \xrightarrow{d} A^1 \xrightarrow{d} A^2 \xrightarrow{d} \dots$$

is exact. If the modules A^i have a property $\mathcal{P}$, we can refer to a **right $\mathcal{P}$-resolution**.

An injective resolution always means a right injective resolution.

5.1 Existence of projective resolutions

Proposition 5.3. *Let M be an R-module. Then M has free, projective, and flat resolutions.*

Proof. Since free implies projective implies flat, it is enough to show that free resolutions exist. Use the fact that for any module L, there exist a free module F and $K \leq F$ such that $L \cong F/K$. So we get a short exact sequence

$$0 \to K \to F \to L \to 0.$$

It follows that we can find $F_0, F_1, F_2, \dots$, and $K_0 \leq F_0, K_1 \leq F_1, K_2 \leq F_2, \dots$ such that

$$0 \to K_0 \to F_0 \to M \to 0, \qquad 0 \to K_1 \to F_1 \to K_0 \to 0, \qquad 0 \to K_2 \to F_2 \to K_1 \to 0, \qquad \dots$$

are all exact. Since $K_i \leq F_i$, we may consider the maps $F_{i+1} \to K_i$ as maps $F_{i+1} \to F_i$ with image K_i. But K_i is the kernel of the map $F_i \to K_{i-1}$, so the sequence

$$\dots \to F_2 \to F_1 \to F_0 \to M \to 0$$

is exact, and a free resolution for M. ☐

5.2 Existence of injective resolutions

Injective coresolutions exist too, but the proof is more intricate. It involves making use of properties of the abelian group $\mathbb{Q}/\mathbb{Z}$.

Proposition 5.4. *Let A be an abelian group, and let $a \in A \setminus \{0\}$. There is a homomorphism $f : A \to \mathbb{Q}/\mathbb{Z}$ such that $f(a) \neq 0$.*

Proof. Start by defining $f_0 : \langle a \rangle \to \mathbb{Q}/\mathbb{Z}$. If a has finite order t, then $f_0 : a \mapsto 1/t + \mathbb{Z}$. If a has infinite order, then $f_0 : a \mapsto \frac{1}{2} + \mathbb{Z}$. We will use Zorn's lemma. Let X be the set

$$\{(B, f) \mid B \leq A,\ a \in B,\ f : B \to \mathbb{Q}/\mathbb{Z},\ f \text{ extends } f_0\}.$$

Then X is non-empty, since $(\langle a \rangle, f_0) \in X$. Define a partial order $\leq$ on X by $(B_1, f_1) \leq (B_2, f_2)$ if $B_1 \leq B_2$ and f_2 extends f. Let $\{(B_s, f_s) \mid s \in S\}$ be a chain in X, where S is a suitable indexing set. Then $\{B_s \mid s \in S\}$ is a chain of subgroups of A. So the union $B = \bigcup_{s \in S} B_s$ is a subgroup of A, containing a. Define

$$f : \begin{array}{ccc} B & \longrightarrow & \mathbb{Q}/\mathbb{Z} \\ b & \longmapsto & f_s(b) \end{array}, \qquad b \in B_s.$$

This is well-defined since if $b \in B_t$ then $f_s(b) = f_t(b)$. Now (B, f) is an upper bound for $\{B_s \mid s \in S\}$ in X. So by Zorn's lemma, X has a maximal element, which we will call (B, f). We show that $B = A$. Since $f(a) = f_0(a)$, this will complete the proof. Suppose $x \in A \setminus B$. Then let $I < \mathbb{Z}$ be defined by

$$I = \{k \mid kx \in B\}.$$

Since $\mathbb{Z}$ is a PID, we have $I = n\mathbb{Z}$ for some n. We have $\langle B, x\rangle \le A$, and $\langle B, x\rangle \cong (B \oplus \langle x\rangle) / \langle nx - b_0\rangle$, where $b_0 = nx$ in A. Define

$$\begin{array}{cccc} \phi & : & B \oplus \langle x\rangle & \longrightarrow & \mathbb{Q}/\mathbb{Z} \\ & & (b, kx) & \longmapsto & f(b) + \dfrac{kf(b_0)}{n} \end{array},$$

so sending x to $f(b_0)/n$. We see that $\phi(nx - b_0) = 0$, so ϕ induces a map $(B \oplus \langle x\rangle) / \langle nx - b_0\rangle \to \mathbb{Q}/\mathbb{Z}$, and hence a map $f' : \langle B, x\rangle \to \mathbb{Q}/\mathbb{Z}$. But $f'(a) = f_0(a)$, so $(\langle B, x\rangle, f)$ is an element of X greater than (B, f), contradicting maximality of (B, f). Hence $B = A$ as required. □

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Proposition 5.5. *For every abelian group A, there is an injective abelian group I such that A is isomorphic to a subgroup of I.*

Proof. We know that $\mathbb{Q}/\mathbb{Z}$ is injective, as a $\mathbb{Z}$-module, since it is divisible, and $\mathbb{Z}$ is a PID. So $\prod_{s\in S} \mathbb{Q}/\mathbb{Z}$ is also injective. Take $S = A \setminus \{0\}$. Then define, for each $s \in S$, $f_s : A \to \mathbb{Q}/\mathbb{Z}$ such that $f_s(s) \neq 0$. Define

$$\begin{array}{cccc} f & : & A & \longrightarrow & \prod_{s\in S} \mathbb{Q}/\mathbb{Z} \\ & & a & \longmapsto & (f_s(a))_{s\in S} \end{array}.$$

Now if $s \in A \setminus \{0\}$, then $f_s(s) \neq 0$, so $f(s) \neq 0$. So f is injective. It is easy to check that f is a homomorphism. □

Proposition 5.6. *Let M be a right R-module, and let A be an abelian group. Then $\mathrm{Hom}_{\mathbb{Z}}(M, A)$ is a left R-module, with the R-action defined by $(rf)(m) = f(mr)$.*

Proof. This is clearer if we write the map f on the right instead of the left. Then the proposition becomes $(m)(rf) = (mr)f$, and it is easy to see this works. □

Proposition 5.7. *Let M be a left R-module, and A an abelian group. Then $\mathrm{Hom}_{\mathbb{Z}}(R, A)$ is a left R-module, and there is a natural isomorphism*

$$\mathrm{Hom}_R(M, \mathrm{Hom}_{\mathbb{Z}}(R, A)) \cong \mathrm{Hom}_{\mathbb{Z}}(M, A).$$

Proof. Write $H = \mathrm{Hom}_{\mathbb{Z}}(R, A)$. Define

$$\begin{array}{cccc} \Phi & : & \mathrm{Hom}_R(M, H) & \longrightarrow & \mathrm{Hom}_{\mathbb{Z}}(M, A) \\ & & f & \longmapsto & (m \mapsto f(m)(1)) \end{array}, \qquad m \in M, \qquad 1 \in R.$$

Check the following.

- $\Phi(f)$ is a homomorphism, since

$$\begin{aligned} \Phi(f)(m_1 + m_2) &= f(m_1 + m_2)(1) \\ &= (f(m_1) + f(m_2))(1) \\ &= f(m_1)(1) + f(m_2)(1) && \text{definition of } + \text{ in } \mathrm{Hom}_{\mathbb{Z}}(R, A) \\ &= \Phi(f)(m_1) + \Phi(f)(m_2). \end{aligned}$$

- Φ is a homomorphism, since

$$\begin{aligned} \Phi(f_1 + f_2)(m) &= (f_1 + f_2)(m)(1) \\ &= (f_1(m) + f_2(m))(1) && \text{definition of } + \text{ in } \mathrm{Hom}_{\mathbb{Z}}(M, A) \\ &= f_1(m)(1) + f_2(m)(1) \\ &= \Phi(f_1)(m) + \Phi(f_2)(m) \\ &= (\Phi(f_1) + \Phi(f_2))(m) && \text{definition of } + \text{ in } \mathrm{Hom}_{\mathbb{Z}}(M, A), \end{aligned}$$

  so since m was arbitrary, $\Phi(f_1 + f_2) = \Phi(f_1) + \Phi(f_2)$.

Now define

$$\begin{array}{rcccl} \Psi & : & \mathrm{Hom}_{\mathbb{Z}}(M, A) & \longrightarrow & \mathrm{Hom}_R(M, H) \\ & & p & \longmapsto & (m \mapsto (r \mapsto p(rm))) \end{array}, \qquad m \in M, \qquad r \in R.$$

Check the following.

- $\Psi(p)(m)$ is a homomorphism, since

$$\begin{aligned} \Psi(p)(m)(r_1 + r_2) &= p((r_1 + r_2)m) = p(r_1 m + r_2 m) \\ &= p(r_1 m) + p(r_2 m) = \Psi(p)(m)(r_1) + \Psi(p)(m)(r_1). \end{aligned}$$

- $\Psi(p)$ is an R-module homomorphism, since

$$\begin{aligned} \Psi(p)(m_1 + m_2)(r) &= p(r(m_1 + m_2)) = p(rm_1 + rm_2) = p(rm_1) + p(rm_2) \\ &= \Psi(p)(m_1)(r) + \Psi(p)(m_2)(r) = (\Psi(p)(m_1) + \Psi(p)(m_2))(r), \end{aligned}$$

  so $\Psi(p)(m_1 + m_2) = \Psi(p)(m_1) + \Psi(p)(m_2)$, and for $h \in H$, we have $(sh)(r) = h(rs)$, by definition of the R-module structure on H, so

$$s\Psi(p)(m)(r) = \Psi(p)(m)(rs) = p(rsm) = \Psi(p)(sm)(r),$$

  so $s\Psi(p)(m) = \Psi(p)(sm)$.

- Ψ is a homomorphism, since

$$\begin{aligned} \Psi(p_1 + p_2)(m)(r) &= (p_1 + p_2)(rm) = p_1(rm) + p_2(rm) \\ &= \Psi(p_1)(m)(r) + \Psi(p_2)(m)(r) = (\Psi(p_1) + \Psi(p_2))(m)(r), \end{aligned}$$

  so $\Psi(p_1 + p_2) = \Psi(p_1) + \Psi(p_2)$.

Then $\Psi \circ \Phi = \mathrm{id}_{\mathrm{Hom}_R(M,H)}$ and $\Phi \circ \Psi = \mathrm{id}_{\mathrm{Hom}_{\mathbb{Z}}(M,A)}$. [4] Hence Φ and Ψ are isomorphisms. $\square$

We are interested in the case $A = \mathbb{Q}/\mathbb{Z}$. Write $S = \mathrm{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z})$. Lecture 18 Tuesday 18/02/20

Proposition 5.8. *S is injective as a left R-module.*

Proof. Let M and N be R-modules, and $\alpha : M \to N$ an injective homomorphism. By identifying M with $\mathrm{Im}\,\alpha$, we may assume that $M \le N$, and α is the inclusion map. Since $\mathbb{Q}/\mathbb{Z}$ is injective as an abelian group, any $\mathbb{Z}$-module homomorphism $M \to S$ extends to a homomorphism $N \to S$. Define

$$\begin{array}{rcccl} \Theta & : & \mathrm{Hom}_{\mathbb{Z}}(N, \mathbb{Q}/\mathbb{Z}) & \longrightarrow & \mathrm{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z}) \\ & & f & \longmapsto & f|_M \end{array},$$

the restriction to M. We see that Θ is surjective. Similarly, we can define

$$\begin{array}{rcccl} \Theta' & : & \mathrm{Hom}_R(N, S) & \longrightarrow & \mathrm{Hom}_R(M, S) \\ & & f & \longmapsto & f|_M \end{array}.$$

Then Θ' is an abelian group homomorphism. But we know there is a naturally defined isomorphism between $\mathrm{Hom}_R(M, S)$ and $\mathrm{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z})$. So we get

$$\begin{tikzcd} \mathrm{Hom}_{\mathbb{Z}}(N, \mathbb{Q}/\mathbb{Z}) \arrow[r, "\Theta"] \arrow[d, "\Psi"', "\sim"] & \mathrm{Hom}_{\mathbb{Z}}(M, \mathbb{Q}/\mathbb{Z}) \arrow[d, "\sim"', "\Psi"] \\ \mathrm{Hom}_R(N, S) \arrow[r, "\Theta'"'] & \mathrm{Hom}_R(M, S) \end{tikzcd}.$$

It is easy to see that this diagram commutes. It follows that Θ' is surjective. So any R-module homomorphism $M \to S$ extends to a homomorphism $N \to S$. Hence S is injective. $\square$

[4] Exercise

Proposition 5.9. *Let M be a left R-module, and $m \in M \setminus \{0\}$. Then there exists $f : M \to S$ such that $f(m) \neq 0$.*

Proof. We know there is an abelian group homomorphism $g : M \to \mathbb{Q}/\mathbb{Z}$ such that $g(m) \neq 0$. Now $\Psi(g) \in \mathrm{Hom}_R(M, S)$, and $\Psi(g)(m)(1) = g(m) \neq 0$ for $1 \in R$, so $\Psi(g)(m)$ is not the zero map. ☐

Proposition 5.10. *Let M be a left R-module. There exists an injective R-module I such that M is isomorphic to a submodule of I. Equivalently, there exists an injection $M \to I$.*

Proof. Same as abelian groups. Let $T = M \setminus \{0\}$. Then $I = \prod_{t \in T} S$ is injective. Let f_t be a homomorphism $M \to S$ such that $f_t(t) \neq 0$. Then

$$\begin{array}{rcccl} f & : & M & \longrightarrow & I \\ & & m & \longmapsto & (f_t(m))_{t \in T} \end{array}$$

is injective, and a homomorphism. ☐

Proposition 5.11. *Every R-module admits an injective resolution.*

Thus there exist injective $I_0, I_1, I_2, \ldots$ such that

$$0 \to M \to I_0 \to I_1 \to I_2 \to \ldots$$

is exact.

Proof. Let M be an R-module. Then M injects into some injective module I_0. Let $C_0 = I_0 / \mathrm{Im}(M \to I_0)$. Then C_0 injects into some injective I_1. This induces a map $I_0 \to I_1$ whose kernel is $\mathrm{Im}(M \to I_0)$. Further terms in the sequence are constructed in an identical manner. ☐

5.3 Uniqueness of projective resolutions

Proposition 5.12. *Let M and N be R-modules, and $\phi : M \to N$. Let (P_i) be a projective resolution for M, and (Q_i) a projective resolution for N.*

1. *There exist R-module homomorphisms $f_i : P_i \to Q_i$ such that the diagram*

$$\begin{tikzcd} \ldots \arrow[r, "d_2"] & P_2 \arrow[r, "d_1"] \arrow[d, dashed, "f_2"] & P_1 \arrow[r, "d_0"] \arrow[d, dashed, "f_1"] & P_0 \arrow[r, "p"] \arrow[d, dashed, "f_0"] & M \arrow[r] \arrow[d, "\phi"] & 0 \\ \ldots \arrow[r, "d_2'"'] & Q_2 \arrow[r, "d_1'"'] & Q_1 \arrow[r, "d_0'"'] & Q_0 \arrow[r, "q"'] & N \arrow[r] & 0 \end{tikzcd}$$

   commutes.

2. *Let $g_i : P_i \to Q_i$ be such that the diagram*

$$\begin{tikzcd} \ldots \arrow[r, "d_2"] & P_2 \arrow[r, "d_1"] \arrow[d, bend right, "g_2"'] \arrow[d, bend left, "f_2"] & P_1 \arrow[r, "d_0"] \arrow[d, bend right, "g_1"'] \arrow[d, bend left, "f_1"] & P_0 \arrow[r, "p"] \arrow[d, bend right, "g_0"'] \arrow[d, bend left, "f_0"] & M \arrow[r] \arrow[d, "\phi"] & 0 \\ \ldots \arrow[r, "d_2'"'] & Q_2 \arrow[r, "d_1'"'] & Q_1 \arrow[r, "d_0'"'] & Q_0 \arrow[r, "q"'] & N \arrow[r] & 0 \end{tikzcd}$$

   commutes. Then there exist homomorphisms $s_i : P_i \to Q_{i+1}$ such that

$$g_i - f_i = \begin{cases} s_{i-1} \circ d_{i-1} + d_i' \circ s_i & i > 0 \\ d_0' \circ s_0 & i = 0 \end{cases},$$

   so

$$\begin{tikzcd} \ldots \arrow[r, "d_2"] & P_2 \arrow[r, "d_1"] \arrow[dl, dashed, "s_2"'] & P_1 \arrow[r, "d_0"] \arrow[dl, dashed, "s_1"'] & P_0 \arrow[r, "p"] \arrow[dl, dashed, "s_0"'] & M \arrow[r] \arrow[d, "\phi"] & 0 \\ \ldots \arrow[r, "d_2'"'] & Q_2 \arrow[r, "d_1'"'] & Q_1 \arrow[r, "d_0'"'] & Q_0 \arrow[r, "q"'] & N \arrow[r] & 0 \end{tikzcd}.$$

Proof.

1. The map $q : Q_0 \to N$ is surjective. There is a map $p : P_0 \to N$, given by composing $P_0 \to M$ with ϕ. Since P_0 is projective there exists $f_0 : P_0 \to Q_0$ such that $p = q \circ f_0$. Suppose the maps $f_0, \dots, f_{t-1}$ have been constructed, so

$$\begin{tikzcd} \dots \arrow[r, "d_t"] & P_t \arrow[r, "d_{t-1}"] \arrow[d, dashed, "f_t"] & P_{t-1} \arrow[r, "d_{t-2}"] \arrow[d, "f_{t-1}"] & P_{t-2} \arrow[r] \arrow[d, "f_{t-2}"] & \dots \\ \dots \arrow[r, "d'_t"'] & Q_t \arrow[r, "d'_{t-1}"'] & Q_{t-1} \arrow[r, "d'_{t-2}"'] & Q_{t-2} \arrow[r] & \dots \end{tikzcd}.$$

Observe that $d'_{t-2} \circ f_{t-1} \circ d_{t-1} = f_{t-2} \circ d_{t-2} \circ d_{t-1}$, since the existing squares of the diagram commute. But $d_{t-2} \circ d_{t-1} = 0$. So $d'_{t-2} \circ f_{t-1} \circ d_{t-1} = 0$, so $\operatorname{Im}(f_{t-1} \circ d_{t-1}) \le \operatorname{Ker} d'_{t-2} = \operatorname{Im} d'_{t-1}$. Now the map $d'_{t-1} : Q_t \to \operatorname{Im} d'_{t-1}$ is obviously surjective, and P_t is projective. So there is a map $f_t : P_t \to Q_t$ such that $f_{t-1} \circ d_{t-1} = d'_{t-1} \circ f_t$. Now inductively, maps f_i exist for all i.

2. We want s_i such that $g_i - f_i = d'_i \circ s_i + s_{i-1} \circ d_{i-1}$. Let $h_i = g_i - f_i$. We see that the diagram

$$\begin{tikzcd} \dots \arrow[r, "d_2"] & P_2 \arrow[r, "d_1"] \arrow[d, "h_2"] & P_1 \arrow[r, "d_0"] \arrow[d, "h_1"] & P_0 \arrow[r, "p"] \arrow[d, "h_0"] & M \arrow[r] \arrow[d, "0"] & 0 \\ \dots \arrow[r, "d'_2"'] & Q_2 \arrow[r, "d'_1"'] & Q_1 \arrow[r, "d'_0"'] & Q_0 \arrow[r, "q"'] & N \arrow[r] & 0 \end{tikzcd}$$

commutes, since we want $h_i \circ d_i = d'_i \circ h_{i+1}$, but we have

$$h_i \circ d_i = g_i \circ d_i - f_i \circ d_i = d'_i \circ g_{i+1} - d'_i \circ f_{i+1} = d'_i \circ h'_{i+1},$$

so we are fine.

Base case. Let $x \in P_0$. Then $(q \circ h_0)(x) = (0 \circ p)(x) = 0$ so $\operatorname{Im} h_0 \le \operatorname{Ker} q = \operatorname{Im} d'_0$. We have a surjective map $d'_0 : Q_1 \to \operatorname{Im} d'_0$, and a map $h_0 : P_0 \to \operatorname{Im} d'_0$. Since P_0 is projective, there exists $s_0 : P_0 \to Q_1$ such that $h_0 = d'_0 \circ s_0$.

Inductive step. Suppose we have maps $s_0, \dots, s_{t-1}$, with $s_i : P_i \to Q_{i+1}$, and $h_i = d'_i \circ s_i + s_{i-1} \circ d_{i-1}$ for $i = 1, \dots, t-1$, so

$$\begin{tikzcd} \dots \arrow[r, "d_{t+1}"] & P_{t+1} \arrow[r, "d_t"] \arrow[d, "h_{t+1}"'] & P_t \arrow[r, "d_{t-1}"] \arrow[d, "h_t"'] \arrow[dl, dashed, "s_t"'] & P_{t-1} \arrow[r, "d_{t-2}"] \arrow[d, "h_{t-1}"'] \arrow[dl, "s_{t-1}"'] & P_{t-2} \arrow[r, "d_{t-3}"] \arrow[d, "h_{t-2}"'] \arrow[dl, "s_{t-2}"'] & \dots \\ \dots \arrow[r, "d'_{t+1}"'] & Q_{t+1} \arrow[r, "d'_t"'] & Q_t \arrow[r, "d'_{t-1}"'] & Q_{t-1} \arrow[r, "d'_{t-2}"'] & Q_{t-2} \arrow[r, "d'_{t-3}"'] & \dots \end{tikzcd}.$$

Look at $h_t - s_{t-1} \circ d_{t-1}$. We want to show that the image of this map is contained in $\operatorname{Im} d'_t = \operatorname{Ker} d'_{t-1}$. So check

$$\begin{aligned} d'_{t-1} \circ (h_t - s_{t-1} \circ d_{t-1}) &= d'_{t-1} \circ h_t - d'_{t-1} \circ s_{t-1} \circ d_{t-1} \\ &= h_{t-1} \circ d_{t-1} - (h_{t-1} - s_{t-2} \circ d_{t-2}) \circ d_{t-1} \\ &= h_{t-1} \circ d_{t-1} - h_{t-1} \circ d_{t-1} + s_{t-2} \circ d_{t-2} \circ d_{t-1}. \end{aligned}$$

Now $d_{t-2} \circ d_{t-1} = 0$, so we have $d'_{t-1} \circ (h_t - s_{t-1} \circ d_{t-1}) = 0$. So $h_t - s_{t-1} \circ d_{t-1} \in \operatorname{Ker} d'_{t-1}$. Now we have the situation

$$\begin{tikzcd} & P_t \arrow[d, "h_t - s_{t-1} \circ d_{t-1}"] \arrow[dl, dashed, "s_t"'] \\ Q_{t+1} \arrow[r, "d'_t"'] & \operatorname{Im} d'_t \end{tikzcd},$$

and since P_t is projective, there exists s_t such that $d'_t \circ s_t = h_t - s_{t-1} \circ d_{t-1}$, so $h_t = d'_t \circ s_t + s_{t-1} \circ d_{t-1}$ as required.

□

5.4 Uniqueness of injective resolutions

The following is the equivalent result for injectives.

Proposition 5.13. *Let M and N be R-modules, and $\phi : M \to N$ a homomorphism. Let (I_t) be an injective resolution for M, and (J_t) another injective resolution for N. Then*

- *there exist maps $f_i : I_i \to J_i$ such that the diagram*

$$\begin{tikzcd}
0 \arrow[r] & M \arrow[r, "i"] \arrow[d, "\phi"] & I_0 \arrow[r, "d_0"] \arrow[d, dashed, "f_0"] & I_1 \arrow[r, "d_1"] \arrow[d, dashed, "f_1"] & I_2 \arrow[r, "d_2"] \arrow[d, dashed, "f_2"] & \dots \\
0 \arrow[r] & N \arrow[r, "j"'] & J_0 \arrow[r, "d_0'"'] & J_1 \arrow[r, "d_1'"'] & J_2 \arrow[r, "d_2'"'] & \dots
\end{tikzcd}$$

  commutes, and

- *if (g_i) is another set of maps $g_i : I_i \to J_i$ such that the diagram*

$$\begin{tikzcd}
0 \arrow[r] & M \arrow[r, "i"] \arrow[d, "\psi"] & I_0 \arrow[r, "d_0"] \arrow[d, bend right, "f_0"'] \arrow[d, bend left, "g_0"] & I_1 \arrow[r, "d_1"] \arrow[d, bend right, "f_1"'] \arrow[d, bend left, "g_1"] & I_2 \arrow[r, "d_2"] \arrow[d, bend right, "f_2"'] \arrow[d, bend left, "g_2"] & \dots \\
0 \arrow[r] & N \arrow[r, "j"'] & J_0 \arrow[r, "d_0'"'] & J_1 \arrow[r, "d_1'"'] & J_2 \arrow[r, "d_2'"'] & \dots
\end{tikzcd}$$

  commutes, then there exist maps $s_i : I_{i+1} \to J_i$ such that

$$g_i - f_i = \begin{cases} s_i \circ d_i + d_{i-1}' \circ s_{i-1} & i > 0 \\ s_0 \circ d_0 & i = 0 \end{cases},$$

  so

$$\begin{tikzcd}
0 \arrow[r] & M \arrow[r, "i"] \arrow[d, "\psi"] & I_0 \arrow[r, "d_0"] & I_1 \arrow[r, "d_1"] \arrow[dl, dashed, "s_0"'] & I_2 \arrow[r, "d_2"] \arrow[dl, dashed, "s_1"'] & \dots \arrow[dl, dashed, "s_2"'] \\
0 \arrow[r] & N \arrow[r, "j"'] & J_0 \arrow[r, "d_0'"'] & J_1 \arrow[r, "d_1'"'] & J_2 \arrow[r, "d_2'"'] & \dots
\end{tikzcd}.$$

Proof. Very similar to Proposition 5.12. □

Lecture 19 is a problems class. Lecture 19 Friday 21/02/20

6 Complexes and homology

6.1 Chain complexes

Lecture 20
Monday
24/02/20

Definition 6.1. A **chain complex** is a series $A_* = (A_i)$, with maps $d_i^A = d_i = d : A_{i+1} \to A_i$ such that $d^2 = 0$, that is $d_{i+1} \circ d_i = 0$, or $\operatorname{Im} d_{i+1} \le \operatorname{Ker} d_i$.

Definition 6.2. A **cochain complex** is a series $A^* = \left(A^i\right)$ with maps $d_i^A = d_i = d : A^i \to A^{i+1}$ such that $d^2 = 0$, or $\operatorname{Im} d_i \le \operatorname{Ker} d_{i+1}$.

Let A_* and B_* be chain complexes. Let $f = (f_i)$ be a family of R-module homomorphisms $f_i : A_i \to B_i$. Say that f is a **map of chain complexes** if $f \circ d = d \circ f$, that is $f_i \circ d_i^A = d_i^B \circ f_{i+1}$. So

$$\begin{tikzcd}
\dots \arrow[r, "d_{n+1}"] & A_{n+1} \arrow[r, "d_n"] \arrow[d, "f_{n+1}"] & A_n \arrow[r, "d_{n-1}"] \arrow[d, "f_n"] & A_{n-1} \arrow[r, "d_{n-2}"] \arrow[d, "f_{n-1}"] & \dots \\
\dots \arrow[r, "d_{n+1}"'] & B_{n+1} \arrow[r, "d_n"'] & B_n \arrow[r, "d_{n-1}"'] & A_{n-1} \arrow[r, "d_{n-2}"'] & \dots
\end{tikzcd}$$

commutes. Say that f **has property** $\mathcal{P}$ if all f_i have property $\mathcal{P}$, where $\mathcal{P}$ is injective, surjective, etc. A sequence

$$A_* \xrightarrow{f} B_* \xrightarrow{g} C_*$$

is **exact** at B_* if

$$A_n \xrightarrow{f_n} B_n \xrightarrow{g_n} C_n$$

is exact at B_n for all n. A sequence of chain complexes is **exact** if it is exact everywhere. An **exact sequence**

$$0 \to A_* \to B_* \to C_* \to 0$$

is a short exact sequence of chain complexes.

6.2 Homology groups

Definition 6.3. Let A_* be a chain complex. The n**-th homology group** of A_* is $\operatorname{Ker} d_{n-1} / \operatorname{Im} d_n$. We write $\mathrm{H}_n(A_*)$. Also write $\mathrm{H}_*(A_*) = (\mathrm{H}_n(A_*))$.

Definition 6.4. Let A^* be a cochain complex. The n**-th cohomology group** of A^* is $\operatorname{Ker} d_n / \operatorname{Im} d_{n-1}$. We write $\mathrm{H}^n(A^*)$, and $\mathrm{H}^*(A^*) = (\mathrm{H}^n(A^*))$.

Example. Let $A_i = \mathbb{Z}^3$ for all i, and let $d(a,b,c) = (0,0,a)$. Certainly $d^2 = 0$, so this is a chain complex. Then

$$\operatorname{Ker} d = \{(0,b,c)\} = 0 \oplus \mathbb{Z}^2, \qquad \operatorname{Im} d = \{(0,0,a)\} = 0^2 \oplus \mathbb{Z}.$$

Now

$$\operatorname{Ker} d_{n-1} / \operatorname{Im} d_n = \left\{(0,b,0) + 0^2 \oplus \mathbb{Z}\right\}.$$

Proposition 6.5. *A map of chain complexes $f : A_* \to B_*$ induces a map on the homology,*

$$f_* : \mathrm{H}_*(A_*) \to \mathrm{H}_*(B_*),$$

given by

$$\begin{array}{cccc} f_{*i} & : & \mathrm{H}_i(A_*) & \longrightarrow & \mathrm{H}_i(B_*) \\ & & x + \operatorname{Im} d_i^A & \longmapsto & f_i(x) + \operatorname{Im} d_i^B \end{array}.$$

Proof. Let $x \in \operatorname{Ker} d_{i-1}^A$. Then $\left(f_{i-1} \circ d_{i-1}^A\right)(x) = 0$, so $\left(d_{i-1}^B \circ f_i\right)(x) = 0$. Hence $f_i(x) \in \operatorname{Ker} d_{i-1}^B$. So f_i certainly induces a map $\overline{f_i} : \operatorname{Ker} d_{i-1}^A \to \operatorname{Ker} d_{i-1}^B / \operatorname{Im} d_i^B$. So there exists $y \in A_{i+1}$ with $d_i^A(y) = x$. Now $f_i(x) = \left(f_i \circ d_i^A\right)(y) = \left(d_i^B \circ f_{i+1}\right)(y) \in \operatorname{Im} d_i^B$, so $\overline{f_i}(x) = 0$. Hence $\operatorname{Im} d_i^A \le \operatorname{Ker} \overline{f_i}$ so $\overline{f_i}$ induces a map

$$\operatorname{Ker} d_{i-1}^A / \operatorname{Im} d_i^A = \mathrm{H}_i(A_*) \to \operatorname{Ker} d_{i-1}^B / \operatorname{Im} d_i^B = \mathrm{H}_i(B_*).$$

$\square$

Let A_* and B_* be chain complexes, and let f and g be maps between them. We say that f and g are **equal up to homotopy** if there exist maps $s_i : A_i \to B_{i+1}$ such that

$$g_i - f_i = s_{i-1} \circ d^A_{i-1} + d^B_i \circ s_i.$$

Proposition 6.6. *If $f, g : A_* \to B_*$ are equal up to homotopy, then $f_* = g_*$, so f and g induce the same map on homology.*

Proof. Exercise. [5] □

6.3 The long exact sequence in homology

Proposition 6.7. *Let*

$$0 \to A_* \xrightarrow{f} B_* \xrightarrow{g} C_* \to 0$$

be a short exact sequence. This induces a long exact sequence

$$\dots \to \mathrm{H}_{n+1}(A_*) \to \mathrm{H}_{n+1}(B_*) \to \mathrm{H}_{n+1}(C_*) \to \mathrm{H}_n(A_*) \to \mathrm{H}_n(B_*) \to \mathrm{H}_n(C_*) \to \dots.$$

Proof. We have a commuting diagram with exact rows

$$\begin{array}{ccccccccc} 0 & \longrightarrow & A_{n+1} & \xrightarrow{f_{n+1}} & B_{n+1} & \xrightarrow{g_{n+1}} & C_{n+1} & \longrightarrow & 0 \\ & & \downarrow d^A_n & & \downarrow d^B_n & & \downarrow d^C_n & & \\ 0 & \longrightarrow & A_n & \xrightarrow[f_n]{} & B_n & \xrightarrow[g_n]{} & C_n & \longrightarrow & 0 \end{array}.$$

Notice $\mathrm{Im}\, d_n \le \mathrm{Ker}\, d_{n-1}$, so we can change this to

$$\begin{array}{ccccccccc} 0 & \longrightarrow & A_{n+1} & \xrightarrow{f_{n+1}} & B_{n+1} & \xrightarrow{g_{n+1}} & C_{n+1} & \longrightarrow & 0 \\ & & \downarrow d^A_n & & \downarrow d^B_n & & \downarrow d^C_n & & \\ 0 & \longrightarrow & \mathrm{Ker}\, d^A_{n-1} & \xrightarrow[f_n]{} & \mathrm{Ker}\, d^B_{n-1} & \xrightarrow[g_n]{} & \mathrm{Ker}\, d^C_{n-1} & & \end{array}.$$

Now $\mathrm{Im}\, d_{n+1} \le \mathrm{Ker}\, d_n$, so the maps $A_{n+1} \to \mathrm{Ker}\, d_{n+1}$ induce maps $A_{n+1}/\mathrm{Im}\, d_{n+1} \to \mathrm{Ker}\, d_{n-1}$. So we get a diagram

$$\begin{array}{ccccccccc} & & A_{n+1}/\mathrm{Im}\, d^A_{n+1} & \xrightarrow{f_{n+1}} & B_{n+1}/\mathrm{Im}\, d^B_{n+1} & \xrightarrow{g_{n+1}} & C_{n+1}/\mathrm{Im}\, d^C_{n+1} & \longrightarrow & 0 \\ & & \downarrow \overline{d^A_n} & & \downarrow \overline{d^B_n} & & \downarrow \overline{d^C_n} & & \\ 0 & \longrightarrow & \mathrm{Ker}\, d^A_{n-1} & \xrightarrow[f_n]{} & \mathrm{Ker}\, d^B_{n-1} & \xrightarrow[g_n]{} & \mathrm{Ker}\, d^C_{n-1} & & \end{array}.$$

We are now in the position to apply the snake lemma, so

$$\mathrm{Ker}\, \overline{d^A_n} \to \mathrm{Ker}\, \overline{d^B_n} \to \mathrm{Ker}\, \overline{d^C_n} \to \mathrm{Coker}\, \overline{d^A_n} \to \mathrm{Coker}\, \overline{d^B_n} \to \mathrm{Coker}\, \overline{d^C_n}$$

is an exact sequence. Then

$$\mathrm{Ker}\, \overline{d^A_n} = \mathrm{Ker}\, d^A_n / \mathrm{Im}\, d^A_{n+1} = \mathrm{H}_{n+1}(A_*), \qquad \mathrm{Coker}\, \overline{d^A_n} = \mathrm{Ker}\, d^A_{n-1} / \mathrm{Im}\, d^A_n = \mathrm{H}_n(A_*).$$

Similarly for B_* and C_*. So we have an exact sequence

$$\mathrm{H}_{n+1}(A_*) \to \mathrm{H}_{n+1}(B_*) \to \mathrm{H}_{n+1}(C_*) \to \mathrm{H}_n(A_*) \to \mathrm{H}_n(B_*) \to \mathrm{H}_n(C_*).$$

Since consecutive values of i give a sequence overlapping in three terms we can glue them together, to give the long exact sequence in the proposition. □

[5] Exercise

7 Derived functors

7.1 Covariant and contravariant functors

Lecture 21 Tuesday 25/02/20

The following are two variations.

Definition 7.1. A **covariant functor** F from the category of left or right R-modules to the category of abelian groups is a map from R-modules to abelian groups such that if $\phi : M \to N$ is an R-module homomorphism then there exists an abelian group homomorphism

$$F(\phi) : F(M) \to F(N),$$

which respects identity maps, so $F(\mathrm{id}_M) = \mathrm{id}_{F(M)}$, and respects composition, so

$$F(\phi_1 \circ \phi_2) = F(\phi_1) \circ F(\phi_2).$$

The map F on homomorphisms is **additive** if $F(\phi_1 + \phi_2) = F(\phi_1) + F(\phi_2)$. If

$$0 \to A \to B \to C \to 0$$

be a short exact sequence, then F is **right exact** if

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

is exact, **left exact** if

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

is exact. Then F is **exact** if both left and right exact.

Definition 7.2. A **contravariant functor** F from the category of left or right R-modules to the category of abelian groups is a map from R-modules to abelian groups such that if $\phi : M \to N$ is an R-module homomorphism then there exists an abelian group homomorphism

$$F(\phi) : F(N) \to F(M),$$

which respects identity maps, so $F(\mathrm{id}_M) = \mathrm{id}_{F(M)}$, and respects composition, so

$$F(\phi_1 \circ \phi_2) = F(\phi_2) \circ F(\phi_1).$$

Similarly, if

$$0 \to A \to B \to C \to 0$$

be a short exact sequence, then F is **right exact** if

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

is exact, and **left exact** if

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

is exact.

Example. Some functors we have seen. Fix a left R-module M.

- $F(A) = \mathrm{Hom}_R(M, A)$, where

$$F(\phi) \quad : \quad \begin{array}{rcl} F(A) = \mathrm{Hom}_R(M, A) & \longrightarrow & F(B) = \mathrm{Hom}_R(M, B) \\ f & \longmapsto & \phi \circ f \end{array}, \qquad \phi : A \to B,$$

  is covariant, left exact, and exact if and only if M is projective.

- $F(A) = \mathrm{Hom}_R(A, M)$, where

$$F(\phi) \quad : \quad \begin{array}{rcl} F(B) = \mathrm{Hom}_R(B, M) & \longrightarrow & F(A) = \mathrm{Hom}_R(A, M) \\ f & \longmapsto & f \circ \phi \end{array}, \qquad \phi : A \to B,$$

  is contravariant, left exact, and exact if and only if M is injective.

- For a right R-module A, $F(A) = A \otimes_R M$ is covariant, right exact, and exact if and only if M is flat.

7.2 Left derived functors

Let F be the functor $F(A) = A \otimes_R M$, where M is a fixed R-module. Let $P_* \to A$ be a projective resolution for A. So $P_* = (P_i)_{i \geq 0}$ for projective P_i, and

$$\dots \xrightarrow{d_2} P_2 \xrightarrow{d_1} P_1 \xrightarrow{d_0} P_0 \xrightarrow{\phi} A \to 0$$

is exact. Consider the sequence

$$\dots \to P_2 \to P_1 \to P_0 \to 0.$$

This is no longer exact, but it is a chain complex. And if we apply F, we get a chain complex $F(P_*)$,

$$\dots \to F(P_2) \to F(P_1) \to F(P_0) \to 0.$$

Define **left derived functors**

$$\mathrm{L}_n F(A) = \mathrm{H}_n(F(P_*)).$$

Theorem 7.3.

1. *$\mathrm{L}_n F(A)$ does not depend on the choice of resolution P_*.*
2. *$\mathrm{L}_n F$ is an additive functor from right R-modules to abelian groups.*
3. *$\mathrm{L}_0 F(A) = F(A)$.*

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Proof.

1. Let $P_* \to A$ and $Q_* \to A$ be projective resolutions. Then there exist maps of chain complexes $f : P_* \to Q_*$ and $g : Q_* \to P_*$. So $g \circ f : P_* \to P_*$, so

$$\begin{tikzcd} \dots \arrow[r, "d_2"] & P_2 \arrow[r, "d_1"] \arrow[d, "g_2 \circ f_2"] & P_1 \arrow[r, "d_0"] \arrow[d, "g_1 \circ f_1"] & P_0 \arrow[r] \arrow[d, "g_0 \circ f_0"] & A \arrow[r] \arrow[d, "\mathrm{id}"] & 0 \\ \dots \arrow[r, "d_2"'] & P_2 \arrow[r, "d_1"'] & P_1 \arrow[r, "d_0"'] & P_0 \arrow[r] & A \arrow[r] & 0 \end{tikzcd},$$

and $g \circ f$ is equal to id up to homotopy. Apply F to everything. Since F is right exact,

$$\begin{tikzcd} \dots \arrow[r, "F(d_2)"] & F(P_2) \arrow[r, "F(d_1)"] \arrow[d, "F(g_2) \circ F(f_2)"] & F(P_1) \arrow[r, "F(d_0)"] \arrow[d, "F(g_1) \circ F(f_1)"] & F(P_0) \arrow[r] \arrow[d, "F(g_0) \circ F(f_0)"] & F(A) \arrow[r] \arrow[d, "\mathrm{id}"] & 0 \\ \dots \arrow[r, "F(d_2)"'] & F(P_2) \arrow[r, "F(d_1)"'] & F(P_1) \arrow[r, "F(d_0)"'] & F(P_0) \arrow[r] & F(A) \arrow[r] & 0 \end{tikzcd}.$$

The diagram remains commutative, since F preserves composition. Now

$$g_i \circ f_i - \mathrm{id} = s_{i-1} \circ d_{i-1} + d_i \circ s_i,$$

for suitable maps s_i. Then

$$F(g_i) \circ F(f_i) - \mathrm{id} = F(s_{i-1}) \circ F(d_{i-1}) + F(d_i) \circ F(s_i).$$

So $F(g_i) \circ F(f_i)$ is id up to homotopy. Hence $F(g) \circ F(f)$ induces the identity on homology $\mathrm{H}_*(F(P_*))$. Also $F(f) \circ F(g)$ induces the identity on $\mathrm{H}_*(F(Q_*))$. Now we have

$$\overline{F(f_i)} : \mathrm{H}_i(F(P_*)) \to \mathrm{H}_i(F(Q_*)), \qquad \overline{F(g_i)} : \mathrm{H}_i(F(Q_*)) \to \mathrm{H}_i(F(P_*)),$$

and $\overline{F(f_i)} \circ \overline{F(g_i)} = \mathrm{id}$ and $\overline{F(g_i)} \circ \overline{F(f_i)} = \mathrm{id}$, so $\overline{F(f_i)}$ and $\overline{F(g_i)}$ are isomorphisms. So

$$\mathrm{H}_n(F(P_*)) \cong \mathrm{H}_n(F(Q_*)),$$

as required. This argument tells us nothing about $\mathrm{H}_0(F(P_*))$.

2. Let $\phi : A \to B$. Let $P_* \to A$ and $Q_* \to B$ be projective resolutions. Then there exists $f : P_* \to Q_*$ such that

$$\begin{tikzcd} P_* \arrow[r] \arrow[d, "f"'] & A \arrow[r] \arrow[d, "\phi"] & 0 \\ Q_* \arrow[r] & B \arrow[r] & 0 \end{tikzcd}$$

commutes. Then F is covariant and right exact. So

$$\begin{tikzcd} F(P_*) \arrow[r] \arrow[d, "F(f)"'] & F(A) \arrow[r] \arrow[d, "F(\phi)"] & 0 \\ F(Q_*) \arrow[r] & F(B) \arrow[r] & 0 \end{tikzcd}$$

is commutative, where $F(f) = (F(f_i))$. If $g : P_* \to Q_*$ is such that

$$\begin{tikzcd} P_* \arrow[r] \arrow[d, "g"'] & A \arrow[r] \arrow[d, "\phi"] & 0 \\ Q_* \arrow[r] & B \arrow[r] & 0 \end{tikzcd}$$

commutes, then $\overline{f}$ and $\overline{g}$, the induced maps on homology, are equal. So there exists a map $\overline{F(f_i)} : \mathrm{L}_i F(A) \to \mathrm{L}_i F(B)$, and is independent of the choice of f. So we can write $\mathrm{L}_n F(\phi) = \overline{F(f_i)}$. Then $\mathrm{L}_n F$ preserves identity and compositions and is additive, since F is an additive functor. [6]

3. We have a short exact sequence
$$0 \to \operatorname{Im} d_0 \xrightarrow{\subseteq} P_0 \xrightarrow{\phi} A \to 0.$$
Since F is right exact, we get an exact sequence
$$F(\operatorname{Im} d_0) \to F(P_0) \to F(A) \to 0.$$
Now $d_0 : P_1 \to \operatorname{Im} d_0$ is surjective, and F preserves surjectivity. So $F(d_0) : F(P_1) \to F(\operatorname{Im} d_0)$ is surjective. So
$$F(P_1) \to F(P_0) \to F(A) \to 0$$
is exact. So, setting $P_{-1} = 0$, we get $\mathrm{L}_0 F(P_*) = F(P_0) / \operatorname{Im} F(d_0) = F(A)$.

□

[6] Exercise

7.3 The long exact sequence of left derived functors

Proposition 7.4 (Horseshoe lemma)**.** *Suppose*

$$0 \to A \to B \to C \to 0$$

is an exact sequence of R-modules. Suppose $P_* \to A$ and $R_* \to C$ are projective resolutions. Define $Q_i = P_i \oplus R_i$. Then there exist maps $Q_{i+1} \to Q_i$ and $Q_0 \to B$ such that $Q_* \to B$ is a projective resolution, and such that

$$\begin{tikzcd}
 & 0 \arrow[d] & 0 \arrow[d] & 0 \arrow[d] & 0 \arrow[d] & \\
\dots \arrow[r] & P_2 \arrow[r] \arrow[d, "\iota"] & P_1 \arrow[r] \arrow[d, "\iota"] & P_0 \arrow[r] \arrow[d, "\iota"] & A \arrow[r] \arrow[d] & 0 \\
\dots \arrow[r, dashed] & Q_2 \arrow[r, dashed] \arrow[d, "\pi"] & Q_1 \arrow[r, dashed] \arrow[d, "\pi"] & Q_0 \arrow[r, dashed] \arrow[d, "\pi"] & B \arrow[r, dashed] \arrow[d] & 0 \\
\dots \arrow[r] & R_2 \arrow[r] \arrow[d] & R_1 \arrow[r] \arrow[d] & R_0 \arrow[r] \arrow[d] & C \arrow[r] \arrow[d] & 0 \\
 & 0 & 0 & 0 & 0 &
\end{tikzcd}$$

commutes, where if $x \in P_i$ and $y \in R_i$ then $\iota(x) = (x, 0)$ and $\pi(x, y) = y$.

Note. Q_i is a direct sum of projectives, so is itself projective.

Proof. We have the setup

$$\begin{tikzcd}
0 \arrow[d] & 0 \arrow[d] & \\
P_0 \arrow[r, "\phi"] \arrow[d, "\iota"'] & A \arrow[r] \arrow[d, "f"] & 0 \\
Q_0 \arrow[d, "\pi"'] & B \arrow[d, "g"] & \\
R_0 \arrow[r, "\psi"'] \arrow[d] & C \arrow[r] \arrow[d] & 0 \\
0 & 0 &
\end{tikzcd}.$$

Since $B \to C$ is surjective, and R_0 is projective, there exists $h : R_0 \to B$ such that $g \circ h = \psi$. Now define

$$\chi \quad : \quad \begin{array}{ccc} Q_0 & \longrightarrow & B \\ (x, y) & \longmapsto & (f \circ \phi)(x) + h(y) \end{array}, \qquad x \in P_0, \qquad y \in R_0.$$

This construction guarantees that the squares are commutative. It is easy to see that χ is surjective, so

$$\begin{tikzcd}
0 \arrow[d] & 0 \arrow[d] & \\
P_0 \arrow[r, "\phi"] \arrow[d, "\iota"'] & A \arrow[r] \arrow[d, "f"] & 0 \\
Q_0 \arrow[r, dashed, "\chi"] \arrow[d, "\pi"'] & B \arrow[r, dashed] \arrow[d, "g"] & 0 \\
R_0 \arrow[r, "\psi"'] \arrow[ur, dashed, "h"] \arrow[d] & C \arrow[r] \arrow[d] & 0 \\
0 & 0 &
\end{tikzcd}.$$

Now we have a short exact sequence

$$0 \to \operatorname{Ker} \phi \xrightarrow{\iota} \operatorname{Ker} \chi \xrightarrow{\pi} \operatorname{Ker} \psi \to 0,$$

by the snake lemma. So now we can iterate, replacing A, B, C with these kernels, to construct a map $Q_1 \to Q_0$, and so on. $\square$

Proposition 7.5. *Let F be an additive functor, and let A and B be R-modules. There is a canonical isomorphism $F(A) \oplus F(B) \to F(A \oplus B)$.*

Proof. Let $M = A \oplus B$. Consider functions

$$p_1 : \begin{array}{ccc} M & \longrightarrow & M \\ (a,b) & \longmapsto & (a,0) \end{array}, \qquad p_2 : \begin{array}{ccc} M & \longrightarrow & M \\ (a,b) & \longmapsto & (0,b) \end{array}.$$

Then $p_i^2 = p_i$, $p_1 \circ p_2 = p_2 \circ p_1 = 0$, and $p_1 + p_2 = \mathrm{id}_M$. If q_1 and q_2 are maps on a module M satisfying these relations, then $M = q_1(M) \oplus q_2(M)$. ☐

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Proposition 7.6. *Let*

$$0 \to A \to B \to C \to 0$$

be a short exact sequence of right R-modules. This gives rise to a long exact sequence

$$\cdots \to \mathrm{L}_n F(A) \to \mathrm{L}_n F(B) \to \mathrm{L}_n F(C) \to \cdots \to \mathrm{L}_0 F(A) \to \mathrm{L}_0 F(B) \to \mathrm{L}_0 F(C) \to 0.$$

Proof. Let $P_* \to A$ be a projective resolution and $R_* \to C$ be a projective resolution. By the horseshoe lemma, there exists a projective resolution $Q_* \to B$ such that

$$0 \to P_* \to Q_* \to R_* \to 0$$

is a split short exact sequence of chain complexes, that is $Q_i = P_i \oplus R_i$. Since $Q_i = P_i \oplus R_i$, and since F is an additive functor, we have $F(Q_i) = F(P_i) \oplus F(R_i)$. So

$$0 \to F(P_*) \to F(Q_*) \to F(R_*) \to 0$$

is a short exact sequence. Therefore we get a long exact sequence on homology,

$$\cdots \to \mathrm{H}_n(F(P_*)) \to \mathrm{H}_n(F(Q_*)) \to \mathrm{H}_n(F(R_*)) \to \dots.$$

Since $\mathrm{H}_n(F(P_*)) = \mathrm{L}_n F(A)$ this gives the long sequence that we need. Since $\mathrm{L}_0 F(A) = F(A)$, and F is right exact, the sequence terminates

$$\mathrm{L}_0 F(A) \to \mathrm{L}_0 F(B) \to \mathrm{L}_0 F(C) \to 0,$$

as required. ☐

7.4 General derived functors

Proposition 7.7.

- *Let F be any covariant, right exact, additive functor from left or right R-modules to abelian groups. Then the left derived functors $\mathrm{L}_n F$ can be defined in just the same way as we did for the case $F(A) = A \otimes_R M$. All of the results we have proved follow in the more general case, by the same arguments.*
- *If F is a covariant, left exact, additive functor from R-modules to abelian groups, then we can define* ***right derived functors*** $\mathrm{R}^i F$ *in a similar manner. Instead of working with a projective resolution, we use an injective resolution,*

  $$0 \to A \to I_0 \to I_1 \to I_2 \to \dots.$$

  By similar arguments, we show that $\mathrm{R}^i F(A)$ is independent of the choice of injective resolution. All of the results we proved for left derived functors have natural analogies for right derived functors. The argument requires a version of the horseshoe lemma for injective resolutions, which is exactly what one might expect.
- *We can even construct derived functors for contravariant functors. If F is contravariant and right exact, so*

  $$0 \to A \to I_0 \to I_1 \to I_2 \to \dots$$

  is exact implies that

  $$\cdots \to F(I_2) \to F(I_1) \to F(I_0) \to F(A) \to 0$$

  is exact, we get a left derived functor, which is defined using an injective resolution. If F is contravariant and left exact, we get a right derived functor, which is defined using a projective resolution.

8 Tor and Ext

8.1 Balancing theorems

Definition 8.1. Let F be the functor $F(A) = A \otimes_R B$. Then F is covariant, right exact, and additive. So $\mathrm{L}_n F$ exists. Define
$$\mathrm{Tor}_i^R(A, B) = \mathrm{L}_i F(A).$$

Fact. Let F' be the functor $F'(B) = A \otimes_R B$. Then F' is covariant, right exact, and additive. So $\mathrm{L}_n F'$ exists. We have
$$\mathrm{L}_i F'(B) \cong \mathrm{L}_i F(A) = \mathrm{Tor}_i^R(A, B).$$

Definition 8.2. Let F be the functor $F(B) = \mathrm{Hom}_R(A, B)$. Then F is covariant, left exact, and additive, so $\mathrm{R}^n F$ exists. Define
$$\mathrm{Ext}_R^i(A, B) = \mathrm{R}^i F(B).$$

Fact. Let F' be the functor $F'(A) = \mathrm{Hom}_R(A, B)$. Then F' is contravariant, left exact, and additive, so $\mathrm{R}^n F'$ exists. We have
$$\mathrm{R}^i F'(A) \cong \mathrm{R}^i F(B) = \mathrm{Ext}_R^i(A, B).$$

The two facts above are the **balancing theorems** for Tor and Ext. Their proof is beyond the scope of the course.

8.2 Tor, flatness, and torsion

The following is an observation. Suppose A is projective. Then a projective resolution for A is
$$0 \to \cdots \to 0 \to A \xrightarrow{\mathrm{id}} A \to 0.$$

So $\mathrm{L}_i F(A) = 0$ for $i \geq 1$, and $\mathrm{L}_0 F(A) = F(A)$, for F possessing left derived functors. Similarly, if A is injective, then an injective resolution is
$$0 \to A \xrightarrow{\mathrm{id}} A \to 0 \to \cdots \to 0,$$

so $\mathrm{R}^i F(A) = 0$ for $i \geq 1$, and $\mathrm{R}^0 F(A) = F(A)$, for F possessing right derived functors. In fact the property $\mathrm{Tor}_i^R(A, B) = 0$ for all $i \geq 0$ characterises flat modules, so either A or B is flat.

Proposition 8.3. *Let $F(A) = A \otimes_R B$. Then $\mathrm{L}_i F(A) = \mathrm{Tor}_i^R(A, B) = 0$ for all $i \geq 1$ and for all A if and only if B is flat.*

Similarly if $F'(B) = A \otimes_R B$, then $\mathrm{L}_i F'(B) = 0$ for all $i \geq 1$ and for all B if and only if A is flat. Lecture 24 Tuesday 03/03/20

Proof.

$\Longleftarrow$ If B is flat then $F(A) = A \otimes_R B$ is exact, so
$$0 \to L \to M \to N \to 0$$
is exact implies that
$$0 \to F(L) \to F(M) \to F(N) \to 0$$
is exact, or F maps kernels to kernels and cokernels to cokernels. Let $P_* \to A$ be a projective resolution. Then
$$\cdots \to P_2 \to P_1 \to P_0 \to 0$$
is exact everywhere except P_0. So
$$\cdots \to F(P_2) \to F(P_1) \to F(P_0) \to 0$$
is exact everywhere except $F(P_0)$. So $\mathrm{L}_n F(P_*) = 0$ for $n \geq 1$. But $\mathrm{L}_n F(P_*) = \mathrm{Tor}_n^R(A, B)$.

$\Longrightarrow$ Conversely, suppose $\mathrm{Tor}_i^R(A,B) = 0$ for all A. Let

$$0 \to L \to M \to N \to 0$$

be exact. This gives a long exact sequence of homology groups

$$\ldots \longrightarrow \mathrm{L}_1 F(L) \longrightarrow \mathrm{L}_1 F(M) \longrightarrow \underbrace{\mathrm{L}_1 F(N)}_{\cong\, \mathrm{Tor}_1^R(N,B)} \longrightarrow L \otimes_R B \longrightarrow M \otimes_R B \longrightarrow N \otimes_R B \longrightarrow 0.$$

Since $\mathrm{Tor}_1^R(N,B) = 0$, we get a short exact sequence

$$0 \to L \otimes_R B \to M \otimes_R B \to N \otimes_R B \to 0.$$

So $F(A) = A \otimes_R B$ is left exact, and so B is flat.

□

Proposition 8.4. *Let A and B be abelian groups. Then*

$$\mathrm{Tor}_n^{\mathbb{Z}}(A,B) = 0, \qquad n > 1.$$

Proof. A is a quotient of some free module K, say

$$K \xrightarrow{f} A \to 0.$$

Now $\mathrm{Ker}\, f \le K$, and since $\mathbb{Z}$ is a PID, $\mathrm{Ker}\, f$ is free, since it is a submodule of a free module. So

$$\cdots \to 0 \to \mathrm{Ker}\, f \to K \to A \to 0$$

is a projective resolution for A. Since all of the modules above P_1 in the resolution are zero, clearly $\mathrm{H}_n(P_*) = 0$ for $n > 1$. □

Fact.

$$\mathrm{Tor}_1^{\mathbb{Z}}(A, \mathbb{Q}/\mathbb{Z}) = \mathrm{T}(A) = \{a \in A \mid a \text{ has finite order}\}.$$

The proof is omitted.

8.3 Baer sums of extensions

Proposition 8.5. *Let A and B be abelian groups. Then*

$$\mathrm{Ext}_{\mathbb{Z}}^n(A,B) = 0, \qquad n > 1.$$

Proof. Problem sheet question. □

More generally, $\mathrm{Ext}_R^1(A,C)$ tells us about **extensions** of C by A, that is B such that

$$0 \to A \to B \to C \to 0.$$

Let B_1 and B_2 be two extensions of C by A. Write $B_1 \sim B_2$ if there exists a **map of extensions** $f : B_1 \to B_2$ such that

$$\begin{tikzcd} & & B_1 \arrow[dd, "f"] \arrow[dr, "\beta_1"] & & \\ 0 \arrow[r] & A \arrow[ur, "\alpha_1"] \arrow[dr, "\alpha_2"'] & & C \arrow[r] & 0 \\ & & B_2 \arrow[ur, "\beta_2"'] & & \end{tikzcd}$$

commutes.

Proposition 8.6. *Any such f is an isomorphism.*

Proof.

- f is surjective. Suppose $y \in B_2$. Then $\beta_2(y) \in C$, and β_1 is surjective, so $\beta_2(y) = \beta_1(x)$ for some $x \in B_1$. Now $f(x) - y \in \operatorname{Ker} \beta_2 = \operatorname{Im} \alpha_2$, so $f(x) - y = \alpha_2(a)$ for some $a \in A$. So $f(x) - y = (f \circ \alpha_1)(a)$, and so $y = f(x) - (f \circ \alpha_1)(a) = f(x - \alpha_1(a))$.
- f is injective. Suppose $f(x) = f(y)$ for $x, y \in B_1$. Then $f(x - y) = 0$, so $(\beta_2 \circ f)(x - y) = 0$, so $\beta_1(x - y) = 0$. So $x - y \in \operatorname{Ker} \beta_1 = \operatorname{Im} \alpha_1$, so $x - y = \alpha_1(a)$ for some $a \in A$. Now $\alpha_2(a) = (f \circ \alpha_1)(a) = f(x - y) = 0$. But α_2 is injective, so $a = 0$, so $x - y = 0$.

$\square$

Hence the relation $\sim$ is an equivalence relation. Write $\mathrm{E}_C(A)$ for the set of $\sim$-equivalence classes. We will put an abelian group structure on $\mathrm{E}_C(A)$. Let B_1 and B_2 be extensions, so

$$0 \to A \xrightarrow{\alpha_1} B_1 \xrightarrow{\beta_1} C \to 0, \qquad 0 \to A \xrightarrow{\alpha_2} B_2 \xrightarrow{\beta_2} C \to 0.$$

Define maps α^* and β^* by

$$\begin{array}{cccccc} \alpha^* & : & A & \longrightarrow & B_1 \oplus B_2 \\ & & a & \longmapsto & (\alpha_1(a), -\alpha_2(a)) \end{array}, \qquad \begin{array}{cccccc} \beta^* & : & B_1 \oplus B_2 & \longrightarrow & C \\ & & (b_1, b_2) & \longmapsto & \beta_1(b_1) - \beta_2(b_2) \end{array}.$$

Now $\beta^* \circ \alpha^* = 0$. So

$$0 \to A \xrightarrow{\alpha^*} B_1 \oplus B_2 \xrightarrow{\beta^*} C \to 0$$

is a chain complex. Define

$$H = \mathrm{H}(B_1, B_2),$$

the **Baer sum** of $[B_1]$ and $[B_2]$, to be the homology group at $B_1 \oplus B_2$, that is $H = \operatorname{Ker} \beta^* / \operatorname{Im} \alpha^*$. More explicitly,

$$H = \{(b_1, b_2) \in B_1 \oplus B_2 \mid \beta_1(b_1) = \beta_2(b_2)\} / \{(\alpha_1(a), -\alpha_2(a)) \mid a \in A\}.$$

Clearly H is an R-module. Now define maps

$$\begin{array}{cccccc} \alpha & : & A & \longrightarrow & H \\ & & a & \longmapsto & (\alpha_1(a), 0) + \operatorname{Im} \alpha^* \end{array}, \qquad \begin{array}{cccccc} \beta & : & H & \longrightarrow & C \\ & & (b_1, b_2) + \operatorname{Im} \alpha^* & \longmapsto & \beta_1(b_1) \end{array}.$$

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Note. $(b_1, b_2) \in \operatorname{Ker} \beta^*$, so $\beta_1(b_1) = \beta_2(b_2)$. Also $(\alpha_1(a), 0) = (0, \alpha_2(a)) + (\alpha_1(a), -\alpha_2(a))$, so $(\alpha_1(a), 0) + \operatorname{Im} \alpha^* = (0, \alpha_2(a)) + \operatorname{Im} \alpha^*$.

Proposition 8.7.

$$0 \to A \xrightarrow{\alpha} H \xrightarrow{\beta} C \to 0$$

is a short exact sequence.

Proof.

- First check that β is well-defined. If $(b_1, b_2) \in (b_1', b_2') + \operatorname{Im} \alpha^*$ then $(b_1, b_2) = (b_1', b_2') + (\alpha_1(a), -\alpha_2(a))$ for some $a \in A$. So

  $$\beta((b_1, b_2) + \operatorname{Im} \alpha^*) = \beta_1(b_1) = \beta_1(b_1 - \alpha_1(a)) = \beta((b_1', b_2') + \operatorname{Im} \alpha^*),$$

  since $\beta_1 \circ \alpha_1 = 0$.
- Next check α is injective. Suppose $\alpha(a) = (0, 0) + \operatorname{Im} \alpha^*$. Then $(\alpha_1(a), 0) = \alpha^*(a')$ for some a'. So $(\alpha_1(a), 0) = (\alpha_1(a'), -\alpha_2(a'))$. Since α_1 and α_2 are injective, $a = a' = 0$.
- Next, show β is surjective. Take $c \in C$. Then $c = \beta_1(b_1)$ for some $b_1 \in B_1$. Since β_2 is surjective, there exists $b_2 \in B_2$ with $\beta_2(b_2) = \beta_1(b_1) = c$. Now $(b_1, b_2) \in \operatorname{Ker} \beta^*$, and $\beta((b_1, b_2) + \operatorname{Im} \alpha^*) = \beta_1(b_1) = c$.

- Finally, show that
$$0 \to A \to H \to C \to 0$$
is exact, that is $\operatorname{Ker}\beta = \operatorname{Im}\alpha$. It is clear that $\operatorname{Im}\alpha \le \operatorname{Ker}\beta$, since $\beta_1 \circ \alpha_1 = 0$. For the reverse containment, let $(b_1, b_2) + \operatorname{Im}\alpha^* \in \operatorname{Ker}\beta$. So $(b_1, b_2) \in \operatorname{Ker}\beta^*$, so $\beta_1(b_1) = \beta_2(b_2)$. And $\beta_1(b_1) = 0$, so $\beta_2(b_2) = 0$ as well. But $\operatorname{Ker}\beta_i = \operatorname{Im}\alpha_i$ for $i = 1, 2$, so there exist $a_1, a_2 \in A$ with $\alpha_1(a_1) = b_1$ and $\alpha_2(a_2) = b_2$. Now
$$\begin{aligned}(b_1, b_2) &= (\alpha_1(a_1), \alpha_2(a_2)) = (\alpha_1(a_1 + a_2), 0) + (-\alpha_1(a_2), \alpha_2(a_2)) \\ &\in (\alpha_1(a_1 + a_2), 0) + \operatorname{Im}\alpha^* = \alpha(a_1 + a_2) \in \operatorname{Im}\alpha.\end{aligned}$$

∎

We have shown that H is an extension of C by A.

Proposition 8.8. *If $B_1 \sim B_1'$ and $B_2 \sim B_2'$ then $\mathrm{H}(B_1, B_2) \sim \mathrm{H}(B_1', B_2')$, where $B \sim B'$ if there exists a map of extensions $f : B \to B'$ such that*

$$\begin{tikzcd} & B \arrow[d, "f"] \arrow[dr] & & \\ 0 \arrow[r] & A \arrow[u] \arrow[d] & C \arrow[r] & 0 \\ & B' \arrow[ur] & & \end{tikzcd}$$

commutes.

Proof. Suppose $f_1 : B_1 \to B_1'$ and $f_2 : B_2 \to B_2'$ are maps of extensions. Then there exists a map of chain complexes

$$\begin{tikzcd} & B_1 \oplus B_2 \arrow[d, "(f_1, f_2)"] \arrow[dr] & & \\ 0 \arrow[r] & A \arrow[u] \arrow[d] & C \arrow[r] & 0 \\ & B_1' \oplus B_2' \arrow[ur] & & \end{tikzcd} \cdot$$

This induces a map on homology, $\overline{f} : \mathrm{H}(B_1, B_2) \to \mathrm{H}(B_1', B_2')$. It is easy to check

$$\begin{tikzcd} & \mathrm{H}(B_1, B_2) \arrow[d, "\overline{f}"] \arrow[dr] & & \\ 0 \arrow[r] & A \arrow[u] \arrow[d] & C \arrow[r] & 0 \\ & \mathrm{H}(B_1', B_2') \arrow[ur] & & \end{tikzcd}$$

commutes, so $\mathrm{H}(B_1, B_2) \sim \mathrm{H}(B_1', B_2')$. ∎

Write $[B]$ for the equivalence class of B. If $H = \mathrm{H}(B_1, B_2)$, write $[H] = [B_1] + [B_2]$, or $[H] = [B_1] +_{\mathrm{B}} [B_2]$.

Proposition 8.9. *$+$ gives an abelian group operation on the set $\mathrm{E}_C(A)$ of equivalence classes of extensions.*

Proof.

- Check $+$ is commutative. This follows easily from the facts that
$$\alpha(a) = (\alpha_1(0), 0) + \operatorname{Im}\alpha^* = (0, \alpha_2(a)) + \operatorname{Im}\alpha^*, \qquad \beta((b_1, b_2) + \operatorname{Im}\alpha^*) = \beta_1(b_1) = \beta_2(b_2).$$
- Associativity is an exercise. [7]
- The identity is $[A \oplus C]$, the **split extension**. Let
$$0 \to A \xrightarrow{\alpha} A \oplus C \xrightarrow{\beta} C \to 0, \qquad 0 \to A \xrightarrow{\alpha'} B \xrightarrow{\beta'} C \to 0.$$
There is a map $\pi : A \oplus C \to A$ such that $\pi \circ \alpha = \mathrm{id}_A$. Consider a map
$$\begin{array}{cccc} f & : & \mathrm{H}(B, A \oplus C) & \longrightarrow & B \\ & & (b_1, b_2) + \operatorname{Im}\alpha^* & \longmapsto & b_1 + \alpha'(a) \end{array}, \qquad \beta'(b_1) = \beta(b_2), \qquad b_2 = (a, c) \in A \oplus C.$$
It is easy to check this gives a map of extensions.

[7] Exercise

- Inverses. Suppose
$$0 \to A \xrightarrow{\alpha} B \xrightarrow{\beta} C \to 0.$$
Then the inverse of [B] is given by the extension
$$0 \to A \xrightarrow{\alpha} B \xrightarrow{-\beta} C \to 0.$$

□

8.4 Ext and classes of extensions

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Definition 8.10. Let
$$0 \to A \to B \to C \to 0$$
be an extension of C by A. The **class** of this extension is simply defined as $\eta(\mathrm{id}_C)$ in the long exact sequence
$$0 \to \mathrm{Hom}_R(C, A) \to \mathrm{Hom}_R(C, B) \to \mathrm{Hom}_R(C, C) \xrightarrow{\eta} \mathrm{Ext}^1_R(C, A) \to \dots .$$

Proposition 8.11.

- *Equivalent extensions have the same class.*
- *The map between equivalence classes of extensions and* $\mathrm{Ext}^1_R(C, A)$ *is a bijection.*
- *In fact class is an isomorphism* $(\mathrm{E}_C(A), +_{\mathrm{B}}) \to \mathrm{Ext}^1_R(C, A)$.

Lemma 8.12. *Suppose*
$$\begin{tikzcd} 0 \arrow[r] & L \arrow[r] \arrow[d] & M \arrow[r] \arrow[d] & N \arrow[r] \arrow[d] & 0 \\ 0 \arrow[r] & X \arrow[r] & Y \arrow[r] & Z \arrow[r] & 0 \end{tikzcd}$$
commutes, where the rows are exact. We get long exact sequences
$$\begin{tikzcd} 0 \arrow[r] & \mathrm{Ext}^0_R(C, L) \arrow[r] \arrow[d] & \mathrm{Ext}^0_R(C, M) \arrow[r] \arrow[d] & \mathrm{Ext}^0_R(C, N) \arrow[r] \arrow[d] & \mathrm{Ext}^1_R(C, L) \arrow[r] \arrow[d] & \dots \\ 0 \arrow[r] & \mathrm{Ext}^0_R(C, X) \arrow[r] & \mathrm{Ext}^0_R(C, Y) \arrow[r] & \mathrm{Ext}^0_R(C, Z) \arrow[r] & \mathrm{Ext}^1_R(C, X) \arrow[r] & \dots \end{tikzcd},$$
where the vertical arrows are given by the functoriality of $\mathrm{Ext}^1_R(C, \cdot)$. *This diagram commutes.*

Proof. Omitted. □

Proof of Proposition 8.11. We show that class gives a map $\mathrm{E}_C(A) \to \mathrm{Ext}^1_R(C, A)$, which is bijective.

- Every element of $\mathrm{Ext}^1_R(C, A)$ is the class of an extension. Take $x \in \mathrm{Ext}^1_R(C, A)$. Let I be an injective module containing A as a submodule. Then
$$0 \to A \to I \to I/A \to 0$$
is a short exact sequence, which gives a long exact sequence
$$0 \to \mathrm{Hom}_R(C, A) \to \mathrm{Hom}_R(C, I) \to \mathrm{Hom}_R(C, I/A) \xrightarrow{\mu} \mathrm{Ext}^1_R(C, A) \to \mathrm{Ext}^1_R(C, I) \to \dots .$$
Then $\mathrm{Ext}^1_R(C, I) = 0$ since I is injective. So μ is surjective. Let $\phi \in \mathrm{Hom}_R(C, I/A)$ be such that $\mu(\phi) = x$, and let
$$X_\phi = \{(i, c) \in I \oplus C \mid i + A = \phi(c)\}$$
be the pullback via ϕ, so
$$\begin{tikzcd} & & X_\phi \arrow[r, "\pi_C"] \arrow[d, "\pi_I"] & C \arrow[r] \arrow[d, "\phi"] & 0 \\ 0 \arrow[r] & A \arrow[ur, "\iota_I"] \arrow[r, "\le"'] & I \arrow[r] & I/A \arrow[r] & 0 \end{tikzcd}.$$

From Lemma 8.12, there is a commuting square

$$\begin{tikzcd} \mathrm{Hom}_R(C,C) \arrow[d, "\overline{\phi}"'] \arrow[dr, "\eta"] & \\ \mathrm{Hom}_R(C,I/A) \arrow[r, "\mu"'] & \mathrm{Ext}^1_R(C,A) \end{tikzcd} .$$

For $f \in \mathrm{Hom}_R(C,C)$, $\overline{\phi}(f) = \phi \circ f$. So the class of the extension

$$0 \to A \to B \to C \to 0$$

is $\eta(\mathrm{id}_C) = \mu(\phi \circ \mathrm{id}_C) = \mu(\phi) = x$.

- Extensions giving the same class are equivalent. Suppose that ψ is another element of $\mathrm{Hom}_R(C, I/A)$ such that $\mu(\psi) = x$. Tracing back through the definition of the connecting homomorphism, in the proof of the snake lemma, it can be shown that $\psi = \phi + q \circ f$, where $f : C \to I$, and q is the quotient map $I \to I/A$. Now it is easy to show that the map given by

$$\begin{array}{ccc} I \oplus C & \longrightarrow & I \oplus C \\ (i,c) & \longmapsto & (i + f(c), c) \end{array}$$

is bijective, and it maps $X_\phi \to X_\psi$. The diagram

$$\begin{tikzcd} & & X_\phi \arrow[d, "f"] \arrow[dr] & & \\ 0 \arrow[r] & A \arrow[ur] \arrow[dr] & X_\psi \arrow[r] & C \arrow[r] & 0 \end{tikzcd}$$

commutes, and so the extensions are equivalent. We need to show that every extension arises as X_ϕ for some ϕ. Suppose

$$0 \to A \xrightarrow{\alpha} B \to C \to 0$$

is an extension. Let $A \le I$ where I is injective. Then there exists $\lambda : B \to I$ such that $(\lambda \circ \alpha)(a) = a$ for all $a \in A$. We have $\lambda' : C \cong B/\alpha(A) \to I/A$. We get short exact sequences

$$\begin{tikzcd} & & B \arrow[r] \arrow[d, "\lambda"] & C \arrow[r] \arrow[d, "\lambda'"] & 0 \\ 0 \arrow[r] & A \arrow[ur] \arrow[r] & I \arrow[r] & I/A \arrow[r] & 0 \end{tikzcd} .$$

Now we have $B \cong X_{\lambda'}$, since this is the same construction as before. Lecture 27 Tuesday 10/03/20

- Equivalent extensions have the same class. Suppose

$$\begin{tikzcd} & & B_1 \arrow[d, "f"] \arrow[dr] & & \\ 0 \arrow[r] & A \arrow[ur] \arrow[dr] & B_2 \arrow[r] & C \arrow[r] & 0 \end{tikzcd}$$

commutes. We get maps

$$\begin{tikzcd} \mathrm{Hom}_R(C,C) \arrow[r, bend left, "\mu_1"] \arrow[r, bend right, "\mu_2"'] & \mathrm{Ext}^1_R(C,A) \end{tikzcd}$$

commuting. So $\mu_1 = \mu_2$. Hence the extensions B_1 and B_2 have the same class.

It remains to show that it is a group homomorphism. Let

$$0 \to A \to B_i \to C \to 0, \qquad i = 1, 2.$$

Suppose $B_i = X_{\phi_i}$ for $\phi_i : C \to I/A$, where I is an injective containing A. From the arguments earlier, we have

$$\begin{tikzcd} & & B_i \arrow[r] \arrow[d, "\rho_i"] & C \arrow[r] \arrow[d, "\phi_i"] & 0 \\ 0 \arrow[r] & A \arrow[ur] \arrow[dr] & & & \\ & & I \arrow[r] & I/A \arrow[r] & 0 \end{tikzcd}.$$

Use the diagram above for $i = 1, 2$ to construct a new commuting diagram

$$\begin{tikzcd} 0 \arrow[r] & A \oplus A \arrow[r] \arrow[d, "+"] & B_1 \oplus B_2 \arrow[r] \arrow[d, "\rho_1 + \rho_2"] & C \oplus C \arrow[r] \arrow[d, "\phi_1 + \phi_2"] & 0 \\ 0 \arrow[r] & A \arrow[r] & I \arrow[r] & I/A \arrow[r] & 0 \end{tikzcd}.$$

Define

$$A^+ = \{(a, a) \mid a \in A\} \le A \oplus A, \qquad A^- = \{(a, -a) \mid a \in A\} \le A \oplus A, \qquad C^+ = \{(c, c) \mid c \in C\} \le C \oplus C.$$

Quotienting by A^-, $(A \oplus A) / A^- \cong A$, since $(a_1, a_2) = (a_1 + a_2, 0) - (a_2, -a_2)$. Then

$$\begin{tikzcd} & & (B_1 \oplus B_2) / A' \arrow[r] \arrow[d] & C \oplus C \arrow[r] \arrow[d, "\phi_1 + \phi_2"] & 0 \\ 0 \arrow[r] & A \arrow[ur] \arrow[dr] & & & \\ & & I \arrow[r] & I/A \arrow[r] & 0 \end{tikzcd},$$

where A' is the image of A^- in $B_1 \oplus B_2$, so if

$$A \xrightarrow{\alpha_1} B_1 \xrightarrow{\beta_1} C, \qquad A \xrightarrow{\alpha_2} B_2 \xrightarrow{\beta_2} C,$$

then $A' = \{(\alpha_1(a), -\alpha_2(a))\}$. Let $X \le (B_1 \oplus B_2) / A'$ be the preimage of C^+ in the map $(B_1 \oplus B_2) / A' \to C \oplus C$. Then

$$0 \to A \to X \to C^+ \to 0$$

is exact, and we have $C^+ \cong C$. We get

$$\begin{tikzcd} & & X \arrow[r] \arrow[d] & C \arrow[r] \arrow[d, "\phi_1 + \phi_2"] & 0 \\ 0 \arrow[r] & A \arrow[ur] \arrow[dr] & & & \\ & & I \arrow[r] & I/A \arrow[r] & 0 \end{tikzcd},$$

identifying the maps

$$\begin{array}{rcccl} \phi_1 + \phi_2 & : & C \oplus C & \longrightarrow & I/A \\ & & (c, c) & \longmapsto & \phi_1(c) + \phi_2(c) \end{array}, \qquad \begin{array}{rcccl} \phi_1 + \phi_2 & : & C & \longrightarrow & I/A \\ & & c & \longmapsto & \phi_1(c) + \phi_2(c) \end{array},$$

so $X = X_{\phi_1 + \phi_2}$. Recall from the definition of the Baer sum,

$$0 \to A \xrightarrow{(\alpha_1, -\alpha_2)} B_1 \oplus B_2 \xrightarrow{\beta_1 - \beta_2} C \to 0,$$

and $H = \mathrm{Ker}(\beta_1 - \beta_2) / \mathrm{Im}(\alpha_1, -\alpha_2)$. But $\mathrm{Im}(\alpha_1, -\alpha_2)$ is precisely the module A', and $\mathrm{Ker}(\beta_1 - \beta_2)$ is the preimage of C^+ in $B_1 \oplus B_2$. So $X = H$, and so $[X_{\phi_1}] + [X_{\phi_2}] = [X_{\phi_1 + \phi_2}]$. $\square$

We have shown that elements of $\mathrm{Ext}^1_R(C, A)$ corresponds to equivalence classes of extensions. Since the identity in $\mathrm{E}_C(A)$ is the class of split extensions, it follows that $0 \in \mathrm{Ext}^1_R(C, A)$ corresponds to split extensions $C \oplus A$.

Example. Take $R = \mathbb{Z}$. Calculate $\mathrm{Ext}^1_R(\mathbb{Z}_n, H)$ for H an abelian group. Use the functor $F(A) = \mathrm{Hom}_{\mathbb{Z}}(A, H)$. This is contravariant, so we need a projective resolution of $\mathbb{Z}_n$. This is given by

$$0 \to \mathbb{Z} \xrightarrow{n} \mathbb{Z} \to \mathbb{Z}_n \to 0.$$

This gives a long exact sequence

$$0 \to \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_n, H) \to \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}, H) \xrightarrow{n} \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}, H) \to \mathrm{Ext}^1_R(\mathbb{Z}_n, H) \to 0,$$

since $\mathrm{Ext}^i_n(\mathbb{Z}, H) = 0$ for $i > 1$ since $\mathbb{Z}$ is projective. Now

$$\mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_n, H) \cong H_n = \{h \in H \mid nh = 0\}, \qquad \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}, H) \cong H.$$

So

$$0 \to H_n \to H \xrightarrow{n} H \to \mathrm{Ext}^1_R(\mathbb{Z}_n, H) \to 0,$$

so $\mathrm{Ext}^1_R(\mathbb{Z}_n, H) \cong H/nH$.

Lecture 28 is a problems class. Lecture 28 Friday 13/03/20

9 Dimension

9.1 Projective, injective, and flat dimensions

Lecture 29
Monday
16/03/20

Definition 9.1. Let M be a R-module. The **projective dimension** $\mathrm{pd}\, M$ is the smallest d such that there exists a projective resolution $P_* \to M$ such that $P_{d+1} \to 0$, or infinity if no such d exists. The **injective dimension** $\mathrm{id}\, M$ is similar for injective resolutions. The **flat dimension** is similar for flat resolutions.

Every projective is flat, so $\mathrm{fd}\, M \le \mathrm{pd}\, M$.

Example.

- $\mathbb{Z}$ as a module for itself. Then $\mathbb{Z}$ is projective, and flat, so a projective or flat resolution is

$$0 \to \mathbb{Z} \to \mathbb{Z} \to 0,$$

  so $\mathrm{fd}\, \mathbb{Z} = \mathrm{pd}\, \mathbb{Z} = 0$. Since $\mathbb{Z}$ is not injective, an injective resolution is

$$0 \to \mathbb{Z} \to \mathbb{Q}/\mathbb{Z} \to \mathbb{Q}/\mathbb{Z} \to 0,$$

  so $\mathrm{id}\, \mathbb{Z} = 1$.

- $\mathbb{Q}$ as a module for $\mathbb{Z}$. This is flat but not projective, so $\mathrm{fd}\, \mathbb{Q} = 0$ and $\mathrm{pd}\, \mathbb{Q} = 1$.

Proposition 9.2. *The following are equivalent.*

1. $\mathrm{pd}\, M \le d$.
2. $\mathrm{Ext}_R^{d+1}(M, N) = 0$ *for all* N.

Proof.

$\implies$ Assume 1. Then there exists a projective resolution

$$0 \to P_d \to \cdots \to P_0 \to M \to 0.$$

Let F be the functor $F(A) = \mathrm{Hom}_R(A, N)$. Then $\mathrm{Ext}_R^*(M, N)$ is calculated from the chain complex

$$0 \to F(P_d) \to \cdots \to F(P_{d-1}) \to F(P_0) \to 0,$$

so clearly $\mathrm{Ext}_R^n(M, N) = \mathrm{L}_n F(P_*) = 0$ for $n > d$.

$\impliedby$ For the converse, suppose that $\mathrm{Ext}_R^{d+1}(M, N) = 0$ for all N. Suppose

$$P_{d-1} \to P_{d-2} \to \cdots \to P_0 \to M \to 0$$

is exact. Let K_{d-1} be the kernel of $P_{d-1} \to P_{d-2}$, the $(d-1)$-dimensional **syzygy** of M. So

$$0 \to K_{d-1} \to P_{d-1} \to P_{d-2} \to \cdots \to P_0 \to M \to 0.$$

A fact is that

$$\mathrm{Ext}_R^{d+1}(M, N) \cong \mathrm{Ext}_R^1(K_{d-1}, N).$$

Suppose $\mathrm{Ext}_R^{d+1}(M, N) = 0$. Then $\mathrm{Ext}_R^1(K_{d-1}, N) = 0$. So K_{d-1} is projective. Hence

$$0 \to K_{d-1} \to P_{d-1} \to P_{d-2} \to \cdots \to P_0 \to M \to 0$$

is a projective resolution. So $\mathrm{pd}\, M \le d$.

$\square$

Proposition 9.3. *The following are equivalent.*

- $\operatorname{id} N \leq d$.
- $\operatorname{Ext}_R^{d+1}(M, N) = 0$ *for all* M.

Proof. Similar to Proposition 9.2. Use the **cosyzygy**. ☐

Proposition 9.4. *The following are equivalent.*

- $\operatorname{fd} M \leq d$.
- $\operatorname{Tor}_{d+1}^R(M, N) = 0$ *for all* N.

Fact. Any flat resolution for M can be used to calculate Tor.

Proof. Using the fact, the proof is the same as above. ☐

9.2 Global dimension

We will be interested in defining dimension for the ring R.

Definition 9.5. Claim that

$$\sup \{\operatorname{pd} M \mid M \text{ a left } R\text{-module}\} = \sup \{\operatorname{id} M \mid M \text{ a left } R\text{-module}\} = \sup \left\{d \;\middle|\; \exists M, N,\ \operatorname{Ext}_R^d(M, N) \neq 0\right\},$$

where the supremums are in $\mathbb{N} \cup \{\infty\}$. This number is the **left global dimension** $\operatorname{lgd} R$ of R. The **right global dimension** $\operatorname{rgd} R$ is defined similarly, but using right modules.

There exist rings R such that $\operatorname{lgd} R \neq \operatorname{rgd} R$.

Definition 9.6. Say that R satisfies the **ascending chain condition on right ideals** if whenever $I_0 \leq I_1 \leq \dots$ is a chain of right ideals, there exists d such that $I_d = I_{d+1} = \dots$. The condition that R satisfies the **ascending chain condition on left ideals** is similar. If R satisfies the ascending chain condition on both left and right ideals, it is **noetherian**.

Fact. For any noetherian ring R, $\operatorname{lgd} R = \operatorname{rgd} R$.

Definition 9.7. So in this context we can refer to **global dimension**, $\operatorname{gd} R$. Claim that

$$\sup \{\operatorname{fd} N \mid N \text{ a left } R\text{-module}\} = \sup \{\operatorname{fd} M \mid M \text{ a right } R\text{-module}\} = \sup \left\{d \;\middle|\; \exists M, N,\ \operatorname{Tor}_d^R(M, N) \neq 0\right\}.$$

This number is the **weak global dimension** $\operatorname{wgd} R$.

Since $\operatorname{fd} M \leq \operatorname{pd} M$, $\operatorname{wgd} R \leq \operatorname{gd} R$.

9.3 Krull dimension

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The following is another ring dimension. Let R be a commutative ring.

Definition 9.8. The **Krull dimension** $\dim R$ is the length of the longest chain of prime ideals of R, where $I \leq R$ is **prime** if $I \neq R$, and $ab \in I$ implies that $a \in I$ or $b \in I$.

In particular, any maximal ideal of R is prime.

Example. Let V be an **affine variety** in F^n, defined by the zeros of a set of polynomials in $F[x_1, \dots, x_n]$. Then V corresponds to an ideal I_V in $F[x_1, \dots, x_n]$, and V is **irreducible** if I_V is prime. Then

$$\dim F[x_1, \dots, x_n] / I_V = \dim V.$$

Fact. $\dim R \leq \operatorname{gd} R$.

Definition 9.9. A ring is **local** if it has a unique maximal ideal, so the non-units of R form an ideal. Let $I \leq R$ be a prime ideal. The **localisation** of R at I is the ring

$$\left\{ \frac{r}{q} \;\middle|\; r \in R,\ q \in R \setminus I \right\}.$$

The unique maximal ideal is

$$\left\{ \frac{i}{q} \;\middle|\; i \in I,\ q \in R \setminus I \right\},$$

so this ring is local. This is a basic tool in algebraic geometry.

Theorem 9.10 (Serre)**.** *Let R be a noetherian local ring such that $\dim R$ is finite. Then*

$$\dim R = \operatorname{gd} R.$$

Example. $R = F[x_1, \dots, x_n]$ corresponds to the zero variety. This is not local, but $\dim R = \operatorname{gd} R = n$. The fact that $\operatorname{gd} R = n$ is **Hilbert's syzygy theorem**.

- Let $n = 3$. Note that F is a module for R, by the multiplication $x_i \lambda = 0$ for all x_i and $\lambda \in F$. Let us calculate a projective resolution, keeping track of the syzygies. If

  $$0 \to K_1 \to R \to F \to 0,$$

  then

  $$\begin{aligned} K_1 &= \operatorname{Ker} \begin{pmatrix} R & \longrightarrow & F \\ x_i & \longmapsto & 0 \\ 1 & \longmapsto & 1 \end{pmatrix} \\ &= \langle x_1, x_2, x_3 \rangle \leq R. \end{aligned}$$

  If

  $$0 \to K_2 \to R^3 \to K_1 \to 0,$$

  then

  $$\begin{aligned} K_2 &= \operatorname{Ker} \begin{pmatrix} R^3 & \longrightarrow & K_1 \\ (r_1, r_2, r_3) & \longmapsto & r_1 x_1 + r_2 x_2 + r_3 x_3 \end{pmatrix} \\ &= \{(r_1, r_2, r_3) \mid r_1 x_1 + r_2 x_2 + r_3 x_3 = 0\} \\ &= \langle (0, x_3, -x_2), (-x_3, 0, x_1), (x_2, -x_1, 0) \rangle \leq R^3. \end{aligned}$$

  If

  $$0 \to K_3 \to R^3 \to K_2 \to 0,$$

  then

  $$\begin{aligned} K_3 &= \operatorname{Ker} \begin{pmatrix} R^3 & \longrightarrow & K_2 \\ (r_1, r_2, r_3) & \longmapsto & (r_3 x_2 - r_2 x_3, r_1 x_3 - r_3 x_1, r_2 x_1 - r_1 x_2) \end{pmatrix} \\ &= \langle (x_1, x_2, x_3) \rangle \cong R. \end{aligned}$$

  Our projective resolution is

  $$0 \to R \to R^3 \to R^3 \to R \to F \to 0.$$

- Generally for arbitrary n, this construction gives

  $$P_j = R^{\binom{n}{j}}.$$

  Generators of $K_j \leq P_{j-1}$ correspond to subsets of size j of $\{1, \dots, n\}$. The generator corresponding to a subset S of size j will have a coordinate for each subset T of size $j - 1$. This coordinate is zero if $T \not\subseteq S$ and $\pm x_i$ if $S = T \cup \{i\}$.

This is an example of a **Koszul complex**, and is a technique used for calculating syzygies explicitly in certain situations.