M4P63 Algebra IV

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Spring 2020

Syllabus

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

$$r*(m_1+m_2) = r*m_1+r*m_2, \qquad (r_1+r_2)*m = r_1*m+r_2*m, \qquad (r_1r_2)*m = r_1*(r_2*m), \qquad 1*m = m.$$

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 $\left(x^2+3x-2\right) * v = M^2v + 3Mv - 2v$.
- 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

$$(m_1+m_2)*r = m_1*r+m_2*r, \qquad m*(r_1+r_2) = m*r_1+m*r_2, \qquad m*(r_1r_2) = (m*r_1)*r_2, \qquad m*1 = m.$$

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 $(r_1r_2)m = r_2(r_1m)$. But in a left module, we have $(r_1r_2)m = r_1(r_2m)$.

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

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

and surjective maps

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

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.

$\Longrightarrow$ 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.

$\Longleftarrow$ 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

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

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.

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

$\Longleftarrow$ 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

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

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*

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

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

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

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

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.

$\Longrightarrow$ 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

$\Longleftarrow$ 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 $\beta\left(b_t\right) = \left(f \circ \pi_M\right)(t)$. 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

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

So

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

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

$\square$

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

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

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.

∎

[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]

□

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*

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

- *We can also define*

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

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 $f_1 = f_2$. $\square$

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 $m \in M$. $\square$

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 $\mathrm{Hom}_R(B, M)$. ☐

Lecture 7 Friday 24/01/20

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

  $$\begin{array}{ccccc} f & : & \mathbb{Q} & \longrightarrow & \mathbb{Z} \\ & & 1 & \longmapsto & k \ne 0 \end{array}.$$

  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 $\mathrm{Hom}_R(M, B)$. ☐

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
$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_2,\mathbb{Z}_2) & \xrightarrow{\alpha_*} & \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_2,\mathbb{Z}_4) & \xrightarrow{\beta_*} & \mathrm{Hom}_{\mathbb{Z}}(\mathbb{Z}_2,\mathbb{Z}_2) \\ & & \cong & & \cong & & \cong \\ & & \mathbb{Z}_2 & & \mathbb{Z}_2 & & \mathbb{Z}_2 \end{array}.$$
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 $y \in \mathbb{Z}_3$,

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

Lecture 9 Tuesday 28/01/20

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

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

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*

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

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

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

   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*

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

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

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

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

2. Similarly.

□

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

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

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

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

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.

□

Lecture 10 Friday 31/01/20

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

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

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 $\operatorname{Im} \alpha' \leq \operatorname{Ker} \beta'$. 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. ☐

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

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

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. ☐

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

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

and it is easy to check that R is flat. ☐

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. ☐

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 $F_1 \le F_2$, 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 $|B_1| \le |B_2|$. In particular, if $M \le R^n$, then $M \cong R^m$ for some $m \le n$. 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 $\le$ 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 $\le$. 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 $\le$ 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 $U \le F$ is an R-submodule of F. Define R_t to be the submodule of F generated by $\{e_s \mid s \le t\}$, so

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

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

$$U_t = U \cap R_t.$$

So $t_1 < t_2$ implies that $U_{t_1} \le U_{t_2}$. 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

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

- Claim that B generates U. We will actually prove that $B_t = \{u_s \mid s \le t\}$ 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 $a_{s_k} \ne 0$, 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 $|B| \le |S|$. ∎

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Lecture 13 is a problems class.

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. $\square$

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. $\square$

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. $\square$

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. $\square$

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. $\square$

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. ☐

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 $A_0 \le A$ 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. ☐

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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 $U \le \mathrm{F}(T)$, 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 $U \le \mathrm{F}(T)$. 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. ☐

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.

∎

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

$$\begin{tikzcd} 0 \arrow[r] & K \arrow[r] \arrow[d, phantom, "\cong"] & F_A \arrow[r] \arrow[d, hook] & \alpha A \arrow[r] \arrow[d, hook] & 0 \\ 0 \arrow[r] & K \arrow[r] & F \arrow[r] & B \arrow[r] & 0 \end{tikzcd}.$$

Tensoring with M,

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

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

Lecture 16 Friday 14/02/20

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

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

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

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

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 exists 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

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

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. ☐

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

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. ☐

[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 $\Psi(g) \in \operatorname{Hom}_R(M, S)$, and $\Psi(g)(m)(1) = g(m) \neq 0$ for $1 \in R$, so $\Psi(g)(m)$ is not the zero map. $\square$

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

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

is injective, and a homomorphism. $\square$

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

Thus there exists injective $I_0, I_1, I_2, \dots$ such that

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

is exact.

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

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*

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

commutes.

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

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

commutes. 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

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

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 $\mathrm{Im}\,(f_{t-1} \circ d_{t-1}) \le \mathrm{Ker}\, d'_{t-2} = \mathrm{Im}\, d'_{t-1}$. Now the map $d'_{t-1} : Q_t \to \mathrm{Im}\, d'_{t-1}$ 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 $\mathrm{Im}\, h_0 \le \mathrm{Ker}\, q = \mathrm{Im}\, d'_0$. We have a surjective map $d'_0 : Q_1 \to \mathrm{Im}\, d'_0$, and a map $h_0 : P_0 \to \mathrm{Im}\, d'_0$. 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 $\mathrm{Im}\, d'_t = \mathrm{Ker}\, d'_{t-1}$. 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 $h_t - s_{t-1} \circ d_{t-1} \in \mathrm{Ker}\, d'_{t-1}$. Now we have the situation

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

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 Chain and cochain complexes

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 $\operatorname{Im} d_{i+1} \leq \operatorname{Ker} d_i$.

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 $\operatorname{Im} d_i \leq \operatorname{Ker} d_{i+1}$.

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

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

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 $\operatorname{Im} d_i^A \leq \operatorname{Ker} \overline{f_i}$ 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

$$\begin{tikzcd} 0 \arrow[r] & A_{n+1} \arrow[r, "f_{n+1}"] \arrow[d, "d^A_n"] & B_{n+1} \arrow[r, "g_{n+1}"] \arrow[d, "d^B_n"] & C_{n+1} \arrow[r] \arrow[d, "d^C_n"] & 0 \\ 0 \arrow[r] & A_n \arrow[r, "f_n"] & B_n \arrow[r, "g_n"] & C_n \arrow[r] & 0 \end{tikzcd}.$$

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

$$\begin{tikzcd} 0 \arrow[r] & A_{n+1} \arrow[r, "f_{n+1}"] \arrow[d, "d^A_n"] & B_{n+1} \arrow[r, "g_{n+1}"] \arrow[d, "d^B_n"] & C_{n+1} \arrow[r] \arrow[d, "d^C_n"] & 0 \\ 0 \arrow[r] & \mathrm{Ker}\, d^A_{n-1} \arrow[r, "f_n"] & \mathrm{Ker}\, d^B_{n-1} \arrow[r, "g_n"] & \mathrm{Ker}\, d^C_{n-1} & \end{tikzcd}.$$

Now $\mathrm{Im}\, d_{n+1} \leq \mathrm{Ker}\, d_n$, 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

$$\begin{tikzcd} & A_{n+1}/\,\mathrm{Im}\, d^A_{n+1} \arrow[r, "f_{n+1}"] \arrow[d, "\overline{d^A_n}"] & B_{n+1}/\,\mathrm{Im}\, d^B_{n+1} \arrow[r, "g_{n+1}"] \arrow[d, "\overline{d^B_n}"] & C_{n+1}/\,\mathrm{Im}\, d^C_{n+1} \arrow[r] \arrow[d, "\overline{d^C_n}"] & 0 \\ 0 \arrow[r] & \mathrm{Ker}\, d^A_{n-1} \arrow[r, "f_n"] & \mathrm{Ker}\, d^B_{n-1} \arrow[r, "g_n"] & \mathrm{Ker}\, d^C_{n-1} & \end{tikzcd}.$$

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

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

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

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

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

is exact. Consider the sequence

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

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

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

Define

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

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. *$\mathrm{L}_0 F = F$.*

Proof.

1.
2.
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 $\mathrm{L}_0 F(P_*) = F(P_0) / \operatorname{Im} F(d_0) = F(A)$.

$\square$