

Problem Set 8

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1 Regular Problems

1.1 Problem 1

1.1.1 Part a

Define a map

$$\begin{aligned}\phi_{\text{ev}} : \text{hom}_{\mathbb{Z}}(\mathbb{Z}_m, A) &\rightarrow A \\ (f : \mathbb{Z}_m \rightarrow A) &\mapsto f(1)\end{aligned}$$

Then ϕ_{ev} is a \mathbb{Z} -module homomorphism, since

$$\begin{aligned}\phi_{\text{ev}}(nf + g) &= (nf + g)(1) \\ &= nf(1) + g(2) \\ &= n\phi_{\text{ev}}(f) + \phi_{\text{ev}}(g)\end{aligned}$$

But this forces $f(\bar{0}) = 0_A$ (where $\bar{0} : \mathbb{Z}_m \rightarrow A$ is the zero map), we have

$$0 = f(0) = f(m) = mf(1),$$

we must have $mf(1) = 0$ in A . So

$$\text{im } \phi_{\text{ev}} = \{a \in A \mid ma = 0\} := A[m].$$

It is also the case that

$$\ker \phi_{\text{ev}} = \{f \in \text{hom}_{\mathbb{Z}}(\mathbb{Z}_m, A) \mid f(1) = 0\} = \{\bar{0}\},$$

which follows from the fact that $\mathbb{Z}_m = \langle 1 \bmod m \rangle$ and $A = \langle 1_A \rangle$ as \mathbb{Z} -modules, so if $f(1 \bmod m) = 0_A$ then

$$f(n \bmod m) = nf(1 \bmod m) = 0$$

and so f is necessarily the zero map. So $\ker \phi = \bar{0}$.

We can then apply the first isomorphism theorem,

$$\frac{\text{hom}_{\mathbb{Z}}(\mathbb{Z}_m, A)}{\ker \phi_{\text{ev}}} \cong \text{im } \phi_{\text{ev}} \implies \text{hom}_{\mathbb{Z}}(\mathbb{Z}_m, A) \cong A[m].$$

1.1.2 Part 2

Lemma: If $x \mid n$ and $x \mid m$ then $x \mid \gcd(m, n)$

Proof: We have $x \mid km + \ell n$ for any integers k, ℓ . So let $d = \gcd(m, n)$, then there exist integers a, b such that $am + bn = d$. But we can now just take $k = a$ and $\ell = b$. \square

We claim that $\mathbb{Z}_n[m] \cong \mathbb{Z}_{(m,n)}$, from which the result immediately follows by part 1.

Define a map

$$\begin{aligned}\phi : \mathbb{Z} &\rightarrow \mathbb{Z}_n[m] \\ 1 &\mapsto [1] \bmod n.\end{aligned}$$

The claim is that this is an isomorphism.

Then ϕ is clearly surjective (since $\mathbb{Z} \rightarrow \mathbb{Z}_n$ is a quotient map and $\mathbb{Z}_n[m]$ is a subgroup of \mathbb{Z}_n) and if we let $d := \gcd(m, n)$, we have

$$\begin{aligned} \ker \phi &= \{x \in \mathbb{Z}_n \mid mx = 0\} \\ &= \{x \in \mathbb{Z}_n \mid x \mid m\} \\ &= \{x \in \mathbb{Z} \mid x \mid n \text{ and } x \mid m\} \\ &= \{x \in \mathbb{Z} \mid x \mid d\} \quad \text{by the lemma} \\ &= d\mathbb{Z}. \end{aligned}$$

Then by the first isomorphism theorem, we have

$$\frac{\mathbb{Z}}{\ker \phi} \cong \text{im } \phi \implies \frac{\mathbb{Z}}{\gcd(m, n)\mathbb{Z}} := \mathbb{Z}_{\gcd(m, n)} \cong \mathbb{Z}_n[m].$$

1.1.3 Part 3

Let $f \in \mathbb{Z}^* = \text{hom}_{\mathbb{Z}}(\mathbb{Z}_m, \mathbb{Z})$, so $f : \mathbb{Z}_m \rightarrow \mathbb{Z}$. These are both \mathbb{Z} -modules generated by their identity elements, so such a map is determined by where it sends $[1]_{\text{mod } m}$.

So let $f([1]_{\text{mod } m}) = n \in \mathbb{Z}$. Since f is a module homomorphism, we have $f([0]_{\text{mod } m}) = 0$, and in particular we have

$$\begin{aligned} 0 &= f([0]_{\text{mod } m}) \\ &= f([m]_{\text{mod } m}) \\ &= f([1m]_{\text{mod } m}) \\ &= mf([1]_{\text{mod } m}), \end{aligned}$$

which forces $f([1]) \in \mathbb{Z}[m] = \{0\}$, so f must be the zero map and $\mathbb{Z}^* = 0$.

Note: $\mathbb{Z}[m] = 0$ because \mathbb{Z} is an integral domain, so $mx = 0$ forces $m = 0$ or $x = 0$.

1.1.4 Part 4

To see that \mathbb{Z}_m is a \mathbb{Z}_{mk} module, we define an action

$$\begin{aligned} \mathbb{Z}_{mk} &\curvearrowright \mathbb{Z}_m \\ [x]_{mk} &\curvearrowright [y]_m := [xy]_m \end{aligned}$$

This is a well-defined action:

If $[x_1]_{mk} = [x_2]_{mk}$ are two representatives of the same equivalence class, then

$$[x_1]_{mk} - [x_2]_{mk} = [x_1 - x_2]_{mk} = [0]_{mk} \implies m \mid x_1 - x_2.$$

But then

$$\begin{aligned} ([x_1]_{mk} \curvearrowright [y]_m) - ([x_2]_{mk} \curvearrowright [y]_m) &= [x_1 y]_m - [x_2 y]_m \\ &= [(x_1 - x_2)y]_m \\ &= [0]_m, \end{aligned}$$

which shows that their resulting actions on \mathbb{Z}_m are equal.

This action yields a module structure:

- $r.(x + y) = r.x + r.y$:

$$[r]_{mk} \curvearrowright ([x]_m + [y]_m) = [r]_{mk} \curvearrowright [x + y]_m = [r(x + y)]_m = [rx]_m + [ry]_m.$$

- $(r + s).x = r.x + s.x$:

$$[r]_{mk} + [s]_{mk} \curvearrowright [x]_m = [r + s]_{mk} \curvearrowright [x]_m = [(r + s)x]_m = [rx]_m + [sx]_m.$$

- $(rs).x = r.s.x$:

$$\begin{aligned} [r]_{mk} \cdot [s]_{mk} \curvearrowright [x]_m &= [rs]_{mk} \curvearrowright [x]_m \\ &= [(rs)x]_m \\ &= [r]_{mk} \curvearrowright [sx]_m \\ &= [r]_{mk} \curvearrowright ([s]_{mk} \curvearrowright [x]_m). \end{aligned}$$

- $1.x = x$:

$$[1]_{mk} \curvearrowright [x]_m = [1x]_m = [x]_m.$$

$$\mathbb{Z}_m^* := \text{hom}_{\mathbb{Z}_{mk}}(\mathbb{Z}_m, \mathbb{Z}_{mk}) \cong \mathbb{Z}_m:$$

Define a map

$$\begin{aligned} \phi : \text{hom}_{\mathbb{Z}_{mk}}(\mathbb{Z}_m, \mathbb{Z}_{mk}) &\rightarrow \mathbb{Z}_m \\ f &\mapsto [f([1]_m)]_m \end{aligned}$$

ϕ is a homomorphism, as

$$\begin{aligned} \phi(f + g) &= [(f + g)([1]_m)]_m = [f([1]_m) + g([1]_m)]_m = [f([1]_m)]_m + [g([1]_m)]_m, \\ \phi([r]_{mk} \curvearrowright f) &= [[r]_{mk} f([1]_m)]_m = [r]_m \cdot [f([1]_m)]_m = [r]_{mk} \curvearrowright \phi(f). \end{aligned}$$

ϕ is **injective**, as $[f([1]_m)]_m = [0]_m$, then for any $1 \leq \ell \leq m$, we have

$$[f([\ell]_m)]_m = [\ell f([1]_m)]_m = \ell[f([1]_m)]_m = \ell[0]_m = [0]_m,$$

so f must be the zero map.

ϕ is **surjective**, since if $[\ell]_m \in \mathbb{Z}_m$, we can define

$$\begin{aligned} f_\ell : \mathbb{Z}_m &\rightarrow \mathbb{Z}_{mk} \\ [1]_m &\mapsto [\ell]_{mk} \end{aligned}$$

which makes sense and is well-defined because $\mathbb{Z}_m \hookrightarrow \mathbb{Z}_{mk}$, and the map is defined on the generator.

So we have the desired bijection. \square

1.2 Problem 2

We have the map

$$\begin{aligned} \pi : \mathbb{Z} &\rightarrow \mathbb{Z}_2 \\ x &\mapsto [x]_2 \end{aligned}$$

which is a surjection and thus an epimorphism in the category $\mathbb{Z}\text{-Mod}$, and if we apply the functor $\text{hom}_{\mathbb{Z}}(\mathbb{Z}_2, \cdot)$ to π we obtain an induced map

$$\begin{aligned} \bar{\pi} : \text{hom}_{\mathbb{Z}}(\mathbb{Z}_2, \mathbb{Z}) &\rightarrow \text{hom}_{\mathbb{Z}}(\mathbb{Z}_2, \mathbb{Z}_2) \\ f &\mapsto \pi \circ f. \end{aligned}$$

The claim is that $\bar{\pi}$ is *not* a surjection, and thus not an epimorphism (in the same category).

To see that this is the case, we can simply note that $\text{hom}_{\mathbb{Z}}(\mathbb{Z}_2, \mathbb{Z}) = 0$ by part 3 of Problem 1, whereas $\text{hom}_{\mathbb{Z}}(\mathbb{Z}_2, \mathbb{Z}_2) \neq 0$.

For example, one can define $\text{id}_{\mathbb{Z}_2} : \mathbb{Z}_2 \rightarrow \mathbb{Z}_2$, $[x]_2 \mapsto [x]_2$, which is a nontrivial module homomorphism.

So any such f appearing must be the zero map, and thus $\bar{\pi}$ is also the zero map. \square

1.3 Problem 3

Let $f : R \rightarrow R$ be an endomorphism of R in the category of rings. We can then check that for any $r \in R$, we have $f(r) = f(r1_R) = rf(1_R)$, which says that f is given by right-multiplication by some fixed element $x_f := f(1_R)$, i.e.

$$\begin{aligned} f : R &\rightarrow R \\ r &\mapsto r \cdot x_f \end{aligned}$$

and so we can attempt to define

$$\begin{aligned} \phi_1 : \text{hom}_R(R, R) &\rightarrow R \\ f &\mapsto x_f := f(1_R) \end{aligned}$$

We can check that

$$(g \circ f)(r) = g(f(r)) = g(r \cdot x_f) = r \cdot x_f \cdot x_g,$$

which shows that in fact

$$\phi(g \circ f) = x_f \cdot x_g,$$

which reverses the multiplication. So the correct codomain is R^{op} , and we amend the definition:

$$\begin{aligned} \phi_2 : \text{hom}_R(R, R) &\rightarrow R^{op} \\ f &\mapsto x_f := f(1_R) \end{aligned}$$

By construction, ϕ_s **is a ring homomorphism**. If R is commutative, then $x_f \cdot x_g = x_g \cdot x_f$, which makes ϕ_1 a ring homomorphism as well. It remains to check that it is an isomorphism/

ϕ_1 is in injective: We can check that $\ker \phi_1 = 0$ as a ring. To that end, suppose $\phi_1(f) = x_f = 0$. Then $f(r) = r \cdot 0 = 0$, so f can only be the zero map.

ϕ_1 is surjective: Let $x \in R$ be arbitrary, then we can define $f : R \rightarrow R$ by $f(1_R) = x$, so $f(r) = r \cdot x$. This is an endomorphism of R , and thus an element of $\text{hom}_R(R, R)$.

By the first isomorphism theorem for rings, we thus have $\text{hom}_R(R, R) \cong R$. \square

1.4 Problem 4

We have maps

$$\begin{aligned} \theta_A : A &\rightarrow (A^\vee)^\vee \\ a &\mapsto (\text{ev}_a : f \mapsto f(a)) \end{aligned}$$

$$\begin{aligned} \theta_B : B &\rightarrow (B^\vee)^\vee \\ b &\mapsto (\text{ev}_b : g \mapsto g(b)) \end{aligned}$$

$$\begin{aligned} f &: A \rightarrow B \\ a &\mapsto f(a) \end{aligned}$$

$$\begin{aligned} f^\vee &: B^\vee \rightarrow A^\vee \\ g &\mapsto g \circ f \end{aligned}$$

$$\begin{aligned} f^{\vee\vee} &: A^{\vee\vee} \rightarrow B^{\vee\vee} \\ h &\mapsto h \circ f^\vee \end{aligned}$$

We can now check that $f^{\vee\vee} \circ \theta_A = \theta_B \circ f$ as maps from A to $B^{\vee\vee}$. Letting $a \in A$, and $h \in B^{\vee\vee}$ (so $h : B^\vee \rightarrow R$), we will show that both maps act on h in the same way.

For notational convenience, write $\phi \curvearrowright h := h \circ \phi$. We then have

$$\begin{aligned} (f^{\vee\vee} \circ \theta_A)(a) \curvearrowright h &:= f^{\vee\vee}(\theta_A(a)) \curvearrowright h \\ &:= f^{\vee\vee}(\text{ev}_a) \curvearrowright h \\ &= (\text{ev}_a \circ f^\vee) \curvearrowright h \\ &:= h \circ (\text{ev}_a \circ f) \\ &:= h(f(a)) \\ &= \text{ev}_{f(a)} \curvearrowright h \\ &:= \theta_B(f(a)) \curvearrowright h \\ &:= (\theta_B \circ f)(a) \curvearrowright h, \end{aligned}$$

which shows that these actions agree, and thus the diagram commutes.

1.5 Problem 5

Let E be a free module over R an integral domain. Then E has a basis $\{\mathbf{e}_i\} \subseteq F$, so if $x \neq 0 \in E$, we have

$$x = \sum_i r_i \mathbf{e}_i$$

where each $r_i \in R$. Moreover, since $x \neq 0$, at least one $r_i \neq 0$, so let r_j denote one of the nonzero coefficients.

Now suppose x is a torsion element, so $mx = 0$ for some $m \neq 0 \in E$. We can then write

$$mx = m \sum_i r_i \mathbf{e}_i = \sum_i mr_i \mathbf{e}_i = 0$$

But by linear independence, this forces $mr_i = 0$ for all i . In particular, $mr_j = 0$ where $r_j \neq 0$. But this exhibits either m or r_j as a zero divisor, and since the only zero divisor in an integral domain is zero, we must have $m = 0$ or $r_j = 0$, a contradiction.

So x can not be a torsion element. But since $x \in E$ was arbitrary, E must be torsion-free.

For an example of a torsion-free module over an integral domain that is *not* free, consider \mathbb{Q} as a \mathbb{Z} -module. Then \mathbb{Q} is clearly torsion-free, since it is an integral domain and the same argument as above applies.

But \mathbb{Q} is not free as \mathbb{Z} -module. Supposing that $\mathcal{B} = \{\mathbf{b}_1, \mathbf{b}_2, \dots\} \subset \mathbb{Q}$ was a \mathbb{Z} -basis, consider $\mathbf{b}_1 = \frac{p_1}{q_1}$ and $\mathbf{b}_2 = \frac{p_2}{q_2}$. Then $\mathbf{b}_1, \mathbf{b}_2$ can not be linearly independent over \mathbb{Z} , which follows from the fact that

$$q_1 p_2 \mathbf{b}_1 + q_2 p_1 \mathbf{b}_2 = p_2 p_1 - p_1 p_2 = 0,$$

while $q_1 p_2, q_2 p_1 \neq 0 \in \mathbb{Z}$. \square

1.6 Problem 6

If A is a cyclic module over a commutative ring R , so we have $A = Ra$ for some $a \in A$. By Hungerford's definition, the submodule A has order $r \iff$ the element a has order $r \iff$ the order ideal $\mathcal{O}_a := \{x \in R \mid xa = 0\} = (r)$.

In particular, $ra = 0$.

1.6.1 Part 1

Since $(r, s) = (1)$, we can find $t_1, t_2 \in R$ such that

$$\begin{aligned} t_1 r + t_2 s = 1 &\implies t_1 r a + t_2 s a = 1 a \\ &\implies t_1 (r a) + t_2 s a = a \\ &\implies t_2 s a = a && \text{since } r a = 0 \\ &\implies s(t_2 a) = a && \text{since } R \text{ is commutative,} \end{aligned}$$

which implies that $a \in sA$ and thus $A \subseteq sA$. However, we always have $sA \subseteq A$ for modules, so this shows that $A = sA$.

To see that $A[s] = \{x \in A \mid sx = 0\} = 0$, let $x \in A[s]$; we will show $x = 0$. Since $x \in A = Ra$, we have $x = r_1 a$, and in particular

$$ra = 0 \implies rx = rr_1 a = r_1 (ra) = 0.$$

So we now have $rx = 0$ and $sx = 0$, and we can write

$$\begin{aligned}
x &= (t_1r + t_2s)x \\
&= t_1(rx) + t_2(sx) \\
&= t_10 + t_20 \\
&= 0.
\end{aligned}$$

So $x = 0$ and thus $A[s] = 0$. \square

1.6.2 Part 2

Suppose $r = sk$. Toward an application of the first isomorphism theorem, define a map

$$\begin{aligned}
\phi : R &\rightarrow sA = sRa \\
x &\mapsto sxa.
\end{aligned}$$

ϕ is well-defined:

This follows from that fact that $a \in A \implies xA \in A$ for any $x \in R$, so the codomain is in fact sA .

ϕ is an R -module homomorphism:

We have

$$\begin{aligned}
t \in R &\implies \phi(tx) = s(tx)a = t(sxa) = t\phi(x) \\
x, y \in R &\implies \phi(x + y) = s(x + y)a = sxa + sya = \phi(x) + \phi(y)
\end{aligned}$$

$\ker \phi = (k)$:

Suppose $x \in \ker \phi$ so $sxa = 0_A$; we'd like to show $x \in (k)$.

By definition $sx \in \mathcal{O}_a$, and by assumption $\mathcal{O}_a = (r)$, so $sx = t_1r$ for some $t_1 \in R$.

$$\begin{aligned}
sxa &= 0_A \\
\implies sx &= t_1r && \text{since } sx \in \mathcal{O}_a \\
\implies sx &= t_1(sk) && \text{since } r = sk \text{ by assumption} \\
\implies sx &= s(t_1k) && \text{since elements in } R \text{ and } A \text{ commute} \\
\implies x &= t_1k && \text{since } R \text{ is a domain, so } sm = sn, s \neq 0 \implies m = n,
\end{aligned}$$

which exhibits $x = t_1k \implies x \in (k)$ as desired.

ϕ is surjective:

Since $A = Ra$, we have $sA = sRA$ and thus $x \in sA \implies x = sra$ for some $r \in R$; but then $\phi(r) = sra = x$.

We thus have

$$R/\ker \phi \cong \text{im } \phi \implies R/(k) \cong sA.$$

Similarly, define a map

$$\begin{aligned} \psi : R &\rightarrow A[s] \\ x &\mapsto kxa \end{aligned}$$

ψ is well-defined:

It suffices to check that $\text{im } \psi \subseteq A[s]$ (since we will show surjectivity shortly), i.e. that s annihilates anything in the image. This follows from

$$s(kxa) = (sk)xa = rxa = x(ra) = 0,$$

since $ra = 0$ by assumption.

ψ is an R -module homomorphism:

We can check

$$\psi(tr_1 + r_2) = k(tr_1 + r_2)s = tkr_1s + kr_2s = t\psi(r_1) + \psi(r_2)$$

which follows because elements of R commute with those from A under multiplication.

$\ker \psi = (s)$:

Suppose $x \in \ker \psi$, so $kxa = 0$. Then $kx \in \mathcal{O}_a = (r)$, so $kx = rt_1$. Then

$$\begin{aligned} kxa &= 0_A \\ \implies kx &= rt_1 && \text{since } kx \in \mathcal{O}_a \\ \implies kx &= (sk)t_1 && \text{since } r = sk \\ \implies kx &= k(st_1) && \text{since } R \text{ is commutative} \\ \implies x &= st_1 && \text{since } R \text{ is a domain,} \end{aligned}$$

and so $x \in (s)$ as desired.

ψ is surjective:

Letting $y \in A[s]$ be arbitrary. We have

$$\begin{aligned}
y \in A[s] &\implies x = t_1 a, \quad sx = 0 \\
&\implies s(t_1 a) = 0 \\
&\implies st_1 \in \mathcal{O}_a \implies \exists x \in R \ni st_1 = xr = x(sk) \\
&\implies st_1 = sxk \\
&\implies t_1 = xk \quad \text{since } R \text{ is a domain} \\
&\implies y = t_1 a = (xk)a = kxa,
\end{aligned}$$

so $\psi(x) = y$.

We can then apply the first isomorphism theorem

$$R/\ker \psi \cong \text{im } \psi \implies R/(s) \cong A[s].$$

□

1.7 Problem 7

Lemma: If M is a cyclic module over a PID, then M has exactly 1 invariant factor.

Lemma: Let A be a cyclic module, so $A = Ra$. If the order of A is r , so $\mathcal{O}_a = (r)$, then $A \cong R/(r)$.

This means that we can write $A = R/(a)$ and $B = R/(b)$, and a, b are the invariant factors of A, B respectively.

We can now write

$$A \oplus B = R/(a) \oplus R/(b)$$

TODO

2 Qual Problems

2.1 Problem 8

2.1.1 Part 1

The claim is that every element in $M := R^n/\text{im } A$ is torsion \iff the matrix rank of A is exactly $n \iff$ the Smith normal form of A has exactly n nonzero invariant factors.

To see that this is the case, we can apply the structure theorem for finitely-generated modules over a PID. This gives us

$$M \cong F \oplus \bigoplus R/(r_i)$$

where F is free of finite rank, $R/(r_i)$ is cyclic torsion, and $r_i \mid r_{i+1} \mid \dots$ are the invariant factors of M .

We thus have

$$M \cong R^n / \text{im } A \cong F \oplus \bigoplus R/(r_i),$$

which will be pure torsion if and only if $F = 0$.

But if we compute the smith normal form of A , we obtain

$$SNF(A) = \begin{bmatrix} d_1 & 0 & \cdots & 0 & \cdots & 0 \\ 0 & d_2 & & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \cdots & 0 \\ 0 & 0 & \cdots & d_n & \cdots & 0 \end{bmatrix}$$

where $d_1 \mid d_2 \mid \cdots \mid d_n$, and thus

$$\text{im } A \cong \text{im } SNF(A) \cong d_1 R \oplus d_2 R \oplus \cdots \oplus d_n R$$

$$\implies M = R^n / \text{im } A \cong \frac{R^n}{d_1 R \oplus d_2 R \oplus \cdots \oplus d_n R}$$

$$\cong R/(d_1) \oplus R/(d_2) \cdots \oplus R/(d_n)$$

where $R/(d_i)$ is a cyclic torsion module precisely when $d_i \neq 0$. If instead some $d_i = 0$, we then have $R/(d_i) \cong R$, which is a free R -module, yielding non-torsion elements in M .

But $\det(A) = \det(SNF(A)) = \prod_{i=1}^n d_i$, and so if $d_i = 0$ for some i iff $\det A = 0$ iff $\text{rank } A < n$.

2.1.2 Part 2

Identifying

$$R \times F = F[x] \oplus F \cong F[x] \oplus \frac{F[x]}{(f)}$$

where f is any degree 1 polynomial in $F[x]$, by the structure theorem we can pick a matrix $A \in M_2(F[x])$ with invariant factors $d_1 = 0, d_2 = f$. Then by the same argument given in part 1, we would have

$$(F[x])^2 / \text{im } A \cong \frac{F[x]}{(d_1)} \oplus \frac{F[x]}{(d_2)} = F[x] \oplus \frac{F[x]}{(f)}$$

So we can choose $n = 2$, and say $f(x) = x + 1$, and then just pick a matrix that is already in Smith normal form:

$$A = \begin{bmatrix} x+1 & 0 \\ 0 & 0 \end{bmatrix}.$$

2.2 Problem 9

2.2.1 Part 1

Let M be a finitely generated module over R a PID.

Then

$$M \cong F \oplus \bigoplus_{i=1}^n R/(d_i)$$

where F is free of finite rank and $R/(d_i)$ are cyclic torsion modules (the *invariant factors*) satisfying $d_1 \mid d_2 \mid \cdots \mid d_n$.

Equivalently,

$$M \cong F \oplus \bigoplus_{i=1}^n R/(p_i^{s_i})$$

where F is free of finite rank, $p^i \in R$ are (not necessarily distinct) prime elements (the *elementary divisors*), and $s_i \in \mathbb{Z}^{\geq 1}$.