

V

More on Groups

Part V: Contents

16	Group actions overkill AIME problems	209
16.1	Definition of a group action	209
16.2	Stabilizers and orbits	210
16.3	Burnside's lemma	211
16.4	Conjugation of elements	212
16.5	A few harder problems to think about	213
17	Find all groups	215
17.1	Sylow theorems	215
17.2	(Optional) Proving Sylow's theorem	216
17.3	(Optional) Simple groups and Jordan-Hölder	218
17.4	A few harder problems to think about	219
18	The PID structure theorem	221
18.1	Finitely generated abelian groups	221
18.2	Some ring theory prerequisites	222
18.3	The structure theorem	223
18.4	Reduction to maps of free R -modules	224
18.5	Uniqueness of primary form	225
18.6	Smith normal form	227
18.7	A few harder problems to think about	230

16 Group actions overkill AIME problems

Consider this problem from the 1996 AIME:

(AIME 1996) Two of the squares of a 7×7 checkerboard are painted yellow, and the rest are painted green. Two color schemes are equivalent if one can be obtained from the other by applying a rotation in the plane of the board. How many inequivalent color schemes are possible?

What's happening here? Let X be the set of the $\binom{49}{2}$ possible colorings of the board. What's the natural interpretation of "rotation"? Answer: the group $\mathbb{Z}/4\mathbb{Z} = \langle r \mid r^4 = 1 \rangle$ somehow "acts" on this set X by sending one state $x \in X$ to another state $r \cdot x$, which is just x rotated by 90° . Intuitively we're just saying that two configurations are the same if they can be reached from one another by this "action".

We can make all of this precise using the idea of a group action.

§16.1 Definition of a group action

Prototypical example for this section: The AIME problem.

Definition 16.1.1. Let X be a set and G a group. A **group action** is a binary operation $\cdot : G \times X \rightarrow X$ which lets a $g \in G$ send an $x \in X$ to $g \cdot x$. It satisfies the axioms

- $(g_1 g_2) \cdot x = g_1 \cdot (g_2 \cdot x)$ for any $g_1, g_2 \in G$ for all $x \in X$.
- $1_G \cdot x = x$ for any $x \in X$.

Example 16.1.2 (Examples of group actions)

Let $G = (G, \star)$ be a group.

- The group $\mathbb{Z}/4\mathbb{Z}$ can act on the set of ways to color a 7×7 board either yellow or green.
- The group $\mathbb{Z}/4\mathbb{Z} = \langle r \mid r^4 = 1 \rangle$ acts on the xy -plane \mathbb{R}^2 as follows: $r \cdot (x, y) = (y, -x)$. In other words, it's a rotation by 90° .
- The dihedral group D_{2n} acts on the set of ways to color the vertices of an n -gon.
- The group S_n acts on $X = \{1, 2, \dots, n\}$ by applying the permutation $\sigma : \sigma \cdot x := \sigma(x)$.
- The group G can act on itself (i.e. $X = G$) by left multiplication: put $g \cdot g' := g \star g'$.

Exercise 16.1.3. Show that a group action can equivalently be described as a group homomorphism from G to S_X , where S_X is the symmetric group of permutations on X .

§16.2 Stabilizers and orbits

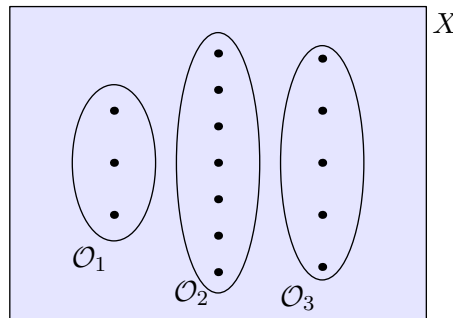
Prototypical example for this section: Again the AIME problem.

Given a group action G on X , we can define an equivalence relation \sim on X as follows: $x \sim y$ if $x = g \cdot y$ for some $g \in G$. For example, in the AIME problem, \sim means “one can be obtained from the other by a rotation”.

Question 16.2.1. Why is this an equivalence relation?

In that case, the AIME problem wants the number of equivalence classes under \sim . So let's give these equivalence classes a name: **orbits**. We usually denote orbits by \mathcal{O} .

As usual, orbits carve out X into equivalence classes.



It turns out that a very closely related concept is:

Definition 16.2.2. The **stabilizer** of a point $x \in X$, denoted $\text{Stab}_G(x)$, is the set of $g \in G$ which fix x ; in other words

$$\text{Stab}_G(x) := \{g \in G \mid g \cdot x = x\}.$$

Example 16.2.3

Consider the AIME problem again, with X the possible set of states (again $G = \mathbb{Z}/4\mathbb{Z}$). Let x be the configuration where two opposite corners are colored yellow. Evidently 1_G fixes x , but so does the 180° rotation r^2 . But r and r^3 do not preserve x , so $\text{Stab}_G(x) = \{1, r^2\} \cong \mathbb{Z}/2\mathbb{Z}$.

Question 16.2.4. Why is $\text{Stab}_G(x)$ a subgroup of G ?

Once we realize the stabilizer is a group, this leads us to what I privately call the “fundamental theorem of how big an orbit is”.

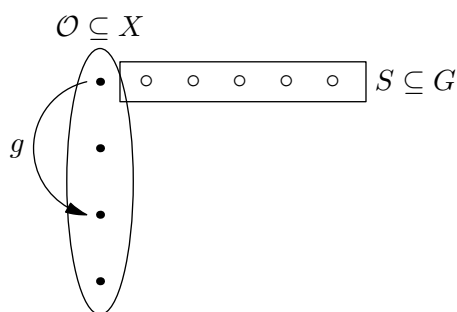
Theorem 16.2.5 (Orbit-stabilizer theorem)

Let \mathcal{O} be an orbit, and pick any $x \in \mathcal{O}$. Let $S = \text{Stab}_G(x)$ be a subgroup of G . There is a natural bijection between \mathcal{O} and left cosets. In particular,

$$|\mathcal{O}| |S| = |G|.$$

In particular, the stabilizers of each $x \in \mathcal{O}$ have the same size.

Proof. The point is that every coset gS just specifies an element of \mathcal{O} , namely $g \cdot x$. The fact that S is a stabilizer implies that it is irrelevant which representative we pick.



Since the $|\mathcal{O}|$ cosets partition G , each of size $|S|$, we obtain the second result. \square

§16.3 Burnside's lemma

Now for the crux of this chapter: a way to count the number of orbits.

Theorem 16.3.1 (Burnside's lemma)

Let G act on a set X . The number of orbits of the action is equal to

$$\frac{1}{|G|} \sum_{g \in G} |\text{FixPt } g|$$

where $\text{FixPt } g$ is the set of points $x \in X$ such that $g \cdot x = x$.

The proof is deferred as a bonus problem, since it has a very olympiad-flavored solution. As usual, this lemma was not actually proven by Burnside; Cauchy got there first, and thus it is sometimes called *the lemma that is not Burnside's*. Example application:

Example 16.3.2 (AIME 1996)

Two of the squares of a 7×7 checkerboard are painted yellow, and the rest are painted green. Two color schemes are equivalent if one can be obtained from the other by applying a rotation in the plane of the board. How many inequivalent color schemes are possible?

We know that $G = \mathbb{Z}/4\mathbb{Z}$ acts on the set X of $\binom{49}{2}$ possible coloring schemes. Now we can compute $\text{FixPt } g$ explicitly for each $g \in \mathbb{Z}/4\mathbb{Z}$.

- If $g = 1_G$, then every coloring is fixed, for a count of $\binom{49}{2} = 1176$.
- If $g = r^2$ there are exactly 24 coloring schemes fixed by g : this occurs when the two squares are reflections across the center, which means they are preserved under a 180° rotation.
- If $g = r$ or $g = r^3$, then there are no fixed coloring schemes.

As $|G| = 4$, the average is

$$\frac{1176 + 24 + 0 + 0}{4} = 300.$$

Exercise 16.3.3 (MathCounts Chapter Target Round). A circular spinner has seven sections of equal size, each of which is colored either red or blue. Two colorings are considered the same if one can be rotated to yield the other. In how many ways can the spinner be colored? (Answer: 20)

Consult [Ma13b] for some more examples of “hands-on” applications.

§16.4 Conjugation of elements

Prototypical example for this section: In S_n , conjugacy classes are “cycle types”.

A particularly common type of action is the so-called **conjugation**. We let G act on itself as follows:

$$g: h \mapsto ghg^{-1}.$$

You might think this definition is a little artificial. Who cares about the element ghg^{-1} ? Let me try to convince you this definition is not so unnatural.

Example 16.4.1 (Conjugacy in S_n)

Let $G = S_5$, and fix a $\pi \in S_5$. Here’s the question: is $\pi\sigma\pi^{-1}$ related to σ ? To illustrate this, I’ll write out a completely random example of a permutation $\sigma \in S_5$.

$$\begin{array}{rcl} \text{If } \sigma = & \begin{array}{l} 1 \mapsto 3 \\ 2 \mapsto 1 \\ 3 \mapsto 5 \\ 4 \mapsto 2 \\ 5 \mapsto 4 \end{array} & \text{then } \pi\sigma\pi^{-1} = \begin{array}{l} \pi(1) \mapsto \pi(3) \\ \pi(2) \mapsto \pi(1) \\ \pi(3) \mapsto \pi(5) \\ \pi(4) \mapsto \pi(2) \\ \pi(5) \mapsto \pi(4) \end{array} \end{array}$$

Thus our fixed π doesn’t really change the structure of σ at all: it just “renames” each of the elements 1, 2, 3, 4, 5 to $\pi(1)$, $\pi(2)$, $\pi(3)$, $\pi(4)$, $\pi(5)$.

But wait, you say. That’s just a very particular type of group behaving nicely under conjugation. Why does this mean anything more generally? All I have to say is: remember Cayley’s theorem! (This was **Problem 1F†**.)

In any case, we may now define:

Definition 16.4.2. The **conjugacy classes** of a group G are the orbits of G under the conjugacy action.

Let’s see what the conjugacy classes of S_n are, for example.

Example 16.4.3 (Conjugacy classes of S_n correspond to cycle types)

Intuitively, the discussion above says that two elements of S_n should be conjugate if they have the same “shape”, regardless of what the elements are named. The right way to make the notion of “shape” rigorous is cycle notation. For example, consider the permutation

$$\sigma_1 = (1\ 3\ 5)(2\ 4)$$

in cycle notation, meaning $1 \mapsto 3 \mapsto 5 \mapsto 1$ and $2 \mapsto 4 \mapsto 2$. It is conjugate to the permutation

$$\sigma_2 = (1\ 2\ 3)(4\ 5)$$

or any other way of relabeling the elements. So, we could think of σ as having conjugacy class

$$(- - -)(- -).$$

More generally, you can show that two elements of S_n are conjugate if and only if they have the same “shape” under cycle decomposition.

Question 16.4.4. Show that the number of conjugacy classes of S_n equals the number of partitions of n .

As long as I’ve put the above picture, I may as well also define:

Definition 16.4.5. Let G be a group. The **center** of G , denoted $Z(G)$, is the set of elements $x \in G$ such that $xg = gx$ for every $g \in G$. More succinctly,

$$Z(G) := \{x \in G \mid gx = xg \forall g \in G\}.$$

You can check this is indeed a subgroup of G .

Question 16.4.6. Why is $Z(G)$ normal in G ?

Question 16.4.7. What are the conjugacy classes of elements in the center?

A trivial result that gets used enough that I should explicitly call it out:

Corollary 16.4.8 (Conjugacy in abelian groups is trivial)

If G is abelian, then the conjugacy classes all have size one.

§16.5 A few harder problems to think about

Problem 16A (PUMaC 2009 C8). Taotao wants to buy a bracelet consisting of seven beads, each of which is orange, white or black. (The bracelet can be rotated and reflected in space.) Find the number of possible bracelets.

Problem 16B. Show that two elements in the same conjugacy class have the same order.



Problem 16C. Prove Burnside’s lemma.

Problem 16D* (The “class equation”). Let G be a finite group. We define the **centralizer** $C_G(g) = \{x \in G \mid xg = gx\}$ for each $g \in G$. Show that

$$|G| = |Z(G)| + \sum_{s \in S} \frac{|G|}{|C_G(s)|}$$

where $S \subseteq G$ is defined as follows: for each conjugacy class $C \subseteq G$ with $|C| > 1$, we pick a representative of C and add it to S .



Problem 16E† (Classical). Assume G is a finite group and p is the smallest prime dividing its order. Let H be a subgroup of G with $|G|/|H| = p$. Show that H is normal in G .

Problem 16F (Athemath Community-Building Event #1, Fall 2022). A group action \cdot of a group G on set X is said to be

- **transitive** if for all $x_1, x_2 \in X$, there exists a g such that $g \cdot x_1 = x_2$;
- **faithful** if the only element $g \in G$ such that $g \cdot x = x$ for every $x \in X$ is $g = 1_G$. In other words, the only element which acts trivially on the entire set X is the identity element of G .

Does there exist a faithful transitive action of S_5 on a six-element set?

17 Find all groups

The following problem will hopefully never be proposed at the IMO.

Let n be a positive integer and let $S = \{1, \dots, n\}$. Find all functions $f: S \times S \rightarrow S$ such that

- (a) $f(x, 1) = f(1, x) = x$ for all $x \in S$.
- (b) $f(f(x, y), z) = f(x, f(y, z))$ for all $x, y, z \in S$.
- (c) For every $x \in S$ there exists a $y \in S$ such that $f(x, y) = f(y, x) = 1$.

Nonetheless, it's remarkable how much progress we've made on this "problem". In this chapter I'll try to talk about some things we have accomplished.

§17.1 Sylow theorems

Here we present the famous Sylow theorems, some of the most general results we have about finite groups.

Theorem 17.1.1 (The Sylow theorems)

Let G be a group of order $p^n m$, where $\gcd(p, m) = 1$ and p is a prime. A **Sylow p -subgroup** is a subgroup of order p^n . Let n_p be the number of Sylow p -subgroups of G . Then

- (a) $n_p \equiv 1 \pmod{p}$. In particular, $n_p \neq 0$ and a Sylow p -subgroup exists.
- (b) n_p divides m .
- (c) Any two Sylow p -subgroups are conjugate subgroups (hence isomorphic).

Sylow's theorem is really huge for classifying groups; in particular, the conditions $n_p \equiv 1 \pmod{p}$ and $n_p \mid m$ can often pin down the value of n_p to just a few values. Here are some results which follow from the Sylow theorems.

- A Sylow p -subgroup is normal if and only if $n_p = 1$.
- Any group G of order pq , where $p < q$ are primes, must have $n_q = 1$, since $n_q \equiv 1 \pmod{q}$ yet $n_q \mid p$. Thus G has a normal subgroup of order q .
- Since any abelian group has all subgroups normal, it follows that any abelian group has exactly one Sylow p -subgroup for every p dividing its order.
- If $p \neq q$, the intersection of a Sylow p -subgroup and a Sylow q -subgroup is just $\{1_G\}$. That's because the intersection of any two subgroups is also a subgroup, and Lagrange's theorem tells us that its order must divide both a power of p and a power of q ; this can only happen if the subgroup is trivial.

Here's an example of another "practical" application.

Proposition 17.1.2 (Triple product of primes)

If $|G| = pqr$ is the product of distinct primes, then G must have a normal Sylow subgroup.

Proof. WLOG, assume $p < q < r$. Notice that $n_p \equiv 1 \pmod{p}$, $n_p | qr$ and cyclically, and assume for contradiction that $n_p, n_q, n_r > 1$.

Since $n_r | pq$, we have $n_r = pq$ since n_r divides neither p nor q as $n_r \geq 1 + r > p, q$. Also, $n_p \geq 1 + p$ and $n_q \geq 1 + q$. So we must have at least $1 + p$ Sylow p -subgroups, at least $1 + q$ Sylow q -subgroups, and at least pq Sylow r -subgroups.

But these groups are pretty exclusive.

Question 17.1.3. Take the $n_p + n_q + n_r$ Sylow subgroups and consider two of them, say H_1 and H_2 . Show that $|H_1 \cap H_2| = 1$ as follows: check that $H_1 \cap H_2$ is a subgroup of both H_1 and H_2 , and then use Lagrange's theorem.

We claim that there are too many elements now. Indeed, if we count the non-identity elements contributed by these subgroups, we get

$$n_p(p-1) + n_q(q-1) + n_r(r-1) \geq (1+p)(p-1) + (1+q)(q-1) + pq(r-1) > pqr$$

which is more elements than G has! □

§17.2 (Optional) Proving Sylow's theorem

The proof of Sylow's theorem is somewhat involved, and in fact many proofs exist. I'll present one below here. It makes extensive use of group actions, so I want to recall a few facts first. If G acts on X , then

- The orbits of the action form a partition of X .
- if \mathcal{O} is any orbit, then the orbit-stabilizer theorem says that

$$|\mathcal{O}| = |G| / |\text{Stab}_G(x)|$$

for any $x \in \mathcal{O}$.

- In particular: suppose in the above that G is a **p -group**, meaning $|G| = p^t$ for some t . Then either $|\mathcal{O}| = 1$ or p divides $|\mathcal{O}|$. In the case $\mathcal{O} = \{x\}$, then by definition, x is a **fixed point** of every element of G : we have $g \cdot x = x$ for every g .

Note that when I say x is a fixed point, I mean it is fixed by **every** element of the group, i.e. the orbit really has size one. Hence that's a really strong condition.

§17.2.i Definitions

Prototypical example for this section: Conjugacy in S_n .

I've defined conjugacy of elements previously, but I now need to define it for groups:

Definition 17.2.1. Let G be a group, and let X denote the set of subgroups of G . Then **conjugation** is the action of G on X that sends

$$H \mapsto gHg^{-1} = \{ghg^{-1} \mid h \in H\}.$$

If H and K are subgroups of G such that $H = gKg^{-1}$ for some $g \in G$ (in other words, they are in the same orbit under this action), then we say they are **conjugate** subgroups.

Because we somehow don't think of conjugate elements as "that different" (for example, in permutation groups), the following shouldn't be surprising:

Question 17.2.2. Show that for any subgroup H of a group G , the map $H \rightarrow gHg^{-1}$ by $h \mapsto ghg^{-1}$ is in fact an isomorphism. This implies that any two conjugate subgroups are isomorphic.

Definition 17.2.3. For any subgroup H of G the **normalizer** of H is defined as

$$N_G(H) := \{g \in G \mid gHg^{-1} = H\}.$$

In other words, it is the stabilizer of H under the conjugation action.

We are now ready to present the proof.

§17.2.ii Step 1: Prove that a Sylow p -subgroup exists

What follows is something like the probabilistic method. By considering the set X of ALL subsets of size p^n at once, we can exploit the "deep number theoretic fact" that

$$|X| = \binom{p^n m}{p^n} \not\equiv 0 \pmod{p}.$$

(It's not actually deep: use Lucas' theorem.)

Here is the proof.

- Let G act on X by $g \cdot X := \{gx \mid x \in X\}$.
- Take an orbit \mathcal{O} with size not divisible by p . (This is possible because of our deep number theoretic fact. Since $|X|$ is nonzero mod p and the orbits partition X , the claimed orbit must exist.)
- Let $S \in \mathcal{O}$, $H = \text{Stab}_G(S)$. Then p^n divides $|H|$, by the orbit-stabilizer theorem.
- Consider a second action: let H act on S by $h \cdot s := hs$ (we know $hs \in S$ since $H = \text{Stab}_G(S)$).
- Observe that $\text{Stab}_H(s) = \{1_H\}$. Then all orbits of the second action must have size $|H|$. Thus $|H|$ divides $|S| = p^n$.
- This implies $|H| = p^n$, and we're done.

§17.2.iii Step 2: Any two Sylow p -subgroups are conjugate

Let P be a Sylow p -subgroup (which exists by the previous step). We now prove that for any p -group Q , $Q \subseteq gPg^{-1}$. Note that if Q is also a Sylow p -subgroup, then $Q = gPg^{-1}$ for size reasons; this implies that any two Sylow subgroups are indeed conjugate.

Let Q act on the set of left cosets of P by left multiplication. Note that

- Q is a p -group, so any orbit has size divisible by p unless it's 1.
- But the number of left cosets is m , which isn't divisible by p .

Hence some coset gP is a fixed point for every q , meaning $qgP = gP$ for all q . Equivalently, $qg \in gP$ for all $q \in Q$, so $Q \subseteq gPg^{-1}$ as desired.

§17.2.iv Step 3: Showing $n_p \equiv 1 \pmod{p}$

Let \mathcal{S} denote the set of all the Sylow p -subgroups. Let $P \in \mathcal{S}$ be arbitrary.

Question 17.2.4. Why does $|\mathcal{S}|$ equal n_p ? (In other words, are you awake?)

Now we can proceed with the proof. Let P act on \mathcal{S} by conjugation. Then:

- Because P is a p -group, $n_p \pmod{p}$ is the number of fixed points of this action. Now we claim P is the only fixed point of this action.
- Let Q be any other fixed point, meaning $xQx^{-1} = Q$ for any $x \in P$.
- Define the normalizer $N_G(Q) = \{g \in G \mid gQg^{-1} = Q\}$. It contains both P and Q .
- Now for the crazy part: apply Step 2 to $N_G(Q)$. Since P and Q are Sylow p -subgroups of it, they must be conjugate.
- Hence $P = Q$, as desired.

§17.2.v Step 4: n_p divides m

Since $n_p \equiv 1 \pmod{p}$, it suffices to show n_p divides $|G|$. Let G act on the set of all Sylow p -groups by conjugation. Step 2 says this action has only one orbit, so the orbit-stabilizer theorem implies n_p divides $|G|$.

§17.3 (Optional) Simple groups and Jordan-Hölder

Prototypical example for this section: Decomposition of $\mathbb{Z}/12\mathbb{Z}$ is $1 \trianglelefteq \mathbb{Z}/2\mathbb{Z} \trianglelefteq \mathbb{Z}/4\mathbb{Z} \trianglelefteq \mathbb{Z}/12\mathbb{Z}$.

Just like every integer breaks down as the product of primes, we can try to break every group down as a product of “basic” groups. Armed with our idea of quotient groups, the right notion is this.

Definition 17.3.1. A **simple group** is a group with no normal subgroups other than itself and the trivial group.

Question 17.3.2. For which n is $\mathbb{Z}/n\mathbb{Z}$ simple? (Hint: remember that $\mathbb{Z}/n\mathbb{Z}$ is abelian.)

Then we can try to define what it means to “break down a group”.

Definition 17.3.3. A **composition series** of a group G is a sequence of subgroups H_0, H_1, \dots, H_n such that

$$\{1\} = H_0 \trianglelefteq H_1 \trianglelefteq H_2 \trianglelefteq \dots \trianglelefteq H_n = G$$

of maximal length (i.e. n is as large as possible, but all H_i are of course distinct). The **composition factors** are the groups $H_1/H_0, H_2/H_1, \dots, H_n/H_{n-1}$.

You can show that the “maximality” condition implies that the composition factors are all simple groups.

Let’s say two composition series are equivalent if they have the same composition factors (up to permutation); in particular they have the same length. Then it turns out that the following theorem *is* true.

Theorem 17.3.4 (Jordan-Hölder)

Every finite group G admits a unique composition series up to equivalence.

Example 17.3.5 (Fundamental theorem of arithmetic when $n = 12$)

Let's consider the group $\mathbb{Z}/12\mathbb{Z}$. It's not hard to check that the possible composition series are

$$\begin{aligned} \{1\} &\trianglelefteq \mathbb{Z}/2\mathbb{Z} \trianglelefteq \mathbb{Z}/4\mathbb{Z} \trianglelefteq \mathbb{Z}/12\mathbb{Z} \text{ with factors } \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}/3\mathbb{Z} \\ \{1\} &\trianglelefteq \mathbb{Z}/2\mathbb{Z} \trianglelefteq \mathbb{Z}/6\mathbb{Z} \trianglelefteq \mathbb{Z}/12\mathbb{Z} \text{ with factors } \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}/3\mathbb{Z}, \mathbb{Z}/2\mathbb{Z} \\ \{1\} &\trianglelefteq \mathbb{Z}/3\mathbb{Z} \trianglelefteq \mathbb{Z}/6\mathbb{Z} \trianglelefteq \mathbb{Z}/12\mathbb{Z} \text{ with factors } \mathbb{Z}/3\mathbb{Z}, \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}/2\mathbb{Z}. \end{aligned}$$

These correspond to the factorization $12 = 2^2 \cdot 3$.

This suggests that classifying all finite simple groups would be great progress, since every finite group is somehow a “product” of simple groups; the only issue is that there are multiple ways of building a group from constituents.

Amazingly, we actually *have* a full list of simple groups, but the list is really bizarre. Every finite simple group falls in one of the following categories:

- $\mathbb{Z}/p\mathbb{Z}$ for p a prime,
- For $n \geq 5$, the subgroup of S_n consisting of “even” permutations.
- A simple group of Lie type (which I won't explain), and
- Twenty-six “sporadic” groups which do not fit into any nice family.

The two largest of the sporadic groups have cute names. The **baby monster group** has order

$$2^{41} \cdot 3^{13} \cdot 5^6 \cdot 7^2 \cdot 11 \cdot 13 \cdot 17 \cdot 19 \cdot 23 \cdot 31 \cdot 47 \approx 4 \cdot 10^{33}$$

and the **monster group** (also “friendly giant”) has order

$$2^{46} \cdot 3^{20} \cdot 5^9 \cdot 7^6 \cdot 11^2 \cdot 13^3 \cdot 17 \cdot 19 \cdot 23 \cdot 29 \cdot 31 \cdot 41 \cdot 47 \cdot 59 \cdot 71 \approx 8 \cdot 10^{53}.$$

It contains twenty of the sporadic groups as subquotients (including itself), and these twenty groups are called the “**happy family**”.


Math is weird.



Question 17.3.6. Show that “finite simple group of order 2” is redundant in the sense that any group of order 2 is both finite and simple.

§17.4 A few harder problems to think about

Problem 17A* (Cauchy's theorem). Let G be a group and let p be a prime dividing $|G|$. Prove¹ that G has an element of order p .

Problem 17B. Let G be a finite simple group. Show that $|G| \neq 56$.

 **Problem 17C** (Engel's PSS?). Consider the set of all words consisting of the letters a and b . Given such a word, we can change the word either by inserting a word of the form www , where w is a word, anywhere in the given word, or by deleting such a sequence from the word. Can we turn the word ab into the word ba ?

  **Problem 17D.** Let p be a prime and suppose G is a simple group whose order is a power of p . Show that $G \cong \mathbb{Z}/p\mathbb{Z}$.

¹Cauchy's theorem can be proved without the Sylow theorems, and in fact can often be used to give alternate proofs of Sylow.

18 The PID structure theorem

The main point of this chapter is to discuss a classification theorem for finitely generated abelian groups. This won't take long to do, and if you like, you can read just the first section and then move on.

However, since I'm here, I will go ahead and state the result as a special case of the much more general *structure theorem*. Its corollaries include

- All finite-dimensional vector spaces are $k^{\oplus n}$.
- The classification theorem for finitely generated abelian groups,
- The Jordan decomposition of a matrix from before,
- Another canonical form for a matrix: “Frobenius normal form”.

§18.1 Finitely generated abelian groups

Remark 18.1.1 — We talk about abelian groups in what follows, but really the morally correct way to think about these structures is as \mathbb{Z} -modules.

Definition 18.1.2. An abelian group $G = (G, +)$ is **finitely generated** if it is finitely generated as a \mathbb{Z} -module. (That is, there exists a finite collection $b_1, \dots, b_m \in G$, such that every $x \in G$ can be written in the form $c_1 b_1 + \dots + c_m b_m$ for some $c_1, \dots, c_m \in \mathbb{Z}$.)

Example 18.1.3 (Examples of finitely generated abelian groups)

- (a) \mathbb{Z} is finitely generated (by 1).
- (b) $\mathbb{Z}/n\mathbb{Z}$ is finitely generated (by 1).
- (c) $\mathbb{Z}^{\oplus 2}$ is finitely generated (by two elements $(1, 0)$ and $(0, 1)$).
- (d) $\mathbb{Z}^{\oplus 3} \oplus \mathbb{Z}/9\mathbb{Z} \oplus \mathbb{Z}/2016\mathbb{Z}$ is finitely generated by five elements.
- (e) $\mathbb{Z}/3\mathbb{Z} \oplus \mathbb{Z}/5\mathbb{Z}$ is finitely generated by two elements.

Exercise 18.1.4. In fact $\mathbb{Z}/3\mathbb{Z} \oplus \mathbb{Z}/5\mathbb{Z}$ is generated by *one* element. What is it?

You might notice that these examples are not very diverse. That's because they are actually the only examples:

Theorem 18.1.5 (Fundamental theorem of finitely generated abelian groups)

Let G be a finitely generated abelian group. Then there exists an integer r , prime powers q_1, \dots, q_m (not necessarily distinct) such that

$$G \cong \mathbb{Z}^{\oplus r} \oplus \mathbb{Z}/q_1\mathbb{Z} \oplus \mathbb{Z}/q_2\mathbb{Z} \oplus \dots \oplus \mathbb{Z}/q_m\mathbb{Z}.$$

This decomposition is unique up to permutation of the $\mathbb{Z}/q_i\mathbb{Z}$.

Definition 18.1.6. The **rank** of a finitely generated abelian group G is the integer r above.

Now, we could prove this theorem, but it is more interesting to go for the gold and state and prove the entire structure theorem.

§18.2 Some ring theory prerequisites

Prototypical example for this section: $R = \mathbb{Z}$.

Before I can state the main theorem, I need to define a few terms for UFD's, which behave much like \mathbb{Z} :

Our intuition from the case $R = \mathbb{Z}$ basically carries over verbatim.

We don't even need to deal with prime ideals and can factor elements instead.

Definition 18.2.1. If R is a UFD, then $p \in R$ is a **prime element** if (p) is a prime ideal and $p \neq 0$. For UFD's this is equivalent to: if $p = xy$ then either x or y is a unit.

So for example in \mathbb{Z} the set of prime elements is $\{\pm 2, \pm 3, \pm 5, \dots\}$. Now, since R is a UFD, every element r factors into a product of prime elements

$$r = up_1^{e_1} p_2^{e_2} \dots p_m^{e_m}$$

Definition 18.2.2. We say r **divides** s if $s = r'r$ for some $r' \in R$. This is written $r \mid s$.

Example 18.2.3 (Divisibility in \mathbb{Z})

The number 0 is divisible by every element of \mathbb{Z} . All other divisibility as expected.

Question 18.2.4. Show that $r \mid s$ if and only if the exponent of each prime in r is less than or equal to the corresponding exponent in s .

Now, the case of interest is the even stronger case when R is a PID:

Proposition 18.2.5 (PID's are Noetherian UFD's)

If R is a PID, then it is Noetherian and also a UFD.

Proof. The fact that R is Noetherian is obvious. For R to be a UFD we essentially repeat the proof for \mathbb{Z} , using the fact that (a, b) is principal in order to extract $\gcd(a, b)$. \square

In this case, we have a Chinese remainder theorem for elements.

Theorem 18.2.6 (Chinese remainder theorem for rings)

Let m and n be relatively prime elements, meaning $(m) + (n) = (1)$. Then

$$R/(mn) \cong R/(m) \times R/(n).$$

Here the ring product is as defined in [Example 4.3.8](#).

Proof. This is the same as the proof of the usual Chinese remainder theorem. First, since $(m, n) = (1)$ we have $am + bn = 1$ for some a and b . Then we have a map

$$R/(m) \times R/(n) \rightarrow R/(mn) \quad \text{by} \quad (r, s) \mapsto r \cdot bn + s \cdot am.$$

One can check that this map is well-defined and an isomorphism of rings. (Diligent readers invited to do so.) \square

Finally, we need to introduce the concept of a Noetherian R -module.

Definition 18.2.7. An R -module M is **Noetherian** if it satisfies one of the two equivalent conditions:

- Its submodules obey the ascending chain condition: there is no infinite sequence of modules $M_1 \subsetneq M_2 \subsetneq \dots$
- All submodules of M (including M itself) are finitely generated.

This generalizes the notion of a Noetherian ring: a Noetherian ring R is one for which R is Noetherian as an R -module.

Question 18.2.8. Check these two conditions are equivalent. (Copy the proof for rings.)

§18.3 The structure theorem

Our structure theorem takes two forms:

Theorem 18.3.1 (Structure theorem, invariant form)

Let R be a PID and let M be any finitely generated R -module. Then

$$M \cong \bigoplus_{i=1}^m R/(s_i)$$

for some s_i (possibly zero) satisfying $s_1 \mid s_2 \mid \dots \mid s_m$.

Corollary 18.3.2 (Structure theorem, primary form)

Let R be a PID and let M be any finitely generated R -module. Then

$$M \cong R^{\oplus r} \oplus R/(q_1) \oplus R/(q_2) \oplus \dots \oplus R/(q_m)$$

where $q_i = p_i^{e_i}$ for some prime element p_i and integer $e_i \geq 1$.

Proof of corollary. Factor each s_i into prime factors (since R is a UFD), then use the Chinese remainder theorem. \square

Remark 18.3.3 — In both theorems the decomposition is unique up to permutations of the summands.

§18.4 Reduction to maps of free R -modules

Definition 18.4.1. A **free R -module** is a module of the form $R^{\oplus n}$ (or more generally, $\bigoplus_I R$ for some indexing set I , just to allow an infinite basis).

The proof of the structure theorem proceeds in two main steps. First, we reduce the problem to a *linear algebra* problem involving free R -modules $R^{\oplus d}$. Once that's done, we just have to play with matrices; this is done in the next section.

Suppose M is finitely generated by d elements. Then there is a surjective map of R -modules

$$R^{\oplus d} \twoheadrightarrow M$$

whose image on the basis of $R^{\oplus d}$ are the generators of M . Let K denote the kernel.

We claim that K is finitely generated as well. To this end we prove that

Lemma 18.4.2 (Direct sum of Noetherian modules is Noetherian)

Let M and N be two Noetherian R -modules. Then the direct sum $M \oplus N$ is also a Noetherian R -module.

Proof. It suffices to show that if $L \subseteq M \oplus N$, then L is finitely generated. One guess is that $L = P \oplus Q$, where P and Q are the projections of L onto M and N . Unfortunately this is false (take $M = N = \mathbb{Z}$ and $L = \{(n, n) \mid n \in \mathbb{Z}\}$) so we will have to be more careful.

Consider the submodules

$$\begin{aligned} A &= \{x \in M \mid (x, 0) \in L\} \subseteq M \\ B &= \{y \in N \mid \exists x \in M : (x, y) \in L\} \subseteq N. \end{aligned}$$

(Note the asymmetry for A and B : the proof doesn't work otherwise.) Then A is finitely generated by a_1, \dots, a_k , and B is finitely generated by b_1, \dots, b_ℓ . Let $x_i = (a_i, 0)$ and let $y_i = (*, b_i)$ be elements of L (where the $*$'s are arbitrary things we don't care about). Then x_i and y_i together generate L . \square

Question 18.4.3. Deduce that for R a PID, $R^{\oplus d}$ is Noetherian.

Hence $K \subseteq R^{\oplus d}$ is finitely generated as claimed. So we can find another surjective map $R^{\oplus f} \twoheadrightarrow K$. Consequently, we have a composition

$$\begin{array}{ccccc} & & K & & \\ & \nearrow & \hookrightarrow & \searrow & \\ R^{\oplus f} & \xrightarrow{T} & R^{\oplus d} & \twoheadrightarrow & M \end{array}$$

Observe that M is the *cokernel* of the linear map T , i.e. we have that

$$M \cong R^{\oplus d} / \text{im}(T).$$

So it suffices to understand the map T well.

§18.5 Uniqueness of primary form

In this section, we will prove that if $M \cong R^{\oplus r} \oplus R/(q_1) \oplus R/(q_2) \oplus \cdots \oplus R/(q_m)$, then the integer r and the prime powers q_i are unique, up to permutations.

First, we consider the case where M is free.

Theorem 18.5.1 (Uniqueness of free module's rank)

For a commutative integral domain R , if a free module M has a finite basis, then every other basis has the same number of elements.

It was mentioned once in [Theorem 9.4.7](#) that the strategy of the proof is to pass to the field case. Indeed, we're going to pass to the field F being the fraction field of R , then directly apply the dimension theorem for vector spaces.

Proof. As before, but we prove by contradiction this time. Assume v_1, \dots, v_n is a basis for the free module M of rank n , while w_1, \dots, w_m are any elements of M such that $m > n$.

Let F be the fraction field of R , and embed the R -module $M \cong R^n$ into the F -vector space $V \cong F^n$.

Then, because $m > n$, as elements of V , the elements w_1, \dots, w_m are linearly dependent, which means there are some elements $f_1, \dots, f_m \in F$ not all zero, such that $f_1 w_1 + \cdots + f_m w_m = 0$.

By clearing denominators, we can obtain ring elements $r_1, \dots, r_m \in R$ not all zero such that $r_1 w_1 + \cdots + r_m w_m = 0$. This means w_1, \dots, w_m cannot be a basis for M . \square

Next, we prove the case where the rank r is 0. This case needs a different strategy, but it still boils down to applying the dimension theorem for appropriately constructed vector spaces.

Theorem 18.5.2

Let R be a PID, let p be a prime element of R , and let $M \cong R/(p^{e_1}) \oplus R/(p^{e_2}) \oplus \cdots \oplus R/(p^{e_m})$ for positive integers e_1, \dots, e_m . Then the e_i are unique, up to permutations.

Intuitively, what the following proof is trying to do is:

If we can compute the exponents e_i from intrinsic properties of M , then the exponents must be unique.

Let us consider a simple case — consider $R = \mathbb{Z}$ and $M = \mathbb{Z}/4\mathbb{Z}$. This module has 4 elements, but it's not the same as $\mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$. In this case, the difference between the two modules can be detected by the fact that in M , the element 1 (mod 4) is not zero when multiplied by 2, on the other hand, multiplying by 2 makes every element in $\mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ zero.

For notational convenience,

Definition 18.5.3. For $r \in R$ and a R -module M , define $rM = \{rm \mid m \in M\}$. (Check that this is still a R -module.)

Then, what the paragraph above says is that $M \not\cong \mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ because $|2M| = 2 \neq 1 = |2(\mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z})|$. In other words, in this case, counting the number of elements of $2M$ suffices to distinguish the two modules.

For modules of the form $M \cong R/(p^{e_1}) \oplus R/(p^{e_2}) \oplus \cdots \oplus R/(p^{e_m})$ where $R = \mathbb{Z}$, this almost works in general — except we also need to consider the number of elements in pM , p^2M , p^3M , etc.

Equivalently, we may also consider the number of elements in the successive quotients: M/pM , pM/p^2M , p^2M/p^3M , etc.

Example 18.5.4

Let $R = \mathbb{Z}$, $p = 3$, and $M = \mathbb{Z}/3^2\mathbb{Z} \oplus \mathbb{Z}/3^5\mathbb{Z}$. Then:

- $|M/3M| = 9$,
- $|3M/3^2M| = 9$,
- $|3^2M/3^3M| = 3$,
- $|3^3M/3^4M| = 3$,
- $|3^4M/3^5M| = 3$,
- $|3^eM/3^{e+1}M| = 1$ for all integer $e \geq 5$.

You can already see where this is going — each decrement of the size of the quotient corresponds to a prime power p^{e_i} .

When the quotient is infinite however, we can no longer do this. However, note that:

Lemma 18.5.5

For each integer $e \geq 0$, then $p^eM/p^{e+1}M$ is a $R/(p)$ -vector space.

Thus, instead of counting the number of elements in $p^eM/p^{e+1}M$, we count the *dimension* of the $p^eM/p^{e+1}M$ as a $R/(p)$ -vector space — by [Theorem 9.4.7](#), this is indeed intrinsic to the module M .

Proof of Theorem 18.5.2. Note that, since $M \cong R/(p^{e_1}) \oplus R/(p^{e_2}) \oplus \cdots \oplus R/(p^{e_m})$, we have

$$\pi(M) \cong \pi(R/(p^{e_1})) \oplus \pi(R/(p^{e_2})) \oplus \cdots \oplus \pi(R/(p^{e_m}))$$

where $\pi(M) = p^eM/p^{e+1}M$ for any integer $e \geq 0$.

This means, as $R/(p)$ -vector space,

$$\dim \pi(M) = \dim \pi(R/(p^{e_1})) + \dim \pi(R/(p^{e_2})) + \cdots + \dim \pi(R/(p^{e_m})).$$

Note that, for each term $R/(p^{e_i})$, then

$$\dim p^e(R/(p^{e_i}))/p^{e+1}(R/(p^{e_i})) = \begin{cases} 1 & e < e_i \\ 0 & \text{otherwise.} \end{cases}$$

With some arithmetic, you can see that the values e_i are indeed uniquely determined by $\dim p^eM/p^{e+1}M$, up to permutation. \square

Note that this can be easily generalized to the case where the primes in the denominator may be different – because for different primes p and q of R , then $p^e(R/(q))/p^{e+1}(R/(q))$ is a 0-dimensional $R/(p)$ -vector space.

Finally, we handle the general case.

Theorem 18.5.6

If $M \cong R^{\oplus r} \oplus R/(q_1) \oplus R/(q_2) \oplus \cdots \oplus R/(q_m)$, then the integer r and the prime powers q_i are unique, up to permutations.

Proof. From the two theorems above, it suffices if we can prove that the $R^{\oplus r}$ part and the $R/(q_1) \oplus R/(q_2) \oplus \cdots \oplus R/(q_m)$ part are uniquely determined from M .

For notational convenience, we call an element $a \in M$ a **torsion element** if there is $r \in R$, $r \neq 0$ such that $ra = 0$.

Then,

- If an element $a \in M$ has the $R^{\oplus r}$ component zero, then $q_1 q_2 \cdots q_m \cdot a = 0$, thus a is a torsion element.
- If an element $a \in M$ has the $R^{\oplus r}$ component nonzero, then a is not a torsion element.

In other words, the submodule consisting of all torsion elements is identical to the submodule of the elements with $R^{\oplus r}$ component zero, thus is isomorphic to $R/(q_1) \oplus R/(q_2) \oplus \cdots \oplus R/(q_m)$.

For notation convenience, let $\text{Tor}(M)$ be the submodule of M consisting of all torsion elements. Then $\text{Tor}(M) \cong R/(q_1) \oplus R/(q_2) \oplus \cdots \oplus R/(q_m)$ and $M/\text{Tor}(M) \cong R^{\oplus r}$, in other words, the $R^{\oplus r}$ part and the $R/(q_1) \oplus R/(q_2) \oplus \cdots \oplus R/(q_m)$ part are uniquely determined from M , so we're done. \square

§18.6 Smith normal form

The idea is now that we have reduced our problem to studying linear maps $T: R^{\oplus m} \rightarrow R^{\oplus n}$, which can be thought of as a generic matrix

$$T = \begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nm} \end{bmatrix}$$

for a basis e_1, \dots, e_m of $R^{\oplus m}$ and f_1, \dots, f_n of $R^{\oplus n}$.

Of course, as you might expect it ought to be possible to change the given basis of T such that T has a nicer matrix form. We already saw this in *Jordan form*, where we had a map $T: V \rightarrow V$ and changed the basis so that T was “almost diagonal”. This time, we have *two* sets of bases we can change, so we would hope to get a diagonal basis, or even better.

Before proceeding let's think about how we might edit the matrix: what operations are permitted? Here are some examples:

- Swapping rows and columns, which just corresponds to re-ordering the basis.
- Adding a multiple of a column to another column. For example, if we add 3 times the first column to the second column, this is equivalent to replacing the basis

$$(e_1, e_2, e_3, \dots, e_m) \mapsto (e_1, e_2 + 3e_1, e_3, \dots, e_m).$$

- Adding a multiple of a row to another row. One can see that adding 3 times the first row to the second row is equivalent to replacing the basis

$$(f_1, f_2, f_3, \dots, f_n) \mapsto (f_1 - 3f_2, f_2, f_3, \dots, f_n).$$

More generally,

If A is an invertible $n \times n$ matrix we can replace T with AT .

This corresponds to replacing

$$(f_1, \dots, f_n) \mapsto ((FA^{-1})_1, \dots, (FA^{-1})_n)$$

(the “invertible” condition just guarantees the latter is a basis). Here, F is the $n \times n$ matrix with columns being f_1, \dots, f_n , and $(FA^{-1})_1$ denotes the first column of FA^{-1} .

Of course similarly we can replace T with TB where B is an invertible $m \times m$ matrix; this corresponds to

$$(e_1, \dots, e_m) \mapsto ((EB)_1, \dots, (EB)_m)$$

where E is the $m \times m$ matrix with columns being e_1, \dots, e_m .

Armed with this knowledge, we can now approach:

Theorem 18.6.1 (Smith normal form)

Let R be a PID. Let $M = R^{\oplus m}$ and $N = R^{\oplus n}$ be free R -modules and let $T: M \rightarrow N$ be a linear map. Set $k = \min\{m, n\}$.

Then we can select a pair of new bases for M and N such that T has only diagonal entries s_1, s_2, \dots, s_k and $s_1 \mid s_2 \mid \dots \mid s_k$.

So if $m > n$, the matrix should take the form

$$\begin{bmatrix} s_1 & 0 & 0 & 0 & \dots & 0 \\ 0 & s_2 & 0 & 0 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & s_n & \dots & 0 \end{bmatrix}.$$

and similarly when $m \leq n$.

Question 18.6.2. Show that Smith normal form implies the structure theorem.

Remark 18.6.3 — Note that this is not a generalization of Jordan form.

- In Jordan form we consider maps $T: V \rightarrow V$; note that the source and target space are the *same*, and we are considering one basis for the space V .
- In Smith form the maps $T: M \rightarrow N$ are between *different* modules, and we pick *two* sets of bases (one for M and one for N).

Example 18.6.4 (Example of Smith normal form)

To give a flavor of the idea of the proof, let’s work through a concrete example with

the \mathbb{Z} -matrix

$$\begin{bmatrix} 18 & 38 & 48 \\ 14 & 30 & 32 \end{bmatrix}.$$

The GCD of all the entries is 2, and so motivated by this, we perform the **Euclidean algorithm on the left column**: subtract the second row from the first row, then three times the first row from the second:

$$\begin{bmatrix} 18 & 38 & 48 \\ 14 & 30 & 32 \end{bmatrix} \mapsto \begin{bmatrix} 4 & 8 & 16 \\ 14 & 30 & 32 \end{bmatrix} \mapsto \begin{bmatrix} 4 & 8 & 16 \\ 2 & 6 & -16 \end{bmatrix}.$$

Now that the GCD of 2 is present, we move it to the upper-left by switching the two rows, and then kill off all the entries in the same row/column; since 2 was the GCD all along, we isolate 2 completely:

$$\begin{bmatrix} 4 & 8 & 16 \\ 2 & 6 & -16 \end{bmatrix} \mapsto \begin{bmatrix} 2 & 6 & -16 \\ 4 & 8 & 16 \end{bmatrix} \mapsto \begin{bmatrix} 2 & 6 & -16 \\ 0 & -4 & 48 \end{bmatrix} \mapsto \begin{bmatrix} 2 & 0 & 0 \\ 0 & -4 & 48 \end{bmatrix}.$$

This reduces the problem to a 1×2 matrix. So we just apply the Euclidean algorithm again there:

$$\begin{bmatrix} 2 & 0 & 0 \\ 0 & -4 & 0 \end{bmatrix} \mapsto \begin{bmatrix} 2 & 0 & 0 \\ 0 & 4 & 0 \end{bmatrix}.$$

Now all we have to do is generalize this proof to work with any PID. It's intuitively clear how to do this: the PID condition more or less lets you perform a Euclidean algorithm.

Proof of Smith normal form. Begin with a generic matrix

$$T = \begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{n1} & \cdots & a_{nm} \end{bmatrix}$$

We want to show, by a series of operations (gradually changing the given basis) that we can rearrange the matrix into Smith normal form.

Define $\gcd(x, y)$ to be any generator of the principal ideal (x, y) .

Claim 18.6.5 (“Euclidean algorithm”). If a and b are entries in the same row or column, we can change bases to replace a with $\gcd(a, b)$ and b with something else.

Proof. We do just the case of columns. By hypothesis, $\gcd(a, b) = xa + yb$ for some $x, y \in R$. We must have $(x, y) = (1)$ now (we're in a UFD). So there are u and v such that $xu + yv = 1$. Then

$$\begin{bmatrix} x & y \\ -v & u \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} \gcd(a, b) \\ \text{something} \end{bmatrix}$$

and the first matrix is invertible (check this!), as desired. ■

Let $s_1 = (a_{ij})_{i,j}$ be the GCD of all entries. Now by repeatedly applying this algorithm, we can cause s to appear in the upper left hand corner. Then, we use it to kill off all the

entries in the first row and the first column, thus arriving at a matrix

$$\begin{bmatrix} s_1 & 0 & 0 & \cdots & 0 \\ 0 & a'_{22} & a'_{23} & \cdots & a'_{2n} \\ 0 & a'_{32} & a'_{33} & \cdots & a'_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & a'_{m2} & a'_{m3} & \cdots & a'_{mn} \end{bmatrix}.$$

Now we repeat the same procedure with this lower-right $(m-1) \times (n-1)$ matrix, and so on. This gives the Smith normal form. \square

With the Smith normal form, we have in the original situation that

$$M \cong R^{\oplus d} / \text{im } T$$

and applying the theorem to T completes the proof of the structure theorem.

§18.7 A few harder problems to think about

Now, we can apply our structure theorem!

Problem 18A[†] (Finite-dimensional vector spaces are all isomorphic). A vector space V over a field k has a finite spanning set of vectors. Show that $V \cong k^{\oplus n}$ for some n .

Problem 18B[†] (Frobenius normal form). Let $T: V \rightarrow V$ where V is a finite-dimensional vector space over an arbitrary field k (not necessarily algebraically closed). Show that one can write T as a block-diagonal matrix whose blocks are all of the form

$$\begin{bmatrix} 0 & 0 & 0 & \cdots & 0 & * \\ 1 & 0 & 0 & \cdots & 0 & * \\ 0 & 1 & 0 & \cdots & 0 & * \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1 & * \end{bmatrix}.$$

(View V as a $k[x]$ -module with action $x \cdot v = T(v)$.)

Problem 18C[†] (Jordan normal form). Let $T: V \rightarrow V$ where V is a finite-dimensional vector space over an arbitrary field k which is algebraically closed. Prove that T can be written in Jordan form.



Problem 18D. Find two abelian groups G and H which are not isomorphic, but for which there are injective homomorphisms $G \hookrightarrow H$ and $H \hookrightarrow G$.



Problem 18E. Let $A \subseteq B \subseteq C$ be rings. Suppose C is a finitely generated A -module. Does it follow that B is a finitely generated A -module?