12. Presentations and Groups of small order

Definition-Lemma 12.1. *Let A be a set. A* **word** *in A is a string of elements of A and their inverses. We say that the word w' is obtained from w by a* **reduction**, *if we can get from w to w' by repeatedly applying the following rule,*

- *replace aa^{-1} (or $a^{-1}a$) by the empty string.*

Given any word w, the **reduced word** *w' associated to w is any word obtained from w by reduction, such that w' cannot be reduced any further.*

Given two words w_1 and w_2 of A, the **concatenation** *of w_1 and w_2 is the word $w = w_1w_2$. The empty word is denoted e.*

The set of all reduced words is denoted F_A. With product defined as the reduced concatenation, this set becomes a group, called the **free group with generators** *A.*

It is interesting to look at examples. Suppose that A contains one element a. An element of $F_A = F_a$ is a reduced word, using only a and a^{-1}. The word $w = aaaa^{-1}a^{-1}aaa$ is a string using a and a^{-1}. Given any such word, we pass to the reduction w' of w. This means cancelling as much as we can, and replacing strings of a's by the corresponding power. Thus

$$\begin{aligned} w &= aaa^{-1}aaa \\ &= aaaa \\ &= a^4 = w', \end{aligned}$$

where equality means up to reduction. Thus the free group on one generator is isomorphic to $\mathbb{Z}$.

The free group on two generators is much more complicated and it is not abelian. A typical reduced word might be

$$a^3b^{-2}a^5b^{13}.$$

Clearly $F_{a,b}$ has quite a few elements. Free groups have a very useful universal property.

Lemma 12.2. *Let $F = F_S$ be a free group with generators S. Let G be any group. Suppose that we are given a function $f\colon S \longrightarrow G$.*

Then there is a unique homomorphism

$$\phi\colon F \longrightarrow G$$

that extends f. In other words, the following diagram commutes

$$\begin{tikzcd} S \arrow[r, "f"] \arrow[d, hook] & G \\ F. \arrow[ur, dashed, "\phi"'] & \end{tikzcd}$$

Proof. Given a reduced word w in F, send this to the element given by replacing every letter by its image in G. It is easy to see that this is a homomorphism, as there are no relations between the elements of F. $\square$

In other words if $S = \{a, b\}$ and you send a to g and b to h then you have no choice but to send $w = a^2b^{-3}a$ to $g^2h^{-3}g$, whatever that element is in G.

This gives us a convenient way to present a group G. Pick generators S of G. Then we get a homomorphism

$$\phi\colon F_S \longrightarrow G.$$

As S generates G, ϕ is surjective. Let the kernel be H. By the First Isomorphism Theorem, G is isomorphic to F_S/H. To describe H, we need to write down generators R for H. These generators are called relations, since they describe relations amongst the generators, such that if we mod out by these relations, then we get G.

Definition 12.3. *A* **presentation** *of a group G is a choice of generators S of G and a description of the* **relations** *R amongst these generators.*

It is probably easiest to give some examples.

Let G be a cyclic group of order n. Pick a generator a. Then we get a homorphism

$$\phi\colon F_a \longrightarrow G.$$

The kernel of ϕ is equal to H, which contains all elements of the form a^m, where m is a multiple of n, $H = \langle a^n \rangle$. Thus a presentation for G is given by the single generator a with the single relation $a^n = e$.

Take the group D_4, the symmetries of the square. This has two natural generators g and f, where g is rotation through $\pi/2$ and f is reflection about a diagonal.

Thus we get a map

$$F_{a,b} \longrightarrow D_4$$

given by sending a to g and b to f. What are the relations, that is, what is the kernel? Well $f^2 = e$ and $g^4 = e$, so two obvious elements of the kernel are f^2 and g^4. On the other hand

$$fgf^{-1} = g^{-1}.$$

Using this relation, any word w can be manipulated into the form

$$f^i g^j,$$

where $i \in \{0, 1\}$ and $j \in \{0, 1, 2, 3\}$. Since this gives eight elements of the quotient and there are eight elements of G, it follows that the kernel is generated by

$$f^2, g^4, fgf^{-1}g.$$

The relations are

$$f^2 = e, g^4 = e, fgf^{-1} = g^{-1}.$$

Definition 12.4. *Let S be a set. The* **free abelian group** A_S **generated by** S *is the quotient of F_S, the free group generated by S, and the relations R given by the commutators of the elements of S.*

Let $S = \{a, b\}$. Then $A_{a,b}$ is isomorphic to $\mathbb{Z} \times \mathbb{Z}$. Similarly for any finite set.

Lemma 12.5. *Let S be any set and let G be any abelian group. Given any map $f : S \longrightarrow G$ there is a unique homomorphism*

$$A_S \longrightarrow G.$$

Proof. As F_S is a free group, there is a unique homomorphism

$$\phi \colon F_S \longrightarrow G.$$

As G is abelian the kernel of ϕ contains the commutator subgroup. But then, as A_S is by definition the quotient of F_S by the commutator subgroup, there is a unique map $A_S \longrightarrow G$ extending f. □

Lemma 12.6. *Let G be any finitely generated abelian group.*

Then G is a quotient of $\mathbb{Z} \times \mathbb{Z} \times \mathbb{Z} \times \cdots \times \mathbb{Z}$.

Proof. Pick a finite set of generators S of G. By (12.5) there is a unique homomorphism

$$A_S \longrightarrow G.$$

As S generates G this map is surjective. On the other hand A_S is isomorphic to a direct sum of copies of $\mathbb{Z}$. □

Theorem 12.7. *Let G be a finitely generated abelian group.*

Then G is isomorphic to $\mathbb{Z} \times \mathbb{Z} \times \cdots \times \mathbb{Z} \times T$, where T may be presented uniquely as either,

(1) $\mathbb{Z}_{q_1} \times \mathbb{Z}_{q_2} \times \cdots \times \mathbb{Z}_{q_r}$, where each q_i is a power of a prime, or
(2) $\mathbb{Z}_{m_1} \times \mathbb{Z}_{m_2} \times \cdots \times \mathbb{Z}_{m_r}$, where $m_i | m_{i+1}$.

Given this, we can classify all abelian groups of a fixed finite order. For example, take $n = 60 = 2^2 \cdot 3 \cdot 5$. Then we have

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_3 \times \mathbb{Z}_5 \qquad \text{or} \qquad \mathbb{Z}_4 \times \mathbb{Z}_3 \times \mathbb{Z}_5,$$

using the first representation, or

$$\mathbb{Z}_2 \times \mathbb{Z}_{30} \qquad \text{or} \qquad \mathbb{Z}_{60}$$

using the second representation.

Finally let me mention that in general if one is given generators and relations, it can be very hard to describe the resulting quotient.

Theorem 12.8. *There is no effective algorithm to solve any of the following problems,*

Given relations R, decide if

(1) two words w_1 and w_2 are equivalent, modulo the relations.
(2) a word w is equivalent, modulo the relations, to the identity.

Succintly, the method of representing groups by generators and relations is an art not a science.

Let's now try to classify all groups of order at most ten, up to isomorphism. To do this we recall some basic results. First note that for every natural number n, there is at least one group of order n, namely a cyclic group of order n.

Lemma 12.9. *Let G be a group of order a prime p.*

Then G is cyclic.

Proof. Pick any element g of G other than the identity and let H be the subgroup generated by g. Then the order of H is greater than one and divides the order of G, by Lagrange. As the order of G is a prime, it follows that $H = G$ so that G is cyclic, generated by any element other than the identity. $\square$

Look at the numbers from one to ten. Of these, 2, 3, 5 and 7 are prime. Thus by (12.9) there is exactly one group of order 1, 2, 3, 5 and 7, up to isomorphism.

The numbers that are left are 4, 6, 8, 9 and 10. The next thing to do is to start looking for intersting subgroups. The easiest way to find a subgroup, is to pick an element and look at the cyclic subgroup that it generates.

Lemma 12.10. *Let G be a group in which every element has order two.*

Then G is abelian.

Proof. Suppose that a, b and ab all have order two. We will show that a and b commute. By assumption

$$\begin{aligned} e &= (ab)^2 \\ &= abab. \end{aligned}$$

As a and b are their own inverses, multiplying on the left by a and then b, we get

$$ba = ab. \qquad \square$$

On the other hand, the classification of finite abelian groups is easy. There are two of order 4,

$$\mathbb{Z}_2 \times \mathbb{Z}_2, \qquad \mathbb{Z}_4,$$

one of order six,

$$\mathbb{Z}_6,$$

three of order 8,

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2, \qquad \mathbb{Z}_2 \times \mathbb{Z}_4, \qquad \mathbb{Z}_8,$$

two of order nine,

$$\mathbb{Z}_3 \times \mathbb{Z}_3, \qquad \mathbb{Z}_9,$$

and one of order ten

$$\mathbb{Z}_{10}.$$

Let us start with order four. Let $g \in G$ be an element of G other than the identity. Then the order of g is 2 or 4. If it is four then G is cyclic. Otherwise g has order two. If G is not cyclic then, every element, other than the identity, must have order two, and G is abelian, by (12.10). Thus every group of order 4 is abelian.

Now suppose that G has order six. If G is abelian, then G is cyclic. Otherwise, every element of G has order two or three. By (12.10) not every element has order two. Let a be an element of order three. Let $H = \langle a \rangle$.

Lemma 12.11. *Let G be a group and let H be a subgroup of index two.*

Then H is normal in G.

Proof. It suffices to prove that the set of left cosets is equal to the set of right cosets.

The left cosets, partition the elements of G into two parts. One part is equal to H. By definition o a partition, the other part is the complement of H. By the same token, the right cosets consist of H and its complement.

Hence both partitions are equal and H is normal. $\square$

Pick $b \in G$, where $b \notin H$. As H has index two, G/H has order two. Thus $b^2 \in H$. If $b^2 \neq e$, then $b^2 = a$ or $b^2 = a^2$ and b has order six, a contradiction. Thus $b^2 = e$ and b has order two. Clearly $G = \langle a, b \rangle$. Consider the conjugate of a by b,

$$bab^{-1}.$$

As H is normal in G, $bab^{-1} \in G$, so that $bab^{-1} = a$ or $bab^{-1} = a^2$. If the former then $ab = ba$ and G is abelian. Otherwise G is isomorphic to D_3 as they both have the same presentation. Thus there are two groups of order 6, a cyclic group and S_3.

Now suppose that the order is ten. If G is not abelian, then every element, other than the identity must have order 2 or 5. Not every element has order two. Let a be an element of order five. Let $H = \langle a \rangle$. Then H has index two. Thus H is normal in G. Let $b \in G$, $b \notin H$. As before $b^2 = e$. Once again consider the conjugate of a by b,

$$bab^{-1}$$

This is an element of H, of order five. Thus $bab^{-1} = a^i$, some $i \neq 0$. Suppose that $i \neq 1$, else G is abelian. If $i = 4$, then $bab^{-1} = a^{-1}$ and G is isomorphic to D_5, the symmetries of a pentagon.

Suppose that $bab^{-1} = a^2$. Then

$$\begin{aligned}
a &= b^2ab^{-2} \\
&= b(bab^{-1})b^{-1} \\
&= ba^2b^{-1} \\
&= (bab^{-1})(bab^{-1} \\
&= a^2a^2 \\
&= a^4.
\end{aligned}$$

But then $a^4 = a$ and so $a^3 = e$, a contradiction. Similarly $bab^{-1} \neq a^3$. Thus a group of order ten is either cyclic or isomorphic to D_5.

Now suppose that G is a non-abelian group of order eight. There are no elements of order eight, as G is not cyclic and not every element has order two, by (12.10).

Thus G has an element a of order 4. Let $H = \langle a \rangle$. Then H has index two in G. Pick $b \in G$, with $b \notin H$. Then $b^2 \in H$. $b^2 \neq a$, a^3, otherwise b has order 8.

There are two possibilities. $b^2 = e$. In this case, consider as before, the conjugate of a by b. As before, we must have $bab^{-1} = a^3$ and we have the dihedral group D_4. Call this group G_1.

Otherwise $b^2 = a^2$. Call this group G_2. Again we consider the conjugate of a by b. It must be a^3 as before. Note that this rule translates to $ba = a^3b$. Let $H = \langle a \rangle$ and $K = \langle b \rangle$. Then $G = \langle a, b \rangle = H \vee K = HK$, where we use the rule

$$ba = a^3b,$$

to prove that HK is closed under products and inverses, so that HK is a subgroup of G. We will see later that there is indeed a group of order eight with this presentation. Note that G_1 and G_2 are not isomorphic. Indeed G_1 has only two elements of order 4, a and a^3, whilst G_2 has at least three, a, a^3 and b.

Finally consider the case where G has order nine. Then every element of G, other than the identity must have order 3. Pick an element $a \neq e$ and let $H = \langle a \rangle$. Let S be the set of left cosets of H in G. Then S has three elements. As in the proof of Cayley's Theorem there is a group homomorphism

$$\phi \colon G \longrightarrow A(S) \simeq S_3$$

We send $g \in G$ to the permutation of S that sends aH to gaH. The kernel of ϕ is a normal subgroup of G that is contained in H. The image of ϕ has order at most six, and as G has order nine, the kernel of ϕ cannot be the trivial subgroup. It follows that $\operatorname{Ker} \phi = H$ so that H is normal in G.

Pick $b \in G - H$. Then bH is an element of G/H and so it must have order three. In particular $b^3 \in H$. But then $b^3 = e$, else b has order nine. Let $K = \langle b \rangle$. By symmetry K is normal in G. As $H \cap K = \{e\}$, it follows that the elements of H and K commute. But $G = \langle a, b \rangle$. Thus G is abelian, a contradiction.