CLASSIFICATION OF FINITE ABELIAN GROUPS

1. The main theorem

Theorem 1.1. *Let A be a finite abelian group. There is a sequence of prime numbers*

$$p_1 \leq p_2 \leq \cdots \leq p_n$$

(not necessarily all distinct) and a sequence of positive integers

$$a_1, a_2, \ldots, a_n$$

such that A is isomorphic to the direct product

$$A \xrightarrow{\sim} \mathbb{Z}_{p_1^{a_1}} \times \mathbb{Z}_{p_2^{a_2}} \times \cdots \times \mathbb{Z}_{p_n^{a_n}}.$$

In particular

$$|A| = \prod_{i=n}^{n} p_i^{a_i}.$$

Example 1.2. *We can classify abelian groups of order $144 = 2^4 \times 3^2$. Here are the possibilities, with the partitions of the powers of 2 and 3 on the right:*

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_3 \times \mathbb{Z}_3;\ (4,2) = (1+1+1+1, 1+1)$$

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_4 \times \mathbb{Z}_3 \times \mathbb{Z}_3;\ (4,2) = (1+1+2, 1+1)$$

$$\mathbb{Z}_4 \times \mathbb{Z}_4 \times \mathbb{Z}_3 \times \mathbb{Z}_3;\ (4,2) = (2+2, 1+1)$$

$$\mathbb{Z}_2 \times \mathbb{Z}_8 \times \mathbb{Z}_3 \times \mathbb{Z}_3;\ (4,2) = (1+3, 1+1)$$

$$\mathbb{Z}_{16} \times \mathbb{Z}_3 \times \mathbb{Z}_3;\ (4,2) = (4, 1+1)$$

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_9;\ (4,2) = (1+1+1+1, 2)$$

$$\mathbb{Z}_2 \times \mathbb{Z}_2 \times \mathbb{Z}_4 \times \mathbb{Z}_9;\ (4,2) = (1+1+2, 2)$$

$$\mathbb{Z}_4 \times \mathbb{Z}_4 \times \mathbb{Z}_9;\ (4,2) = (2+2, 2)$$

$$\mathbb{Z}_2 \times \mathbb{Z}_8 \times \mathbb{Z}_9;\ (4,2) = (1+3, 2)$$

$$\mathbb{Z}_{16} \times \mathbb{Z}_9 \text{ cyclic, isomorphic to } \mathbb{Z}_{144};\ (4,2) = (4,2).$$

There are 10 non-isomorphic abelian groups of order 144.

Theorem 1.1 can be broken down into two theorems.

Theorem 1.3. *Let A be a finite abelian group. Let $q_1, \ldots, q_r$ be the* distinct *primes dividing $|A|$, and say*

$$|A| = \prod_j q_j^{b_j}.$$

Then there are subgroups $A_j \subseteq A$, $j = 1, \ldots, r$, with $|A_j| = q_j^{b_j}$, and an isomorphism

$$A \xrightarrow{\sim} A_1 \times A_2 \times \cdots \times A_r.$$

Let p be a prime number. A finite group (abelian or not) is called a *p-group* if its order is a power of p.

Theorem 1.4 (Abelian p-groups)**.** *Let p be a prime and let A be a finite abelian group of order p^N for some $N \geq 1$. Then there is a sequence of positive integers $c_1 \leq c_2 \cdots \leq c_s$ and an isomorphism*

$$A \xrightarrow{\sim} \mathbb{Z}_{p^{c_1}} \times \mathbb{Z}_{p^{c_2}} \times \cdots \times \mathbb{Z}_{p^{c_s}}.$$

Theorem 1.3 is essentially a series of applications of the Chinese Remainder Theorem, and is not very hard, apart from one Key Lemma. It will be presented in class.

Theorem 1.4 is a more complicated induction argument that needs to be studied in order to be understood. It will be carried out in the next section.

Guide to the proof. Here is a short summary to help guide your reading of the proof: Theorem 1.4 is obvious when the group A has order p. So we assume it is true for abelian groups of order p^k for $k < N$. We introduce the notion of *exponent* of a finite p-group and choose an element $a \in A$ of maximal order, which is equal to the exponent of A. We then show that there is a subgroup $H \subset A$ of order p such that $H \cap \langle a \rangle$ contains just the identity. It follows that the image $\bar{a} \in A/H$ of a is of maximal order – in other words, its order is the exponent of A/H – and since $|A/H| < |A|$, the induction step implies that the theorem holds for A/H. Thus $A/H \xrightarrow{\sim} \langle a \rangle \times B'$ for some B', and a short argument then allows us to conclude that $A \xrightarrow{\sim} \langle a \rangle \times B$, where $B = \tilde{B}'$ is the subgroup of A corresponding to the subgroup B' of A/H.

This completes the proof of the Lemma, and then a second application of the induction step, this time to B, completes the proof of Theorem 1.4.

2. The induction step (a very long lemma)

Let p and A be as in Theorem 1.4. We prove it by induction on the integer N, of course. If $N = 1$ then $|A| = p$. In that case we know that A is a cyclic group isomorphic to $\mathbb{Z}_p$. So we assume the theorem is known for groups of order p^k with $k < N$. The induction step is to show that it is then known when $|A| = p^N$.

Definition 2.1. Let A be a finite p-group. The *exponent* of A is the largest integer m such that there is an element $a \in A$ of order exactly p^m. In other words $a^{p^m} = e$ but $a^{p^{m-1}} \neq e$.

Thus if A is cyclic of order p^N, the exponent of A is N: a generator has order p^N but not p^{N-1}. We need the following facts about the exponent.

Fact 2.2. *Let A be a finite p-group, $H \subset A$ a normal subgroup. Suppose the exponent of A is m. Then the exponent of A/H is $\leq m$.*

Proof. Let $\pi : A \to A/H$ be the reduction map. Every element $x \in A/H$ is of the form $\pi(a)$ for some element $a \in A$. We know that $a^{p^r} = e$ for some $r \leq m$. It follows that

$$x^{p^r} = (\pi(a))^{p^r} = \pi(a^{p^r}) = \pi(e) = e.$$

So $x^{p^m} = e$ for all $x \in A/H$,which implies that the exponent of A/H is at most m. □

Fact 2.3. *Let A be a finite p-group, $H \subset A$ a normal subgroup, $a \in A$. Suppose*

$$\langle a \rangle \cap H = \{e\},$$

where $\langle a \rangle \subset A$ is the cyclic subgroup generated by a. Suppose a is of order p^m. Let $\pi : A \to A/H$ be the reduction map and let $\bar{a} = \pi(a) \in A/H$. Then $\bar{a}$ is of order p^m in A/H.

Proof. In any case $\bar{a}^{p^m} = e$ for the reason already seen in the proof of Fact 2.2. Suppose $\bar{a}$ is of order less than p^m, say $\bar{a}^s = e$ for some $1 \leq s < p^m$. That means that $\pi(a^s) = e$, or $a^s \in \ker \pi$, which implies that $a^s \in H$. Thus $a^s \in \langle a \rangle \cap H = \{e\}$, which implies that $a^s = e$, and this contradicts the assumption that a is of order p^m. □

Here is the main step in the proof.

Lemma 2.4. *Let A be a finite abelian p-group of order p^N and exponent m, so that the cyclic group $\langle a \rangle$ has order p^m. Let $a \in A$ be an element of order p^m. Then there is a subgroup $B \subseteq A$ such that $B \cap \langle a \rangle = \{e\}$, and the inclusion of B and $\langle a \rangle$ as subgroups of A defines an isomorphism*

$$B \times \langle a \rangle \xrightarrow{\sim} A.$$

Proof. This is an induction on N. If $N = 1$ then A is cyclic and we are done. Suppose we know the statement for $1 \leq k < N$. We have already chosen a of maximal exponent. Now we choose $h \in A$ of *smallest* order such that $h \notin \langle a \rangle$. (We will soon see that h is of order p.) If no such h exists, then every $h \in A$ belongs to $\langle a \rangle$ and so $A = \langle a \rangle$ is cyclic, and we can take $B = \{e\}$.

So we assume such an h exists. Let $u = h^p$. If $u = e$ then h has order p. If not, then h has order p^r for some $r > 1$, by Lagrange's theorem, because A is a p-group. And then $u^{p^{r-1}} = h^{p(p^{r-1})} = h^{p^r} = e$, so u has smaller order than h, which by definition implies that $u \in \langle a \rangle$, say $u = a^s$, for some integer $s \in \{1, 2, \dots p^m - 1\}$. Thus $h^p = a^s$, so

$$(a^s)^{p^{m-1}} = (h^p)^{p^{m-1}} = h^{p^m} = e$$

since m is the exponent of A. It follows that a^s has order strictly less than p^m, so a^s is not a generator of the cyclic group $\langle a \rangle$. Thus s is divisible by p, say $s = pc$. Then

$$h^p = (a^c)^p \Rightarrow (a^{-c}h)^p = e.$$

Let $h' = a^{-c}h$. If $h' \in \langle a \rangle$ then so is $a^c h' = h$, but h was chosen not in $\langle a \rangle$, contradiction. So $h' \in A$ is an element of order p that is not in $\langle a \rangle$. Since h has the smallest order of elements not in $\langle a \rangle$, it follows that h has order p after all.

Let $H =< h >$. We see $H = | < h > | = p$, and $\langle a \rangle \cap H = \{e\}$, since $h \notin \langle a \rangle$. Consider the composite homomorphism

$$\langle a \rangle \hookrightarrow A \to A/H.$$

We call this composite ϕ, and write $\bar{a} = \phi(a)$. Since $\langle a \rangle \cap H = \{e\}$, it follows from Fact 2.3 that $\bar{a} = \phi(a)$ has order p^m.

Now it follows from Fact 2.2 that A/H has exponent at most m. But $\bar{a} \in A/H$ has order exactly p^m, so A/H has exponent m. On the other hand $|A/H|$ has order $|A|/|H| = p^N/p < |A|$. By induction on N, it follows that there is a subgroup $B' \subset A/H$ such that $B' \cap \langle \bar{a} \rangle = \{e\}$ and

$$B' \times \langle \bar{a} \rangle \xrightarrow{\sim} A/H.$$

In particular

$$|A/H| = |A|/p = |B'| \cdot |\langle \bar{a} \rangle|; \; |A| = p \cdot |B'| \cdot |\langle \bar{a} \rangle| = p \cdot |B'| \cdot p^m.$$

We know that there is a unique subgroup $\tilde{B}' \subset A$ containing H such that $\tilde{B}'/H = B'$, and thus

$$|\tilde{B}'| = p \cdot |B'|.$$

We claim that

$$\langle a \rangle \cap \tilde{B}' = \{e\}.$$

This implies that the homomorphism

$$\phi' : \langle a \rangle \times \tilde{B}' \to A$$

has trivial kernel. Thus

$$p^N = |A| \geq |\langle a \rangle \times \tilde{B}'| = |\langle a \rangle||\tilde{B}'| = p^m \cdot |\tilde{B}'| = p^m \cdot p \cdot |B'| = |A|.$$

Thus ϕ' is the isomorphism we are seeking.

It remains to prove $\langle a \rangle \cap \tilde{B}' = \{e\}$. But if $b \in \langle a \rangle \cap \tilde{B}'$ then the coset $bH \in A/H$ belongs to

$$\langle aH \rangle \cap \tilde{B}'/H = \langle \bar{a} \rangle \cap B' = e_{A/H}.$$

In other words, $b \in H$, but $b \in \langle a \rangle$, hence $b = e$.

□

3. Completion of the proof of Theorem 1.4

Now let A be any abelian p group. We have seen that A is isomorphic to a product

$$A \xrightarrow{\sim} \langle a \rangle \times B,$$

where B is a subgroup of A. We can write this

$$A \xrightarrow{\sim} B \times \mathbb{Z}_{p^m}.$$

Now $|B| < |A|$, so by induction B is isomorphic to a product

$$B \xrightarrow{\sim} \mathbb{Z}_{p^{c_1}} \times \mathbb{Z}_{p^{c_2}} \times \cdots \times \mathbb{Z}_{p^{c_{s-1}}}$$

where $c_1 \leq c_2 \cdots \leq c_{s-1}$. Since m is the exponent of A, we know that $c_{s-1} \leq m$. Thus setting $c_s = m$, we have

$$A \xrightarrow{\sim} \mathbb{Z}_{p^{c_1}} \times \mathbb{Z}_{p^{c_2}} \times \cdots \times \mathbb{Z}_{p^{c_s}}$$

and this completes the proof.