

Classification of Finite Groups

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Contents

I	Done	2
1	Groups of Order 6	2
2	Generalisation to Groups of Order $2p$	2
3	Groups of order 4	3
4	Generalisation to Groups of Order p^2	3
5	Groups of Order pq	4
II	In Progress	4
6	Theorems and Lemmas	5
6.1	Sylow Theorems	5
6.2	Isomorphism Theorems	5
7	Groups of order 12	6
8	Generalisation to Groups of order $4p$	7
9	Groups of Order 30	7
III	To Do	8
10	Semi-Direct Product	8
11	Groups of order 9 (Might skip)	8
12	Groups of Order 18	8
12.1	Groups of Order p^2q	8
13	Groups of Order p^3	8
13.1	Groups of Order 8	8
13.2	Groups of Order 27	8
13.3	General Case?	8

Part I

Done

1 Groups of Order 6

Let G be a group of order 6, and n_3 denote the number of Sylow 3-subgroups of G . Then by Theorem 6.3:

$$n_3 \equiv 1 \pmod{3} \quad \text{and} \quad n_3 \mid 2 \implies n_3 = 1$$

So G has one Sylow 3-subgroup, N , and because 3 is prime, it is isomorphic to C_3 . Let $N = \langle x \rangle$. Any Sylow 2-subgroup, $H \leq G$, will have order 2, and so $H \cong C_2$. Let $H = \langle y \rangle$. Lagrange's Theorem tells us that N has elements of orders 1 and 3, and H has elements of order 1 and 2 hence:

$$N \cap H = \mathbf{1}$$

By Lemma 6.7:

$$|NH| = \frac{|N| \cdot |H|}{|N \cap H|} = \frac{3 \cdot 2}{1} = 6$$

So $G = NH$, $N \trianglelefteq G$ and $N \cap H = \mathbf{1}$, which means $G = N \rtimes H$, the semidirect product of N by H .

Now we need to determine $\text{Aut } N$. An automorphism, φ of N preserves element order. In particular, φ maps generators to generators. Hence, $x\varphi = x$ or x^2 because they are the generators of N . So $\text{Aut } N \cong C_2$.

Now we want a homomorphism $\psi : H \rightarrow \text{Aut } N$. If ψ is trivial, then it maps H to the trivial group, so every element of H gets sent to the trivial automorphism. If ψ is not trivial, then at least one element of H is not sent to the trivial automorphism. It cannot be 1 because then element order is not preserved, so it must be the generator, y . Hence we obtain 2 possibilities for G :

Case 1:

$$\begin{aligned} G &= \langle x, y \mid x^3 = y^2 = 1, y^{-1}xy = x \rangle \\ &= \langle x, y \mid x^3 = y^2 = 1, xy = yx \rangle \\ &= C_3 \times C_2 \cong C_6 \end{aligned}$$

Case 2:

$$\begin{aligned} G &= \langle x, y \mid x^3 = y^2 = 1, y^{-1}xy = x^{-1} \rangle \\ &\cong D_6 \end{aligned}$$

These are clearly not isomorphic, because C_6 is abelian, and D_6 is not.

Hence G is isomorphic one of:

$$C_6 \quad \text{or} \quad D_6$$

2 Generalisation to Groups of Order $2p$

Now that we have seen groups of order 6, let's try and work towards a more general case: groups of order 2 times a prime number. So let G be a group of order $2p$ where p is a prime number, and n_p denote the number of Sylow p -subgroups of G . Then by Theorem 6.3:

$$n_p \equiv 1 \pmod{p} \quad \text{and} \quad n_p \mid 2 \implies n_p = 1$$

So G has one Sylow p -subgroup, say N , and it is isomorphic to C_p . Let $N = \langle x \rangle$. A Sylow 2-subgroup, $H \leq G$ will have order 2 so $H \cong C_2$. Let $H = \langle y \rangle$. Lagrange's Theorem tells us that N has elements of orders 1 and p , and H has elements of order 1 and 2 hence:

$$N \cap H = 1$$

By Lemma 6.7:

$$|NH| = \frac{|N| \cdot |H|}{|N \cap H|} = \frac{p \cdot 2}{1} = 2p$$

So $G = N \rtimes H$ as before.

We know by Lemma 6.8 that $\text{Aut } N \cong \mathbb{Z}/p\mathbb{Z}^*$, so let's look for the elements of order 2. An element $x \in \mathbb{Z}/p\mathbb{Z}^*$ of order 2 satisfies $x^2 = 1$, hence $x = 1$ or -1 . But 1 has order 1, so x can only be -1 . From the proof of Lemma 6.8, this corresponds to the inverse map $\beta : x \mapsto x^{-1}$.

Now we want a homomorphism $\psi : H \rightarrow \text{Aut } N$. By the same argument as for groups of order 6, we have two possibilities for G :

Case 1:

$$\begin{aligned} G &= \langle x, y \mid x^p = y^2 = 1, y^{-1}xy = x \rangle \\ &= C_p \times C_2 \cong C_{2p} \end{aligned}$$

Case 2:

$$\begin{aligned} G &= \langle x, y \mid x^p = y^2 = 1, y^{-1}xy = x^{-1} \rangle \\ &\cong D_{2p} \end{aligned}$$

Again, these are clearly not isomorphic, because C_{2p} is abelian, and D_{2p} is not. Hence a group of order $2p$ is isomorphic to one of:

$$C_{2p} \quad \text{or} \quad D_{2p}$$

3 Groups of order 4

From the Fundamental Theorem of Finite Abelian Groups, we know that a group G of order 4 could be isomorphic to one of C_4 and $C_2 \times C_2$. Now to show that these are the only possibilities. The Sylow theorems are not so helpful here, because any Sylow 2-subgroup will be of order 4, which is just G . Lagrange's Theorem tells us every element of G has order 1, 2 or 4.

If $x \in G$ has order 4, then x generates G so $G \cong C_4$.

If instead there is no element of order 4 in G , then every $x \in G$ except the identity is of order 2. Consider $a, b \in G$ with $a \neq b$, and their product, ab . It must be that ab is the third element of order 2, otherwise we reach a contradiction. So it is easy to see that $G \cong C_2 \times C_2$.

So any group of order 4 is isomorphic to one of:

$$C_4 \quad \text{or} \quad C_2 \times C_2$$

4 Generalisation to Groups of Order p^2

Let G be a group of order p^2 . By Lagrange's Theorem, the elements of G have order 1, p or p^2 .

If $x \in G$ has order p^2 , then x generates G so $G \cong C_{p^2}$.

If G does not have an element of order p^2 then all elements, except the identity, have order p . We know that G must have a subgroup of order p , P , and because p is prime, $P \cong C_p$. Pick a generator for P , say x and an element $y \in G$ such that $y \notin P$. Then $y \neq x^i$ for any i .

If $y^j = x^i$ for some i and j , then:

$$(y^j)^{1-j} = (x^i)^{1-j} = y^{j-j+1} = y = x^{i(1-j)} = x^k \quad \text{for some } k, \text{ a contradiction.}$$

So no power of y is equal to any power of x . Because y has order p , it generates a subgroup of order p , \bar{P} with $P \cap \bar{P} = \mathbf{1}$. By Lemma 6.7, $|P\bar{P}| = p^2 = |G|$ so:

$$G = P \times \bar{P} \cong C_p \times C_p$$

If G has no elements of order p or p^2 , then it only has elements of order 1, which is the trivial group.

Hence any group of order p^2 is isomorphic to one of:

$$C_{p^2} \quad \text{or} \quad C_p \times C_p$$

5 Groups of Order pq

Let G be a group of order pq where p, q are prime numbers with $p > q$, and let n_p and n_q denote the number of Sylow p -subgroups and Sylow q -subgroups of G respectively. Then by Theorem 6.3:

$$n_p \equiv 1 \pmod{p} \quad \text{and} \quad n_p \mid q \implies n_p = 1$$

$$n_q \equiv 1 \pmod{q} \implies n_q = 1, q+1, 2q+1, \dots \quad \text{and} \quad n_q \mid p$$

So G has a unique Sylow p -subgroup, say $P \trianglelefteq G$, and a Sylow q -subgroup, $Q \leq G$. Because p and q are prime numbers, $P \cong C_p$ and $Q \cong C_q$. Pick generators for each, say $\langle x \rangle = P$ and $\langle y \rangle = Q$. We have 2 possibilities for n_q : $p-1$ is a multiple of q or 1.

Case 1: $q \nmid p-1$.

If $p-1$ is not a multiple of q then $n_q = 1$ and $Q \trianglelefteq G$, hence:

$$G = P \times Q \cong C_{pq}$$

Case 2: $q \mid p-1$.

If $p-1$ is a multiple of q then $n_q = p$ and so Q is not normal in G . By Lagrange's Theorem, $P \cap Q = \mathbf{1}$ and by Lemma 6.7, $|PQ| = pq$. Hence, as well as the direct product, we have $G = P \rtimes Q$, some non-trivial semidirect product.

By Lemma 6.8, $\text{Aut } C_p \cong \mathbb{Z}/p\mathbb{Z}^* \cong C_{p-1}$. So if $\nu \in \mathbb{Z}/p\mathbb{Z}^*$, then $x \mapsto x^\nu$ is an automorphism. We know also that C_{p-1} has a unique subgroup of order q , hence G has the presentation:

$$G = \langle x, y \mid x^p = y^q = 1, y^{-1}xy = x^\alpha \rangle$$

where α is a generator for the subgroup of order q in $\mathbb{Z}/p\mathbb{Z}^*$.

Notice that picking different generators are equivalent up to isomorphism because the composition of two isomorphisms is an isomorphism.

So any group of order pq is isomorphic to either:

$$\begin{array}{ll} C_{pq} & \text{or} \quad \langle x, y \mid x^p = y^q = 1, y^{-1}xy = x^\alpha \rangle \quad \text{if } q \mid p-1 \\ & C_{pq} \quad \text{if } q \nmid p-1 \end{array}$$

Part II

In Progress

6 Theorems and Lemmas

6.1 Sylow Theorems

Let G be a group of order $p^n m$ where p is a prime and $p \nmid m$.

Theorem 6.1 (1st Sylow Theorem). G has a Sylow p -subgroup, i.e. a subgroup of order p^n .

Theorem 6.2 (2nd Sylow Theorem). All Sylow p -subgroups of G are conjugate to each other. In particular, if G has a unique Sylow p -subgroup, then it is a normal subgroup.

Theorem 6.3 (3rd Sylow Theorem). Let n_p denote the number of Sylow p -subgroups of G . Then:

$$(i) \ n_p \mid m$$

$$(ii) \ n_p \equiv 1 \pmod{p}$$

6.2 Isomorphism Theorems

Theorem 6.4.

Theorem 6.5.

Theorem 6.6.

Lemma 6.7. For a group G with $N \leq G$ and $H \leq G$, then

$$|NH| = |\{nh \mid n \in N, h \in H\}| = \frac{|N| \cdot |H|}{|N \cap H|}$$

Lemma 6.8. The automorphism group of C_n is isomorphic to the multiplicative group of integers mod n .

$$\text{i.e. } \text{Aut } C_n \cong \mathbb{Z}/n\mathbb{Z}^*$$

Proof. Let $C_n = \langle x \rangle$. Any automorphism, φ of C_n has the property:

$$(x^i)\varphi = (x\varphi)^i$$

Hence φ is determined by its effect on a generator, x , and preserves element order. In particular, φ sends generators to generators. So for φ to be an automorphism, it must send x to another generator, say x^k . An element x^k generates C_n if x^k has order n , i.e. when k and n are co-prime. Denote the automorphism sending x to x^k by φ_k .

Let's now investigate how these automorphisms behave. Consider:

$$x\varphi_k\varphi_l = (x^k)\varphi_l = (x^k)^l = x^{(kl)} = x\varphi_{kl} \pmod{n}$$

Because multiplication modulo n is commutative, $x^{kl} = x^{lk}$, so $\text{Aut } C_n$ is abelian.

Now consider $\theta : \text{Aut } C_n \rightarrow \mathbb{Z}/n\mathbb{Z}^*$ defined by $\varphi_k\theta = k$. We will show θ is an isomorphism. Every $k \in \mathbb{Z}/n\mathbb{Z}^*$ is co-prime to n and so x^k is a generator of C_n , hence there is some $\varphi_k \in \text{Aut } C_n$ such that $\varphi_k\theta = k$. So θ is surjective. If $\varphi_k, \varphi_l \in \text{Aut } C_n$ such that $\varphi_k\theta = \varphi_l\theta$ then $k = l$, so θ is also injective. Finally, θ is a homomorphism because

$$(\varphi_k\varphi_l)\theta = \varphi_{kl}\theta = kl = (\varphi_k\theta)(\varphi_l\theta)$$

So $\theta : \text{Aut } C_n \rightarrow \mathbb{Z}/n\mathbb{Z}^*$ is an isomorphism. □

7 Groups of order 12

Let G be a group of order $12 = 2^2 \cdot 3$, and n_3 and n_2 denote the number of Sylow 3-subgroups and Sylow 2-subgroups of G respectively. By Theorem 6.3:

$$n_2 \equiv 1 \pmod{2} \text{ and } n_2 \mid 3 \implies n_2 = 1$$

$$n_3 \equiv 1 \pmod{3} \text{ and } n_3 \mid 4 \implies n_3 = 1 \text{ or } 4$$

G has a unique Sylow 2-subgroup of order $2^2 = 4$, say $H \trianglelefteq G$, and we have already classified groups of order 4, so either C_4 or $V_4 \trianglelefteq G$. A Sylow 3-subgroup of G will have order 3, so $C_3 \leq G$, and for some groups, $C_3 \trianglelefteq G$.

Lagrange's Theorem tells us H has elements of order 1, 2, and 4, and C_3 has elements of order 1 and 3. Hence $H \cap C_3 = \mathbf{1}$.

Lemma 6.7 tells us:

$$|HC_3| = \frac{|H| \cdot |C_3|}{|H \cap C_3|} = 12$$

Hence $G = HC_3$, $C_3 \leq G$, $H \trianglelefteq G$, and $H \cap C_3 = \mathbf{1} \implies G = H \rtimes C_3$.

Since an automorphism, φ , must map generators to generators, $\text{Aut } C_4 \cong C_2$ because the generators of C_4 are x and x^{-1} . An automorphism of V_4 corresponds to a permutation of the three non-identity elements, hence $\text{Aut } V_4 \cong S_3$.

Case 1: $H = C_4$ i.e. $G = C_4 \rtimes C_3$.

A homomorphism $\psi : C_3 \rightarrow \text{Aut } C_4 \cong C_2$, preserves order and together with Lagrange's Theorem means that the only possibility for ψ is trivial, i.e. $C_3\psi = \mathbf{1}$.

Hence $G \cong C_4 \times C_3 \cong C_{12}$.

Case 2: $H = V_4$ i.e. $G = (C_2 \times C_2) \rtimes C_3$.

A trivial homomorphism $C_3\psi = \mathbf{1}$ yields the direct product $G \cong C_2 \times C_2 \times C_3 \cong C_2 \times C_6$.

S_3 has one subgroup of order 3, hence there is essentially only one homomorphism $\psi : C_3 \rightarrow \text{Aut } V_4$.

Still need to show this is A_4 .

If we instead consider G where $C_3 \trianglelefteq G$, i.e. $G = C_3 \rtimes H$, then we again have two cases:

Case 1: $H = C_4$ i.e. $G = C_3 \rtimes C_4$.

Say $C_3 = \langle x \rangle$ and $C_4 = \langle y \rangle$. We know $\text{Aut } C_3 \cong C_2$ so a homomorphism ψ maps C_4 to the trivial group, $\mathbf{1}$ or to $\langle \beta : x \mapsto x^{-1} \rangle$.

If $C_4\psi = \mathbf{1}$ then $G = C_3 \times C_4 \cong C_4 \times C_3$, which we have already seen.

If $C_4\psi = \langle \beta \rangle$ then we have:

$$G = \langle x, y \mid x^3 = y^4 = 1, y^{-1}xy = x^{-1} \rangle$$

Case 2: $H = V_4$ i.e. $G = C_3 \rtimes (C_2 \times C_2)$.

If $\psi : (C_2 \times C_2) \rightarrow \text{Aut } C_3$ is trivial then we obtain $G = C_3 \times C_2 \times C_2 \cong C_2 \times C_6$ which we have seen before.

The image of a non-trivial homomorphism $\psi : (C_2 \times C_2) \rightarrow \text{Aut } C_3$ is C_2 , so by Theorem 6.4: $\ker \theta = C_2$.

Choose $a, b \in C_2 \times C_2$ with $a, b \neq 1$ such that $a\theta = \beta : x \mapsto x^{-1}$ and $b\theta = \text{id} : x \mapsto x$. Then:

$$G = \langle x, a, b \mid x^3 = a^2 = b^2 = 1, ab = ba, a^{-1}xa = x^{-1}, b^{-1}xb = x \rangle$$

Let $y = xb$. The order of $y = \text{lcm}(\text{o}(x), \text{o}(b)) = \text{lcm}(2, 3) = 6$ because x and b commute. $y^3 = x^3b^3 = b$ so:

$$a^{-1}ya = a^{-1}xba = a^{-1}xab = x^{-1}b = x^2b = y^2y^3 = y^{-1}$$

Hence:

$$G = \langle a, y \mid y^6 = a^2 = 1, a^{-1}ya = y^{-1} \rangle \cong D_{12}$$

So a group G of order 12 is isomorphic to one of:

$$C_{12}, \quad C_2 \times C_6, \quad A_4, \quad D_{12}, \quad \text{or} \quad \langle x, y \mid x^3 = y^4 = 1, y^{-1}xy = x^{-1} \rangle$$

8 Generalisation to Groups of order $4p$

Suppose G is a group of order $4p$ where p is a prime number. Let n_2 denote the number of Sylow 2-subgroups.

9 Groups of Order 30

Let G be a group of order $30 = 2 \cdot 3 \cdot 5$, and let n_3 and n_5 denote the number of Sylow 3-subgroups and Sylow 5-subgroups of G respectively. Then by Theorem 6.3:

$$n_3 = 1 \text{ or } 10 \quad \text{and} \quad n_5 = 1 \text{ or } 6$$

If $n_3 = 10$, then there are 20 elements of order 3, and if $n_5 = 6$ then there are 24 elements of order 5 in G . G only has 30 elements, so then either:

$$n_3 = 1 \text{ and } n_5 = 6, \quad n_3 = 10 \text{ and } n_5 = 1 \quad \text{or} \quad n_3 = n_5 = 1$$

Hence either $C_3 \trianglelefteq G$ or $C_5 \trianglelefteq G$.

Let $H = C_3C_5$ and by Lagrange's Theorem, $C_3 \cap C_5 = \mathbf{1}$, hence $|H| = 15$ by Lemma 6.7. We know from our classification of groups of order pq that $H \cong C_{15}$. Notice that C_2 is a Sylow 2-subgroup of G , and by the same argument, $C_2 \cap C_{15} = \mathbf{1}$ and $|C_2C_{15}| = 30$. Hence $G = C_2C_{15}$.

Because $|C_{15}| = 15 = \frac{30}{2}$, the index of C_{15} in G is 2, and we know a subgroup of index 2 is normal, so $C_{15} \trianglelefteq G$. Moreover, $G = C_{15} \rtimes C_2$.

By Lemma 6.8:

$$\text{Aut } C_{15} = \mathbb{Z}/15\mathbb{Z}^* \cong (\mathbb{Z}/3\mathbb{Z} \times \mathbb{Z}/5\mathbb{Z})^* \cong \mathbb{Z}/3\mathbb{Z}^* \times \mathbb{Z}/5\mathbb{Z}^* \cong C_2 \times C_4$$

A homomorphism, $\psi : C_2 \rightarrow C_2 \times C_4$ preserves element order, and there are 3 elements of order 2 in $C_2 \times C_4$: $(x, 1)$, $(1, y^2)$ and (x, y^2) where $\langle x, y \rangle = C_2 \times C_4$. We know ψ is determined by its effect on a generator, so if $\langle z \rangle = C_2$ then $z\psi$ has four possibilities:

Case 1: $z\psi = (1, 1)$.

When $z\psi = (1, 1)$, then ψ is the trivial homomorphism, and so we obtain:

$$G \cong C_2 \times C_{15} \cong C_{30}$$

Case 2: $z\psi = (x, 1)$.

Case 3: $z\psi = (1, y^2)$.

Case 4: $z\psi = (x, y^2)$.

Part III

To Do

10 Semi-Direct Product

11 Groups of order 9 (Might skip)

12 Groups of Order 18

12.1 Groups of Order p^2q

13 Groups of Order p^3

13.1 Groups of Order 8

13.2 Groups of Order 27

13.3 General Case?

14 Groups of Order 24

15 Groups of Order 16