

Group Theory Notes

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1 Recapping from previous courses

1.1 Groups, Subgroups, Cosets, oh my!

Definition 1.1.1: Group

A **group** consists of a set G together with a function $G \times G \rightarrow G$ which maps an ordered pair $(g, h) \in G \times G$ to an element $g * h \in G$. The following axioms must be satisfied:

1. **Associativity:** $(g * h) * k = g * (h * k)$ for each triple $(g, h, k) \in G \times G \times G$
2. **Identity:** There is an element $e \in G$ s.t. $e * g = g = g * e$ for each element $g \in G$
3. **Inverse:** To each element $g \in G$ there is an element $h \in G$ s.t. $gh = e = hg$

Every single course seems to have its own definition for a group, this one is a bit more compact than others. FPM had the **closure** axiom, but that is satisfied by the definition of the function $G \times G \rightarrow G$

Note on notation: Usually just write gh instead of $g * h$. Additionally g^{-1} is the inverse of g

Definition 1.3.1: Subgroups

If H is a nonempty subset of G , then H is a **subgroup** provided that

1. $hk \in H$ for all $h, k \in H$
2. $h^{-1} \in H$ for each $h \in H$

Alternatively, we can say " H is closed under the group operation"

Notation

- $H \leq G$ means H is a subgroup of G , whereas $H \subseteq G$ means H is a subset of G .
- $H < G$ means that H is a subgroup of G and also $H \neq G$.
- A subgroup is **proper** if $H \neq G$
- A subgroup is **non-trivial** if $H \neq \{e\}$

Note: $e \in H$ follows from the definition, and associativity follows from the fact that G is a group. Any subgroup H of G is a group using the same product as G

Definition 1.3.6: Cosets

Let $H \leq G$ and let $g \in G$. Then the **left coset of H determined by g** is the set $gH := \{gh : h \in H\}$. $Hg := \{hg : h \in H\}$ is the **right coset of H determined by g**

Notation

- The set of left cosets of H is denoted G/H , the set of right cosets is denoted $H \backslash G$.
- The number of elements in a group G is denoted by $\#G$ or $|G|$, and is known as the **order** of G . We will use $|G|$ in this course.
- The number of left cosets of a subgroup H of G is the **index** of H in G and is denoted by $|G : H|$ or $[G : H]$ (That is, $[G : H] = |G/H|$). We will use $[G : H]$ in this course.

Theorem 1.1.1: Coset Lemmas

If H is finite, $|gH| = |H|$

If $g_1H \cap g_2H \neq \emptyset$, then $g_1H = g_2H$

Theorem 1.3.8: Lagrange's Theorem

Let H be a subgroup of a finite group G . Then

$$|G| = [G : H] \cdot |H|$$

Consequences and Results

- The order of a subgroup must divide the order of the group, e.g. A group of order 12 cannot have a subgroup of order 8
- The converse of Lagrange's Theorem is false, e.g. there is a group of order 12 that doesn't have a subgroup of order 6

Example: If $G = S_3$ and $H = \{e, (12)\}$, what are the left cosets of H ?

$$H = eH = \{e, (12)\} \quad \{(23), (132)\} \quad \{(13), (123)\}$$

Example: If $H \trianglelefteq G$ then the left cosets are right cosets

Proof.

$$gH = \{gh : h \in H\} = \{(ghg^{-1})g : h \in H\} \subseteq Hg$$

□

Theorem 1.3.9: Cauchy's Theorem

If G is a finite group and p is a prime that divides the order of G , then G has a subgroup of order p

Definition 1.3.10: Order of an element

Let $g \in G$. The **order** of g is the least positive integer such that $g^n = e$ or ∞ if such n does not exist. We write the order of g as $o(g)$. Note that $o(g) = |\langle g \rangle|$.

It thus follows from Lagrange's Theorem that the order of an element of G must divide $|G|$, since if $o(g) = n$ then $\langle g \rangle = \{g, g^2, \dots, g^n = e\}$ is a subgroup of G . We also have:

Corollary 1.3.11: If $|G|$ is prime, then G is cyclic

Example A: Examples of Groups and Subgroups

- \mathbb{Z}/n under addition, where $a * b = a + b \pmod n$
- $(\mathbb{R} \setminus \{0\}, \times)$, or $K \setminus \{0\}$ for any field K
- Alternating group: $A_n \subset S_n$ - permutations from an even number of transpositions?

1.2.1 S_n , the **n -th symmetric group** is the group of permutations of $\{1, 2, \dots, n\}$. The

group operation is composition of functions

1.2.6 A group $(G, *)$ is **abelian** if $g * h = h * g$ for all $g, h \in G$

- Let F be a field
 - The **general linear group** $GL(n, F)$ is the set of all invertible $n \times n$ matrices
 - The **special linear group** $SL(n, F)$ is the set of all invertible $n \times n$ matrices with determinant equal to 1

1.3.5 Let G be a group and let $g \in G$. Then $\langle g \rangle := \{g^n : n \in \mathbb{Z}\}$ is a subgroup of G . It is called the **subgroup generated by g** . If $G = \langle g \rangle$ for some $g \in G$, then G is referred to as **cyclic**

1.3.7 A subgroup $H \leq G$ is **normal** if $gH = Hg$ for all $g \in G$. In this case we write $H \trianglelefteq G$

1.2 Group Homomorphisms

Definition 1.4.1: Group Homomorphism

Let G, H be groups. A function $\phi : G \rightarrow H$ such that

$$\phi(ab) = \phi(a)\phi(b)$$

for all $a, b \in G$ is a **group homomorphism**

Example: If ϕ is a group homomorphism then $\phi(e) = e$

Proof.

$$\begin{aligned}\phi(e \cdot e) &= \phi(e)\phi(e) \\ \implies \phi(e) &= \phi(e)\phi(e) \\ \text{multiply by } \phi(e)^{-1} \quad e &= \phi(e)^{-1}\phi(e)\phi(e) = \phi(e)\end{aligned}$$

□

Example: Show $\phi(g^{-1}) = \phi(g)^{-1}$

Proof.

$$\begin{aligned}\phi(g \cdot g^{-1}) &= \phi(g)\phi(g^{-1}) \\ \phi(e) &= \phi(g)\phi(g^{-1}) \\ \text{Multiply by } \phi(g)^{-1} \quad \phi(g)^{-1}\phi(e) &= \phi(g)^{-1}\phi(g)\phi(g^{-1}) \\ \phi(g)^{-1} &= \phi(g^{-1})\end{aligned}$$

□

Example 1.4.2: Cyclic Group Homomorphisms

Let C_n be the **cyclic group of order n** . We can think of C_n as the set of rotations of an equilateral n -gon. If g is a rotation of $2\pi/n$ radians, then $C_n = \{g, g^2, \dots, g^n = e\}$. The group C_n is cyclic since all elements are powers of a single element g . Then

$$\begin{aligned}\phi : \mathbb{Z} &\rightarrow C_n \\ a &\mapsto g^a\end{aligned}$$

is a group homomorphism. (proof in lecture notes)

Definition 1.4.3: Group Isomorphism

If G and H are groups and $\psi : G \rightarrow H$ is a bijective *group homomorphism*, we say that ψ is a **group isomorphism** and that G and H are **isomorphic**

Definition 1.4.5: Kernel of a Homomorphism

Let $\phi : G \rightarrow H$ be a group homomorphism. The **kernel** of ϕ is $\{g \in G : \phi(g) = e\}$

Definition 1.4.6: Automorphisms

Let G be a group. The set of all isomorphisms $\phi : G \rightarrow G$ is also a group. It is called the **automorphism group of G** , and is written $\text{Aut}(G)$. The group operation is composition of functions

Example: What is $\text{Aut}(C_3)$?

Proof.

$$C_3 = \{e, r, r^{-1}\}$$

□

Definition 1.4.8: Direct Product

Let G, H be groups. The **product** (or **direct product**) $G \times H$ is a group, with group operation $*$ given by

$$(g, h) * (g', h') = (g *_G g', h *_H h')$$

Note: we usually just say that $(g, h) * (g', h') = (gg', hh')$

1.3 something...

Let $H \leq G$ (H a subgroup of G). TFAE

1. $\forall g \in G, h \in H, ghg^{-1} \in H$
2. $gHg^{-1} = H, \forall g \in G$
3. $gH = Hg, \forall g \in G$

Proof. Show conditions imply each other

- (2) \implies (1) immediately
- (1) says that $gHg^{-1} \subseteq H, \forall g \in G$
WTS: $gHg^{-1} \supseteq H$

$$H = g^{-1}gHg^{-1}g \subseteq g^{-1}Hg, \forall g \in G$$

replacing g with g^{-1} :

$$H \subseteq gHg^{-1}, \forall g \in G$$

- (2) \implies (3): Multiply by g on right
- (3) \implies (2): Multiply by g^{-1} on left

□

Theorem 1.3.1: lma

If $\phi : G \rightarrow H$ is a group homomorphism, then $\ker \phi \trianglelefteq G$

Proof. If $\phi(x) = e$, then

$$\phi(gxg^{-1}) = \phi(g)\phi(x)\phi(g) = \phi(g)e\phi(g)^{-1} = \phi(g)\phi(g)^{-1} = e$$

□

Theorem 1.3.2

If $N \leq G$, then $N \triangleleft G$ iff $\exists \phi : G \rightarrow H$ s.t. $N = \ker \phi$

Proof. $\ker \phi$ is normal by the above lemma

Conversely, given $N \triangleleft G$, we can form **factor group** G/N

G/N is the set of left cosets, with:

- Identity N
- Inverses $(gN)^{-1} : g^{-1}N$
- Multiplication: $(g_1N) \times (g_2N) := g_1g_2N$

Check that the group is well defined

1. If $gN = g'N$, then $g' = gx$ for $x \in N$

$$(g'N)^{-1} = (g')^{-1}N = (gx)^{-1}N = x^{-1}g^{-1}N$$

As N is normal, $gx^{-1}g^{-1} \in N$

$$\implies x^{-1}g^{-1}N = g^{-1}(gx^{-1}g^{-1})N = g^{-1}N, \text{ as } gx^{-1}g^{-1} \in N$$

2. If $g_1N = g'_1N$ and $g_2N = g'_2N$, then $g'_1 = g_1x$ and $g'_2 = g_2y$ for $x, y \in N$

$$(g'_1N) \times (g'_2N) = g'_1g'_2N = g_1xg_2yN$$

$$yN = N, \text{ so } g_1xg_2yN = g_1xg_2N$$

$$N \text{ normal, so } g_2^{-1}xg_2 \in N \implies g_1g_2(g_2^{-1}xg_2)N = g_1g_2N$$

then prove the group axioms lol

Define $\text{can} : G \rightarrow G/N$, $g \mapsto gN$. This is a group homomorphism

$$\text{can}(g_1g_2) = g_1g_2N = (g_1N) * (g_2N) = \text{can}(g_1) * \text{can}(g_2)$$

Kernel of can

$$\ker(\text{can}) = \{g \in G : \text{can}(g) = N\} = \{g \in G : gN = N\} = N$$

□

Example: If $G = \mathbb{Z}$, (normal) subgroups are $n\mathbb{Z} = \{ni : i \in \mathbb{Z}\}$. What is $\mathbb{Z}/n\mathbb{Z}$?

Elements of $\mathbb{Z}/n\mathbb{Z}$ are cosets, $i + n\mathbb{Z}$ (fixed i), or $\{x \in \mathbb{Z} : x \equiv i \pmod{n}\}$

Group operation: $(i + n\mathbb{Z}) * (j + n\mathbb{Z}) = i + j + n\mathbb{Z} = i + j \pmod{n}$

soooo... $\mathbb{Z}/n\mathbb{Z} \cong \mathbb{Z}/n$, where elements are $n\mathbb{Z}, 1 + n\mathbb{Z}, \dots, n-1 + n\mathbb{Z}$

lol !

1.4 First Isomorphism Theorem and stuff

Theorem 1.4.1: First Isomorphism Theorem

If $\theta : G \rightarrow H$ a group homomorphism, then:

- $\text{im}(\theta)$ is a subgroup of H
- $\ker(\theta) \triangleleft G$
- \exists a group homomorphism $\bar{\theta} : \theta / \ker \theta \xrightarrow{\sim} \text{im}(\theta)$

Proof. Prove all 3

- If $\theta(a), \theta(b) \in \text{im}(\theta)$, then $\theta(a)\theta(b) = \theta(ab) \in \text{im}(\theta)$
 $\theta(a)^{-1} = \theta(a^{-1}) \in \text{im}(\theta)$ therefore $\text{im}(\theta) \leq H$
- Already $\ker(\theta) \triangleleft G$
- Let $N = \ker(\theta)$. Then $gN \in G/N$. Define $\bar{\theta}(gN) := \theta(g)$.
 Well defined: If $gN = g'N$, then $g' = gx$ for some $x \in N$. Then $\bar{\theta}(g'N) = \theta(g') = \theta(g)\theta(x) = \theta(g)e$ as $x \in \ker(\theta) = \theta(g)$

□

Ex 1: $\theta : \mathbb{C} \rightarrow \mathbb{C} \setminus \{0\}$

Theorem 1.4.2: Property of Finite Groups

If $N \triangleleft$, then for any homomorphism $\psi : G \rightarrow H$ with $N \subseteq \ker \psi$. \exists a group homomorphism $\bar{\psi} : G/N \rightarrow H$ s.t. $\psi = \bar{\psi} \circ \text{can}$

If $\psi : G \rightarrow K$ surjective...? $\psi : G \rightarrow H$ with $\ker \phi \subseteq \ker \psi$, then $\exists \bar{\psi} : K \rightarrow H$ s.t. $\psi = \bar{\psi} \circ \psi$

Theorem 1.4.3

Let $N \triangleleft G$, $\text{can} : G \rightarrow G/N$ and $K \leq G/N$

1. $\text{can}^{-1}(K) \leq G$ with $\text{can}^{-1}(K) \geq N$
2. $\text{can}^{-1}(K) \triangleleft G \iff K \triangleleft G/N$

Theorem 1.4.4: Correspondence Theorem

If we have $N \triangleleft G$, $\text{can} : G \rightarrow G/N$, then:

- $H \rightarrow \text{can}(H)$ gives a bijection between subgroups of G/N and subgroups of G containing N
- Normal subgroups of G containing $N \iff$ normal subgroups of G/N
- If $A, B \leq G$ with $N \subseteq A, N \subseteq B$, then: $A \subseteq B$ iff $\text{can}(A) \subseteq \text{can}(B)$

Proof. Given $K < G/N$, $\text{can}^{-1}K \leq G$ and $N \leq \text{can}^{-1}K$ since $\text{can}^{-1}\{e\} = N$
 Last prop says: $\text{can}^{-1}\text{can}(H) = H$ when $N \subseteq H$

$$\text{can}(\text{can}^{-1}K) \subseteq K$$

Since can is surjective, $\forall x \in K$, $\exists y \in G$ s.t. $\text{can}(y) = x$. Then $y \in \text{can}^{-1}K$ so $x \in \text{can}(\text{can}^{-1}K)$
 So, $\text{can}(\text{can}^{-1}K) = K$ since can is surjective. Therefore can & can^{-1} give a bijection

$$\{\text{subgroups of } G \text{ containing } N\} \rightsquigarrow \{\text{subgroups of } G/N\}$$

□

1.4.5 Recap of last time (which is not on the notes)

- $\text{can}(H) \triangleleft G/N \iff H \triangleleft G$
- If $A \subseteq B$ then $\text{can}(A) \subseteq \text{can}(B)$
 Conversely, if $\text{can}(A) \subseteq \text{can}(B)$ then $\text{can}^{-1}\underbrace{\text{can}(A)}_{=A} \subseteq \text{can}^{-1}\underbrace{\text{can}(B)}_{=B}$

Definition 1.4.6: Random notation

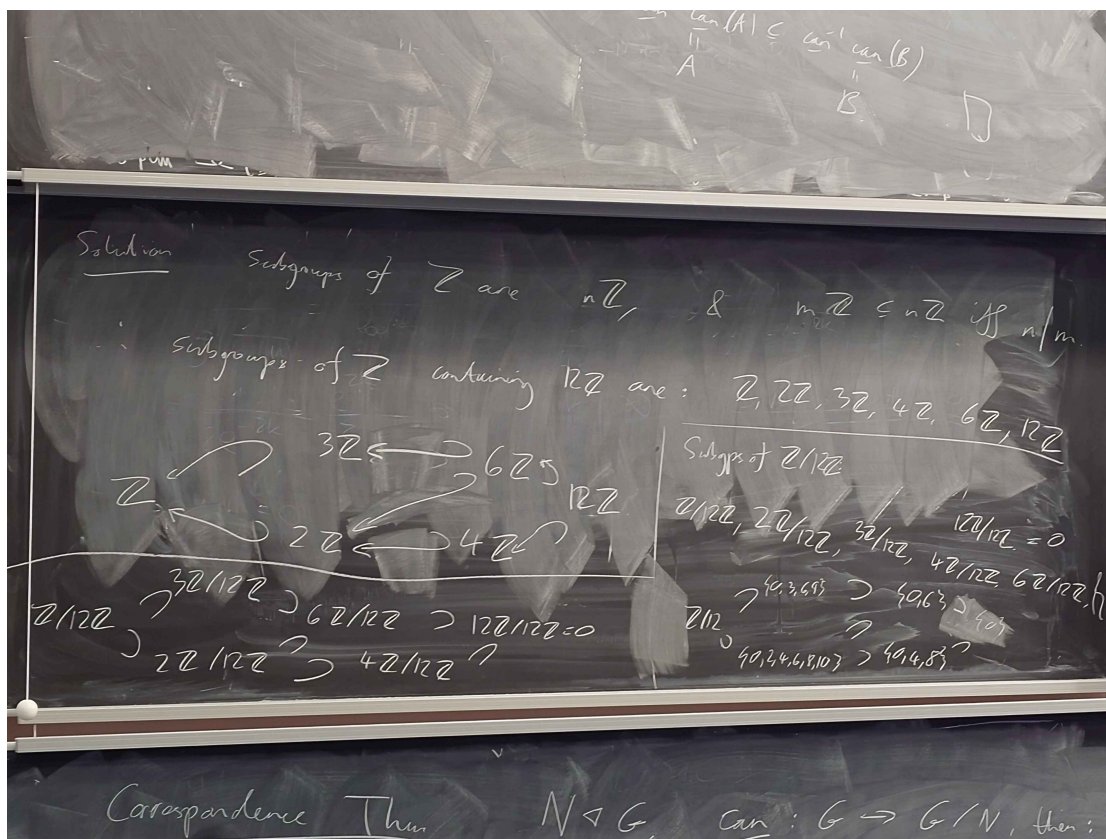
- \exists : There exists
- $\exists!$: There exists unique
- \nexists : there does not exist

Example: Let $G = \mathbb{Z}$, $N = 12\mathbb{Z}$.

- Find all subgroups of G containing N and all inclusions between them
- Find all subgroups of $\mathbb{Z}/12$

Solution: Subgroups of \mathbb{Z} are of the form $n\mathbb{Z}$. $m\mathbb{Z} \subseteq n\mathbb{Z}$ iff n/m
 Therefore, subgroups of \mathbb{Z} containing $12\mathbb{Z}$ are:

$$\mathbb{Z}, 2\mathbb{Z}, 3\mathbb{Z}, 4\mathbb{Z}, 6\mathbb{Z}, 12\mathbb{Z}$$



Subgroups of $\mathbb{Z}/12\mathbb{Z}$:

$$12\mathbb{Z}/12\mathbb{Z}, \mathbb{Z}/12\mathbb{Z}, 2\mathbb{Z}/12\mathbb{Z}, 3\mathbb{Z}/12\mathbb{Z}, 4\mathbb{Z}/12\mathbb{Z}, 6\mathbb{Z}/12\mathbb{Z}$$

some working out

Theorem 1.4.7: Third Isomorphism Theorem

If $N, H \triangleleft G$, with $N \leq H$, then

$$(G/N)/(H/N) \cong G/H$$

Proof. $N \leq \ker(\text{can}_H) = H$, so $\exists! \pi$ by universal property of finite groups

π is surjective, because can_H is isomorphic

Explicitly,

$$\pi(gN) = gH = \pi(\text{can}_N(g)) = \text{can}_H(g)$$

$$\ker(\pi) = \{gN : g \in H\} = H/N$$

By the first isomorphism theorem,

$$G/H \cong (G/N)/\ker \pi = (G/N)/(H/N)$$

□

Theorem 1.4.8: Second Isomorphism Theorem

Let $N \triangleleft G$ and $H \leq G$. Then:

1. $HN \leq G$
2. $N \triangleleft HN$
3. $H \cap N \triangleleft H$
4. $HN/N \cong H/H \cap N$

Proof. Let $h_1h_2 \in H$, $n_1n_2 \in N$

1.

$$h_1n_1h_2n_2 = \underbrace{h_1h_2}_{\in H} \underbrace{(h_2^{-1}n_1h_2)n_2}_{\in N}$$

$$(hn)^{-1} = n^{-1}h^{-1} = \underbrace{h^{-1}}_{\in H} \underbrace{(hn^{-1}h^{-1})}_{\in N}$$

2. If $g \in HN$ and $n \in N$, then $g \cap g^{-1} \in n$ since $g \in G$

3. If $x \in H \cap N$ and $h \in H$, then $\underbrace{h x h^{-1}}_{N \triangleleft G} \in N$ and $\underbrace{h x h^{-1}}_{x \in H} \in H$

4. Need $\theta : H \rightarrow HN/N$ surjective with kernel $H \cap N$

Let $\theta(h) = hN$ i.e. $\theta = \text{can}_N|_H$, $(\text{can}_N G \rightarrow G/N)$

Surjective: cosets of HN/N are cosets xN for $x \in HN$ but $x = hn$, $h \in H$, $n \in N$ and $xN = hN = \theta(h)$ (wtf?)

Kernel: If $\theta(h) = e$, $hN = N$, so $h \in N$, so $\ker \theta = H \cap N$, so by the correspondence theorem,

$$H/H \cap N \subseteq HN/N$$

□

2 Group Actions

Definition 2.0.1: Free Group

The **free group on generators** x_1, \dots, x_m is the group whose elements are words in the symbols $x_1, \dots, x_m, x_1^{-1}, \dots, x_m^{-1}$, subject to the group axioms and all logical consequences. The group operation is concatenation. The free group is written

$$\langle x_1, \dots, x_m \rangle$$

Example: Find presentations for:

$$\bullet \mathbb{Z}^2 = \langle x, y \mid xy = yx \rangle = \langle x, y \mid xyx^{-1}y^{-1} = e \rangle \cong \{x^i y^j = i, j \in \mathbb{Z}\}$$

Example 2.0.2: Random group action E

Let

$$E = \langle a, b \mid a^2, b^5, (ab)^2 \rangle$$

Lemma 2.0.3

Any element $x \in E$ can be written $x = a^i b^j$, where $i \in \{0, 1\}$ and $j \in \{0, 1, 2, 3, 4\}$

Corollary 2.0.4

Group homomorphisms

$$\phi : \langle x_1, \dots, x_n \mid r_1(\underline{x}), \dots, r_n(\underline{x}) \rangle \rightarrow G$$

correspond to multiples $(g_1, \dots, g_m) \in G^m$ s.t. $r_1(\underline{g}) = e, \dots, r_n(\underline{g}) = e$

Example: For $E = \langle a, b \mid a^2, b^5, (ab)^2 \rangle$

Group homomorphism - $Q : E \rightarrow G$ correspond to:

$$(g, h) \in G \times G \quad \text{s.t.} \quad g^2 = e, h^5 = e, (gh)^2 = e$$

In particular, we have:

$$\begin{aligned} \phi : E &\rightarrow D_5 \\ b &\mapsto \text{rotation} \\ a &\mapsto \text{reflection} \end{aligned}$$

We also have that $\text{im}(Q) = D_5$, and Q surjective

Definition 2.0.5: Reduced Word

A word $x^{m_1} y^{n_1} x^{m_2} y^{n_2} \dots x^{m_k} y^{n_k}$ is **reduced** if no $m_i, n_j = 0$ except possibly for m_1 or n_k (That is, a word doesn't need to start with a power of x or end with a power of y)

Lemma 2.0.6

Every element of $\langle x, y \rangle$ has a unique expansion as a reduced word

2.1 Sylow Theorems

Definition 2.1.1: Sylow Subgroups

Let G be a finite group and let p be a prime. A subgroup H of G is a **p -subgroup of G** if it is a p -group, that is it has order p^n for some n , and it is a **Sylow p -subgroup of G** if its order is the highest power of p that divides the order of G . We say that H is a **Sylow subgroup of G** if it is a Sylow p -subgroup for some prime p

Theorem 2.1.2: Cauchy

If a prime p divides $|G|$, then \exists a (cyclic) subgroup of order p

Theorem 2.1.3: Sylow I

Let $|G| = n$ and suppose that p is a prime that divides n . Write $n = p^m r$ with p not dividing r . Then there exists at least one subgroup of order p^m ; that is, there is at least one Sylow p -subgroup

Theorem 2.1.4: Sylow II

Let $|G| = n$ and suppose that p is a prime that divides n . Write $n = p^m r$ with p not dividing r . Suppose that P is a Sylow p -subgroup and that $H \leq G$ is any p -subgroup of G . Then there exists $x \in G$ with $H \subseteq xPx^{-1}$. In particular, any two Sylow p -subgroups of G are conjugate in G

Theorem 2.1.5: Sylow III

Let $|G| = n$ and suppose that p is a prime that divides n . Write $n = p^m r$ with p not dividing r . Let n_p be the number of distinct Sylow p -subgroups of G . Then $n_p \mid r$ and $n_p \equiv 1 \pmod{p}$

Lemma 2.1.6

If $n_p = 1$, then the Sylow p -subgroup P is normal in G .

Prop 2.1.7

Every group G with $|G| = 30$ has a normal subgroup

2.2 Group Actions

Definition 2.2.1: Group Action

An **action** of a group G on a set X is a function

$$\begin{aligned} G \times X &\rightarrow X \\ (g, x) &\mapsto g \cdot x \end{aligned}$$

such that

- $e \cdot x = x$ for all $x \in X$
- $(gh) \cdot x = g \cdot (h \cdot x)$ for all $g, h \in G$ and $x \in X$

Examples of actions

- D_n acting on an n -gon
- S_n acting on $\{1, 2, \dots, n\}$
- $\text{GL}_n(F)$ acting on F^n

Definition 2.2.2: Orbits

Given a G acting on X , and $x \in X$, define

- The **Orbit** $G \cdot x$ or $\text{Orb}_G(x)$ is $\{g \cdot x : g \in G\} \subseteq X$
- The **Stabiliser** $\text{Stab}_G(x)$ is $\{h \in G : h \cdot x = x\} \subseteq G$

Lemma 2.2.3

$\text{Stab}_G(x)$ is a subgroup of G

Proof. If $g_1 h \in \text{Stab}_G(x)$, then $(gh) \cdot x = g \cdot (h \cdot x) = g \cdot x = x$
 $g^{-1} \cdot x = g^{-1} \cdot (g \cdot x) = (g^{-1}g) \cdot x = e \cdot x = x$ □

Theorem 2.2.4: Orbit-Stabiliser Theorem

Let G be a finite group acting on a set X , and let $x \in X$. then

$$|G| = |\text{Stab}_G(x)| |G \cdot x|$$

Or more cleanly,

$$G \cdot x \cong G / \text{Stab}_G(x)$$

Lemma 2.2.5

Let G act on X

1. An action defines an equivalence relation $X : x \sim y \iff \exists g \in G \text{ s.t. } g \cdot x = y$
2. Equivalence relations are orbits
3. The orbits partition X

[diagram of D3]