

Math 493

Honors Algebra I

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INTRODUCTION & MOTIVATION

We will study

- (a) Linear algebra
- (b) Group Theory
- (c) Finite Group Representations

In 494 we will study

- (a) Ring Theory
- (b) Fields
- (c) Galois Theory

This class is good preparation for 575 or 676. The official textbook is Artin's Second edition. We will probably proceed in a different order than Artin. Other than Artin's look into Dummit & Foote, Lang, Hirstine. Pick the book that you like and read it. Sit four to a table.

Sometimes a polished proof will not be presented in class and you are expected to finish the proof at home.

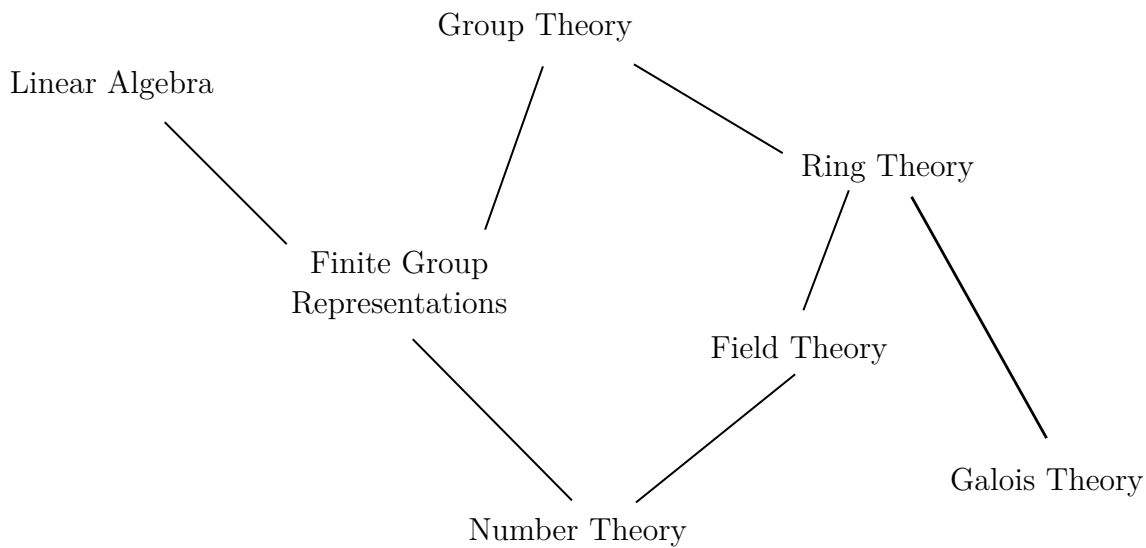


Figure 1: Partial Ordering of Course Topics

GROUP THEORY

Definition. (Group)

A group is a set G with a binary operation $\star : G \times G \rightarrow G$.

- (i) $\exists e \in G$ such that $e \star a = a \star e = a$ for all $a \in G$ (existence of identity)
- (ii) $\forall a, b, c \in G$ we have $(a \star b) \star c = a \star (b \star c)$ (associativity of \star)
- (iii) $\forall a \in G, \exists a' \in G$ such that $a \star a' = a' \star a = e$ (existence of inverses)

Examples:

- (a) The trivial group
- (b) $(\mathbb{Z}, +)$
- (c) $(\mathbb{Z}/2\mathbb{Z}, \oplus)$
- (d) $(\mathbb{Z}/n\mathbb{Z}, +)$
- (e) $(\mathbb{Q}^\times, \cdot)$ (nonzero rationals)
- (f) $\text{Aut}(S)$ for any set S , this is the symmetric group S_n when $|S| = n \in \mathbb{N}$
- (g) Rotations of a square
- (h) Free group on n elements

Consider S_1, S_2, S_3, \dots

Already, S_3 is quite complex. Recall that $|S_n| = n!$.

Note that S_2 has one generator and S_3 has two generators:

$$\sigma = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \tau = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

Every column and row in the Cayley Table of S_n has every element exactly once.

S_1	e	S_2	e	σ	S_3	e	τ	τ^2	σ	$\sigma\tau$	$\sigma\tau^2$
e	e	e	e	e	e	e	τ	τ^2	σ	$\sigma\tau$	$\sigma\tau^2$
e	e	e	e	e	τ	τ	τ^2	e	$\sigma\tau^2$	σ	$\sigma\tau$
e	e	e	e	e	τ^2	τ^2	e	τ	$\sigma\tau$	$\sigma\tau^2$	σ
e	e	e	e	e	σ	σ	$\sigma\tau$	$\sigma\tau^2$	e	τ	τ^2
e	e	e	e	e	$\sigma\tau$	$\sigma\tau$	$\sigma\tau^2$	σ	τ^2	e	τ
e	e	e	e	e	$\sigma\tau^2$	$\sigma\tau^2$	σ	$\sigma\tau$	τ	τ^2	e

Note that $\tau\sigma = \sigma\tau^2 \implies \tau^k\sigma = \sigma\tau^{2k}$ for $k \in \mathbb{N}$.

Definition. (Subgroup)

Suppose G is a group and $H \subseteq G$ such that

- (a) $e \in H$
- (b) $\forall a, b \in H$ we have $a \star b \in H$
- (c) $\forall a \in H$ we have $a^{-1} \in H$

H is a group with the group law inherited from G . If $S \subseteq G$, then $\langle S \rangle$ is the subgroup generated by S (note that S may be a singleton).

Now we find all subgroups of S_3 : $S_3, \{e\}, \{e, \tau, \tau^2\}, \{e, \sigma\}, \{e, \sigma\tau\}, \{e, \sigma\tau^2\}$. There are three subsets of S_3 that are isomorphic to S_2 and one isomorphic to $\mathbb{Z}/3\mathbb{Z}$. You can find subgroups by taking a single element and taking all powers of it (positive and negative). We obtain a lattice of subgroups.

Definition. (Order)

If $a \in G$, the **order** of a is $\mu n \in \mathbb{N}$ such that $a^n = e$. If no such n exists, then a has **infinite order**. Note that the order of all elements in a finite group are finite (pigeon hole principal).

Note that $S_3 \cong D_3$, the rigid symmetries of an equilateral triangle. We have three reflections over each axis and rotations by $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$.

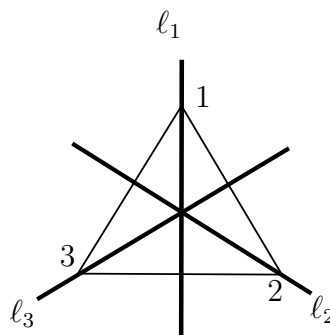


Figure 2: D_3

As isomorphisms of \mathbb{R}^2 we have

$$S_3 \cong D_3 \cong \left\{ I_2, \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}, \begin{bmatrix} 0 & -1 \\ -1 & 0 \end{bmatrix}, \begin{bmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{\sqrt{3}}{2} & -\frac{1}{2} \end{bmatrix}, \begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} & -\frac{1}{2} \end{bmatrix} \right\}$$

Since rotations of \mathbb{R}^2 are parametrized by $\begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}$.

D_n is the group of rigid rotations of a regular n -gon. Note that $D_n \hookrightarrow S_n$ and $|D_n| = 2n$. Explicitly D_n is the group with presentation

$$D_n = \langle x, y : x^n = e = y^2, xyx^{-1} = y^{-1} \rangle.$$

Geometrically, it is clear that $y^{-1} = y$ and $x^{-1} = x^{n-1}$.

Lagrange's Theorem & Quotient Groups

Theorem. (Lagrange's Theorem)

If $H \subseteq G$ a subgroup of a finite group G , then $|H|$ divides $|G|$.

Proof.

$P = \{gH : g \in G\}$ defines an equally sized partition on G . Since G is finite, the partition is finite and it must be that $|P| \cdot |H| = |G|$. \square

Definition. (Cosets)

Let $H \subseteq G$ be a subgroup.

A **left coset** of H in G is a subset of G of the form $aH = \{ah : h \in H\}$.

Similarly, A **right coset** of H in G is a subset of G of the form $Ha = \{ha : h \in H\}$.

Find all left and right cosets of all subgroups of S_3 . Let $H = \{e, \tau, \tau^2\}$, then $eH \sqcup \sigma H \cong S_3$. Note that $eH = \tau H = \tau^2 H$ and $\sigma \tau H = \sigma H = \sigma \tau^2 H$. Similarly, for $K = \{e, \sigma\}$ we have $eK = \sigma K$, $\tau K = \sigma \tau^2 K$, and $\tau^2 K = \sigma \tau K$.

Subgroup	Left Cosets	Right Cosets
G	G	Gb
$\{e\}$	$\{\{a\} : a \in G\}$	$\{\{a\} : a \in G\}$
$K = \{e, \tau, \tau^2\}$	$K, \sigma K$	$K, K\sigma$
$H_1 = \{e, \sigma\}$	$H_1, \tau H_1, \tau^2 H_1$	$H_1, H_1\tau, H_1\tau^2$
$H_2 = \{e, \sigma\tau\}$	$H_2, \tau H_2, \tau^2 H_2$	$H_2, H_2\tau, H_2\tau^2$
$H_3 = \{e, \sigma\tau^2\}$	$H_3, \tau H_3, \tau^2 H_3$	$H_3, H_3\tau, H_3\tau^2$

But note that $\tau^m H_k \neq H_k \tau^m$ for $m \in [2]$ and $k \in [3]$.

Fix a subgroup $H \subseteq G$. We now prove **Lagrange's Theorem** via three statements.

- (a) Any two left cosets of H in G are either identical or disjoint.

Proof.

Suppose $aH \cap bH \neq \emptyset$ so then there exists

$$c = ah_1 = bh_2 \implies a = b(h_2h_1^{-1}) \in bH \implies a \in bH.$$

Now for any element ah_3 of aH we have

$$ah_3 = b(h_2h_1^{-1})h_3 \in bH$$

Thus $aH \subseteq bH$. Interchanging the roles of aH and bH shows $bH \subseteq aH$. \square

- (b) All cosets have the same cardinality.

Proof.

Let $H \subseteq G$ be a subgroup and take $a \in G$. Define $f : H \rightarrow aH$ given by $f(x) = ax$. f is surjective by construction and if $f(x) = ax = ay = f(y)$, then $x = y$ by cancellation. So f is a bijection. Thus $|eH| = |aH|$ for all $a \in G$. \square

- (c) Finally, $G = \sqcup(\text{left cosets})$

Proof.

Given (a) it suffices to show $G = \cup(\text{left cosets})$. Pick $a \in G$, then $a \in aH \in (\text{left cosets})$. \square

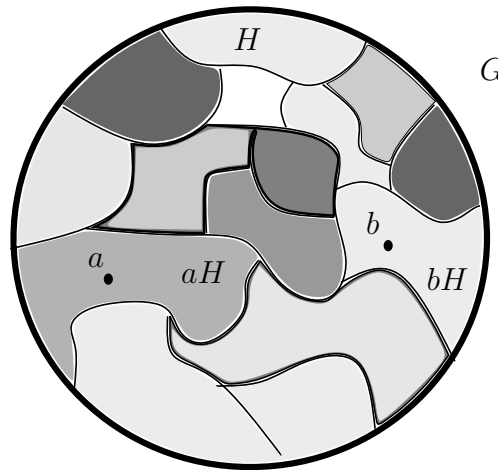


Figure 3: Cosets partition G

Definition. (Index)

The **index** of a subgroup $H \subseteq G$ is given by $[G : H]$ and gives the cardinality of the number of left cosets (which equals the number of right cosets).

Prove at home this holds for finite and infinite number of cosets.

Definition. (Cyclic Group)

A group G is said to be **cyclic** provided that $G = \langle a \rangle$ for some $a \in G$. Therefore, every cyclic group is countable and isomorphic to either \mathbb{Z} or—if finite— $\mathbb{Z}/n\mathbb{Z}$ for some $n \in \mathbb{N}$.

Proposition.

If $|G| = p$, a prime number, then G is cyclic.

Note: For every $n \in \mathbb{N}$, \exists a cyclic group of order n . We write this group C_n .

Definition. (Homomorphism)

A **homomorphism** is a map $\phi : G_1 \rightarrow G_2$ such that $\phi(ab) = \phi(a)\phi(b)$ and we call ϕ an **isomorphism** if ϕ is bijective.

Exercise: Classify groups of small order up to isomorphism.

Definition. (Direct Product)

Suppose G_1, G_2 are groups. Then $G_1 \times G_2$ with componentwise multiplication and inverses is a group of order $|G_1| \cdot |G_2|$. Note the direct product of cyclic groups is cyclic.

We prove that we have exhausted all groups of order four. Suppose there is an element of order four, then $G \cong C_4$. Suppose there is no element of order four, then every nontrivial element has order 2. The very cute fact about groups which have this property is that $\forall a, b \in G$ we have $(ab)^{-1} = b^{-1}a^{-1} = ba = ab$. Another way to prove this is $(ab)^2 = e = a^2b^2$.

Order	Groups
1	C_1
2	C_2
3	C_2
4	$C_4, C_2 \times C_2$
5	C_5
6	C_6, S_3
7	C_7
8	$C_8, (C_2)^3, D_4$

We prove that we have exhausted all groups of order six. Let G be an arbitrary group of order six. If there is an element of order six then $G \cong C_6$. Suppose there are no elements of order six ...

Definition. (Normal Subgroup)

Let $N \subseteq G$ be a subgroup. The following are equivalent

- (i) $aN = Na$ for all $a \in G$.
- (ii) $aNa^{-1} = N \forall a \in G$
- (iii) $a^{-1}Na = N \forall a \in G$
- (iv) $aNa^{-1} \subseteq N \forall a \in G$
- (v) $N \subseteq aNa^{-1} \forall a \in G$
- (vi) Every left coset of N in G is a right coset.
- (vii) Every right coset of N in G is a left coset.

Definition

N is said to be **normal** in G if it satisfies any of the aforementioned conditions. We write $N \trianglelefteq G$ to denote that N is normal in G .

Proof.

(i) \implies (ii) \implies (iii) \implies (iv) \implies (v) is clear.

Suppose every left coset of N is a right coset this means that $\forall a \in G, aN = Nb$ for some $b \in G$. Certainly $a \in Nb$. Since right cosets are disjoint the only right coset that contains a is Na so a and b are representatives for the same right coset. \square

Exercise: Identify all $N_1 \subseteq S_3$ and $N_2 \subseteq D_4$ such that $N_1 \trianglelefteq S_3$ and $N_2 \trianglelefteq D_4$.

The moment you find one conjugate that is different you know it is not normal. Note that all $H \subseteq S_3$ such that $H \cong S_2$ are conjugate to each other.

Group	Normal Subgroups
S_3	$\{e\}, \{e, \tau, \tau^2\}, S_3$
D_4	$\{e\}, \{e, x^2\}, \{e, x, x^2, x^3\}, \{e, yx, yx^3, x^2\}, \{e, y, yx^2, x^2\}$

A subgroup of order two is normal only when it is contained in the center. This follows since you need $ak = ka$ for the one nontrivial $k \in K \subseteq G$.

Cute Fact: Any subgroup of index two is normal. This follows since if $K \subseteq G$ has index two, then the right cosets are K and $G - K$ (certainly the same thing holds of the left cosets).

Let $\phi : G \rightarrow \{K, G \setminus K\}$ be given by $\phi(g) = gK$. Now $\phi \in \text{Hom}(G, C_2)$ and $\ker(\phi) = K$. Since $\{K, G \setminus K\} \cong C_2$ we are done (WHY?).

Definition. (Quotient Group)

Let $N \subseteq G$ be a normal subgroup. Then we can define the **quotient group** G/N which is as a set is the collection of left (resp. right) cosets and has group law $aN \star bN = abN$. This is well defined. G/N has identity $eN = N$ and inverses $(aN)^{-1} = a^{-1}N$.

Proof.

$$aN \star bN = (aN)(bN) = a(Nb)N = (ab)NN = abN$$

were the third equality follows since N is normal, shows that the product is well defined. □

Proposition. (Normal Subgroups are Kernels of Homomorphism)

If $\varphi \in \text{Hom}(G, H)$, then $\ker \varphi = \{g \in G : \varphi(g) = e\}$ is a normal subgroup.

Proof.

$aNa^{-1} \subseteq N \forall a \in G$. Given $n \in N$, ana^{-1} is annihilated by φ . Meaning,

$$\varphi(ana^{-1}) = \varphi(a)\varphi(n)\varphi(a^{-1}) = aea^{-1} = e.$$

The converse is also true. So the normal subgroups are exactly the kernels of $\varphi \in \text{Hom}(G, H)$.

Now to prove the converse, Define a map $\psi : G \rightarrow G/N$ where $\psi(a) = aN$. Then $N = \ker(\psi)$ by construction. □

We can now give a characterization of quotients. Taking successive quotients of a group leads to subsets of subsets and becomes cumbersome.

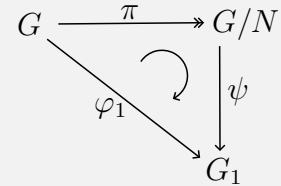
Proposition. (Universal Property of Quotient Map)

Let $\varphi_1 : G \rightarrow G_1$ be any homomorphism such that $N \subseteq \ker(\varphi_1)$.

In other words φ_1 annihilates N .

Then $\exists! \psi \in \text{Hom}(G/N, G_1)$ such that $\varphi_1 = \psi \circ \pi$.

Moreover, $N = \ker(\varphi_1) \iff \psi$ is injective.



Uniqueness is easiest to check because we only need to check the diagram commutes. If ψ exists, it must be unique and must be given by the formula $\psi(aN) = \varphi_1(a)$ since φ is surjective.

Now we need to check that the map ψ is well defined (since it is defined via coset representatives). Suppose $aN = bN$, so $a = bn$ for $n \in N$. This gives $\varphi_1(a) = \varphi_1(b)\varphi_1(n) = \varphi_1(b)$.

Now we show the second portion. Suppose $N = \ker(\varphi_1)$, then ψ is injective because $\ker(\psi) = \{e\}$. This follows since $\psi(aN) = e \iff \varphi_1(a) = e \iff a \in N$.

Now suppose that ψ is injective, so $\ker(\psi) = \{e\}$. This means that $\varphi_1(a) = e \iff a \in N$.

By prof: ψ is injective $\iff \ker(\psi) = \{e\} \iff K/N = \{e\} \iff K = N$. □

Theorem. (First Isomorphism Theorem)

Let $\varphi \in \text{Hom}(G, H)$. Then we can **factor** φ through $\ker(\varphi)$. Meaning, $\exists! \psi \in \text{Hom}(G/\ker(\varphi), H)$ such that $\varphi = \psi \circ \pi$ where π is projection onto the kernel, ψ is an isomorphism witnessing $G/\ker(\varphi) \cong \text{Im}(\varphi)$, and ι denotes the inclusion map.

$$\begin{array}{ccc} G & \xrightarrow{\varphi} & H \\ \pi \downarrow & & \uparrow \iota \\ G/\ker(\varphi) & \xrightarrow{\psi} & \text{Im}(\varphi) \end{array}$$

A natural question to ask arises. How are subgroups of G/N related to subgroups of G ?

Proposition. (The Correspondence Theorem)

Let $N \subseteq G$ be a subgroup. There is a bijection g between subgroups of G containing N and subgroups of G/N . $h(K) = K/N$ and $h(K/N) = h^{-1}(K)$ (or the fibres of K under h). The normality of a subgroup is preserved under the map h .

Proof.

See homework. □

We should interpret this as saying that the lattice of subgroups of G/N describes the lattice of subgroups of G at the “top”.

Cauchy’s Theorem

Lemma. (Order Lemma)

Let $h : G \rightarrow G_1$ be a homomorphism. Take $x \in G_1$, $o(g)$ for $g \in h^{-1}(x)$ is a multiple of $o(x)$.

Definition. (Conjugates)

Let $x, y \in G$. We say x and y are **conjugate** in G provided that $\exists g \in G$ such that $y = gxg^{-1}$.

So $C_x = \{y \in G : \exists g \text{ s.t. } y = gxg^{-1}\}$

Note that conjugacy is an equivalence relation. Let’s take a look at the equivalence classes produced by conjugation in S_3 . $C_e = \{e\}$, $C_\tau = \{\tau, \tau^2\}$, and $C_\sigma = \{\sigma, \sigma\tau, \sigma\tau^2\}$.

Note: In an abelian group all conjugacy classes are singletons.

Note: Elements of the same conjugacy class have the same order because

$$(gxg^{-1})^n = gx^n g^{-1}.$$

Think about how when we want to take powers of a matrix, we first try to diagonalize the matrix.

Notation: Let $H \subseteq G$ be a subgroup.

Then G/H is the set of left cosets H in G and $G H$ is the set of right cosets of H in G .

Theorem. (Size of Conjugacy Class)

Let G be a finite group. Let $x \in G$, then the cardinality of the conjugacy class of x divides the order of G .

Take $x, g_1, g_2 \in G$. Then,

$$g_1 x g_1^{-1} = g_2 x g_2^{-1} \iff (g_2^{-1} g_1) x = x (g_2^{-1} g_1) \iff g_2^{-1} g_1 \text{ commutes with } x \iff g_2^{-1} g_1 \in \mathcal{Z}_G(x)$$

Exercise: Write $\mathcal{Z}_G(x) = \{g \in G : gx = xg\}$.

(i) Show that $\mathcal{Z}_G(x)$ is a subgroup of G .

(ii) Furthermore, show there is a bijection $C_x \leftrightarrow G/\mathcal{Z}_G(x)$.

Proof.

Certainly $e \in \mathcal{Z}_G(x)$ and suppose $a, b \in \mathcal{Z}_G(x)$. Then, $ax = xa \implies bax = bxa \implies bax = xab$ since $bx = xb$. Also $ax = xa \implies xa^{-1} = a^{-1}x$.

Now we show there is a bijection. Let $\gamma : G \rightarrow C_x$ be given by $\gamma(g) = gxg^{-1}$. This map is surjective by definition. Now

$$\gamma(g_1) = \gamma(g_2) \iff g_2^{-1} g_1 \in \mathcal{Z}_G(x) \iff g_1 \in g_2 \mathcal{Z}_G(x) \iff g_1 \mathcal{Z}_G(x) = g_2 \mathcal{Z}_G(x).$$

Which shows that γ gives a bijection $G/\mathcal{Z}_G(x) \rightarrow C_x$.

□

The center of a group consists of exactly the elements which have singleton conjugacy classes.

Theorem. (Class Equation)

Let G be a finite group. Then

$$|G| = \sum_{x \in G} |C_x| = |\mathcal{Z}(G)| + \sum_{x \in G \setminus \mathcal{Z}(G)} |C_x| = |\mathcal{Z}(G)| + \sum_{x \in G \setminus \mathcal{Z}(G)} \frac{|G|}{|\mathcal{Z}_G(x)|}$$

Theorem. (Cauchy's Theorem)

Let G be a finite group. Let p be a prime number such that p divides $|G|$, then G contains an element of order p .

Proof.

Case I: Suppose G is cyclic, then there is an element x such that $\langle x \rangle = G$ and x has order $|G| = n$. If p is prime and divides n , then $n = pm$ and x^m has order p .

Case II: Suppose G is abelian. If $|G| = 2$, then we know $G \cong C_2$ which satisfies the theorem. Assume inductively that the theorem holds for all G such that $|G| < k$ for $k \in \mathbb{N}$. Take nontrivial $x \in G$ and consider $H = \langle x \rangle$, which is cyclic. If p divides the order of H we are done by Case I, if not then consider G/H (H is normal since G is abelian). $|G/H| = |G|/|H|$ which is less than k (and divisible by p), so the inductive hypothesis guarantees that G/H has an element of order p . Call this element aH .

Now we can lift this to an element of order p in G by the natural isomorphism between G/H and subgroups of G containing H .

Case III:

Here are the hints. (i) Use the class equation, (ii) use the abelian case, and (iii) induct on $|G|$.

If p divides $|\mathcal{Z}(G)|$ then we are done by Case II since the center of a group is abelian. Suppose not, then at least one summand is not divisible by p (i.e. $\exists x$ such that p does not divide $\frac{|G|}{|\mathcal{Z}_G(x)|}$). This follows since if every summand was divisible by p then $|G|$ would not be divisible by p .

So if p does not divide the ratio (which is the summand), then p must divide the denominator $|\mathcal{Z}_G(x)|$ which is less than $|G|$. By induction, we are done. \square

Proposition. (Groups of Prime Order have Nontrivial Centers)

If $|G| = p^n$ for p prime, then $\mathcal{Z}(G) \neq \{e\}$.

Corollary.

Any group of order p^2 is abelian.

Proof.

If G is abelian we are done. Suppose not. Take $x \notin \mathcal{Z}(G)$, then since $\mathcal{Z}_G(x) \subseteq G$ by Lagrange's Theorem $|\mathcal{Z}_G(x)| = p^i$ for $i < n$. Since $|G| = p^n$ we know $p \mid \frac{|G|}{|\mathcal{Z}_G(x)|}$. Now the Class Equation ensures that $p \mid |\mathcal{Z}(G)|$ which shows $|\mathcal{Z}(G)| \geq p$.

\therefore the center of G is nontrivial.

Now we prove the Corollary.

Let $|G| = p^2$ for a prime p . We know that $|\mathcal{Z}(G)| \in \{p, p^2\}$. Suppose $|\mathcal{Z}(G)| = p$. Take $y \notin \mathcal{Z}(G)$. Note that $\mathcal{Z}_G(y) \supset \mathcal{Z}(G)$. But both of these are subgroups, so since $|\mathcal{Z}(G)| = p$ it must be that $|\mathcal{Z}_G(y)| = p^2 = |G|$. Contradiction! Thus every group of order p^2 is abelian.

\square

The Sylow Theorems

Definition. (p -Sylow Subgroup)

Let G be a finite group such that $|G| = p^r \cdot m$ where p is prime, $r \geq 1$, and p does not divide m . A p -Sylow subgroup of G is a subgroup $H \subseteq G$ such that $|H| = p^r$.

Theorem. (Sylow Theorems)

Let G be a finite group with $|G| = p^r \cdot m$ where p is prime, $r \geq 1$, and p does not divide m .

- (1) G contains a p -Sylow subgroup H .
- (2) (Weak version) Any two p -Sylow subgroups are conjugate in G . Meaning, if $H_1, H_2 \subseteq G$ are p -Sylow then $\exists g \in G$ such that $H_2 = gH_1g^{-1}$.
- (3) The number of p -Sylow subgroups
 - divides m and
 - is congruent to 1 mod p .

Exercise: Classify all groups of order 15.

Note that $15 = 5 \cdot 3$. Take $p = 5$ and $m = 3$, this makes $r = 1$. By (3) any group of order 15 has exactly one 5-Sylow subgroup and exactly one 3-Sylow subgroup. These subgroups must be cyclic because they have prime order. Furthermore their intersection must be trivial.

Take an element not in the union of the aforementioned subgroups. Its order must be 15 because (a) it cannot be the identity, (b) its order cannot be 3 since that would generate a new 3-Sylow subgroup, (c) cannot have order 5 for the same reason.

$C_{15} \cong C_5 \times C_3$ by the internal direct product construction. Both C_5 and C_3 are normal in G because conjugation produces another 5-Sylow and 3-Sylow respectively. But C_5 and C_3 are the unique Sylow subgroups. This gives us the conditions to satisfy the internal direct product construction. Thus we have determined all groups of order 15 up to isomorphism.

Exercise: Classify all groups of order 21. This one is trickier because $7 \bmod 3 \equiv 1$.

There is a unique 7-Sylow subgroup which is cyclic. If there is only one 3-Sylow subgroup then the group is isomorphic to C_{21} since C_{21} is the internal direct product of C_3 and C_7 (by the same argument as the previous exercise).

Now suppose there are seven 3-Sylow subgroups. They have trivial intersection because they are cyclic. So these give $2 \cdot 7 + 1 + 6$ elements accounted for so far. Fix a 3-Sylow K and a generator y . Take a generator x for the 7-Sylow H . Note that H is normal because it is the unique 7-Sylow. So now we know that HK is a group because $HK = KH$ since $hk = kk^{-1}hk$ and $k^{-1}hk \in H$ since H is normal in G . But this now gives us that $G \cong HK = \{x^i y^j : 0 \leq i \leq 6 \wedge 0 \leq j \leq 2\}$ so G is cyclic. Because H is normal, $xyx^{-1} \in H$ so it is of the form x^i for some $i \in [6]$. Note that $i = 0 \implies x = e$ which is not possible. Also $i \neq 1$ since this gives us the abelian case and $G \cong C_{21}$ again. Recall that y has order three, so

$$y^2 xy^{-2} = yx^i y^{-1} = (yxy^{-1})^i = x^{i^2} \implies x = y^3 xy^{-3} = yx^{i^2} y^{-1} = (yxy^{-1})^{i^2} = x^{i^3}$$

So now $x^1 = x^{i^3}$ so $i^3 \equiv 1 \bmod 7$. So 1, 2, 4 are the only values of i that work.

So now $yxy^{-1} \in \{x, x^2, x^4\}$ so there are at most three groups of order 21. The guess is that both the x^2 and x^4 case are isomorphic.

Wait until the next homework to find out !

Definition. (Group Actions)

Let G be a group and S a set. A **group action** is a map $G \times S \rightarrow S$ given by $(g, s) \mapsto g \cdot s = gs$.

The map should satisfy

- (i) $e \cdot s = s$ for all $s \in S$,
- (ii) $(g_1 g_2) \cdot s = g_1 \cdot (g_2 \cdot s)$

Examples:

- (a) Forget the group structure on G to obtain a set S and have the action be standard group product (but right multiplication would not work).
- (b) Forget the group structure on G to obtain a set S and have the action be right multiplication by the inverse of g .

- (c) Forget the group structure on G to obtain a set S and have the action be conjugation.
- (d) Forget the group structure on G to obtain a set S and
- (e) S is a compact polytope and G is its set of symmetries.
- (f) D_n acting on \mathbb{R}^2 as linear maps.

This gives us a preview into **group representations** where we will ask about $G \times V \rightarrow V$ where $v \mapsto gv$ is a linear transformation.

Definition. (Orbit and Stabilizer)

The **orbit** of s is $O(s) = \{gs : g \in G\}$ and the **stabilizer** of s is $\text{Stab}(s) = \{g \in G : gs = s\}$.

So when the group action is conjugation, $O(s) = C_s$ and $\text{Stab}(s) = Z_G(s)$ the centralizer of s .

Proposition. ()

$G_s \trianglelefteq G$ and as sets $O(s) \cong G/G_s$.

Corollary.

$|O(s)| = [G : G_s]$ which equals $\frac{|G|}{|G_s|}$ when G is finite.

Note that $O(s)$ may not be a group.

Clearly $e \in G_s$. Now suppose $a, b \in G_s$ then $abs = as = s$. $as = s \implies s = a^{-1}s$. $G_s \trianglelefteq G$ by definition.

Let $\gamma_s : G \rightarrow O(s)$ be given by the group action. So $\gamma_s(g) = g \cdot s$ is surjective. Now

$$g_1 \cdot s = g_2 \cdot s \iff g_2^{-1}g_1 \in G_s \iff g_1 \in g_s G_s \iff g_1 G_s = g_s G_s.$$

This gives a bijection $G/G_s \longleftrightarrow O(s)$.

Theorem. (General Class Equation)

$$|S| = \sum_{[s]} |O(s)|$$

Theorem. (First Sylow Theorem)

Let $|G| = g^r \cdot m$ with $r \geq 1$ and $p \nmid m$ then G contains a subgroup of order p^r .

Proof.

Step I: Let $S = \{M \in \mathcal{P}(G) : |M| = p^r\}$. Let G act on S by left multiplication so $g \cdot s = gs$.

First we claim that $p \nmid |s|$.

$$|S| = \binom{p^r \cdot m}{p^r} = \frac{p^r m (p^r m - 1) \cdots (p^r m - (p^r - 1))}{p^r (p^r - 1) \cdots (p^r - (p^r - 1))} = \frac{p^r m - i}{p^r - i}$$

where $i = p^j \cdot k$ with $j < r$ and $p \nmid k$.

$$\frac{p^r m - i}{p^r - i} = \frac{p^r m - p^j k}{p^r - p^j k} = \frac{p^r m - p^j k}{p^r - p^j k} =$$

THINK ABOUT AT HOME

From this claim we obtain some $s \in S$ such that $|O(s)|$ is prime to p . But we know

$$p^r \cdot m = |G| = |G_s| \cdot |O(s)| \implies p^r \mid |G_s|.$$

So $s = \{g_1, g_2, \dots, g_{p^r}\}$ and $G_s g_1 \subseteq s$ because G_s stabilizes the set s (we could have used any element in s). This gives us that $|G_s| \leq |s| = p^r$ but since $|G_s| \mid p^r$ we conclude that $|G_s| = p^r$.

You never need to remember the proof of this theorem. □

“You are one of the most on brand people I know” -Nikki

“Today we are doing a worksheet but if anyone comes let tell them theres a quiz going on.”

Theorem. (Strong Second Sylow)

Let G be a finite group with $p \mid |G|$. Let H be a p -Sylow subgroup of G . Let K be any subgroup of G . Then there exists an element $a \in G$ such that $K \cap aHa^{-1}$ is a p -Sylow subgroup of K .

The following theorem follows from the above.

Theorem. (Consequences of Strong Second Sylow)

Let G be a finite group. Any two p -Sylow subgroups of G are conjugate in G .

If $K \subseteq G$ is a subgroup that is a p -group (i.e. one whose order is a power of p), then K is contained in a p -Sylow subgroup of G .

Proof.

Let H_1, H_2 be p -Sylow subgroups of G . Let $|G| = p^r m$ where $p \nmid m$. Then $|H_1| = p^r = |H_2|$. Then take $K = H_1$ and the Second Sylow Theorem gives an element a such that $H_1 \cap aH_2a^{-1}$ is p -Sylow in H_1 . Note that $|H_2| = |aH_2a^{-1}|$. This means that $|H_1 \cap aH_2a^{-1}| = p^r$. This implies that $|H_1| = |H_1 \cap aH_2a^{-1}|$ Consequently, $H_1 = aH_2a^{-1}$ since $H_1 \supseteq H_1 \cap aH_2a^{-1}$.

Suppose $|G| = p^r m$ and $|K| = p^\ell$ for $\ell < r$. The only p -Sylow subgroups of K is K itself. Suppose that H is a p -Sylow subgroup, then from Strong Second Sylow $\exists g \in G$ such that gHg^{-1} is a p -Sylow in K . So $K \subseteq gHg^{-1}$.

Consider the group action $G \times G/H \rightarrow G/H$ given by left multiplication. This group action is transitive (has a single orbit) because $ba^{-1} \cdot aH \rightarrow bH$. Note that $\text{Stab}(aH) = aHa^{-1}$. Now take $g \in \text{Stab}(aH)$. Then

$$gaH = aH \iff a^{-1}gaH = H \iff g \in H \iff g = aha^{-1}$$

for some $h \in H$.

Consider the restriction of the group action to K . Then $\text{Stab}(aH) = K \cap aHa^{-1} \cap K$.

Let's use the fact that H is p -Sylow in G . So $|G/H|$ is prime to p . The size of the full set is the sum of the sizes of the orbits. There must exist some orbit $O(aH)$ which has cardinality prime to p . Now the Orbit Stabilizer Theorem tells us

$$|O(aH)| \cdot |\text{Stab}(aH)| = |K| \implies |O(aH)| = |aHa^{-1} \cap K| = |K|.$$

The powers of p that divide $|K|$ and $|aHa^{-1} \cap K|$ are the same. So K is a p -Sylow subgroup.

Be ready to work through 5 and 6 on the board next time.

Problem 5 on the worksheet Take $g \in \text{Stab}(s)$. Then $g \cdot s = gsg^{-1}$.

Theorem. (Third Sylow)

Suppose $|G| = p^r m$ with $p \nmid m$. The number of p -Sylow subgroups of G divides m and is congruent to 1 mod p .

Step I: Let S be the set of p -Sylow subgroups of G and consider the action of G on S by conjugation:

$$G \times S \rightarrow S, \quad (g, H) \mapsto gHg^{-1}.$$

Since the action is transitive (by the previous theorem), we get

$$|S| |\text{Stab}(H)| = |G|.$$

We show that $\text{Stab}(H) = N_G(H)$, and conclude that $|S|$ divides m .

$\text{Stab}(H) = N_G(H)$ by definition. Since this group action is transitive then $O(s) = S$ for $s \in S$. Now the Orbit Stabilizer Theorem gives $|S| |\text{Stab}(H)| = |G|$. This tells us that $|S| = \frac{|G|}{|N_G(H)|} = [G : N_G(H)]$. Since $[N_G(H) : H] \cdot [G : N_G(H)] = [G : H]$ we obtain that $|S|$ divides s . It may be useful to use $|S| = [G : N_G(H)]$.

Step II: Now fix a p -Sylow subgroup H and restrict the last action to an action $H \times S \rightarrow S$. If K is a p -Sylow subgroup of G , we show that $|O(K)| = 1 \iff K = H$, and otherwise $|O(K)|$ is divisible by p .

Suppose $H = K$ then for all $h \in H$, $hKh^{-1} = K \implies O(K) = K$. Now suppose $|O(K)| = 1$. Then $O(K) = K$ which gives $H \subseteq \text{Stab}(K) = N_G(K)$. Now $K \trianglelefteq N_G(K)$ which gives that K is p -Sylow in $N_G(K)$. Since H is also p -Sylow in $N_G(K)$ but there is a unique p -Sylow inside the normalizer by the Second Sylow Theorem, so $H = K$. This is a good trick to apply the second Sylow to the normalizer of K .

Now we conclude that $|S| \equiv 1 \pmod{p}$, thus finishing the proof of Theorem the Third Sylow.

Now $|O(K)| > 1 \implies p \mid |O(K)|$ and by the Orbit Stabilizer theorem $|O(K)| \cdot |\text{Stab}(K)| = |H| = p^r$. So $|O(K)| = p^\ell$ for some $\ell \in \mathbb{N}$. We know that

$$|S| = \sum_{[K]} |O(K)| = |O(H)| + \sum_{[K] \neq [H]} |O(K)| \equiv 1 \pmod{p}$$

This completes the proof. □

Group Actions on Sets

As we have seen that classifying finite groups becomes increasingly hard. Classifying groups of order only 16 is very difficult. This leads us to a new approach. We will study groups by studying their normal subgroups and their quotients.

Definition. (Simple)

A group G is said to be **simple** if it contains no normal subgroups other than $\{e\}$ and G .

Examples:

- (i) Any group of prime order.
- (ii) Finite abelian groups if and only if it has prime order. This follows since if $p \mid |G|$, by Cauchy's Theorem, G contains an element of order p called x and $\langle x \rangle \trianglelefteq G$.
- (iii)

Exercise: Show that if G is non-abelian, $|G| < 60$, then G is not simple. There is a unique non-abelian group which is simple but we will.

Recall that we have shown that the center of a group is normal and group of order p^n has nontrivial center.

After removing groups of these orders we have

6, 10, 12, 15, 20, 21, 22, 24, 26, 28, 30, 33, 34, 35, 39, 40, 42, 44, 45, 46, 48, 51, 52, 54, 56, 57

Let p and q be primes with $p < q$.

Suppose G is a group of order $2p$.

Suppose G is order $p \cdot q$. Then the number of q -Sylows n_q is congruent to 1 mod q and divides p , p does not satisfy this since $p < q$ so then there is a unique q -Sylow (which is normal) so G cannot be simple.

Suppose G is order $p \cdot q^2$. If $c_q = 1$ then the unique q -Sylow is normal and G is not simple. Suppose $C_q = 1$ or $C_q = p^2$. Then $p^2(q-1)$ elements of G are of order q . Exactly p^2 elements are left. So there is a unique p -Sylow.

We are left with

24, 36, 40, 48, 56, 60

So $24 = 2^3 \cdot 3$. The number of 2-Sylows C_2 divides 3 and is congruent to 1 mod 2. We cannot have $C_2 = 3$ and $C_3 = 4$, so either $C_2 = 1$ or $C_3 = 1$. Each 2-Sylow has order eight.

Suppose $C_3 = 3$ and $C_3 = 4$. We can make a homomorphism to another group with a non-trivial kernel which will give a normal a subgroup of G . A group action $G \times S \rightarrow S$ induces a homomorphism $G \rightarrow \text{Aut}(S)$.

Call the 2-Sylows $S = \{K_1, K_2, K_3\}$. We know by the Second Sylow Theorem these sets are conjugate. Let G act on S by conjugation. Then We obtain a map $\varphi : G \rightarrow \text{Aut}(S) \cong S_3$. This

map is transitive, so $\ker(\varphi) \neq G$ and $\ker(\varphi) \neq (e)$ since φ cannot be injective. We conclude that $\ker(\varphi)$ is a nontrivial normal subgroup. We conclude that G is not simple.

We can eliminate 40 by seeing there is only 1 5-Sylow.

We can also eliminate 56 by seeing there is either $C_7 \in \{1, 8\}$. Because if there are 8 7-Sylows, then $8 \cdot 6 = 48$ elements of order 7. But this means that there is a unique 2-Sylow. So groups of order 56 are not simple.

Now we consider $|G| = 36 = 2^2 \cdot 3^2$. So $C_2 \in \{1, 3, 9\}$ and $C_3 \in \{1, 4\}$. First suppose $C_3 = 4$. Then put S to be the four 3-Sylows. Let G act on S by conjugation. This induces a map $\varphi : G \rightarrow \text{Aut}(S)$. $\ker(\varphi) \neq G$ because elements of S are conjugate (the group action is transitive) and $|\text{Aut}(S)| = |S_4| = 24 < 36$ so φ cannot be injective.

For 48 we look at the 2-Sylows which are either 1 or 3 and the same argument as above suffices.

□

Simple Groups

Now we move on to the initial results of the important program: **the classification of finite simple groups**.

Definition. (Alternating Group)

Consider the homomorphism $\text{sgn} : S_n \rightarrow \{\pm 1\}$ defined by

$$f(x) = \prod_{i < j} (x_i - x_j) \quad \text{sgn}(\pi)f(x) = \prod_{i < j} (x_{\pi(i)} - x_{\pi(j)})$$

Now we can use cycle notation to describe elements of S_3 for example $(123)(45) \in S_5$ written with disjoint cycles. Then

$$S_3 = \{e, (12), (13), (23), (123), (132)\}$$

Then,

$\pi \in S_n$	$\text{sgn}(\pi)$
e	$+1$
(12)	-1
(13)	-1
(23)	-1
(123)	$+1$
(132)	$+1$

The $\text{sgn}(\text{transposition}) = -1$.

Fact. (Permutation's are Products of Transpositions)

Any element of S_n is a product of transpositions. The number of such transpositions is invariant under automorphism.

Proof.

The first statement follows from inspection.

$$\pi = \prod_{i \in [\ell]} \tau_i \implies \operatorname{sgn}(\pi) = \prod_{i \in [\ell]} \operatorname{sgn}(\tau_i) = (-1)^\ell$$

□

Note that S_n is not simple since $\ker(\operatorname{sgn})$ gives a nontrivial normal subgroup.

Theorem. (Simplicity of A_n)
 A_n is simple for $n \geq 5$.

Proposition. (A_5 is Simple)

The group A_5 has order 60, is simple, and non-abelian. If $|G| = 60$ and is simple then $G \cong A_5$.

Proof.

Let $P \trianglelefteq H \trianglelefteq G$ and suppose P is a p -Sylow subgroup of H . We show that $P \trianglelefteq G$. So P is the unique p -Sylow in H . If $x \in H$, then $xPx^{-1} = P$ so we are done. Suppose $x \in G \setminus H$, then consider $xPx^{-1} \subseteq xHx^{-1} = H$, so now that xPx^{-1} has the same order as P , so it must be the unique p -Sylow.

Now if $|G| \in \{15, 20, 30\}$ then G has a unique 5-Sylow. This follows immediately from the Third Sylow for 15 and 20. Now from the homework we know that groups of order 30 contain a normal subgroup of order 15 isomorphic to C_{15} which is cyclic (so its center is the whole subgroup). Now the previous paragraph shows that $C_5 \trianglelefteq G$ since C_5 is the unique 5-Sylow in C_{15} .

Let G be a group of order 60. Then $\operatorname{Syl}_5 \in \{1, 6\}$ by the Third Sylow. Now suppose $\operatorname{Syl}_5 = 6$ (these are all cyclic), and G contains a nontrivial proper normal subgroup H . If $|H| \in \{5, 10, 15, 20, 30\}$ then H contains a normal 5-Sylow and by two paragraphs ago there is a unique 5-Sylow in G but we assumed this was not the case. So now $|H| \in \{2, 3, 4, 6, 12\}$.

Now suppose there exists an H of order 6 or 12. If $|H| = 6$, then H has a unique 3-Sylow. If $|H| = 12$ then H might have four 3-Sylows, if this is the case then there is a unique 2-Sylow which has order four. So now if $|H| = 6$, then there is a nontrivial proper normal subgroup H' with order in $\{2, 3, 4\}$.

Now consider the quotient G/H' which must have order 15, 20, or 30 by Lagrange's Theorem. Then by the argument above G/H' has a unique 5-Sylow which can be lifted to a subgroup K which is normal in G and contains a group of order 5. So $5 \mid |K|$.

The conclusion from all of this is that if $\operatorname{Syl}_5 = 6$ there is no such nontrivial, proper, normal subgroup in G . Checking that in A_5 it is the case that $\operatorname{Syl}_5 = 6$. □

Proposition. (There is a Unique Simple Group of Order 60)
 Up to isomorphism, A_5 is the unique simple group of order 60.

Proof.

Suppose G is a simple group of order 60. We will show that G cannot have a subset $H \subset G$ such

that $[H : G] < 5$. G is not simple so there cannot be subsets with index 1, 2 (since these subgroups will be normal) since this does not divide 60. Suppose G has a subgroup of index 3 (resp. 4). Take $n \in \{3, 4\}$. Consider the group action given by left multiplication acting on G/H . Then the group action induces a homomorphism $h : G/H \rightarrow S_n$. This map cannot be trivial since the map is surjective. Now if $n < 5$, then $n! < 60$ so the map cannot be an injection.

Now suppose G has a subgroup H of index 5, show that G is isomorphic to A_5 . Use the same map as above to obtain a homomorphism $h : G \rightarrow S_5$, we know this map is injective (since it is not a trivial map and G is simple). Compose with the quotient map to obtain $G \rightarrow S_5 \rightarrow S_5/A_5$ and we want to show this is trivial. Since if everything in G is annihilated by this map, then the image of G is contained in A_5 . The size of the map of this kernel is at least 30, but it cannot be between 30 and 60 since G is simple (and the kernel is a normal subgroup). So, now we know that G must size 30, and so the composed map is trivial.

$$G \xhookrightarrow{\iota} S_n \xrightarrow{\pi} C_2$$

Figure 4: Composed Homomorphism

We know that $\text{Syl}_2 \in \{1, 3, 5, 15\}$. Suppose $\text{Syl}_2 \notin \{1, 3\}$. It cannot be one since then G would not be normal. Similarly, cannot be three since then we can induce a homomorphism by the group action of conjugation acting on the set of two Sylows into S_3 . We can also frame this in terms of cosets, since the orbit of this group action is in bijection with the cosets of the normalizer of a 2-Sylow. Now the same argument as above works to show $G \cong A_5$.

Now we need to rule out that $\text{Syl}_2 \neq 15$. If all the Note that there are at least $\text{Syl}_5 \geq 6$ and all elements in these groups have order five. It cannot be the case that all the 2-Sylows are disjoint since then we would have accounted for at least $4 \cdot 6 + 3 \cdot 15$ elements.

Let P and Q be 2-Sylows with nontrivial intersection. Consider $N_G(P \cap Q)$. $|P| = 4 = |Q|$ and $P, Q \subset N_G(P \cap Q)$.

FINISH AT HOME

□

Theorem. (A_n is simple for $n \geq 5$)

A_n is simple for $n \geq 5$ and is the unique simple group of this order.

Product of permutations $(132)(45)(1452) = (15)(23)$.

Conjugation in S_n : $\sigma(i_1 i_2 \cdots i_r) \sigma^{-1}$. For example $\sigma = (132)$ and $\tau = (14)(523)$ then $\sigma \tau \sigma^{-1} = (125)(34) = (34)(512) = (\sigma(1)\sigma(4))(\sigma(5)\sigma(2)\sigma(3))$. In general, $\sigma(i_1 i_2 \cdots i_r) \sigma^{-1} = (\sigma(i_1)\sigma(i_2) \cdots \sigma(i_r))$.

First we show that the product of two transpositions can be written as the product of two three cycles. $(i_1 i_2)(i_3 i_4) = (i_3 i_2 i_4)(i_1 i_3 i_2)$ if they have nothing in common. And if they have an element in common then $(i_1 i_2)(i_2 i_3) = (i_1 i_2 i_3)$ as a singleton product. Since A_n can be generated by even permutations, and even permutations are a product of an even number of transpositions. We can group these into pairs, which becomes tuples of three cycles. Three cycles are contained in A_n , so thus A_n is generated by three-cycles.

Now we show that three cycles are conjugate in S_n . Let $\sigma(x) = x'$. Note that $\sigma(abc)\sigma^{-1} = (a'b'c')$. Now pick $r, s \notin \{a, b, c\}$. Now $\sigma(rs)(abc)(rs)\sigma^{-1} = (a'b'c')$.

Suppose $N \trianglelefteq A_n$. We will show that $n = (e)$ or N contains a 3-cycle. Since N is finite, there is a nontrivial element $\sigma \in N$ that has maximal element with respect to number of fixed points. Suppose σ can be written as a product of disjoint transpositions. So $\sigma = \prod_{i=1}^t (a_i b_i)$ where $t \geq 2$ since $\sigma \in A_n$. Now we take $r \in \{1, \dots, n\}$ such that $r \notin \{a_i b_i : i \in [t]\}$. Put $\tau = (a_1 b_1 r)$. Now show that the **commutator** $\tau \sigma \tau^{-1} \sigma^{-1}$ lies in N since N is normal. In this case the commutator is not trivial. Then $\tau^{-1} = (a_1 r b_1)$ and $\sigma^{-1} = \sigma$ then we have

$$\tau \sigma \tau^{-1} \sigma^{-1} = \tau(\sigma(a_1) \sigma(r) \sigma(b_1)) = \tau(b_1 \sigma(r) a_1) = (a_1 r)(b_1 \sigma(r)).$$

So in our proof this forces r and $\sigma(r)$ to be in the set.

In the class proof we contradicted the maximality.

□

Definition. (Normal Series)

Let G be a group. A **normal series** for G is a sequence of nested subgroups

$$G = G_0 \supseteq G_1 \cdots \supseteq G_r = (e).$$

Two normal series $\{G_i\}_{i \in [r]}$ and $\{H_j\}_{j \in [s]}$ are said to be **equivalent** provided that the collection of quotients $\{G_i/G_{i+1}\}$ is the same as the quotients $\{H_j/H_{j+1}\}$ up to isomorphism. In particular if each are distinct then $r = s$ is a necessary condition for equivalence.

Definition. (Composition Series)

A **composition series** for G is a normal series in which each quotient G_i/G_{i+1} is nontrivial and simple.

Theorem. (Jordan-Holder)

If G has a composition series, then any two composition series are equivalent.

Proposition. (Finite Groups Admit Composition Series)

If G is a finite group, then G has a composition series.

Proof.

Suppose G is finite. Suppose G has no composition series.

Consider all paths through the

If G is simple then we are done, since $(G, (e))$ is a composition series for G . We induct on the order of G . If $|G| = 1$ then G is simple and $((e))$ is a composition series. Now assume inductively that all groups with $|G| < k$ have a composition series. If G is not simple, then G has a maximal nontrivial normal subgroup N_1 . Then G/N_1 has order strictly less than G . By the inductive hypothesis G/N_1 has a composition series $(\overline{G_2}, \dots, \overline{G_r})$. The correspondence theorem lifts this sequence to a series (G_2, \dots, G_r) of subgroups in G . Lifting preserves normality. Then (G_1, G_2, \dots, G_r) is a composition series for G . □

Exercise: Find composition series for the following groups

-
- (i) S_3 . S_3 has the normal subgroup $T = \{e, \tau, \tau^2\}$. So then $(S_3, T, (e))$ is a composition series for S_3 .
 - (ii) D_4 . Put $N = \{e, x, x^2, x^3\}$ then $(D_4, N, \{e, x^2\}, (e))$ is a composition series. Any subgroup of index two is
 For any p -group, every composition series looks like $(G, C_p, \dots, C_p, (e))$. Any path through the subgroup lattice generates a p -group. We can also reverse N and $\{e, x^2\}$ to get a new composition series.A
 - (iii) Q the quaternions. Let $I = \{e, \pm i\}$ and define J, K similarly. Then $(Q, I, J, (e))$ is a composition series. The composition series look like $(Q, N_1, N_2, (e))$ where $N_1, N_2 \in \{I, J, K\}$ are distinct.
 - (iv) $C_3 \times C_3$. This is a simple group so $(C_3 \times C_3, (e), (e))$ is the only composition series.
 - (v) C_9 . This group is abelian, so every subgroup is normal. So the only composition series is $(C_9, \{e, x^3, x^6\}, (e))$.

I WAS SICK HERE

Definition. (Commutator)

Let G be a group with $x, y \in G$. Define the **commutator** of x and y as $[x, y] = xyx^{-1}y^{-1}$. Then $[x, y] = e \iff xy = yx$.

Definition. (Commutator Subgroup)

The **commutator subgroup** or (derived subgroup) of G is the subgroup of G generated by all commutators $[x, y]$ with $x, y \in G$. We denote this $G', G^{(1)}$, or $[G, G]$.

A subgroup generated by a set S is the

- (a) smallest subgroup of G containing S ,
- (b) intersection of all subgroups containing S , and
- (c) S^* where $*$ is the Kleene star operator.

Now we show that $G' \trianglelefteq G$. Take $g, x, y \in G$ and then $gxyx^{-1}y^{-1}g^{-1} = g[x, y]g^{-1} = gxyg^{-1} = [gxyg^{-1}, gxyg^{-1}]$.

Now we compute G' for S_3, D_4, Q, D_5 .

- (a) $[S_3, S - 3] = \{e, x, x^2\}$
- (b) $[D_4, D_4] = \{e, x^2\}$
- (c) $[Q, Q] = \{\pm I_2\}$
- (d) $[D_5, D_5] = \{e, x, x^2, x^3\}$

Theorem. (Universal Property of Commutator Subgroup)

G/G' is abelian. Moreover if $\psi \in \text{Hom}(G, A)$ where A is abelian, then $G' \subseteq \ker(\psi)$ and there is a unique homomorphism $\bar{\psi} \in \text{Hom}(G/G', A)$ then the following diagram commutes.

DIAGRAM

So the commutator is the \subseteq -smallest $H \subseteq G$ such that G/H is abelian.

Take $[x], [y] \in G/G'$ and compute $[[x], [y]] = [x][y][x]^{-1}[y]^{-1} = [xyx^{-1}y^{-1}] = [e]$.

Definition. (Commutator Series)

Iteratively take commutators of G . The **derived series** or **commutator series** of G is

$$G = G^{(0)} \supseteq G^{(1)} \supseteq \dots$$

It might be that if we keep taking commutators then we eventually get (e) .

Definition. (Solvable)

G is said to be **solvable** if it admits a normal series in which every successive quotient is abelian. We will use this definition when we study Galois Theory.

Theorem. (Characterization of Solvability)

G is solvable when the commutator series is a normal series. So we eventually get (e) when we take successive commutators.

Proof.

If G is solvable then it has a normal series. By definition of solvable, $G^{(1)} \subseteq G_1$ and similarly, $G^{(k)} \subseteq G_k$. Eventually some k gives $G_k = (e)$ which shows the commutator series is a normal series.

Now for the other direction. □

Group Presentation

Definition. (Universal Property of Free Groups)

The **free group** on S (a set) is a group $f(S)$ together with an injection $\iota : S \hookrightarrow f(S)$ with the property that the following diagram commutes.

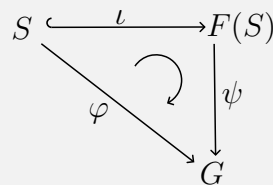
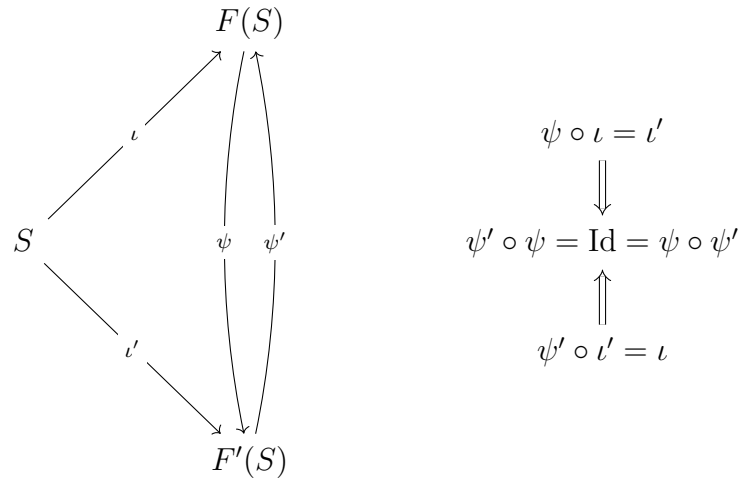


Figure 5: Universal property of free groups.

Furthermore ψ is unique.

Taking G to be $f'(S)$



So all that is left is to argue uniqueness of the map ψ .

Definition. (Construction of Free Group)

The free group on S is the set of all reduced words on S (where no cancellations are possible). Every word can be simplified to a unique reduced word. The free group $F(S) = S^*/\sim$ where $*$ is the Kleene star operator and the group product is given by concatenation where \sim is the equivalence relation that identifies words of the same reduced word.

Exercise: Show that in fact this gives a construction of the free group.

Let $\varphi : S \rightarrow G$ be a set-theoretic map. Any such $\psi \in \text{Hom}(S^*/\sim, G)$ is determined by φ on the coset representatives of $x \in S$.

For example $F(\{x, y\})$ maps surjectively onto D_n for all $n \in \mathbb{Z}^+ \cup \{\infty\}$.

Let $S = \{x, y\}$. Now take $N = N_{F(S)}(\langle x^n, y^2, xyxy^{-1} \rangle)$. Then $F(S)/N \cong D_n$.

SYMMETRY

We want to understand geometric symmetries. In \mathbb{R}^n these are isometries or rigid motions.

Definition. (Isometry)

A **rigid motion** or **isometry** is a map $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ that preserves distances.

One can check that every isometry is a bijection. So the set of isometries M_n on \mathbb{R}^n forms a group.

For $n = 1$, this group is $\{x \mapsto x + r, x \mapsto -x + r : r \in \mathbb{R}\}$. Let H be the set of translations on \mathbb{R} and K the set of reflections about any point in \mathbb{R} .

Note that H is isomorphic to $\langle \mathbb{R}, + \rangle$. Then K is isomorphic to C_2 .

So then K is normal in M_1 .

This gives us $\mathbb{R} \rtimes C_2$ and conjugation gives a map $C_2 \rightarrow \text{Aut}(\mathbb{R}, +)$.

Let M_1 be the set of reflections.

So $M_1/\mathbb{R} \cong C_2$. Any two subgroups of M_1 of order two are conjugate.

Now we should consider M_2 . The set of translations is a subset of M_2 that is isomorphic to $\langle \mathbb{R}^2, + \rangle$, or T the set of rotations. Now take \mathcal{O}_2 the set of isometries that fix the origin. Then $M_2/T \cong \mathcal{O}_2$. We can rotate by any $\theta \in \mathbb{R}/2\pi\mathbb{Z}$. The set of rotations in \mathcal{O}_2 has index two, so it is normal and its quotient is C_2 . So $\mathcal{O}_2 \cong \{\text{rotations fixing } 0\} \rtimes C_2$.

Proposition. (Isometries are Affine)

Every isometry that fixes the origin is linear in \mathbb{R}^n .

Proof.

Choose A an orthogonal matrix, so $A^T = A^{-1}$. A induces an isometry on \mathbb{R}^n , because the columns of A form an orthonormal basis of \mathbb{R}^n . This follows since A fixes the dot product, so A fixes distances too.

All isometries that fix the origin are induced by some orthonormal matrix. Let $L \in M_n$, an isometry. So $\|x\| = \|L(x)\| \implies \langle x, x \rangle = \langle L(x), L(x) \rangle$. Also $\|x - y\| = \|L(x) - L(y)\|$ which implies $\langle x - y, x - y \rangle = \langle L(x) - L(y), L(x) - L(y) \rangle$. Expanding this gives the equation $\langle x, y \rangle = \langle L(x), L(y) \rangle$. So now we know every isometry on \mathbb{R}^n preserves the dot product. Put $A = (L(e_1), \dots, L(e_n))$. Then the columns of A must be orthogonal since e_1, \dots, e_n are orthogonal. Take $x \in \mathbb{R}^n$ write $x = \sum_{i \in [n]} a_i e_i$ and $L(x) = \sum_{i \in [n]} a_i L(e_i)$. Now apply A and A^T to x and we will get x .

To recap the set of translations T , we have $T \trianglelefteq M_n$ and $M_n/T \cong \mathcal{O}_n$.

Now take $A \in \mathcal{O}_2$. Suppose $\det(A) = 1$. Since A is angle preserving A must be a rotation and is thus given in the form

$$\begin{bmatrix} \cos(\theta) & \sin(\theta) \\ \sin(\theta) & -\cos(\theta) \end{bmatrix}$$

If instead $\det(A) = -1$. Then it must include a reflection so it is a reflection about the line. This is the reflection over the angle bisector of e_1 and Ae_1 .

Now take $\rho_\theta \in \text{SO}_2$. Then $r\rho_\theta^{-1} = \rho_{-\theta}$ where r is rotation about the x -axis.

Let t_α be the translation by $\alpha \in \mathbb{R}^2$. Everything in O_2 is of the form ρ_θ or $\rho_\theta r$. Since $M_2 = T \rtimes O_2$ so we can write every element in the form $t_\alpha \rho_\theta r$.

$$(a) \quad \rho_\theta t_\alpha(x) = \rho_\theta(x + \alpha) = \rho_\theta(x) + \rho_\theta(\alpha) = \rho_\theta(x) t_{\rho_\theta(\alpha)}$$

(b)

(c)

(d)

(e)

The projection map $\pi_1 : M_2 \rightarrow O_2$ commutes with change of coordinates if the change of coordinates map is translation.

Find a b such that $t_b \cdot m t_b^{-1} = t_b \cdot t_a \rho_\theta \cdot t_{-b} = t_{a+b} t_{\rho_\theta(-b)} \rho_\theta = t_{a+b-\rho_\theta(b)} \rho_\theta = 0$

So we are going to solve for $\rho_\theta(b) - b = a$. We can check $\rho_\theta(b) - b$ is non-singular. Its determinant is $2(1 - \cos(\theta))$. So if $\theta > 0$ with $\theta \in \mathbb{R}/2\pi\mathbb{Z}$.

LINEAR ALGEBRA

Bilinear Forms