

# Algebra

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## 1 Major Theorems

**Theorem 1** (Cauchy). For any prime  $p$  dividing the order of  $G$ , there is an element  $x$  of order  $p$  (and thus a subgroup  $H = \langle x \rangle$ ).

**Theorem 2** (Lagrange). If  $H \leq G$  is a subgroup, then  $|H| \mid |G|$ .

**Theorem 3** (Sylow 1). If  $|G| = n = \prod p_i^{a_i}$  as a prime factorization, then  $G$  has subgroups of order  $p_i^{a_i}$  for every  $i$ . Moreover, this holds for any  $1 \leq r \leq a_i$ .

**Theorem 4** (Classification of finitely generated abelian groups). If  $G$  is a finitely generated abelian group, then  $G \cong F \oplus T$ , where  $F$  is free abelian and  $T$  is a torsion group. If  $|T| = n$ , then  $T \cong \bigoplus \mathbb{Z}_{p_i^{\alpha_i}}$  where  $n = \prod p_i^{\alpha_i}$  is some factorization of  $n$  with the  $p_i$  **not necessarily distinct**.

**Theorem 5.** Conjugacy classes partition  $G$

$$|G| = |Z(G)| + \sum_{\text{One representative in each orbit}} |C_G(g_i)| = \sum_{\text{asdsa}} [G : C(g_i)].$$

Some nice lemmas:

- Every subgroup of a cyclic group is itself cyclic.

## 2 Lecture 1 (Thu 15 Aug 2019)

We'll be using Hungerford's Algebra text. Show that a finite abelian group that is not cyclic contains a subgroup which is isomorphic

### 2.1 Definitions

The following definitions will be useful to know by heart:

- The order of a group
- Cartesian product
- Relations
- Equivalence relation
- Partition
- Binary operation
- Group
- Isomorphism
- Abelian group
- Cyclic group
- Subgroup
- Greatest common divisor
- Least common multiple
- Permutation
- Transposition
- Orbit
- Cycle
- The symmetric group  $S^n$
- The alternating group  $A_n$
- Even and odd permutations
- Cosets
- Index
- The direct product of groups
- Homomorphism
- Image of a function
- Inverse image of a function

- Kernel
- Normal subgroup
- Factor group
- Simple group

Here is a rough outline of the course:

- Group Theory
  - Groups acting on sets
  - Sylow theorems and applications
  - Classification
  - Free and free abelian groups
  - Solvable and simple groups
  - Normal series
- Galois Theory
  - Field extensions
  - Splitting fields
  - Separability
  - Finite fields
  - Cyclotomic extensions
  - Galois groups
  - Solvability by radicals
- Module theory
  - Free modules
  - Homomorphisms
  - Projective and injective modules
  - Finitely generated modules over a PID
- Linear Algebra
  - Matrices and linear transformations
  - Rank and determinants
  - Canonical forms
  - Characteristic polynomials
  - Eigenvalues and eigenvectors

## 2.2 Preliminaries

**Definition 1.** A **group** is an ordered pair  $(G, \cdot : G \times G \rightarrow G)$  where  $G$  is a set and  $\cdot$  is a binary operation, which satisfies the following axioms:

- Associativity:  $(g_1 g_2) g_3 = g_1 (g_2 g_3)$ ,
- Identity:  $\exists e \in G \ni ge = eg = g$ ,
- Inverses:  $g \in G \implies \exists h \in G \ni gh = gh = e$ .

**Example 1.**

- $(\mathbb{Z}, +)$
- $(\mathbb{Q}, +)$
- $(\mathbb{Q}^\times, \times)$
- $(\mathbb{R}^\times, \times)$
- $(\text{GL}(n, \mathbb{R}), \times) = \{A \in \text{Mat}_n \ni \det(A) \neq 0\}$

- $(S_n, \circ)$

**Definition 2.** A subset  $S \subseteq G$  is a **subgroup** of  $G$  iff

1.  $s_1, s_2 \in S \implies s_1 s_2 \in S$
2.  $e \in S$
3.  $s \in S \implies s^{-1} \in S$

We denote such a subgroup  $S \leq G$ .

Examples of subgroups:

- $(\mathbb{Z}, +) \leq (\mathbb{Q}, +)$
- $\text{SL}(n, \mathbb{R}) \leq \text{GL}(n, \mathbb{R})$ , where  $\text{SL}(n, \mathbb{R}) = \{A \in \text{GL}(n, \mathbb{R}) \mid \det(A) = 1\}$

## 2.3 Cyclic Groups

**Definition 3.** A group  $G$  is **cyclic** iff  $G$  is generated by a single element.

**Exercise 1.** Show  $\langle g \rangle = \{g^n \mid n \in \mathbb{Z}\} \cong \bigcap \{H \leq G \mid g \in H\}$ .

**Theorem 6.** Let  $G$  be a cyclic group, so  $G \cong \langle g \rangle$ .

- If  $|G| = \infty$ , then  $G \cong \mathbb{Z}$ .
- If  $|G| = n < \infty$ , then  $G \cong \mathbb{Z}_n$ .

**Definition 4.** Let  $H \leq G$ , and define a **right coset** of  $H$  by  $aH = \{ah \mid h \in H\}$ . A similar definition can be made for **left cosets**.

Then  $aH = bH \iff b^{-1}a \in H$  and  $Ha = Hb \iff ab^{-1} \in H$ .

Some facts:

- Cosets partition  $G$ , i.e.  $b \notin H \implies aH \cap bH = \emptyset$ .
- $|H| = |aH| = |Ha|$  for all  $a \in G$ .

**Theorem 7** (Lagrange). If  $G$  is a finite group and  $H \leq G$ , then  $|H| \mid |G|$ .

**Definition 5.** A subgroup  $N \leq G$  is **normal** iff  $gN = Ng$  for all  $g \in G$ , or equivalently  $gNg^{-1} \subseteq N$ . I denote this  $N \trianglelefteq G$ .

When  $N \trianglelefteq G$ , the set of left/right cosets of  $N$  themselves have a group structure. So we define

$$G/N = \{gN \mid g \in G\} \text{ where } (g_1N)(g_2N) = (g_1g_2)N.$$

Given  $H, K \leq G$ , define  $HK = \{hk \mid h \in H, k \in K\}$ . We have a general formula,

$$|HK| = \frac{|H||K|}{|H \cap K|}.$$

## 2.4 Homomorphisms

**Definition 6.** Let  $G, G'$  be groups, then  $\varphi : G \rightarrow G'$  is a **homomorphism** if  $\varphi(ab) = \varphi(a)\varphi(b)$ .

**Example 2.** •  $\exp : (\mathbb{R}, +) \rightarrow (\mathbb{R}^{>0}, \cdot)$  where  $\exp(a+b) = e^{a+b} = e^a e^b = \exp(a) \exp(b)$ .

- $\det : (\mathrm{GL}(n, \mathbb{R}), \times) \rightarrow (\mathbb{R}^\times, \times)$  where  $\det(AB) = \det(A) \det(B)$ .
- Let  $N \trianglelefteq G$  and  $\varphi : G \rightarrow G/N$  given by  $\varphi(g) = gN$ .
- Let  $\varphi : \mathbb{Z} \rightarrow \mathbb{Z}_n$  where  $\phi(g) = [g] = g \bmod n$  where  $\mathbb{Z}_n \cong \mathbb{Z}/n\mathbb{Z}$

**Definition 7.** Let  $\varphi : G \rightarrow G'$ . Then  $\varphi$  is a **monomorphism** iff it is injective, an **epimorphism** iff it is surjective, and an **isomorphism** iff it is bijective.

## 2.5 Direct Products

Let  $G_1, G_2$  be groups, then define

$$G_1 \times G_2 = \{(g_1, g_2) \mid g_1 \in G_1, g_2 \in G_2\} \text{ where } (g_1, g_2)(h_1, h_2) = (g_1 h_1, g_2 h_2).$$

We have the formula  $|G_1 \times G_2| = |G_1| |G_2|$ .

## 2.6 Finitely Generated Abelian Groups

**Definition 8.** We say a group is **abelian** if  $G$  is commutative, i.e.  $g_1, g_2 \in G \implies g_1 g_2 = g_2 g_1$ .

**Definition 9.** A group is **finitely generated** if there exist  $\{g_1, g_2, \dots, g_n\} \subseteq G$  such that  $G = \langle g_1, g_2, \dots, g_n \rangle$ .

This generalizes the notion of a cyclic group, where we can simply intersect all of the subgroups that contain the  $g_i$  to define it.

We know what cyclic groups look like – they are all isomorphic to  $\mathbb{Z}$  or  $\mathbb{Z}_n$ . So now we'd like a structure theorem for abelian finitely generated groups.

**Theorem 8.** Let  $G$  be a finitely generated abelian group. Then

$$G \cong \mathbb{Z}^r \times \prod_{i=1}^s \mathbb{Z}_{p_i^{\alpha_i}}$$

for some finite  $r, s \in \mathbb{N}$  and  $p_i$  are (not necessarily distinct) primes.

**Example 3.** Let  $G$  be a finite abelian group of order 4. Then  $G \cong \mathbb{Z}_4$  or  $\mathbb{Z}_2^2$ , which are not isomorphic because every element in  $\mathbb{Z}_2^2$  has order 2 where  $\mathbb{Z}_4$  contains an element of order 4.

## 2.7 Fundamental Homomorphism Theorem

Let  $\varphi : G \rightarrow G'$  be a group homomorphism and define  $\ker \varphi = \{g \in G \mid \varphi(g) = e'\}$ .

### 2.7.1 The First Homomorphism Theorem

**Theorem 9.** There exists a map  $\varphi' : G/\ker \varphi \rightarrow G'$  such that the following diagram commutes:

$$\begin{array}{ccc} G & \xrightarrow{\varphi} & G' \\ \eta \downarrow & \nearrow \varphi' & \\ G/\ker \varphi & & \end{array}$$

That is,  $\varphi = \varphi' \circ \eta$ , and  $\varphi'$  is an isomorphism onto its image, so  $G/\ker \varphi = \text{im } \varphi$ . This map is given by  $\varphi'(g(\ker \varphi)) = \varphi(g)$ .

**Exercise 2.** Check that  $\varphi$  is well-defined.

### 2.7.2 The Second Theorem

**Theorem 10.** Let  $K, N \leq G$  where  $N \trianglelefteq G$ . Then

$$\frac{K}{N \cap K} \cong \frac{NK}{N}$$

*Proof.* Define a map  $K \xrightarrow{\varphi} NK/N$  by  $\varphi(k) = kN$ . You can show that  $\varphi$  is onto by looking at  $\ker \varphi$ ; note that  $kN = \varphi(k) = N \iff k \in N$ , and so  $\ker \varphi = N \cap K$ .  $\square$

## 3 Lecture 2

Last time: the fundamental homomorphism theorems.

**Theorem 1:** Let  $\varphi : G \rightarrow G'$  be a homomorphism. Then there is a canonical homomorphism  $\eta : G \rightarrow G/\ker \varphi$  such that the usual diagram commutes. Moreover, this map induces an isomorphism  $G/\ker \varphi \cong \text{im } \varphi$ .

**Theorem 2:** Let  $K, N \leq G$  and suppose  $N \trianglelefteq G$ . Then there is an isomorphism

$$\frac{K}{K \cap N} \cong \frac{NK}{N}$$

(Show that  $K \cap N \trianglelefteq K$ , and  $NK$  is a subgroup exactly because  $N$  is normal).

**Theorem 3:** Let  $H, K \trianglelefteq G$  such that  $H \leq K$ .

1.  $H/K$  is normal in  $G/K$ .
2. The quotient  $(G/K)/(H/K) \cong G/H$ .

*Proof:* We'll use the first theorem. First make a map

$$\begin{aligned} G/K &\rightarrow G/H \\ \phi(gk) &= gH \end{aligned}$$

**Exercise:** Show that this map is onto, and that  $\ker \phi \cong H/K$ .

### 3.1 Permutation Groups

Let  $A$  be a set, then a *permutation* on  $A$  is a bijective map  $A \rightarrow A$ . This can be made into a group with a binary operation given by composition of functions. Denote  $S_A$  the set of permutations on  $A$ .

**Theorem:**  $S_A$  is in fact a group. Check associativity, inverses, identity, etc.

In the special case that  $A = \{1, 2, \dots, n\}$ , then  $S_n := S_A$ .

Recall two line notation

$$\begin{pmatrix} 1 & 2 & \cdots & n \\ \sigma(1) & \sigma(2) & \cdots & \sigma(n) \end{pmatrix}$$

Moreover,  $|S_n| = n!$  by a combinatorial counting argument.

Example:  $S_3$  is the symmetries of a triangle (see notes).

Example: The symmetries of a square are *not* given by  $S_4$ , it is instead  $D_4$  (see notes).

### 3.2 Orbits

Permutations  $S_A$  “acts” on  $A$ , and if  $\sigma \in S_A$ , then  $\langle \sigma \rangle$  also acts on  $A$ .

Define  $a \sim b$  iff there is some  $n$  such that  $\sigma^n(a) = b$ . This is an equivalence relation, and thus induces a partition of  $A$ . See notes for diagram. The equivalence classes under this relation are called the *orbits* under  $\sigma$ .

Example:

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 8 & 2 & 6 & 3 & 7 & 4 & 5 & 1 \end{pmatrix} = (18)(2)(364)(57).$$

Definition: A permutation  $\sigma \in S_n$  is a *cycle* iff it contains at most one orbit with more than one element. The *length* of a cycle is the number of elements in the largest orbit.

Recall cycle notation:  $\sigma = (\sigma(1)\sigma(2)\cdots\sigma(n))$ . Note that this is read right-to-left by convention!

Theorem: Every permutation  $\sigma \in S_n$  can be written as a product of disjoint cycles.

Definition: A *transposition* is a cycle of length 2. Moreover, we have

and so every permutation is a product of transpositions. This is not a unique decomposition, however, as e.g.  $\text{id} = (12)^2 = (34)^2$ .

Theorem: Any  $\sigma \in S_n$  can be written as **either** an even number of transpositions or an odd number of transpositions.

Define  $A_n = \{\sigma \in S_n \mid \sigma \text{ is even}\}$ . We claim that  $A_n \trianglelefteq S_n$ .

1. Closure: If  $\tau_1, \tau_2$  are both even, then  $\tau_1\tau_2$  also has an even number of transpositions.
2. The identity has an even number of transpositions, since zero is even.
3. Inverses: If  $\sigma = \prod_{i=1}^s \tau_i$  where  $s$  is even, then  $\sigma^{-1} = \prod_{i=1}^s \tau_{s-i}$ . But each  $\tau$  is order 2, so  $\tau^{-1} = \tau$ , so there are still an even number of transpositions.

So  $A_n$  is a subgroup. It is normal because it is index 2, or the kernel of a homomorphism, or by a direct computation.

### 3.3 Groups Acting on Sets

Think of this as a generalization of a  $G$ -module.

Definition: A group  $G$  is said to *act* on a set  $X$  if there exists a map  $G \times X \rightarrow X$  such that

1.  $e \curvearrowright x = x$

Examples:

1.  $G = S_A \curvearrowright A$
2.  $H \leq G$ , then  $G \curvearrowright X = G/H$  where  $g \curvearrowright xH = (gx)H$ .
3.  $G \curvearrowright G$  by conjugation, i.e.  $g \curvearrowright x = gxg^{-1}$ .

Definition: Let  $x \in X$ , then define the *stabilizer subgroup*

$$G_x = \{g \in G \mid g \curvearrowright x = x\} \leq G$$

We can also look at the dual thing,

$$X_g = \{x \in X \mid g \curvearrowright x = x\}.$$

We then define the *orbit* of an element  $x$  as

$$Gx = \{g \curvearrowright x \mid g \in G\}$$

and we have a similar result where  $x \sim y \iff x \in Gy$ , and the orbits partition  $X$ .

Theorem: Let  $G$  act on  $X$ . We want to know the number of elements in an orbit, and it turns out that

Proof: Construct a map  $Gx \xrightarrow{\psi} G/Gx$  where  $\psi(g \curvearrowright x) = gGx$ . Exercise: Show that this is well-defined, so if 2 elements are equal then they go to the same coset. Exercise: Show that this is surjective.

Injectivity:  $\psi(g_1x) = \psi(g_2x)$ , so  $g_1Gx = g_2Gx$  and  $(g_2^{-1}g_1)Gx = Gx$  so  $g_2^{-1}g_1 \in Gx \iff g_2^{-1}g_1 \curvearrowright x = x \iff g_1x = g_2x$ .

Next time: Burnside's theorem, proving the Sylow theorems.

## 4 Lecture 3 (Aug 22)

Last time: let  $G$  be a group and  $X$  be a set; we say  $G$  acts on  $X$  (or that  $X$  is a  $G$ -set) when there is a map  $G \times X \rightarrow X$  such that  $ex = x$  and  $(gh) \curvearrowright x = g \curvearrowright (h \curvearrowright x)$ . We then define the *stabilizer of  $x$*  as

$$G_x = \{g \in G \mid g \curvearrowright x = x\} \leq G,$$

and the *orbit*

$$G.x = \mathcal{O}_x = \{g \curvearrowright x \mid g \in G\} \subseteq X.$$

When  $G$  is finite, we have

$$\#G.x = \frac{\#G}{\#G_x}.$$

We can also consider the fixed points of  $X$ ,

$$X_g = \{x \in X \mid g \curvearrowright x = x \forall g \in G\} \subseteq X$$



## 4.1 Burnside's Theorem

Theorem (Burnside): Let  $X$  be a  $G$ -set and  $v$  be the number of orbits. Then

$$v \# G = \sum_{g \in G} \# X_g.$$

Proof:

Define  $N = \{(g, x) \mid g \curvearrowright x = x\} \subseteq G \times X$ , we then have

$$\begin{aligned} |N| &= \sum_{g \in G} |X_g| \\ &= \sum_{x \in X} |G_x| \\ &= \sum_{x \in X} \frac{|G|}{|G \cdot x|} \\ &= |G| \left( \sum_{x \in X} \frac{1}{|Gx|} \right) \\ &= |G|v. \end{aligned}$$

Since the orbits partition  $X$ , say into  $X = \bigcup_{i=1}^v \sigma_i$ , let  $\sigma = \{\sigma_i \mid 1 \leq i \leq v\}$  and abuse notation slightly by replacing each orbit in  $\sigma$  with a representative element  $x_i \in \sigma_i \subset X$ . We then have

$$\sum_{x \in \sigma} \frac{1}{|G \cdot x|} = \frac{1}{|Gx|} |\sigma| = 1.$$

Application: Consider seating 10 people around a circular table. How many distinct seating arrangements are there?

Let  $X$  be the set of configurations,  $G = S_{10}$ , and let  $G \curvearrowright X$  by permuting configurations. Then  $v$ , the number of orbits under this action, yields the number of distinct seating arrangements. By Burnside, we have

$$v = \frac{1}{|G|} \sum_{g \in G} |Xg| = \frac{1}{10!} (10!) = 9!,$$

since  $Xg = \{x \in X \mid gx = x\} = \emptyset$  unless  $g = e$ , and  $X_e = X$ .

## 4.2 Sylow Theory

Recall Lagrange's theorem: If  $H \leq G$  and  $G$  is finite, then  $\#H \mid \#G$ .

Consider the converse: if  $n \mid \#G$ , does there exist a subgroup of size  $n$ ? The answer is no in general, and a counterexample is  $A_4$  which has  $4!/2 = 12$  elements but no subgroup of order 6.

### 4.2.1 Class Functions

Let  $X$  be a  $G$ -set, and choose orbit representatives  $x_1 \cdots x_v$ . Then

$$|X| = \sum_{i=1}^v |Gx_i|.$$

We can then separately count all orbits with exactly one element, which is exactly  $X_G = \{x \in G \ni g \curvearrowright x = x \forall g\}$

We then have

$$|X| = |X_G| + \sum_{i=j}^v$$

for some  $j$  where  $|Gx_i| > 1$  for all  $i \geq j$ .

Theorem: Let  $G$  be a group of order  $p^n$  for  $p$  a prime, then

$$|X| \equiv |X_G| \pmod{p}$$

Proof: We know that  $|Gx_i| = [G : G_{x_i}]$  for  $j \leq i \leq v$ , and  $|Gx_i| > 1$  implies that  $Gx_i \neq G$  and thus  $p \mid [G : Gx_i]$ . The result follows.

Application: If  $|G| = p^n$ , then the center  $Z(G)$  is nontrivial. Let  $X = G$  act on itself by conjugation, so  $g \curvearrowright x = gxg^{-1}$ . Then

$$X_G = \{x \in G \ni gxg^{-1} = x\} = \{x \in G \ni gx = xg\} = Z(G)$$

But then, by the previous theorem, we have  $|Z(G)| \equiv |X| \equiv |G| \pmod{p}$ , but since  $Z(G) \leq G$  we have  $|Z(G)| \equiv 0 \pmod{p}$ , and so in particular,  $Z(G) \neq \{e\}$ .

Definition: A group  $G$  is a  $p$ -group iff every element in  $G$  has order  $p^k$  for some  $k$ . A subgroup is a  $p$ -group exactly when it is a  $p$ -group in its own right.

### 4.2.2 Cauchy's Theorem

Theorem (Cauchy): Let  $G$  be a finite group, where  $p \mid |G|$  is a prime. Then  $G$  is an element (and thus a subgroup) of order  $p$ .

Proof: Consider  $X = \{(g_1, g_2, \dots, g_p) \in G^{\oplus p} \ni g_1 g_2 \cdots g_p = e\}$ . Given any  $p-1$  elements, say  $g_1 \cdots g_{p-1}$ , the remaining element is completely determined by  $g_p = (g_1 \cdots g_{p-1})^{-1}$ . So  $|X| = |G|^{p-1}$ .

Since  $p \mid |G|$ , we have  $p \mid |X|$ . Now let  $\sigma \in S_p$  the symmetric group act on  $X$  by index permutation, i.e.  $\sigma \curvearrowright (g_1, g_2 \cdots g_p) = (g_{\sigma(1)}, g_{\sigma(2)}, \dots)$ .