

# Introduction to Algebra I

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### **Abstract**

The Introduction to Algebra course by professor 佐藤信夫.

# Contents

<b>1</b>	<b>I don't know how to parse different chapters</b>	<b>2</b>
1.1	Why study groups? . . . . .	2
1.2	Basis Properties of Groups . . . . .	6
1.3	Group homomorphisms/isomorphisms . . . . .	10
1.4	Properties of homomorphism . . . . .	11
1.5	Equivalenec relation . . . . .	12
1.6	Normal subgroups . . . . .	16
1.7	Direct Product (= Cartesian Product) . . . . .	18
1.8	Group action . . . . .	20
1.9	Symmetric groups . . . . .	22
1.10	Sylow's theorem . . . . .	27
1.11	Semidirect Product . . . . .	31

# Chapter 1

## I don't know how to parse different chapters

### Lecture 1

#### 1.1 Why study groups?

10 Sep. 13:20

Since groups appear everywhere, so we have to study them.

- Galois Theory: permutations of roots of polynomials.
- Number Theory: Ideal Class Group, Unit Group (unique factorization).
- Topology:

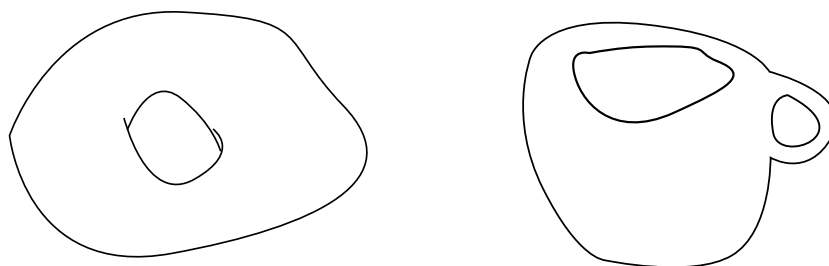


Figure 1.1: Fundamental Groups

- Physics/Chemistry: crystal symmetries and Gauge theory.

**Definition 1.1.1 (mod).** For two integers  $a, b$  we define  $a \equiv b \pmod{N}$  if and only if  $a - b \mid n$ .

Consider the sequence  $1, 2, 4, 8, 16, 32, \dots$ , and observe the remainders after mod  $p$  for different prime  $p$ , then

- $p = 5$ :  $\overbrace{1, 2, 4, 3}, \overbrace{1, 2, 4, 3}, \dots$
- $p = 7$ :  $\overbrace{1, 2, 4, 1}, \overbrace{2, 4, 1}, \dots$

**Theorem 1.1.1 (Fermat's little theorem).** The period divides  $p - 1$ .

**Note 1.1.1.** This is the special case of Lagrange's theorem.

Consider the symmetry of a triangle.

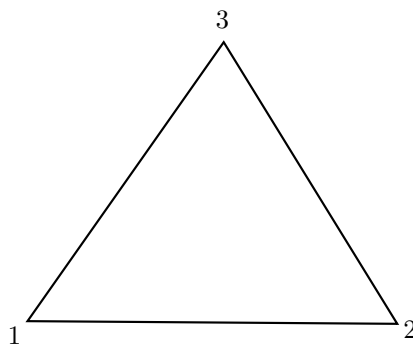


Figure 1.2: Triangle

Consider the rotation:

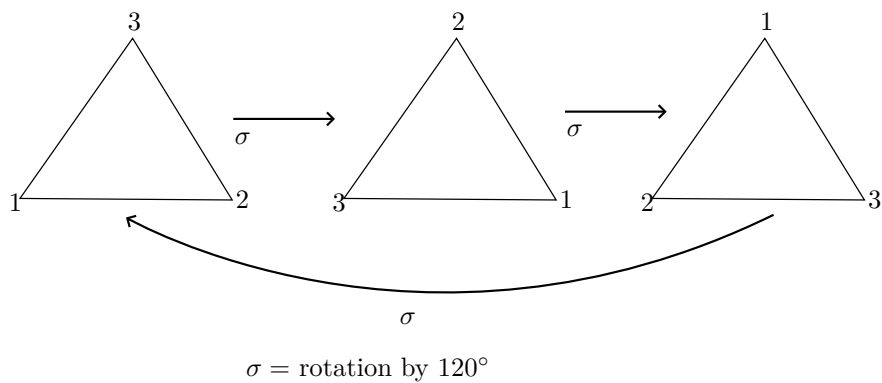


Figure 1.3: title

and reflection

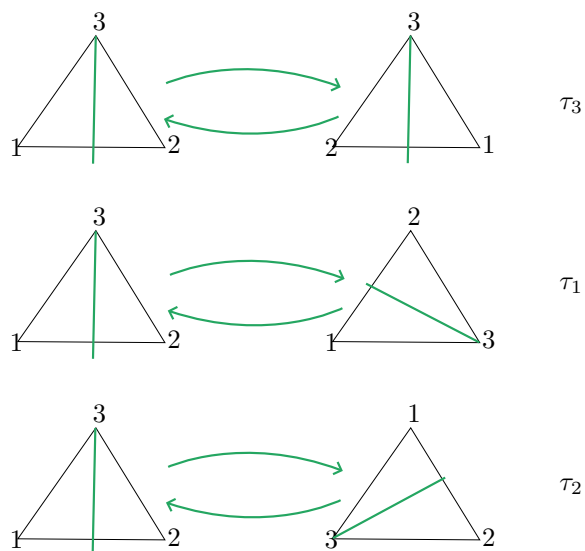


Figure 1.4: title

Hence, symmetries are defined by permutations of the vertices  $\{1, 2, 3\}$ , and thus there are 6 operations  $id, \sigma, \sigma^2, \tau_1, \tau_2, \tau_3$ . It is trivial that there are  $3 \times 2 \times 1$  permutations of  $\{1, 2, 3\}$ . Next, consider the six functions

$$\begin{aligned}\varphi_1(x) &= x \\ \varphi_2(x) &= 1 - x \\ \varphi_3(x) &= \frac{1}{x} \\ \varphi_4(x) &= \frac{x-1}{x} \\ \varphi_5(x) &= \frac{1}{1-x} \\ \varphi_6(x) &= \frac{x}{x-1}\end{aligned}$$

Observe that

$$\begin{aligned}\varphi_2(\varphi_3(x)) &= 1 - \frac{1}{x} = \frac{x-1}{x} \\ \varphi_4(\varphi_4(x)) &= \frac{1}{1-x} = \varphi_5(x) \\ \varphi_4(\varphi_4(\varphi_4(x))) &= x = \varphi_1(x)\end{aligned}$$

**Theorem 1.1.2.**  $\varphi_1, \varphi_2, \dots, \varphi_6$  are closed under composition.

**Note 1.1.2.** There's a fact that:

operations preserving symmetry of triangle  
 $\Leftrightarrow$  permutations on  $\{1, 2, 3\}$   
 $\Leftrightarrow$  compositions of  $\varphi_1, \dots, \varphi_6$

Actually, below things are somewhere similar,

- Addition of integers,
- Addition of classes of integers  $\bmod p$ ,
- Operations on geometric shape,

- Permutation on letters,
- Composition of functions.

Since they are all binary operations.

**Definition 1.1.2 (Binary operations).** Suppose  $X$  is a set. Binary operation  $\star$  is a rule that allocates an element of  $X$  to a pair of elements of  $X$ .

**Example 1.1.1.**

- Addition on  $\mathbb{N}, \mathbb{Z}, \mathbb{Q}, \mathbb{R}, \mathbb{C}$  or vector spaces.
- Subtractions on  $\mathbb{Z}, \mathbb{Q}, \mathbb{R}, \mathbb{C}$  or vector spaces.
- A map  $X \rightarrow X$  (self map) with composition  $(\varphi_1 \star \varphi_2)(x) = \varphi_1(\varphi_2(x))$ .
- Set of subsets of  $\mathbb{R}$ . We can define

$$- (A, B) \mapsto A \cup B$$

$$- (A, B) \mapsto A \cap B$$

$$- (A, B) \mapsto A \setminus B.$$

- $n \times n$  real square matrices

$$(A, B) \mapsto A \cdot B.$$

**Definition (Special relations).** Suppose  $X$  is a set and  $*$  is a binary operation on  $X$ .

**Definition 1.1.3 (Associativity).**  $(a * b) * c = a * (b * c)$ .

**Definition 1.1.4 (Identity).**  $\exists e \in X$  s.t.  $a * e = e * a = a$  for all  $a \in X$ .

**Definition 1.1.5 (Inverse).**  $\forall a \in X, \exists a^{-1} \in X$  s.t.  $a * a^{-1} = a^{-1} * a = e$ .

**Definition 1.1.6 (Commutativity).**  $a * b = b * a$ .

**Definition 1.1.7.** Some names:

**Definition 1.1.8 (Semigroup).** Only has Associativity.

**Definition 1.1.9 (Monoid).** Only has Associativity and Identity.

**Definition 1.1.10 (Group).** Only has Associativity and Identity and Inverse.

**Definition 1.1.11 (Abelian Group).** Has all the 4 properties.

**Note 1.1.3.** Actually, in these algebra structure, we also need closure under operations.

## Lecture 2

Set is a collection of elements.

12 Sep. 13:20

**Example 1.1.2.** Different sets:

$$\mathbb{N} = \{1, 2, 3, \dots\}$$

$$\mathbb{Z} = \{0, \pm 1, \pm 2, \dots\}$$

$$\mathbb{R} = \{\text{real numbers}\}$$

$$M_2(\mathbb{R}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbb{R} \right\}$$

$$\text{GL}_2(\mathbb{R}) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \mid a, b, c, d \in \mathbb{R}, ad - bc \neq 0 \right\}$$

The set of integers modulo 5 =  $\{\bar{0}, \bar{1}, \bar{2}, \bar{3}, \bar{4}\}$ , where  $\bar{i} = \{5k + i \mid k \in \mathbb{N} \cup \{0\}\}$ .

**Notation.** For a set  $X$ ,  $x \in X$  means that  $x$  is a member of  $X$ . For sets  $X, Y$ , a map  $f$  from  $X$  to  $Y$  means that  $f$  is a rule that assigns a member of  $Y$  to every member of  $X$ . It is commonly denoted as  $f : X \rightarrow Y$ . The assigned element of  $Y$  to  $x \in X$  is denoted as  $f(x)$ .  $X$  is said to be a subset of  $Y$  if all numbers of  $X$  are members of  $Y$ . It is denoted by  $X \subseteq Y$ . Sets are often denoted as

$$\{x \mid \text{conditions on } x\} \text{ or } \{x \in X \mid \text{extra conditions on } x\}$$

**Example 1.1.3.**  $(\mathbb{N}, +)$  is a semigroup, and  $(\mathbb{N} \cup \{0\}, +)$  is a monoid with identity 0, and  $(\mathbb{N}, \times)$  is a monoid with identity 1.

**Example 1.1.4.**  $(X, +)$  with  $X = \mathbb{Z}, \mathbb{Q}, \mathbb{R}$  are abelian groups.  $(X, \cdot)$  with  $X = \mathbb{Q} \setminus \{0\}, \mathbb{R} \setminus \{0\}$  are abelian groups. Also,  $(\bar{0}, \bar{1}, \bar{2}, \bar{3}, \bar{4}, +)$  is an abelian group.

**Example 1.1.5.**  $\mathcal{S}_n = \{\text{Permutations on } n \text{ letters}\}$  is a group, and non-abelian if  $n \geq 3$  and abelian if  $n = 1, 2$ .

**Example 1.1.6.** Suppose  $\text{GL}_n(\mathbb{R}) = \{\text{real invertible } n \times n \text{ matrices}\}$ , then  $(\text{GL}(\mathbb{R}), \cdot)$  is a non-abelian group for  $n \geq 2$ , and abelian for  $n = 1$ .

## 1.2 Basis Properties of Groups

**Theorem 1.2.1.** Suppose  $G = (G, *)$  is a group, then

1. Identity element is unique.
2. For  $g \in G$ ,  $g^{-1}$  is unique.
3. For  $g, h \in G$ , then  $(g * h)^{-1} = h^{-1} * g^{-1}$ .
4. For  $g \in G$ ,  $(g^{-1})^{-1} = g$ .

**Proof.**

1. Suppose  $e, e'$  are identities, i.e.

$$\begin{aligned} e * g &= g = g * e \\ e' * g &= g = g * e', \end{aligned}$$

then  $e = e * e' = e'$ .



2. Suppose  $h, h'$  such that

$$\begin{aligned} g * h &= h * g = e \\ h' * g &= g * h' = e. \end{aligned}$$

Then,

$$h' = e * h' = h * g * h' = h e = h.$$

3. Since the inverse is unique, it suffices to show that  $h^{-1}g^{-1}$  is the inverse of  $gh$ , so  $h^{-1}g^{-1} = (gh)^{-1}$ .

4. Trivial. ■

## Lecture 3

**As previously seen.**  $G = (G, *)$  is called a group if

17 Sep. 13:20

- (1)  $(a * b) * c = a * (b * c)$
- (2)  $\exists e \in G$  s.t.  $a * e = a = e * a$ .
- (3) For  $a \in G$ ,  $\exists a^{-1} \in G$  s.t.  $a * a^{-1} = e = a^{-1} * a$ .

Also, we have shown that  $e$  is unique and for every  $a \in G$ ,  $a^{-1}$  is also unique.

**Definition 1.2.1 (Subgroup).** Suppose  $G = (G, *)$  is a group, and  $H \subseteq G$ , then  $H$  is called a subgroup if  $(H, *)$  is a group.

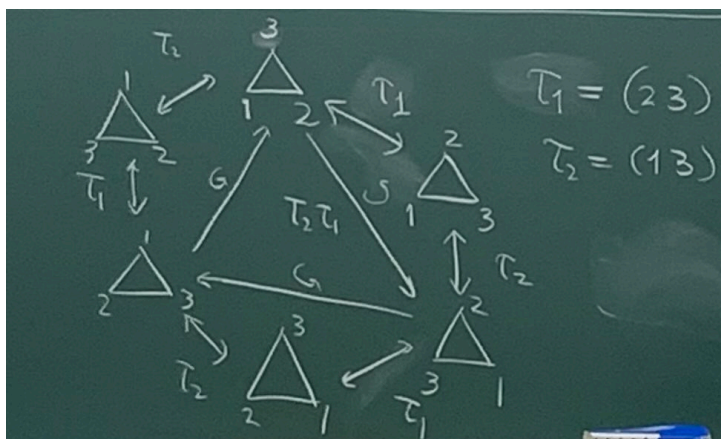


Figure 1.5: Traingle groups

**Example 1.2.1.** Consider the case when

$$G = \{\text{permutations on } \{1, 2, 3\}\} = S_3,$$

then what is the subgroup of  $G$ ?

**Proof.** Note that

$$G = \{id, \tau_1, \tau_2, \tau_1\tau_2\tau_1, \tau_1\tau_2, \tau_2, \tau_1\}.$$

Then,

$$H = \{id\}, \{id, \tau_1\}, \{id, \tau_2\}, \{id, \tau_1 \tau_2 \tau_1\}, \\ \{id, \tau_1 \tau_2, \tau_2 \tau_1\}, G$$

These 6 subgroups are all subgroups of  $G$ . In general, identity  $\{id\}$  and  $G$  itself are always subgroups.  $\circledast$

**Note 1.2.1.** We will talk about Sylow's theorem later, which claims that if

$$|G| = p_1^{e_1} \dots p_r^{e_r},$$

then  $G$  has subgroups of order  $p_i^{e_i}$  for  $1 \leq i \leq r$ .

**Example 1.2.2.** If  $G = (\mathbb{Z}, +)$ , what is the subgroup of  $G$ ?

**Proof.** Suppose  $n \in H$ , then  $n + n = 2n \in H$ , and  $-n \in H$ , and then  $3n = 2n + n \in H$ . Hence, all multiples of  $n \in H$ , which means  $n\mathbb{Z} \subseteq H$ . If  $n_1, \dots, n_r \in H$ , then

$$\underbrace{n_1\mathbb{Z} + n_2\mathbb{Z} + \dots + n_r\mathbb{Z}}_{d\mathbb{Z}} \subseteq H,$$

where  $d = \gcd(n_1, n_2, \dots, n_r)$ . Hence, the only subgroups are of the form  $d\mathbb{Z}$ . In particular,  $0\mathbb{Z} = \{0\}$ , which is the identity subgroup, and  $1\mathbb{Z} = \mathbb{Z}$  is  $G$  itself.  $\circledast$

**Example 1.2.3.** If  $G = \mathbb{R}^\times = (\mathbb{R} \setminus \{0\}, \times)$ , what are the finite subgroups of  $G$ ?

**Proof.** Consider  $H = \{1\}, \{1, -1\}$ , and these are all finite subgroups.  $\circledast$

**Example 1.2.4.** Suppose

$$G = \text{GL}_n(\mathbb{R}) = (\{n \times n \text{ invertible matrices}\}, \times),$$

then what are the subgroups?

**Proof.** Consider

$$\text{SL}_n(\mathbb{R}) = \{g \in \text{GL}_n(\mathbb{R}) \mid \det g = 1\},$$

then since  $\det g \det h = \det(gh)$ , so  $\text{SL}_n(\mathbb{R})$  is a subgroup. Also, consider the set of all diagonal  $n \times n$  real matrices, then it is also a subgroup of  $\text{GL}_n(\mathbb{R})$ .  $\circledast$

**Remark 1.2.1.** We define orthogonal subgroup to be the subgroup preserving distances. For example, suppose  $g \in \text{GL}_n(\mathbb{R})$ , and if we have norm here, then  $|gv| = |v|$  if and only if  $g^t g = I$ .

**Exercise 1.2.1.** Show that

$$O_n(\mathbb{R}) = \{g \in \text{GL}_n(\mathbb{R}) \mid g^t g = I\}$$

forms a subgroup of  $\text{GL}_n(\mathbb{R})$ .

## Lecture 4

As previously seen.

19 Sep. 13:20

- $\mathbb{Z} = (\mathbb{Z}, +)$  is a infinite cyclic group s.t. its subgroup is  $d\mathbb{Z}$  with all  $d = 0, 1, 2, \dots$

- $C_n = (\mathbb{Z}/n\mathbb{Z}, +)$  is a cyclic group of order  $n$ .

$$C_1 = \{1\}$$

$$C_2 = \{1, \sigma\} \text{ with } \sigma^2 = 1$$

$$C_3 = \{1, \sigma, \sigma^2\} \text{ with } \sigma^3 = 1.$$

$$C_4 = \{1, \sigma, \sigma^2, \sigma^3\} \text{ with } \sigma^4 = 1.$$

$$C_5 = \{1, \sigma, \sigma^2, \sigma^3, \sigma^4\} \text{ with } \sigma^5 = 1.$$

$$C_6 = \{1, \sigma, \sigma^2, \sigma^3, \sigma^4, \sigma^5\} \text{ with } \sigma^6 = 1.$$

Observe that the subgroups of  $C_n$  are of the form  $C_d$  with  $d \mid n$  (+ unique for each  $d$ ).

**Exercise 1.2.2.** Prove it.

- $S_n$ : the symmetric group of degree  $n$ .  $S_3 = \{1, \sigma, \sigma^2, \tau, \tau\sigma, \tau\sigma^2\}$ .
- $g \in O_n(\mathbb{R}) \Leftrightarrow \langle gv, gw \rangle = \langle v, w \rangle$ , where  $\langle v, w \rangle = v_1w_1 + v_2w_2 + \cdots + v_nw_n$ . Also,

$$\langle gv, gw \rangle = \langle v, w \rangle \Leftrightarrow \|gv\| = \|v\|.$$

Note that

$$SO_n(\mathbb{R}) = \{g \in O_n(\mathbb{R}) \mid \det g = 1\},$$

and

$$O_n(\mathbb{R}) = SO_n(\mathbb{R}) \cup \varepsilon SO_n(\mathbb{R})$$

where  $\varepsilon \in O_n(\mathbb{R})$  s.t.  $\det \varepsilon = -1$ .

- Suppose  $G, H$  are groups and

$$G \times H = \{(g, h) \mid g \in G, h \in H\},$$

then  $G \times H$  is a group since we can define

$$(g_1, h_1) * (g_2, h_2) = (g_1g_2, h_1h_2).$$

**Example 1.2.5.** Suppose

$$C_2 = \{1, \tau\} \text{ with } \tau^2 = 1$$

$$C_3 = \{1, \sigma, \sigma^2\} \text{ with } \sigma^3 = 1.$$

Then,

$$C_2 \times C_3 = \{(1, 1), (1, \sigma), (1, \sigma^2), (\tau, 1), (\tau, \sigma), (\tau, \sigma^2)\}.$$

Note that  $C_2 \times C_3$  is not isomorphic to  $S_3$  because  $S_3$  is not commutative and  $C_2 \times C_3$  is. What is the subgroups?

**Proof.**

$$(\tau, \sigma)^2 = (1, \sigma^2)$$

$$(\tau, \sigma)^3 = (\tau, 1)$$

$$(\tau, \sigma)^4 = (1, \sigma)$$

$$(\tau, \sigma)^5 = (\tau, \sigma^2)$$

$$(\tau, \sigma)^6 = (1, 1)$$

Letting  $\mu = (\tau, \sigma)$ , then we know that

$$C_2 \times C_3 = \{1, \mu, \mu^2, \mu^3, \mu^4, \mu^5\} \simeq C_6.$$

As groups,

$$\begin{aligned} S_3 &\simeq (\{f_1, f_2, f_3, f_4, f_5, f_6\}, \circ) \text{ where } f_1(x) = x, f_2(x) = 1 - x, f_3(x) = \frac{1}{x} \dots \\ &\simeq \text{symmetry of triangle} \\ &\simeq C_6 \end{aligned}$$

⊗

### 1.3 Group homomorphisms/isomorphisms

The idea of isomorphisms is: Suppose  $G, H$  are groups and  $\phi : G \rightarrow H$  is defined by  $g \mapsto \phi(g)$ . Now if  $g_1, g_2 \in G$ , we want that  $g_1 g_2$  corresponds to  $\phi(g_1) \phi(g_2)$ . Hence, if we have  $\phi(g_1 g_2) = \phi(g_1) \phi(g_2)$ , then it would be a great property, and it seems that  $G, H$  have same structure. But, consider the map

$$\phi : G \rightarrow \{1\},$$

then this map satisfies  $\phi(g_1 g_2) = \phi(g_1) \phi(g_2)$ , but obviously  $G$  and  $\{1\}$  do not have same structure, so we have to give further restriction. Hence, we should restrict that

- Any two elements of  $G$  should not be mapped to the same element.

Hence, if we have a map from  $G$  to  $G \times H$  with

$$g \mapsto (g, 1),$$

then it also satisfies  $\phi(g_1 g_2) = \phi(g_1) \phi(g_2)$ . However, it is not enough, we need the surjection so that we can say any two isomorphic things have same structure.

- The image of  $\phi$  should cover  $H$ .

#### Summary

- The first restriction  $\Leftrightarrow \forall g_1 \neq g_2 \in G$ , we must have  $\phi(g_1) \neq \phi(g_2)$ .
- The second restriction  $\Leftrightarrow \forall h \in H, \exists g \in G$  s.t.  $h = \phi(g)$ .

**Definition 1.3.1.** A map  $\phi : G \rightarrow H$  is said to be a homomorphism if

$$\phi(g_1 g_2) = \phi(g_1) \phi(g_2)$$

for all  $g_1, g_2 \in G$ .

**Definition 1.3.2.** A homomorphism  $\phi : G \rightarrow H$  is said to be an isomorphism if  $\phi$  is said to be an isomorphism if it is injective and surjective.

**Definition 1.3.3 (Another definition of Isomorphism).** A map  $\phi : G \rightarrow H$  is an **isomorphism** if it is a group homomorphism that is also a bijection. An equivalent, and often more formal, definition is: Two groups  $G$  and  $H$  are said to be **isomorphic** ( $G \cong H$ ) if there exist two group homomorphisms,  $\phi : G \rightarrow H$  and  $\psi : H \rightarrow G$ , such that they are mutual inverses:

$$\begin{cases} \phi(g_1 g_2) = \phi(g_1) \phi(g_2) & \text{for } g_1, g_2 \in G \\ \psi(h_1 h_2) = \psi(h_1) \psi(h_2) & \text{for } h_1, h_2 \in H \end{cases}$$

AND

$$\begin{cases} \psi \circ \phi(g) = g & \text{for all } g \in G \\ \phi \circ \psi(h) = h & \text{for all } h \in H. \end{cases}$$

**Exercise 1.3.1.** Check that two definitions agree.

Note that  $(\mathbb{Z}/3\mathbb{Z}, +) \simeq C_3$ , and  $(\mathbb{Z}/3\mathbb{Z})^\times \simeq C_2 \simeq (\mathbb{Z}/2\mathbb{Z}, +)$ . Also,  $(\mathbb{Z}/5\mathbb{Z})^\times \simeq C_4 \simeq (\mathbb{Z}/4\mathbb{Z}, +)$ . Thus, more generally, we can see that

$$(\mathbb{Z}/p\mathbb{Z})^\times \simeq C_{p-1} \simeq (\mathbb{Z}/(p-1)\mathbb{Z}, +)$$

for all prime  $p$ .

**Example 1.3.1.**  $\exp : \mathbb{R} \rightarrow \mathbb{R}_{>0}$ . Note that it satisfies  $\exp(x+y) = \exp(x)\exp(y)$ . In terms of the group structure,  $\exp$  gives a group homomorphism

$$(\mathbb{R}, +) \rightarrow (\mathbb{R}_{>0}, \cdot)$$

## 1.4 Properties of homomorphism

**Definition 1.4.1.** Let  $\phi : G \rightarrow H$  to be a group homomorphism.

- $\ker \phi = \{g \in G \mid \phi(g) = 1\}$ , which can be used to measure how far it is from being injective.
- $\text{Im } \phi = \{\phi(g) \mid g \in G\}$ , which can be used to measure how far it is from being surjective.

### Summary

$$\begin{cases} \ker \phi = \{1\} \Leftrightarrow \phi \text{ is injective} \\ \text{Im } \phi = H \Leftrightarrow \phi \text{ is surjective.} \end{cases}$$

## Lecture 5

**As previously seen.** Group homomorphism means there exists  $\varphi : (G, *) \rightarrow (H, \circ)$  with

24 Sep. 13:20

$$\varphi(g_1 * g_2) = \varphi(g_1) \circ \varphi(g_2).$$

Thus, we have

$$\begin{cases} \varphi(1_G) = 1_H \\ \varphi(g^{-1}) = \varphi(g)^{-1} \end{cases}.$$

Group isomorphism means  $\varphi : G \rightarrow H$  is an homomorphism and there exists another group homomorphism  $\psi : H \rightarrow G$  s.t.

$$\begin{cases} \psi \circ \varphi : G \rightarrow G \\ \varphi \circ \psi : H \rightarrow H \end{cases}$$

are identity groups. Note that

- $\varphi$  is surjective if  $\varphi(G) = H$ .
- $\varphi$  is injective if  $\forall g_1 \neq g_2 \in G, \varphi(g_1) \neq \varphi(g_2)$ .

Also, we know

- surjective  $\Leftrightarrow \text{Im } \varphi = H$
- injective  $\Leftrightarrow \ker \varphi = \{1\}$ .

**why  $\ker \varphi = \{1\}$  means injective?** Suppose  $\varphi(g_1) = \varphi(g_2)$ , then

$$1_H = \varphi(g_1)^{-1} \varphi(g_1) = \varphi(g_1)^{-1} \varphi(g_2) = \varphi(g_1^{-1}) \varphi(g_2) = \varphi(g_1^{-1} g_2).$$

Hence, we have  $g_1^{-1}g_2 = 1_G$ , and thus  $g_1 = g_2$ . ■

**Theorem 1.4.1.** Let  $\varphi : G \rightarrow H$  be a group homomorphism, then  $\varphi$  is an isomorphism iff  $\ker \varphi = \{1\}$  and  $\text{Im } \varphi = H$ .

## 1.5 Equivalence relation

**Definition 1.5.1 (relation).** Let  $S$  be a set. A subset  $R \subseteq S \times S$  is called a relation.

**Example 1.5.1.** Suppose  $S = \{1, 2, 3, 4\}$ , then

$$R = \{(1, 2), (1, 3), (1, 4), (2, 3), (2, 4), (3, 4)\}$$

is the relation  $<$ .

**Notation.**  $(a, b) \in R$  is commonly denoted as  $a \cdot b$  with some symbol  $\cdot$ .

**Definition 1.5.2 (Equivalence relation).** Let  $S$  be a set and  $\sim$  is a relation on  $S$ , then  $\sim$  is called an equivalence relation if it satisfies:

- Reflexive:  $x \sim x$
- Symmetric: If  $x \sim y$ , then  $y \sim x$ .
- Transitive: If  $x \sim y$  and  $y \sim z$ , then  $x \sim z$ .

**Definition 1.5.3 (Equivalence class).** Suppose  $S$  is a set and  $\sim$  is an equivalence relation on  $S$ . We define

$$C(x) = \{y \in S \mid x \sim y\}.$$

**Example 1.5.2.** Suppose  $S = \{1, 2, 3, 4, 5, 6\}$ , and  $x \sim y$  if  $x - y \in 3\mathbb{Z}$ , then  $\sim$  is an equivalence relation. List all the equivalence classes.

**Proof.**

$$\begin{aligned} C(1) &= C(4) = \{1, 4\} \\ C(2) &= C(5) = \{2, 5\} \\ C(3) &= C(6) = \{3, 6\}. \end{aligned}$$

⊛

**Theorem 1.5.1.**

- If  $y, z \in C(x)$ , then  $y \sim z$ .
- If  $y \in C(x)$ , then  $C(x) = C(y)$ .
- If  $C(x) \cap C(y) \neq \emptyset$ , then  $C(x) = C(y)$ .

## Lecture 6

26 Sep. 13:20

**Definition 1.5.4 (Quotient Group).** Let  $G$  be a group and  $H \trianglelefteq G$  a normal subgroup. The *quotient group* of  $G$  by  $H$ , denoted  $G/H$ , is the set of left cosets of  $H$  in  $G$ :

$$G/H = \{gH : g \in G\}.$$

The group operation on  $G/H$  is defined by

$$(gH)(kH) = (gk)H, \quad \text{for all } g, k \in G.$$

This operation is well-defined because  $H$  is normal in  $G$ .

**Definition 1.5.5 (Quotient Set).** Let  $S$  be a set, and let  $\sim$  be an equivalence relation on  $S$ . Then, the quotient set is defined to be

$$S/\sim := \{\text{equivalence classes}\}$$

**Example 1.5.3.** Consider the set  $\{1, 2, \dots, 10\}$  and the relation  $\equiv \pmod{2}$ , then

$$\{1, 2, \dots, 10\}/(\equiv \pmod{2}) = \{\{1, 3, 5, 7, 9\}, \{2, 4, 6, 8, 10\}\}.$$

**Example 1.5.4.**

$$\mathbb{Z}/N\mathbb{Z} = \{\text{Congruence classes to } N\mathbb{Z} \text{ under the operation } \pmod{N}\}$$

**Definition 1.5.6 (Quotient map).** We say  $\pi : S \rightarrow S/n$  is a "quotient map" if  $\pi(x) = \bar{x}$ .

**Example 1.5.5.**  $\pi : \mathbb{Z} \rightarrow \mathbb{Z}/n\mathbb{Z}$ .

**Definition 1.5.7 (Representative elements).** Representative element is whatever element of an equivalence class.

**Definition 1.5.8 (Complete system of representative (CSR)).**  $R \subseteq S$  is called complete system of representative if  $R$  contains all elements that represent the quotient set without redundancy.

**Example 1.5.6.** For the quotient group  $\mathbb{Z}/N\mathbb{Z}$ , several complete systems of representatives are possible:

$$\{0, 1, \dots, N-1\}, \quad \{1, 2, \dots, N\}, \quad \{2N, 2N+1, \dots, 3N-1\}, \quad \text{etc.}$$

In general, any set of  $N$  consecutive integers forms a complete system of representatives.

**Example 1.5.7.**  $\{0, 1, 2, \dots, N\}$  is NOT a CSR because 0 and  $N$  are two representatives of the same class. Also,  $\{0, 2, 3, \dots, N\}$  is NOT a CSR because there no representative for  $1 + N\mathbb{Z}$ .

Now we talk about the quotient of group by an equivalence relation defined by its subgroup.

**Definition 1.5.9.** For a group  $G$  and its subgroup  $H$ , we define the set of all left cosets as

$$G/H := G/\sim$$

where  $g_1 \sim g_2$  if  $\exists h \in H$  s.t.  $g_1 = g_2h$ . In the same way, the set of all right cosets is defined as

$$H \backslash G := G/\sim$$

where  $g_1 \sim g_2$  if  $\exists h \in H$  s.t.  $g_1 = hg_2$ .

We first need to check  $\sim$  is an equivalence relation on  $G$ .

- Reflexive:  $g = g \cdot 1_G$
- Symmetry:  $g_1 \sim g_2$  iff  $\exists h \in H$  s.t.  $g_1 = g_2 h$  and this holds if and only if  $\exists h' \in H$  s.t.  $g_2 = g_1 h'$ . Here  $h' = h^{-1}$  which exists because  $H$  is a subgroup.
- Transitivity: If  $g_1 \sim g_2$  and  $g_2 \sim g_3$ , then  $g_1 = g_2 h_1$  and  $g_2 = g_3 h_2$  for some  $h_1, h_2 \in H$ , then

$$g_1 = (g_3 h_2) h_1 = g_3 (h_2 h_1),$$

which shows  $g_1 \sim g_3$ .

Thus, we verify the well-definedness of the quotient  $G/H$ , and similarly we can show  $H \backslash G$  is well-defined.

**Notation.** The element of  $G/H$  is commonly denoted as  $gH$ , and the right coset is denoted by  $Hg$ .

**Note 1.5.1.** If  $H$  is clear from the context, then  $gH$  may be denoted more simply as  $\bar{g}$ .

**Example 1.5.8.** If we have  $G = (\mathbb{Z}, +)$  and  $H = (N\mathbb{Z}, +)$ , then

$$G/H = \{0 + N\mathbb{Z}, 1 + N\mathbb{Z}, \dots, (N-1) + N\mathbb{Z}\}.$$

**Remark 1.5.1.** For a finite set  $S$ , we denote by  $|S| = \#$  of elements of  $S$ .

**Theorem 1.5.2.**

- $|G/H| = |H \backslash G|$ .
- $|gH| = |Hg|$ .

given that the numbers are finite.

**Proof.** We first show that  $|G/H| = |H \backslash G|$ . We define a map  $\varphi(gH) = Hg^{-1}$ , we will show that it is well-defined and bijective, so we can conclude that  $|G/H| = |H \backslash G|$ . Suppose  $g_1 H = g_2 H$ , we now show that  $\varphi(g_1 H) = \varphi(g_2 H)$ , which is equivalent to show that  $Hg_1^{-1} = Hg_2^{-1}$ . Since we have  $g_1 = g_2 h$  for some  $h \in H$ , so  $g_2^{-1} = h g_1^{-1} \in Hg_1^{-1}$ , so for all  $h_2 \in H$ , we have  $h_2 g_2^{-1} = h_2 h g_1^{-1} \in Hg_1^{-1}$ , which means  $Hg_2^{-1} \subseteq Hg_1^{-1}$ , and similarly we can show  $Hg_1^{-1} \subseteq Hg_2^{-1}$ , and this means  $Hg_1^{-1} = Hg_2^{-1}$ . Now we show that  $\varphi$  is bijective. Suppose  $\varphi(g_1 H) = \varphi(g_2 H)$ , we want to show that  $g_1 H = g_2 H$ . This means  $Hg_1^{-1} = Hg_2^{-1}$  and we want to show  $g_1 H = g_2 H$ , and this can be proved by the same method above. Also, surjectivity is trivial.

Now we show that  $|gH| = |Hg|$ . We can build a map  $\phi : gH \rightarrow Hg$  by  $\phi(gh) = h$ , then this is a well-defined bijective map (easy to show), so  $|gH| = |Hg|$ , and we can similarly show  $|Hg| = |H|$ , and we're done. ■

**Notation.**

$$|G/H| = |H \backslash G|$$

is called the index of  $H \subseteq G$ , and denoted as  $(G : H)$ .

**Theorem 1.5.3.**

$$|G| = (G : H) \cdot |H|.$$

**Corollary 1.5.1** (Lagrange's theorem). For any subgroup  $H$  of  $G$ ,  $H$  divides  $|G|$ .



**Example 1.5.9.** For a prime  $p$ ,

$$(\mathbb{Z}/p\mathbb{Z}) \setminus \{\bar{0}\} = \{\bar{1}, \bar{2}, \dots, \overline{p-1}\}$$

forms a (commutative) group by " $\cdot$ " (multiplication), where we called it  $(\mathbb{Z}/p\mathbb{Z})^\times$ . In this case, if we have a subgroup  $H \subseteq (\mathbb{Z}/p\mathbb{Z})^\times$ , then we have

$$|H| \mid |(\mathbb{Z}/p\mathbb{Z})^\times| = p-1.$$

In particular, consider the subset

$$H = \{\bar{1}, \bar{2}, \bar{2}^2, \dots\},$$

then it forms a subgroup. Also, if  $r$  is the smallest positive integer s.t.  $\bar{2}^r = \bar{1}$ , then we know  $|H|$  is the period of  $2^n \bmod p$ , and thus this period divides  $p-1$ .

## Lecture 7

**As previously seen.**

1 Oct. 13:20

$$G/\sim = \{gH : g \in G\}.$$

Note that if  $g \in G$  belongs to a coset, then  $gh$  must belong to the same coset.

Note that

$$|G/H| = |H \setminus G|$$

since  $gH \leftrightarrow Hg^{-1}$  is a well-defined bijective map between these two sets. (since  $gh \leftrightarrow hg^{-1}$  is a bijective map).

**Theorem 1.5.4.** Suppose  $G$  is finite, then

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

where  $[G : H] = |G/H|$ .

**Proof.** Consider the map  $H \rightarrow gH$  by  $h \mapsto gh$ , we say this map is  $\psi$ , then  $\psi$  is obviously surjective, and injectivity can be checked as follows: If  $\psi(h_1) = \psi(h_2)$ , then  $gh_1 = gh_2$ , and thus  $h_1 = h_2$ , which shows  $\psi$  is injective. Thus,  $\psi$  is bijective. Hence,  $|H| = |gH|$ . Now we know the number of cosets is  $[G : H]$ , and since we can partition  $G$  by the equivalence relation given by  $G/H$ , and thus we know  $|G| = [G : H] \cdot |H|$ . ■

**Proposition 1.5.1.** If  $|G|$  is a prime  $p$ , then  $G \simeq \mathbb{Z}/p\mathbb{Z}$  (cyclic subgroup of order  $p$ ).

**Proof.** Suppose  $H$  is a subgroup of  $G$ . Since  $|H|$  divides  $|G|$ , so  $H = \{1\}$  or  $G$ . Suppose  $G$  is not cyclic, then for  $g \in G$ , consider the subgroup generated by  $g$  i.e.

$$\langle g \rangle = \{\dots, g^{-1}, 1, g, g^2, \dots\}.$$

Since  $\langle g \rangle \subseteq G$  and  $|G| < \infty$ , so  $\langle g \rangle$  is also finite, so there exists  $i > j \in \mathbb{Z}$  s.t.  $g^i = g^j$ , so  $g^{j-i} = 1$ . Thus, there exists  $N \in \mathbb{Z}_{>0}$  s.t.  $g^N = 1$ , pick the smallest such  $N$ , then

$$\langle g \rangle = \{1, g, \dots, g^{N-1}\} \simeq \mathbb{Z}/N\mathbb{Z},$$

which is a cyclic group. However, it is a subgroup of  $G$ , so  $\langle g \rangle = \{1\}$  or  $G$ . If  $\langle g \rangle = \{1\}$ , then  $o(g) = 1$ , which means  $g = 1$ . If  $g \neq 1$ , then  $\langle g \rangle = G$ , but it shows  $G$  is cyclic, which gives a contradiction. Hence,  $g = 1$  is the only element of  $G$ , but  $|G|$  is prime, so  $|G| > 1$ , and thus it is impossible. ■

**Note 1.5.2.** If  $G \simeq \mathbb{Z}/p\mathbb{Z}$  for some  $\mathbb{Z}$ , then  $G$  is cyclic. This is because  $G \simeq \mathbb{Z}/p\mathbb{Z}$  means there exists an isomorphism  $\phi : \mathbb{Z}/p\mathbb{Z} \rightarrow G$ , and since  $\langle 1 \rangle = \mathbb{Z}/p\mathbb{Z}$ , so we have  $G = \langle \phi(1) \rangle$ .

## 1.6 Normal subgroups

**Question.** When does  $G/H$  admit a group structure (inherited from  $G$ )?

**Example 1.6.1.**  $G = (\mathbb{Z}, +)$  and  $H = (n\mathbb{Z}, +)$ , then

$$G/H = \{n\mathbb{Z}, 1 + n\mathbb{Z}, \dots, (n-1) + n\mathbb{Z}\}.$$

In this case,  $G/H$  with addition naturally forms a group.

Hence, if we have  $g_1H$  and  $g_2H$ , then we want that  $(g_1g_2)H$  is the result of operating  $g_1H$  and  $g_2H$ . That is, for  $h_1, h_2 \in H$ , we want

$$g_1h_1 * g_2h_2 = (g_1g_2)h_3$$

for some  $h_3 \in H$ . Fix  $g_1, g_2$ , then for any  $h_1, h_2 \in H$  there must be  $h_3 \in H$  s.t. the equation holds. Note that

$$g_1h_1g_2h_2 = g_1g_2h_3 \Leftrightarrow h_1g_2h_2 = g_2h_3 \Leftrightarrow g_2^{-1}h_1g_2h_2 = h_3 \Leftrightarrow g_2^{-1}h_1g_2 = h_3h_2^{-1} \in H.$$

Thus, the requirement is that  $g^{-1}Hg \subseteq H$  for all  $g \in G$ , which means  $H \subseteq gHg^{-1}$  for all  $g \in G$ . This gives  $H \subseteq g^{-1}Hg$  by replacing  $g^{-1}$  with  $g$ . This gives  $g^{-1}Hg = H$ .

**Definition 1.6.1.** Suppose  $H \subseteq G$ ,  $H$  is called a normal subgroup if

$$g^{-1}Hg = H \quad \forall g \in G.$$

**Theorem 1.6.1.** The quotient  $G/H$  inherits the group structure of  $G$  if and only if  $H$  is a normal subgroup.

## Lecture 8

**As previously seen.** We want to solve a question: For what  $H < G$ , does  $G/H$  form a group by

3 Oct. 13:20

$$(g_1H)(g_2H) = (g_1g_2)H.$$

**Note 1.6.1.**  $g^{-1}Hg = H$  for all  $g \in G$  iff  $\forall g \in G$  and  $h \in H$ ,  $g^{-1}hg \in H$ .

We have the answer is [Theorem 1.6.1](#).

**Example 1.6.2.** If  $G$  is abelian, then every subgroup is normal.

**Proof.** Let  $H < G$  and  $h \in H$ ,  $g \in G$ , then  $g^{-1}hg = g^{-1}gh = h \in H$ , so  $H \trianglelefteq G$ . ⊛

**Example 1.6.3.** If  $G = S_3$ , show that  $V_3 = \{(1), (123), (132)\}$  form a normal subgroup, where

$$\{(1), (12)\}, \{(1), (13)\}, \{(1), (23)\}$$

are not normal subgroups.

**Example 1.6.4.** If  $G = \text{GL}_n(\mathbb{R}) = \{\text{invertible } n \times n \text{ real matrices}\}$ , then

$$\text{SL}_n(\mathbb{R}) = \{g \in \text{GL}_n(\mathbb{R}) \mid \det g = 1\}$$

forms a normal subgroup of  $G$ .

**Proof.** It is enough to show

$$\forall g \in G, h \in H \Rightarrow g^{-1}hg \in H.$$

Since  $h \in \text{SL}_n(\mathbb{R})$  and  $\det h = 1$ , then

$$\det(g^{-1}hg) = \det(g^{-1}) \det(h) \det(g) = \det(g^{-1}g) \det(h) = 1 \cdot 1 = 1.$$

Thus,  $g^{-1}hg \in H$ , and thus  $H \trianglelefteq G$ . ⊛

**Example 1.6.5 (First isomorphism theorem).** Let  $\phi : G \rightarrow H$  be a group homomorphism, then

- (1)  $\text{Im } \phi < H$ .
- (2)  $\ker \phi \trianglelefteq G$ .
- (3)  $G/\ker \phi \simeq \text{Im } \phi$ .

**Proof.**

- (1) Enough to show

- (i) For  $h_1, h_2 \in \text{Im } \phi$ ,  $h_1 \cdot h_2 \in \text{Im } \phi$ .
- (ii)  $\forall h \in \text{Im } \phi$ ,  $h^{-1} \in \text{Im } \phi$ .

For (i),  $\exists g_1, g_2 \in G$  s.t.  $h_1 = \phi(g_1)$  and  $h_2 = \phi(g_2)$ , then  $h_1 h_2 = \phi(g_1)\phi(g_2) = \phi(g_1 g_2)$ , so  $h_1 h_2 \in \text{Im } \phi$ . For (ii), for  $h \in H$ ,  $\exists g \in G$  s.t.  $h = \phi(g)$ , so

$$h^{-1} = \phi(g)^{-1} = \phi(g^{-1}) \in \text{Im } \phi.$$

- (2) Enough to show

- (i)  $\ker \phi < G$
- (ii)  $g \in G, h \in \ker \phi$ ,  $g^{-1}hg \in \ker \phi$ .

We first show (i). Let  $g_1, g_2 \in \ker \phi$ , then  $\phi(g_1) = \phi(g_2) = 1$ . Thus,  $\phi(g_1 g_2) = \phi(g_1)\phi(g_2) = 1$ , and thus  $g_1 g_2 \in \ker \phi$ . Now for  $g \in \ker \phi$ , we have  $\phi(g) = 1$ . Thus,  $\phi(g^{-1}) = \phi(g)^{-1} = 1^{-1} = 1$ , so  $g^{-1} \in \ker \phi$ . Now we show (ii). Let  $g \in G$  and  $h \in \ker \phi$ , then  $\phi(h) = 1$ . Now since

$$\phi(g^{-1}hg) = \phi(g^{-1})\phi(h)\phi(g) = \phi(gg^{-1})\phi(h) = 1 * 1 = 1,$$

so  $g^{-1}hg \in \ker \phi$ .

- (3) Let  $N = \ker \phi$ , and note that the map we want is something like  $g \mapsto \phi(g)$ . We can think of decomposing  $\phi$  to

$$\underbrace{G \rightarrow G/\ker(\phi)}_{\text{surj}} \rightarrow \underbrace{\text{Im } \phi \rightarrow H}_{\text{inj}}.$$

$$g \mapsto \bar{g} \mapsto \phi(g) \mapsto \phi(g),$$

where the  $G/\ker(\phi) \rightarrow \text{Im}(\phi)$  part is an isomorphism, and we call it  $\tilde{\phi} : G/\ker \phi \rightarrow \text{Im } \phi$ . We have to show that the map is well-defined first, suppose

$$\bar{g} = \{g_1, g_2, g_3, \dots\},$$

then we want to show  $\phi(g_1) = \phi(g_2) = \phi(g_3)$ . More precisely, we have to check that if  $g_1N = g_2N$ , then  $\phi(g_1) = \phi(g_2)$ . Since  $g_1N = g_2N$ , so  $g_2 = g_1n$  for some  $n \in N$ . Thus,

$$\phi(g_2) = \phi(g_1n) = \phi(g_1)\phi(n) = \phi(g_1).$$

Thus, the map is well-defined. Then, we have to show that the  $\bar{g} \mapsto \phi(g)$  part is bijective and it is an homomorphism. For surjectivity. Let  $h \in \text{Im } \phi$ , then  $\exists g \in G$  s.t.  $h = \phi(g)$ . By well-definedness of  $\tilde{\phi}$ , we know  $h = \tilde{\phi}(gN) \in \text{Im } \tilde{\phi}$ . Next we show the injectivity. Assuming the homomorphism of  $\tilde{\phi}$ , it is enough to show  $\ker \tilde{\phi} = \{\bar{1}\} = \bar{N} \in G/N$ . Hence, we want to show that if  $gN \in \ker \tilde{\phi}$ , then  $gN = N$ . Suppose  $gN \in \ker \tilde{\phi}$ , then  $\phi(g) = \tilde{\phi}(gN) = 1$ . Thus,  $g \in \ker \phi = N$ . Hence,  $gN = N$ . (Since  $g^{-1} \in \ker \phi$ ) Next, we show the homomorphism:

$$\tilde{\phi}(g_1N * g_2N) = \tilde{\phi}((g_1 * g_2)N) = \phi(g_1 * g_2) = \phi(g_1)\phi(g_2) = \tilde{\phi}(g_1N)\tilde{\phi}(g_2N)$$

since  $N$  is normal, so  $\tilde{\phi}$  is an homomorphism.

Combining the well-definedness, surjectivity, injectivity, and group homomorphism, we know  $\tilde{\phi}$  is an isomorphism.

⊗

**Example 1.6.6.** Consider

$$\det : \text{GL}_n(\mathbb{R}) \rightarrow \mathbb{R}^\times (= (\mathbb{R} \setminus \{0\}), \cdot),$$

then  $\text{Im } \phi = \mathbb{R}^\times$ , and  $\ker \phi = \{g \in \text{GL}_n(\mathbb{R}) \mid \det(g) = 1\}$ . Hence,

$$G / \ker \phi = \text{GL}_n(\mathbb{R}) / \text{SL}_n(\mathbb{R}) = \{g \cdot \text{SL}_n(\mathbb{R}) \mid g \in \text{GL}_n(\mathbb{R})\},$$

which means each equivalence class contains matrices with same determinant, and it is isomorphic to  $\mathbb{R}^\times$ .

## 1.7 Direct Product (= Cartesian Product)

**Proposition 1.7.1.** Let  $G$  be a group and  $H, K \trianglelefteq G$  s.t.  $H \cap K = \{1\}$ , then for  $h \in H$  and  $k \in K$ ,  $hk = kh$ .

**Proof.** The goal is  $hk = kh$ , which means  $h^{-1}k^{-1}hk = 1$ . Note that  $h^{-1}k^{-1}h \in K$  and  $k \in K$ , so  $h^{-1}k^{-1}hk \in K$ . Also,  $h^{-1} \in H$  and  $k^{-1}hk \in H$ , so  $h^{-1}k^{-1}hk \in H$ . Hence,  $h^{-1}k^{-1}hk \in H \cap K = \{1\}$ . ■

**Proposition 1.7.2.** Suppose  $H, K \trianglelefteq G$  satisfy

$$\begin{cases} H \cap K = \{1\} \\ H \cdot K = \{h \cdot k \mid h \in H, k \in K\} = G, \end{cases}$$

then

$$\begin{aligned} \phi : H \times K &\rightarrow G \\ (h, k) &\mapsto hk \end{aligned}$$

is an isomorphism. Note that in  $H \times K$ , for  $(h_1, k_1), (h_2, k_2) \in H \times K$ , we have

$$(h_1, k_1) \cdot (h_2, k_2) = (h_1h_2, k_1k_2).$$

**Proof.**

(1) Homomorphism: Let  $(h_1, k_1), (h_2, k_2) \in H \times K$ , then

$$\phi((h_1, k_1) \cdot (h_2, k_2)) = \phi((h_1 h_2, k_1 k_2)) = h_1 h_2 k_1 k_2 = h_1 k_1 h_2 k_2 = \phi(h_1 k_1) \phi(h_2 k_2)$$

by [Proposition 1.7.1](#).

(2) Surjectivity: Trivial.

(3) Injectivity: Need to show  $\ker \phi = \{1\}$ . Let  $(h, k) \in \ker \phi$ , then  $hk = 1$ . Thus,  $h = k^{-1} \in K$ , and  $h \in H$ , so  $h \in H \cap K = \{1\}$ , so  $h = k = 1$ .

By (1), (2), (3), we know  $\phi$  is an isomorphism. ■

**Theorem 1.7.1.** If  $(m, n) = 1$ , then

$$\mathbb{Z}/(mn)\mathbb{Z} \simeq \mathbb{Z}/n\mathbb{Z} \times \mathbb{Z}/m\mathbb{Z}.$$

## Lecture 9

**Theorem 1.7.2.** Let  $m, n$  be coprime integers, then

$$\phi : \mathbb{Z}/mn\mathbb{Z} \rightarrow \mathbb{Z}/m\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z}$$

with  $a + mn\mathbb{Z} \mapsto (a + m\mathbb{Z}, a + n\mathbb{Z})$  is an isomorphism.

8 Oct. 13:20

**Example 1.7.1.**  $m = 2, n = 3$

$\mathbb{Z}/6\mathbb{Z}$	$\mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/3\mathbb{Z}$
$\bar{0}$	$(\bar{0}, \bar{0})$
$\bar{1}$	$(\bar{1}, \bar{1})$
$\bar{2}$	$(\bar{0}, \bar{2})$
$\bar{3}$	$(\bar{1}, \bar{0})$
$\bar{4}$	$(\bar{0}, \bar{1})$
$\bar{5}$	$(\bar{1}, \bar{2})$

Table 1.1: The case  $m = 2, n = 3$

**proof of Theorem 1.7.2.** We have to show injectivity, surjectivity, and homomorphism. Note that if we have  $|G| = |H|$ , then injectivity is equivalent to surjectivity since surjectivity gives  $|G| \geq |H|$  and injectivity gives  $|H| \geq |G|$ . (Suppose the map is  $G \rightarrow H$ ) Now since

$$|\mathbb{Z}/mn\mathbb{Z}| = mn = |\mathbb{Z}/m\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z}|,$$

so we just need to show the injectivity and group homomorphism. Now if

$$\phi(\bar{x}) = (\bar{0}, \bar{0}),$$

then  $x \in m\mathbb{Z} \cap n\mathbb{Z} = mn\mathbb{Z} = \bar{0}$ , so  $\ker \phi = \{\bar{0}\}$ .

**Exercise 1.7.1.** Show the homomorphism part. ■

**Question.** Now that we know  $\phi$  is an isomorphism, can we construct  $\phi^{-1}$ ?

**Answer.** First, find integers  $a, b$  s.t.

$$ma + nb = 1,$$

then for  $(\bar{x}, \bar{y}) \in \mathbb{Z}/m\mathbb{Z} \times \mathbb{Z}/n\mathbb{Z}$ , we can set

$$\phi^{-1}(\bar{x}, \bar{y}) = \overline{may + nbx}.$$

This definition works since

$$nb \equiv 1 \pmod{m} \quad ma \equiv 1 \pmod{n}.$$

Check that  $\phi \circ \phi^{-1}(\bar{x}, \bar{y}) = (\bar{x}, \bar{y})$ . \*

**Question.** How about the step of finding such  $a, b$ ?

**Answer.** Suppose  $m \geq n$ . Let  $r_0 = m, r_1 = n$ , then

$$\begin{aligned} r_0 &= q_1 r_1 + r_2 & 0 \leq r_2 < r_1 \\ r_1 &= q_2 r_2 + r_3 & 0 \leq r_3 < r_2 \\ r_2 &= q_3 r_3 + r_4 & 0 \leq r_4 < r_3 \\ &\vdots \\ r_{n-2} &= q_{n-1} r_{n-1} + r_n & 0 \leq r_n < r_{n-1} \\ r_{n-1} &= q_n r_n. \end{aligned}$$

Now since for every  $r_i$ ,  $\gcd(r_i, r_{i+1}) = \gcd(m, n)$ , and  $\gcd(r_{n-1}, r_n) = r_n$ , so it works. Since  $\gcd(m, n) = 1$ , so  $r_n = 1$ , and thus

$$\begin{aligned} 1 &= r_n = r_{n-2} - q_{n-1} r_{n-1} \\ &= r_{n-2} - q_{n-1} (r_{n-3} - q_{n-2} r_{n-2}) \\ &= -q_{n-1} r_{n-3} + (1 + q_{n-1} q_{n-2}) r_{n-2} \\ &= \dots \end{aligned}$$

so we can recover it to  $1 = ar_0 + br_1 = am + bn$ . \*

## 1.8 Group action

### Lecture 10

**Definition 1.8.1 (Group Action).** If  $G$  is a group and  $X$  is a set, then we say  $G$  acts on  $X$  if there exists a map

$$G \times X \rightarrow X, \quad (g, x) \mapsto g \cdot x$$

satisfying  $g(hx) = (gh) \cdot x$  and  $e \cdot x = x$ , and we call this map a group action.

15 Oct. 13:20

**Example 1.8.1.**  $X = G$  and  $g \cdot x = gx$ .

**Example 1.8.2.**  $X = G$  and  $g \cdot x = gxg^{-1}$ . We call this a conjugation.

**Definition 1.8.2.** We say

$$Gx = \{g \cdot x \mid g \in G\} \text{ for some } x \in X$$

is an orbit of a group action.

**Example 1.8.3.**  $Gx \subseteq G$  for all  $x \in G$ .

**Example 1.8.4.**

$$Gx = \{gxg^{-1} \mid g \in G\} = \{h^{-1}xh \mid h \in G\}.$$

**Definition.** We introduce some important subgroup of a group:

**Definition 1.8.3 (Orbit).** Let  $G$  be a group acting on a set  $X$ . For any  $x \in X$ , the *orbit* of  $x$  under the action of  $G$  is defined as

$$\text{Orb}(x) = \{g(x) \mid g \in G\}.$$

**Definition 1.8.4 (Stabilizer).** Let  $G$  be a group acting on a set  $X$ . For any  $x \in X$ , the *stabilizer* of  $x$  in  $G$  is defined as

$$\text{Stab}(x) = \{g \in G \mid g(x) = x\}.$$

It is a subgroup of  $G$ .

**Definition 1.8.5 (Normalizer).** Let  $H$  be a subgroup of a group  $G$ . The *normalizer* of  $H$  in  $G$  is defined as

$$N_G(H) = \{g \in G \mid gHg^{-1} = H\}.$$

It is the largest subgroup of  $G$  in which  $H$  is normal.

**Definition 1.8.6 (Centralizer).** Let  $G$  be a group and  $g \in G$ . The *centralizer* of  $g$  in  $G$  is defined as

$$C_G(g) = \{x \in G \mid xg = gx\}.$$

More generally, for a subset  $S \subseteq G$ ,

$$C_G(S) = \{x \in G \mid xs = sx \text{ for all } s \in S\}.$$

**Definition 1.8.7 (Center).** Let  $G$  be a group. The *center* of  $G$  is defined as

$$Z(G) = \{g \in G \mid gx = xg \text{ for all } x \in G\}.$$

It consists of all elements of  $G$  that commute with every element of  $G$ .

**Definition 1.8.8 (Conjugacy classes).** We call the  $G$ -orbits under the conjugation actions the conjugacy classes. It is an equivalence class defined by

$$x \sim g^{-1}xg,$$

so we have

$$|G| = \sum_{C \in \text{Conj}(G)} |C|,$$

where  $\text{Conj}(G)$  is the set of all conjugation classes of  $G$ .

**Note 1.8.1.** The definition of the equivalence relation in the conjugation classes is

$$x \sim y \text{ iff } \exists g \in G \text{ s.t. } x = g^{-1}yg.$$

**Proposition 1.8.1.**

$$|C(x)| = \frac{|G|}{|Z_G(x)|},$$

where

$$Z_G(x) = \{g \in G \mid g^{-1}xg = x\}.$$

**Remark 1.8.1.** See orbit-stabilizer theorem. (HW5)

## 1.9 Symmetric groups

**Definition 1.9.1.**

$$S_n = \{\text{permutations on } n \text{ letters}\}.$$

**Question.** What are the conjugation classes of  $S_n$ ?

Consider

$$\tau = \begin{pmatrix} 1 & 2 & \cdots & n \\ i_1 & i_2 & \cdots & i_n \end{pmatrix},$$

then what is  $\sigma^{-1}\tau\sigma$ ?

**Note 1.9.1.** Here we first operate  $\sigma^{-1}$  rather than  $\sigma$ , it is from left to right.

Thus, we have

$$\sigma^{-1}\tau\sigma = \begin{pmatrix} \sigma(1) & \sigma(2) & \cdots & \sigma(n) \\ \sigma(i_1) & \sigma(i_2) & \cdots & \sigma(i_n) \end{pmatrix}.$$

**Example 1.9.1.** If

$$\tau = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 2 & 1 \end{pmatrix} = (13)(2),$$

then

$$\sigma^{-1}\tau\sigma = \begin{pmatrix} \sigma(1) & \sigma(2) & \sigma(3) \\ \sigma(3) & \sigma(2) & \sigma(1) \end{pmatrix}.$$

Note that  $\sigma^{-1}\tau\sigma$  can be either:

$$(13)(2), \quad (12)(3), \quad (23)(1).$$

Thus, the cycle type is preserved. Vice versa, if two permutations have the same cycle type, then they are conjugate to each other.

**Theorem 1.9.1.** Conjugacy classes of  $S_n$  are described by the partition of  $n$ .

For example,  $7 = 1 + 2 + 4$ , then it represents the conjugacy class of type

$$(a)(bc)(defg).$$

**Example 1.9.2.** For  $S_3$ , the conjugation classes are

$$\begin{aligned} 3 &\leftrightarrow (123), (132) \\ 1 + 2 &\leftrightarrow (1)(23), (2)(13), (3)(12) \\ 1 + 1 + 1 &\leftrightarrow (1)(2)(3). \end{aligned}$$



## Lecture 11

17 Oct. 13:20

**As previously seen.** A group  $G$  acts on a set  $X$  means for each  $g \in G$ , it gives a map sends  $x$  to  $g(x)$  where  $g(x) \in X$  and the maps satisfy  $(gh)(x) = g(h(x))$ .  $\Leftrightarrow$  Formally, it is  $G \times X \rightarrow X$  with  $(g, x) \mapsto g(x)$  s.t.  $(gh)(x) = g(h(x))$ .  $\Leftrightarrow$  There is a group homomorphism s.t.  $G \rightarrow \text{Aut}(X)$ .

**Remark 1.9.1.** Last equivalence is because we can let

$$\Phi : G \rightarrow \text{Aut}(X), \quad \Phi(g) = \phi_g, \quad \text{where } \phi_g(x) = g(x).$$

Conjugation is a group action on the group itself defined by

$$G \times G \rightarrow G, \quad (g, x) \mapsto gxg^{-1},$$

and the conjugating class is a  $G$ -orbit, which means

$$C(x) = \{gxg^{-1} \mid g \in G\} \text{ for all } g \in G.$$

**Note 1.9.2.**  $G$  is abelian iff  $C(x) = \{x\}$  for all  $x \in G$ .

Symmetric group has cycle representation, and conjugation class of  $S_n$  is the set of all permutations of same cycle types.

**Theorem 1.9.2.** Conjugation classes of  $S_n$  are cycle types  $(n_1, n_2, \dots, n_k)$  with  $n_1 \leq n_2 \leq \dots \leq n_k$  and  $k \geq 1$  s.t.  $n_1 + n_2 + \dots + n_k = n$ , and the corresponding class consists of all elements having that cycle type.

Note that for  $H \triangleleft G$ , we know  $gHg^{-1} = H$ . Hence, a normal subgroup is a union of conjugating classes:

$$H = \bigcup_{x \in H} C(x).$$

Vice versa, if a subgroup  $H < G$  is a union of conjugating classes, then  $H \triangleleft G$ .

**Note 1.9.3.** For  $G$  finite, one can look at conjugating classes to classify normal subgroups.

**Theorem 1.9.3 (Class equation).** Suppose  $C$  represents the conjugacy classes, then

$$|G| = \sum_C |C|,$$

and

(1)  $\#\{C \mid |C| = 1\}$  divides  $|G|$ .

(2)  $|C|$  divides  $|G|$ .

**Proof.** Since we can define an equivalence relation s.t.  $x \sim y$  iff  $x = gyg^{-1}$  for some  $g \in G$ , and the equivalence classes corresponding to this relation are the conjugacy classes, so

$$|G| = \sum_C |C|.$$

(1) If  $|C| = 1$ , then there exists  $x \in G$  s.t.  $C(x) = \{x\}$ . Hence, we know  $gxg^{-1} = x$  for all  $g \in G$ , which means  $gx = xg$  for all  $g \in G$ . Define

$$Z(G) = \{x \in G \mid gx = xg\},$$

which is the center of  $G$ , then this forms a subgroup of  $G$ . (This is easy to check). Now since  $\bigcup_{|C|=1} C = Z(G)$ , and  $Z(G) \triangleleft G$ , so we have

$$\#\{C \mid |C| = 1\} = |Z(G)|,$$

and by Lagrange's theorem, we know  $|Z(G)| \mid |G|$ , so we're done.

- (2) Let  $Z_G(x) = \{g \in G \mid gx = xg\}$ . Then  $Z_G(x)$  is a subgroup of  $G$ . (This is easy to check). Now consider  $G/Z_G(x)$ , we know it is the collection of equivalence classes, and for all conjugacy classes  $C$ , there is a one-to-one correspondence mapping  $C$  to  $\{xgx^{-1} \mid g \in G\} = \{hxh^{-1} \mid h \in G/Z_G(x)\}$ , so

$$|C(x)| = |G/Z_G(x)| = \frac{|G|}{|Z_G(x)|},$$

and we're done. ■

Here we go back to  $S_n$ . If  $C = (n_1, \dots, n_k)$  with  $n_1 + \dots + n_k = n$ , then what is  $|C|$ ? We can easily show that the answer is

$$|C(1^{v_1} 2^{v_2} 3^{v_3} \dots r^{v_r})| = \frac{n!}{1^{v_1}(v_1!) 2^{v_2}(v_2!) 3^{v_3}(v_3!) \dots},$$

and we can find that

$$|C(1^{v_1} 2^{v_2} 3^{v_3} \dots r^{v_r})| = \frac{|S_n|}{|Z_{S_n}(x)|}, \text{ where } x \in (1^{v_1} 2^{v_2} \dots).$$

## Lecture 12

As previously seen. We have learnt that

22 Oct. 13:20

$$\{\text{Conjugacy classes of } S_n\} = \{\text{cycle types } (1)^{v_1} (2)^{v_2} \dots \text{ with } 1 \cdot v_1 + 2 \cdot v_2 + \dots = n\}.$$

Also, we know

$$|(1)^{v_1} (2)^{v_2} \dots| = \frac{n!}{1^{v_1} v_1! 2^{v_2} v_2! \dots}.$$

Besides, we have learnt that

$$H \triangleleft G \Leftrightarrow H \text{ is a union of conj classes of } G \text{ i.e. } H = \bigcup_{x \in H} C(x).$$

• $S_3$			• $S_4$			$S_4 \supset 2A_4 \supset \mathcal{V}_4 \supset 1$ $\mathbb{Z}/2\mathbb{Z} \quad \mathbb{Z}/3\mathbb{Z} \quad (\mathbb{Z}/2\mathbb{Z})^2$		
Class	Size	[Possible Normal Sub]	Class	Size	[Possible Normal Sub]	Order	N. Subgp	
$(1)^3$	1	Order 6, $S_3$ ✓	$(1)^4$	1	Order 24, $S_4$ ✓	24	$S_4$	✓
$(1)(2)$	3	Order 3, $(1) \cup (2)$ ✓	$(1)^2(2)$	6	Order 12, $(1)^2 \cup (2) \cup (1)(2)$ ✓	12	$(1)^2 \cup (2) \cup (1)(2)$	✓
$(3)$	2	Order 2, X	$(2)^2$	3	Order 8, X	8	X	$2A_4$
		Order 1, $(1)^3$ ✓	$(1)(3)$	8	Order 6, X	6	X	
			$(4)$	6	Order 4, $(1)^2 \cup (2)^2 = \mathcal{V}_4$	4	$(1)^2 \cup (2)^2 = \mathcal{V}_4$	
					Order 3, X	3	X	
					Order 2, X	2	X	
					Order 1, $(1)^4 = 1$	1	$(1)^4 = 1$	

$S_3 \supset 2A_3 \supset 1$   
 $\mathbb{Z}/2\mathbb{Z} \quad \mathbb{Z}/3\mathbb{Z}$

[Note: These sequences can be used to solve cubic and quartic equations]

Figure 1.6: Possible normal subgroups of  $S_3$  and  $S_4$

**Remark 1.9.2.** Since we know  $H$  is a normal subgroup of  $S_n$  iff  $H = \bigcup_{x \in H} C(x)$ , where  $C(x)$  is the conjugacy class of  $S_n$ , and conjugacy classes of symmetric groups are the sets of permutations of same cycle form, and since the size of a subgroup of  $S_n$  must divide  $|S_n| = n!$ , so we can deduce all normal subgroups of  $S_n$ .

**Definition 1.9.2 (Transpositions).** We say a permutation  $\pi \in S_n$  is a transposition iff  $\pi \in (1)^{n-2}(2)$ .

**Theorem 1.9.4.** Every  $\sigma \in S_n$  is a product of transpositions. More specifically, this argument holds with adjacent transpositions.

**Proof.** Since  $\sigma$  can be factored into independent cyclic permutations, so we just need to show any cyclic permutation is a product of transpositions. Suppose we have

$$\tau = \begin{pmatrix} a_1 & a_2 & \dots & a_n \\ a_2 & a_3 & \dots & a_1 \end{pmatrix},$$

then we have:

$$(a_1 a_2)(a_2 a_3) \dots (a_{n-1} a_n) I_n = \tau.$$

Note that we first operate  $(a_1 a_2)$ , then  $(a_2 a_3)$ , and so on.

Actually, if we do bubble sort on  $\sigma$ , then it can become  $I_n$ , then we can do the inverse operation to make  $I_n$  go back to  $\sigma$ , so  $\sigma$  is just the product of adjacent transpositions. ■

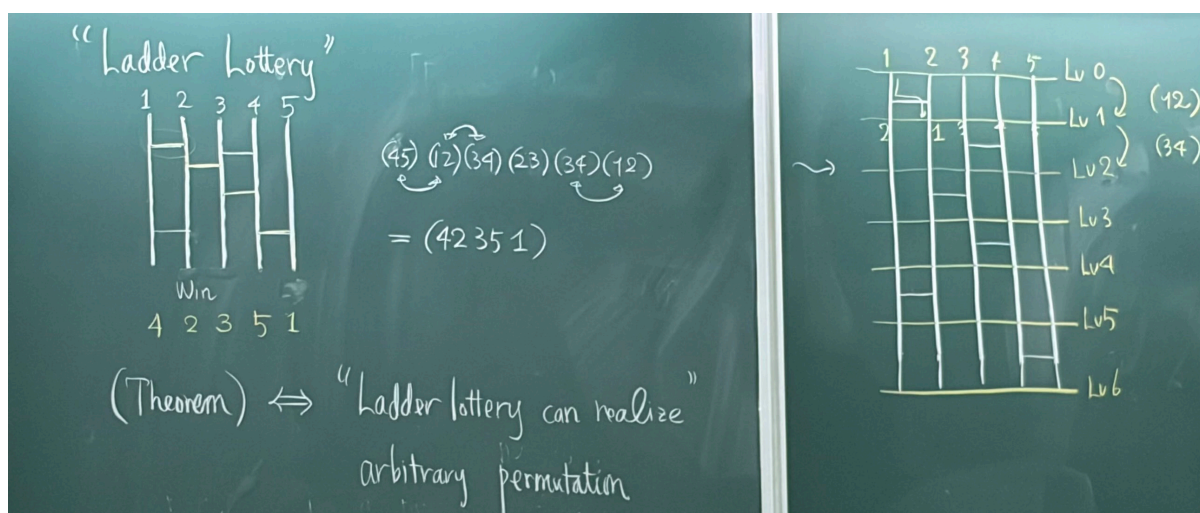


Figure 1.7: Ladder Lottery can realize arbitrary permutations

**Remark 1.9.3.** In ladder lottery, whenever we meet a bridge, we must go through it no matter we go left or go right, so every bridge is a (adjacent) transposition, and since every permutation can be decomposed into adjacent transpositions, so ladder lottery can realize all permutations.

**Theorem 1.9.5.** For  $\sigma \in S_n$ , let

$$\text{inv}(\sigma) = \# \{(i, j) \mid 1 \leq i < j \leq n, \sigma(i) > \sigma(j)\},$$

then

$$\text{inv}(\sigma\tau) \equiv \text{inv}(\sigma) + \text{inv}(\tau) \pmod{2} \text{ for } \sigma, \tau \in S_n.$$

**Proof.** If we can show it is true for  $\sigma$  is a general permutation and  $\tau$  is  $(i, i+1)$  for all  $1 \leq i \leq n$ ,

then for  $\tau = \tau_1 \tau_2 \dots \tau_l$ , we have

$$\begin{aligned} \text{inv}(\sigma\tau) &\equiv \text{inv}(\sigma\tau_1\tau_2\dots\tau_l) \\ &\equiv \text{inv}(\sigma\tau_1\dots\tau_{l-1}) + \text{inv}(\tau_l) \equiv \dots \equiv \text{inv}(\sigma) + \text{inv}(\tau_1) + \text{inv}(\tau_2) + \dots + \text{inv}(\tau_l) \\ &\equiv \text{inv}(\sigma) + \text{inv}(\tau_1\tau_2\dots\tau_l) \equiv \text{inv}(\sigma) + \text{inv}(\tau). \end{aligned}$$

Now we show that it is true for  $\sigma$  is a general permutation and  $\tau = (i, i+1)$  for some  $1 \leq i \leq n$ .

- Case 1:  $\sigma(i) > \sigma(i+1)$ , then  $\text{inv}(\sigma\tau) = \text{inv}(\sigma) - 1$  and  $\text{inv}(\tau) = 1$ , so

$$\text{inv}(\sigma\tau) \equiv \text{inv}(\sigma) - 1 \equiv \text{inv}(\sigma) - \text{inv}(\tau) \equiv \text{inv}(\sigma) + \text{inv}(\tau) \pmod{2}.$$

- Case 2:  $\sigma(i) < \sigma(i+1)$ , then  $\text{inv}(\sigma\tau) = \text{inv}(\sigma) + 1$  and  $\text{inv}(\tau) = 1$ , so it is true in this case.

**Note 1.9.4.** Here we first operate  $\sigma$  then  $\tau$ .

Now we can define

$$\text{sgn} : S_n \rightarrow \{\pm 1\} \subseteq \mathbb{R}^\times$$

by  $\text{sgn}(\sigma) = (-1)^{\text{inv}(\sigma)}$ .

**Theorem 1.9.6.** For every  $n \geq 2$ , there exists a unique surjective group homomorphism

$$\text{sgn} : S_n \rightarrow \{\pm 1\}.$$

**Proof.** Since

$$\text{sgn}(\sigma\tau) = (-1)^{\text{inv}(\sigma\tau)} = (-1)^{\text{inv}(\sigma)}(-1)^{\text{inv}(\tau)} = \text{sgn}(\sigma)\text{sgn}(\tau),$$

so the existence is true. (This uses previous theorem, and surjectivity is trivial since transpositions give  $-1$  and composition of transpositions give  $1$ ). Now if

$$\varphi : S_n \rightarrow \{\pm 1\}$$

is a surjective group homomorphism, then since  $\{\pm 1\}$  is an abelian group, so

$$\varphi(\tau\sigma\tau^{-1}) = \varphi(\tau)\varphi(\sigma)\varphi(\tau)^{-1} = \varphi(\sigma),$$

so conjugates elements are mapped to same sign. Now that transpositions are all conjugate (same cycle types so conjugate), so all transpositions have same sign. If  $\varphi((ij)) = 1$  for some  $i, j$ , then since for all  $\sigma \in S_n$ ,  $\sigma$  can be written to a product of transpositions, so  $\varphi(\sigma) = \prod \varphi((ij)) = 1$ , then  $\varphi$  is not surjective, so  $\varphi((ij)) = -1$ . Hence,  $\varphi$  is uniquely defined. (See next proposition) ■

**Lemma 1.9.1.** For a transposition  $t \in S_n$ ,  $\text{inv}(t)$  is odd.

**Proof.** Suppose  $t = (i, i+k)$  for some  $1 \leq i \leq n$  s.t.  $i+k \leq n$  and  $k > 0$ , then since  $t(i) = i+k$ , so  $t(i) > t(i+j) = i+j$  for all  $1 \leq j \leq k$ . Hence, we know there are  $k$  inverse pairs, also since for all  $i+1 \leq j \leq i+k-1$ , we know  $j = t(j) > t(i+k) = i$ , so there are  $k-1$  inverse pairs, and thus there are  $2k-1$  inverse pairs, and thus  $\text{inv}(t)$  is odd. ■

**Proposition 1.9.1.** If  $\pi$  can be decomposed into  $c_1 c_2 \dots c_n$  and  $c'_1 c'_2 \dots c'_m$ , where  $c_i$ 's and  $c'_i$ 's are transpositions, then  $2 \mid n - m$ .

**Proof.** If  $2 \nmid n - m$ , then since

$$0 \equiv \text{inv}(\pi\pi^{-1}) \equiv \text{inv}(\pi) + \text{inv}(\pi^{-1}) \equiv \sum_{i=1}^n \text{inv}(c_i) + \sum_{i=1}^m \text{inv}(c'_{m+1-i}) \pmod{2},$$

and since  $\text{inv}(t)$  is odd for all transpositions  $t$ , and  $n + m$  is odd, so we know  $\sum_{i=1}^n \text{inv}(c_i) + \sum_{i=1}^m \text{inv}(c'_{m+1-i})$  is a sum of  $n + m$  of odd numbers, which is the sum of odd numbers many of odds, and it is still an odd, so it is a contradiction. ■

**Definition 1.9.3** (Alternating group of degree  $n$ ). We define

$$\begin{aligned} A_n &= \ker(\text{sgn}) = \{\sigma \in S_n \mid \text{sgn}(\sigma) = 1\} \\ &= \{\text{all elements expressed as a product of even number of transpositions}\} \\ &= \bigcup_{(1-1)v_1 + (2-1)v_2 + \dots \text{ is even}} (1)^{v_1} (2)^{v_2} \dots \end{aligned}$$

since  $\text{sgn}((a_1 a_2 \dots a_n)) = (-1)^{n-1}$  (It is the product of  $n - 1$  transpositions).

**Proposition 1.9.2.**  $\sigma = (1)^{v_1} (2)^{v_2} \dots$  is an even permutation ( $\sigma \in A_n$ ) iff  $v_2 + v_4 + \dots$  is even.

**Proof.** We know  $\sigma \in A_n$  iff

$$(1-1)v_1 + (2-1)v_2 + \dots \equiv 0 \pmod{2} \Leftrightarrow v_2 + 3v_4 + \dots \equiv 0 \pmod{2} \Leftrightarrow v_2 + v_4 + \dots \equiv 0 \pmod{2}.$$

**Definition 1.9.4** (Simple group). A group  $G$  is said to be simple if  $G$  has no proper ( $\{1\}$  nor  $G$ ) normal subgroup.

**Note 1.9.5.**  $G \triangleright H$  means  $G/H$  is a subgroup, and we say  $G$  can be described by  $H$  and  $G/H$  (as a semi-direct product).

**Example 1.9.3.**  $\mathbb{Z}/n\mathbb{Z}$  is simple iff  $n$  is prime.

**Proof.** If  $\mathbb{Z}/n\mathbb{Z}$  is simple but  $n = ms$  for some  $m, s > 1$  s.t.  $\gcd(m, s) = 1$ , then if  $\mathbb{Z}/n\mathbb{Z} = \langle g \rangle$ , then we know  $\langle g^m \rangle$  is a proper normal subgroup of  $\mathbb{Z}/n\mathbb{Z}$ , which is a contradiction. Now if  $n$  is a prime, then  $\mathbb{Z}/n\mathbb{Z}$  has no proper subgroup by Lagrange's theorem, so  $\mathbb{Z}/n\mathbb{Z}$  is simple. \*

**Example 1.9.4.**  $S_n$  is not a simple group for all  $n \geq 3$  because  $A_n \triangleleft S_n$  is proper and normal.

**Example 1.9.5.**  $A_3 \simeq \mathbb{Z}/3\mathbb{Z}$  is simple but  $V_4 = \{e, (12)(34), (13)(24), (14)(23)\} \triangleleft A_4 = V_4 = A_4 \cup \{\text{permutations of a cycle of size 4}\}$  is proper normal, so  $A_4$  is not simple.

**Proof.**  $V_4$  is the union of some conjugacy classes, so it is normal. \*

**Theorem 1.9.7.**  $A_n$  is a simple group for all  $n \geq 5$ .

## Lecture 13

### 1.10 Sylow's theorem

5 Nov. 13:20

**Definition 1.10.1** (Sylow  $p$ -group). Let  $G$  be a finite group with  $|G| = p^m a$  where  $p \nmid a$  and  $p$  is prime. A subgroup  $H < G$  with  $|H| = p^m$  is called Sylow  $p$ -group.

**Theorem 1.10.1** (Sylow's theorem).

- (1) Sylow  $p$ -subgroup exists.
- (2) If  $K < G$  has the order  $|K| = p^l$  with  $l \leq m$ , then there exists Sylow  $p$ -subgroup containing  $K$ .
- (3) Sylow  $p$ -subgroup are conjugate to each other i.e. if  $P_1, P_2$  are Sylow  $p$ -subgroup, then there exists  $g \in G$  s.t.  $P_2 = gP_1g^{-1}$ .
- (4) Let  $n_p := \# \{\text{Sylow } p\text{-subgroups}\}$ , then  $n_p \equiv 1 \pmod{p}$ .

**Application of Sylow's theorem**

**Proposition 1.10.1.** Let  $G$  be a group of order  $pq$  with  $p, q$  distinct ( $p < q$ ) and both prime s.t.  $q \not\equiv 1 \pmod{p}$ , then

$$G \simeq \mathbb{Z}/pq\mathbb{Z}.$$

i.e. The group of order  $pq$  is unique.

**Proof.** Since  $|G| = pq$ , we know  $n_q \equiv 1 \pmod{q}$ . Also, since we can define a group actions of  $G$  on  $\text{Syl}_q(G) = \{\text{Sylow } q\text{-subgroup}\}$  by

$$\varphi : (G, \text{Syl}_q(G)) \rightarrow \text{Syl}_q(G), \quad g \cdot P = gPg^{-1},$$

and this action is well-defined by (3) of Sylow's theorem. Thus, we know  $\text{Syl}_q(G) = \text{Orb}(Q)$  for some  $Q \in \text{Syl}_q(G)$  since (1) of Sylow's theorem guarantee the existence. Thus, by orbit-stabilizer theorem we know

$$\text{Orb}(Q) \cdot \text{Stab}(Q) = |G| \Rightarrow \text{Syl}_q(G) = \text{Orb}(Q) \mid |G| = pq,$$

and since  $n_q \equiv 1 \pmod{q}$ , so we have  $n_q \mid p$ , so  $n_q = 1, p$ . If  $n_q = p$ , then  $p \equiv 1 \pmod{q}$ , which means  $q \mid p - 1$ , but

$$p - 1 < q - 1 < q,$$

so this is impossible. Now we know  $n_q = 1$ . Thus, we know Sylow  $q$ -subgroup is a unique  $Q$ , and it is normal by plugging  $P_1, P_2$  both to be  $Q$  in (3) of Sylow's theorem. Similarly we can show  $n_p = 1$  and thus Sylow  $p$ -subgroup is a normal  $P$ . Hence,  $|P| = p$  and  $|Q| = q$ , and since  $P \cap Q$  is a subgroup of  $P$  and  $Q$ , so  $|P \cap Q| \mid p$  and  $|P \cap Q| \mid q$ , so we have  $P \cap Q = \{1\}$ , which means

$$P \times Q \simeq PQ = G$$

since

$$|PQ| = \frac{|P||Q|}{|P \cap Q|} = |P||Q|.$$

This proves  $G \simeq \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/q\mathbb{Z}$  and since  $p, q$  are distinct prime (implies  $P, Q$  are cyclic), so

$$\mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/q\mathbb{Z} \simeq \mathbb{Z}/pq\mathbb{Z}.$$

■

**Example 1.10.1.** If  $|G| = 15$ , then  $G \simeq \mathbb{Z}/15\mathbb{Z}$ , but if  $|G| = 21$ , then  $G$  may be non-abelian since  $7 \equiv 1 \pmod{3}$ .

**Proposition 1.10.2.** If  $|G| = pq$  with  $p, q$  distinct primes s.t.  $q \equiv 1 \pmod{p}$ , then there are two possibilities:

- $G \simeq \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/q\mathbb{Z}$ .
- $G \simeq \mathbb{Z}/q\mathbb{Z} \rtimes \mathbb{Z}/p\mathbb{Z}$ , where  $\rtimes$  is the semi-direct product.

**Definition 1.10.2 (Semi-direct product).** Let  $G$  be a group, then  $G = N \rtimes H$  means  $N \triangleleft G$  and  $H < G$  and  $N \cap H = \{1\}$ , and there exists  $\varphi : H \rightarrow \text{Aut}(N)$  s.t.

$$\varphi(h)(n) = hnh^{-1}.$$

Then, we can define a product structure on  $N \times H$  as

$$(n, h) \cdot (n', h') = (nhn^{-1}n', hh')$$

since for

$$g = nh(n \in N, h \in H) \quad g' = n'h'(n' \in N, h' \in H),$$

and

$$gg' = nhn'h' = nhn'h^{-1}hh' \in N \cdot H \text{ (Note that } n \in N, hnh^{-1} \in N, hh' \in H).$$

The upshot is suppose  $G$  is a group and  $N \triangleleft G$  and there exists  $H < G$  s.t.  $H \simeq G/N$  with  $h \mapsto hN$ . Then,  $G$  can be reconstructed by the information of  $H, N$  and  $\varphi$ , which is a group action of  $H$  acts on  $N$ .

## Lecture 14

Let  $G$  be finite group and  $p$  prime. Suppose  $|G| = p^e m$ , and  $\gcd(p, m) = 1$ , then

7 Nov. 13:20

$$\text{Syl}_p(G) = \{H < G \mid |H| = p^e\},$$

and for  $H \in \text{Syl}_p(G)$ , we call it a Sylow  $p$ -subgroup.

**Theorem 1.10.2 (Sylow's theorem).**

- (1)  $\text{Syl}_p(G)$  is non-empty i.e. Sylow  $p$ -subgroup exists.
- (2) Suppose  $H < G$  has  $|H| = p^i$  for some  $0 \leq i \leq e$ , then there exists  $P \in \text{Syl}_p(G)$  s.t.  $H < P$ .
- (3) For  $P, P' \in \text{Syl}_p(G)$ , there exists  $g \in G$  s.t.  $P' = gPg^{-1}$  i.e. all Sylow  $p$ -subgroups are conjugate in  $G$ .
- (4) Let  $n_p := |\text{Syl}_p(G)|$ , then  $n_p \equiv 1 \pmod{p}$  and  $n_p \mid |G|$ .

**Proposition 1.10.3.** With the same setting, let  $r \leq e$ , then there exists  $H < G$  s.t.  $|H| = p^r$ .

**Proof.** First consider all subsets of size  $p^r$ . Let  $\mathcal{S} := \{S \subseteq G \mid |S| = p^r\}$ . At least,  $h \in \mathcal{S}$  if exists. Suppose  $|G| = p^e m = p^r M$ . First observe that

$$|\mathcal{S}| = \binom{p^r M}{p^r} = \frac{p^r M (p^r M - 1) \dots (p^r M - (p^r - 1))}{p^r (p^r - 1) \dots 1},$$

and note that all factors  $p$  in the denominators are cancelled since

$$p^r M - i \equiv p^r - i \pmod{p^r} \quad \forall 1 \leq i \leq p^r - 1.$$

Hence,  $\text{ord}_p |\mathcal{S}| = \text{ord}_p(M) = s$ . Now consider a group action of  $G$  on  $\mathcal{S}$  given by

$$G \times \mathcal{S} \rightarrow \mathcal{S}, \quad (g, S) \mapsto g \cdot S \text{ (left-multiplication)}.$$

Let  $\mathcal{S} = \cup_i \mathcal{S}_i$  be the decomposition into orbits (cosets). Thus,

$$|\mathcal{S}| = \sum_i |\mathcal{S}_i|,$$



and  $|\mathcal{S}|$  is divisible by  $p$  exactly  $s$  times, and thus at least one of  $\mathcal{S}_i$  has  $p^{s+1} \nmid |\mathcal{S}_i|$ . WLOG, suppose  $p^{s+1} \nmid |\mathcal{S}_1|$ . Let  $S_1 \in \mathcal{S}_1$ . Note that  $\mathcal{S}_1 = \{g \cdot S_1 \mid g \in G\}$ . Now define  $H = \{h \in G \mid h \cdot S_1 = S_1\}$ . Then,  $H < G$ . We will show  $|H| = p^r$ :

- As  $G$  acts on  $\mathcal{S}_1$  transitively,

$$G/H \rightarrow \mathcal{S}_1, \quad gH \mapsto g \cdot S_1$$

is bijective. Thus,  $|\mathcal{S}_1| = \frac{|G|}{|H|}$ . Hence,  $|H| = \frac{|G|}{|\mathcal{S}_1|}$ , and since  $|G| = p^r M = p^r p^s m$ , and  $p^{s+1} \nmid |\mathcal{S}_1|$ , so  $|\mathcal{S}_1| \mid M$ . Hence,  $|H|$  is a multiple of  $p^r$ , which means  $|H| \geq p^r$ .

- Next, fix  $x \in S_1$ , then

$$\varphi : H \rightarrow S_1, \quad h \mapsto h \cdot x$$

is injective. Thus,  $|H| \leq |S_1| = p^r$ .

Thus,  $|H| = p^r$ . ■

**Remark 1.10.1.** Our goal is to find  $H < G$  s.t.  $|H| = p^r$ .

Now we show the Sylow's theorem:

**proof of (1).** By previous proposition, it is true. ■

**proof of (2).** Let  $P \in \text{Syl}_p(G)$ , and

$$A_p = \{gPg^{-1} \mid g \in G\} \subseteq \mathcal{S}.$$

Let  $N_G(P) := \{g \in G \mid gPg^{-1} = P\} < G$ . Note:  $P \triangleleft N_G(P)$ . Hence,

$$|A_p| = \frac{|G|}{|N_G(P)|} = [G : N_G(P)].$$

This means

$$|A_p| = \frac{\left(\frac{|G|}{|P|}\right)}{\left(\frac{|N_G(P)|}{|P|}\right)} \Rightarrow |A_p| \mid \frac{|G|}{|P|} = \frac{p^e m}{p^e} = m.$$

Hence,  $p \nmid |A_p|$ . Next, consider the group action of  $H$  on  $A_p$  by

$$H \times A_p \rightarrow A_p, \quad (h, Q) \mapsto hQh^{-1},$$

and let  $A_p = \bigcup_{i=1} A_p^{(i)}$  be the decomposition into the orbits with  $A_p^{(1)} = \{hPh^{-1} \mid h \in H\}$ . let  $P_i$  be a representative of  $A_p^{(i)}$  i.e.

$$A_p^{(i)} = \{hP_ih^{-1} \mid h \in H\},$$

and we know

$$|A_p^{(i)}| = \frac{|H|}{|N_H(P_i)|} = \frac{|H|}{|H \cap N_G(P_i)|}$$

is a power of  $p$ . By the previous argument, we know  $p \nmid |A_p|$ . Thus, there exists  $j$  s.t.  $p \nmid |A_p^{(j)}|$ , which means  $|A_p^{(j)}| = 1$ . Thus,  $|H| = |H \cap N_G(P_j)|$ , so  $H \subseteq N_G(P_j)$ , which means  $H < N_G(P_j)$ . Now recall the second isomorphism theorem:



**Theorem 1.10.3 (Second Isomorphism Theorem).** Suppose  $H < G$  and  $N \triangleleft G$ , then

- $HN < G$
- $N \triangleleft HN$
- $H \cap N \triangleleft H$
- $HN/N \simeq H/(H \cap N)$ .

Since we know  $H < N_G(P_j)$  and  $P_j \triangleleft N_G(P_j)$ , so

$$\frac{|HP_j|}{|P_j|} = \frac{|H|}{|H \cap P_j|},$$

Thus, we have

$$\begin{aligned} \text{L.H.S. } & \frac{|G|}{|HP_j|} \cdot \frac{|HP_j|}{|P_j|} = \frac{|G|}{|P_j|} = \frac{p^e m}{p^e} = m \\ \text{R.H.S. } & |H|, \text{ which is the power of } p, \end{aligned}$$

so we know L.H.S. and R.H.S. are equal to 1. Thus,  $H = H \cap P_j$ , and thus  $H \subseteq P_j$ , so  $H < P_j$ , where  $P_j \in A_p \subseteq \text{Syl}_p(G)$ . ■

**proof of (3).** Let  $P, H \in \text{Syl}_p(G)$ , then by (2) we know  $H \subseteq P_j \in A_p$  for some  $j$ . Since  $|H| = |P_j| = p^e$ , so  $H = P_j \in A_p$ : conjugation of  $P$  in  $G$ . So (3) is true. ■

**proof of (4).** Let  $P \in \text{Syl}_p(G)$ . By changing  $H$  as  $P$  in (2), we know  $A_p^{(1)} = \{P\}$ , whereas  $|A_p^{(i)}| > 1$  if  $i \geq 2$ . (If  $\{P_i\} = |A_p^{(i)}| = 1$ , then  $P = H \subseteq P_i$ , and thus  $P_i = P$ , which means  $i = 1$ .) Therefore,

$$|\text{Syl}_p(G)| = |A_p| = \sum_i |A_p^{(i)}| = |A_p^{(1)}| + \sum_{i \geq 2} |A_p^{(i)}| = 1 + \sum_i p^{l_i} \equiv 1 \pmod{p}.$$

Also,

$$|\text{Syl}_p(G)| = |A_p| = \frac{|G|}{|N_G(p)|} = [G : N_G(p)]$$

is a divisor of  $|G|$ . ■

## Lecture 15

### 1.11 Semidirect Product

12 Nov. 13:20

Suppose  $N, N'$  are groups, then

$$N \times N' = \{(n, n') \mid n \in N, n' \in N'\}$$

has a componentwise multiplication

$$(n_1, n'_1) \cdot (n_2, n'_2) = (n_1 n_2, n'_1 n'_2),$$

and we call it the outer product.

Besides, starting from the product group  $G$ , suppose  $N \triangleleft G$  and  $N' \triangleleft G$  s.t.  $NN' = G$  and  $N \cap N' = \{1\}$ , then  $g = nn'$  is unique. Since if  $n_1 n'_1 = n_2 n'_2$ , then  $n_2^{-1} n_1 = n'_2 n'_1{}^{-1} \in N \cap N' = \{1\}$ .

Thus,

$$N \times N' \simeq NN', \quad (n, n') \mapsto nn'.$$

Now let's generalize this. Let  $G$  be a group and suppose  $N \triangleleft G$  and  $H < G$  s.t.  $NH = G$  and  $N \cap H = \{1\}$ , then we can similarly deduce that  $g = nh$  is unique. Besides, for  $nh, n'h' \in NH = G$ , we know

$$(nh) \cdot (n'h') = nhn'h^{-1}hh' = n(hn'h^{-1})hh' \in NH$$

since  $n, hn'h^{-1} \in N$  and  $hh' \in H$ . So in terms of the multiplication on the set  $N \times H$ , the multiplication in  $G$

$$\Leftrightarrow (n, h) \cdot (n', h') = (n\varphi_h(n'), hh')$$

with  $\varphi_h(n) := hn'h^{-1}$  for  $h \in H$  and  $n \in N$ .

**Note 1.11.1.** The inner viewpoint requires the multiplication of  $G$  in  $\varphi_h$ .

**Question.** How can we reconstruct such groups?

Observe that  $\varphi_h : N \rightarrow N$  is a group automorphism, so there is a group action of  $H$  on  $N$ :

$$(h, n) \mapsto \varphi_h(n).$$

Now we can equivalently define

$$\varphi : H \rightarrow \text{Aut}(N), \quad h \mapsto \varphi_h.$$

In fact,

$$\varphi_g \circ \varphi_h(n) := \varphi_g(\varphi_h(n)) = ghnh^{-1}g^{-1} = \varphi_{gh}(n).$$

This shows

$$\varphi : H \rightarrow \text{Aut}(N)$$

is a group homomorphism.

**Question.** What if we start with a general group action of  $H$  on  $N$ :

$$H \rightarrow \text{Aut}(N), \quad h \mapsto \varphi_h,$$

and define a multiplication on the set  $N \times H$  as

$$(*) \quad (n, h) \cdot (n', h') := (n\varphi_h(n'), hh')?$$

**Theorem 1.11.1.** The binary operation  $(*)$  satisfies all group laws, so it defines a group structure on  $N \times H$  (the product set).

**Notation.** The resulting group is defined as

$$N \rtimes_{\varphi} H,$$

where  $\varphi$  may be omitted if it is clear.

Here,

$$\begin{cases} N \times \{1\} \triangleleft N \rtimes_{\varphi} H \\ \{1\} \times H < N \rtimes_{\varphi} H \end{cases}$$

using these subgroups.

**(Check the group axioms).**

- Associativity:

$$\begin{aligned} & (n_1, h_1) \cdot ((n_2, h_2) \cdot (n_3, h_3)) \\ &= (n_1, h_1) \cdot (n_2\varphi_{h_2}(n_3), h_2h_3) \\ &= (n_1\varphi_{h_1}(n_2\varphi_{h_2}(n_3)), h_1h_2h_3) \\ &= (n_1\varphi_{h_1}(n_2)\varphi_{h_1}(\varphi_{h_2}(n_3)), h_1h_2h_3) \\ &= (n_1\varphi_{h_1}(n_2)\varphi_{h_1h_2}(n_3), h_1h_2h_3). \end{aligned}$$

Also, we know

$$((n_1, h_1) \cdot (n_2, h_2)) \cdot (n_3, h_3) = (n_1 \varphi_{h_1}(n_2) \varphi_{h_1 h_2}(n_3), h_1 h_2 h_3),$$

so the associativity holds.

- Inverse:

$$(n, h)^{-1} = (\varphi_{h^{-1}}(n^{-1}), h^{-1}).$$

■

#### Example 1.11.1.

- If  $\varphi : H \rightarrow \text{Aut}(N)$  is trivial i.e.  $\varphi(H) = \{1\}$ , then

$$N \rtimes_{\varphi} H = N \times H.$$

- Suppose  $N = \mathbb{Z}/m\mathbb{Z} = C_m$ , which is cyclic, then since  $\mathbb{Z}/m\mathbb{Z} = \langle 1 \rangle$ , so  $\varphi \in \text{Aut}(\mathbb{Z}/m\mathbb{Z})$  is determined by  $\varphi(1)$  since  $\varphi(1^n) = (\varphi(1))^n$ , so we need  $\varphi(1)$  coprime to  $m$ . That is,  $\varphi(1) \in (\mathbb{Z}/m\mathbb{Z})^{\times}$ .

# Appendix