

# Algebra

October 15, 2016

# 1 Group theory

## 1.1 Week 1

**Def 1.** A non-empty set  $G$  with a binary function  $f : G \times G \rightarrow G, (a, b) \mapsto ab$  is a **group** if it satisfies

1.  $(ab)c = a(bc)$ .
2.  $\exists 1 \in G$  s.t.  $1a = a1 = a, \forall a \in G$ .
3.  $\exists a^{-1} \in G$  s.t.  $aa^{-1} = a^{-1}a = 1$ .

CONCON

**Def 2.** Let  $G$  be a group. Then  $G$  is said to be **abelian** if  $\forall a, b \in G, ab = ba$ .

**Ex 1.1.1.** Let  $G$  be a semigroup. Then TFAE (the following are equivalent)

1.  $G$  is a group.
2. For all  $a, b \in G$  and the equations  $bx = a, yb = a$ , each of them has a solution in  $G$ .
3.  $\exists e \in G$  s.t.  $ae = a \forall a \in G$  and if we fix such  $e$ , then  $\forall b \in G \exists b' \in G$  s.t.  $bb' = e$ .

**Ex 1.1.2.** Let  $G$  be a group. Show that

1.  $\forall a \in G, a^2 = 1$ , then  $G$  is abelian.
2.  $G$  is abelian  $\iff \forall a, b \in G, (ab)^n = a^n b^n$  for three consecutive integer  $n$ .

**Def 3.** Let  $G$  be a group and  $H \subseteq G, H \neq \emptyset$ . Then  $H$  is said to be a subgroup of  $G$ , denoted by  $H \leq G$ , if

1.  $\forall a, b \in H, ab \in H$ .
2.  $1 \in H$ .
3.  $\forall a \in H, a^{-1} \in H$ .

useful criterion:  $H \leq G \iff \forall a, b \in H, ab^{-1} \in H$ .

**pf:**

$\implies b \in H \implies b^{-1} \in H$ , and  $a \in H$ , so  $ab^{-1} \in H$ .

- $\Leftarrow$
1.  $H \neq \emptyset \implies \exists a \in H \implies aa^{-1} = 1 \in H$ .
  2.  $1, a \in H \implies 1a^{-1} = a^{-1} \in H$ .
  3.  $a, b^{-1} \in H \implies a(b^{-1})^{-1} = ab \in H$ . □

**Ex 1.1.1.**  $(\mathbb{Z}, +, 0) \leq (\mathbb{Q}, +, 0) \leq (\mathbb{R}, +, 0) \leq (\mathbb{C}, +, 0) ; (\mathbb{Q}^\times, \times, 1) \leq (\mathbb{R}^\times, \times, 1) \leq (\mathbb{C}^\times, \times, 1)$

**Eg 1.1.2.**

- Special linear group  $\text{SL}(n, \mathbb{F}) = \{ A \in \text{GL}(n, \mathbb{F}) \mid \det A = 1 \}$
- Orthogonal group  $\text{O}(n) = \{ A \in \text{GL}(n, \mathbb{R}) \mid A^t A = I_n \}$
- Unitary group  $\text{U}(n) = \{ A \in \text{GL}(n, \mathbb{C}) \mid A^* A = I_n \}$
- Special orthogonal group  $\text{SO}(n) = \text{SL}(n, \mathbb{R}) \cap \text{O}(n)$

- Special unitary group  $SU(n) = SL(n, \mathbb{C}) \cap U(n)$

**Def 4.** Let  $f : G_1 \rightarrow G_2$ .  $f$  is called an **isomorphism** if

1.  $f$  is 1-1 and onto.
2.  $\forall a, b \in G_1, f(ab) = f(a)f(b)$ . (**homomorphism**)

, denoted by  $G_1 \cong G_2$ .

**Remark 1.** (practice)

1.  $f(1) = 1$ .
2.  $f(a^{-1}) = f(a)^{-1}$ .
3. If  $f$  is an isomorphism, then  $\exists f^{-1}$  is also a homomorphism.

**Eg 1.1.3.**

- $U(1) = \{ z \in \mathbb{C}^\times \mid \bar{z}z = 1 \}, z = \cos \theta + \sin \theta i$
- $SO(2) = \left\{ \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} : \theta \in \mathbb{R} \right\}$

notice that  $U(1) \cong SO(2)$ .  $S^1 = \{ (a, b) \in \mathbb{R}^2 \mid a^2 + b^2 = 1 \}$ , 可被賦予群的結構.

**Eg 1.1.4.** Let  $A \in SU(2) \implies A = \begin{pmatrix} \alpha & \beta \\ -\bar{\beta} & \bar{\alpha} \end{pmatrix}, \alpha\bar{\alpha} + \beta\bar{\beta} = 1, \alpha, \beta \in \mathbb{C}$ .

Quaternion(四元數):  $\mathbb{H} = \{ a + bi + cj + dk \mid a, b, c, d \in \mathbb{R} \}$  with  $i^2 = j^2 = k^2 = -1, ij = k, jk = i, ki = j (\implies ij = -ji)$ .

Let  $x = a + bi + cj + dk, \bar{x} = a - bi - cj - dk$ , then  $N(x) = x\bar{x} = a^2 + b^2 + c^2 + d^2$ , For  $x \neq 0, N(x) \neq 0, x^{-1} = \frac{1}{N(x)}\bar{x}$

Now, for  $x = a + bi + cj + dk = (a + bi) + (c + di)j$ . So  $SU(2) \cong \{ x \in \mathbb{H}^\times \mid N(x) = 1 \}$ .  $S^3 = \{ (a, b, c, d) \in \mathbb{R}^4 \mid a^2 + b^2 + c^2 + d^2 = 1 \}$ , 可被賦予群的結構.

★ The only spheres with continuous group law are  $S^1, S^3$ .

**Ex 1.1.3.** Find a way to regard  $M_{n \times n}(\mathbb{H})$  as a subset of  $M_{2n \times 2n}(\mathbb{C})$ , which preserves addition and multiplication, and then there is a way to characterize  $GL(n, \mathbb{H})$ .

**Def 5** (symplectic group).  $Sp(n, \mathbb{F}) = \{ A \in GL(2n, \mathbb{F}) \mid A^t J A = J \}$  where  $J = \begin{pmatrix} O & I_n \\ -I_n & O \end{pmatrix}$ .

( $A^t J A = J$  preserving non-degenerate skew-symmetric forms)

$Sp(n) = \{ A \in GL(n, \mathbb{H}) \mid A^* A = I_n \}$ .

**Ex 1.1.4.** Show  $Sp(n) \cong U(2n) \cap Sp(n, \mathbb{C})$ .

Ques: Find the smallest subgroup of  $SU(2)$  containing  $\begin{pmatrix} i & 0 \\ 0 & -i \end{pmatrix}$ .

## 1.2 Week 2

### 1.2.1 Permutation groups and Dihedral groups

**Def 6.** A permutation of a set  $B$  is a 1-1 and onto function from  $B$  to  $B$ .

Let  $S_B :=$  the set of permutations of  $B$ . Then  $(S_B, \cdot, \text{Id}_B)$  forms a group.

If  $B = \{a_1, \dots, a_n\}$ , then  $S_B \cong S_{\{1, \dots, n\}}$  and write  $S_n = S_{\{1, \dots, n\}}$ , called the symmetric group of degree  $n$ .

**Theorem 1** (Cayley theorem). Any group is isomorphic to a subgroup of some permutation group.

(Hint): Let  $G$  be a group. Set  $B = G$ . Consider  $a \in G$  as  $\sigma_a : G \rightarrow G, x \mapsto ax$ . Then  $\sigma_a \in S_G \implies G \leq S_G$ .

**Fact 1.2.1.**  $S_n$  is a finite group of order  $n!$ , i.e.  $|S_n| = n!$ .

**pf:** EASY =O

□

Cyclic notation:  $\sigma \in S_5$ , say  $\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 4 & 3 & 5 & 1 & 2 \end{pmatrix}$ . Write  $\sigma = (1\ 4)(2\ 3\ 5)$ .

$\Rightarrow$  Any permutation can be written as a product of disjoint cycles.

**Eg 1.2.1.** In  $S_7$ ,  $\sigma_1 = (1\ 2\ 3)(4\ 5\ 6)(7)$ ,  $\sigma_2 = (1\ 3\ 5\ 6)(2\ 4\ 7)$ .  
Then  $\sigma_1\sigma_2 = (2\ 5\ 4\ 7\ 3\ 6)$ ,  $\sigma_1^{-1} = (1\ 3\ 2)(4\ 6\ 5)$ .

**Def 7.** A 2 cycle is called a **transposition**.

**Eg 1.2.2.**  $(1\ 2\ 3) = (1\ 3)(1\ 2)$ ,  $(1\ 2\ 3\ 4\ 5) = (1\ 5)(1\ 4)(1\ 3)(1\ 2)$ .  
Any permutation is a product of 2 cycles.

Useful formula:  $\sigma \in S_n$ ,  $\sigma(j_1 \dots j_m)\sigma^{-1} = (\sigma(j_1) \dots \sigma(j_m))$ .

**Eg 1.2.3.** Let  $\sigma = (1\ 2\ 3)(4\ 5\ 6\ 7)$ ,  $\sigma(2\ 3\ 4)\sigma^{-1} = (3\ 1\ 5)$ .

**pf:** Note that both sides are functions. For  $i \in \{1, \dots, n\}$ ,

Case 1:  $\exists k$  s.t.  $\sigma(j_k) = i$ , CONCON

Case 2: Otherwise, CONCON

□

**Fact 1.2.2.**  $S_n = \langle (1\ 2), \dots, (1\ n) \rangle$ .

**pf:**  $(1\ i)^{-1} = (1\ i)$  and  $(i\ j) = (1\ i)(1\ j)(1\ i)^{-1}$ .

□

**Def 8.** Let  $G$  be a group and  $S \subset G$ . The subgroup generated by  $S$  defined to be the smallest subgroup of  $G$  which contains  $S$ , denoted by  $\langle S \rangle$ .

**Ex 1.2.1.**

1.  $S_n = \langle (1\ 2), (2\ 3), \dots, (n-1\ n) \rangle$ ,  $n \geq 2$ .

2.  $S_n = \langle (1\ 2), (1\ 2 \dots n) \rangle$ ,  $n \geq 2$ .

**Def 9.**  $A_n = \{\text{even permutations of } S_n\} \leq S_n, |A_n| = \frac{n!}{2}$ .

**Ex 1.2.2.**

1.  $A_n = \langle (1\ 2\ 3), (1\ 2\ 4), \dots, (1\ 2\ n) \rangle, n \geq 3.$
2.  $A_n = \langle (1\ 2\ 3), (2\ 3\ 4), \dots, (n-2\ n-1\ n) \rangle, n \geq 3.$

**Remark 2.**  $\langle S \rangle = \bigcap_{S \subseteq H \leq G} H = \{a_1 a_2 \dots a_k \mid k \in \mathbb{N}, a_i \in S \cup S^{-1}\} \cup \{1\}$

The orthogonal transformations on  $\mathbb{R}^2$ :  $O(2)$ .

Let  $A = \begin{pmatrix} a_1 & a_2 \\ b_1 & b_2 \end{pmatrix} \in O(2).$

略... (這邊討論旋轉和反射的矩陣)

Case 1:  $A = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix}$  is counterclockwise rotation w.r.t.  $\alpha$ .

Case 2:  $A = \begin{pmatrix} \cos \alpha & \sin \alpha \\ \sin \alpha & -\cos \alpha \end{pmatrix}$  is the reflection.  $A^2 = I_2 \implies$  eigenvalues are  $\pm 1$ .

Easy to show that  $L_A(v) = v - 2\langle v, v_2 \rangle v_2$ .

$O(2) = \{\text{rotations}\} \cup \{\text{reflections}\}.$

**Def 10.** The dihedral group  $D_n$  is the group of symmetries of a regular  $n$ -gon.  
In general,  $D_n = \langle T, R \mid T^n = 1, R^2 = 1, TR = RT^{-1} \rangle \leq O(2) \leq S_n, |D_n| = 2n.$

**Def 11.** Let  $T$  be a linear transformation from  $\mathbb{R}^n \rightarrow \mathbb{R}^n$ .

- $T$  is called a rotation if  $\exists$  a  $T$ -invariant subspace  $W \subseteq \mathbb{R}^n$  with  $\dim W = 2$  s.t.  $\begin{cases} T|_W \text{ is a rotation} \\ T|_{W^\perp} = \text{id}_{W^\perp} \end{cases}$
- $T$  is called a reflection if  $\exists$  a  $T$ -invariant subspace  $W \subseteq \mathbb{R}^n$  with  $\dim W = 1$  s.t.  $\begin{cases} T|_W = -\text{id}_W \\ T|_{W^\perp} = \text{id}_{W^\perp} \end{cases}$

Main result: the group of orthogonal transformations =  $\langle \text{rotations, reflections} \rangle.$

**Prop 1.2.1.** For  $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$ ,  $\exists$  a  $T$ -invariant subspace  $W \subseteq \mathbb{R}^n$  with  $1 \leq \dim W \leq 2$ .

**pf:** Let  $A = [T]_\alpha \in M_{n \times n}(\mathbb{R}) \subseteq M_{n \times n}(\mathbb{C})$ . Consider  $\widetilde{L}_A : \mathbb{C}^n \rightarrow \mathbb{C}^n, v \mapsto Av$ .

Then  $\exists$  an eigenvalue  $\lambda \in \mathbb{C}$  and an eigenvector  $v \in \mathbb{C}^n$  for  $\widetilde{L}_A$ . Let  $\lambda = \lambda_1 + \lambda_2 i, v = v_1 + v_2 i$ . By definition, we have

$$Av = \widetilde{L}_A(v) = \lambda v = (\lambda_1 + \lambda_2 i)(v_1 + v_2 i) \implies \begin{cases} Av_1 = \lambda_1 v_1 - \lambda_2 v_2 \\ Av_2 = \lambda_2 v_1 + \lambda_1 v_2 \end{cases},$$

so  $W = \langle v_1, v_2 \rangle.$

□

**Ex 1.2.3.**

1. If  $T$  is orthogonal, then  $W^\perp$  is also  $T$ -invariant.
2. Use induction on  $n$  to show the main result.

For  $n = 3, A \in O(3)$ , we have  $A \sim \begin{pmatrix} \cos \alpha & -\sin \alpha & \\ \sin \alpha & \cos \alpha & \\ & & \pm 1 \end{pmatrix}.$

### 1.2.2 Cyclic groups and internal direct product

**Def 12.** If  $G = \langle a \rangle = \{\dots, a^{-2}, a^{-1}, a, 1, a, a^2, \dots\} = \{a^n \mid n \in \mathbb{Z}\}$ , then  $G$  is a cyclic group generated by  $a$ .

**Eg 1.2.4.**  $\mathbb{Z} = \langle 1 \rangle = \langle -1 \rangle$ .

**Eg 1.2.5.** Let  $A = \begin{pmatrix} \cos \frac{2\pi}{n} & -\sin \frac{2\pi}{n} \\ \sin \frac{2\pi}{n} & \cos \frac{2\pi}{n} \end{pmatrix} \in \text{SO}(2)$ . Then  $\langle A \rangle = \{I_2, A, A^2, \dots, A^{n-1}\}$  and  $A^n = I_2$ ,  $A^m = A^r$  where  $m \equiv r \pmod{n}$ .

**Eg 1.2.6.**  $\mathbb{Z}/n\mathbb{Z} = \{\bar{0}, \bar{1}, \dots, \overline{(n-1)}\}$  with  $\bar{j} = \{m \in \mathbb{Z} \mid m \equiv j \pmod{n}\}$ . Define  $\bar{i} + \bar{j} = \begin{cases} \overline{i+j} & \text{if } 0 \leq i+j \leq n \\ \overline{i+j-n} & \text{otherwise} \end{cases} \implies (\mathbb{Z}/n\mathbb{Z}, +, \bar{0})$  forms a group.

**Remark 3.**  $\bar{i} \times \bar{j} = \overline{i \times j}$ .

- 略
- If  $\gcd(j, n) = d, \exists h, k \in \mathbb{Z}$  s.t.  $hj + kn = d$ .

**Def 13.**  $(\mathbb{Z}/n\mathbb{Z})^\times = \{j \in \mathbb{Z}/n\mathbb{Z} \mid \gcd(j, n) = 1\} \implies ((\mathbb{Z}/n\mathbb{Z})^\times, \times, \bar{1})$  forms a group.

**Eg 1.2.7.** 略... 简化剩余系, 原根 (generator)  $(1, 2, 4, p^k, 2p^k, p \text{ is an odd prime})$

**Def 14.**

- The **order** of a finite group  $G$  is the number of elements in  $G$ , denoted by  $|G|$ .
- Let  $a \in G$ , the order of  $a$  is defined to be the least positive integer  $n$  s.t.  $a^n = 1$ , denoted by  $\text{ord}(a) = n$ .
- If  $a^n \neq 1 \quad \forall n \in \mathbb{N}$ , then we call “ $a$  has infinite order”.

**Prop 1.2.2.** Let  $G = \langle a \rangle$  with  $\text{ord}(a) = n$ . Then

1.  $a^m = 1 \iff n \mid m$ .

**pf:**

$\Leftarrow$ : Let  $m = dn$ , then  $a^m = (a^n)^d = 1$ .

$\Rightarrow$ : Let  $m = qn + r, 0 \leq r < n$ . If  $r \neq 0$ , then  $a^r = a^{m-qn} = (a^m)(a^n)^{-q} = 1$ . But  $r < n$ , which is a contradiction. Hence  $r = 0 \implies n \mid m$ .  $\square$

2.  $\text{ord}(a^r) = n / \gcd(r, n)$ .

**pf:** Let  $\gcd(r, n) = d, n = dn', r = dr'$  with  $\gcd(n', r') = 1$ . Plan to show “ $\text{ord}(a^r) = n'$ .”

- $(a^r)^{n'} = a^{r'n'} = (a^n)^{r'} = 1 \implies \text{ord}(a^r) \mid n'$ .
- $1 = (a^r)^{\text{ord}(a^r)} = a^{r \cdot \text{ord}(a^r)} \implies n \mid r \cdot \text{ord}(a^r) \implies n' \mid r' \cdot \text{ord}(a^r) \implies n' \mid \text{ord}(a^r)$ .

$\square$

**Prop 1.2.3.** Any subgroup of a cyclic group is cyclic.

**pf:** Let  $G = \langle a \rangle$  and  $H \leq G$ . If  $H = \{1\}$ , then  $H = \langle 1 \rangle$ , done!

Otherwise,  $d = \min\{m \in \mathbb{N} \mid a^m \in H\}$ , by well-ordering axiom. Claim  $H = \langle a^d \rangle$ .

$\supset$ :  $a^d \in H$  by the definition of  $d$ .

$\subset$ :  $\forall a^m \in H$ , write  $m = qd + r$ ,  $0 \leq r < d$ . If  $r \neq 0$ , then  $a^r = a^{m-qd} = a^m(a^d)^{-q} \in H$ , which is a contradiction. Hence  $r = 0 \implies d \mid m$ .

□

**Ex 1.2.4.**

1.  $\text{ord}(a) = \text{ord}(a^{-1}) = n$ .
2.  $\langle a^r \rangle = \langle a^{\gcd(n,r)} \rangle$ .
3.  $\langle a^{r_1} \rangle = \langle a^{r_2} \rangle \iff \gcd(n, r_1) = \gcd(n, r_2)$ .
4.  $\forall m \mid n, \exists! H \leq \langle a \rangle$  s.t.  $|H| = m$ . Conversely, if  $H \leq \langle a \rangle$ , then  $|H| \mid n$ .

**Prop 1.2.4.** Let  $G = \langle a \rangle$ . Then

1.  $\text{ord}(a) = n \implies G \cong \mathbb{Z}/n\mathbb{Z}$
2.  $\text{ord}(a) = \infty \implies G \cong \mathbb{Z}$

**Ex 1.2.5.** Show Prop 1.2.4.

**Def 15.** Let  $G_1, G_2 \leq G$ .  $G$  is the internal direct product of  $G_1, G_2$  if  $G_1 \times G_2 \rightarrow G, (g_1, g_2) \mapsto g_1g_2$  is an isom.

**Remark 4.** In this case, we find that

- $G = G_1G_2 = \{g_1g_2 \mid g_1 \in G_1, g_2 \in G_2\}$ .
- $G_1 \cap G_2 = \{1\}$ . (consider  $a \neq 1 \in G_1 \cap G_2$ , then  $(1, a) \mapsto a, (a, 1) \mapsto a$ , but the function is 1-1, which is a contradiction.)
- If  $a \in G$  with  $a = g_1g_2 = g'_1g'_2$ , then  $(g'_1)^{-1}g_1 = (g'_2)g_2^{-1} \in G_1 \cap G_2 = \{1\} \implies \begin{cases} g_1 = g'_1 \\ g_2 = g'_2 \end{cases}$ .
- For  $g_1 \in G_1, g_2 \in G_2, (g_1, g_2) = (g_1, 1)(1, g_2) = (1, g_2)(g_1, 1) \implies g_1g_2 = g_2g_1$ .

**Ex 1.2.6.** TFAE

1.  $G$  is the internal direct product of  $G_1, G_2$ .
2.  $\forall a \in G, \exists! g_1 \in G_1, g_2 \in G_2$  s.t.  $a = g_1g_2$ ;  $\forall g_1 \in G_1, g_2 \in G_2, g_1g_2 = g_2g_1$ .
3.  $G_1 \cap G_2 = \{1\}$ ;  $G = G_1G_2$ ;  $\forall g_1 \in G_1, g_2 \in G_2, g_1g_2 = g_2g_1$ .

**Eg 1.2.8.**

1.  $G = \mathbb{Z}/6\mathbb{Z} = \{\bar{0}, \bar{1}, \bar{2}, \bar{3}, \bar{4}, \bar{5}\}, G_1 = \{\bar{0}, \bar{3}\}, G_2 = \{\bar{0}, \bar{2}, \bar{4}\}$ . We have  $G \cong G_1 \times G_2$ .
2.  $G = S_3, G_1 = \langle (1\ 2) \rangle, G_2 = \langle (1\ 2\ 3) \rangle$ . We have  $G_1 \times G_2 \not\cong G$  since  $(1\ 2)(1\ 2\ 3) \neq (1\ 2\ 3)(1\ 2)$ .

**Eg 1.2.9.**  $G = S_3, G_1 = \langle (1\ 2) \rangle, G_2 = \langle (2\ 3) \rangle, G_1G_2 = \{1, (1\ 2), (2\ 3), (1\ 2\ 3)\} \not\leq G$  since  $(1\ 3\ 2) = (1\ 2\ 3)^{-1} \notin G_1G_2$ .

**Prop 1.2.5.** Let  $H, K \leq G$ . Then  $HK \leq G \iff HK = KH$ .

**pf:**

$$\Rightarrow: \begin{cases} H \leq HK \\ K \leq HK \end{cases} \implies KH \subseteq HK ; \forall hk \in HK, \exists h'k' \in HK \text{ s.t. } (hk)(h'k') = 1 \implies hk = (k')^{-1}(h')^{-1} \in KH \implies HK \subseteq KH.$$

$$\Leftarrow: \text{ For } h_1k_1, h_2k_2 \in HK, (h_1k_1)(h_2k_2)^{-1} = h_1k_1k_2^{-1}h_2^{-1} = h_1h'k' \in HK.$$

□



## 1.3 Week 3

### 1.3.1 Coset and Quotient Group

Let  $f : G_1 \rightarrow G_2$  be a group homo. Define  $\text{Im } f := f(G_1)$ .

Notice that  $\text{Im } f \leq G_2$ .

**pf:** Let  $z_1 = f(a_1), z_2 = f(a_2)$ , then  $z_1 z_2^{-1} = f(a_1) f(a_2)^{-1} = f(a_1) f(a_2^{-1}) = f(a_1 a_2^{-1}) \in \text{Im } f$ .  $\square$

**Def 16.**  $\ker f := \{x \in G_1 \mid f(x) = 1\} \leq G_1$ .

**Fact 1.3.1.**

1.  $x \in (\ker f)a \iff f(x) = f(a)$ .
2.  $\ker f = \{1\} \iff f$  is 1-1.

**Def 17.** Let  $H \leq G, \forall a \in G, Ha$  is called a **right coset** of  $H$  in  $G$ .

**Fact 1.3.2.**

1. For 2 right cosets  $Ha, Hb$ , either  $Ha = Hb$  or  $Ha \cap Hb = \phi$  must hold.
2.  $\{Ha : a \in G\}$  forms a partition of  $G$ .

**Theorem 2** (Lagrange). Let  $|G| < \infty$  and  $H \leq G, |H| \mid |G|$ .

**pf:**

$\square$

**Remark 5.**  $r$  is called the **index** of  $H$  in  $G$ , denoted by  $[G : H]$ . (The concept of index can be extended to infinite  $G, H$ .)

**Ex 1.3.1.** no subgroup of  $A_4$  has order 6. (converse of Lagrange thm. is false.)

**Coro 1.3.1.** If  $|G| = p$  is a prime in  $\mathbb{Z}$ , then  $G$  is cyclic.

**pf:**

$\square$

**Coro 1.3.2.** If  $|G| < \infty, a \in G$ , then  $a^{|G|} = 1$ .

**pf:**

$\square$

**Remark 6.**

1. Let  $H \leq G, a \in G, aH$  is called a **left coset**.
2.  $\{\text{right cosets of } H\} \leftrightarrow \{\text{right cosets of } H\}$  by  $Ha \mapsto a^{-1}H$ .

Ques: How to make  $\{aH : a \in G\}$  to be a group? For  $aH, bH$ , we must have  $(aH)(bH) = abH$ .  
In general,  $(aH)(bH) = abH$  is not well-defined.

**Ex 1.3.1.** Let  $H = \langle (1\ 2) \rangle \leq S_3$ .  $a_1 = (1\ 3), a_2 = (1\ 2\ 3), b_1 = (1\ 3\ 2), b_2 = (2\ 3)$ . 出慘點

If we hope  $a_1 b_1 H = a_2 b_2 H$ , then we need  $(a_1 b_1)^{-1} a_2 b_2 \in H$ .

$$b_1^{-1} a_1^{-1} a_2 b_2 = b_1^{-1} b_2 b_2^{-1} a_1^{-1} a_2 b_2$$

Notice that  $b_1^{-1} b_2, a_1^{-1} a_2 \in H$ , so we need  $b_2^{-1} a_1^{-1} a_2 b_2 \in H$ .

**Def 18.** Let  $H \leq G$ .  $H$  is said to be **normal subgroup** of  $G$  if  $\forall g \in G, h \in H, g^{-1}hg \in H$  (or  $g^{-1}Hg \subseteq H$ ), denoted by  $H \triangleleft G$ .

**Def 19.** Let  $H \triangleleft G$ . The set  $\{aH \mid a \in G\}$  forms a group under  $(aH)(bH) = abH, a, b \in G$ . We call it the **quotient group** of  $G$  by  $H$ , denoted by  $G/H$ .  
(Note: The identity is  $H = hH$  and  $(aH)^{-1} = a^{-1}H$ .)

**Remark 7.** Define  $q : G \rightarrow G/H, a \mapsto aH$ , called the quotient homomorphism.

**Ex 1.3.2.** Let  $H \leq G$ . Then TFAE

- (a)  $H \triangleleft G$ .
- (b)  $\forall x \in G, xHx^{-1} = H$ .
- (c)  $\forall x \in G, xH = Hx$ .
- (d)  $\forall x, y \in G, (xH)(yH) = (xy)H$ .

Ques: How to find a normal subgroup of  $G$ ?

**Prop 1.3.1.**

- 1. If  $G$  is abelian, then  $\forall H \leq G \rightsquigarrow H \triangleleft G$ . (done by (c))
- 2. If  $H \leq G$  with  $[G : H] = 2$ , then  $H \triangleleft G$ .

**Ex 1.3.2.**  $n \leq 3, [S_n : A_n] = 2 \implies A_n \triangleleft S_n$ .

**pf:** We can write  $G = H \cup Ha = H \cup aH \implies aH = Ha, \forall a \notin H$ . □

**Def 20.** Define the center of  $G$  to be  $Z_G = \{a \in G \mid ax = xa, \forall x \in G\} \leq G$ .

**Prop 1.3.2.**

- 1.  $Z_G \triangleleft G$ . (by (c) and def.)
- 2. If  $G/Z_G$  is cyclic, then  $G$  is abelian.

**pf:** Let  $G/Z_G = \langle aZ_G \rangle$ , (let  $\bar{a} := aZ_G$ ) for some  $a \in G$ . For  $x_1, x_2 \in G$ , let  $x_1 = a^{k_1}z_1, x_2 = a^{k_2}z_2$ , then  $x_1x_2 = a^{k_1+k_2}z_1z_2 = x_2x_1$ . ( $z_i$  可以各種交換) □

**Def 21.** The commutator of  $G$  is define to be  $[G, G] = \langle xyx^{-1}y^{-1} \mid x, y \in G \rangle$ .

**Prop 1.3.3.**  $[G, G] \triangleleft G ; [G, G] = 1 \iff G$  is abelian.

**pf:**  $\forall x \in G, a \in [G, G], xax^{-1} = xax^{-1}a^{-1}a$  and  $xax^{-1}a^{-1}, a \in [G, G]$ . □

**Ex 1.3.3.**

- 1. If  $H \leq S_n$  and  $\exists \sigma \in H$  is odd, then  $[H : H \cap A_n] = 2$ .
- 2. For  $n \geq 3, [S_n, S_n] = A_n$ .

**Ex 1.3.4.** Let  $H \leq G$ . Then  $H \triangleleft G$  and  $G/H$  is abelian  $\iff [G, G] \leq H$ . (hint:  $G/[G, G]$  is "max" among all abelian quotient groups)

### 1.3.2 Isomorphism theorems & Factor theorem

**Theorem 3** (1st isomorphism theorem). Let  $f : G_1 \rightarrow G_2$  be a group homo. Then  $G_1/\ker f \cong \text{Im } f$ .

**pf:** Define  $\varphi : a \ker f \mapsto f(a)$ .

- well-defined:  $a \ker f = b \ker f \implies a^{-1}b \in \ker f \implies f(a^{-1}b) = 1 \implies f(a)^{-1}f(b) = 1 \implies f(a) = f(b)$ .
- group homo:  $\varphi((a \ker f)(b \ker f)) = \varphi(ab \ker f) = f(ab) = f(a)f(b) = \varphi(a \ker f)\varphi(b \ker f)$ .
- onto: by def. of  $\text{Im } f$ .
- 1-1:  $f(a) = f(b) \implies a \ker f = b \ker f$  (easy).

□

**Theorem 4** (Factor theorem). Let  $f : G_1 \rightarrow G_2$  be a group homo. and  $H \triangleleft G_1, H \leq \ker f$ . Then  $\exists$  a group homo.  $\varphi : G/H \rightarrow G_2$  s.t. 一個正圖

**Eg 1.3.3.** Let  $G = \langle a \rangle$  with  $\text{ord}(a) = n$ . Then  $G \cong \mathbb{Z}/n\mathbb{Z}$ . (1st isom. thm.)

**Eg 1.3.4.**  $\varphi : \mathbb{Z} \rightarrow \mathbb{Z}/2\mathbb{Z}, 4\mathbb{Z} \leq 2\mathbb{Z}$ , so by factor thm.,  $\mathbb{Z}/4\mathbb{Z} \rightarrow \mathbb{Z}/2\mathbb{Z}$ .

**Eg 1.3.5.**  $\det : \text{GL}(n, \mathbb{F}) \rightarrow \mathbb{F}^\times \implies \text{GL}(n, \mathbb{F})/\text{SL}(n, \mathbb{F}) \cong \mathbb{F}^\times$

**Eg 1.3.6.**  $\text{sgn} : S_n \rightarrow \{\pm 1\} \implies S_n/A_n \cong \{\pm 1\}$

**Theorem 5** (2nd isomorphism theorem). Let  $H \leq G, K \triangleleft G$ . Then  $HK/K \cong H/H \cap K$ .

**pf:** First,  $\begin{cases} H \leq G \\ K \triangleleft G \end{cases} \implies HK = KH \implies HK \leq G ; K \triangleleft G \implies K \triangleleft HK$ .

Define  $\varphi : H \rightarrow HK/K, h \mapsto hK$ . which is a group homo.

- onto:  $\forall (hk)K, hK = hK, \text{ so } \varphi(h) = hK = hkK$ .
- Find  $\ker \varphi$ :  $a \in \ker \varphi \iff \begin{cases} a \in H \\ aK = K \end{cases} \iff a \in H \cap K, \text{ so } \ker \varphi = H \cap K$ .

Then by 1st isom. thm.

□

**Eg 1.3.7.**  $G = \text{GL}(2, \mathbb{C}), H = \text{SL}(2, \mathbb{C}), K = \mathbb{C}^\times I_2 = Z_G \triangleleft G$ .

By 2nd isom. thm.,  $G/K \cong H/\{\pm I_2\}$ . ( $G = HK, \{\pm I_2\} = H \cap K$ )

projective linear group:  $\text{PGL}(2, \mathbb{C}) = G/K$ .

projective special linear group:  $\text{PSL}(2, \mathbb{C}) = H/H \cap K$ .

齊次座標...OTL

**Ex 1.3.5.**

1. Let  $H_1 \triangleleft G_1, H_2 \triangleleft G_2$ . Then  $(H_1 \times H_2) \triangleleft (G_1 \times G_2)$  and  $G_1 \times G_2 / H_1 \times H_2 \cong G_1 / H_1 \times G_2 / H_2$ .
2. Let  $H \triangleleft G, K \triangleleft G$  s.t.  $G = HK$ . Then  $G / H \cap K \cong G / H \times G / K$ .

**Ex 1.3.6.** Let  $H \triangleleft G$  with  $[G : H] = p$ , which is a prime in  $\mathbb{Z}$ . Then  $\forall K \leq G$ , either (1)  $K \leq H$  or (2)  $G = HK$  and  $[K : K \cap H] = p$ .

**Theorem 6** (3rd isomorphism theorem). Let  $K \triangleleft G$ .

1. There is a 1-1 correspondence between  $\{H \leq G \mid K \leq H\}$  and  $\{\text{subgroups of } G/K\}$ . ( $H \triangleleft G$  ... normal)

**pf:** Define  $\varphi : H \mapsto H/K$ . ( $H/K \leq G/K$ )

- 1-1: Assume  $H_1/K = H_2/K$ . For  $a \in H_1$ ,  $aK \in H_1/K = H_2/K$ . so  $\exists b \in H_2$  s.t.  $aK = bK \implies b^{-1}a \in K \leq H_2 \implies a \in bH_2 = H_2$ . So  $H_1 \leq H_2$ . By symmetry,  $H_2 \leq H_1$ , and thus  $H_1 = H_2$ .
- onto: Given a subgroup  $Q$  of  $G/K$ , consider  $H = q^{-1}(Q)$  where  $q : G \rightarrow G/K$ .
  - $H \leq G$ :  $\forall a, b \in H, q(a), q(b) \in Q \implies q(a)q(b)^{-1} \in Q \implies q(ab^{-1}) \in Q \implies ab^{-1} \in H \implies H \leq G$ .
  - $K \leq H$ :  $\forall a \in K, q(a) = aK = K \in Q \implies a \in H \implies K \leq H$ .
  - $Q = H/K$ :  $\forall aK \in Q, aK = q(a) \implies a \in H \implies aK \in H/K \implies Q \subseteq H/K$ .  
And  $\forall aK \in H/K (a \in H), q(a) \in Q \implies H/K \subseteq Q$ . So  $Q = H/K$ .
- $H \triangleleft G, K \leq H \iff \forall g \in G, gHg^{-1} = H, K \leq H \iff \forall \bar{g} \in G/K, \bar{g}(H/K)\bar{g}^{-1} = H/K \iff H/K \triangleleft G/K$ .  $\square$

2. If  $H \triangleleft G$  with  $K \leq H$ , then  $(G/K)/(H/K) \cong G/H$ .

**pf:** Define  $\varphi : G \rightarrow (G/K)/(H/K)$  with  $\varphi : a \mapsto aK(H/K)$ .

- onto: ... easy.
- Find  $\ker \varphi$ :  $a \in \ker \varphi \iff aK(H/K) = H/K \iff aK \in H/K \iff a \in H$ .

By 1st isom. thm.,  $(G/K)/(H/K) \cong G/H$ .  $\square$

**Eg 1.3.8.**  $m\mathbb{Z} + n\mathbb{Z}/m\mathbb{Z} \cong n\mathbb{Z}/m\mathbb{Z} \cap n\mathbb{Z}$ . ( $m\mathbb{Z} + n\mathbb{Z} = \gcd(m, n)\mathbb{Z}, m\mathbb{Z} \cap n\mathbb{Z} = \text{lcm}(m, n)\mathbb{Z}$ )

Ques:  $G/K \cong G'/K'$  and  $K \cong K' \not\Rightarrow G \cong G'$ .

**Eg 1.3.9.**  $Q_8$  and  $D_4$  交給陳力

Extension problem: given two groups  $A, B$ , how to find  $G$  and  $K \triangleleft G$ , s.t.  $K \cong A, G/K \cong B$ ?  
( $1 \rightarrow H \rightarrow G \rightarrow G/H \rightarrow 1$ , short exact sequence)  
(e.g.  $G = A \times B, K = A \times \{1\}$ )

## 1.4 Week 4

### 1.4.1 Universal property and direct sum & product

In general, let  $f_1 : G_1 \rightarrow G, f_2 : G_2 \rightarrow G$  are group homo.  $f_1 \times f_2 : G_1 \times G_2 \rightarrow G, (a, b) \mapsto f_1(a)f_2(b)$ . But we have  $(a, b) = (a, 1)(1, b) = (1, b)(a, 1)$ , so  $f_1(a)f_2(b) = f_2(b)f_1(a) \implies$  need  $G$  to be abelian.

So we intend to define the direct sum in the category of abelian group.

Notation: For abelian groups, we use “+” to denote the group operation and “0” to denote the identity.

**Def 22.** Given a non-empty family of abelian groups  $\{G_s \mid s \in \Lambda\}$ , a (external) direct sum of  $\{G_s \mid s \in \Lambda\}$  is an abelian group  $\bigoplus_{s \in \Lambda} G_s$  with the embedding mappings  $i_{s_0} : G_{s_0} \rightarrow \bigoplus_{s \in \Lambda} G_s, \forall s_0 \in \Lambda$  satisfying the universal property:

for any abelian group  $H$  and group homo.  $\varphi_s : G_s \rightarrow H \forall s \in \Lambda, \exists!$  group homo.  $\varphi : \bigoplus_{s \in \Lambda} G_s \rightarrow H$  s.t. 又一個 $\tau$ 圖

**Theorem 7.**  $\bigoplus_{s \in \Lambda} G_s$  exists and is unique up to isomorphisms.

**pf:** Existence:  $\bigoplus_{s \in \Lambda} G_s = \{(g_s)_{s \in \Lambda} \mid g_s \in G_s, \text{ almost all of the } g_s' \text{ are } 0\}$  and

$$i_{s_0} : G_{s_0} \rightarrow \bigoplus_{s \in \Lambda} G_s, a_{s_0} \mapsto (g_{s_0})_{s \in \Lambda} \text{ with } g_{s_0} = a_{s_0}, g_s = 0, \forall s \neq s_0.$$

group operation:  $(g_s)_{s \in \Lambda} + (g'_s)_{s \in \Lambda} := (g_s + g'_s)_{s \in \Lambda} \in \bigoplus_{s \in \Lambda} G_s$ . 這邊也一個 $\tau$ 圖

Uniqueness: Assume  $\exists$  another  $G$  satisfies the universal property, 一個大 $\tau$ 圖  $(G, \bigoplus_{s \in \Lambda} G_s)$  互相有唯一一個映射可以 keep  $i_{s_0}, \varphi \circ \psi = \text{id}_G, \psi \circ \varphi = \text{id}_{\bigoplus_{s \in \Lambda} G_s}$   $\square$

**Def 23.** Given a non-empty family of groups  $\{G_s \mid s \in \Lambda\}$ , a direct product of  $\{G_s \mid s \in \Lambda\}$  is a group  $\prod_{s \in \Lambda} G_s$  with projections  $p_{s_0} : \prod_{s \in \Lambda} G_s \rightarrow G_{s_0}, \forall s_0 \in \Lambda$  satisfying the following universal property:

for any group  $H$  with group homo.  $\varphi_s : H \rightarrow G_s, \forall s \in \Lambda, \exists! \varphi : H \rightarrow \prod_{s \in \Lambda} G_s$  s.t. 又一個 $\tau$ 圖

**Theorem 8.**  $\prod_{s \in \Lambda} G_s$  exists and is unique up to isomorphisms.

**pf:** Existence:  $\prod_{s \in \Lambda} G_s = \{(g_s)_{s \in \Lambda} \mid g_s \in G_s\}$  and

$$p_{s_0} : \prod_{s \in \Lambda} G_s \rightarrow G_{s_0}, (g_s)_{s \in \Lambda} \mapsto g_{s_0}, \forall s_0 \in \Lambda$$

- group operation:  $(g_s)_{s \in \Lambda} \cdot (g'_s)_{s \in \Lambda} := (g_s g'_s)_{s \in \Lambda} \in \prod_{s \in \Lambda} G_s$ .
- Define  $\varphi$ : 這邊也一個 $\tau$ 圖 which is uniquely defined.

Uniqueness: Assume  $\exists$  another  $G$  satisfies the universal property, 一個大 $\tau$ 圖  $(G, \prod_{s \in \Lambda} G_s)$  互相有唯一一個映射可以 keep  $i_{s_0}, \varphi \circ \psi = \text{id}_G, \psi \circ \varphi = \text{id}_{\prod_{s \in \Lambda} G_s}$   $\square$

**Ex 1.4.1.** Google the definition of the **direct limit** and show the existence and uniqueness.

**Ex 1.4.2.** Google the definition of the **inverse limit** and show the existence and uniqueness.

Motivation:  $\zeta_m$  is called an  $m$ -th root of unity if  $\zeta_m^m = 1$ .

$$\varinjlim_n \mathbb{Z}/2^n \mathbb{Z} \cong \{2^n\text{-th roots of unity} : n \in \mathbb{N}\}$$

$$\varinjlim_n \mathbb{Z}/2^n \mathbb{Z} = \left( \bigoplus_{n \in \mathbb{N}} \mathbb{Z}/2^n \mathbb{Z} \right) / \langle i_k(a) - i_j(f_{kj}(a)) \mid k \leq j, a \in \mathbb{Z}/2^k \mathbb{Z} \rangle$$

where  $f_{kj} : \mathbb{Z}/2^k\mathbb{Z} \rightarrow \mathbb{Z}/2^j\mathbb{Z}$ .  
Inverse limit:

$$\varprojlim \mathbb{Z}/2^n\mathbb{Z} = \left\{ (n_1, n_2, \dots) \in \prod_n \mathbb{Z}/2^n\mathbb{Z} \mid \forall i < j, n_i \equiv n_j \pmod{2^{i+1}} \right\}$$

### 1.4.2 Rings and fields

**Def 24.** A **ring** is a non-empty set  $R$  with two operations  $R \times R \rightarrow R$

$$(a, b) \mapsto a + b \quad \text{and} \quad (a, b) \mapsto ab$$

satisfying

1.  $(R, +, 0)$  is an abelian group.
2.  $(R, \cdot)$  is a semigroup. (if it is a monoid, then it is called “a ring with 1.”)
3. (Distributive laws)  $\forall a, b, c \in R, \begin{cases} a(b + c) = ab + ac \\ (b + c)a = ba + ca \end{cases}$

**Eg 1.4.1.**  $\mathbb{Z}, \mathbb{R}, \mathbb{C}, \mathbb{Z}/n\mathbb{Z}, M_{n \times n}(\mathbb{F})$

**Eg 1.4.2.** Let  $G$  be an abelian group. Define (endomorphism, automorphism)

$$\text{End}(G) := \{ \text{group homo. } G \rightarrow G \} \quad \text{Aut}(G) := \{ \text{group isom. } G \rightarrow G \}$$

A natural ring structure on  $\text{End}(G)$  is:

$$\forall a \in G, \begin{cases} (f + g)(a) := f(a) + g(a) \\ (f \cdot g)(a) := f(g(a)) \end{cases}$$

**Eg 1.4.3.**  $\mathbb{Z}[\sqrt{2}] = \{ a + b\sqrt{2} \mid a, b \in \mathbb{Z} \} \subset \mathbb{R}$ .

**Def 25.** Let  $R$  be a ring with 1.

- (a)  $\forall a \in R, a \neq 0$ ,  $a$  is called a unit if  $\exists a^{-1} \in R$ .
- (b)  $(R^\times = \{\text{units in } R\}, \cdot, 1)$  forms a group.
- (c)  $R$  is called a division ring if  $R \setminus \{0\} = R^\times$ .
- (d)  $R$  is said to be commutative if  $ab = ba, \forall a, b \in R$ .
- (e)  $R$  is a field if  $R$  is a commutative division ring.
- (f)  $a \neq 0$  is called a left zero divisor if  $\exists b \in R, b \neq 0$  s.t.  $ab = 0$ .
- (g)  $a$  is called a zero divisor if  $a$  is either a left or right zero divisor.
- (h)  $R$  is called an integral domain if  $R$  is a commutative ring without zero divisors.

Fact:

1. fields  $\implies$  integral domains.
2. finite + integral domain  $\implies$  fields.

**pf:** Let  $R = \{0, a_1, \dots, a_n\}$ , for  $a \in R, a \neq 0$ ,  $aa_i = aa_j \implies a(a_i - a_j) = 0 \implies i = j$ . So  $\{0, aa_1, \dots, aa_n\} = R \implies \exists a_i$  s.t.  $aa_i = 1$ .  $\square$

**Prop 1.4.1.** TFAE

1.  $\mathbb{Z}/n\mathbb{Z}$  is an integral domain.
2.  $\mathbb{Z}/n\mathbb{Z}$  is a field.
3.  $n = p$  is a prime.

easy to prove.

**Def 26.**

- $f : R_1 \rightarrow R_2$  is called a ring homomorphism if  $\forall a, b \in R, \begin{cases} f(a+b) = f(a) + f(b) \\ f(ab) = f(a)f(b) \end{cases}$ .
- $\text{Im } f$  is a subring of  $R_2$ .
- $\ker f = \{x \in R_1 \mid f(x) = 0\}$  is an additive group of  $R_1$  and  $\forall r \in R_1, x \in \ker f, f(rx) = f(r)f(x) = f(r)0 = 0 \implies rx \in \ker f, xr \in \ker f$ .
- $R_1/\ker f$  is an additive group and  $R_1/\ker f \cong \text{Im } f$  (additive isomorphism).

**Def 27.** Let  $I$  be an additive subgroup of  $R$ .  $I$  is called an ideal if  $\forall r \in R, x \in I, rx \in I, xr \in I$ .  $(R/I, +, \cdot)$  forms a quotient ring under

$$\forall r_1, r_2 \in R, (r_1 + I)(r_2 + I) = r_1 r_2 + I$$

well-defined: easy to show.

**Ex 1.4.3.** State and show the isomorphism theorems and the factor theorem.

**Prop 1.4.2.** If  $R$  is a ring with 1, then  $\exists!$  ring homo.  $\varphi : \mathbb{Z} \rightarrow R$  s.t.  $\varphi(1) = 1$ .

**pf:** Let  $\varphi : \mathbb{Z} \rightarrow R$  is a ring homo. s.t.  $\varphi(1) = 1$ . Then  $\forall n \in \mathbb{Z}, \varphi(n) = \varphi(1) + \dots + \varphi(1) = n1$ . Now  $\forall n, m \in \mathbb{Z}, \varphi(n)\varphi(m) = (n1)(m1) = n(m1) = (nm)1$  by the distributive law. So  $\varphi$  is well-defined and unique.  $\square$

**Def 28.** In Prop 1.4.2,  $\ker \varphi = m\mathbb{Z}$  for some  $m > 0$ . We call  $m$  the characteristic of  $R$ , denoted by  $\text{char } R = m$ .

**Prop 1.4.3.**

1. If  $R$  is an integral domain, then  $\text{char } R = 0$  or  $p$ , where  $p$  is a prime. (try to prove this)
2. In the case of  $\text{char } R = p, \forall a, b \in R, (a+b)^p = a^p + b^p$ .

**pf:**

$$(a+b)^p = a^p + \binom{p}{1}a^{p-1}b + \dots + b^p = a^p + b^p$$

$$\text{because } p \mid \binom{p}{i} \implies \binom{p}{i}a^{p-i}b^i = 0.$$

$\square$

**Ex 1.4.4.** Let  $F$  be a field. Show that

1. if  $\text{char } F = 0$ , then  $\mathbb{Q} \hookrightarrow$  subfield of  $F$ .
2. if  $\text{char } F = p$ , then  $\mathbb{Z}/p\mathbb{Z} \hookrightarrow$  subfield of  $F$ .

**Theorem 9.** If  $F$  is a finite field, then  $|F| = p^n$  for some  $n \in \mathbb{N}$  and  $p$  is a prime.

**pf:** By Ex. 1.4.4,  $\text{char } F = p$ ,  $p$  is a prime and  $\mathbb{Z}/p\mathbb{Z} \hookrightarrow F$ .

We have  $\mathbb{Z}/p\mathbb{Z} \times F \rightarrow F, (r, v) \mapsto rv$ .  $F$  can be regarded as a vector space over  $\mathbb{Z}/p\mathbb{Z}$ .

Let  $\dim_{\mathbb{Z}/p\mathbb{Z}} F = n$ , then  $F \cong (\mathbb{Z}/p\mathbb{Z})^n \implies |F| = p^n$ . □

**Theorem 10.** Let  $F$  be a field. Then any finite subgroup  $G$  of  $(F^\times, \cdot, 1)$  is cyclic.

**pf:** Let  $|G| = n$ . Define  $h$  to be the max order of an element in  $G$ , say  $a^h = 1$ .

If  $h = n$ , then  $|\langle a \rangle| = h = n = |G|$  and  $\langle a \rangle \subseteq G$ , so  $G = \langle a \rangle$ .

Otherwise,  $h < n$ . We know that  $x^h - 1$  has at most  $h$  roots. So  $\exists b \in G$  is not a root of  $x^h - 1$ .

Let  $\text{ord}(b) = h'$ , so  $h' \mid n$  and  $h' \nmid h$ . So  $\exists$  a prime  $p$  s.t.  $p^r \mid h'$  but  $p^r \nmid h$ .

Write  $h = mp^s$ ,  $s < r$  and  $\gcd(m, p) = 1 \implies \text{ord}(a^{p^s}) = m$ .

Write  $h' = qp^r \implies \text{ord}(b^q) = p^r$ .

Since  $\gcd(m, p^r) = 1$ ,  $\text{ord}(a^{p^s} b^q) = mp^r > mp^s = h$ , which is a contradiction. □

**Ex 1.4.5.**

1. Let  $a, b \in G$  with  $ab = ba$  and  $\text{ord}(a) = m, \text{ord}(b) = n$ . If  $\gcd(m, n) = 1$ , then  $\text{ord}(ab) = mn$ .  
In general, is the order of  $ab$  equal to  $\text{lcm}(m, n)$ ?

2. Let  $G$  be a finite group and  $H, K \leq G$ . Then  $|HK| = \frac{|H||K|}{|H \cap K|}$ .



## 1.5 Week 5

### 1.5.1 Group actions I

**Def 29.** A group  $G$  is said to act on a nonempty set  $X$  if  $\exists$  a map  $G \times X \rightarrow X$  with  $(g, x) \mapsto gx$  s.t.

1.  $1x = x$
2.  $(g_1g_2)x = g_1(g_2x) \quad \forall g_1, g_2 \in G$

**Prop 1.5.1.**  $\{\text{actions of } G\} \leftrightarrow \{\text{group homo. } G \rightarrow S_X\}$

**pf:** Given an action  $(g, x) \mapsto gx$ , consider  $\varphi : G \rightarrow S_X$  s.t.  $\varphi : g \mapsto (\tau_g : x \mapsto gx)$ .

- 1-1:  $gx = gy \implies g^{-1}(gx) = y \implies x = y$ .
- onto:  $\forall y \in X$ , let  $x = g^{-1}y$ , then  $y = gx$ .
- group homo.:  $\varphi(gg') = (\tau_{gg'} : x \mapsto gg'x) = \tau_g \circ \tau_{g'} = \varphi(g)\varphi(g')$ .

Conversely, given a group homo.  $\varphi : G \rightarrow S_X$ , consider  $(g, x) \mapsto \varphi(g)(x)$ .

- $1x = \varphi(1)(x) = \text{Id}(x) = x$ .
- $g_1g_2x = \varphi(g_1g_2)(x) = \varphi(g_1) \circ \varphi(g_2)(x) = g_1(g_2x)$ . □

**Def 30.** A representation of  $G$  on a vector space  $V$  is a group action of  $G$  on  $V$  linearly. i.e.  $\exists$  group homo.  $\varphi : G \rightarrow \text{GL}(V)$ .

**Eg 1.5.1.**

$$\mathbb{Z}/m\mathbb{Z} \rightarrow \text{SO}(2), \quad \bar{k} \mapsto \begin{pmatrix} \cos \frac{2k\pi}{m} & -\sin \frac{2k\pi}{m} \\ \sin \frac{2k\pi}{m} & \cos \frac{2k\pi}{m} \end{pmatrix}$$

**Eg 1.5.2.**

$$S_n \rightarrow \text{GL}(n, \mathbb{R}), \quad \sigma \mapsto (\tau_\sigma : e_i \mapsto e_{\sigma(i)})$$

**Remark 8.**

1. An action  $G \times X \rightarrow X$  is said to be faithful if the corresponding group homo.  $\varphi : G \hookrightarrow S_X$ , denoted by  $G \curvearrowright X$ .
2. In general,  $\ker \varphi = \{g \in G \mid gx = x \quad \forall x \in X\} = \bigcap_{x \in X} \{g \mid gx = x\}$ .  
Define  $G_x = \{g \mid gx = x\} \leq G$  is the isotropy subgroup of  $G$  at  $x$ . (the stabilizer of  $G$  at  $x$ )
3.  $\varphi : G \rightarrow S_X \implies G/\ker \varphi \hookrightarrow S_X$ . So  $G/\ker \varphi \times X \rightarrow X$  is faithful.
4. Let  $\mathcal{C}(X) = \{f : X \rightarrow \mathbb{C}\}$ . If  $G \curvearrowright X$ , then  $G \curvearrowright \mathcal{C}(X)$  by  $G \times \mathcal{C}(X) \rightarrow \mathcal{C}(X)$  with  $(g, f) \mapsto gf(x) = f(g^{-1}x)$ .  
The reason:  $(g_1g_2)f(x) = f((g_1g_2)^{-1}x) = f(g_2^{-1}g_1^{-1}x) = g_1(g_2f)(x)$ .

**Def 31.** Let  $G \curvearrowright X$  and  $x \in X$ .

- The **orbit** of  $x$  is defined to be  $Gx = \{gx \mid g \in G\}$ .
- $G \curvearrowright X$  is said to be transitive if  $\exists$  only one orbit. i.e.  $\forall x, y \in X, \exists g \in G$  s.t.  $y = gx$ .

The set of orbits forms a partition:  $x \sim y \iff \exists g \in G$  s.t.  $y = gx$ .

**Prop 1.5.2.** Let  $G \curvearrowright X$  and  $x \in X$ . Then  $|Gx| = [G : G_x]$ .

In particular,  $|G| < \infty \implies |G| = |Gx||G_x| \quad \forall x \in X$ .

**pf:** Define  $\psi : Gx \rightarrow \{\text{left coset of } G_x\}$  as  $\psi : gx \mapsto gG_x$ .

- well-defined and 1-1:  $g_1x = g_2x \iff g_2^{-1}g_1x = x \iff g_2^{-1}g_1 \in G_x \iff g_2^{-1}g_1G_x = G_x \iff g_1G_x = g_2G_x$ .
- onto:  $\forall g \in G, \psi(gx) = gG_x$ .

□

### 1.5.2 Action by left multiplication

- The action  $G \times G \rightarrow G, (g, x) \mapsto gx$  is associated with  $\varphi : G \hookrightarrow S_G$ . It is faithful (Cayley theorem) and transitive.
- Let  $H \leq G$  and  $X := \{\text{left coset of } H\}$ .