Algebra

October 29, 2016

1 Group theory

1.1 Week 1

Def 1. A non-empty set G with a binary function $f : G \times G \to G, (a, b) \mapsto ab$ 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 $H \subseteq G, H \neq \phi$. 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. $\forall a \in H, a^{-1} \in H$.

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

pf:

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

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

Eg 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 $\mathrm{SL}(n, \mathbb{F}) = \{ A \in \mathrm{GL}(n, \mathbb{F}) \mid \det A = 1 \}$

- Orthogonal group $\mathrm{O}(n) = \{ A \in \mathrm{GL}(n, \mathbb{R}) \mid A^{\mathrm{t}} A = I_n \}$

- Unitary group $\mathrm{U}(n) = \{ A \in \mathrm{GL}(n, \mathbb{C}) \mid A^* A = I_n \}$

- Special orthogonal group $\mathrm{SO}(n) = \mathrm{SL}(n, \mathbb{R}) \cap \mathrm{O}(n)$

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

Def 4. Let $f : G_1 \to G_2$. 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.

- $\mathrm{U}(1) = \{\, z \in \mathbb{C}^{\times} \mid \bar{z}z = 1 \,\}, z = \cos\theta + \sin\theta i$

- $\mathrm{SO}(2) = \left\{ \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} : \theta \in \mathbb{R} \right\}$

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

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

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 $\mathrm{SU}(2) \cong \{\, x \in \mathbb{H}^{\times} \mid N(x) = 1 \,\}$.
$S^3 = \{\, (a, b, c, d) \in \mathbb{R}^4 \mid a^2 + b^2 + c^2 + d^2 = 1 \,\}$, 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 $\mathrm{GL}(n, \mathbb{H})$.

Def 5 (symplectic group). $\mathrm{Sp}(n, \mathbb{F}) = \{\, A \in \mathrm{GL}(2n, \mathbb{F}) \mid A^{\mathrm{t}}JA = J \,\}$ where $J = \begin{pmatrix} O & I_n \\ -I_n & O \end{pmatrix}$.
($A^{\mathrm{t}}JA = J$ preserving non-degenerate skew-symmetric forms)
$\mathrm{Sp}(n) = \{\, A \in \mathrm{GL}(n, \mathbb{H}) \mid A^*A = I_n \,\}$.

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

Ques: Find the smallest subgroup of $\mathrm{SU}(2)$ 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 $(S_B, \cdot, \mathrm{Id}_B)$ forms a group.
If $B = \{a_1, \ldots, a_n\}$, then $S_B \cong S_{\{1,\ldots,n\}}$ and write $S_n = S_{\{1,\ldots,n\}}$, 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 $\sigma_a : G \to G, x \mapsto ax$. 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 $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad\square$

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

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 $i \in \{1, \ldots, n\}$,

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

Case 2: Otherwise, CONCON

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad\square$

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

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

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

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

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

Ex 1.2.2.

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

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

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

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)

<u>Case 1</u>: $A = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix}$ is counterclockwise roration w.r.t. α.

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

    Easy to show that $\mathrm{L}_A(v) = v - 2\langle v, v_2 \rangle v_2$.

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

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

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

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

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

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

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

pf: Let $A = [\mathrm{T}]_\alpha \in M_{n \times n}(\mathbb{R}) \subseteq M_{n \times n}(\mathbb{C})$. Consider $\widetilde{\mathrm{L}_A} : \mathbb{C}^n \to \mathbb{C}^n, v \mapsto Av$.
Then $\exists$ an eigenvalue $\lambda \in \mathbb{C}$ and an eigenvector $v \in \mathbb{C}^n$ for $\widetilde{\mathrm{L}_A}$. Let $\lambda = \lambda_1 + \lambda_2 i, v = v_1 + v_2 i$. By definition, we have

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

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

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 $G = \langle a \rangle = \{\ldots, a^{-2}, a^{-1}, a, 1, a, a^2, \ldots\} = \{a^n \mid n \in \mathbb{Z}\}$, 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 $A = \begin{pmatrix} \cos\frac{2\pi}{n} & -\sin\frac{2\pi}{n} \\ \sin\frac{2\pi}{n} & \cos\frac{2\pi}{n} \end{pmatrix} \in \mathrm{SO}(2)$. Then $\langle A \rangle = \{I_2, A, A^2, \ldots, a^{n-1}\}$ and $A^n = I_2, A^m = A^r$ where $m \equiv r \pmod{n}$.

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

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

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

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

Eg 1.2.7. 略... 簡化剩餘系, 原根 (generator) $(1, 2, 4, p^k, 2p^k, p$ is an odd prime$)$

Def 14.

- The **order** of a finite gorup 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 $\mathrm{ord}(a) = n$.

- If $a^n \neq 1 \quad \forall n \in \mathbb{N}$, then we call "$a$ has infinte order".

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

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

   pf:

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

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

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

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

   - $(a^r)^{n'} = a^{r'dn'} = (a^n)^{r'} = 1 \implies \mathrm{ord}(a^r) \mid n'$.
   - $1 = (a^r)^{\mathrm{ord}(a^r)} = a^{r\,\mathrm{ord}(a^r)} \implies n \mid r\,\mathrm{ord}\,a^r \implies n' \mid r'\,\mathrm{ord}(a^r) \implies n' \mid \mathrm{ord}(a^r)$.

   $\qquad\square$

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

pf: Let $G = \langle a \rangle$ and $H \le G$. 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 $H = \langle a^d \rangle$.

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

⊂: $\forall a^m \in H$, 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 $r = 0 \implies d \mid m$.

$\square$

Ex 1.2.4.

1. $\mathrm{ord}(a) = \mathrm{ord}(a^{-1}) = n$.

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. $\mathrm{ord}(a) = n \implies G \cong \mathbb{Z}/n\mathbb{Z}$

2. $\mathrm{ord}(a) = \infty \implies G \cong \mathbb{Z}$

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 $G_1 \times G_2 \to G, (g_1, g_2) \mapsto g_1 g_2$ is an isom.

Remark 4. In this case, we find that

- $G = G_1 G_2 = \{\, g_1 g_2 \mid g_1 \in G_1, g_2 \in G_2 \,\}$.

- $G_1 \cap G_2 = \{1\}$. (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 $a = g_1 g_2 = g_1' g_2'$, 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 $g_1 \in G_1, g_2 \in G_2, (g_1, g_2) = (g_1, 1)(1, g_2) = (1, g_2)(g_1, 1) \implies g_1 g_2 = g_2 g_1$.

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. $a = g_1 g_2$; $\forall g_1 \in G_1, g_2 \in G_2, g_1 g_2 = g_2 g_1$.

3. $G_1 \cap G_2 = \{1\}$; $G = G_1 G_2$; $\forall g_1 \in G_1, g_2 \in G_2, g_1 g_2 = g_2 g_1$.

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

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

pf:

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

$\Leftarrow$: For $h_1 k_1, h_2 k_2 \in HK$, $(h_1 k_1)(h_2 k_2)^{-1} = h_1 k_1 k_2^{-1} h_2^{-1} = h_1 h' k' \in HK.$

$\square$

1.3 Week 3

1.3.1 Coset and Quotient Group

Let $f : G_1 \to G_2$ be a group homo. Define $\operatorname{Im} f := f(G_1)$.
Notice that $\operatorname{Im} f \leq G_2$.

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

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: $\quad\square$

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: $\quad\square$

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

pf: $\quad\square$

Remark 6.

1. Let $H \leq G, a \in G$, aH is called a **left coset**.

2. {right cosets of H} $\leftrightarrow$ {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.

Eg 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 $H \lhd G$.

Def 19. Let $H \lhd G$. 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 indentity is $H = hH$ and $(aH)^{-1} = a^{-1}H$.)

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

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

(a) $H \lhd G$.

(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 $\forall H \leq G \rightsquigarrow H \lhd G$. (done by (c))

2. If $H \leq G$ with $[G : H] = 2$, then $H \lhd G$.

   Eg 1.3.2. $n \leq 3, [S_n : A_n] = 2 \implies A_n \lhd S_n$.

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

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. $Z_G \lhd G$. (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 $x_1 x_2 = a^{k_1+k_2}z_1 z_2 = x_2 x_1$. ($z_i$ 可以各種交換) $\qquad\square$

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. $[G, G] \lhd G$; $[G, G] = 1 \iff G$ is abelian.
pf: $\forall x \in G, a \in [G, G], xax^{-1} = xax^{-1}a^{-1}a$ and $xax^{-1}a^{-1}, a \in [G, G]$. $\qquad\square$

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 $H \lhd G$ 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 $f : G_1 \to G_2$ be a group homo. Then $G_1/\ker f \cong \operatorname{Im} f$.

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 $\operatorname{Im} f$.

- 1-1: $f(a) = f(b) \implies a \ker f = b \ker f$ (easy).

$\square$

Theorem 4 (Factor theorem). Let $f : G_1 \to G_2$ be a group homo. and $H \lhd G_1, H \leq \ker f$. Then $\exists$ a group homo. $\varphi : G/H \to G_2$ s.t. 一個ざ圖

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

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

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

Eg 1.3.6. $\operatorname{sgn} : S_n \to \{\pm 1\} \implies S_n/A_n \cong \{\pm 1\}$

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

pf: First, $\begin{cases} H \leq G \\ K \lhd G \end{cases} \implies HK = KH \implies HK \leq G \, ; \, K \lhd G \implies K \lhd HK$.
Define $\varphi : H \to HK/K, h \mapsto hK$. which is a group homo.

- onto: $\forall (hk)K, hkK = hK$, so $\varphi(h) = hK = hkK$.

- Find $\ker \varphi$: $a \in \ker \varphi \iff \begin{cases} a \in H \\ aK = K \end{cases} \iff a \in H \cap K$, so $\ker \varphi = H \cap K$.

Then by 1st isom. thm.

$\square$

Eg 1.3.7. $G = \operatorname{GL}(2, \mathbb{C}), H = \operatorname{SL}(2, \mathbb{C}), K = \mathbb{C}^\times I_2 = Z_G \lhd G$.
By 2nd isom. thm., $G/K \cong H/\{\pm I_2\}$. ($G = HK, \{\pm I_2\} = H \cap K$)
projective linear group: $\operatorname{PGL}(2, \mathbb{C}) = G/K$.
projective special linear group: $\operatorname{PSL}(2, \mathbb{C}) = H/H \cap K$.

齊次座標...OTL

Ex 1.3.5.

1. Let $H_1 \lhd G_1, H_2 \lhd G_2$. Then $(H_1 \times H_2) \lhd (G_1 \times G_2)$ and $G_1 \times G_2/H_1 \times H_2 \cong G_1/H_1 \times G_2/H_2$.

2. Let $H \lhd G, K \lhd G$ s.t. $G = HK$. Then $G/H \cap K \cong G/H \times G/K$.

Ex 1.3.6. Let $H \lhd G$ 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 $\{$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 $q : G \to G/K$.
     - $H \leq G$: $\forall a, b \in H, q(a), q(b) \in Q \implies q(a)q(b)^{-1} \in Q \implies q(ab^{-1}) \in Q \implies ab^{-1} \in H \implies H \leq G$.
     - $K \leq H$: $\forall a \in K, q(a) = aK = K \in Q \implies a \in H \implies K \leq H$.
     - $Q = H/K$: $\forall aK \in Q, aK = q(a) \implies a \in H \implies aK \in H/K \implies Q \subseteq H/K$. And $\forall aK \in H/K (a \in H), q(a) \in Q \implies H/K \subseteq Q$. So $Q = H/K$.
   - $H \triangleleft G, K \leq H \iff \forall g \in G, gHg^{-1} = H, K \leq H \iff \forall \overline{g} \in G/K, \overline{g}(H/K)\overline{g}^{-1} = H/K \iff H/K \triangleleft G/K$. $\qquad\square$

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

   pf: Define $\varphi : G \to (G/K)/(H/K)$ 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., $(G/K)/(H/K) \cong G/H$. $\qquad\square$

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

Ques: $G/K \cong G'/K'$ and $K \cong K' \implies\!\!\!\!\!/\ \ G \cong G'$.

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. $K \cong A, G/K \cong B$?
($1 \to H \to G \to G/H \to 1$, 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 $f_1 : G_1 \to G, f_2 : G_2 \to G$ are group homo. $f_1 \times f_2 : G_1 \times G_2 \to G, (a, b) \mapsto f_1(a)f_2(b)$. 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.

<u>Notation</u>: 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 $i_{s_0} : G_{s_0} \to \bigoplus_{s \in \Lambda} G_s, \forall s_0 \in \Lambda$ satisfying the universal property:

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

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

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

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

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 $p_{s_0} : \prod_{s \in \Lambda} G_s \to G_{s_0}, \forall s_0 \in \Lambda$ satifsfying the following universal property:

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

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

- group operaion: $(g_s)_{s \in \Lambda} \cdot (g'_s)_{s \in \Lambda} := (g_s g'_s)_{s \in \Lambda} \in \prod_{s \in \Lambda} G_s$.

- Define φ: 這邊也一個ㄈ圖 which is uniquely defined.

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

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.

<u>Motivation</u>: ζ_m is called an m-th root of unity if $\zeta_m^m = 1$.

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

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

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

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

1.4.2 Rings and fields

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

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

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) $\forall a, b, c \in \mathbb{R}$, $\begin{cases} a(b + c) = ab + ac \\ (b + c)a = ba + ca \end{cases}$

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)

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

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. $\mathbb{Z}\left[\sqrt{2}\right] = \left\{ a + b\sqrt{2} \,\middle|\, a, b \in \mathbb{Z} \right\} \subset \mathbb{R}$.

Def 25. Let R be a ring with 1.

(a) $\forall a \in R, a \neq 0$, a in 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. $aa_i = 1$. $\qquad \square$

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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.

- $f : R_1 \to R_2$ is called a ring homomorphism if $\forall a, b \in R$, $\begin{cases} f(a+b) & = f(a) + f(b) \\ f(ab) & = f(a)f(b) \end{cases}$.

- $\operatorname{Im} f$ 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 $R_1/\ker f \cong \operatorname{Im} f$ (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. $\varphi : \mathbb{Z} \to R$ s.t. $\varphi(1) = 1$.

pf: Let $\varphi : \mathbb{Z} \to R$ is a ring homo. s.t. $\varphi(1) = 1$. Then $\forall n \in \mathbb{Z}, \varphi(n) = \varphi(1) + \cdots + \varphi(1) = n1$. Now $\forall n, m \in \mathbb{Z}, \varphi(n)\varphi(m) = (n1)(m1) = n(m1) = (nm)1$ by the distributive law. So φ 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 $\operatorname{char} R = m$.

Prop 1.4.3.

1. If R is an integral domain, then $\operatorname{char} R = 0$ or p, where p is a prime. (try to prove this)

2. In the case of $\operatorname{char} R = p$, $\forall a, b \in R, (a+b)^p = a^p + b^p$.

   pf:
   $$(a+b)^p = a^p + \binom{p}{1}a^{p-1}b + \cdots + b^p = a^p + b^p$$
   because $p \mid \binom{p}{1} \implies \binom{p}{i}a^{p-i}b^i = 0$. $\square$

Ex 1.4.4. Let F be a field. Show that

1. if $\operatorname{char} F = 0$, then $\mathbb{Q} \hookrightarrow$ subfield of F.

2. if $\operatorname{char} F = p$, 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, $\operatorname{char} F = p$, p is a prime and $\mathbb{Z}/p\mathbb{Z} \hookrightarrow F$.
We have $\mathbb{Z}/p\mathbb{Z} \times F \to F, (r,v) \mapsto rv$. F can be rearded as a vector space over $\mathbb{Z}/p\mathbb{Z}$.
Let $\dim_{\mathbb{Z}/p\mathbb{Z}} F = n$, then $F \cong (\mathbb{Z}/p\mathbb{Z})^n \implies |F| = n$. $\qquad\square$

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 $\operatorname{ord}(b) = h'$, 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 $\gcd(m,p) = 1 \implies \operatorname{ord}\left(a^{p^s}\right) = m$.
Write $h' = qp^r \implies \operatorname{ord}\left(b^q\right) = p^r$.
Since $\gcd(m, p^r) = 1, \operatorname{ord}\left(a^{p^s} b^q\right) = mp^r > mp^s = h$, which is a contradiction. $\qquad\square$

Ex 1.4.5.

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

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 $G \times X \to X$ with $(g, x) \mapsto gx$ s.t.

1. $1x = x$

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

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

pf: Given an action $(g, x) \mapsto gx$, consider $\varphi : G \to S_X$ 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. $\varphi : G \to S_X$, consider $(g, x) \mapsto \varphi(g)(x)$.

- $1x = \varphi(1)(x) = \mathrm{Id}(x) = x$.

- $g_1 g_2 x = \varphi(g_1 g_2)(x) = \varphi(g_1) \circ \varphi(g_2)(x) = g_1(g_2 x)$. $\qquad \square$

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. $\varphi : G \to \mathrm{GL}(V)$.

Eg 1.5.1.
$$\mathbb{Z}/m\mathbb{Z} \to \mathrm{SO}(2), \quad \overline{k} \mapsto \begin{pmatrix} \cos \frac{2k\pi}{m} & -\sin \frac{2k\pi}{m} \\ \sin \frac{2k\pi}{m} & \cos \frac{2k\pi}{m} \end{pmatrix}$$

Eg 1.5.2.
$$S_n \to \mathrm{GL}(n, \mathbb{R}), \quad \sigma \mapsto (\tau_\sigma : e_i \mapsto e_{\sigma(i)})$$

Remark 8.

1. An action $G \times X \to X$ 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. $\varphi : G \to S_X \implies G/\ker \varphi \hookrightarrow S_X$. So $G/\ker \varphi \times X \to X$ is faithful.

4. Let $\mathcal{C}(X) = \{\, f : X \to \mathbb{C} \,\}$. If $G \curvearrowright X$, then $G \curvearrowright \mathcal{C}(X)$ by $G \times \mathcal{C}(X) \to \mathcal{C}(X)$ with $(g, f) \mapsto gf(x) = f(g^{-1}x)$.
   The reason: $(g_1 g_2)f(x) = f((g_1 g_2)^{-1}x) = f(g_2^{-1}g_1^{-1}x) = g_1(g_2 f)(x)$.

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

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

- well-defined and 1-1: $g_1 x = g_2 x \iff g_2^{-1} g_1 x = x \iff g_2^{-1} g_1 \in G_x \iff g_2^{-1} g_1 G_x = G_x \iff g_1 G_x = g_2 G_x$.

- onto: $\forall g \in G, \psi(gx) = gG_x$. $\qquad\square$

1.5.2 Action by left multiplication

- The action $G \times G \to G, \quad (g,x) \mapsto gx$ is associated with $\varphi : G \hookrightarrow S_G$. It is faithful (Cayley theorem) and transitive.

- Let $H \leq G$ and $X := \{\text{left coset of } H\}$. The group action $(g, xH) \mapsto gxH \rightsquigarrow \varphi : G \to S_X$.

$$\ker \varphi = \bigcap_{x \in G} \underbrace{xHx^{-1}}_{\text{a conjugate of } H} \leq H$$

which is the largest normal subgroup in G contained in H.

pf: If $\begin{cases} N \lhd G \\ N \leq H \end{cases}$, $\forall x \in G, xNx^{-1} \leq xHx^{-1} \implies N = N(xx^{-1}) = xNx^{-1} \leq xHx^{-1}$. $\qquad\square$

Prop 1.5.3. Let $H \leq G$ with $[G : H] = p$ being the smallest prime dividing $|G|$. Then $H \lhd G$.

pf: Let $X = \{a_1 H, \ldots, a_p H\}$ (all left coests of H) and $\varphi : G \to S_p$ be the associated group homo. for the group action $(g, a_i H) \mapsto ga_i H$.
By the 1st isom. thm., $G/\ker \varphi \hookrightarrow S_p$.
By Lagrange thm. $|G/\ker \varphi| \,\big|\, |S_p| = p!$ and $|G/\ker \varphi| \,\big|\, |G| \implies |G/\ker \varphi| \,\big|\, p$.
So $|G/\ker \varphi| = 1$ or p.
If $|G/\ker \varphi| = 1 \implies G = \ker \varphi \leq H \lneq G$, which is a contradiction.
So $|G/\ker \varphi| = p \implies [G : \ker \varphi] = p \implies [G : H][H : \ker \varphi] = p \implies [H : \ker \varphi] = 1 \implies H = \ker \varphi \lhd G$. $\qquad\square$

1.5.3 Action by conjugation

- The action $G \times G \to G \quad (g, x) \mapsto gxg^{-1}$ is associated with the group homo. $\varphi : G \to S_G \quad g \mapsto (\tau_g : x \mapsto gxg^{-1})$.
$$\mathrm{Inn}(G) := \{\, \tau_g \mid g \in G \,\}$$

  Fact 1.5.1. τ_g is an automorphism. (isom. $G \to G$)

  So $\varphi : G \twoheadrightarrow \mathrm{Inn}(G) \leq \mathrm{Aut}(G) \leq S_G$.
  $\ker \varphi = \{\, g \in G \mid gxg^{-1} = x \quad \forall x \in G \,\} = Z_G$.
  By the 1st isom. thm., $G/\ker \varphi \cong \mathrm{Inn}(G)$.

  - The conjugacy class: $Gx = \{\, gxg^{-1} \mid g \in G \,\} = \mathrm{Cl}(x)$.
  - The centralizer of x in G: $G_x = \{\, g \in G \mid gxg^{-1} = x \,\} = Z_G(x)$.

  $$|\mathrm{Cl}(x)| = [G : Z_G(x)], \text{ if } |G| < \infty, |G| = |\mathrm{Cl}(x)||Z_G(x)|$$

- For $H \lhd G$, define $G \times H \to H \quad (g, h) \mapsto ghg^{-1}$ with the group homo. $\varphi : G \to \mathrm{Aut}(H)$.

  $$\ker \varphi = \{\, g \in G \mid gxg^{-1} = x \quad \forall x \in H \,\} = Z_G(H) \implies G/Z_G(H) \leq \mathrm{Aut}(H)$$

- The normalizer of H in G: $N_G(H) = \{\, g \in G \mid gHg^{-1} = H \,\}$

1.6   Week 6

1.6.1   Group actions II

Def 32.   Let $G \curvearrowright X$ and $|X| < \infty$. Write $\operatorname{Fix} G := \{\, x \in X \mid gx = x \quad \forall g \in G \,\}$.

- $x \in \operatorname{Fix} G$, $Gx = \{x\}$.

- $x \notin \operatorname{Fix} G$, $|Gx| = [G : G_x]$.

Let $\{G_{x_1}, \ldots, G_{x_n}\}$ be the set of distinct orbits. After rearrangement, assume $x_1, \ldots, x_r \in \operatorname{Fix} G, x_{r+1}, \ldots, x_n \notin \operatorname{Fix} G$. Then

$$|X| = |\operatorname{Fix} G| + \sum_{i=r+1}^{n} [G : G_{x_i}]$$

Theorem 11 (class equation).   Let $|G| < \infty$. Then either $G = Z_G$ or $\exists a_1, \ldots, a_m \in G \setminus Z_G$ s.t.

$$|G| = |Z_G| + \sum_{i=1}^{n} [G : G_{a_i}]$$

pf: Consider the action $(g, x) \mapsto gxg^{-1}$, then

$$\operatorname{Fix} G = \{\, x \in G \mid gxg^{-1} = x \quad \forall g \in G \,\} = Z_G$$

It follows from the above argument. $\qquad \square$

Def 33. G is called a p-group if $|G| = p^n$, where p is a prime, $n \in \mathbb{N}$.

Prop 1.6.1.   If G is a p-group, then $Z_G \neq \{1\}$.

pf: Let $|G| = p^n$. If $G = Z_G$, then done. Otherwise, by the class equation (use action by conjugation), $|G| = |Z_G| + \sum_{i=1}^{n} [G : G_{a_i}], \quad a_i \notin Z_G$.
$G_{a_i} = Z_G(a_i)$, so $a_i \notin Z_G \implies Z_G(a_i) \lneq G \implies p \mid [G : Z_G(a_i)] = \frac{|G|}{|Z_G(a_i)|}$.
So $|Z_G| = |G| - \sum_{i=1}^{n} [G : Z_G(a_i)] \implies p \mid |Z_G| \implies Z_G \neq \{1\}$. $\qquad \square$

Prop 1.6.2.   If $|G| = p^2$, then G is abelian. ($\mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}$ and $\mathbb{Z}/p^2\mathbb{Z}$)

pf: Assume that G is not abelian. By prop 1.6.1, $|Z_G| = p \implies |G/Z_G| = p \implies G/Z_G$ is cyclic $\implies G$ is abelian. (contradiction) $\qquad \square$

Prop 1.6.3.   If $|G| = p^3$ and G is not abelian, then $|Z_G| = p$.
(Abelian: $\mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}, \mathbb{Z}/p^2\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}, \mathbb{Z}/p^3\mathbb{Z}$)

Prop 1.6.4.   Let $|G| = p^n$. Then $\forall 0 \leq k \leq n, \exists G_k \triangleleft G$ s.t. $|G_k| = p^k$ and $G_i \lneq G_{i+1}$.
In general, for a finite group G, $\exists \{1\} = G_r \triangleleft G_{r-1} \triangleleft \cdots \triangleleft G_1 \triangleleft G_0 = G$ s.t. G_i/G_{i+1} is cyclic. we call G a solvable group.

pf: By induction on n, $n = 1$ is trivial. For $n > 1$, assume that the statement a holds for $n - 1$. By prop 1.6.1, $Z_G \neq \{1\}$. $\exists a \in Z_G, a \neq 1$. Let $\operatorname{ord}(a) = p^l$, then $\operatorname{ord}(a^{p^{l-1}}) = p$. $\implies$ in any case, $\exists a \in Z_G$ with $\operatorname{ord}(a) = p$.
Now $|G/\langle a \rangle| = p^{n-1}$, so by induction hypothesis, $\forall 0 \leq k \leq n-1, \exists \overline{G_k} \triangleleft G/\langle a \rangle$ s.t. $|\overline{G_k}| = p^k, \overline{G_i} \lneq \overline{G_{i+1}}$.
By 3rd isom. thm., $\exists G_{k+1} \triangleleft G$ s.t. $\overline{G_k} = G_{k+1}/\langle a \rangle, G_j \lneq G_{j+1}$ and $|G_{k+1}| = p^{k+1}$.
$\qquad \square$

Prop 1.6.5. Let a p-group $G \curvearrowright X$ with $|X| < \infty$. Then $|X| \equiv |\operatorname{Fix} G| \pmod{p}$.

Theorem 12 (Cauchy theorem). Let $p \mid |G|$. Then $\exists a \in G$ s.t. $\operatorname{ord}(a) = p$. Consider

$$X = \{ (a_1, \ldots, a_p) \mid a_i \in G, a_1 a_2 \ldots a_p = 1 \}$$

and the action $\mathbb{Z}/p\mathbb{Z} \times X \to X$:

$$(\overline{k}, (a_1, \ldots, a_p)) \mapsto (a_{k+1}, \ldots, a_p, a_1, \ldots, a_k)$$

(This is well-defined since $ab = 1 \implies ba = 1$ in a group.) We find that $(a_1, \ldots, a_p) \in \operatorname{Fix} \mathbb{Z}/p\mathbb{Z} \iff a_1 = a_2 \ldots = a_p$. By prop 1.6.5, $|\operatorname{Fix} \mathbb{Z}/p\mathbb{Z}| \equiv |X| \pmod{p}$. And $|X| = |G|^{p-1} \equiv 0 \pmod{p}$. Since $(1, \ldots, 1) \in \operatorname{Fix} \mathbb{Z}/p\mathbb{Z}, |\mathbb{Z}/p\mathbb{Z}| \neq 0 \implies |\mathbb{Z}/p\mathbb{Z}| \geq p$.
So $\exists (a, \ldots, a) \in \operatorname{Fix} \mathbb{Z}/p\mathbb{Z} \implies a^p = 1$.

Application: Let $|G| = p^3$ and G be non-abelian (p is odd). By prop 1.6.3, $|G/Z_G| = p^2$. Since G is non-abelian, we have $G/Z_G \cong \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}$. That is, $\forall a \in G, a^p \in Z_G$.
So,
$$\exists \varphi : G \to Z_G \cong C_p \text{ with } \varphi : a \mapsto a^p$$

Since G/Z_G is abelian, $[G, G] \leq Z_G$. And

$$\begin{cases} |[G,G]| \,\big|\, |Z_G| = p \\ G \text{ is non-abelian} \end{cases} \implies [G, G] = Z_G$$

Def 34. $[x, y] = x^{-1} y^{-1} x y \in [G, G], [x, y]^p = 1$.

So $a^p b^p = a^p b^p [b, a]^p$ ... 換換換總共需要 $p(p-1)/2$

$$a^p b^p = (ab)^p [b, a]^{\frac{p(p-1)}{2}} = (ab)^p$$

So φ is a group homo.
Now if $\ker \varphi = G$ ($\forall a \in G, a^p = 1$), i.e. φ is trivial, then φ is useless. Else, $\exists a \in G$ s.t. $\operatorname{ord}(a) = p^2$, then $H = \langle a \rangle \triangleleft G$. ($[G : H] = p$ is the smallest prime dividing $|G|$)
Also, in this case, $\varphi : G \twoheadrightarrow Z_G \implies G/\ker \varphi \cong Z_G$. Let $E = \ker \varphi, |E| = p^2$. By the def. of $\ker \varphi$, $E \cong \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}$.
We find that $H \cap E = \langle a^p \rangle$. Pick $b \in E \setminus H$ and let $K = \langle b \rangle \implies |K| = p, H \cap K = \{1\}, HK = G$.

1.6.2 Semidirect product

Fact 1.6.1. $K \triangleleft G, H \triangleleft G, K \cap H = \{1\} \implies KH = K \times H$
($\forall k \in K, h \in H, khk^{-1}h^{-1} \in H \cap K = \{1\}, \implies kh = hk$)

Fact 1.6.2. Let K, H be two groups, and $G = K \times H \implies K \times \{1\} \triangleleft K \times H, \{1\} \times H \triangleleft K \times H$

Observation 1. $K \leq G, H \triangleleft G, K \cap H = \{1\}$ (K 慘 H 好，簡稱慘好集)
$\implies$ elements in KH has unique representation ? 好事喔
$KH \iff K \times H$ 1-1 corresp, $(kh) \leftrightarrow (k, h)$

Group operation : $\forall k_1, k_2 \in K, h_1, h_2 \in H, (k_1 h_1)(k_2 h_2) = k_1 k_2 (k_2^{-1} h_1 k_2) h_2$
Let $\tau : K \to \operatorname{Aut}(H), k \mapsto (\tau(k) : h \mapsto khk^{-1})$ (類似 $\in \operatorname{Inn}(H)$)

Def 35 (Semi-Direct Product (慘好積)). $K \times_\tau H = \{(k, h) \mid k \in K, h \in H\}$ with group operation : $(k_1, h_1)(k_2, h_2) = (k_1 k_2, \tau(k_2^{-1})(h_1)(h_2))$ where $\tau : K \to \operatorname{Aut}(H)$ (need not to be inner homomorphism)

Properties:

- Associativity: Good, ex

- The identity $= (1, 1)$

- Inverse : $(k, h)^{-1} = (k^{-1}, \tau(k)(h^{-1}))$

- $K \cong K \times \{1\} \leq K \times_\tau H : (k_1, 1)(k_2, 1) = (k_1 k_2, \tau(k_2^{-1})(1)1) = (k_1 k_2, 1) \in K \times \{1\}$
  $H \cong \{1\} \times H \leq K \times \tau H : (1, h+1), (1, h_2) = (1, \tau(1^{-1})(h_1)h_2) = (1, h_1 h_2) \in \{1\} \times K$

- $H \lhd K \times_t H : (k, h)(1, h')(k, h)^{-1} = (k, hh')(k^{-1}, \tau(k)(h^{-1})) = (1, \tau(k)(hh')\tau(k)(h^{-1})) \in H$

- $\tau(k)(h) = khk^{-1} : (k, 1)(1, h)(k^{-1}, 1) = (k, h)(k^{-1}, 1) = (1, \tau(k)(h))$

- If τ is trivial $\implies K \times_t H \cong K \times H$

Remark 9. Some definition swaps the order of H and K, i.e. $(h_1, k_1)(h_2, k_2) = (h_1 \phi(k_1)(h_2), k_1 k_2)$

Ex 1.6.1. Show that $H \rtimes_\phi K$ is a group and satisfies the above properties.

Eg 1.6.1. Construct a non-abelian group of order 21.

Fact 1.6.3. $\text{Aut}(\mathbb{Z}/p\mathbb{Z}) \cong (\mathbb{Z}/p\mathbb{Z})^\times \cong C_{p-1}$

Sol : $\phi_k : \mathbb{Z}/p\mathbb{Z} \to \mathbb{Z}/p\mathbb{Z}, \bar{1} \mapsto \bar{k}$
$\phi_{k_2} o \phi_{k_1}(T) = \phi_{k_2}(\bar{k_1}) = \phi_{k_2}(T + \cdots + T) = \bar{k_2} + \cdots \bar{k_2} = \overline{k_1 k_2}$
Let $K = C_3, H = C_7$, define $\tau : C_3 \to \text{Aut}(C_7) \cong C_6, a \mapsto \phi_2$
$\phi_k : b \mapsto b^k$
$G = \langle a, b | a^3 = 1, b^7 = 1, aba^{-1} = b^2 \rangle$

Eg 1.6.2. p : odd, $|G| = p^3$, G is non-abelian.

(sol) $\phi : G \to Z(G), a \mapsto a^p$ non trivial case $\exists a \in G$ with $\text{ord}(a) = p^2$. Let $H = \langle a \rangle$ here ϕ is onto and $E = \ker \phi \cong \mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}$ And $|H \cap E| = p$ $H \lhd G$ because $[G : H] = p$ Pick $b \in E \setminus H$ and let $K = \langle b \rangle \implies |K| = p, K \cap H = \{1\}$ so $|G| = |KH| = p^3$

Fact 1.6.4. $\text{Aut}(\mathbb{Z}/p^2\mathbb{Z}) \cong (\mathbb{Z}/p^2\mathbb{Z})^\times$

Sol : $\phi_k : \mathbb{Z}/p^2\mathbb{Z} \to \mathbb{Z}/p^2\mathbb{Z}, \bar{1} \mapsto \bar{k}, \gcd(k, p) = 1$
Find a group homo $\tau : K \implies \text{Aut}(H)$ because $(1 + p)^p \equiv 1 \mod p^2$, $\text{ord}(\overline{1+p}) \in \mathbb{Z}/p^2\mathbb{Z}$ Let $P = \langle \overline{1+p} \rangle$ is the only subgroup of order p. (if $\exists |Q| = p, P \neq Q$ then $P \cap Q = 1, |PQ| = p^2$, miserable.) So let $\tau : b \mapsto (\phi_{1+p} : a \mapsto a^{1+p})$ so $G = \langle a, b | a^{p^2} = 1, b^p = 1, bab^{-1} = a^{1+p} \rangle$ is a non-abelian group of order p^3.

Eg 1.6.3. Isometry of R^n

Def 36 (Isometry). An isometry of R^n is a function $h : R^n \to R^n$ that preserves the distance between vectors.

$h = t \circ k$ where t is translation, k is an isometry fixing the origin, i.e. $k \in O(n)$. Let T be the group of translations on R^n, $T \cong (R^n, +, 0), t \mapsto t(0)$.
Let $\tau : O(n) \to \text{Aut}(T), A \mapsto L_A : R^n \to R^n, v \mapsto Av$
$\implies \text{Isom}(R^n) = O(n) \times_\tau R^n$

Eg 1.6.4. Quaternium $Q_8 = \{\pm 1, \pm i, \pm j, \pm k\}$ is not a semi-deriect product of any two proper subgroups.

pf: since $\{\pm 1\}$ is contained in any non-trivial subgroups, can't find $H \cap K = \{1\}$.

Eg 1.6.5. $A_4, V_4 = \{1, (12)(34), (14)(23), (13)(24)\} \lhd A_4, V_4 \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2\mathbb{Z}$

Let $H = \langle (123) \rangle \cong C_3$, define $\tau : H \to \text{Aut}(V_4) \cong GL_2(\mathbb{Z}/2\mathbb{Z})$ $(123) \mapsto (\overline{01}; \overline{11})$ so $A_4 \cong C_3 \times_\tau V_4$.

Ex 1.6.2. Construct D_n as a semi-direct product of $\mathbb{Z}/n\mathbb{Z}$ and $\mathbb{Z}/2\mathbb{Z}$.

Ex 1.6.3.

1. Show that S_4 is a semi-direct product of V_4 and $H = \{\, \sigma \in S_4 | \sigma(4) = 4 \,\} \sim S_3$.

2. Show that S_n is a semi-direct product of A_n and $H = \langle (12) \rangle$.

Remark 10.

- $\text{Aut}(\mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}) \cong GL_2(\mathbb{Z}/p\mathbb{Z})$ (regarded as a vector space over $\mathbb{Z}/p\mathbb{Z}$)

- $\text{Aut}(\mathbb{Z}/p\mathbb{Z} \times \mathbb{Z}/p\mathbb{Z}) \cong \text{Aut}(\mathbb{Z}/p\mathbb{Z}) \times \text{Aut}(\mathbb{Z}/q\mathbb{Z}) \cong C_{p-1} \times C_{q-1}$

1.7 Week 7

1.7.1 Composition series

Ques: How to simplify a finite group G?
Strategy:

- If $G = \{1\}$, then done.

- Otherwise, check whether G has a nontrivial proper normal subgroup.

- If no, then G is said to be a simple group.

- Otherwise, find a normal subgroup G_1 as large as possible s.t. G/G_1 is simple.

- If G_1 is simple, then done.

- Otherwse, repeat above on G_1 and get $G_2, \ldots, G_n$ s.t.

$$G_n = \{1\} \lhd G_1 \lhd \cdots \lhd G_1 \lhd G_0 = G \quad G_i/G_{i+1} \text{ is simple}$$

$$\searrow \text{ composition factors}$$

   Say "it is a composition series" with $\text{length}(G) = n$.

Hence simple groups can be regarded as basic building blocks of groups.
The classification of all finite simple groups is given as follows:

1. $\mathbb{Z}/p\mathbb{Z}$, p is a prime.

2. $A_n, n \geq 5$.

3. simple groups of Lie type.

4. 26 sporadic simple groups.

Eg 1.7.1. $G = S_4, G_1 = A_4, G_2 = V_4, G_3 = \langle (1\ 2)(3\ 4) \rangle, G_4 = \{1\} \rightsquigarrow \text{length}(S_4) = 4$.
factors: C_2, C_3, C_2, C_2.

Eg 1.7.2. $G = \mathbb{Z}/12\mathbb{Z} = \langle \bar{1} \rangle$.

- $G_1 = \langle \bar{2} \rangle, G_2 = \langle \bar{4} \rangle, G_3 = \langle \bar{0} \rangle \rightsquigarrow \text{length}(3)$, factors: C_2, C_2, C_3.

- $G_1' = \langle \bar{2} \rangle, G_2' = \langle \bar{6} \rangle, G_3' = \langle \bar{0} \rangle \rightsquigarrow \text{length}(3)$, factors: C_2, C_3, C_2.

- $G_1'' = \langle \bar{3} \rangle, G_2'' = \langle \bar{6} \rangle, G_3'' = \langle \bar{0} \rangle \rightsquigarrow \text{length}(3)$, factors: C_3, C_2, C_2.

Eg 1.7.3. Let $|G| = p^n$. We know $\forall 0 \leq k \leq n, \exists G_k \lhd G$ with $|G_k| = p^k$ and $G_i \lneq G_{i+1}$.
$\text{length}(G) = n$, factors: $C_p, \ldots, C_p$. (n times)

Theorem 13 (Jorden-Hölder theorem). If G has a composition series, then any two composition series have the same length and the same factors up to permutation.

Lemma 1 (Zassenhaus lemma). Let $H' \lhd H \leq G, K' \lhd K \leq G$. Then $(H \cap K')H' \lhd (H \cap K)H', (H' \cap K)K' \lhd (H \cap K)K'$ and

$$(H \cap K)H'/(H \cap K')H' \cong (H \cap K)K'/(H' \cap K)K'.$$

Theorem 14 (Schreier theorem). Any two normal series of G have equivalent refinements.
refinements: inserting a finite number of subgroups into the normal series.

pf: For two normal series:

$$\{1\} = H_r \lhd H_{r-1} \lhd \cdots \lhd H_1 \lhd H_0 = G$$
$$\{1\} = K_s \lhd K_{r-1} \lhd \cdots \lhd K_1 \lhd K_0 = G$$

We define

$$H_{ij} = (H_i \cap K_j)H_{i+1}$$
$$K_{ji} = (H_i \cap K_j)K_{j+1}.$$

Then we have

$$\{1\} = H_{(r-1)s} \lhd H_{(r-1)(s-1)} \lhd \cdots \lhd H_{(r-1)0} = H_{r-1} = H_{(r-2)s} \lhd \cdots \lhd H_{10} = H_1 = H_{0s} \lhd \cdots \lhd H_{00} = G$$
$$\{1\} = K_{(s-1)r} \lhd K_{(s-1)(r-1)} \lhd \cdots \lhd K_{(s-1)0} = K_{s-1} = K_{(s-2)r} \lhd \cdots \lhd K_{10} = K_1 = K_{0r} \lhd \cdots \lhd K_{00} = G$$

Both have size $= rs$. By lemma, $H_{ij}/H_{i(j+1)} \cong K_{ji}/K_{j(i+1)}$. Note that if $H_{ij} = H_{i(j+1)}$, then $K_{ji} = K_{j(i+1)}$. $\hfill\square$

proof of Jorden-Hölder theorem. Let

$$\begin{cases} \{1\} = G_n \lhd \cdots \lhd G_1 \lhd G_0 = G & (*) \\ \{1\} = G'_m \lhd \cdots \lhd G'_1 \lhd G'_0 = G & (**) \end{cases}$$

be two composition series.
By Schreier theorem, we get two refined equivalent series $(*)', (**)'$. Since $(*), (**)$ are already composition series, $(*) = (*)', (**) = (**)'$ So $(*), (**)$ are equivalent. $\hfill\square$

proof of lemma. First prove $(H \cap K')H' \lhd (H \cap K)H'$.

- $\forall g \in H \cap K, gK'g^{-1} = K' \rightsquigarrow (gHg^{-1}) \cap (gK'g^{-1} = H \cap K'$ and $gH'g^{-1} = H'$. So

$$g(H \cap K')H'g^{-1} = (H \cap K')H'$$

- $\forall g \in H', ab \in (H \cap K')H',$

To prove
$$(H \cap K)H'/(H \cap K')H' \cong (H \cap K)K'/(H' \cap K)K'.$$

$$\begin{aligned} (H \cap K)H'/(H \cap K')H' &\cong (H \cap K)(H \cap K')H'/(H \cap K')H' \\ &\cong (H \cap K)/(H \cap K) \cap (H \cap K')H' \\ &\cong (H \cap K)/K \cap (H \cap K')H' \\ &\cong (H \cap K)/(H' \cap K)(H \cap K') \end{aligned}$$

$(K \cap (H \cap K')H' = (H' \cap K)(H \cap K')$, tricky) By symmetry,

$$(H \cap K)K'/(H' \cap K')K' \cong (H \cap K)/(H' \cap K)(H \cap K')$$

$\hfill\square$

Prop 1.7.1. Let $|G| < \infty$. Then G is solvable $\iff$ all composition factors are cyclic of prime order.

pf: "$\Leftarrow$": by def.
"$\Rightarrow$": If $G_i/G_{i+1} \cong C_n$ with $n = p_1^{m_1}p_2^{m_2}\ldots p_r^{m_r}$. $\hfill\square$

Observation. Let $K \lhd G$. 把 $K, G/K$ 拆成兩個 composition series 的話, 就可以把兩串接起來, 長度就是加起來。

Ex 1.7.1. Let $\{1\} = G_n \lhd G_{n-1} \lhd \cdots \lhd G_1 \lhd G_0 = G$ be a composition series of G and $K \lhd G$. Then after we eliminate equalities,

1. $\{1\} = (K \cap G_n) \lhd (K \cap G_{n-1}) \lhd \cdots \lhd (K \cap G_1) \lhd (K \cap G_0) = K$ is a composition series of K.

2. $\{\bar{1}\} = KG_n/K \lhd KG_{n-1}/K \lhd \cdots \lhd KG_1/K \lhd KG_0/K = G/K$ is a composition series of G/K.

Ex 1.7.2. Let $\begin{cases} H \lhd G \\ K \lhd G \end{cases}$ with $H \neq K$ s.t. $G/H, G/K$ are simple. Then $H/H \cap K, K/K \cap H$ are simple too.

Ex 1.7.3. Let $\{1\} = G_n \lhd G_{n-1} \lhd \cdots \lhd G_1 \lhd G_0 = G$ be a composition series of length n. Show by induction on n that for every composition series of G:

$$\{1\} = H_m \lhd H_{n-1} \lhd \cdots \lhd H_1 \lhd H_0 = G,$$

we have $m = n$ and

$$\{H_{n-1}/H_n, \ldots, H_0/H_1\} = \{G_{n-1}/G_n, \ldots, G_0/G_1\}$$

Ex 1.7.4. Exhibit all composition series for $Q_8, D_4, \mathbb{Z}/8\mathbb{Z}, \mathbb{Z}/4\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}, \mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z} \oplus \mathbb{Z}/2\mathbb{Z}$ respectively.

1.7.2 Modules over a PID

Def 37. Let R be a ring with 1. A R-moduule is an abelian group M (wriiten additively) on which R acts linearly. $R \times M \to M \quad (r, x) \mapsto rx$

1. $r(x + y) = rx + ry \quad r \in R, x, y \in M$

2. $(r_1 + r_2)x = r_1 x + r_2 x \quad r_1, r_2 \in R, x \in M$

3. $(r_1 r_2)x = r_1(r_2 x) \quad r_1, r_2 \in R, x \in M$

4. $1x = x \quad x \in M$

Eg 1.7.4. A k-vector space is a k-module.

Eg 1.7.5. An abelian group G can be regarded as a $\mathbb{Z}$-module.

$$\begin{array}{c} \mathbb{Z} \times G \to G \\ (n, a) \mapsto na \end{array} \quad \text{by} \quad na = \begin{cases} \underbrace{a + \cdots + a}_{n \text{ times}} & \text{if } n \geq 0 \\ \underbrace{(-a) + \cdots + (-a)}_{n \text{ times}} & \text{if } n < 0 \end{cases}$$

Eg 1.7.6. Let I be an ideal of R. Then I can be regarded as an R-module since $\forall r \in R, a \in I, \quad ra \in I$.

Def 38. A submodule N of M is an additive subgroup of M s.t. $\forall r \in R, a \in N, \quad ra \in N$.

Prop 1.7.2. Let $\phi \neq S \subseteq M$. The submodule generated by S is defined to be

$$\langle S \rangle_R = \left\{ \sum_{\text{finite}} r_i x_i \,\middle|\, x_i \in S, r_i \in R \right\} = \text{the least submodule containg } S$$

$$= \bigcap_{S \subset N \subset M} N$$

Def 39. An R-module M is said to be finitely generated if $\exists x_1, \ldots, x_n \in M$ s.t. $M = \langle x_1, \ldots, x_n \rangle_R = Rx_1 + Rx_2 + \ldots Rx_n$

Eg 1.7.7. R is generated by 1 as an R-module.

Def 40. An additive group homo. $\varphi : M_1 \to M_2$ is called an R-module homo. if
$$\varphi(rx) = r\varphi(x) \quad \forall r \in R, x \in M_1$$

Def 41. An integral domain R is called a principal ideal domain (PID) if $\forall I$ ieal in R, $\exists a \in R$ s.t. $I = \langle a \rangle_R$.

Eg 1.7.8. $\mathbb{Z}$ is a PID.
For $I \subseteq \mathbb{Z}$, I is an additive subgroup, so $I = m\mathbb{Z} = \langle m \rangle_{\mathbb{Z}}$.

Def 42. M is said to be a free module of rank n if $M \cong R^n = R \oplus \cdots \oplus R$ (or $R \times \cdots \times R$)

Theorem 15. If R is a PID, then any submodule of R^n is free of rank $\leq n$.

pf: By induction on n, $n = 1$, $\forall I \subseteq R, \exists a \in R$ s.t. $I = \langle a \rangle_R = Ra \cong R$ (**as a R-module**).
Let $n > 1$ and N be a submodule of R^n. Consider
$$\pi_1 : \begin{matrix} R^n & \to R \\ (r_1, \ldots, r_n) & \mapsto r_1 \end{matrix} \quad \text{and} \quad \pi = \pi_1\Big|_N : N \to R$$

case 1: $\operatorname{Im} \pi = \{0\}$. In this case, $N \subseteq \ker \pi_1 \cong R^{n-1}$. By induction hypothesis, N is free of rank $\leq n - 1 < n$.

case 2: $\operatorname{Im} \pi = \langle a \rangle$, say $\pi(x) = a$. Claim: $N = Rx \oplus \ker \pi, \ker \pi \subseteq \ker \pi_1 \cong R^{n-1}$.

- $Rx \cap \ker \pi = \{0\}$: $rx \in Rx \cap \ker \pi \implies \pi(rx) = 0 \implies r = 0 \implies rx = 0$
- $\forall y \in N, \pi(y) = r_0 a$ for some $r_0 \in R$, $\pi(y - r_0 x) = 0 \implies y - r_0 x \in \ker \pi$. So $N \subseteq Rx \oplus \ker \pi$. $\qquad\square$

Recall that the elementary matrices are

- $D_i(u) = \operatorname{diag}(1, \ldots, 1, u, 1, \ldots, 1)$. $D_i(u) \in \operatorname{GL}(n, R)$ if u is a unit.
- $B_{ij}(a) = I_n + ae_{ij}, a \in R, i \neq j$. $B_{ij}(a)^{-1} = B_{ij}(-a) \implies B_{ij}(a) \in \operatorname{GL}(n, R)$.
- $P_{ij} = I_n - e_{ii} - e_{jj} + e_{ij} + e_{ji}$.

Fact 1.7.1. If R is a PID and $\langle a, b \rangle_R = \langle d \rangle_R$, then $d = \gcd(a, b)$.

pf:

- $a \in \langle d \rangle_R \implies a = rd$ for some $r \in R \implies d \mid a$. $v \in \langle d \rangle_R \implies d \mid b$.
- Let $c \mid a, c \mid b$, say $a = k_1 c, b = k_2 c$. $d \in \langle a, b \rangle_R \implies d = x_1 a + x_2 b$ for some $x_1, x_2 \in R$. So $d = x_1 k_1 c + x_2 k_2 c = (x_1 k_1 + x_2 k_2)c \implies c \mid d$. $\qquad\square$

Theorem 16. Let R be a PID and $A \in M_{n \times m}(R)$. Then $\exists P \in \operatorname{GL}_n(R)$ and $Q \in \operatorname{GL}_m(R)$ s.t.

$$PAQ = \begin{pmatrix} d_1 & & & & & & \\ & d_2 & & & & & \\ & & \ddots & & & & \\ & & & d_r & & & \\ & & & & 0 & & \\ & & & & & \ddots & \\ & & & & & & 0 \end{pmatrix} \quad \text{with} \quad d_i \mid d_{i+1} \quad \forall i = 1, \ldots, r - 1$$

pf: Define the length $l(a)$ of $a \neq 0$ to be r if $a = p_1 p_2 \dots p_r$ where $p_1, \dots, p_r$ are prime elements. prime elements: $p \mid ab \implies p \mid a$ or $p \mid b$.

1. We may assume $a_{11} \neq 0$ and $l(a_{11}) \leq l(a_{ij}) \forall a_{ij} \neq 0$. (換一換就上去了...XD)

2. We may assume $\begin{cases} a_{11} \mid a_{1k} & \forall k = 2, \dots, m \\ a_{11} \mid a_{k1} & \forall k = 2, \dots, n \end{cases}$. If $a_{11} \nmid a_{1k}$, then we can interchange 2nd and kth columns to assume $a = a_{11} \nmid a_{12} = b$.

   Let $d = \gcd(a, b) \implies \begin{cases} l(d) < l(a) \\ d = ax + by \text{ for some } x, y \in R \end{cases} \implies 1 = \frac{a}{d}x + \frac{b}{d}y$. Write $b' = \frac{b}{d}, a' = -\frac{a}{d}$. Then

   $$\begin{pmatrix} -a' & b' \\ y & -x \end{pmatrix} \begin{pmatrix} x & b' \\ y & a' \end{pmatrix} = I_2$$

   反正就是移一下減掉，length 會一直變小 $\implies$ 這個操作會停.

3. 有這個 $\begin{cases} a_{11} \mid a_{1k} & \forall k = 2, \dots, m \\ a_{11} \mid a_{k1} & \forall k = 2, \dots, n \end{cases}$ 就可以全部消掉變成

   $$\begin{pmatrix} a_{11} & 0 & \dots & 0 \\ 0 & b_{22} & \dots & b_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & b_{n2} & \dots & b_{nm} \end{pmatrix}$$

4. May assume $a_{11} \mid b_{kl}$ $\forall k, l$. 不是的話就把該 row 往第一 row 加上去，重複前面的操作，$l(a_{11})$ 總是變小，因此會停.

5. 遞迴下去...

最後就弄出想要的矩陣了. $\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ $\square$