

Algebra (Honor Track)

Spring 2024

Commutative Algebra

Notes

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PERSONAL USE

<https://github.com/flaricy/algebra-notes>

The author hopes to take notes while learning abstract algebra. Reference books are *Introduction to communitative algebra* by Atiyah, Michael. Starts from Feb 21st, 2024.



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1. Group Theory

1.1 Groups and subgroups

Definition 1.1.1 — direct product. Let $(G, *)$ and (H, \circ) be groups, then we may form a new group structure on $G \times H$ with group operation given by

$$(g, h) \star (g', h') = (g * g', h \circ h')$$

This is called the **direct product** of G and H.

1.1.1 Important Examples of Groups

Definition 1.1.2 — Dihedral groups 二面体群.

D_{2n} = symmetric group of a regular n-gon

It can be rewritten as

$$D_{2n} = \langle r, s | r^n = 1, s^2 = 1, rsr = s^{-1} \rangle$$

Definition 1.1.3 — Permutation Groups. Let Ω be a set. The set

$$S_\Omega = \{\text{bijections } \sigma : \Omega \xrightarrow{\sim} \Omega\}$$

admits a group structure:

- the group operation is composition
- the identity element is *id*
- the inverse of the element σ is the inverse map.

This S_Ω is called the symmetry group or the permutation group of Ω . When $\Omega = \{1, 2, \dots, n\}$, we write S_n instead.

Definition 1.1.4 — cyclic groups. A group H is called cyclic if it can be generated by one element x , i.e.

$$H = \langle x \rangle$$

Lemma 1.1.1 There are 2 kinds of cyclic groups up to isomorphism.

- (1) $H \cong \mathbf{Z}_n$
- (2) $H \cong \mathbf{Z}$

Definition 1.1.5 — The quaternion group.

$$Q_8 = \{1, -1, i, -i, j, -j, k, -k\}$$

1.1.2 exercises

■ **Example 1.1** suppose G is cyclic.

- (1) Any subgroup of G is cyclic.
- (2) If $|G| = \infty$, then all the subgroups but $\{e\}$ have order of infinity.
- (3) If $|G| = n$, then the order of subgroup is a factor of n . For every $d|n$, G has only one d -ordered group.

■ **Example 1.2** G is a group. $\forall x \in G, x^2 = 1$. Then G is abelian.

④ If G has an element with order ≥ 3 , then there exists $a \neq b, a, b \neq 1$ such that $ab = ba$.

1.2 cosets, Lagrange theorem, quotient groups

1.2.1 Conjugation, normal subgroups, and quotient groups.

Definition 1.2.1 — conjugate. Let $a, g \in G$, then gag^{-1} is called the **conjugate of a by g** .

Definition 1.2.2 — 定义-命题. If H is a subgroup of G and $g \in G$, then $gHg^{-1} := \{ghg^{-1} | h \in H\}$ is a subgroup, called the conjugate of H by g

Proof. We just need to verify that $\forall a, b \in H, gag^{-1} \cdot (gbg^{-1})^{-1} \in gHg^{-1}$. ■

Definition 1.2.3 — normal subgroup. If $H \leq G$ and all conjugates of H is H itself, we denote $H \trianglelefteq G$. Note that this condition is also equivalent to $gH = Hg$ (as subsets) for any $g \in G$.

Definition 1.2.4 — quotient group. Let $H \trianglelefteq G$, then $\forall a, b \in G$, we define

$$aH \cdot bH := \{kl | k \in aH, l \in bH\} = abH$$

as subsets of G . This defines a group structure on G/H , called the **quotient group** or the **factor group** of G by H .

1.2.2 Some Technical Results

Proposition 1.2.1 Let H and K be subgroups of a group G . Define $HK = \{hk | h \in H, k \in K\}$. When G is finite, we have

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

Proof. to be written ■

The following lemmas tells when HK is a (normal) subgroup.

Lemma 1.2.2 Let H and K be subgroups of G . If $HK = KH$ as sets, then HK is a subgroup of G . In particular, if K is a normal subgroup, then $hK = Kh$ for any $h \in H$, and thus $HK = KH$ is a subgroup of G .

Proof. We need to verify that $\forall h_1k_1 \cdot (h_2k_2)^{-1} = h_1k_1k_2^{-1}h_2^{-1} \in HK$. Since $h_1(k_1k_2^{-1}) \in HK = KH$, there exists h, k such that $h_1k_1k_2^{-1} = kh$. Then $khk^{-1}h^{-1} \in KH = HK$. ■

Lemma 1.2.3 If H, K are both normal subgroups of G , then HK is also a normal subgroup of G .

Proof. $\forall g \in G$, we have $gHK = HgK = HKg$. ■

1.2.3 homomorphism

Definition 1.2.5 — Kernel as a group homomorphism. For a homomorphism $\phi : G \rightarrow H$ of groups, the **kernel** is

$$\ker \phi = \{g \in G | \phi(g) = e_H\}$$

Lemma 1.2.4 Let $\phi : G \rightarrow H$ be a group homomorphism.

- (1) The image $\phi(G)$ is a subgroup of H .
- (2) The kernel $\ker \phi$ is a normal subgroup of G .

Proof. (1) It follows from that $\phi(g_1)\phi(g_2)^{-1} = \phi(g_1g_2^{-1}) \in \phi(G)$

(2) If $g_1, g_2 \in \ker \phi$, then

$$\phi(g_1g_2^{-1}) = e_H e_H^{-1} = e_H$$

For any $g' \in G$, and any $g \in \ker \phi$,

$$\phi(g'gg'^{-1}) = \phi(g')e_H\phi(g')^{-1} = e_H$$

■

Lemma 1.2.5 A homomorphism $\phi : G \rightarrow H$ of groups is injective if and only if $\ker \phi = \{e_G\}$.

1.3 isomorphism theorems, composition series, statement of Holder Theorem

1.3.1 isomorphism theorems

Theorem 1.3.1 — The first isomorphism theorem. If $\phi : G \rightarrow H$ is a homomorphism of groups,

then $\ker \phi \trianglelefteq G$ and

$$G/\ker \phi \cong \phi(G)$$

Theorem 1.3.2 — The second homomorphism theorem. Let G be a group, and let $A \leq G$ be a subgroup and $B \trianglelefteq G$ a normal subgroup. Then AB is a subgroup of G , $B \trianglelefteq AB$, $A \cap B \trianglelefteq A$, and

$$AB/B \cong A/(A \cap B)$$

Proof. By lemma 1.2.2 we know AB is a subgroup of G .

For any $ab \in AB$, since B is normal to G , $abB = aB = Ba$ and $aB = aBb = Bab$. So $B \trianglelefteq AB$.

It is clear that $A \cap B \leq A$. For any $a \in A, x \in A \cap B$, we have $axa^{-1} \in B$, since B is normal. Also $axa^{-1} \in A$, since $x \in A$. So $A \cap B \trianglelefteq A$.

To show the isomorphism, we define $\phi : AB \rightarrow A/(A \cap B)$ by $\phi(ab) = a(A \cap B)$. It's easy to verify that ϕ is well-defined, surjective and a homomorphism, with $\ker \phi = B$. By Theorem 1.3.1, we know the statement is true.

$$\begin{array}{ccc} AB & \xrightarrow{\phi} & A/(A \cap B) \\ & \searrow q & \nearrow f \\ & AB/B & \end{array}$$

■

Theorem 1.3.3 — The third isomorphism theorem. Let G be a group and H, K be normal subgroups with $H \leq K$. Then $K/H \trianglelefteq G/H$, and

$$(G/H)/(K/H) \cong G/K$$

Proof. Consider the map

$$\phi : G/H \longrightarrow G/K$$

$$gH \longmapsto gK$$

- ϕ is well-defined. We can simply redefine ϕ as $\phi(gH) = gH \cdot K = gK$ as product of subsets of G .
- ϕ is homomorphism. Easy to verify.
- ϕ is surjective.
- $\ker \phi = \{gH \mid gK = K\} = \{gH \mid g \in K\} = K/H$. So $K/H \trianglelefteq G/H$. And by the first isomorphism theorem, we statement holds.

■

Theorem 1.3.4 — The fourth isomorphism theorem/ Lattice isomorphism theorem. Let G be a group and $N \trianglelefteq G$. Then there is a bijection

$$\{\text{subgroups of } G \text{ containing } N\} \longleftrightarrow \{\text{subgroups of } G/N\}$$

$$A \longleftrightarrow A/N$$

$$\pi^{-1}(A) \longleftrightarrow A$$

where $\pi : G \rightarrow G/N$ is the natural projection.

This bijection preserves

- inclusion of groups
- intersections
- normality of subgroups
- quotients of subgroups

Visually, we have: Lattice of subgroups of G containing $N \iff$ Lattice of subgroups of G/N .

1.4 Lattice

Definition 1.4.1 Let (S, \leq) be a set equipped with a partial order. (S, \leq) is called a *Lattice* if any $x, y \in S$, $\{x, y\}$ has a maximal lower bound and a minimal upper bound. The lower bound is denoted by $x \wedge y$, while the upper bound is denoted by $x \vee y$.

■ **Example 1.3** 设 n 为正整数, A_n 为 n 的所有正因数的集合, 则 A_n 关于整除关系构成格。

■

■ **Example 1.4** 设 $P(B)$ 为 B 的幂集, 则 $P(B)$ 关于包含关系 \subseteq 构成格, 称为幂集格。 ■

■ **Example 1.5 — 子群格.** 群 G 的所有子群, 关于包含关系。 ■

1.5 composition series, Jordan-Holder Theorem, simplicity of An, direct product groups

Definition 1.5.1 — composition series. In a group G , a series of subgroups

$$\{0\} = N_0 \leq N_1 \leq \dots \leq N_k = G$$

such that $N_{i-1} \trianglelefteq N_i$ and N_i/N_{i-1} is a simple group for $1 \leq i \leq k$ is called **composition series**. In this case, N_i/N_{i-1} is called a **composition factor**.

Definition 1.5.2 — solvable. A group G is called **solvable** if there exists a composition series

$$\{0\} = N_0 \leq N_1 \leq \dots \leq N_k = G$$

such that N_i/N_{i-1} is abelian.

Corollary 1.5.1 a finite group is solvable if and only if all the composition factors are \mathbf{Z}_p .

Theorem 1.5.2 — Jordan-Holder. Let G be a non-trivial group,

(1) G has a composition series.

(2) Assume that a group G has the following two composition series,

$$\{0\} = A_0 \leq A_1 \leq \dots \leq A_m = G, \quad \{0\} = B_0 \leq B_1 \leq \dots \leq B_n = G$$

then $m = n$ and there exists a bijection $\sigma : \{1, 2, \dots, m\} \rightarrow \{1, 2, \dots, n\}$

$$A_{\sigma(i)} / A_{\sigma(i-1)} \cong B_i / B_{i-1}$$

for $i = 1, 2, \dots, m$

Proof. to be written ■

1.5.1 The simplicity of $A_n, n \geq 5$

Proposition 1.5.3

1.6 recognizing direct product, group actions, semi-direct product

1.6.1 recognizing direct products

Theorem 1.6.1 — criterion of direct product group. Suppose G is a group with subgroups H, K such that

(1) H, K are normal.

(2) $H \cap K = \{1\}$

Then $HK \cong H \times K$

Proof. Recall that Lemma 1.2.1 and 1.2.2 ensures that $HK = KH$ are normal subgroup of G . Consider the map

$$\phi : \quad H \times K \longrightarrow HK$$

$$(h, k) \longmapsto hk$$

- ϕ is a homomorphism. $\phi((h_1, k_1)(h_2, k_2)) = \phi((h_1 h_2, k_1 k_2)) = h_1 h_2 k_1 k_2$. It suffices to show that $h_2 k_1 = k_1 h_2$, or $h_2 k_1 h_2^{-1} k_1^{-1} = 1$. Since $h_2 k_1 h_2^{-1} \in K, k_1 h_2^{-1} k_1^{-1} \in H$, we know $h_2 k_1 h_2^{-1} k_1^{-1} \in H \cap K = \{1\}$.
- ϕ is surjective.
- $\ker \phi = \{(h, k) : hk = 1\} = \{(1, 1)\}$.

1.6.2 group actions

Definition 1.6.1 Let G be a group and X a set. A left G -action on X is a map

$$\begin{aligned} G \times X &\rightarrow X \\ (g, x) &\mapsto g \cdot x \end{aligned}$$

satisfying the following conditions:

- (1) for any $x \in X$, $e \cdot x = x$
- (2) for any $g, h \in G$ and $x \in X$, we have

$$g(hx) = (gh)x$$

- ④ for any $g \in G$, the induced $X \rightarrow X$ given by $x \mapsto g \cdot x$ is a bijection. Because the inverse is given by $x \mapsto g^{-1}x$.

Definition 1.6.2 — conjugate action. for $g \in G$, consider

$$\begin{aligned} Ad_g : G &\rightarrow G \\ Ad_g(x) &:= gxg^{-1} \end{aligned}$$

Proposition 1.6.2 Let G be a group acting on a set X . Then we have a natural homomorphism from G to the permutation group of X :

$$\Phi : \quad G \longrightarrow S_X$$

$$g \longmapsto (\phi_g : x \mapsto g \cdot x)$$

In fact, to give a group action is equivalent to give a homomorphism $\Phi : G \rightarrow S_X$.

Proof. $\Phi(gh) = \phi_{gh}$, and $\phi_g \circ \phi_h(x) = g \cdot (h \cdot x) = (gh) \cdot x = \phi_{gh}(x)$. ■

Definition 1.6.3 (1) If the above Φ is injective, we say this action is **faithful**.
 (2) If Φ is trivial, i.e. $\phi_g = id$ for any $g \in G$, we say the action is **trivial**.

Theorem 1.6.3 — Cayley. Every group is isomorphic to a subgroup of some symmetry group. If $|G| = n$, then G is isomorphic to a subgroup of S_n .

Proof. Consider Prop. 1.6.2, it induces a homomorphism (injective) $G \rightarrow S_G$. ■

1.6.3 Automorphism groups

Definition 1.6.4 An **automorphism** of a group G is an isomorphism $\sigma : G \rightarrow G$. Then

$$Aut(G) := \{ \text{automorphisms of } G \}$$

forms a group. It's a subgroup of S_G .

1.6.4 semi-direct products

1.7 Stabilizers, orbits of group actions, class equations

1.7.1 Stabilizers and orbits of group actions

Definition 1.7.1 Let G be a group acting on a set X . For each $x \in X$,

- define the **stabilizer subgroup** at x to be $Stab_G(x) = \{g \in G | g \cdot x = x\}$
- define the **orbit** of x to be $Orb_G(x) = \{g \cdot x | g \in G\} \subseteq X$
- define the **fixed points** of set X to be $X^G = \{x \in X | \forall g, gx = x\}$. Then for any $x \in X^G$, $Stab_G(x) = G$.

Proposition 1.7.1 Let G be a group acting on a set X and $x \in X$.

- (1) $Stab_G(x)$ is a subgroup.
- (2) For $x, y \in X$, either $Orb_G(x) = Orb_G(y)$ or $Orb_G(x) \cap Orb_G(y) = \emptyset$. X is the disjoint union of orbits for the G -action.
- (3) If $y \in Orb_G(x)$, i.e. $y = g \cdot x$ for some $g \in G$, then $Stab_G(y) = g Stab_G(x) g^{-1}$. Namely, the stabilizers at different points of an orbit are conjugate to each other.

Proof. all very trivial. ■

■ **Example 1.6 — conjugacy classes.** Definition 1.6.2 gives a group action of G on itself.

- (1) If G is abelian, the conjugacy class of $a \in G$ is just $\{a\}$.
- (2) For $G = GL_n(\mathbb{C})$, every matrix can be conjugated into a Jordan block.

$\{conjugacy\ classes\ of\ G\} \iff \{Jordan\ canonical\ form\ (with\ nonzero\ eigenvalues\ up\ to\ permutation)\}$

- (3) $G = S_n$, the conjugacy classes are in one-to-one correspondence with partitions of $n = n_1 + n_2 + \dots + n_t$. ■

Definition 1.7.2 — centralizer, center, normalizer. Let G be a group, H a subgroup, and $S \subseteq G$ a subset.

- (1) The subgroup $C_G(S) := \{g \in G | \text{for every } s \in S, gsg^{-1} = s\}$ is called the **centralizer** of S in G
- (2) The subgroup $Z(G) := \{g \in G | \forall h \in G, ghg^{-1} = h\} = C_G(G)$ is called the **center** of G .
- (3) The subgroup $N_G(H) := \{g \in G | gHg^{-1} = H\}$ is called the **normalizer** of H in G .

④ Note that $Z(G)$ is abelian.

Proposition 1.7.2 (1) The Conjugation action induces a homomorphism $Ad : G \rightarrow Aut(G)$. Then $Z(G) = \ker(Ad)$. Thus, $Z(G)$ is a normal subgroup of G .

Proof. $\ker(Ad) = \{g | Ad_g = id\}$ ■

Definition 1.7.3 — G -equivariant. Let G be a group acting on two sets X and Y . We say a map $\phi : X \rightarrow Y$ is G -equivalent if for all $g \in G, x \in X$, we have $\phi(g \cdot x) = g \cdot \phi(x)$.

Definition 1.7.4 — transitive. Let G be a group acting on a set X . We say that the action is **transitive** if for any $x, y \in X$, there exists $g \in G$, such that $x = gy$.

Proposition 1.7.3 If a group G acts transitively on a set X , for every element $x \in X$, put $H = Stab_G(x)$. Then there is a G -equivalent bijection

$$\phi : \quad G/H \xrightarrow{\cong} X$$

$$gH \longrightarrow gx$$

(Here G/H is not a quotient group, but simply equivalence class)

Proof. verify that ϕ is well-defined, bijective, surjective, and preserves group action. ■

Corollary 1.7.4 Let G be a group acting on a set X . For each $x \in X$, G acts transitively on $Orb_G(x)$, thus we have

$$Orb_G(x) \cong G/Stab_G(x)$$

as G —equivalence. And

$$X \cong \bigsqcup_{G\text{-orbits } G \cdot x} G/Stab_G(x)$$

Corollary 1.7.5 If X is a finite set, G is a p -group acting on X , then

$$|X| \equiv |X^G| \pmod{p}$$

Proof. A direct corollary from Corollary 1.7.4. ■

1.7.2 class equations

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Theorem 1.7.6 — class equation. Let G be a finite group (acting on itself by conjugation)

(1) For each $g \in G$, the number of elements in its conjugacy class is

$$|Ad_G(g)| = \frac{|G|}{C_G(g)} = [G : C_G(g)]$$

(2) If g_1, g_2, \dots, g_r are representatives of conjugacy classes of G that are not contained in $Z(G)$, then

$$|G| = |Z(G)| + \sum_{i=1}^r [G : C_G(g_i)]$$

Proposition 1.7.7 For a non-trivial p -group, $Z(G)$ is nontrivial.

1.8 Sylow's Theorem

Definition 1.8.1 For p :prime,

- (1) A p -group is a finite group whose order is a power of p .
- (2) If G is a finite group of order $|G| = p^r m$, and $p \nmid m$, a subgroup H of G of order exactly p_r is called a **Sylow p -subgroup**. write

$$Syl_p(G) := \{ \text{Sylow } p\text{-subgroup of } G \} \quad \text{and} \quad n_p := |Syl_p(G)|$$

Theorem 1.8.1 — Sylow's theorem. Let G be a finite group with $|G| = p_r m, p \nmid m$.

- (First Sylow Theorem) Sylow p -subgroup exists.
- (Second Sylow Theorem) If P is a Sylow p -subgroup, and $Q \leq G$ is of p -power order, then there exists $g \in G$ such that $Q \leq gPg^{-1}$ (note that gPg^{-1} is also a Sylow p -subgroup).
- In other words, we have
 - all Sylow p -subgroups are conjugate.
 - all subgroups of p -power order is contained in a Sylow p -subgroup.
- (Third Sylow Theorem) $n_p = |Syl_p(G)|$ satisfies
 - (1) $n_p \equiv 1 \pmod{p}$
 - (2) $n_p \mid m$

proof of first Sylow Theorem – version 1. Induce on $|G|$. When $|G| = 1$, trivial.

Suppose that the theorem is proved for finite groups of order $< n$. Let G be a finite group of order $n = p^r m, p \nmid m$.

Case 1: If $r = 0$, trivial. Case 2: If $p \mid |Z(G)|$, then $Z(G)$ is a finitely generated abelian group. So

$$Z(G) = \mathbb{Z}_p^{r_1} \times \dots \times \mathbb{Z}_p^{r_s} \times \dots$$

We write $Z(G)_p$ for the p -part of $Z(G)$; then $|Z(G)_p| = p^{r'} \text{ for some } r' \geq 1$.

Consider the quotient homomorphism

$$G \xrightarrow{\pi} G/Z(G)_p =: \bar{G}$$

where the quotient \bar{G} has order $p^{r-r'}m < n$. By inductive hypothesis, \bar{G} contains a Sylow p -subgroup $H := \bar{H}$ of order $p^{r-r'}$. Then $\pi^{-1}(\bar{H})$ is a subgroup of G (By the fourth isomorphism theorem) of order

$$|\bar{H}| \cdot |\ker \pi| = p^r.$$

So H is a Sylow p -subgroup of G .

Case 3: If $p \nmid |Z(G)|$ but $p \mid |G|$.

Then class equation

$$|G| = |Z(G)| + \sum_{i=1}^t [G : C_G(g_i)]$$

follows that there exists some i such that $[G : C_G(g_i)]$ is not divisible by p . Thus $|C_G(g_i)|$ has order $p^r m'$ for some $m' \mid m$ but $m' \neq m$. By inductive hypothesis we know there exists a Sylow p -subgroup H of $C_G(g_i)$, which is also a subgroup of G . ■

- (R) The above proof can be easily modified to show a stronger result:
If $|G| = p^r m$, then for every $0 \leq k \leq r$, there exists some subgroup $H \leq G$, such that $|H| = p^k$.

Now introduce a similar theorem, which is also an application of group action and orbit decomposition.

Theorem 1.8.2 — A. L. Cauchy. G is finite, p is a divisor of $|G|$, then there exists $g \in G$ such that $\text{ord}(g) = p$.

Proof. Let $H = \mathbb{Z}/p\mathbb{Z}$ (note that it's a p-group) acts on the following set

$$X = \{(g_1, \dots, g_p) | g_1 \dots g_p = 1\}$$

Since g_p is uniquely determined by (g_1, \dots, g_{p-1}) , we know $|X| = p^{p-1}$. We define the group action by

$$\bar{k} \cdot (g_1, \dots, g_p) = (g_{1+k}, g_{2+k}, \dots, g_{p+k})$$

The "+" operation in the index is under modulo. The fixed points of X is

$$X^H = \{(g_1, \dots, g_p) \in X | \forall \bar{k}, \bar{k} \cdot (g_1, \dots, g_p) = (g_1, \dots, g_p)\} = \{(g, g, \dots, g) \in X\} = \{(g, \dots, g) | g^p = 1\}$$

Since $(1, \dots, 1) \in X^H$, X^H is not empty.

By Corollary 1.7.5, we know $|X| \equiv |X^H| (\text{mod } p)$, which implies $|X^H| \equiv 0 (\text{mod } p)$. Hence, there exists some $g \in G$, $\text{ord}(g) = p$. ■

We also use group action to prove the second Sylow Theorem.

proof of the second Sylow Theorem. Let $P \leq G$ be a Sylow p-subgroup, $Q \leq G$ a subgroup of p-power order.

When $|Q| = 1$, done.

Now assume $|Q| = p^{r'}$ with $r' \geq 1$. Consider the translation action of Q on G/P

$$Q \curvearrowright G/P$$

by $q \cdot gP := qgP$.

Then we have

$$|G/P| = \sum_{i=1}^t |Q/\text{Stab}_i|$$

Since the left side is not divisible by p , there exists some i such that $[Q : \text{Stab}_i]$ is not divisible by p . Let

$$Q' = \{q \in Q | qgP = gP\} = \text{Stab}_i \leq Q$$

Then $|Q'| = p^{r'} = |Q|$. So $Q' = Q$. For any $q \in Q$, we have $qgP = gP \implies qg \in gP \implies q \in gPg^{-1}$. So we deduce that $Q \leq gPg^{-1}$. ■

Corollary 1.8.3 All Sylow subgroups are conjugate.

Proof. Note that gPg^{-1} is also a Sylow p-subgroup if $P \in Syl_p(G)$. ■

Corollary 1.8.4 $|Syl_p(G)| = 1 \iff$ there is a Sylow p-subgroup P is normal.

Proof. By Corollary 1.7.10, it's trivial. ■

Corollary 1.8.5 If P is a Sylow p-subgroup, then $N_G(N_G(P)) = N_G(P)$, and $N_G(P)$ contains a unique Sylow p-subgroup, which is P .

Proof. Since $P \trianglelefteq N_G(P)$, by Corollary 1.7.11, $N_G(P)$ contains a unique normal Sylow p-subgroup. P is a group, so $N_G(P) \subseteq N_G(N_G(P))$.

For any $g \in G$ such that $gN_G(P)g^{-1} = N_G(P)$, we have $gPg^{-1} \in N_G(P)$ is a Sylow p-subgroup in $N_G(P)$. Thus, $gPg^{-1} = P$, which is equivalent to $g \in N_G(P)$. ■

proof of the third Sylow Theorem. (1) Consider the conjugation action of G on $Syl_p(G)$. By second Sylow theorem we know this action is **transitive** (There is only one orbit). From this, we deduce that for some $P \in Syl_p(G)$

$$n_p = |Syl_p(G)| = \frac{|G|}{|N_G(P)|} = \frac{p^r \cdot m}{p^r \cdot [N_G(P) : P]}$$

Thus, $n_p \mid m$.

(2) Choose any Sylow p-subgroup P . Consider the conjugation action of P on $Syl_p(G)$. Then we have

$$n_p = \sum_{\text{orbits } Ad_P(P_i)} |P/Stab_P(P_i)|$$

If $Stab_P(P_i) \neq P$, then $p \mid |P/Stab_P(P_i)|$.

If $Stab_P(P_i) = P$, then $P \subseteq N_G(P_i)$. By Corollary 1.7.12 we know there is a unique Sylow p-subgroup in $N_G(P_i)$. So $P = P_i$. It follows that $n_p \equiv 1 \pmod{p}$. ■

1.8.1 Applications of Sylow's theorem



2. Rings and Ideals

If not pointed out specifically, the notion "ring" refers to a commutative ring with an identity element.

2.1 rings, ideals, quotient rings

Definition 2.1.1 — ring homomorphism. Let A, B be rings, $f : A \rightarrow B$ is a homomorphism when

(1) $f(x+y) = f(x) + f(y)$. So f is a homomorphism of abelian groups.

(2) $f(xy) = f(x)f(y)$, $f(1) = 1$. So f is a homomorphism between the monoids (A, \cdot) and (B, \cdot) .

Definition 2.1.2 — ideal of a ring. An ideal I of a ring A is an additive subgroup and is such that $AI \subseteq I$.

■ **Example 2.1** Every ring A has 2 trivial ideals: $\{0\}$ and A . ■

Below, I denotes the ideal of ring A .

Definition 2.1.3 — quotient ring. Define multiplication in the quotient group A/I by

$$(a+I) \cdot (b+I) = ab+I$$

It is well defined. Now A/I is made into a ring called the *quotient ring*. The mapping $\phi : A \rightarrow A/I$ which maps each $x \in A$ to its coset $x+I$ is a surjective ring homomorphism.

Proposition 2.1.1 There is a one-to-one order preserving correspondence between

$$\{J | I \subseteq J \subseteq A, J : \text{ideal}\} \xleftarrow{1:1} \{\bar{J} | \text{ideal } \bar{J} \subseteq A/I\}$$

$$J \longmapsto J+I$$

$$\phi^{-1}(\bar{J}) \longleftarrow \bar{J}$$

Proof. First, Let's show that $J + I$ is an ideal in A/I .

$J + I$ is abelian : trivial; $\forall x + I \in A/I, (x + I) \cdot (J + I) = (Jx + I) \subseteq (J + I)$, since J is an ideal.
Second, we can verify this mapping to be invertible. ■

Corollary 2.1.2 If $f : A \rightarrow B$ is any ring homomorphism, the *kernel* of $f (= f^{-1}(0))$ is an ideal of A , and the image of $f (= f(A))$ is a subring C of B , but may not be an ideal.

Proof. Consider the embedding mapping

$$\mathbb{Q} \hookrightarrow \mathbb{Q}[X]$$

The image is absolutely not an ideal. ■

Theorem 2.1.3 — fundamental homomorphism theorem. $f : A \rightarrow B$ is a ring homomorphism, I is the kernel of f , $g(a+I) := f(a)$ then g is a ring isomorphism.

$$\begin{array}{ccccc} A & \xrightarrow{f} & \text{Im}(f) & \hookrightarrow & B \\ & \searrow \phi & \uparrow g & & \\ & & A/I & & \end{array}$$

2.2 Chinese Remainder Theorem

Theorem 2.2.1 Let $N \in \mathbb{N}^+, N = n_1 n_2 \dots n_k$, where $n_i, n_j (i \neq j)$ are coprime. We have

$$\begin{aligned} \phi : \mathbb{Z}/N\mathbb{Z} &\rightarrow \prod_{i=1}^k \mathbb{Z}/n_i\mathbb{Z} \\ [x]_N &\mapsto ([x_i]_{n_i})_{i=1}^k \end{aligned}$$

is an isomorphism of rings.

2.3 zero-divisors, nilpotent elements, units

Definition 2.3.1 — zero-divisor. a zero-divisor in a ring A is an element x for which there exists $y \neq 0$ in A such that $xy = 0$

Definition 2.3.2 — integral domain. a ring with no zero-divisors $\neq 0$ and not a zero ring.

Definition 2.3.3 — nilpotent. An element $x \in A$ is *nilpotent* if $x^n = 0$ for some $n > 0$.

(R) A nilpotent element is a zero-divisor.

Definition 2.3.4 — unit 可逆元. A unit in A is an element x such that $xy = 1$ for some $y \in A$. Note that y is uniquely determined by x , and is written as x^{-1} .

(R) The units in A form a abelian group under multiplication.

Definition 2.3.5 — field. A field is a ring A which $1 \neq 0$ and every non-zero elem. is a unit.

Proposition 2.3.1 Let A be a ring $\neq 0$. The following are equivalent:

- (1) A is a field;
- (2) The only ideals in A are 0 and (1) ;
- (3) Every non-trivial homomorphism of A into a non-zero ring B is injective.

2.4 prime ideals and maximal ideals

Definition 2.4.1 — prime ideal. An ideal \mathfrak{p} in A is *prime* if $\mathfrak{p} \neq (1)$ and if $xy \in \mathfrak{p} \implies x \in \mathfrak{p}$ or $y \in \mathfrak{p}$

Definition 2.4.2 — maximal ideal. An ideal \mathfrak{m} in A is *maximal* if $\mathfrak{m} \neq (1)$ and if there is no ideal α such that $\mathfrak{m} \subset \alpha \subset (1)$ (strict inclusion).

(R) \mathfrak{m} can be $\{0\}$.

Proposition 2.4.1 \mathfrak{p} is prime $\iff A/\mathfrak{p}$ is an integral domain.

Proof. Easy to verify. ■

Proposition 2.4.2 \mathfrak{m} is maximal $\iff A/\mathfrak{m}$ is a field. Hence, a maximal ideal is prime.

Proof. By Proposition 2.1.1 and Proposition 2.2.1, the statement holds. ■

Proposition 2.4.3 If $f : A \rightarrow B$ is a ring homomorphism and q is a prime ideal of B , then $f^{-1}(q)$ is a prime ideal in A .

Proof. If $a, b \in A$ such that $f(a) = f(b) \in q$. Then $f(a - b) = f(a) - f(b) \in q$. Thus, $f^{-1}(q)$ is abelian. For any $a \in f^{-1}(q), x \in A$, we have $f(ax) = f(a)f(x) \in Bq = q$. Thus, $f^{-1}(q)$ is an ideal. For any $a, b \in A, ab \in f^{-1}(q) \iff f(ab) \in q \iff f(a) \cdot f(b) \in q \iff f(a) \in q \vee f(b) \in q \iff a \in f^{-1}(q) \vee b \in f^{-1}(q) \iff f^{-1}(q)$ is a prime ideal. ■

(R) If m is a maximal ideal of B , it is not necessarily true that $f^{-1}(m)$ is maximal in A . Consider $A = \mathbb{Z}, B = \mathbb{Q}, m = \{0\}$.

Theorem 2.4.4 Every ring $A \neq 0$ has at least one maximal ideal.

This theorem relies on Zorn's Lemma. We first introduce it.

Definition 2.4.3 — chain in a partially ordered set. Let S be a non-empty partially ordered set. A subset T of S is a chain if either $x \leq y$ or $y \leq x$ for every pair of elements in T .

Lemma 2.4.5 — Zorn. If every chain T of S has an upper bound in S , then S has at least one maximal element. Zorn's Lemma is equivalent to the axiom of choice.

Proof. Let's prove theorem 2.3.4, using Zorn's Lemma.

Let $\Sigma = \{I : I \text{ is ideal}, I \neq (1)\}$. Order Σ by inclusion. Σ is not empty, since $0 \in \Sigma$. For each chain, consider the union as another ideal $\neq (1)$ to be an upper bound. Then Zorn's lemma yields that there is a maximal element. ■

(R) If A is Noetherian, we can avoid the use of Zorn's lemma.

Corollary 2.4.6 If $a \neq (1)$ is an ideal of A , there exists a maximal ideal of A containing a .

Proof. Replace Σ by $\{I : I \text{ is ideal containing } a, I \neq (1)\}$ in the proof of Theorem 2.3.4 . ■

Corollary 2.4.7 Every non-unit of A is contained in a maximal ideal.

Definition 2.4.4 — local ring, residue field. If a ring A has exactly one maximal ideal m (e.g. fields), then A is called a *local ring*. The field $k = A/m$ is called the residue field of A .

Proposition 2.4.8 Let A be a ring and $m \neq (1)$ an ideal of A such that $\forall x \in A - m$ is a unit in A . Then A is a local ring and m its maximal ideal.

First, we observe the following

Lemma 2.4.9 Every element in a maximal ideal is not a unit.

proof of Proposition 2.3.8. From corollary 2.3.6 and lemma 2.3.9 we know m is a maximal ideal. Also from lemma 2.3.9, we know there doesn't exist other maximal ideals. Thus, A is a local ring. ■

Proposition 2.4.10 Let A be a ring and m a maximal ideal, such that every element of $1 + m$ is a unit in A . Then A is a local ring.

Proof. Make an analogy to Bezout Theorem. Let $x \in A - m$. Since m is maximal, the ideal generated by x and m is (1) , hence there exists $y \in A, t \in m$ such that $xy + t = 1$. Thus $xy = 1 - t \in 1 + m$, which means x is a unit. ■

■ **Example 2.2** $A = F[X_1, \dots, X_n], F : \text{field}$. Let $f \in A$ be an irreducible polynomial. By unique factorization, the ideal (f) is prime. When $n \geq 2$, it's not a *principal ideal domain*. ■

■ **Example 2.3** Every ideal in \mathbf{Z} is of the form (m) for some $m \geq 0$. The ideal is prime $\iff m = 0$ or is a prime number. For all ideals (p) are maximal. ■

Definition 2.4.5 — principal integral domain. an integral domain where every ideal is principal.

Proposition 2.4.11 Every non-zero prime ideal is maximal in principal integral domain.

Hint. The cancellation law applies in the integral domain.

Let (x) be a prime ideal and $(x) \subset (y)$. Then $x = yz$ for some z . since $y \notin (x)$, we know $z \in (x)$. Thus $z = xt$ and $x = ytx$, which implies $yt = 1$, and $(y) = 1$. ■

2.5 nilradical and Jacobson radical

Proposition 2.5.1 The set \mathfrak{N} of all nilpotent elements in a ring A is an ideal, and A/\mathfrak{N} has no nilpotent element $\neq 0$.

Proof. For any $x, y \in \mathfrak{N}$, there exists $n \geq 0$ such that, $(x - y)^n = 0$. Thus, $x - y \in \mathfrak{N}$ and \mathfrak{N} is abelian group. It's easy to show that \mathfrak{N} is an ideal. If there exists $a \in A$, such that $\exists n > 0$, $(a + \mathfrak{N})^n = 0 = a^n + \mathfrak{N}$, then $a \in \mathfrak{N}$. Hence, A/\mathfrak{N} has no non-zero nilpotent element. ■

The ideal \mathfrak{N} is called the *nilradical* of A .

Proposition 2.5.2 The nilradical of A is the intersection of all the prime ideals of A .

Proof. We observe that every nilpotent element belongs to any prime ideal. Hence, $\mathfrak{N} \subseteq \bigcap_{p: \text{prime ideal } p}$. On the other side, for each element within the intersection of all prime ideals, 试图用Zorn's lemma寻找一个极大理想，证明这也是一个prime ideal. 从而non-nilpotent element不属于这个ideal. ■

Definition 2.5.1 — Jacobson radical. The Jacobson radical \mathfrak{N} of A is defined to be the intersection of all the maximal ideals of A .

It can be characterized as

Proposition 2.5.3 $x \in \mathfrak{N} \iff 1 - xy$ is a unit for all $y \in A$.

Proof. \implies : Suppose $1 - xy$ is not a unit. By corollary 2.3.7 it belongs to some maximal ideal m . But $x \in \mathfrak{N} \subseteq m$, hence $xy \in m$ and $1 \in m$, which is absurd.

\impliedby : 考虑Bezout定理。If $x \notin m$ for some maximal ideal m , then $m + (x)$ generate the unit ideal (1) , so that $u + xy = 1$ for some $u \in m, y \in A$. Hence $1 - xy \in m$ is not a unit. ■

2.6 operations on ideals

Definition 2.6.1 — intersection. the ideal $A \cap B$

 The union of A, B is typically not an ideal.

Definition 2.6.2 — sum. the ideal $A + B$

Definition 2.6.3 — product. AB denotes the ideal generated by elements in set AB , i.e. $AB = \{\sum_{\text{finite}} a_i b_i : a_i \in A, b_i \in B\}$

Definition 2.6.4 — coprime. ideals A, B are coprime if $A + B = (1)$.

- (R) different prime ideals are not necessarily coprime. For example, let $A = F[X, Y]$, $p_1 = (X)$, $p_2 = (Y)$.

Definition 2.6.5 Let A be a ring and $\alpha_1, \dots, \alpha_n$ ideals of A . Define a homomorphism

$$\phi : A \rightarrow \prod_{i=1}^n (A/\alpha_i)$$

by the rule $\phi(x) = (x + \alpha_1, \dots, x + \alpha_n)$.

- (R) Let a, b be ideals of ring A , then $ab \subseteq a \cap b$

Proposition 2.6.1 (1) If a_i, a_j are coprime whenever $i \neq j$, then $\prod a_i = \cap a_i$.
 (2) ϕ is surjective $\iff a_i, a_j$ are coprime whenever $i \neq j$.
 (3) ϕ is injective $\iff \cap a_i = (0)$

Proof. The third statement can be shown by $\ker \phi = \cap \alpha_i$ ■

- (R) (2) is the generalized form of Chinese Remainder Theorem.

Proposition 2.6.2 Let p_1, \dots, p_n be prime ideals and let α be an ideal contained in $\cup_{i=1}^n p_i$. Then $\alpha \subseteq p_i$ for some i .

Proof. Prove by induction on n in the form

$$a \not\subseteq p_i (1 \leq i \leq n) \implies a \not\subseteq \cup_{i=1}^n p_i$$

$n = 1$: trivial. If $n > 1$ and the result is true for $n - 1$, then for each i there exists $x_i \in a$ such that $x_i \notin p_j (\forall j \neq i)$. If there is some i such that $x_i \notin p_i$, succeed. If not, then $x_i \in p_i$ for all i , consider

$$y = \sum_{i=1}^n x_1 x_2 \dots x_{i-1} x_{i+1} \dots x_n$$

.

Proposition 2.6.3 Let a_1, \dots, a_n be ideals and p be a prime ideal, $p \supseteq \cap_{i=1}^n a_i$. Then $p \supseteq a_i$ for some i . If $p = \cap a_i$, then $p = a_i$ for some i .

Proof. We observe that if $x, y \notin p$, then $xy \notin p$. ■

Definition 2.6.6 — ideal quotient. If a, b are ideals in a ring A then their *ideal quotient* is

$$(a : b) = \{x \in A : xb \subseteq a\}$$

(R) $(a : b)$ is an ideal.

Definition 2.6.7 — annihilator. $(0 : b)$ is called the *annihilator* of b and denoted by $\text{Ann}(b)$.

2.7 extension and contraction

let $f : A \rightarrow B$ be a ring homomorphism.

Definition 2.7.1 — extension. If a is an ideal in A , we define the *extension* a^e to be the ideal generated by $f(a)$ in B . Explicitly, a^e is the set of all sums $\sum y_i f(x_i)$ where $x_i \in a, y_i \in B$.

Definition 2.7.2 — contraction. If b is an (prime) ideal of B , then $f^{-1}(b)$ is always an (prime) ideal of A , called the *contraction* b^c of b .

To show its correctness, we have the following

Proposition 2.7.1 Let $f : A \rightarrow B$ be a surjective ring homomorphism. There is a one-to-one correspondence between the ideals of $f(A) = B$ and ideals of A which contain $\ker f$, and prime ideals correspond to prime ideals.

$$\{\text{ideals of } A : A \supseteq \ker f\} \xleftarrow{1:1} \{\text{ideals of } B\}$$

$$I \longmapsto f(I)$$

$$f^{-1}(J) \longleftarrow J$$

Proof. We only show that prime-ideal correspondence. If I is prime, for any $f(a), f(b)$ where $a, b \in I$, $f(a)f(b) \in f(I) \iff f(ab) \in f(I) \iff ab \in I \iff a \in I \text{ or } b \in I \iff f(a) \in f(I) \text{ or } f(b) \in f(I)$. Thus, $f(I)$ is prime. The other side is similar. ■

2.8 polynomial rings

Here, we mainly consider integral domain or field to be the ring. We will use the notion of **degree**.

Lemma 2.8.1 Let R be an integral domain. For all non-zero $f, g \in R[X]$ we have $\deg(fg) = \deg f + \deg g$. And $R[X]$ is also an integral domain, with $R[X]^\times = R^\times$.

Now about polynomials over a field F .

Proposition 2.8.2 — 带余除法. For any $a, d \in F[X], d \neq 0$, there exists unique $q, r \in F[X]$ such that $\deg(r) < \deg(d), a = dq + r$. Here, we define $\deg(0) = -\infty$.

Proof. To find r , consider set $\{a - dq : q \in F[X]\}$. There exists element such that $\deg(a - dq)$ is minimal. ■

Definition 2.8.1 — root. For a commutative ring R , $f \in R[X], a \in R$ such that $f(a) = 0$. Then a is called a root of f .

By proposition 2.7.2, we immediately get

Proposition 2.8.3 $f(a) = 0 \iff (X - a)|f$.

As to the number of roots, we have

Proposition 2.8.4 $F : \text{field}, f \in F[X] - \{0\}$, then f has at most $\deg f$ roots in F .

Proof. Use proposition 2.7.3 and induce on the degree of f . ■

Definition 2.8.2 — Fraction Field of an integral domain. Let A be an integral domain, use $\text{Frac}(A)$ to denote ...

With fraction field, we can extend proposition 2.7.4,

Lemma 2.8.5 Let R be an integral domain, $f \in R[X] - \{0\}$, then f has at most $\deg f$ different roots in R .



3. Module Theory