

MATH 417 Lec06-15

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2021

目录

1	Integers	6
1.1	Proposition 1.4.1: Properties of integers \mathbb{Z}	6
1.2	Definition: Divide	6
1.3	Proposition 1.4.2: properties of integer division	6
1.4	Definitions: Prime, The Greatest common divisor $\gcd(a, b)$	6
1.5	Euclidean Algorithm	7
1.6	Proposition: $\gcd(a, b)$ exists and is the smallest positive integer in the set $M = \{ma + nb m, n \in \mathbb{Z}\}$	7
1.7	Well-Ordering Principle (Least Integer Axiom)	8
1.8	Proposition 1.4.10: $\gcd(b, c), b ac \Rightarrow b a$	8
1.8.1	Corollary: $p ab \Rightarrow p a$ or $p b$	8
1.9	Fundamental Theorem of Arithmetic: Any integer $a \geq 2$ has a unique prime factorization	8
1.9.1	Existence	8
1.9.2	Uniqueness	8
2	Modular arithmetic	9
2.1	Congruences	9
2.1.1	Congruent modulo m : $a \equiv b \pmod{m}$	9
2.1.2	Proposition: For fixed $m \geq 2$, the relation " $a \sim b \Leftrightarrow a \equiv b \pmod{m}$ " is an equivalence relation	10
2.1.3	Theorem: the equivalence relation " $a \sim b \Leftrightarrow a \equiv b \pmod{m}$ " partitions the integers into m disjoint sets $\Omega_i = \{a a \sim i\}, i = 0, 1, \dots, m - 1$	10
2.1.4	Proposition: Addition and Multiplication of Congruences	10
2.2	Solving Linear Equations on Modular m	11
2.2.1	Theorem: unique solution of $aX \equiv b \pmod{m}$ if $\gcd(a, m) = 1$	11

2.3	Chinese Remaindar Theorem (CRT): unique solution for x modulo mn	11
2.4	Congruence Classes: $[a]_n = \{a + kn k \in \mathbb{Z}\}$	12
2.4.1	Set of congruence classes of mod n : $\mathbb{Z}_n = \{[a]_n a \in \mathbb{Z}\} = \{[0], [1], \dots, [n-1]\}$. .	12
2.4.2	Proposition 1.5.5: Addition and Multiplication on Congruence Classes	12
2.4.3	Units(i.e. invertible) in Congruence Classes	13
2.4.4	Proposition 1.5.6: Set of units in congruence classes: $\mathbb{Z}_n^\times = \{[a] \in \mathbb{Z}_n [a] \text{ is a unit}\} = \{[a] \in \mathbb{Z}_n \gcd(a, n) = 1\}$	13
2.4.5	Corollary 1.5.7: if p is prime, $\varphi(p) = \mathbb{Z}_p^\times = \{[1], [2], \dots, [p-1]\}$	13
2.5	Euler phi-function: $\varphi(n) = \mathbb{Z}_n^\times $	13
2.5.1	$m n$, $\pi_{m,n}([a]_n) = [a]_m$	13
2.6	Theorem 1.5.8(Chinese Remainder Theorem): $n = mk, \gcd(m, k) = 1$, $F([a]_n) = (\pi_{m,n}([a]_n), \pi_{k,n}([a]_n)) = ([a]_m, [a]_k)$	14
2.6.1	Proposition 1.5.9+Corollary 1.5.10: $m, n, k > 0, n = mk, \gcd(m, k) = 1$, then $F(\mathbb{Z}_n^\times) = \mathbb{Z}_m^\times \times \mathbb{Z}_k^\times$, then $\varphi(n) = \varphi(m)\varphi(k)$	14
2.7	prime factorization: $n = p_1^{r_1} \dots p_k^{r_k}$, then $\varphi(n) = (p_1 - 1)p_1^{r_1-1} \dots (p_k - 1)p_k^{r_k-1}$	14
3	Complex numbers	15
3.1	Geometric Meaning of Addition and Multiplication	15
3.2	Theorem 2.1.1: $f(x) = a_0 + a_1x + \dots + a_nx^n$ with coefficients $a_0, a_1, \dots, a_n \in \mathbb{C}$. Then f has a root in \mathbb{C} : $\exists \alpha \in \mathbb{C}$ s.t. $f(\alpha) = 0$	16
3.2.1	Corollary 2.1.2: $f(x) = a_n \prod_{i=1}^n (x - k_i) = a_n(x - k_1)(x - k_2) \dots (x - k_n)$, where k_1, k_2, \dots, k_n are roots of $f(x)$	16
3.2.2	Corollary 2.1.3: $a_i \in \mathbb{R}$, f can be expresses as a product of linear and quadratic polynomials	16
4	Field $(\mathbb{F}, +, \cdot)$ (close, associative, commutative, distributive(M over A), identity & inverse(M,A))	17
4.1	Subfield $(\mathbb{K}, +, \cdot)$: $\mathbb{K} \subseteq \mathbb{F}$, closed under $+, \cdot$ and inverse	18
4.1.1	Proposition 2.2.3: Subfield 继承 operations 自成一 field	18
5	Polynomials	18
5.1	$\mathbb{F}[x]$: Polynomial ring 在一个 field 上形成的所有多项式 (方程) 的集合	18
5.1.1	Proposition 2.3.2: Polynomial ring (close, associative, commutative, distributive(M over A), identity(M,A), inverse(only A))	19
5.2	Degree of a Polynomial: $\deg(f)$	19
5.2.1	Lemma 2.3.3: $\deg(fg) = \deg(f) + \deg(g)$, $\deg(f + g) \leq \max\{\deg(f), \deg(g)\}$. .	19
5.3	Corollary 2.3.5: Unit(invertible) in $\mathbb{F}[x]$: constant $\neq 0$ iff $\deg(f) = 0$	19
5.4	Irreducible Polynomials: “无法分解为两个 $\deg \geq 1$ 的多项式积”的多项式: 至少一个是个 constant (i.e. $\deg = 0$)	19

5.5	Theorem 2.3.6: nonconstant polynomials 可以被唯一地分解	20
5.6	Divisibility of Polynomials	20
5.6.1	Greatest common divisor of f and g : is not unique, we denote monic Greatest common divisor as $\gcd(f, g)$	20
5.6.2	Proposition 2.3.9: Euclidean Algorithm of polynomials	21
5.6.3	Proposition 2.3.10: $\gcd(f, g)$ 是 degree 最小的 f, g 的线性组合	21
5.6.4	Proposition 2.3.12: $\gcd(f, g) = 1, f gh \Rightarrow f h$	22
5.6.5	Corollary 2.3.13: irreducible $f, f gh \Rightarrow f g$ or $f h$	22
5.7	Roots	22
5.7.1	Corollary 2.3.16(of Euclidean Algorithm): f 可被分为 $(x - \alpha)q + f(\alpha)$ i.e. if α is a root, then $(x - \alpha) f$	22
5.8	Multiplicity	22
5.8.1	Sum of multiplicity $\leq \deg(f)$	22
5.9	Roots in a field may not in its subfield	22
6	Linear Algebra	23
6.1	Vector Space $(V, +, \times)$ (over a field \mathbb{F})	23
6.1.1	A field is a vector space over its subfield	23
6.1.2	Vector subspace	23
6.2	Linear independent, Linear combination	23
6.3	span V , basis, dimension, Proposition 2.4.10	23
6.3.1	Standard basis vectors	24
6.4	Linear transformation	24
6.4.1	Corollary 2.4.16: 一个线性变换对应一个矩阵 $\text{bijection } \mathcal{L}(V, M) \rightarrow M_{m \times n}(\mathbb{F})$. .	24
6.4.2	Proposition 2.4.19: 线性变换矩阵相乘仍为线性变换矩阵	25
6.5	$GL(V)$: invertible(bijective) linear transformations $V \rightarrow V$	25
7	Euclidean geometry basics	25
7.1	Euclidean distance, inner product	25
7.2	Isometry of \mathbb{R}^n : a bijection $\mathbb{R}^n \rightarrow \mathbb{R}^n$ preserves distance	25
7.2.1	$Isom(\mathbb{R}^n)$: set of all isometries of \mathbb{R}^n	25
7.2.2	$Isom(\mathbb{R}^n)$ is closed under \circ and inverse	25
7.3	$A \in GL(n, \mathbb{R}), T_A(v) = Av: A^t A = I \Leftrightarrow T_A \in Isom(\mathbb{R}^n)$	26
7.4	Linear isometries i.e. orthogonal group $O(n) = \{A \in GL(n, \mathbb{R}) A^t A = I\}$	26
7.4.1	Special orthogonal group $SO(n) = \{A \in O(n) \det(A) = 1\}$: orthogonal group with $\det(A) = 1$	26
7.5	translation: $\tau_v(x) = x + v$	26
7.5.1	translation is an isometry	26

7.6	The composition of a translation and an orthogonal transformation is an isometry	
	$\Phi_{A,v}(x) = \tau_v(T_A(x)) = Ax + v$	26
7.6.1	Theorem 2.5.3: All isometries can be represented by a composition of a <i>translation</i> and an <i>orthogonal transformation</i> , $Isom(\mathbb{R}^n) = \{\Phi_{A,v} A \in O(n), v \in \mathbb{R}^n\}$	27
8	Group $(G, *)$: a set with an operation(associative, identity, inverse)	27
8.1	$(Sym(X), \circ)$ symmetric/permutation group of X	27
8.2	Order of a group $(G, *)$	27
8.3	Abelian group (group that $*$ satisfies commutative)	27
8.4	H : Subgroup of $(G, *)$ ($H \neq \emptyset \subset G$ closed under $*$; inverse $g^{-1} \in H$), written as $H < G$	27
8.4.1	Proposition 2.6.8: $H < G$, $(H, *)$ is a group: A group's operation with its any subgroup is also a group	28
9	Ring $(R, +, \cdot)$: $+$ is associative, commutative, identity, inverse $\in R$; \cdot is associative, distributes over $+$	29
9.1	Commutative ring: ring's \cdot is commutative	29
9.2	Ring with 1: exists multiplication identity $1 \in R$	29
9.3	Field \mathbb{F} is a commutative ring with 1; $\mathbb{F}[x]$ is also a commutative ring with 1	29
9.4	$S \subset R$: Subring (closed under $+$ and \cdot ; additive inverse $-a \in S$)	29
9.4.1	Proposition 2.6.27: $(S, +, \cdot)$ is a ring	29
10	Group theory	29
10.1	Properties of Group Operation	29
10.1.1	Proposition 3.1.1: $g * h = h$ or $h * g = h$, then $g = e$; $g * h = e$ then $g = h^{-1}$ and $h = g^{-1}$	29
10.1.2	Corollary 3.1.: $e^{-1} = e$, $(g^{-1})^{-1} = g$, $(g * h)^{-1} = h^{-1} * g^{-1}$	30
10.1.3	Proposition 3.1.3: $g * h = k * h$ or $h * g = h * k$, then $g = k$	30
10.1.4	Proposition 3.1.4: $g * x = h$ and $x * g = h$ have unique solutions $x \in G$	30
10.2	Power of an Element	30
10.2.1	Proposition 3.1.5: $g^n * g^m = g^{n+m}$, $(g^n)^m = g^{nm}$	30
10.3	$(G \times H, \otimes)$: <u>Direct Product</u> of G and H	30
10.3.1	Proposition 3.1.7: $(G \times H, \otimes)$ is a group	30
10.4	Subgroups and cyclic groups	30
10.4.1	Proposition 3.2.2: Intersection of a Collection of Subgroups is a group	30
10.4.2	Subgroup Generated by A : $\langle A \rangle = \cap_{H < G; A \subset H} H$	31
10.4.3	<u>Cyclic Subgroup</u> generated by a : $\langle a \rangle = \cap_{H < G; a \in H} H$ (G is <u>cyclic</u> if exists g , $\langle g \rangle = G$)	31
10.4.4	Proposition 3.2.3: $\langle g \rangle = \{g^n n \in \mathbb{Z}\}$	31
10.4.5	Corollary 3.2.4: G is a cyclic group $\Rightarrow G$ is abelian	31

10.4.6	Equivalent properties of order of g : $ g = \langle g \rangle < \infty$	31
10.4.7	$(\mathbb{Z}, +)$ Theorem 3.2.9: $H < \mathbb{Z}$ is a subgroup $\Rightarrow H = \{0\}$ or $H = \langle d \rangle$; $\langle a \rangle < \langle b \rangle$ if and only if $b a$	31
10.4.8	$(\mathbb{Z}_n, +)$ Theorem 3.2.10: $H < \mathbb{Z}_n$ is a subgroup $\Rightarrow H = \langle [d] \rangle$; $\langle [d] \rangle < \langle [d'] \rangle$ if and only if $d' d$	32
10.4.9	Subgroup Lattice	32

1 Integers

1.1 Proposition 1.4.1: Properties of integers \mathbb{Z}

Proposition 1 (Proposition 1.4.1.). *The following hold in the integers \mathbb{Z} :*

- (i) *Addition and multiplication are commutative and associative operations in \mathbb{Z} .*
- (ii) $0 \in \mathbb{Z}$ is an identity element for addition; that is, $\forall a \in \mathbb{Z}, 0 + a = a$.
- (iii) Every $a \in \mathbb{Z}$ has an additive inverse, denoted $-a$ and given by $-a = (-1)a$, satisfying $a + (-a) = 0$.
- (iv) $1 \in \mathbb{Z}$ is an identity element for multiplication; that is, for all $a \in \mathbb{Z}, 1a = a$.
- (v) The *distributive* law holds: $\forall a, b, c \in \mathbb{Z}, a(b + c) = ab + ac$.
- (vi) Both $\mathbb{N} = \{x \in \mathbb{Z} | x \geq 0\}$ and $\mathbb{Z}_+ = \{x \in \mathbb{Z} | x > 0\}$ are *closed* under *addition* and *multiplication*. That is, if x and y are in one of these sets, then $x + y$ and xy are also in that set.
- (vii) For any two nonzero integers $a, b \in \mathbb{Z}, |ab| \geq \max\{|a|, |b|\}$. Strict inequality holds if $|a| > 1$ and $|b| > 1$.

From this we get cancellation.

$$ab = ac \Rightarrow b = c \text{ or } a = 0$$

1.2 Definition: Divide

Suppose $a, b \in \mathbb{Z}, b \neq 0$, b divides a if $\exists m \in \mathbb{Z}$, so that $a = bm, b|a$. Otherwise, write $b \nmid a$.

1.3 Proposition 1.4.2: properties of integer division

Proposition 2 (Proposition 1.4.2). $\forall a, b \in \mathbb{Z}$

- (i) if $a \neq 0$, then $a|0$
- (ii) if $a|1$, then $a = \pm 1$
- (iii) if $a|b$ & $b|a$, then $a = \pm b$
- (iv) if $a|b$ & $b|c$, then $a|c$
- (v) if $a|b$ & $a|c$, then $a|(mc + nb) \forall m, n \in \mathbb{Z}$

1.4 Definitions: Prime, The Greatest common divisor $\gcd(a, b)$

$p > 1, p \in \mathbb{Z}$ is called prime if the only divisors are $\pm 1, \pm p$.

Given $a, b \in \mathbb{Z}, a, b \neq 0$, the greatest common divisor of a and b is $c \in \mathbb{Z}, c > 0$ s.t.

- (1) $c|a$ and $c|b$; (2) if $d|a, d|b$, then $d|c$

The c is unique, we write it $\gcd(a, b)$.

1.5 Euclidean Algorithm

Proposition 3 (Proposition 1.4.7(Euclidean Algorithm)). *Given $a, b \in \mathbb{Z}, b \neq 0$, then $\exists q, r \in \mathbb{Z}$ s.t. $a = qb + r, 0 \leq r \leq |b|$.*

Example 1 (Exercise 1.4.3). *For the pair $(a, b) = (130, 95)$, find $\gcd(a, b)$ using the Euclidean Algorithm and express it in the form $\gcd(a, b) = sa + tb$ for $s, t \in \mathbb{Z}$.*

$$130 = 95 + 35; \quad 95 = 2 \times 35 + 25$$

$$35 = 25 + 10; \quad 25 = 2 \times 10 + 5$$

$$10 = 2 \times 5 + 0$$

$$5 = 25 - 2 \times 10 = 25 - 2 \times (35 - 25) = 3 \times 25 - 2 \times 35 = 3 \times (95 - 2 \times 35) - 2 \times 35$$

$$= 3 \times 95 - 8 \times 35 = 3 \times 95 - 8 \times (130 - 95) = 11 \times 95 - 8 \times 130$$

$$\gcd(130, 95) = \gcd(95, 35) = \gcd(35, 25) = \gcd(25, 10) = \gcd(10, 5) = \gcd(5, 0) = 5$$

We can also express it by matrix

	q	r	s	t
-1		130	1	0
0	1	95	0	1
1	2	35	1	-1
2	1	25	-2	3
3	2	10	3	-4
4	2	5	-8	11

Hence $\gcd(130, 95) = 5 = -8 \cdot 130 + 11 \cdot 95$

1.6 Proposition: $\gcd(a, b)$ exists and is the smallest positive integer in the set $M = \{ma + nb | m, n \in \mathbb{Z}\}$

Theorem 1. $d = \gcd(a, b)$ is of the form $sa + tb$

证明. We may assume $0 \leq a \leq b$

For $a = 0$, $d = b = 0 \cdot a + 1 \cdot b$.

For $a > 0$, let $b = q \cdot a + r$ with $0 \leq r < a \leq b$. Then

$$\begin{aligned} \{sa + tb : s, t \in \mathbb{Z}\} &= \{sa + t(q \cdot a + r) : s, t \in \mathbb{Z}\} = \{tr + ua : t, u \in \mathbb{Z}\} \\ &= \dots \{x \cdot 0 + y \cdot d : x, y \in \mathbb{Z}\} = \{\dots, -2d, -d, 0, d, 2d, \dots\} \end{aligned}$$

□

Proposition 4 (第二种表示, 第二种证明). $\forall a, b \in \mathbb{Z}$, not both 0, $\gcd(a, b)$ exists and is the smallest positive integer in the set $M = \{ma + nb | m, n \in \mathbb{Z}\}$. i.e. $\exists m_0, n_0 \in \mathbb{Z}$ s.t. $\gcd(a, b) = m_0 a + n_0 b$.

证明. Let c be the smallest positive integer in the set $M = \{ma + nb \mid m, n \in \mathbb{Z}\}$. $c = m_0a + n_0b > 0$. Let $d = ma + nb \in M$, $d = qc + r$ where $0 \leq r < c$ (by Euclidean Algorithm).

$$r = d - qc = (m - qm_0)a + (n - qn_0)b \in M$$

Since c is the smallest integer in M and $r \in [0, c)$, so $r = 0$. $\Rightarrow d = qc$. So $c \mid d$.

$a = 1a + 0b \in M \Rightarrow c \mid a$, $b = 0a + 1b \in M \Rightarrow c \mid b$.

If $t \mid a, t \mid b$ then $t \mid m_0a + n_0b$ i.e. $t \mid c$. $\Rightarrow c = \gcd(a, b)$. □

1.7 Well-Ordering Principle (Least Integer Axiom)

There is a smallest integer in every nonempty subset S of the natural numbers $\mathbb{N} = \{0, 1, 2, \dots\}$

1.8 Proposition 1.4.10: $\gcd(b, c), b \mid ac \Rightarrow b \mid a$

Proposition 5 (Proposition 1.4.10). Suppose $a, b, c \in \mathbb{Z}$. If b, c are relatively prime i.e. $\gcd(b, c) = 1$ and $b \mid ac$, then $b \mid a$.

证明. $\gcd(b, c) = 1 \Rightarrow \exists m, n \in \mathbb{Z}$ s.t. $1 = mb + nc \Rightarrow a = amb + anc$. Since $b \mid nac, b \mid amb \Rightarrow b \mid a$. □

1.8.1 Corollary: $p \mid ab \Rightarrow p \mid a$ or $p \mid b$

Corollary 1 (Corollary of Prop 1.4.10). $a, b, p \in \mathbb{Z}, p > 1$ prime. If $p \mid ab$, then $p \mid a$ or $p \mid b$.

证明. If $p \mid b$, done. Otherwise, $\gcd(p, b) = 1$. By Prop 1.4.10, $p \mid a$. □

1.9 Fundamental Theorem of Arithmetic: Any integer $a \geq 2$ has a unique prime factorization

1.9.1 Existence

Lemma 1. Any integer $a \geq 2$ is either a prime or a product of primes.

证明. Set $S \subset \mathbb{N}$ be the set of all n without the given property.

Assume that S is nonempty and m is the least element in S .

Since m is not a prime, it can be written as $m = ab$ with $1 < a, b < m$. Since m is the least element in S , $a, b \notin S$. Then m is a product of primes. Contradiction. Thus, $S = \emptyset$. □

1.9.2 Uniqueness

Theorem 2 (Fundamental Theorem of Arithmetic).

Any integer $a > 1$ has a unique prime factorization: $a = p_1^{k_1} \cdot p_2^{k_2} \cdot \dots \cdot p_n^{k_n}$ where $p_i > 1$ is prime, $k_i \in \mathbb{Z}_+, \forall i = 1, \dots, n, p_i \neq p_j, \forall i \neq j$.

证明.

a) Existence: (Previous Lemma)

b) Uniqueness:

1) Method 1:

Suppose $a = p_1^{n_1} \cdot p_2^{n_2} \cdot \dots \cdot p_k^{n_k} = q_1^{r_1} \cdot q_2^{r_2} \cdot \dots \cdot q_j^{r_j}$. Where $p_1 > p_2 > \dots > p_k, q_1 > q_2 > \dots > q_j, n_i, r_i \geq 1$.

$p_1 | a \Rightarrow \exists q_i \text{ s.t. } p_1 | q_i$. Similarly, $\exists q_i \text{ s.t. } q_1 | p_{i'}$.

$q_1 \leq p_{i'} \leq p_1 \leq q_i \Rightarrow q_1 = p_{i'} = p_1 = q_i$

We can also know $n_1 = r_1$, otherwise we would have two prime factorization of the quotient where the largest primes are different by dividing $p_1^{\min\{n_1, r_1\}}$.

Then we can get $b = p_2^{n_2} \cdot \dots \cdot p_k^{n_k} = q_2^{r_2} \cdot \dots \cdot q_j^{r_j}$. Then prove it by induction.

2) Method 2:

Suppose $a = p_1 \cdot p_2 \cdot \dots \cdot p_k = q_1 \cdot q_2 \cdot \dots \cdot q_t$. For a p_i , there must exist a q_j s.t. $p_i = q_j$:

Assume that $p_i \neq q_t$, $\gcd(p_i, q_t) = 1$. Then $\exists a, b$ such that $1 = ap_i + bq_t$. Multiplying both sides by $q_1 \cdot q_2 \cdot \dots \cdot q_{t-1}$:

$$q_1 \cdot q_2 \cdot \dots \cdot q_{t-1} = ap_i q_1 \cdot q_2 \cdot \dots \cdot q_{t-1} + bq_1 \cdot q_2 \cdot \dots \cdot q_t$$

Since $p_i | q_1 \cdot q_2 \cdot \dots \cdot q_t$, we can conclude that $p_i | (ap_i q_1 \cdot q_2 \cdot \dots \cdot q_{t-1} + bq_1 \cdot q_2 \cdot \dots \cdot q_t)$

i.e. $p_i | q_1 \cdot q_2 \cdot \dots \cdot q_{t-1}$ if $p_i \neq q_t$

Then prove by induction.

□

2 Modular arithmetic

2.1 Congruences

2.1.1 Congruent modulo m : $a \equiv b \pmod{m}$

Given $m \in \mathbb{Z}_+$, define a relation on \mathbb{Z} : **congruence modulo m**

$$a \equiv b \pmod{m}, \text{ if } m | (a - b)$$

Read as "a is congruent to b mod n"; Notation: $a \equiv b \pmod{m}$.

Equivalent to: a, b have the same remainder after division by m .

2.1.2 Proposition: For fixed $m \geq 2$, the relation " $a \sim b \Leftrightarrow a \equiv b \pmod{m}$ " is an equivalence relation

Proposition 6 (Proposition 1.5.1). For fixed $m \geq 2$, the relation " $a \sim b \Leftrightarrow a \equiv b \pmod{m}$ " is an equivalence relation

证明.

- 1) Reflexive: $\forall a \in \mathbb{Z}, m|0 = (a - a)$, so $a \equiv a \pmod{m}$ i.e. $a \sim a$.
- 2) Symmetric: $\forall a, b \in \mathbb{Z}, a \equiv b \pmod{m}$, then $m|(a - b) \Rightarrow m|(b - a) \Rightarrow b \equiv a \pmod{m}$. i.e. $a \sim b \Rightarrow b \sim a$.
- 3) Transitive: $\forall a, b, c \in \mathbb{Z}, a \equiv b \pmod{m}, b \equiv c \pmod{m}$. Then $m|(a - b), m|(b - c) \Rightarrow m|(a - b) + (b - c) = (a - c) \Rightarrow a \equiv c \pmod{m}$.

□

2.1.3 Theorem: the equivalence relation " $a \sim b \Leftrightarrow a \equiv b \pmod{m}$ " partitions the integers into m disjoint sets $\Omega_i = \{a | a \sim i\}, i = 0, 1, \dots, m - 1$

Theorem 3. the equivalence relation " $a \sim b \Leftrightarrow a \equiv b \pmod{m}$ " partitions the integers into m disjoint sets $\Omega_i = \{a | a \sim i\}, i = 0, 1, \dots, m - 1$

证明. Prove any $a \in \mathbb{Z}$ belongs to a unique Ω_i .

a) Existence: Division Algorithm $\Rightarrow a = qm + r, 0 \leq r < m. a \in \Omega_r$.

b) Uniqueness: Assume a in two sets, $a \in \Omega_r \cap \Omega_{r^1}, 0 \leq r^1 < r < m$.

Then $m|a - r$ and $m|a - r^1 \Rightarrow m|r - r^1$, which is impossible because $0 < r - r^1 < m$. Contradiction.

□

2.1.4 Proposition: Addition and Mutiplication of Congruences

Proposition 7. Fix integer $m \geq 2$. If $a \equiv r \pmod{m}$ and $b \equiv s \pmod{m}$, then $a + b \equiv r + s \pmod{m}$ and $ab \equiv rs \pmod{m}$

证明.

a) Addition: $m|(a - r), m|(b - s) \Rightarrow m|(a - r) + (b - s) \Rightarrow m|(a + b) - (r + s)$.

b) Mutiplication: $m|(a - r)b + r(b - s) \Rightarrow m|ab - rs$.

□

2.2 Solving Linear Equations on Modular m

2.2.1 Theorem: unique solution of $aX \equiv b \pmod{m}$ if $\gcd(a, m) = 1$

Theorem 4. If $\gcd(a, m) = 1$, then $\forall b \in \mathbb{Z}$ the congruence $aX \equiv b \pmod{m}$ has a unique solution.

证明.

1) Existence: Since $\gcd(a, m) = 1$, $\exists s, t$ such that

$$1 = sa + tm$$

(Version 1)

(Multiplying X)

$$X = saX + tmX$$

$$aX \equiv b \pmod{m} \Leftrightarrow aX = km + b$$

$$\Leftrightarrow X \equiv sb \pmod{m}$$

(Version 2)

(Multiplying s)

$$saX \equiv sb \pmod{m}$$

$$(1 - tm)X \equiv sb \pmod{m}$$

$$X \equiv sb \pmod{m}$$

$X \equiv sb \pmod{m}$ is the solution to $aX \equiv b \pmod{m}$.

2) Uniqueness: Assume x, y are two solutions,

$$ax \equiv b \pmod{m}, ay \equiv b \pmod{m} \Rightarrow a(x - y) \equiv 0 \pmod{m}$$

Since $\gcd(a, m) = 1$, $m \mid (x - y) \Rightarrow x = y$, ($x, y \in \{0, 1, \dots, m - 1\}$)

Example 2. Solve $3X \equiv 5 \pmod{11}$.

$$\gcd(3, 11) = 1, 1 = 4 * 3 - 1 * 11,$$

$$X \equiv 9$$

□

2.3 Chinese Remaindar Theorem (CRT): unique solution for x modulo mn

Theorem 5 (Chinese Remaindar Theorem (CRT)).

If $\gcd(m, n) = 1$. Then $\begin{cases} x \equiv r \pmod{m} & (1) \\ x \equiv s \pmod{n} & (2) \end{cases}$ have a unique solution for x modulo mn .

证明.

(1) $\Rightarrow x = km + r$ for some $k \in \mathbb{Z}$.

$$\begin{aligned} \text{substitute (2)} \Rightarrow km + r &\equiv s \pmod{n} \\ \Leftrightarrow mk &\equiv s - r \pmod{n} \quad (3) \end{aligned}$$

According to previous theorem, $\gcd(m, n) = 1$, (3) has a **unique** solution. We say $k \equiv t \pmod{n}$, $k = ln + t$ for some $n \in \mathbb{Z} \Rightarrow x = (ln + t)m + r = lnm + tm + r$, where $tm + r$ is the unique solution to x modulo mn . \square

2.4 Congruence Classes: $[a]_n = \{a + kn | k \in \mathbb{Z}\}$

将给定 n , 相同余数的数分为一组

Fix $n \in \mathbb{Z}_+$, we call $[a]_n = [a]$ the **congruence class** of a modulo n .

$$[a] = \{b \in \mathbb{Z} | b \equiv a \pmod{n}\} = \{a + kn | k \in \mathbb{Z}\}$$

2.4.1 Set of congruence classes of mod n : $\mathbb{Z}_n = \{[a]_n | a \in \mathbb{Z}\} = \{[0], [1], \dots, [n-1]\}$

The set of *congruence classes* of mod n is denoted $\mathbb{Z}_n = \{[a]_n | a \in \mathbb{Z}\}$

Proposition 8 (Proposition 1.5.2.). *For any $n \geq 1$ there are exactly n congruence classes modulo n , which we may write as*

$$\mathbb{Z}_n = \{[0], [1], \dots, [n-1]\}$$

证明.

For any $a \in \mathbb{Z}$. By Euclidean algorithm, $a = qn + r$, $q, r \in \mathbb{Z}$, $0 \leq r < n \Rightarrow a \in [r]$. So, $\mathbb{Z}_n = \{[0], [1], \dots, [n-1]\}$.

When $0 \leq a < b \leq n-1$, $n \nmid (b-a)$, so $[a] \neq [b]$ the n congruence classes listed are all distinct. Hence, there are exactly n congruence classes. \square

2.4.2 Proposition 1.5.5: Addition and Multiplication on Congruence Classes

Fix $n \in \mathbb{Z}$, we define addition $+$ and multiplication \cdot on \mathbb{Z}_n :

$$\begin{aligned} [a] + [b] &= [a + b] = \{a + b + (k + j)n | k, j \in \mathbb{Z}\} \\ [a] \cdot [b] &= [ab] = \{ab + (aj + bk + kjn)n | k, j \in \mathbb{Z}\} \end{aligned}$$

This is well defined, follows Lemma 1.5.3.

Proposition 9 (Proposition 1.5.5.). *Let $a, b, c, d, n \in \mathbb{Z}, n \geq 1$, then*

- (i) *Addition and multiplication are commutative and associative operations in \mathbb{Z}_n .*
- (ii) $[a] + [0] = [a]$.
- (iii) $[-a] + [a] = [0]$.
- (iv) $[1][a] = [a]$.
- (v) $[a]([b] + [c]) = [a][b] + [a][c]$.

证明.

□

2.4.3 Units(i.e. invertible) in Congruence Classes

将与 n 互质的数分为一组

Say $[a] \in \mathbb{Z}_n$ is a **unit** or is **invertible** if $\exists [b] \in \mathbb{Z}_n$ so that $[a][b] = [1]$.

2.4.4 Proposition 1.5.6: Set of units in congruence classes: $\mathbb{Z}_n^\times = \{[a] \in \mathbb{Z}_n \mid [a] \text{ is a unit}\} = \{[a] \in \mathbb{Z}_n \mid \gcd(a, n) = 1\}$

The set of **invertible** elements in \mathbb{Z}_n will be denoted $\mathbb{Z}_n^\times = \{[a] \in \mathbb{Z}_n \mid [a] \text{ is a unit}\}$.

Proposition 10 (Proposition 1.5.6.). *For all $n \geq 1$, we have $\mathbb{Z}_n^\times = \{[a] \in \mathbb{Z}_n \mid \gcd(a, n) = 1\}$.*

证明.

By Proposition 1.4.8, we know there exists b, c s.t. $ab + cn = 1$. So, $ab \equiv 1 \pmod{n}$, $[1] = [ab] = [a][b]$.

So, $\{[a] \in \mathbb{Z}_n \mid \gcd(a, n) = 1\} \subset \mathbb{Z}_n^\times$

$[a] \text{ is a unit} \Rightarrow \exists [b] \in \mathbb{Z}_n$ so that $[a][b] = [ab] = [1] \Rightarrow ab = 1 + kn, k \in \mathbb{Z} \Rightarrow ab - kn = 1, k \in \mathbb{Z} \Rightarrow \gcd(a, n) = 1$. So, $\mathbb{Z}_n^\times \subset \{[a] \in \mathbb{Z}_n \mid \gcd(a, n) = 1\}$. □

Note 1. *Inverse of $[a]$ is unique, i.e. $[b] = [a]^{-1}$ is unique.*

$$[a][b] = 1, [a][b'] = 1 \Rightarrow [b] = [b][1] = [b][a][b'] = [b']$$

2.4.5 Corollary 1.5.7: if p is prime, $\varphi(p) = \mathbb{Z}_p^\times = \{[1], [2], \dots, [p-1]\}$

Corollary 2 (Corollary 1.5.7). *If $p \geq 2$ is prime, $\mathbb{Z}_p^\times = \{[1], [2], \dots, [p-1]\}$.*

2.5 Euler phi-function: $\varphi(n) = |\mathbb{Z}_n^\times|$

Euler phi-function: $\varphi(n) = |\mathbb{Z}_n^\times|$.

p prime, $\varphi(p) = p - 1$.

2.5.1 $m \mid n, \pi_{m,n}([a]_n) = [a]_m$

Example 3 (Exercise 1.5.4). *If $m \mid n$, we can define $\pi_{m,n} : \mathbb{Z}_n \rightarrow \mathbb{Z}_m$ by $\pi_{m,n}([a]_n) = [a]_m$. Prove it is well-defined.*

证明.

We write $[a]_n = [c]_n$, verify that $[a]_m = [c]_m$.

Since $m \mid n$, there exists $k \in \mathbb{Z}$ s.t. $n = km$.

$$[a]_n = [c]_n \Rightarrow \exists j \in \mathbb{Z} \text{ s.t. } c = a + jn.$$

$$[c]_m = [a + jn]_m = [a + jkm]_m = [a]_m$$

□

2.6 Theorem 1.5.8(Chinese Remainder Theorem): $n = mk, \gcd(m, k) = 1, F([a]_n) = (\pi_{m,n}([a]_n), \pi_{k,n}([a]_n)) = ([a]_m, [a]_k)$

Theorem 6 (Theorem 1.5.8(Chinese Remainder Theorem)). *If $m, n, k > 0, n = mk, \gcd(m, k) = 1$, then $F : \mathbb{Z}_n \rightarrow \mathbb{Z}_m \times \mathbb{Z}_k$ which is given by $F([a]_n) = (\pi_{m,n}([a]_n), \pi_{k,n}([a]_n)) = ([a]_m, [a]_k)$, then F is a bijection.*

证明.

(1)Injective: $F([a]_n) = F([b]_n) \Rightarrow [a]_m = [b]_m, [a]_k = [b]_k$ i.e. $a \equiv b \pmod{m}, a \equiv b \pmod{n}$. $\exists i, j \in \mathbb{Z}$ s.t. $b = a + im = a + jk \Rightarrow k|im$. Since $\gcd(m, k) = 1, k|i \Rightarrow n = mk|im$. Then $[b]_n = [a]_n + [im]_n = [a]_n$.

(2)Surjective: prove $\forall u, v \in \mathbb{Z}, \exists a \in \mathbb{Z}$ s.t. $[a]_m = [u]_m, [a]_k = [v]_k$.

Since $\gcd(m, k) = 1, \exists s, t \in \mathbb{Z}$ so that $1 = sm + tk$.

Let $a = (1 - tk)u + (1 - sm)v, [a]_m = [(u - v)sm + v]_m = [v]_m, [a]_k = [(v - u)tk + u]_k = [u]_k$. \square

Note 2. $F([a]_n[b]_n) = F([ab]_n) = ([ab]_m, [ab]_k) = ([a]_m[b]_m, [a]_k[b]_k)$

Since F is a bijection, $[ab]_n = [1]_n$ iff $([a]_m[b]_m, [a]_k[b]_k) = ([1]_m, [1]_k)$.

2.6.1 Proposition 1.5.9+Corollary 1.5.10: $m, n, k > 0, n = mk, \gcd(m, k) = 1$, then $F(\mathbb{Z}_n^\times) = \mathbb{Z}_m^\times \times \mathbb{Z}_k^\times$, then $\varphi(n) = \varphi(m)\varphi(k)$

Proposition 11 (Proposition 1.5.9+Corollary 1.5.10). *If $m, n, k > 0, n = mk, \gcd(m, k) = 1$, then $F(\mathbb{Z}_n^\times) = \mathbb{Z}_m^\times \times \mathbb{Z}_k^\times$, then $\varphi(n) = \varphi(m)\varphi(k)$.*

2.7 prime factorization: $n = p_1^{r_1} \dots p_k^{r_k}$, then $\varphi(n) = (p_1 - 1)p_1^{r_1-1} \dots (p_k - 1)p_k^{r_k-1}$

Proposition 12. *If $n \in \mathbb{Z}$ is positive integer with prime factorization $n = p_1^{r_1} \dots p_k^{r_k}$, then $\varphi(n) = (p_1 - 1)p_1^{r_1-1} \dots (p_k - 1)p_k^{r_k-1}$*

证明.

$\mathbb{Z}_{p^r} = \{[0], [1], \dots, [p^r - 1]\}$, the number of multiples of p is $\frac{p^r}{p} = p^{r-1}$. Then $\varphi(p^r) = |\mathbb{Z}_{p^r}^\times| = p^r - p^{r-1} = (p - 1)p^{r-1}$. So,

$$\varphi(n) = \varphi(p_1^{r_1}) \dots \varphi(p_k^{r_k}) = (p_1 - 1)p_1^{r_1-1} \dots (p_k - 1)p_k^{r_k-1}$$

\square

3 Complex numbers

$$\mathbb{C} = \{a + bi | a, b \in \mathbb{R}\}, \mathbb{R} = \{a + 0i | a \in \mathbb{R}\} \subset \mathbb{C}$$

Addition & multiplication

$$(a + bi) + (c + di) = (a + c) + (b + d)i$$

$$\begin{aligned}(a + bi)(c + di) &= ac + bci + adi + bdi^2 \\ &= (ac - bd) + (bc + ad)i\end{aligned}$$

Complex conjugation: $z = a + bi, \bar{z} = a - bi, \overline{z\bar{w}} = \bar{z}\bar{w}$

Absolute value: $|z| = \sqrt{a^2 + b^2}, |z|^2 = z\bar{z}$

Additive inverse: $-z = -a - bi$

Multiplicative inverse: $z^{-1} = \frac{1}{z} = \frac{1}{a+bi} = \frac{a-bi}{a^2+b^2} = \frac{\bar{z}}{|z|^2}$

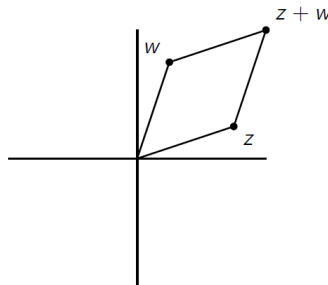
$$z \in \mathbb{C}, \overline{z + \bar{z}} = \bar{z} + \bar{\bar{z}} = z + \bar{z}$$

$$\text{Real part: } \operatorname{Re}(z) = \frac{z + \bar{z}}{2}$$

$$\text{Imaginary part: } \operatorname{Im}(z) = \frac{z - \bar{z}}{2i}$$

3.1 Geometric Meaning of Addition and Multiplication

Addition: parallelogram law



Multiplication:

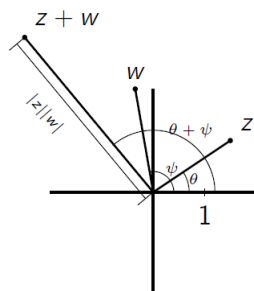
$$z = a + bi \neq 0$$

$$= r \cos \theta + r \sin \theta i$$

$$= r(\cos \theta + i \sin \theta)$$

$$|z|^2 = a^2 + b^2 = r^2$$

$$\begin{aligned}
z &= r(\cos \theta + i \sin \theta) \\
w &= s(\cos \phi + i \sin \phi) \\
zw &= rs[\cos \theta \cos \phi - \sin \theta \sin \phi + i(\cos \theta \sin \phi + \cos \phi \sin \theta)] \\
&= rs[\cos(\theta + \phi) + i \sin(\theta + \phi)] \\
&= |z||w|[\cos(\theta + \phi) + i \sin(\theta + \phi)]
\end{aligned}$$



We will write,

$$\begin{aligned}
\cos \theta + i \sin \theta &= e^{i\theta} \\
e^{i\theta} e^{i\phi} &= e^{i(\theta+\phi)} \\
z &= |z|e^{i\theta}
\end{aligned}$$

3.2 Theorem 2.1.1: $f(x) = a_0 + a_1x + \dots + a_nx^n$ with coefficients $a_0, a_1, \dots, a_n \in \mathbb{C}$. Then f has a root in \mathbb{C} : $\exists \alpha \in \mathbb{C}$ s.t. $f(\alpha) = 0$

Theorem 7 (Theorem 2.1.1). Suppose a nonconstant polynomial $f(x) = a_0 + a_1x + \dots + a_nx^n$ with coefficients $a_0, a_1, \dots, a_n \in \mathbb{C}$. Then f has a root in \mathbb{C} : $\exists \alpha \in \mathbb{C}$ s.t. $f(\alpha) = 0$.

3.2.1 Corollary 2.1.2: $f(x) = a_n \prod_{i=1}^n (x - k_i) = a_n(x - k_1)(x - k_2) \dots (x - k_n)$, where k_1, k_2, \dots, k_n are roots of $f(x)$

Corollary 3 (Corollary 2.1.2). Every nonconstant polynomial with coefficients $a_0, a_1, \dots, a_n \in \mathbb{C}$ can be factored as $f(x) = a_n \prod_{i=1}^n (x - k_i) = a_n(x - k_1)(x - k_2) \dots (x - k_n)$, where k_1, k_2, \dots, k_n are roots of $f(x)$.

3.2.2 Corollary 2.1.3: $a_i \in \mathbb{R}$, f can be expressed as a product of linear and quadratic polynomials

Corollary 4 (Corollary 2.1.3). If $f(x) = a_0 + a_1x + \dots + a_nx^n$ is a nonconstant polynomial $a_0, a_1, \dots, a_n \in \mathbb{R}, a_n \neq 0$. Then f can be expressed as a product of linear and quadratic polynomials.

这里 a_0, a_1, \dots, a_n 是实数!

证明.

(1) Obviously, the corollary holds at $n = 1$ and $n = 2$.

(2) Suppose the corollary holds for all situations that $n < k$.

When $n = k$, $f(x) = a_0 + a_1x + \dots + a_kx^k, a_k \neq 0$.

By F.T.A., f has a root α in \mathbb{C} .

If $\alpha \in \mathbb{R}$, long division $f(x) = q(x)(x - \alpha)$. q has real coefficients, *degree of $q = k - 1$* . Since the corollary holds at $n = k - 1$, $q(x)$ is a product of linear and quadratics. Then, the corollary also holds at $n = k$.

If $\alpha \notin \mathbb{R}$

$$\begin{aligned} 0 &= f(\alpha) = a_0 + a_1\alpha + \dots + a_k\alpha^k \\ 0 &= \overline{f(\alpha)} = a_0 + a_1\bar{\alpha} + \dots + a_n\bar{\alpha}^n = f(\bar{\alpha}) \end{aligned}$$

Since $\bar{\alpha} \neq \alpha$, $(x - \alpha)(x - \bar{\alpha}) | f$.

$(x - \alpha)(x - \bar{\alpha}) = x^2 - (\alpha + \bar{\alpha})x + |\alpha|^2$ is a polynomial with coefficients in \mathbb{R} . So $f(x) = q(x)(x^2 - (\alpha + \bar{\alpha})x + |\alpha|^2)$, q has real coefficients with degree $k - 2$. The corollary also holds at $n = k - 2$, $q(x)$ is a product of linear and quadratics. Then, the corollary also holds at $n = k$.

□

4 Field $(\mathbb{F}, +, \cdot)$ (close, associative, commutative, distributive(M over A), identity & inverse(M,A))

Definition: A field is a nonempty set \mathbb{F} with two operations:

1. addition, written $a + b, \forall a, b \in \mathbb{F}$;
2. multiplication, written $a \cdot b = ab, \forall a, b \in \mathbb{F}$.

such that:

- (i) *addition* and *multiplication* are associative and commutative
- (ii) *multiplication* distributes over *addition*: $a(b + c) = ab + ac, \forall a, b, c \in \mathbb{F}$
- (iii) \exists an additive identity $0 \in \mathbb{F}$ s.t. $0 + a = a, \forall a \in \mathbb{F}$.
- (iv) $\forall a \in \mathbb{F}$, \exists an additive inverse $-a$ s.t. $a + (-a) = 0, \forall a \in \mathbb{F}$.
- (v) \exists a multiplicative identity: $1 \in \mathbb{F}$ s.t. $1a = a, \forall a \in \mathbb{F}, 1 \neq 0$.
- (vi) $\forall a \in \mathbb{F}, a \neq 0$, a has a multiplicative inverse $a^{-1} = \frac{1}{a} \in \mathbb{F} : a \cdot \frac{1}{a} = 1$.

Proposition 13 (Proposition 2.2.2). \mathbb{F} a field, $a, b \in \mathbb{F}$, then

- (i) If $a + b = b$ then $a = 0$
- (ii) If $ab = b$ and $b \neq 0$, then $a = 1$
- (iii) $0a = 0$
- (iv) If $a + b = 0$, then $b = -a$
- (v) If $a \neq 0$ and $ab = 1$, then $b = a^{-1}$

Example 4. \mathbb{Z}_4 is not a field. Because $[2]_4$ doesn't have multiplicative inverse in \mathbb{Z}_4 .

4.1 Subfield $(\mathbb{K}, +, \cdot)$: $\mathbb{K} \subseteq \mathbb{F}$, closed under $+$, \cdot and inverse

Definition: Suppose \mathbb{F} is a field and $\mathbb{K} \subseteq \mathbb{F}$ s.t.

$$0, 1 \in \mathbb{K}$$

$$\forall a, b \in \mathbb{K}, a + b, ab, -a, a^{-1} (\text{if } a \neq 0) \in \mathbb{K}$$

We call \mathbb{K} a subfield of \mathbb{F} .

Example 5. $\mathbb{Q} \subseteq \mathbb{R}, \mathbb{R} \subseteq \mathbb{C}, \mathbb{Q} \subseteq \mathbb{C}$

Example 6. $\mathbb{K} \subseteq \mathbb{Z}_p$ a subfield $\Rightarrow \mathbb{K} = \mathbb{Z}_p$. Prove by induction.

4.1.1 Proposition 2.2.3: Subfield 继承 operations 自成一 field

Proposition 14 (Proposition 2.2.3). Suppose $\mathbb{K} \subset \mathbb{F}$ is a subfield of a field \mathbb{F} . Then the operations of \mathbb{F} make \mathbb{K} into a field.

\Rightarrow We can prove a set is a field by proving it is a subfield of a known field.

5 Polynomials

Let \mathbb{F} be any field. A polynomial over \mathbb{F} in variable x is a formal sum:

$$a_0 + a_1x + a_2x^2 + \dots + a_nx^n = \sum_{i=0}^n a_ix^i$$

where $n \geq 0$ is an integer, $a_1, a_1, \dots, a_n \in \mathbb{F}$.

Polynomial is a sequence $\{a_k\}_{k=0}^{\infty}$ with $a_m = 0, \forall m > n$.

5.1 $\mathbb{F}[x]$: Polynomial ring 在一个 field 上形成的所有多项式 (方程) 的集合

Let $\mathbb{F}[x]$ denote the set of all polynomials with coefficients in the field \mathbb{F} .

$$\mathbb{F}[x] = \left\{ \sum_{i=0}^n a_ix^i \mid n \geq 0, n \in \mathbb{Z}, a_0, \dots, a_n \in \mathbb{F} \right\}$$

We call the $\mathbb{F}[x]$ *polynomial ring* over the field \mathbb{F} .

$$f = \sum_{i=0}^n a_ix^i, g = \sum_{j=0}^n a_jx^j \in \mathbb{F}[x]$$

$$f + g = \sum_{i=0}^n (a_i + b_i)x^i \in \mathbb{F}[x]$$

$$fg = \left(\sum_{i=0}^n a_ix^i \right) \left(\sum_{j=0}^n a_jx^j \right) = \sum_{i=0}^{2n} \left(\sum_{j=0}^i a_jb_{i-j} \right) x^i$$

5.1.1 Proposition 2.3.2: Polynomial ring (close, associative, commutative, distributive(M over A), identity(M,A), inverse(only A))

Proposition 15 (Proposition 2.3.2). *Suppose \mathbb{F} is any field. Then,*

- (i) Addition and multiplication are commutative & associative operations on $\mathbb{F}[x]$
- (ii) Multiplication distributes over addition
- (iii) $0 \in \mathbb{F}$, is additive identity in $F[x] : \forall f \in \mathbb{F}[x], f + 0 = 0$
- (iv) $\forall f \in \mathbb{F}[x], f = (-1)f$ is the additive inverse: $f + (-1)f = 0$.
- (v) $1 \in \mathbb{F}$, is the multiplicative identity in $\mathbb{F}[x] : 1f = f, \forall f \in \mathbb{F}[x]$

5.2 Degree of a Polynomial: $\deg(f)$

$f = \sum_{i=0}^n a_i x^i$, $\deg(f)$ = degree of f is,

$$\deg(f) = \begin{cases} 0 & \text{if } f \text{ is constant, } f \neq 0 \\ n & \text{if } a_n \neq 0 \text{ in above } (a_n = \text{leading coefficient}) \\ -\infty & \text{if } f = 0 \end{cases}$$

Define $-\infty + a = a + (-\infty) = -\infty \forall a \in \mathbb{Z} \cup \{-\infty\}$

5.2.1 Lemma 2.3.3: $\deg(fg) = \deg(f) + \deg(g)$, $\deg(f + g) \leq \max\{\deg(f), \deg(g)\}$

Lemma 2 (Lemma 2.3.3). *For any field \mathbb{F} and $f, g \in \mathbb{F}[x]$,*

$$\begin{aligned} \deg(fg) &= \deg(f) + \deg(g) \\ \deg(f + g) &\leq \max\{\deg(f), \deg(g)\} \end{aligned}$$

5.3 Corollary 2.3.5: Unit(invertible) in $\mathbb{F}[x]$: constant $\neq 0$ iff $\deg(f) = 0$

Corollary 5 (Corollary 2.3.5). *For any field \mathbb{F} and $f \in \mathbb{F}[x]$, Then f is a unit(i.e. invertible) in $\mathbb{F}[x]$ iff $\deg(f) = 0$.*

证明.

Obviously, $\deg(f) = 0 \Rightarrow f$ is a unit.

Suppose f is a unit, i.e. $\exists g \in \mathbb{F}[x]$ s.t. $fg = 1$.

$$0 = \deg(fg) = \deg(f) + \deg(g) \Rightarrow \deg(f), \deg(g) \geq 0 \Rightarrow \deg(f) = 0, \deg(g) = 0. \quad \square$$

5.4 Irreducible Polynomials: “无法分解为两个 $\deg \geq 1$ 的多项式积”的多项式: 至少一个是 constant (i.e. $\deg = 0$)

A nonconstant polynomial f is irreducible if $f = uv$, $u, v \in \mathbb{F}[x]$, then either u or v is a unit(i.e., constant $\neq 0$)

5.5 Theorem 2.3.6: nonconstant polynomials 可以被唯一地分解

Theorem 8 (Theorem 2.3.6). Suppose \mathbb{F} is a field and $f \in \mathbb{F}[x]$ is any nonconstant. Then $f = ap_1p_2 \dots p_k$ where $a \in \mathbb{F}$, $p_1, \dots, p_k \in \mathbb{F}[x]$ are irreducible monic polynomials (monic = i.e. leading coeff. 1). If $f = bq_1q_2 \dots q_r$ with $b \in \mathbb{F}$ and $q_1, q_2, \dots, q_r \in \mathbb{F}[x]$ monic irreducible, then $a = b, k = r$, and after reindexing $p_i = q_i, \forall i$

Lemma 3 (Lemma 2.3.7). Suppose \mathbb{F} is a field and $f \in \mathbb{F}[x]$ is nonconstant monic polynomial. Then $f = p_1p_2 \dots p_k$ where each p_i is monic irreducible.

证明.

Prove it by induction. When $\deg(f) = 1$, $f = uv$, $u, v \in \mathbb{F}[x]$, $\deg(f) = \deg(u) + \deg(v) \Rightarrow$ one of these is 0.

Suppose the lemma holds for all degree $< n$. When $\deg(f) = n$,

Either f is irreducible, done.

Suppose $f = uv$ with $\deg(u), \deg(v) \geq 1$

$\Rightarrow \deg(u), \deg(v) < n \Rightarrow u = p_1p_2 \dots p_k, v = q_1q_2 \dots q_j$ So, $f = p_1p_2 \dots p_kq_1q_2 \dots q_j$. □

Example 7. $x^2 - 1 \in \mathbb{Q}[x]$ reducible

$x - 1, x + 1 \in \mathbb{Q}[x]$ irreducible

$x^2 + 1 \in \mathbb{Q}[x]$ irreducible

$x^2 + 1 \in \mathbb{C}[x]$ reducible

$x^2 - 1 = x^2 + 1 = [1]x^2 + [1] \in \mathbb{Z}_2[x]$ reducible

5.6 Divisibility of Polynomials

$f, g \in \mathbb{F}[x], f \neq 0$, f divides g , $f|g$ means $\exists u \in \mathbb{F}[x]$ s.t. $g = fu$.

Proposition 16 (Proposition 2.3.8). $f, h, g \in \mathbb{F}[x]$, then

- (i) If $f \neq 0, f|0$
- (ii) If $f|1$, f is nonzero constant
- (iii) If $f|g$ and $g|f$, then $f = cg$ for some $c \in \mathbb{F}$
- (iv) If $f|g$ and $g|h$, then $f|h$
- (v) If $f|g$ and $f|h$, then $f|(ug + vh)$ for all $u, v \in \mathbb{F}[x]$.

5.6.1 Greatest common divisor of f and g : is not unique, we denote monic Greatest common divisor as $\gcd(f, g)$

If $f, g \in \mathbb{F}[x]$ are nonzero polynomials, a greatest common divisor of f and g is a polynomial $h \in \mathbb{F}[x]$ such that

(i) $h|f$ and $h|g$, and

(ii) if $k \in \mathbb{F}[x]$ and $k|f$ and $k|g$, then $k|h$.

the gcd is not unique, but the monic gcd is unique. We call it **the monic greatest common divisor**, denote it $gcd(f, g)$.

Example 8.

$$\begin{aligned} x^2 - 1, x^2 - 2x + 1 &\in \mathbb{Q}[x] \\ (x - 1)(x + 1), (x - 1)^2 &\in \mathbb{Q}[x] \\ x - 1 &= gcd(x^2 - 1, x^2 - 2x + 1) \end{aligned}$$

5.6.2 Proposition 2.3.9: Euclidean Algorithm of polynomials

Proposition 17 (Proposition 2.3.9). *Given $f, g \in \mathbb{F}[x]$, $g \neq 0$, then $\exists q, r \in \mathbb{F}[x]$ s.t. $deg(r) < deg(g)$ and $f = qg + r$*

Example 9.

$$\begin{aligned} f &= 3x^3 - 5x^2 - 3x + 5, g = x^3 - 2x^2 + 1 \in \mathbb{Q}[x] \\ f &= 3g + x^2 - 3x + 2 \end{aligned}$$

5.6.3 Proposition 2.3.10: $gcd(f, g)$ 是 degree 最小的 f, g 的线性组合

Proposition 18 (Proposition 2.3.10). *Any 2 nonzero polynomials $f, g \in \mathbb{F}[x]$ have a gcd in $\mathbb{F}[x]$. In fact among all polynomials in the set $M = \{uf + vg | u, v \in \mathbb{F}[x]\}$ any nonconstant of minimal degree are $gcds$.*

证明.

$h \in M$, $deg(h) = d$ minimal. Let $k|f$ and $k|g \Rightarrow k|uf + vg$, $\forall u, v \Rightarrow k|h$.

Suppose $h' \in M$ is any nonzero element. $deg(h') \geq deg(h) \Rightarrow \exists q, r \in \mathbb{F}[x], deg(r) < deg(h)$ $h' = qh + r$. $r = h' - qh \in M$. Since $deg(h) = d$ is nonconstant minimal degree, $r = 0 \Rightarrow h' = qh$. So $\exists q_1, q_2 \in \mathbb{F}[x]$, $1f + 0g = q_1h, 0f + 1g = q_2h \Rightarrow h|g, h|f$. \square

Example 10.

$$\begin{aligned} f &= 3x^3 - 5x^2 - 3x + 5, g = x^3 - 2x^2 + 1 \in \mathbb{Q}[x] \\ f &= 3g + x^2 - 3x + 2 \\ g &= (x + 1)(x^2 - 3x + 2) + x - 1 \\ x^2 - 3x + 2 &= (x - 2)(x - 1) \\ \Rightarrow gcd(f, g) &= x - 1 \\ x - 1 &= g - (x + 1)(x^2 - 3x + 2) = g - (x + 1)(f - 3g) = (3x + 4)g - (x + 1)f \end{aligned}$$

Example 11. *Find a greatest common divisor of $f = x^3 - x^2 - x + 1$ and $g = x^2 - 3x + 2$ in $\mathbb{Q}[x]$, and express it in form $uf + vg$, $u, v \in \mathbb{Q}[x]$.*

$$f = (x + 2)g + 3x - 3$$

$$g = \frac{1}{3}(x - 2)(3x - 3)$$

$$\gcd(f, g) = 3x - 3$$

$$3x - 3 = f - (x + 2)g$$

5.6.4 Proposition 2.3.12: $\gcd(f, g) = 1, f|gh \Rightarrow f|h$

Proposition 19 (Proposition 2.3.12). *If $f, g, h \in \mathbb{F}[x]$, $\gcd(f, g) = 1$, and $f|gh$, then $f|h$.*

5.6.5 Corollary 2.3.13: irreducible f , $f|gh \Rightarrow f|g$ or $f|h$

Corollary 6 (Corollary 2.3.13). *If $f \in \mathbb{F}[x]$ is irreducible, and $f|gh$, then $f|g$ or $f|h$.*

Since f is irreducible, we have two possible situations:

1. $\gcd(f, g) = f$, i.e. $f|g$ done.
2. $\gcd(f, g) = 1$, then according to Prop 2.3.12, we can know $f|h$.

5.7 Roots

Root: $\alpha \in \mathbb{F}$ is a root of f if $f(\alpha) = 0$.

5.7.1 Corollary 2.3.16(of Euclidean Algorithm): f 可被分为 $(x - \alpha)q + f(\alpha)$ i.e. if α is a root, then $(x - \alpha)|f$

Corollary 7 (Corollary 2.3.16(of Euclidean Algorithm)). $\forall f \in \mathbb{F}[x]$ and $\alpha \in \mathbb{F}$, there exists a polynomial $q \in \mathbb{F}[x]$ s.t. $f = (x - \alpha)q + f(\alpha)$. In particular, if α is a root, then $(x - \alpha)|f$.

5.8 Multiplicity

If α is a root of f , say its *multiplicity* is m , if $x - \alpha$ appears m times in irreducible factorization.

5.8.1 Sum of multiplicity $\leq \deg(f)$

Proposition 20 (Proposition 2.3.17). *Given a nonconstant polynomial $f \in \mathbb{F}[x]$, the number of roots of f , counted with multiplicity, is at most $\deg(f)$.*

5.9 Roots in a field may not in its subfield

Note if $\mathbb{F} \subset \mathbb{K}$, then $\mathbb{F}[x] \subset \mathbb{K}[x]$. $f \in \mathbb{F}[x]$ may have no roots in \mathbb{F} , but could have roots in \mathbb{K}

Example 12. $x^n - 1 \in \mathbb{Q}[x]$ has a root in \mathbb{Q} : 1; has 2 roots if n even: ± 1

roots in \mathbb{C} : $\zeta_n = e^{\frac{2\pi i}{n}}$, then $\zeta_n^n = e^{2\pi i} = 1$; $(\zeta_n^k)^n = e^{2\pi ki} = 1$ So, the roots: $\{e^{\frac{2\pi ki}{n}} | k = 0, \dots, n-1\}$
The roots of $x^n - d$: $\{e^{\frac{2\pi ki}{n}} \sqrt[n]{d} | k = 0, \dots, n-1\}$

6 Linear Algebra

6.1 Vector Space $(V, +, \times)$ (over a field \mathbb{F})

A vector space over a field \mathbb{F} is a set V w/ an operation addition $+: V \times V \rightarrow V$ and an operation scalar multiplication $\mathbb{F} \times V \rightarrow V$

- (1) Addition is associative & commutative
- (2) $\exists 0 \in V$, additive identity: $0 + v = v \forall v \in V$
- (3) $1v = v \forall v \in V$ (where $1 \in \mathbb{F}$ is multi. id. in \mathbb{F})
- (4) $\forall \alpha, \beta \in \mathbb{F}, v \in V, \alpha(\beta v) = (\alpha\beta)v$
- (5) $\forall v \in V, (-1)v = -v$ we have $v + (-v) = 0$
- (6) $\forall \alpha \in \mathbb{F}, v, u \in V, \alpha(v + u) = \alpha v + \alpha u$
- (7) $\forall \alpha, \beta \in \mathbb{F}, v \in V, (\alpha + \beta)v = \alpha v + \beta v$

6.1.1 A field is a vector space over its subfield

Example 13. $\mathbb{K} \subset \mathbb{F}$ is a subfield of a field \mathbb{F} . Then \mathbb{F} is a vector space over \mathbb{K} . (Since $\mathbb{F} \subset \mathbb{F}[x]$, then $\mathbb{F}[x]$ is a vector space over \mathbb{F} .)

6.1.2 Vector subspace

Suppose that V is a vector space over \mathbb{F} . A vector subspace or just subspace is a nonempty subset $W \subset V$ closed under addition and scalar multiplication. i.e. $v + w \in W, av \in W, \forall v, w \in W, a \in \mathbb{F}$.

Example 14. $\mathbb{K} \subset \mathbb{L} \subset \mathbb{F}$, then \mathbb{L} is a subspace of \mathbb{F} over \mathbb{K} .

6.2 Linear independent, Linear combination

6.3 span V , basis, dimension, Proposition 2.4.10

A set of elements $v_1, \dots, v_n \in V$ is said to **span** V if every vector $v \in V$ can be expressed as a linear combination of v_1, \dots, v_n . If v_1, \dots, v_n spans and is linearly independent, then we call the set a **basis** for V .

Proposition 21 (Proposition 2.4.10.). Suppose V is a vector space over a field \mathbb{F} having a basis $\{v_1, \dots, v_n\}$ with $n \geq 1$.

- (i) For all $v \in V$, $v = a_1v_1 + \dots + a_nv_n$ for exactly one $(a_1, \dots, a_n) \in \mathbb{F}^n$.
- (ii) If w_1, \dots, w_n span V , then they are linearly independent.
- (iii) If w_1, \dots, w_n are linearly independent, then they span V .

If a vector space V over \mathbb{F} has a basis with n vectors, then V is said to be n -dimensional (over \mathbb{F}) or is said to have **dimension** n .

6.3.1 Standard basis vectors

$$e_1 = (1, 0, \dots, 0), e_2 = (0, 1, 0, \dots, 0), \dots, e_n = (0, 0, \dots, 0, 1) \in \mathbb{F}^n$$

are a basis for \mathbb{F}^n called the **standard basis vectors**.

6.4 Linear transformation

Given two vector spaces V and W over \mathbb{F} a **linear transformation** is a function $T : V \rightarrow W$ such that for all $a \in \mathbb{F}$ and $v, w \in V$, we have

$$T(av) = aT(v) \text{ and } T(v + w) = T(v) + T(w)$$

Proposition 22 (Proposition 2.4.15.). *If V and W are vector spaces and v_1, \dots, v_n is a basis for V then any function from $\{v_1, \dots, v_n\} \rightarrow W$ extends uniquely to a linear transformation $V \rightarrow W$.*

Any $v \in V$, $\exists(a_1, \dots, a_n)$ s.t. $v = a_1v_1 + \dots + a_nv_n$. Then $T(v) = T(a_1v_1 + \dots + a_nv_n) = a_1T(v_1) + \dots + a_nT(v_n)$

6.4.1 Corollary 2.4.16: 一个线性变换对应一个矩阵 **bijection** $\mathcal{L}(V, M) \rightarrow M_{m \times n}(\mathbb{F})$

Corollary 8 (Corollary 2.4.16.). *If v_1, \dots, v_n is a basis for a vector space V and w_1, \dots, w_m is a basis for a vector space W (both over \mathbb{F}), then any linear transformation $T : V \rightarrow W$ determines (and is determined by) the $m \times n$ matrix:*

$$A = A(T) = \begin{bmatrix} A_{11} & A_{12} & \dots & A_{1n} \\ A_{21} & A_{22} & \dots & A_{2n} \\ \vdots & \vdots & \dots & \vdots \\ A_{m1} & A_{m2} & \dots & A_{mn} \end{bmatrix}$$

$$\begin{bmatrix} w_1 & \dots & w_m \end{bmatrix}^T = A \begin{bmatrix} v_1 & \dots & v_n \end{bmatrix}^T$$

$\mathcal{L}(V, M)$ denotes the set of all linear transformations from V to W ; $M_{m \times n}(\mathbb{F})$ the set of $m \times n$ matrix with entries in \mathbb{F} . $T \rightarrow A(T)$ defines a **bijection** $\mathcal{L}(V, M) \rightarrow M_{m \times n}(\mathbb{F})$. $A(T)$ **represents the linear transformation** T .

6.4.2 Proposition 2.4.19: 线性变换矩阵相乘仍为线性变换矩阵

Proposition 23 (Proposition 2.4.19). *Suppose that V , W , and U are vector spaces over \mathbb{F} , with fixed chosen bases. If $T : V \rightarrow W$ and $S : W \rightarrow U$ are linear transformations represented by matrices $A = A(T)$ and $B = B(S)$, then $ST = S \circ T : V \rightarrow U$ is a linear transformation represented by the matrix $BA = B(S)A(T)$.*

6.5 $GL(V)$: invertible(bijective) linear transformations $V \rightarrow V$

Given a vector space V over F , we let $GL(V) \subset \mathcal{L}(V, V)$ denote the subset of **invertible linear transformations**.

$$GL(V) = \{T \in \mathcal{L}(V, V) | T \text{ is a bijection}\} = \mathcal{L}(V, V) \cap Sym(V)$$

7 Euclidean geometry basics

7.1 Euclidean distance, inner product

Euclidean distance on \mathbb{R}^n :

$$|x - y| = \sqrt{(x_1 - y_1)^2 + \dots + (x_n - y_n)^2}$$

Euclidean inner product:

$$x \cdot y = x_1 y_1 + \dots + x_n y_n = x^T y$$

7.2 Isometry of \mathbb{R}^n : a bijection $\mathbb{R}^n \rightarrow \mathbb{R}^n$ preserves distance

An **isometry** of \mathbb{R}^n is a bijection $\Phi : \mathbb{R}^n \rightarrow \mathbb{R}^n$ that preserves distance, which means,

$$|\Phi(x) - \Phi(y)| = |x - y|, \quad \forall x, y \in \mathbb{R}^n$$

7.2.1 $Isom(\mathbb{R}^n)$: set of all isometries of \mathbb{R}^n

We use $Isom(\mathbb{R}^n)$ denotes the set of all isometries of \mathbb{R}^n ,

$$Isom(\mathbb{R}^n) = \{\Phi : \mathbb{R}^n \rightarrow \mathbb{R}^n | |\Phi(x) - \Phi(y)| = |x - y|, \quad \forall x, y \in \mathbb{R}^n\}$$

7.2.2 $Isom(\mathbb{R}^n)$ is closed under \circ and inverse

Proposition 24. $\Phi, \Psi \in Isom(\mathbb{R}^n)$, then $\Phi \circ \Psi, \Phi^{-1} \in Isom(\mathbb{R}^n)$

证明.

Since Φ, Ψ are bijections, so is $\Phi \circ \Psi$. Moreover,

$$|\Phi \circ \Psi(x) - \Phi \circ \Psi(y)| = |\Phi(\Psi(x)) - \Phi(\Psi(y))| = |\Psi(x) - \Psi(y)| = |x - y|$$

Since $id \in Isom(\mathbb{R}^n)$,

$$|x - y| = |id(x) - id(y)| = |\Phi \circ \Phi^{-1}(x) - \Phi \circ \Phi^{-1}(y)| = |\Phi^{-1}(x) - \Phi^{-1}(y)|$$

□

7.3 $A \in GL(n, \mathbb{R})$, $T_A(v) = Av$: $A^t A = I \Leftrightarrow T_A \in Isom(\mathbb{R}^n)$

There is a matrix $A \in GL(n, \mathbb{R})$ i.e. a *invertible linear transformations* $T_A : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is given by $T_A(v) = Av$.

$$T_A(v) \cdot T_A(w) = (Av) \cdot (Aw) = (Av)^t(Aw) = v^t A^t Aw$$

$$A^t A = I \Leftrightarrow T_A(v) \cdot T_A(w) = v \cdot w \Leftrightarrow_{(HW4)} T_A \in Isom(\mathbb{R}^n)$$

7.4 Linear isometries i.e. orthogonal group $O(n) = \{A \in GL(n, \mathbb{R}) | A^t A = I\}$

We define the all isometries in *invertible linear transformations* $\mathbb{R}^n \rightarrow \mathbb{R}^n$ as **orthogonal group**

$$O(n) = \{A \in GL(n, \mathbb{R}) | A^t A = I\} \subset GL(n, \mathbb{R})$$

7.4.1 Special orthogonal group $SO(n) = \{A \in O(n) | \det(A) = 1\}$: **orthogonal group with $\det(A) = 1$**

$O(n)$ are the matrices representing linear isometries of \mathbb{R}^n . $1 = \det(I) = \det(A^t A) = \det(A^t) \det(A) = \det(A)^2 \Rightarrow \det(A) = 1$ or $\det(A) = -1$. We use **special orthogonal group** represents A with $\det(A) = 1$,

$$SO(n) = \{A \in O(n) | \det(A) = 1\}$$

7.5 translation: $\tau_v(x) = x + v$

Define a *translation* by $v \in \mathbb{R}^n$,

$$\tau_v : \mathbb{R}^n \rightarrow \mathbb{R}^n, \tau_v(x) = x + v$$

7.5.1 translation is an isometry

Note 3 (Exercise 2.5.3). $\forall v \in \mathbb{R}^n, \tau_v$ is an isometry.

证明. $|\tau_v(x) - \tau_v(y)| = |(x + v) - (y + v)| = |x - y|$

□

7.6 The composition of a translation and an orthogonal transformation is an isometry $\Phi_{A,v}(x) = \tau_v(T_A(x)) = Ax + v$

Since *the composition of isometries is an isometry*, $\forall A \in O(n)$ and $v \in \mathbb{R}^n$, the composition

$$\Phi_{A,v}(x) = \tau_v(T_A(x)) = Ax + v$$

is an isometry. **which could account for all isometries.**

7.6.1 Theorem 2.5.3: All isometries can be represented by a composition of a *translation* and an *orthogonal transformation*, $Isom(\mathbb{R}^n) = \{\Phi_{A,v} | A \in O(n), v \in \mathbb{R}^n\}$

Theorem 9 (Theorem 2.5.3). $Isom(\mathbb{R}^n) = \{\Phi_{A,v} | A \in O(n), v \in \mathbb{R}^n\}$

8 Group $(G, *)$: a set with an operation (associative, identity, inverse)

A *group* is a nonempty set G with an operation $*$: $G \times G \rightarrow G$ s.t. the following holds

- (1) $*$ is associative
- (2) $\exists e \in G$ an identity element $e * g = g * e = g \ \forall g \in G$
- (3) $\forall g \in G, \exists g^{-1} \in G$ s.t. $g * g^{-1} = g^{-1} * g = e$

8.1 $(Sym(X), \circ)$ symmetric/permutation group of X

Example 15. If X is any nonempty set, permutation group of $X : \{\sigma : X \rightarrow X | \sigma \text{ is a bijection}\}$, then

1. \circ is associative;
2. $id : X \rightarrow X, id(x) = x \ \forall x \in X$ is the identity;
3. $\sigma \in Sym(X), \sigma^{-1} \in Sym(X)$ is the inverse function.

$(Sym(X), \circ)$ is a group called the symmetric group of X

8.2 Order of a group $(G, *)$

$|G|$ = Order of a group $(G, *)$

8.3 Abelian group (group that $*$ satisfies commutative)

$(\mathbb{Z}, +)$ is a group and $+$ is commutative, we call this kind of groups (satisfy commutative) *abelian group*.

Example 16. If \mathbb{F} is a field, then $(\mathbb{F}, +)$ and $(\mathbb{F}^\times, \cdot)$ are abelian group.

Example 17. If V is a vector space over \mathbb{F} , then $(V, +)$ abelian group.

As we know a V is a vector space over \mathbb{F} means V is a field whose subfields include \mathbb{F} .

8.4 H : Subgroup of $(G, *)$ ($H \neq \emptyset \subset G$ closed under $*$; inverse $g^{-1} \in H$), written as $H < G$

$H \neq \emptyset \subset G$ is a *subgroup* of $(G, *)$ if,

1. $\forall g, h \in H, g * h \in H$.

2. $\forall g \in H, g^{-1} \in H$.

write $H < G$ if H is a subgroup of $(G, *)$.

8.4.1 Proposition 2.6.8: $H < G, (H, *)$ is a group: A group's operation with its any subgroup is also a group

Proposition 25 (Proposition 2.6.8). *If $(G, *)$ is a group, $H \subset G$ is a subgroup, then $(H, *)$ is a group.*

Example 18. $(G, *)$ is a group, then $e < G, G < G$.

Example 19. $\mathbb{K} \subset \mathbb{F}$ is a subfield, then $\mathbb{K} < \mathbb{F}, \mathbb{K}^\times < \mathbb{F}^\times$.

Example 20. $W \subset V$ is a vector subspace, $W < V$.

Example 21. $1 \in S^1 \subset \mathbb{C}^\times, S^1 = \{z \in \mathbb{C} \mid |z| = 1\}$. S^1 is a subgroup.

证明.

$S^1 = \{e^{i\theta} \mid \theta \in \mathbb{R}\}$. For any $e^{i\theta}, e^{i\psi} \in S^1, e^{i\theta}e^{i\psi} = e^{i(\theta+\psi)} \in S^1, e^{-i\theta} \in S^1$. □

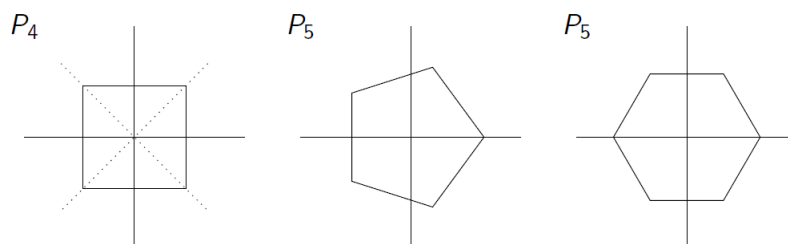
Example 22. $Isom(\mathbb{R}^n) < Sym(\mathbb{R}^n)$

Example 23. If \mathbb{F} is a field, $Aut(\mathbb{F}) = \{\sigma : \mathbb{F} \rightarrow \mathbb{F} \in Sym(\mathbb{F}) \mid \sigma(a+b) = \sigma(a) + \sigma(b), \sigma(ab) = \sigma(a)\sigma(b)\} < Sym(\mathbb{F})$

Example 24. *Dihedral Groups:*

保留多边形

Let $P_n \subset \mathbb{R}^2$ be a regular n -gon



$D_n < Isom(\mathbb{R}^2), D_n = \{\Phi \in Isom(\mathbb{R}^2) \mid \Phi(P_n) = P_n\}$

9 Ring $(R, +, \cdot)$: $+$ is associative, commutative, identity, inverse $\in R$; \cdot is associative, distributes over $+$

Definition 1. A ring is a nonempty set with two operations, called addition and multiplication, $(R, +, \cdot)$ such that

- (1): $(R, +)$ is an abelian group: i.e. $+$ is associative and commutative. $0, -a \in R$
- (2): \cdot is associative.
- (3): \cdot distributes over $+$: $\forall a, b, c \in R, a \cdot (b + c) = a \cdot b + a \cdot c$ and $(b + c) \cdot a = b \cdot a + c \cdot a$

9.1 Commutative ring: ring's \cdot is commutative

If " \cdot " is commutative, we call $(R, +, \cdot)$ a commutative ring.

9.2 Ring with 1: exists multiplication identity $1 \in R$

If there exists an element $1 \in R \setminus \{0\}$ such that $a1 = 1a = a, \forall a \in R$, then we say that R is a ring with 1.

9.3 Field \mathbb{F} is a commutative ring with 1; $\mathbb{F}[x]$ is also a commutative ring with 1

Field $(\mathbb{F}, +, \cdot)$ (close, associative, commutative, distributive(M over A), identity & inverse(M,A))

Proposition 2.3.2: Polynomial ring (close, associative, commutative, distributive(M over A), identity(M,A), inverse(only A))

9.4 $S \subset R$: Subring (closed under $+$ and \cdot ; additive inverse $-a \in S$)

9.4.1 Proposition 2.6.27: $(S, +, \cdot)$ is a ring

Proposition 26 (Proposition 2.6.27). If $S \subset R$ is a subring, then $+, \cdot$ make S into a ring.

10 Group theory

10.1 Properties of Group Operation

10.1.1 Proposition 3.1.1: $g * h = h$ or $h * g = h$, then $g = e$; $g * h = e$ then $g = h^{-1}$ and $h = g^{-1}$

Proposition 27 (Proposition 3.1.1). Let $(G, *)$ be a group with identity $e \in G$, then

- (1) if $g, h \in G$ and either $g * h = h$ or $h * g = h$, then $g = e$
- (2) if $g, h \in G$ and $g * h = e$ then $g = h^{-1}$ and $h = g^{-1}$

10.1.2 Corollary 3.1.: $e^{-1} = e$, $(g^{-1})^{-1} = g$, $(g * h)^{-1} = h^{-1} * g^{-1}$

Corollary 9 (Corollary 3.1.2). $e^{-1} = e$, $(g^{-1})^{-1} = g$, $(g * h)^{-1} = h^{-1} * g^{-1}$

10.1.3 Proposition 3.1.3: $g * h = k * h$ or $h * g = h * k$, then $g = k$

Proposition 28 (Proposition 3.1.3). *If $g * h = k * h$ or $h * g = h * k$, then $g = k$.*

10.1.4 Proposition 3.1.4: $g * x = h$ and $x * g = h$ have unique solutions $x \in G$.

Proposition 29 (Proposition 3.1.4). *$g * x = h$ and $x * g = h$ have unique solutions $x \in G$.*

10.2 Power of an Element

We define g^n recursively for $n \geq 0$ by setting $g^0 = e$ and for $n \geq 1$, we set $g^n = g^{n-1} * g$. For $n \leq 0$, we define $g^n = (g^{-1})^{-n}$.

10.2.1 Proposition 3.1.5: $g^n * g^m = g^{n+m}$, $(g^n)^m = g^{nm}$

Proposition 30 (Proposition 3.1.5). (1) $g^n * g^m = g^{n+m}$; (2) $(g^n)^m = g^{nm}$

10.3 $(G \times H, \otimes)$: Direct Product of G and H

$(G, *)$ a group (H, \star) a group. Define an operation on $G \times H$, \otimes :

$$(h, k) \otimes (h', k') = (h * h', k * k')$$

10.3.1 Proposition 3.1.7: $(G \times H, \otimes)$ is a group

Proposition 31 (Proposition 3.1.7). $(G \times H, \otimes)$ is a group. The identity is (e_G, e_H) , inverse is (g^{-1}, h^{-1})

usually written as

$$(h, k)(h', k') = (hh', kk')$$

10.4 Subgroups and cyclic groups

10.4.1 Proposition 3.2.2: Intersection of a Collection of Subgroups is a group

Proposition 32 (Proposition 3.2.2). *Let G be a group and suppose \mathcal{H} is any collection of subgroups of G . Then $K = \bigcap_{H \in \mathcal{H}} H < G$ is a subgroup of G .*

10.4.2 Subgroup Generated by A : $\langle A \rangle = \cap_{H < G; A \subset H} H$

We define **Subgroup Generated by A** :

$$\langle A \rangle = \cap_{H \in \mathcal{H}(A)} H$$

where $\mathcal{H}(A)$ is the set of all subgroups of G containing the set A :

$$\mathcal{H}(A) = \{H < G \mid A \subset H \text{ and } H \text{ is a subgroup of } G\}$$

10.4.3 Cyclic Subgroup generated by a : $\langle a \rangle = \cap_{H < G; a \in H} H$ (G is cyclic if exists g , $\langle g \rangle = G$)

If $A = \{a\}$, then $\langle a \rangle (= \langle \{a\} \rangle)$ = the cyclic subgroup generated by a

Say G is cyclic if $\exists g \in G$, s.t. $G = \langle g \rangle$; g is called a generator for G in this case.

10.4.4 **Proposition 3.2.3**: $\langle g \rangle = \{g^n \mid n \in \mathbb{Z}\}$

Proposition 33 (Proposition 3.2.3). *Let G be a group, $g \in G$. Then*

$$\langle g \rangle = \{g^n \mid n \in \mathbb{Z}\}$$

10.4.5 **Corollary 3.2.4**: G is a cyclic group $\Rightarrow G$ is abelian

Corollary 10 (Corollary 3.2.4). *If G is a cyclic group (i.e. exists $g \in G$ s.t. $\langle g \rangle = G$), then G is abelian (i.e. commutative).*

10.4.6 **Equivalent properties of order of g** : $|g| = |\langle g \rangle| < \infty$

Proposition 34 (Proposition 3.2.6). *Let G be a group for $g \in G$, the following are equivalent:*

- (i) $|g| < \infty$
- (ii) $\exists n \neq m$ in \mathbb{Z} so that $g^n = g^m$
- (iii) $\exists n \in \mathbb{Z}$, $n \neq 0$ so that $g^n = e$
- (iv) $\exists n \in \mathbb{Z}_+$ so that $g^n = e$

If $|g| < \infty$, then $|g|$ = smallest $n \in \mathbb{Z}_+$ so that $g^n = e$, and $\langle g \rangle = \{e, g, g^2, \dots, g^{n-1}\} = \{g^n \mid n = 0, \dots, n-1\}$

10.4.7 $(\mathbb{Z}, +)$ **Theorem 3.2.9**: $H < \mathbb{Z}$ is a subgroup $\Rightarrow H = \{0\}$ or $H = \langle d \rangle$; $\langle a \rangle < \langle b \rangle$ if and only if $b \mid a$

Theorem 10 (Theorem 3.2.9). *If $H < \mathbb{Z}$ is a subgroup, then either $H = \{0\}$, or else $H = \langle d \rangle$, where*

$$d = \min\{h \in H \mid h > 0\}$$

*Consequently, $a \mapsto \langle a \rangle$ defines a **bijection** from $N = \{0, 1, 2, \dots\}$ to the set of subgroups of \mathbb{Z} . Furthermore, for $a, b \in \mathbb{Z}_+$, we have $\langle a \rangle < \langle b \rangle$ if and only if $b \mid a$.*

10.4.8 $(\mathbb{Z}_n, +)$ **Theorem 3.2.10:** $H < \mathbb{Z}_n$ is a subgroup $\Rightarrow H = \langle [d] \rangle$; $\langle [d] \rangle < \langle [d'] \rangle$ if and only if $d' | d$

Theorem 11 (Theorem 3.2.10). For any $n \geq 2$, if $H < \mathbb{Z}_n$ is a subgroup, then there is a positive divisor d of n so that

$$H = \langle [d] \rangle$$

Furthermore, this defines a bijection between divisors of H and subgroups of \mathbb{Z}_n . Furthermore, if $d, d' > 0$ are two divisors of n , then $\langle [d] \rangle < \langle [d'] \rangle$ if and only if $d' | d$.

If $H = \langle [d] \rangle$ is a subgroup of H , then $[n] \in H$, so $d | n$. And $|H| = |\langle [d] \rangle| = \frac{n}{d}$, so $|H| | d$

10.4.9 Subgroup Lattice

The set of all subgroups of a group of G , together with the data of which subgroups contain which others is called the **subgroup lattice**. We often picture the subgroup lattice in a diagram with the entire group at the top, the trivial subgroup $\{e\}$ at the bottom, and the intermediate subgroups in the middle, with lines drawn from subgroups up to larger groups.

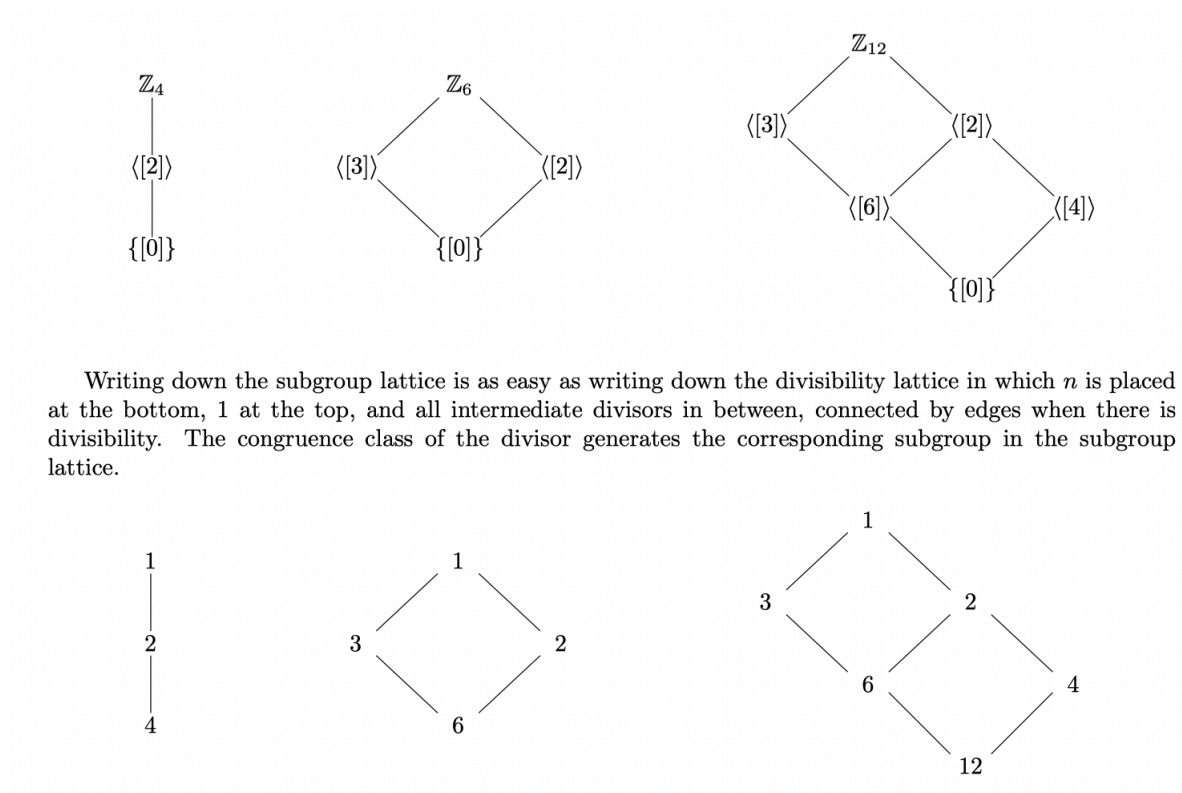


图 1:

参考文献

- [1] Christopher J Leininger Introduction to Abstract Algebra (Draft) 2017.