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Chapter 1

Unique Factorization

1.1 Class Notes 17-01-12

For us, ring means commutative ring with identity.

Definition 1.1.1 A *ring* is a set with two binary operations $(+, \cdot)$ satisfying

1. $(R, +)$ is an *abelian group*, which means
 - $+$ is commutative and associative.
 - $\exists 0_R, a + 0_R = 0_R + a$ for all $a \in R$.
 - Given $a \in R$, $\exists a' \in R$ such that $a + a' = 0_R$.
2. \cdot is commutative and associative.
 $\exists 1_R$ such that $a \cdot 1_R = 1_R \cdot a = a$ for all $a \in R$.
3. \cdot is distributive over addition, which means
 - $a \cdot (b + c) = a \cdot b + a \cdot c$
 - $(a + b) \cdot c = a \cdot c + b \cdot c$

Exercise 1.1.1

1. Show that $a + b = a + c \Rightarrow b = c$. (Cancellation)

Proof.

$$\begin{aligned} a + b = a + c &\Leftrightarrow a' + (a + b) = a' + (a + c) \\ &\Leftrightarrow (a' + a) + b = (a' + a) + c \\ &\Leftrightarrow 0_R + b = 0_R + c \\ &\Leftrightarrow b = c \end{aligned}$$

■

2. Show a' is unique. We denote this a' by $-a$.

Proof. if the statement doesn't hold, then there exist a', a'' such that $a + a' = 0_R = a + a''$. We then apply cancellation and get $a' = a''$. ■

3. Show 0_R is unique.

Proof. Say there are two zero element 0_R and $0'_R$, then we have

$$0_R = 0_R + 0'_R = 0'_R$$

■

4. Show 1_R is unique.

Proof. Say there are two unit element 1_R and $1'_R$, then we have

$$1_R = 1_R \cdot 1'_R = 1'_R$$

■

5. Show $a \cdot 0_R = 0_R \cdot a = 0_R$

Proof. We know that $a \cdot 0_R + a = a \cdot (0_R + 1_R) = a \cdot 1_R = a = 0_R + a$, apply cancellation then we are done. ■

6. Show that $(-1_R) \cdot a = -a$.

Proof. Since $a \cdot 0_R = 0_R$, we have $a \cdot (1_R + (-1_R)) = 0_R$ or $a + (-1_R) \cdot a = 0_R$. Then $-a = (-1_R) \cdot a$, for a' is unique. ■

7. The zero ring is the ring with 1 element. Show R is zero ring $\Leftrightarrow 1_R = 0_R$.

Proof.

“ \Rightarrow ” : Trivial.

“ \Leftarrow ” : Since we have $a \cdot 1_R = 1_R \cdot a = a$ for all $a \in R$ and $1_R = 0_R$, we have $0_R = a \cdot 0_R = a$ for all $a \in R$. ■

8. Does cancellation hold for \cdot ?

Sol. No. Consider $a \cdot b = a \cdot c$ and $a \neq 0_R$, then $a \cdot (b - c) = 0_R$. So if R is an *integral domain*, then we can apply cancellation of non-zero element.

Definition 1.1.2 R is said to be an *integral domain* if

$$a \cdot b = 0 \iff a = 0 \text{ or } b = 0.$$

Definition 1.1.3 R is said to be a field if every non-zero element in R has a multiplication inverse.

Exercise 1.1.2

1. If R is an integral domain, then we can apply cancellation of non-zero element.
2. Show that every field is an integral domain.

Proof. If $a \cdot b = 0$ and $a \neq 0_R$, let a' be the multiplication inverse of a , then $b = 1_R \cdot b = a' \cdot a \cdot b = a' \cdot 0_R = 0$. ■

3. Check that a^{-1} is unique.

Proof. If a^{-1} and a' are both multiplication inverse of a , then $a \cdot a^{-1} = a \cdot a' = 1_R$. Apply cancellation of non-zero element, we have $a' = a^{-1}$. ■

Remark 1.1.1 Though every field is an integral domain, not every integral domain is a field. For example, \mathbb{Z} is an integral domain but not a field.

Ways to make new rings:

Let R be an integral domain, how to construct a new ring?

Let $K = \{(a, b), a, b \in R, b \neq 0\}$. We also define an equivalent relation $(a, b) \sim (c, d)$ if $ad = bc$.

- Check this is an equivalent class.
 - $(a, b) = (a, b)$
 - if $(a, b) \sim (c, d)$ and $(c, d) \sim (e, f)$, then $(a, b) \sim (e, f)$
- We define

- $(a, b) + (c, d) = (ad + bc, bd)$
- $(a, b) \cdot (c, d) = (ac, bd)$

Check these two operation pass to equivalent class.

- $0_K = [(0, 1_R)], 1_K = [(1_R, 1_R)]$

Definition 1.1.4 If R, S are two rings, a homomorphism $\phi : R \rightarrow S$ is a map such that

1. $\phi(1_R) = 1_S$.
2. $\phi(a + b) = \phi(a) + \phi(b)$.
3. $\phi(ab) = \phi(a)\phi(b)$.

An isomorphism is a homomorphism that is both injective and surjective.

$\phi : R \rightarrow S, a \mapsto [(a, 1_R)]$ is an injective homomorphism. For example, we have $\mathbb{Z} \subset \mathbb{Q}$.

Remark 1.1.2 If R is a field, then the homomorphism is isomorphism, i.e., ϕ is also surjective. Because for any $[(a, b)] \in K$, we have $\phi(ab^{-1}) = [(ab^{-1}, 1)] = [(a, b)]$.

Ways to kill elements:

Definition 1.1.5 An ideal I in R is a non-empty subset such that

1. I is closed under addition.
2. I is closed under multiplication by arbitrary elt in R .

Note that $(I, +) \subset (R, +)$ is an abelian subgroup.

■ Example 1

- (0) is an ideal.
- R itself is an ideal.
- if $a \in R$, the $R \cdot a$ is an ideal, denoted by $(a)_R$.
- $n\mathbb{Z}$ is an ideal in \mathbb{Z} .

Quotient Ring: Let $I \subset R$ be an ideal. $R/I =$ coset of I in $R = \{a + I, a \in R\}$, we define

1. $(a + I) \oplus (b + I) = (a + b) + I$.
2. $(a + I) \odot (b + I) = ab + I$.

with zero elt $(0 + I)$ and identity elt $(1 + I)$.

1.2 Unique Factorization in \mathbb{Z}

It will be more convenient to work with \mathbb{Z} rather than restricting ourselves to the positive integers. The notion of divisibility carries over with no difficulty to \mathbb{Z} . If p is a positive prime, $-p$ will also be a prime. We shall not consider 1 or -1 as primes even though they fit the definition. This is simply a useful convention. They are called the units of \mathbb{Z} .

There are a number of simple properties of division that we shall simply list.

1. $a \mid a, a \neq 0$.
2. If $a \mid b$ and $b \mid a$, then $a = \pm b$.
3. If $a \mid b$ and $b \mid c$, then $a \mid c$.
4. If $a \mid b$ and $a \mid c$, then $a \mid (b + c)$.

Lemma 1 Every nonzero integer can be written as a product of primes.

Theorem 1.2.1 For every nonzero integer n there is a prime factorization

$$n = (-1)^{\epsilon(n)} \prod_p p^{a(p)},$$

with the exponents uniquely determined by n . In fact, we have $a(p) = \text{ord}_p n$.

The proof of this theorem is not as easy as it may seem. We shall postpone the proof until we

have established a few preliminary results.

Lemma 2 If $a, b \in \mathbb{Z}$ and $b \geq 0$, there exist $q, r \in \mathbb{Z}$ such that $a = qb + r$ with $0 \leq r < b$.

Definition 1.2.1 If $a_1, a_2, \dots, a_n \in \mathbb{Z}$, we define (a_1, a_2, \dots, a_n) to be the set of all integers of the form $a_1x_1 + a_2x_2 + \dots + a_nx_n$ with $x_1, x_2, \dots, x_n \in \mathbb{Z}$.

Remark 1.2.1 Let $A = (a_1, a_2, \dots, a_n)$. Notice that the sum and difference of two elements in A are again in A . Also, if $a \in A$ and $r \in \mathbb{Z}$, then $ra \in A$, i.e., A is an ideal in the ring \mathbb{Z} .

Lemma 3 If $a, b \in \mathbb{Z}$, then there is a $d \in \mathbb{Z}$ such that $(a, b) = (d)$.

Definition 1.2.2 Let $a, b \in \mathbb{Z}$. An integer d is called a greatest common divisor of a and b if d is a divisor of both a and b and if every other common divisor of a and b divides d .

Remark 1.2.2 The gcd of two numbers, if it exists, is determined up to sign.

Lemma 4 Let $a, b \in \mathbb{Z}$. If $(a, b) = (d)$ then d is a greatest common divisor of a and b .

Definition 1.2.3 We say that two integers a and b are relatively prime if the only common divisors are ± 1 , the units.

It's fairly standard to use the notation (a, b) for the greatest common divisor of a and b . With this convention we can say that a and b are relatively prime if $(a, b) = 1$.

Proposition 1.2.2 Suppose that $a \mid bc$ and that $(a, b) = 1$. Then $a \mid c$.

Corollary 1.2.3 If p is a prime and $p \mid bc$, then either $p \mid b$ or $p \mid c$.

Corollary 1.2.4 Suppose that p is a prime and that $a, b \in \mathbb{Z}$. Then $\text{ord}_p ab = \text{ord}_p a + \text{ord}_p b$.

1.3 Class Notes 17-01-12

Definition 1.3.1 A non-zero element in \mathbb{R} is called a unit if $\exists v \in \mathbb{R}$ such that $uv = 1_{\mathbb{R}}$.

Definition 1.3.2 Two element $a, b \in \mathbb{R}$ are said to be associative if $\exists a \in \mathbb{R}$ such that $a = bu$, denoted by $a \sim b$.

Definition 1.3.3 A non-zero element π in \mathbb{R} is said to be irreducible if π is not a unit and if $a \mid \pi \Rightarrow a$ is a unit or a is associative of π .

Definition 1.3.4 A non-zero element in \mathbb{R} is said to be prime if π is not a unit and $\pi \mid ab \Rightarrow \pi \mid a$ or $\pi \mid b$, $\forall a, b \in \mathbb{R}$.

Proposition 1.3.1 If π is a prime, then π is irreducible.

Proof. Let π be a prime, suppose $a \mid \pi$, then $\pi = ab$ for some $b \in \mathbb{R}$. Thus $\pi \mid ab$ and by definition, $\pi \mid a$ or $\pi \mid b$.

- If $\pi \mid a$, then $a \sim \pi$.
- If $\pi \mid b$, then $a \sim 1$.

■

Remark 1.3.1 A irreducible is not necessary to be a prime.

Let $R = \mathbb{Z}[\sqrt{5}] = \{a + b\sqrt{5} \mid a, b \in \mathbb{Z}\} \subset \mathbb{C}$. We have

$$6 = 2 \cdot 3 = (1 + \sqrt{-5}) \cdot (1 - \sqrt{-5}).$$

We write $\pi = (1 + \sqrt{-5})$ and claim that $2, 3, \pi, \bar{\pi}$ are irreducibles but none of them are associative of each other.

We define the norm function $N : R \rightarrow \mathbb{Z}$, where $N(\alpha) = \alpha\bar{\alpha}$, i.e., if $\alpha = a + bi$, then $N(\alpha) = a^2 + 5b^2$. We notice that

- If $\alpha > 0$, then $N(\alpha) > 0$.
- $N(\alpha\beta) = N(\alpha)N(\beta)$.

Check: 2 is irreducible:

Find unit:

$N(uv) = N(1) = 1 = N(u)N(v) \Rightarrow N(u) = N(v) = 1$. But $a^2 + 5b^2 = 1 \Rightarrow a = \pm 1, b = 0$.

Suppose $2 = \alpha\beta$, then $4 = N(2) = N(\alpha\beta) = N(\alpha)N(\beta)$.

1. If $N(\alpha) = 1, N(\beta) = 4$
Then α is a unit $\Rightarrow 2$ is irreducible.
2. If $N(\alpha) = 2, N(\beta) = 2$
Then $a^2 + 5b^2 = 2$ has no solution.

Definition 1.3.5 An UFD (Unique Factorization Domain) is an integral domain R in which every non-zero element (up to unit) factors uniquely into a product of irreducibles.

Proposition 1.3.2 Let R be a domain in which factorization (of irreducibles) exists. Then R is a UFD \Leftrightarrow every irreducible in R is prime.

Proof.

“ \Leftarrow ” : Let a be an element of R and $a \neq 0$. If $a = \pi_1\pi_2 \cdots \pi_n = \sigma_1\sigma_2 \cdots \sigma_m$ are two factorizations. Since π_1 is prime, $\pi_1 \mid \sigma_i$ for some i . By rearranging, we may assume $\pi_1 \mid \sigma_1$. Thus $\pi_1 \sim \sigma_1$. Repeating this process, we can conclude that the two factorizations are the same.

*****Not Complete*****

■

Remark 1.3.2 There are clearly rings such that no factorization exists. For example, consider the ring $\mathbb{Z}[2^{1/2}, 2^{1/4}, 2^{1/8}, \dots] \subset \mathbb{R}$. It's the smallest subring of \mathbb{R} that contains $2^{1/2}, 2^{1/4}, \dots$

Definition 1.3.6 A ring R is said to be noetherian if it satisfies any of the following equivalent conditions:

1. Any ascending chain of ideals in R terminates.
Namely, $I_1 \subset I_2 \subset I_3 \subset \cdots \Rightarrow I_n = I_{n+1} = \cdots$ for some n .
2. Any ideal I in R is finite generated.
Namely, $I = (a_1, \dots, a_n)$ for some n .

Proof.

“1. \Rightarrow 2.” : Let I be an ideal, if $I \neq 0$, pick $a_1 \in I, a_1 \neq 0$, clearly $(a_1) \subset I$. If $(a_1) = I$, we are done. If not, $\exists a_2 \in I \setminus (a_1) \Rightarrow (a_1, a_2) \subset I$, this chain terminates.

“1. \Leftarrow 2.” : Suppose $I_1 \subset I_2 \subset \dots$ be an ascending ideal. Let $I = \cup I_n$, we claim that I is an ideal. Let $a, b \in I$, then there exists n such that $a, b \in I_n$. Therefore $a + b \in I_n$, and $a + b \in I$. Let $a \in I$, then $a \in I_n$ for some n . Therefore $ra \in I_n \Rightarrow ra \in I$. Thus I is an ideal. But $I = (a_1, \dots, a_m)$, so there exists n , such that $a_1, \dots, a_m \in I_n$. Thus $I = I_n$ and $I_n = I_{n+1} = \dots$. ■

Exercise 1.3.1 Suppose R is a Noetherian domain, show R admits factorizations.

Proof. If b is not irreducible, then $b = ac$ or $(b) \subset (a)$

*****Not Complete*****

■

Definition 1.3.7 A PID (Principle Ideal Domain) is a domain in which every ideal is generated by a single element.

Theorem 1.3.3 Every PID is a UFD.

Proof. Let R be a PID, then it's noetherian. So factorizations exist. So it suffices to show that every irreducible is a prime. Let π be an irreducible in R . Suppose $\pi \mid ab$ and a is not divided by π . We look at $I = (a, \pi)$, there exists $c \in R$, such that $I = (c)$. Thus we have $c \mid \pi, c \mid a$. So $c \sim 1$ or $c \sim \pi$. Since c is not associative of π , c is associative of 1. But then

$$1 = ax + \pi y$$

for some $x, y \in R$. So $b = abx + \pi by$ or $\pi \mid b$.

■

1.4 Class Notes 17-01-17

■ **Example 2** \mathbb{Z} is a PID.

Remark 1.4.1 Any ideal $I \subset \mathbb{Z}$ is of the form of $n\mathbb{Z}$.

Proof. $\forall I \subset \mathbb{Z}$, if $I = (0)$, we are done. If I is not zero ideal, let n be the smallest positive element in I . We claim: $I = n\mathbb{Z}$. Let $b \in I$, then $b = nq + r$, where $0 \leq r < n$. But $r = b - nq \implies r \in I \implies r = 0$. Therefore $b = nq$.

■

If K is a field, let $R = k[x]$ = polynomial in variable x over the field K . What are the units in R ? For arbitrary $f(x), g(x) \in K[x]$, if $f(x)g(x) = 1$, we claim that $f(x), g(x)$ must be constant polynomial. For if we write $f(x) = a_n x^n + a_{n-1} x^{n-1} + \dots$, $g(x) = b_m x^m + b_{m-1} x^{m-1} + \dots$. Then $f(x)g(x) = a_n b_m x^{m+n} + \dots$. Since $a_n \neq 0, b_m \neq 0$ and K is an integral domain, we have $a_n b_m \neq 0$. Therefore

$$\deg f(x)g(x) = \deg f(x) + \deg g(x).$$

We then apply this conclusion to $f(x)g(x) = 1$ and get $\deg f(x) + \deg g(x) = \deg 1 = 0$, thus $f(x), g(x)$ must be constant.

Remark 1.4.2 Whether a polynomial is irreducible depends on the field. For example, if $x^2 + 1 \in \mathbb{R}[x]$, then it's irreducible (why?). But if $x^2 + 1 \in \mathbb{C}[x]$, then it's reducible (why?).

Division Algorithm: Let $f(x), g(x) \in K[x], g(x) \neq 0$, then there exists $q(x), r(x) \in K[x]$, such that

$$f(x) = g(x)q(x) + r(x),$$

where $r(x) = 0$ or $0 \leq \deg r(x) < \deg g(x)$.

Using this fact, we have the following theorem.

Theorem 1.4.1 $K[x]$ is a PID.

Proof. For all ideal $I \in K[x]$, if $I = (0)$, we are done. If $I \neq (0)$, let $g(x) \in I$ be the polynomial of least degree, let $f(x) \in I$, then

$$f(x) = g(x)q(x) + r$$

with $r = 0$ or $0 \leq \deg r(x) < \deg g(x)$ by division algorithm. But then $r(x) = 0$, for otherwise $r(x)$ will be a polynomial whose degree is less than $g(x)$. Therefore $f(x) = g(x)q(x)$, $f(x) \in (g(x))$. ■

Definition 1.4.1 A domain R is said to be an Euclidean domain if there exists a function $\lambda : R \setminus \{0\} \rightarrow \mathbb{Z}^{\geq 0}$, such that given $a, b \in R, b \neq 0$, there exist $q, r \in R$ such that $a = qb + r$ and either $r = 0$ or $0 \leq \lambda(r) < \lambda(b)$.

■ **Example 3** $R = \mathbb{Z}[i]$ is an Euclidean domain.

Proof. Let $N(\alpha) = \alpha\bar{\alpha} = a^2 + b^2$ (if $\alpha = a + bi$). Let $\alpha, \beta \in R, \beta \neq 0$, we have

$$\frac{\alpha}{\beta} = \frac{a + bi}{c + di} = \frac{ac + bd}{c^2 + d^2} + \frac{bc - ad}{c^2 + d^2}i = r + si, (r, s \in \mathbb{Q})$$

Let $m + ni \in \mathbb{Z}[i]$ be the closest element to $r + si$. We denote $r' = r - m, s' = s - n$, then $\frac{\alpha}{\beta} = r + si = m + ni + r' + s'i$, or

$$\alpha = \beta(m + ni) + \beta(r' + s'i),$$

where $(m + ni) \in \mathbb{Z}[i]$ and $\beta(r' + s'i) \in \mathbb{Z}[i]$, we remain to show that $N(\beta(r' + s'i)) < N(\beta)$. This is the case because

$$\begin{aligned} N(\beta(r' + s'i)) &= N(\beta)N(r' + s'i) \\ &\leq N(\beta)\left(\frac{1}{4} + \frac{1}{4}\right) \\ &< N(\beta) \end{aligned}$$

We are done. ■

The Natural question is what are the units in $\mathbb{Z}[i]$? Does a prime in \mathbb{Z} still a prime in $\mathbb{Z}[i]$? To answer the first question, we assume u is a unit in $\mathbb{Z}[i]$. Then by definition there exists some v such that $uv = 1$. But then $1 = N(1) = N(uv) = N(u)N(v) \implies N(u) = 1$. Thus the only possible values of u is $\pm 1, \pm i$. We also check they are actually units. Now, to answer the second question, we try some small cases. We look at 5, 7, 11 and 13.

■ **Example 4** If $5 = ab, a, b \in \mathbb{Z}[i]$, then $25 = N(5) = N(ab) = N(a)N(b) \implies N(a) = 5$. So a can only be $\pm 1 \pm 2i$ or $\pm 2 \pm i$. We try by hand and find $5 = (2 + i)(2 - i)$ is a factorization, so 5 is not a prime.

■ **Example 5** If $7 = ab, a, b \in \mathbb{Z}[i]$, then $49 = N(7) = N(ab) = N(a)N(b) \implies N(a) = 7$. We try by hand and find no factorization, so 7 is a prime.

Use the same method, we find 5, 13 are not prime while 7, 11 are prime.

Remark 1.4.3 Observation:

1. If $p \equiv 1 \pmod{4}$, then $p = \pi\bar{\pi}$, where π is a irreducible.
2. If $p \equiv 3 \pmod{4}$, then p remains prime.
3. If $p = 2$, $2 = (1 + i)(1 - i) = (-i)(1 + i)^2$ (ramification).

Remark 1.4.4 Let $R = \mathbb{Z}[\omega]$, where ω is a primitive cube root of 1, then R is a Euclidean domain.

1.5 Unique Factorization in $k[x]$

In this section we consider the ring $k[x]$ of polynomials with coefficients in a field k . If $f, g \in k[x]$, we say that f divides g if there is an $h \in k[x]$ such that $g = fh$.

If $\deg f$ denotes the degree of f , we have $\deg fg = \deg f + \deg g$ (why? Because a field k is necessarily an integral domain). nonzeros constants are the units of $k[x]$. A nonconstant polynomial p is said to be irreducible if $q \mid p \implies q$ is either a constant or a constant times p .

Lemma 5 Every nonconstant polynomial is the product of irreducible polynomials.

Proof. Simply by induction. ■

Definition 1.5.1 A polynomial f is called monic if its leading coefficient is 1.

Definition 1.5.2 Let p be a monic irreducible polynomial. We define $\text{ord}_p f$ to be the integer a defined by the property that $p^a \mid f$ but that $p^{a+1} \nmid f$.

Remark 1.5.1 $\text{ord}_p f = 0$ iff $p \nmid f$.

Theorem 1.5.1 Let $f \in k[x]$. Then we can write

$$f = c \prod_p p^{a(p)},$$

where the product is over all monic irreducible polynomials and c is a constant. The constant c and the exponents $a(p)$ are uniquely determined by f ; in fact, $a(p) = \text{ord}_p f$.

The existence of such a product follows immediately from Lemma 5. The uniqueness part is more difficult and will be postponed.

Lemma 6 Let $f, g \in k[x]$. If $g \neq 0$, there exist polynomials $h, r \in k[x]$ such that $f = hg + r$, where either $r = 0$ or $r \neq 0$ and $\deg r < \deg g$.

Proof. If $g \mid f$, we are done. If $g \nmid f$, let $r = f - hg$ be the polynomial of least degree among all polynomials of the form $f - lg$ with $l \in k[x]$. We claim that $\deg r < \deg g$. If not, let the leading term of r be ax^d and that of g be bx^m . Then $r - \frac{a}{b}x^{d-m}g(x) = f - (h + \frac{a}{b}x^{d-m})g$ has smaller degree than r and is of the given form. This is a contradiction. ■

Lemma 7 Given $f, g \in k[x]$ there is a $d \in k[x]$ such that $(f, g) = (d)$.

Proof. See Theorem 1.4.1. ■

Definition 1.5.3 Let $f, g \in k[x]$. Then $d \in k[x]$ is said to be a greatest common divisor of f and g if d divides f and g and every common divisor of f and g divides d .

Remark 1.5.2 Notice that the greatest common divisor of two polynomials is determined up to multiplication by a constant. If we require it to be monic, it is uniquely determined and we may speak of the greatest common divisor.

Lemma 8 Let $f, g \in k[x]$. By lemma 7 there is a $d \in k[x]$ such that $(f, g) = (d)$. d is the greatest common divisor of f and g .

Proof. Since $f \in (d)$ and $g \in (d)$ we have $d \mid f$ and $d \mid g$. Suppose that $h \mid f$ and that $h \mid g$. Then h divides every elements in $(f, g) = (d)$. In particular $h \mid d$, we are done. ■

Definition 1.5.4 Two polynomial f and g are said to be relatively prime if the only common divisor of f and g are constants. In other words, $(f, g) = (1)$.

Proposition 1.5.2 If f and g are relatively prime and $f \mid gh$, then $f \mid h$.

Corollary 1.5.3 If p is an irreducible polynomial and $p \mid fg$, then $p \mid g$ or $p \mid f$.

Corollary 1.5.4 If p is a monic irreducible polynomial and $f, g \in k[x]$, we have

$$\text{ord}_p fg = \text{ord}_p f + \text{ord}_p g.$$

Using these tools, we can prove the uniqueness of factorizaion.

1.6 Unique Factorizaion in a Principal Ideal Domain

For this section, we mostly refer to Section 1.3 and supply some details.

Chapter 2

Congruence

2.1 Class Notes 17-01-19

Definition 2.1.1 We write $a \equiv b \pmod{p}$, if $p \mid (a - b)$.

Remark 2.1.1 To solve $ax \equiv b \pmod{m}$ in \mathbb{Z} is the same to solve $[a]x = [b]$ in $\mathbb{Z}/m\mathbb{Z}$.

We now try to solve the equation $a \equiv b \pmod{m}$.

Proposition 2.1.1 A necessary and sufficient condition for this equation to have solutions is $d \mid b$, where $d = (a, m)$ is the gcd of a and m .

Think About: $ax \equiv 1 \pmod{m}$ has solutions is equivalent to $(a, m) = 1$.

Proof.

“ \Rightarrow ”: If we have some solution x_0 such that $ax_0 \equiv 1 \pmod{m}$. Then $ax_0 = 1 + mt$ so that $(a, m) = 1$.

“ \Leftarrow ”: If $(a, m) = 1$, then there exists x_0, t such that $1 = ax_0 - mt$, so $ax_0 \equiv 1 \pmod{m}$. ■

Remark 2.1.2 In $\mathbb{Z}/m\mathbb{Z}$, $[a]x \equiv [1]$ implies that $[a]$ is a unit.

Definition 2.1.2 $\phi(m) = \#$ of units in $\mathbb{Z}/m\mathbb{Z}$.

We give a few example:

m	1	2	3	4	5
$\phi(m)$	1	1	2	2	4

Now we give the formal proof of our proposition.

Proof. Suppose x_0 is a solution, then there exist t such that

$$ax_0 = b + mt,$$

Since $(a, m) \mid a$, $(a, m) \mid m$, we have $(a, m) \mid b$. Conversely, suppose $(a, m) \mid b$, we may write b as $b = (a, m)b'$. Similarly, $a = (a, m)a'$ and $m = (a, m)m'$ with $(a', m') = 1$. Denote $d := (a, m)$, then $da'x \equiv db' \pmod{dm'}$, $a'x \equiv b' \pmod{m'}$. Since $(a', m') = 1$, $a'x \equiv b' \pmod{m'}$ has solutions. ■

Remark 2.1.3 According to the proof, we will have $d = (a, m)$ solutions.

Now we want to introduce *Chinese Remainder Theorem in \mathbb{Z}* . We want to solve a system of congruence equations. Namely, we are looking at the system

$$\begin{aligned} x &\equiv a_1 \pmod{m_1} \\ x &\equiv a_2 \pmod{m_2} \\ &\vdots \\ x &\equiv a_n \pmod{m_n} \end{aligned}$$

where m_i are pairwise coprime.

Theorem 2.1.2 (Chinese Remainder Theorem).

The system always admits solutions.

We notice that if x_0 is a solution to the system, so does $x = km_1m_2 \cdots m_n + x_0$, $k \in \mathbb{Z}$. So the system will have infinitely many solutions. The sketch of the proof is as followed. Suppose we can solve the system

$$\begin{aligned} x_i &\equiv 1 \pmod{m_i} \\ x_i &\equiv 0 \pmod{m_j} \quad \forall j \neq i \end{aligned}$$

then $x = a_1x_1 + a_2x_2 + \cdots + a_nx_n$ is a solution for the original system. But why does the system even have a solution?

Consider the following system as an example,

$$\begin{aligned} x &\equiv 1 \pmod{m_1} \\ x &\equiv 0 \pmod{m_2} \\ &\vdots \\ x &\equiv 0 \pmod{m_n} \end{aligned}$$

We know that since m_i are coprime, $(m_1, m_2m_3 \cdots m_n) = 1$.

$$\begin{aligned} &\Rightarrow \exists c, d_1, \text{ s.t. } cm_1 + d_1m_2m_3 \cdots m_n = 1 \\ &\Rightarrow x = d_1m_2m_3 \cdots m_n \text{ is a solution} \end{aligned}$$

Remark 2.1.4 If there are two solutions for the system, say x and y , then

$$x - y \equiv 0 \pmod{m_1m_2 \cdots m_n} \implies x \equiv y \pmod{m_1m_2 \cdots m_n}.$$

Namely, the solution is unique up to a multiple of $m_1m_2 \cdots m_n$.

In order to generalize CRT, we need some background.

Suppose R, S are two rings, then $R \times S := \{(r, s), r \in R, s \in S\}$. We also define sum and product on $R \times S$, namely,

$$\begin{aligned} (a, b) + (c, d) &= (a + c, b + d), \\ (a, b) \cdot (c, d) &= (ac, bd). \end{aligned}$$

We can check that $R \times S$ is actually a ring. The projection maps are ring homomorphisms, i.e., there exist projection maps E_S, E_R ,

$$\begin{aligned} E_S : R \times S &\rightarrow S \\ E_R : R \times S &\rightarrow R \end{aligned}$$

But there doesn't exist any homomorphism from S or R to $R \times S$.

We know that for a ring homomorphism $\phi : R \rightarrow S$, $\ker \phi = \{x \in R, \phi(x) = 0\}$ is an ideal. For ring homomorphism $\mathbb{Z} \rightarrow \mathbb{Z}/m\mathbb{Z}$, its kernel is exactly the ideal $m\mathbb{Z}$. So in fact, what CRT in \mathbb{Z} says is that the ring homomorphism

$$f : \mathbb{Z} \rightarrow \mathbb{Z}/m_1\mathbb{Z} \times \mathbb{Z}/m_2\mathbb{Z} \times \cdots \times \mathbb{Z}/m_n\mathbb{Z},$$

or

$$a \mapsto ([a]_{m_1}, \dots, [a]_{m_n})$$

is surjective.

$$\begin{array}{ccc} R & \xrightarrow{\phi} & S \\ \downarrow f & \nearrow \tilde{\phi} & \\ R/I & & \end{array}$$

For a ring homomorphism $\phi : R \rightarrow S$, $I = \ker \phi$,

- ϕ is injective if and only if $\ker \phi = \{0\}$.
- There exists a unique ring homomorphism $\tilde{\phi} : R/I \rightarrow S$, or $\tilde{\phi} : [a] \mapsto \phi(a)$ such that the diagram commutes. $\tilde{\phi}$ is also well defined, for if $[a] = [b]$, then we have

$$\begin{aligned} [a] = [b] &\Rightarrow (a - b) \in I \\ &\Rightarrow \phi(a - b) = 0 \\ &\Rightarrow \phi(a) = \phi(b). \end{aligned}$$

Now, let $R = \mathbb{Z}$, $S = \mathbb{Z}/m_1\mathbb{Z} \times \mathbb{Z}/m_2\mathbb{Z} \times \cdots \times \mathbb{Z}/m_n\mathbb{Z}$. Let $m = m_1 m_2 \cdots m_n$, then $\ker \phi = \mathbb{Z}/m\mathbb{Z}$, we have the following diagram.

$$\begin{array}{ccc} \mathbb{Z} & \xrightarrow{\phi} & \mathbb{Z}/m_1\mathbb{Z} \times \mathbb{Z}/m_2\mathbb{Z} \times \cdots \times \mathbb{Z}/m_n\mathbb{Z} \\ \downarrow f & \nearrow \tilde{\phi} & \\ \mathbb{Z}/m\mathbb{Z} & & \end{array}$$

Notice that $\tilde{\phi}$ is an isomorphism.

We have the natural question that what are the units in R and S ? Let $U(R)$ denote the set of units of the ring R , then $U(R \times S) = U(R) \times U(S)$. We thus have a branch of corollaries.

Corollary 2.1.3 $U(\mathbb{Z}/m\mathbb{Z}) \cong U(\mathbb{Z}/m_1\mathbb{Z}) \times \cdots \times U(\mathbb{Z}/m_n\mathbb{Z})$.

Corollary 2.1.4 $\phi(m) = \phi(m_1)\phi(m_2) \cdots \phi(m_n)$.

Corollary 2.1.5 If $m = p_1^{\gamma_1} p_2^{\gamma_2} \cdots p_s^{\gamma_s}$, then

$$\begin{aligned} \phi(m) &= \phi(p_1^{\gamma_1} p_2^{\gamma_2} \cdots p_s^{\gamma_s}) \\ &= \phi(p_1^{\gamma_1}) \phi(p_2^{\gamma_2}) \cdots \phi(p_s^{\gamma_s}), \end{aligned}$$

with $\phi(p_i^{\gamma_i}) = p_i^{\gamma_i} - p_i^{\gamma_i-1}$.

Corollary 2.1.6

$$\sum_{d|n} \phi(d) = n$$

The proof is simply use the fact that the statement is true for primes, and every element of \mathbb{Z} can be factorized as a product of primes.

Proof. We claim that if the statement is true for m, n ($(m, n) = 1$), then it's true for mn .

$$\begin{aligned} \sum_{d|mn} \phi(d) &= \sum_{d_1|m, d_2|n} \phi(d_1 d_2) \\ &= \sum_{d_1|m} \sum_{d_2|n} \phi(d_1) \phi(d_2) \\ &= \left(\sum_{d_1|m} \phi(d_1) \right) \left(\sum_{d_2|n} \phi(d_2) \right) \\ &= m \cdot n. \end{aligned}$$

■

2.2 Class Notes 17-01-24

Suppose $I, J \subset R$ are two ideals, how to make new ideals with I, J ? Evidently, $I \cap J$ and $I + J$ are ideals. Also,

$$I \cdot J := \left\{ \sum a_i b_i, a_i \in I, b_i \in J \right\} \subset I \cap J$$

is an ideal.

■ **Example 6** Let $I = m\mathbb{Z}, J = n\mathbb{Z}$. then we have

$I + J$	$I \cap J$	$I \cdot J$
$((m, n))$	$([m, n])$	$mn\mathbb{Z}$

Definition 2.2.1 We say two ideals I, J are coprime if $I + J = (1)$.

Remark 2.2.1 If I, J are coprime, then $I \cap J = I \cdot J$.

Proof. For some $x \in I \cap J$, since I, J are coprime, there exists some $a \in I, b \in J$ such that $a + b = 1$. But then $a \cdot x + x \cdot b = x \in I \cdot J$. So $I \cap J \subset I \cdot J$. The other direction is obvious. ■

Theorem 2.2.1 (Generalized Chinese Remainder Theorem). Let I_1, I_2, \dots, I_n be pairwise coprime ideals in R , then the map

$$\phi : R \rightarrow R/I_1 \times \dots \times R/I_n$$

- 1) is surjective
- 2) has $\ker \phi = I_1 I_2 \dots I_n = I_1 \cap I_2 \cap \dots \cap I_n$

Lemma 9 We first look at $n = 2$ case. If I, J are coprime ideals in R , then the map

$$\phi : R \rightarrow R/I \times R/J$$

- 1) is surjective.
- 2) has $\ker \phi = I \cap J = IJ$.

Proof. It's enough to solve the system of congruence

$$x \equiv 1 \pmod{I}$$

$$x \equiv 0 \pmod{J}$$

and

$$\begin{aligned}y &\equiv 0 \pmod{I} \\ y &\equiv 1 \pmod{J}\end{aligned}$$

Since I, J are coprime, there exists $c \in I, d \in J$ such that $c + d = 1$. c, d is the solution to our two systems. ■

Lemma 10 I_1 is coprime to $I_2 I_3 \cdots I_n$.

Proof. There exist

$$\begin{aligned}a_2 + b_2 &= 1 \\ a_3 + b_3 &= 1 \\ &\vdots \\ a_n + b_n &= 1,\end{aligned}$$

$a_i \in I_1, b_j \in I_j$.
Then

$$\begin{aligned}b_2 b_3 \cdots b_n &= (1 - a_2) \cdots (1 - a_n) \\ &= 1 + a,\end{aligned}$$

where $a \in I_1$.

By $n = 2$ case

$$\begin{array}{ccc} R & \xrightarrow{\quad} & R/I_1 \times R/(I_2 \times I_3 \times \cdots \times I_n) \\ \downarrow & \nearrow & \\ R/I_1 \times R/I_2 \times \cdots \times R/I_n & & \end{array}$$

■