Contents

Chapter 0

Week 0

0.1 Notation

Let X, Y be sets. Then, we introduce some simple notation: inclusion

$$x \in X$$

union

$$X \cup Y$$

intersection

$$X \cap Y$$

and the cartesian product

$$X \times Y = \{(x, y) : x \in X, y \in Y\}$$

We call the Natural Numbers $\mathbb{N}$, Integers $\mathbb{Z}$, Rationals $\mathbb{Q}$ $(:= \left\{\frac{a}{b} : a, b, \in \mathbb{Z}\right\})$, Reals $\mathbb{R}$, and Complex Numbers $\mathbb{C}$. Notice that $\mathbb{N} \subset \mathbb{Z} \subset \mathbb{Q} \subset \mathbb{R} \subset \mathbb{C}$.

0.2 Maps

Let X, Y be two sets. A ***map*** f between X and Y denoted as

$$f : X \to Y$$

is a rule that takes *every* element of $x \in X$ to *an* element $y = f(x) \in Y$.

0.2.1 Composition

Let X, Y, Z be sets. Suppose $X \xrightarrow{f} Y \xrightarrow{g} Z$. Then a function $h : X \to Z$, $h(x) - g(f(x)) \in Z$ is called the ***composition*** denoted as $h = g \circ f$.

0.2.2 Identity

The ***identity map*** is denoted as $\mathrm{Id}_x : X \to X$, and is defined to be $\mathrm{Id}(x) = x$

0.2.3 Properties

Let X, Y, Z be sets.

Injective

A map $f : X \to Y$ is ***injective (into/one-to-one)*** if for every $x_1, x_2 \in X$, we have $f(x_1) \neq f(x_2)$ Taking the contrapositve, we get the statement: If $f(x_1) = f(x_2)$, then $x_1 = x_2$. In shorthand, it is

$$\forall x_1, x_2 \in X, f(x_1) \neq f(x_2) \iff f(x_1) = f(x_2) \implies x_1 = x_2 \forall x_1, x_2 \in X$$

0.2.4 Surjective

A map $f : X \to Y$ is ***surjective (onto)*** if for every $y \in Y$, there exists some $x \in X$ such that $y = f(x)$. In shorthand, it is

$$\forall y \in Y, \exists x \in X : y = f(x)$$

0.2.5 Bijective

A map $f : X \to Y$ is ***bijective*** if it is both *injective* and *surjective*.

0.2.6 Inverse Maps

Let $f : X \to Y$ be a map. A map $g : Y \to X$ is called the ***inverse of*** f if the composition is the Identity map; that is, $g \circ f = \mathrm{Id}_x$, $f \circ g = \mathrm{Id}_y$ and is denoted as $g = f^{-1}$.

Proposition

A map $f : X \to Y$ has an inverse *if and only if* f is bijective.

Proof. ($\implies$) Let $g : Y \to X$ be an inverse of f. Then $g \circ f = \mathrm{Id}_x, f \circ g = Id_y$. Let $x_1, x_2 \in X$ such that $f(x_1) = f(x_2)$. Then,

$$\begin{aligned} x_1 &= \mathrm{Id}_x(x_1) \\ &= (g \circ f)(x_1) \\ &= g(f(x_1)) \\ &= g(f(x_2)) && f(x_1) = f(x_2) \text{ by assumption} \\ &= (g \circ f)(x_2) \\ &= \mathrm{Id}_x(x_2) \\ x_1 &= x_2 \end{aligned}$$

so f is injective.

Take any $y \in Y$. Then $x := g(y)$ for some $x \in X$. Then,

$$f(x) = f(g(y)) = (f \circ g)(y) = \mathrm{Id}_y(y) = y$$

so f is surjective. Because f is both injective and surjective, it is bijective.

($\impliedby$) Assume f be bijective. Then let $g : Y \to X$. Take any $y \in Y$. There exists a unique $x \in X$ such that $y = f(x)$ because f is bijective. Therefore, g is an inverse of f. □

0.3 Integers

0.3.1 Induction I

Let $n_0 \in \mathbb{Z}$, and $\mathrm{P}(n)$ be a statement for all $n \geq n_0$. Suppose

(i) $\mathrm{P}(n_0)$ is true.

(ii) $\mathrm{P}(n) \implies \mathrm{P}(n+1)$ for every $n \geq n_0$.

Then $\mathrm{P}(n)$ is true for all $n \geq n_0$.

Proposition

$$1 + 2 + \cdots + n = \frac{n(n+1)}{2}$$

Proof. Let $\mathrm{P}(n) := 1 + 2 + \cdots + n = \frac{n(n+1)}{2}$. We will induct on n.

(i) $\mathrm{P}(1)$ is true.

(ii) $\mathrm{P}(n) \implies \mathrm{P}(n+1)$

$$\begin{aligned} 1 + 2 + \cdots + n + (n+1) &= \frac{n(n+1)}{2} + (n+1) \\ &= \frac{(n+1)(n+2)}{2} \end{aligned}$$

so $\mathrm{P}(n+1)$ is true, completing the induction.

□

0.3.2 Induction II (Strong Induction)

Let $n_0 \in \mathbb{Z}$, and $\mathrm{P}(n)$ be a statement for all $n \geq n_0$. Suppose

(i) $\mathrm{P}(n)$ is true.

(ii) For every $n > n_0$, if $\mathrm{P}(k)$ is true for every $n_0 \leq k \leq n$, then $\mathrm{P}(n)$ is true.

Then $\mathrm{P}(n)$ is true for all $n \geq n_0$.

Proposition

Every positive integer can be written in the form

$$n = 2^{K_1} + 2^{K_2} + \cdots + 2^{K_m}$$

where $K_i \in \mathbb{Z}$ and $0 \leq K_1, < K_2, \cdots < K_m$.

Proof. We will induct on n.

(i) $\mathrm{P}(1)$ is true.

(ii) We know that $\mathrm{P}(k)$ is true for $k = 1, 2, \ldots, n-1$. Then for n, we find the largest s such that $2^s \leq n$. There are two cases:

  (i) $n = 2^s$. Then $\mathrm{P}(n)$ is true.

  (ii) $2^s < n$, $p := n - 2^s > 0$.
  Apply $\mathrm{P}(p)$: $p = 2^{K_1} + \cdots 2^{K_m},\ 0 \leq K_1, < K_2 < \cdots K_m$.
  $\implies n = 2^{K_1} + \cdots 2^{K_m} + 2^s$ Then, $p > 2^{K_m}$, so $2^s > 2^{K_m}$
  $\implies s > k_m$, completing the induction.

□

0.3.3 Division of Integers

Let $n, m \in \mathbb{Z}, m \neq 0$. Then, n is divisible by m if there exists some $q \in \mathbb{Z}$ such that $n = mq(\iff \frac{n}{m} \in \mathbb{Z})$ and we denote this as $m \mid n$, read as "m divides n".

Properties

(i) $1 \mid n$ for every $n \in \mathbb{Z}$ and $m \mid 0$ for every $m \neq 0$.

(ii) If $m \mid n_1$ and $m \mid n_2$, then $m \mid (n_1 \pm n_2)$.

  Proof. $n_1 = mq_1$ and $n_2 = mq_2$
  $\implies n_1 \pm n_2 = mq_1 \pm mq_2 = m(q_1 + q_2) \implies m \mid (n_1 \pm n_2)$ since $q_1 + q_2 \in \mathbb{Z}$. □

(iii) If $m \mid n$, then $m \mid an$ for all $a \in \mathbb{Z}$.

Proof. $n = m \cdot q, q \in \mathbb{Z}$, $an = m \cdot (aq), aq \in \mathbb{Z} \implies m \mid an$. □

(iv) If $m \mid n_1$ and $m \mid n_2$, then $m \mid a_1 n_1 + a2_n 2$ for every $a_1, a_2 \in \mathbb{Z}$.

Proof. By *(iii)*, $m \mid a_1 n_1$ and $m \mid a_2 n_2$. By *(ii)*, $m \mid a_1 n_1 + a_2 n_2$. □

(v) If $m \mid n, n \neq 0$, then $|m| \leq |n|$.

Proof. $n = m \cdot q, q \in \mathbb{Z}, q \neq 0, |n| = |m| \cdot |q| \geq |m|$. □

(vi) If $m \mid n$ and $n \mid m$, then $n = \pm m$.

Proof. By *(v)*, $|m| \leq |n| \leq |m| \implies n = \pm m$. □

Division Algorithm

Theorem

Let $n, m \in \mathbb{Z}, m \neq 0$. Then, there are *unique* $q, r \in \mathbb{Z}$ such that

$$n = m \cdot q + r,\ 0 < r < m$$

where q is the partial quotient and r is the remainder on dividing n by m.

Proof. ***Existence***
Define an infinite set $S = \{n - mx, x \in \mathbb{Z}\}$ containing nonnegative integers. Take $S \cap \mathbb{Z}^{\geq 0} \neq \emptyset$, so S is non-empty. Then by the well ordering principle, every non-empty set of $\mathbb{Z}^{\geq 0}$ has a least element,

$$n - mx \in S \cap \mathbb{Z}^{\geq 0}$$

Call $q = x$, $r := n - mx \geq 0$. Then

$$n = mx + r = mq + r$$

To show that $r < m$,

$$r - m = (n - mq) - m = n - m(q+1) \in S$$

This shows that $r - m < r$, but since we chose r to be the *least* element in $S \cap \mathbb{Z}^{\geq 0}$, $r - m \notin S$. So $r - m < 0 \implies r < m$.

Uniqueness
Let $n = mq_1 + r_1 = mq_2 + r_2$ where $0 \leq r_1, r_2 < m$. Then,

$$0 = m(q_1 - q_2) + (r_1 - r_2)$$

so

$$r_1 - r_2 = m(q_2 - q_1)$$

but

$$q_1 - q_2 = 0$$

so

$$r_1 = r_2$$

□

Remark: $r = 0 \iff m \mid n$ and r contains $m - 1$ distinct integers.

Divisors

Let $n > 0$. A non-zero integer d is called a divider of n if $d \mid n$. Moreover,

$$|d| \leq |n| = n \iff -n \leq d \leq n$$

Proposition

Every $n > 0$ has finitely many unique divisors.

Proof. Let $X := \{1, 2, \ldots, n\}$. Then, the set of divisors of n are a subset of X. Since X is finite, any subset of X is also finite. Therefore, n has a finite number of unique divisors. $\square$

Greatest Common Divisor

Take $n, m > 0$ and d the largest common divisor of m and n. Then,

$$d = \gcd(n, m) = (n, m) \geq 1$$

Euclidean Algorithm

Let $n, m > 0$. Then,

$$\begin{aligned}
n &= mq_1 + r_1 & 0 \leq r_1 &< m \\
m &= r_1 q_2 + r_2 & 0 \leq r_2 &< r_1 \\
r_1 &= r_2 q_3 + r_3 & 0 \leq r_3 &< r_2 \\
&\vdots \\
r_{k-2} &= r_{k-1} q_k + r_k & 0 \leq r_k &< r_{k-1} \\
r_{k-1} &= r_k q_{k+1} & r_{k+1} &= 0
\end{aligned}$$

Theorem

$$r_k = \gcd(n, m)$$

Proof. Let $d = \gcd(n, m)$. Then,

$$\begin{aligned}
& d \mid r_1 = n - mq_1 & & \\
& d \mid r_2 = m - r_1 q_2 & r_k &\mid r_{k-1} = r_k q_{k+1} \\
& d \mid r_3 = r_1 - r_2 q_3 & r_k &\mid r_{k-2} = r_{k-1} q_k + r_k \\
& \vdots & & \vdots \\
& d \mid r_k = r_{k-2} - r_{k-1} q_k & r_k &\mid n = mq_1 + r_1
\end{aligned}$$

So $d \mid r_k \implies d \leq r_k$, a common divisor of n and m. So, $r_k \leq d$. Thus, $d = r_k$. $\square$

Bezout's Identity

Theorem

Let $n, m > 0$ and $d = \gcd(n, m)$. Then, there are $x, y \in \mathbb{Z}$ such that

$$d = nx + my$$

Another way of writing this is

$$nx + my = nx + (nm - nm) + my = n(x + m) + m(y - n)$$

Moreover, n and m are relatively prime (coprime) if $\gcd(n, m) = 1$.

Proof. Let $S := \{nx + my, x, y \in \mathbb{Z}\}$. We claim that $s = d$. Then,

$$s = nx + my,\ n = sq + r,\ 0 \leq r < s$$

Rearranging the second equation, we get

$$\begin{aligned} r &= n - sq \\ &= n - (nx + my)q && \text{Substitute equation 1} \\ &= n(1 - x) - myq \in S \end{aligned}$$

This implies that $r = 0 \implies (s \mid n \text{ and } s \mid m) \implies s \leq d$. But $d \mid n$ and $d \mid m$, so $d \mid s \implies d \leq s$. Therefore,

$$d = s = nx + my$$

□

Corollary

Let $n, m > 0$. Then, n and m are relatively prime *if and only if* there exists some $x, y \in \mathbb{Z}$ such that $nx + my = 1$

Proof. ($\implies$) Bezout's Identity

($\impliedby$) $nx + my = 1, d = \gcd(n, m)$. Then $d \mid n$ and $d \mid m$ by definition. This implies that $d \mid (nx + my) \iff d \mid 1$. But $d \geq 1 \implies d = 1$. □

Chapter 1

Week 1

1.1 Prime Numbers

An integer $p > 1$ is called ***prime*** if the *only* divisors of p are ± 1 and $\pm p$. If $n > 0$ and p prime, then $\gcd(n, p) = \begin{cases} 1 & n \text{ and } p \text{ are coprime} \\ p & p \mid n \end{cases}$

Proposition

Every integer $n > 1$ is a product of prime integers.

Proof. We will use strong induction on $n \geq 2$.

(i) $(n_0 = 2)$
2 is prime.

(ii) $(k \implies k+1)$
Assume $\mathrm{P}(k)$ is true for all k such that $2 \leq k < n$. There are two cases.

Case I: n is prime. Then we are done.
Case II: n is composite. Then, there are integers p and q such that $n = p \cdot q$. By definition, $1 < p, q < n$. Then, by the Inductive Hypothesis, $\mathrm{P}(p)$ and $\mathrm{P}(q)$ are true; i.e. p and q are products of primes. Therefore, $n = p \cdot q$ is a product of primes.

$\square$

Lemma

Let p be a prime integer and $n, m > 0$ such that $p \mid nm$. Then, either

$$p \mid n \text{ or } p \mid m$$

Proof. There are two cases.

Case I: $p \mid n$. Then we are done.
Case II: p and n are coprime. Then, by Bezout's Identity we get

$$\begin{aligned} px + ny &= 1 & \\ m(px + ny) &= m & \text{multiply both sides by } m \\ mpx + mny &= m & p \mid pmx,\ p \mid nm \cdot y \end{aligned}$$

so $p \mid m$. $\square$

Corollary

Let p be prime, $n_1, n_2, \ldots, n_s > 0$ such that $p \mid n_1 n_2 \cdots n_s$. Then $p \mid n_i$ for some $i < s$.

Proof. We will induct on $s \in \mathbb{N}$.

(i) $(s = 1)$
This is true by the *Lemma* above.

(ii) $(s - 1 \implies s)$
Consider $p \mid (n_1 n_2 \cdots n_s - 1) \cdot n_s$. Then either $p \mid (n_1 n_2 \cdots n_s - 1)$ by the Inductive Hypothesis or $p \mid n_s$.

□

1.1.1 Unique Factorization

Let $n = p_1 p_2 \cdots p_s = q_1 q_2 \cdots q_t$ and p_i, q_j be prime for all $i, j < s, t$. Then, their factorizations are the same if $s = t$ and $q_j = p_{\alpha(j)}$ for every $j = 1, 2, \ldots, t$ where $\alpha : \{1, 2, \ldots, s\} = \{1, 2, \ldots t\}$

1.1.2 Fundamental Theorem of Arithmetic

Theorem

Every integer $n > 1$ admits a unique factorization into a product of primes.

Proof. Let $n = p_1 p_2 \cdots p_s = q_1 q_2 \cdots q_t$ and p_i, q_j be prime for all $i, j < s, t$. We will induct on $s \in \mathbb{N}$.

(i) $(s = 1)$
$n = p_1 = q_1$ is true.

(ii) $(s - 1 \implies s)$
$p_s \mid n = q_1 q_2 \cdots q_t \overset{Corollary}{\implies} p_s \mid q_j$ for some integer $j \implies p_s = q_j$. Reorder the terms to get $j = t$. Then, $p_s = q_t$. We are left with $p_1 p_2 \cdots p_{s-1} = q_1 q_2 \cdots q_{t-1}$. Apply $\mathrm{P}(s-1)$ to get that $s - 1 = t - 1$. Then, $q_j = p_i$ up to the permutation. That is, $p_s = q_s$.

□

Proposition

Let $n = p_1^{a_1} p_2^{a_2} \cdots p_k^{a_k}$ and $m = p_1^{b_1} p_2^{b_2} \cdots p_k^{b_k}$, $a_k, b_k \geq 0$. Then $m \mid n$ *if and only if* $b_1 \leq a_1, b_2 \leq a_2, \cdots, b_k \leq a_k$.

Proof. $(\implies)$

$$n = m$$
$$p_1^{a_1} p_2^{a_2} \cdots p_k^{a_k} = \left(p_1^{b_1} p_2^{b_2} \cdots p_k^{b_k}\right) \cdot q$$

Then, $b_1 \leq a_1 \iff a_1 = b_1 + c,\ q = p_1^{c_1} \cdots p_k^{c_k}, c_k \geq 0$.

$(\impliedby)$ $n = mq$ where $q = p_1^{a_1 - b_1} \cdots p_k^{a_k - b_k}$. Since $a_i \geq b_i$, $a_i - b_i \geq 0\ \forall i < k \implies m \mid n$ □

1.1.3 Euclid's Theorem

Theorem

There are infinitely many primes.

Proof. Suppose by contradiction that there are exactly n primes $\{p_1, p_2, \ldots, p_n\}$. Define $N := p_1 p_2 \cdots p_n + 1 > 1$. Let p be a divisor of N and $p = p_i$ for some i. Then, $1 = N - p_1 p_2 \cdots p_n \implies p_i \mid 1$, a contradiction. ☐

1.2 Congruences

Let $m > 0$ be an integer. We say that two integers are ***congruent*** modulo m if

$$m \mid (b - a)$$

and denote it as

$$a \equiv b \ (mod\ m)$$

Proposition

$a \equiv b \ (mod\ m)$ *if and only if* a and b have the same remainder on dividing by m.

Proof. ($\implies$) $a \equiv b \ (mod\ m)$ can be rewritten as $m \mid (b-a)$ or $b-a = mx$ where $a = mq+r$, $0 \leq r < m$. Then,

$$\begin{aligned} b &= a + mx \\ &= (mq + r) + mx && \text{substitute } a \\ &= m(q + x) + r \end{aligned}$$

($\impliedby$) Suppose $a = mq + r$ and $b = ms + r$, where $0 \leq r < m$. Then

$$b - a = ms - mq = m(s - q) \implies m \mid (b - a) \iff a \equiv b \ (mod\ m)$$

☐

Corollary

Every integer is congruent modulo m to exactly one integer in the set

$$\{0, 1, \ldots, m - 1\}$$

Proof. Let $a = mq + r$ where $0 \leq r < m$. Then, $r = m \cdot 0 + r \implies a \equiv r \ (mod\ m)$ where $r = \{0, 1, \ldots, m - 1\}$ ☐

1.2.1 Properties

(i) $a \equiv b \ (mod\ m) \implies ax \equiv b \ (mod\ m)$ for every $x \in \mathbb{Z}$.

Proof. $m \mid (b - a) \implies m \mid (b - a)x = bx - ax$ ☐

(ii) $a_1 \equiv b_1 \ (mod\ m)$, $a_1 \equiv b_1 \ (mod\ m) \implies a_1 + a_2 \equiv b_1 + b_2 \ (mod\ m)$.

Proof. $m \mid (b_1 - a_1)$ and $m \mid (b_1 - a_1) \implies m \mid (b_1 - a_1) + (b_2 - a_2) = (b_1 + b_2) - (a_1 + a_2)$.

□

(iii) $a_1 \equiv b_1 \ (mod\ m)$, $a_1 \equiv b_1 \ (mod\ m) \implies a_1 a_2 \equiv b_1 b_2 \ (mod\ m)$.

Proof. $b_1 b_2 - a_1 a_2 = b_1 b_2(-a_1 b_2 + a_1 b_2) + a_1 a_2 = (b_1 - a_1) b_2 + a_1(b_2 - a_2)$. Here, $m \mid (b_1 - a_1)$ and $m \mid (b_2 - a_2)$ by assumption. Then, $m \mid (b_1 b_2 - a_1 a_2)$. □

1.2.2 Linear Congruence

$ax \equiv b \ (mod\ m)$ for $m > 0$, $a, b \in \mathbb{Z}$.

Proposition

If $\gcd(a, n) = 1$, then there is an integer solution x.

Proof.

$$\begin{aligned} ay + mz &= 1 && \text{Bezout's Identity} \\ b(ay + mz) &= b && \text{multiply both sides by } b \\ aby + mbz &= b \\ &\iff \\ b - aby &= mbz \end{aligned}$$

Take $x := aby$. □

1.3 Equivalence Relations

Let X be a set. A ***relation*** $a \sim b$ on X is a subset $\Omega \subset X \times X$. That is, for every $a, b \in X$, $a \sim b$ if $(a, b) \in \Omega$. A relation on X is called an ***equivalence relation*** if

(i) Reflexive: $a \sim a$ for every $a \in X$

(ii) Symmetric $a \sim b \implies b \sim a$ for every $a, b \in X$

(iii) Transitive $a \sim b$, $b \sim c \implies a \sim c$ for every $a, b, c \in X$

1.3.1 Equivalence Classes

Let X be a set and $\sim$ an equivalence relation. Then,

$$a \in X,\ X_a := \{b \in X : b \sim a\} \subset X$$

is an ***equivalence class*** of a.

Proposition

Let $\sim$ be an equivalence relation on a set X. Then

(i) If $a \sim b$, $X_a = X_b$. If $a \not\sim b$, then $X_a \cap X_b = \emptyset$.

(ii) a and b belong to the same equivalence class *if and only if* $a \sim b$.

(iii) X is the disjoint union of all equivalence classes.

Proof. *(i)* Suppose $a \sim b$. Take any $c \in X_a$. Then

$$c \sim a \implies c \sim b \implies c \in X_b \implies X_a \subset X_b$$

$$c \sim b \implies c \sim a \implies c \in X_a \implies X_b \subset X_a$$

so $X_a = X_b$.

Assume $a \not\sim b$ by contradiction. Take $c \in X_a \cap X_b \implies c \sim a$ and $c \sim b \implies a \sim b$, a contradiction.

(ii) ($\implies$) Suppose $a, b \in X_c$. Then $a \sim c, b \sim c \implies c \sim b \implies a \sim b$.

($\impliedby$) Suppose $a \sim b$. Then by *(i)*, $a \in X_a = X_b \ni b$.

(iii) Suppose $a \in X_a$. Then, $\bigcup X_a = X$.

$\square$

Note: The set of all equivalence relations on X is the same as the set of all partitions of X into disjoint union of subsets. That is, $X = \bigcup X_a$.

Chapter 2

Week 2

2.1 Congruence and Equivalent Classes

Proposition

$\equiv$ $(mod\ m)$ is an equivalence relation for all $m \in \mathbb{N}$.

Proof. *(i)* Reflexive: Let $a, m \in \mathbb{Z}$. Then $m \mid a - a = 0$. So $a \equiv a\ (mod\ m)$.

(ii) Symmetric: Suppose $a \equiv b\ (mod\ m)$. Then $m \mid (b-a)$. Then $a-b = -(b-a) \implies b \equiv a\ (mod\ m)$.

(iii) Transitive: Suppose $a \equiv b,\ b \equiv c$. Then,

$$c - a = c(-b + b) - a = (c - b) + (b - a) \implies m \mid (c - a)$$

□

2.1.1 Equivalence Classes

The ***congruence class*** of m is denoted as

$$[a] := [a]_m := \{b \in \mathbb{Z} : b \equiv a\ (mod\ m)\}$$

For example, $[2]_5 = \{\ldots, -8, -3, 2, 7, \ldots\}$.

Properties

(i) $[a] = [b] \iff a \equiv b\ (mod\ m)$.

(ii) $[a] \cap [b] = \emptyset \iff a \not\equiv b\ (mod\ m)$.

(iii) Integers a, b belong to the same congruence class *if and only if* $a \equiv b\ (mod\ m)$.

(iv) $\mathbb{Z}$ is a disjoint union of congruence classes.

(v) There are exactly m congruence classes modulo m $([0], [1], \cdots [m-1])$.

Proof. (*At least*)
Suppose $0 \leq j < k \leq m - 1$. Then

$$0 < k - j \leq m - 1 < m \implies m \not| (k - j) \implies j \not\equiv k\ (mod\ m)$$

(*No more*)
Let $[k]$ be a congruence class. Then $k = am + r$ where $0 \leq r < m$. We can rewrite this as

$$k - r = am \implies m \mid (k - r) \implies [k] = [r]$$

Therefore, there are exactly m congruence classes modulo m. □

2.1.2 Congruence Classes modulo m

We denote congruence clases modulo m as

$$\mathbb{Z}/m\mathbb{Z} := \{congruence\ classes\ mod\ m\}$$

Addition

We will define addition as

$$[a]_m + [b]_m = [a+b]_m$$

Proof. We know

$$a' \equiv a\ (mod\ m)$$
$$b' \equiv b\ (mod\ m)$$

Then

$$m \mid a - a'$$
$$m \mid b - b'$$

or

$$(a+b) - (a'+b') = (a-a') + (b-b') \implies m \mid (a-a') + (b-b')$$

So $+$ is well-defined. ☐

Properties

(i) Commutativity: $[a]_m + [b]_m = [b]_m + [a]_m$.

Proof. $[a]_m + [b]_m = [a+b]_m = [b+a]_m = [b]_m + [a]_m$. ☐

(ii) Associativity: $([a]_m + [b]_m) + [c]_m = [a]_m + ([b]_m + [c]_m)$.

Proof. Trivial. ☐

(iii) Identity: $[a]_m + [0]_m = [a]_m$.

Proof. $[a]_m = [a+0]_m = [a]_m + [0]_m = [a]_m$. ☐

(iv) Inverse: $[a]_m + [-a]_m = [0]_m$.

Proof. $[a]_m + [-a]_m = [a + (-a)]_m = [0]_m$. ☐

Multiplication

We will define multiplication as

$$[a]_m \cdot [b]_m = [a \cdot b]_m$$

Proof. We know

$$a' \equiv a\ (mod\ m)$$
$$b' \equiv b\ (mod\ m)$$

Then

$$m \mid a - a'$$
$$m \mid b - b'$$

or

$$(a \cdot b) \cdot (a' \cdot b') = ab - ab' - a'b + a'b' = a(b-b') + a'(b-b') \implies m \mid (a'b' - ab)$$

So $\cdot$ is well-defined. ☐

Properties

(i) Commutativity: $[a]_m \cdot [b]_m = [b]_m \cdot [a]_m$.

Proof. $[a]_m \cdot [b]_m = [a \cdot b]_m = [b \cdot a]_m = [b]_m \cdot [a]_m$. □

(ii) Associativity: $([a]_m \cdot [b]_m) \cdot [c]_m = [a]_m \cdot ([b]_m \cdot [c]_m)$.

Proof. Trivial. □

(iii) Identity: $[a]_m \cdot [1]_m = [a]_m$.

Proof. $[a]_m = [a \cdot 1]_m = [a]_m \cdot [1]_m = [a]_m$. □

(iv) Distributivity: $[a]_m \cdot ([b]_m + [c]_m) = [a]_m[b]_m + [a]_m[c]_m$.

Proof. $[a]_m \cdot ([b]_m + [c]_m) = [a \cdot (b + c)]_m = [ab + ac]_m = [ab]_m + [ac]_m = [a]_m[b]_m + [a]_m[c]_m$ □

2.1.3 Invertability

We say that $[a]_m$ is ***invertible*** if there exists some $[a]_m^{-1}$ such that

$$[a]_m[b]_m = [1]_m$$

Theorem

A class $[a]_m$ is invertible *if and only if* $\gcd(a, m) = 1$.

Proof. ($\implies$) Assume $[a]_m$ is invertible. Then by definition there is some $[b]_m$ such that $[a]_m[b]_m = [ab]_m = 1 \implies m \mid (ab - 1) \implies ab - 1 = km \iff ab - km = 1$. Suppose $d \mid a$ and $d \mid m$. Then

$$d \mid (ab - km) = 1$$

$$d \mid 1 \implies d = 1$$

($\impliedby$) Assume $\gcd(a, m) = 1$. Then, there is an integer solution to $ax \equiv 1 \ (mod\ m)$. Then, $[ax]_m == [a]_m[x]_m = 1 \implies [a]_m$ is invertible. □

2.1.4 Set of Invertible Classes

We denote the set of invertible classes as

$$(\mathbb{Z}/m\mathbb{Z})^{\times} := \{[a]_m : [a]_m \ \textit{is invertible}\}$$

Note: $m = p$ a prime $\implies |\,(\mathbb{Z}/m\mathbb{Z})^{\times} = p - 1$.

2.2 Euler Totient Function

We denote the number of integers $1, \ldots, m - 1$ coprime to m as

$$\varphi(m)$$

2.2.1 Properties

(i) $m = p$ a prime $\implies \varphi(p) = p - 1$.

(ii) $m = p^k \implies \varphi(p^k) = p^k - p^{k-1} = p^{k-1}(p - 1)$.

Proof. In the set $\{1, 2, \ldots, p^k\}$, every p-th number is a multiple of p. There are p^{k-1} such elements in this set. Therefore, the elements that are coprime to p are $p^k - p^{k-1} = p^{k-1}(p-1)$. □

2.2.2 Chinese Remainder Theorem

Lemma

Let $a \mid n$ and $b \mid n$. If $\gcd(a,b) = 1$, then $ab \mid n$.

Proof. Let $\gcd(a,b) = 1$. Then,

$$\begin{aligned} ax + by &= 1 && \text{Bezout's Identity} \\ n(ax + by) &= n && \text{multiply both sides by } n \\ nax + nby &= n \end{aligned}$$

By assumption, $a \mid n$ and $b \mid n$ so $ab \mid an$ and $ab \mid bn \implies ab \mid n$. $\square$

Corollary

Suppose $m_1 \mid n$, $m_2 \mid n$, ..., $m_k \mid n$ for $m_i \neq m_j, i \neq j$ (pairwise relatively prime). Then $m_1 m_2 \cdots m_k \mid n$.

Proof. We will induct on $k \geq 2$.

(i) ($k = 2$) By the *Lemma*, this is true.

(ii) ($k = k+1$) Consider $m_1(m_2 \cdots m_k)$. Then $\gcd(m_1, m_i) = 1$ for $i \leq k$. Then $(m_1, m_2 \cdots m_k) = 1$. By the Inductive Hypothesis, $m_2 \cdots m_k \mid n$. By the *Lemma*, $m_1 m_2 \cdots m_k \mid n$.

$\square$

Proposition

If $m \mid n$, then $\mathbb{Z}/n\mathbb{Z} \to \mathbb{Z}/m\mathbb{Z}$. That is,

$$[a]_n \mapsto [a]_m$$

Proof. Suppose $[a]_n = [a']_n$. Then $a \equiv a'$ $(mod\ n)$. So

$$m \mid n \mid (a - a') \implies m \mid (a - a') \implies [a]_m = [a']_m$$

So $\mapsto$ is well-defined.

We will now consider $n := m_1 m_2 \cdots m_k$ for some integer k. Then

$$f : \mathbb{Z}/n\mathbb{Z} \to \mathbb{Z}/m_1\mathbb{Z} \times \mathbb{Z}/m_2\mathbb{Z} \times \cdots \times \mathbb{Z}/m_k\mathbb{Z}$$

or

$$[a]_n \mapsto \left([a]_{m_1]} \mapsto [a]_{m_2} \mapsto \cdots \mapsto [a]_{m_k}\right)$$

$\square$

Theorem

If m_i are pairwise relatively prime, then f (defined above) is a bijection.

Proof. ***Injective***
Assume $f([a]_n) = f([b]_n)$. Then

$$([a]_{n_1}, \cdots, [a]_{n_k}) = ([b]_{n_1}, \cdots, [b]_{n_k})$$

$$[a]_i = [b]_i \;\forall i < n \implies m_i \mid (b-a) \implies \prod m_i \mid (b-a) \iff n \mid (b-a) \implies [a]_n = [b]_n$$

Surjective
Trivial. Since f is both injective and surjective, f is a bijection. □

Note: the size of $\mathbb{Z}/n\mathbb{Z}$ is $|\mathbb{Z}/n\mathbb{Z}| = |\mathbb{Z}/m_1\mathbb{Z} \times \cdots \times \mathbb{Z}/m_k\mathbb{Z}|$

Theorem

Consider the following system of congruences:

$$\begin{aligned} x &\equiv b_1 \;(mod\; m_1) \\ x &\equiv b_2 \;(mod\; m_2) \\ &\vdots \\ x &\equiv b_k \;(mod\; m_k) \end{aligned}$$

If $m_1, \ldots, m_k$ are pairwise relatively prime, then there is an integer solution to the above system of congruences.

Proof. Since $f : \mathbb{Z}/n\mathbb{Z} \to \mathbb{Z}/m_1\mathbb{Z} \times \mathbb{Z}/m_2\mathbb{Z} \times \cdots \times \mathbb{Z}/m_k\mathbb{Z}$ is a bijection, there is some $[x]_n$ such that $f([x]_n) = ([b]_{m_1}, \ldots, [b]_{m_k})$ by surjectivity, so $[x]_{m_i} = [b_i]_{m_i} \implies x \equiv b_i \;(mod\; m_i)\; \forall i < k$. ***(i)***

Suppose $[x]_{m_i} = [y]_{m_1}$. Then,

$$m_i \mid (x-y) \implies \prod m_i \mid (x-y)$$

so $[x]_n = [y]_n$. Let $[x]_n$ be a solution; i.e. $y \in [x]_n$. Then

$$m_i \mid n \mid (y-x) \implies m_i \mid (y-x) \implies [y]_m = [x]_m$$

□

2.3 Groups

Let G be a set. A binary operation, $\cdot$, on G is a map

$$G \times G \to G$$

such that

$$(a, b) \mapsto a \cdot b$$

A set G with a binary operation $\cdot$ is a ***group*** if

(i) Associative: $(a \cdot b) \cdot c = a \cdot (b \cdot c)$

(ii) Unique Identity: There exists an $e \in G$ such that $a \cdot e = e \cdot a = a$.

(iii) Unique Inverse: $(a \cdot b) \cdot c = a \cdot (b \cdot c)$

2.3.1 Abelian Groups

A group is said to be ***abelian*** if for every $a, b \in G$, $\cdot$ is commutative; i.e.

$$a \cdot b = b \cdot a$$

Note: If G is abeliean, we usually denote the binary operator as $+$, inverse as $-a$, and identity as 0.

2.3.2 Properties

(i) Unique Identity e.

Proof. Let e_1, e_2 be two identities. Then, since e_1 is an identity, we get

$$e_1 \cdot e_2 = e_2$$

but since e_2 is an identity, we get

$$e_1 \cdot e_2 = e_1$$

so $e_1 = e_2$. $\square$

(ii) Unique Inverse e.

Proof. Let a_1, a_2 be two inverses. Then

$$a_1 = a_1 \cdot e = a_1 \cdot (a \cdot a_2) = (a_1 \cdot a) \cdot a_2 = e \cdot a_2 = a_2$$

$\square$

(iii) Associativity: $(a \cdot b) \cdot c = a \cdot (b \cdot c)$.

(iv) $\left(a^{-1}\right)^{-1} = a$

Proof. $a^{-1} \cdot a = a \cdot a^{-1} = e \implies a = \left(a^{-1}\right)^{-1}$ $\square$

(v) Powers.

$$\begin{aligned} a^0 &= e & \\ a^n &= a \cdot a \cdots a & n \text{ times} \\ a^{-n} &= (a^n)^{-1} = \left(a^{-1}\right)^n = a^{-1} \cdot a^{-1} \cdots a^{-1} & n \text{ times} \end{aligned}$$

(vi) Inverse: $a, b \in G$. Then $(ab)^{-1} = b^{-1}a^{-1}$.

Proof. $e = (ab) \cdot (b^{-1}a^{-1}) = a(bb^{-1})a^{-1} = aea^{-1} = aa^{-1} = e$.
$e = (b^{-1}a^{-1}) \cdot (ab) = a^{-1}(b^{-1}b)a = a^{-1}ea = a^{-1}a = e$. $\square$

(vii) Cancellation: $ax = bx \implies a = b$.

Proof. $a = ae = a\left(xx^{-1}\right) = (ax)x^{-1} = (bx)x^{-1} = b\left(xx^{-1}\right) = be = b$. $\square$

Note: $xa = xb \implies a = b$ but $ax = xb \not\Longrightarrow a = b$ since G need not be abelian!

Chapter 3

Week 3

3.1 Homomorphisms of Groups

Let G, H be two groups. A ***homomorphism*** between G and H is a map

$$f : G \to H$$

such that

$$H \ni f(x \cdot y) = f(x) \cdot f(y) \in H$$

for every $x, y \in G$.

3.1.1 Properties

Let $f : G \to H$ be a homomorphism.

(i) $f(e_G) = e_H$.

Proof. $f(e_G) \cdot f(e_G) = f(e_G \cdot e_G) = f(e_G) = e_H$ □

(ii) $f(x^{-1} = f(x)^{-1}$ for every $x \in G$.

Proof.

$$e_H = f(x^{-1}) \cdot f(x) = f(x^{-1} \cdot x) = f(e_G) = e_H$$
$$e_H = f(x) \cdot f(x^{-1}) = f(x \cdot x^{-1}) = f(e_G) = e_H$$

□

3.2 Isomorphisms of Groups

A homomorphism $f : G \to H$ is an ***isomorphism*** if f is a bijection. Two groups are called ***isomorphic*** if there is an isomorphism $f : G \to H$.

3.2.1 Properties

(i) $\mathrm{Id}_G : G \to G$ is an isomorphism.

(ii) If f is an isomorphism, so is $f^{-1} : H \to G$.

Proof. Let f^{-1} be a bijection. Then,

$$\exists x \in G : f(x) = a \implies x = f^{-1}(a)$$

$$\exists y \in G : f(y) = b \implies y = f^{-1}(b)$$

Then,

$$f(x \cdot y) = f(x) \cdot f(y) = ab$$
$$f^{-1}(ab) = xy = f^{-1}(a) \cdot f^{-1}(b)$$

□

(iii) If $f : G \to H$ and $f' : H \to K$ are isomorphisms, then so is $f' \circ f : G \to K$.

Theorem

The relation $\simeq$ is an equivalence relation.

Proof. *(i)* $\mathrm{Id}_G : G \to G$ is an isomorphism.

(ii) If f is an isomorphism, so is $f^{-1} : H \to G$.

Proof. Let f^{-1} be a bijection. Then,

$$x \in G : f(x) = a \implies x = f^{-1}(a)$$

$$y \in G : f(y) = b \implies y = f^{-1}(b)$$

Then,

$$f(x \cdot y) = f(x) \cdot f(y) = ab$$
$$f^{-1}(ab) = xy = f^{-1}(a) \cdot f^{-1}(b)$$

□

(iii) If $f : G \to H$ and $f' : H \to K$ are isomorphisms, then so is $f' \circ f : G \to K$.

□

3.3 Cyclic Groups

3.3.1 Generator

Let G be a group, and $a \in G$. The element ***generates*** G if every $x \in G$ can be written as

$$x = a^i$$

for some $i \in \mathbb{Z}$. We say that a is a ***generator*** of G.

3.3.2 Order of a Group

Let G be a group, and $a, \in G$. The smallest $n > 0$ such that $a^n = e$ is called the ***order*** of a and is denoted as

$$\mathrm{ord}(a) = n$$

Note that $\mathrm{ord}(a) = \infty$ if such an n does not exist.

3.3.3 Cyclicity

A group G is called ***cyclic*** if G has a generator.

Theorem

Every cyclic group is isomorphic to either $\mathbb{Z}$ or $\mathbb{Z}/n\mathbb{Z}$ for some $n \geq 0$.

Properties

> *Proposition*
>
> $[a]_n \in \mathbb{Z}/n\mathbb{Z}$ a generator *if and only if* $\gcd(a, n) = 1$. There are $\varphi(n)$ generators of $\mathbb{Z}/n\mathbb{Z}$.

Proof. ($\Longrightarrow$) There exists some $i \in \mathbb{Z}$ such that $i \cdot [a]_n = [1]_n$. Then

$$[ia]_n = [1]_n \implies ia \equiv 1 \ (mod\ n) \iff n \mid ia - 1 \iff ia - 1 = nm \iff \gcd(a, n) = 1$$

($\Longleftarrow$) Let $\gcd(a, n) = 1$. Then for some $x, y \in \mathbb{Z}$,

$$1 = ax + ny$$

But $1 - ax$ is divisible by n, so we get

$$1 \equiv ax \ (mod\ n) \iff [1]_n = [ax]_n = x \cdot [a]_n$$

Now, take any $[b]_n \in \mathbb{Z}/n\mathbb{Z}$. We have that

$$[b]_n \equiv bx[a]_n$$

so $[a]_n$ is a generator of $\mathbb{Z}/n\mathbb{Z}$. □

> *Proposition*
>
> Let G be a cyclic group of order n. Then $\sigma \in G$ be a generator *if and only if* $\text{ord}(\sigma) = n$.

Proof. ($\Longrightarrow$) Consider the powers of σ. $\sigma^0 = e$, $\sigma^1 = \sigma$, ..., $\sigma^k = e$, $\sigma^{k+1} = \sigma$, ..., $\sigma^{2k} = e$. Take k to be the smallest integer such that $\sigma^k = \sigma^i$ for $i \leq i \leq k$. We claim that $i = 0$.

If $i > 0$, we have $\sigma^{k-1} = \sigma^{i-1}$ for $0 \leq i < k$¡ a contradiction. Then $\sigma^k = \sigma^0 = e$. So $n = |G| = k \implies n$ is the smallest integer such that $\sigma^n = e$. So $n = \text{ord}(\sigma)$.

($\Longleftarrow$) By definition, n is the smallest integer such that $\sigma^n = e$. Then,

$$\left\{e, \sigma^1, \sigma^2, \ldots, \sigma^{n-1}\right\}$$

are distinct elements. This shows that

$$G = \left\{e, \sigma, \sigma^2, \ldots, \sigma^{n-1}\right\}$$

That is, σ generates G. Thus, $|G| = n = \text{ord}(\sigma)$. □

Chapter 4

Appendix

Binomial Expansion

$$(a+b)^n = \sum_{k=0}^{n} \binom{n}{k} a^{n-k} b^k$$

where

$$\binom{n}{k} = \frac{n!}{k!(n-k)!}$$

Geometric Series

Finite:

$$S = \frac{a(1-r^n)}{1-r}$$

$$S = \frac{a}{1-r}$$