

# Fall 2025 Introduction to Algebra (I)

## Preview Note

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## 0 Preliminaries

### 0.1 Basics

The subset of a given set  $A$  is

$$B = \{a \in A \mid \dots (\text{conditions on } a) \dots\}$$

The *order* (or *cardinality*) of a set  $A$  will be denoted by  $|A|$ . If  $A$  is a finite set, the order of  $A$  is simply the number of elements of  $A$ .

The *Cartesian product* of two sets  $A$  and  $B$  is the collation  $A \times B = \{(a, b) \mid a \in A, b \in B\}$ , of ordered pairs of elements from  $A$  and  $B$ .

The following notation for some common sets of numbers

1. **Integers:**  $\mathbb{Z} = \{0, \pm 1, \pm 2, \dots\}$ .
2. **Rational numbers:**  $\mathbb{Q} = \{a/b \mid a, b \in \mathbb{Z}, b \neq 0\}$ .
3. **Real numbers:**  $\mathbb{R} = \{\text{all decimal expansions } \pm d_1 d_2 \dots d_n . a_1 a_2 a_3 \dots\}$ .
4. **Complex numbers:**  $\mathbb{C} = \{a + bi \mid a, b \in \mathbb{R}, i^2 = -1\}$ .
5.  $\mathbb{Z}^+$ ,  $\mathbb{Q}^+$  and  $\mathbb{R}^+$  will denote the positive (nonzero) elements in  $\mathbb{Z}$ ,  $\mathbb{Q}$  and  $\mathbb{R}$ , respectively.

The notation  $f : A \rightarrow B$  or  $A \xrightarrow{f} B$  to denote a *function* (or *map*)  $f$  from  $A$  to  $B$ , and the value of  $f$  at  $a$  is denoted by  $f(a)$ . The set  $A$  is called the *domain* of  $f$  and  $B$  is called the *codomain* of  $f$ .

The notation  $f : a \mapsto b$  or  $a \mapsto b$  if  $f$  is understood indicates that  $f(a) = b$ , i.e., the function is being specified on *elements*. If the function  $f$  is not specified on elements, it is important in general to check that  $f$  is *well defined*, i.e., is unambiguously determined.

The set

$$f(A) = \{b \in B \mid b = f(a), \text{ for some } a \in A\}$$

is a subset of  $B$ , called the *range* or *image* of  $f$  (or the *image* of  $A$  under  $f$ ).

For each subset  $C$  of  $B$ , the set

$$f^{-1}(C) = \{a \in A \mid f(a) \in C\}$$

consisting of the elements of  $A$  mapping into  $C$  under  $f$  is called the *preimage* or *inverse image* of  $C$  under  $f$ . For each  $b \in B$ , the preimage of  $\{b\}$  under  $f$  is called the *fiber* of  $f$  over  $b$ . Note that  $f^{-1}$  is not in general a function and that the fibers of  $f$  generally contain many elements since there may be many elements of  $A$  mapping to the element  $b$ .

If  $f : A \rightarrow B$  and  $g : B \rightarrow C$ , then the composite map  $g \circ f : A \rightarrow C$  is defined by

$$(g \circ f)(a) = g(f(a))$$

**Definition 0.1-1** Let  $f : A \rightarrow B$

1.  $f$  is *injective* or is an *injection* if whenever  $a_1 \neq a_2$ , then  $f(a_1) \neq f(a_2)$ .
2.  $f$  is *surjective* or is a *surjection* if for all  $b \in B$ , there is some  $a \in A$  such that  $f(a) = b$ .
3.  $f$  is *bijective* or is a *bijection* if it is both injective and surjective. If such a bijection  $f$  exists from  $A$  to  $B$ , we say  $A$  and  $B$  are in *bijective correspondence*.
4.  $f$  has a *left inverse* if there is a function  $g : B \rightarrow A$  such that  $g \circ f : A \rightarrow A$  is the identity map on  $A$ , i.e.,  $(g \circ f)(a) = a$  for all  $a \in A$ .
5.  $f$  has a *right inverse* if there is a function  $h : B \rightarrow A$  such that  $f \circ h : B \rightarrow B$  is the identity map on  $B$ , i.e.,  $(f \circ h)(b) = b$  for all  $b \in B$ .

**Proposition 0.1-1** Let  $f : A \rightarrow B$

1. The map  $f$  is injective if and only if  $f$  has a left inverse.
2. The map  $f$  is surjective if and only if  $f$  has a right inverse.
3. The map  $f$  is a bijection if and only if there exists  $g : B \rightarrow A$  such that  $f \circ g$  is the identity map on  $B$  and  $g \circ f$  is the identity map on  $A$ .
4. If  $A$  and  $B$  are finite sets with the same number of elements (i.e.,  $|A| = |B|$ ), then  $f : A \rightarrow B$  is bijective if and only if  $f$  is injective if and only if  $f$  is surjective.

**Proof.**

1.  $(\Rightarrow)$  Suppose  $f$  is injective. Notice that if  $b \in f(A)$  then there is a unique  $a \in A$  such that  $f(a) = b$ . Choose any  $a_0 \in A$ , and define  $g : B \rightarrow A$  by

$$g(b) = \begin{cases} a & \text{if } b \in f(A) \\ a_0 & \text{if } b \notin f(A) \end{cases}$$

Then  $(g \circ f)(a) = a$  for all  $a \in A$ , so  $g$  is a left inverse of  $f$ .

$(\Leftarrow)$  Suppose  $f$  has a left inverse  $g$ , and that  $f(a) = f(b)$ . Then  $g(f(a)) = g(f(b))$ , and since  $g \circ f : A \rightarrow A$ , we have  $a = b$ , which shows  $f$  is injective.

2.  $(\Rightarrow)$  Suppose  $f$  is surjective. Then every  $b \in B$  is in the image of  $f$ , so for each  $b \in B$  pick an element  $g(b) \in A$  such that  $f(g(b)) = b$ . Then  $g$  is a right inverse of  $f$ .

$(\Leftarrow)$  Suppose  $f$  has a right inverse  $g$  and let  $b \in B$ . Then  $f(g(b)) = b$  as  $f \circ g : B \rightarrow B$ . This shows  $b \in f(A)$ , so  $f(A) = B$  and  $f$  is surjective.

3.  $(\Rightarrow)$  Suppose  $f$  is a bijection, then  $f$  is injective and surjective by definition. By part 1. there exists a left inverse  $g : B \rightarrow A$  such that  $g \circ f : A \rightarrow A$ , and by part 2. there exists a right inverse  $g : B \rightarrow A$  such that  $f \circ g : B \rightarrow B$ .

$(\Leftarrow)$  Suppose there exists  $g : B \rightarrow A$  such that  $f \circ g : B \rightarrow B$  and  $g \circ f : A \rightarrow A$ . Then by part 1.,  $f$  is surjective, and by part 2.,  $f$  is injective. Then  $f$  is a bijection.

4. **Claim:**

- (1) If  $f : A \rightarrow B$  is injective, then  $|A| \leq |B|$ .
- (2) If  $f : A \rightarrow B$  is surjective, then  $|A| \geq |B|$ .
- (3) If  $f : A \rightarrow B$  is a bijection, then  $|A| = |B|$ .

*proof.* Let  $A = \{a_1, a_2, \dots, a_m\}$  has  $m$  elements.

- (1)  $\{f(a_1), f(a_2), \dots, f(a_m)\}$  is a subset of  $B$ , because  $f$  is injective,  $|A| = m \leq |B|$ .
- (2)  $\{f(a_1), f(a_2), \dots, f(a_m)\} = B$  has at most  $m$  different elements because  $f$  is surjective,  $|A| = m \geq |B|$ .
- (3) This follows from (1) and (2), since  $|A| \leq |B|$  and  $|A| \geq |B|$ , we have  $|A| = |B|$ .

The situation of part 3. of **Proposition 0.1-1**, the map  $g$  is necessarily unique and we shall say  $g$  is the *2-sided inverse* (or *inverse*) of  $f$ .

A *permutation* of a set  $A$  is simply a bijection from  $A$  to itself.

If  $A \subseteq B$  and  $f : B \rightarrow C$ , we denote the *restriction* of  $f$  to  $A$  by  $f|_A$ .

If  $A \subseteq B$  and  $g : A \rightarrow C$  and there is a function  $f : B \rightarrow C$  such that  $f|_A = g$ , we shall say  $f$  is an *extension* of  $g$  to  $B$ .

**Definition 0.1-2** Let  $A$  be a nonempty set.

- 1. A *binary relation* on a set  $A$  is a subset  $R$  of  $A \times A$  and we write  $a \sim b$  if  $(a, b) \in R$ .
- 2. The relation  $\sim$  on  $A$  is said to be:
  - (a) *reflexive* if  $a \sim a$ , for all  $a \in A$
  - (b) *symmetric* if  $a \sim b$  implies  $b \sim a$  for all  $a, b \in A$
  - (c) *transitive* if  $a \sim b$  and  $b \sim c$  implies  $a \sim c$  for all  $a, b, c \in A$

A relation is an *equivalence relation* if it is reflexive, symmetric and transitive.

- 3. If  $\sim$  defines an equivalence relation on  $A$ , then the *equivalence class* of  $a \in A$  is defined to be  $\{x \in A \mid x \sim a\}$ . Elements of the equivalence class of  $a$  are said to be *equivalent* to  $a$ . If  $C$  is an equivalence class, any element of  $C$  is called a *representative* of the class  $C$ .
- 4. A *partition* of  $A$  is any collection  $\{A_i \mid i \in I\}$  of nonempty subsets of  $A$  ( $I$  some indexing set) such that
  - (a)  $A = \cup_{i \in I} A_i$
  - (b)  $A_i \cap A_j = \emptyset$  for all  $i, j \in I$  with  $i \neq j$ , i.e.,  $A$  is the disjoint union of the sets in the partition.

**Proposition 0.1-2** Let  $A$  be a nonempty set.

1. If  $\sim$  defines an equivalence relation on  $A$ , then the set of equivalence classes of  $\sim$  form a partition of  $A$ .
2. If  $\{A_i \mid i \in I\}$  is a partition of  $A$ , then there is an equivalence relation on  $A$  whose equivalence classes are precisely the sets  $A_i$ ,  $i \in I$ .

**Proof.** [Link](#)

## 0.2 Properties of the integers

### 0.2.1 Well Ordering of $\mathbb{Z}$

If  $A$  is any nonempty subset of  $\mathbb{Z}^+$ , there is some element  $m \in A$  such that  $m \leq a$ , for all  $a \in A$  ( $m$  is call a *minimal element* of  $A$ ).

### 0.2.2 Divides

If  $a, b \in \mathbb{Z}$  with  $a \neq 0$ , we say  $a$  *divides*  $b$  if there is an element  $c \in \mathbb{Z}$  such that  $b = ac$ . In this case, we write  $a \mid b$ ; if  $a$  does not divide  $b$ , we write  $a \nmid b$ .

### 0.2.3 Greatest Common Divisor (g.c.d.)

If  $a, b \in \mathbb{Z} \setminus \{0\}$ , there is a unique positive integer  $d$ , called the *greatest common divisor* of  $a$  and  $b$  (or g.c.d. of  $a$  and  $b$ ), satisfying:

- (1)  $d \mid a$  and  $d \mid b$  ( $d$  is a common divisor of  $a$  and  $b$ )
- (2) If  $e \mid a$  and  $e \mid b$ , then  $e \leq d$  ( $d$  is the greatest such divisor)

The g.c.d. of  $a$  and  $b$  will be denoted by  $(a, b)$  (or  $\gcd(a, b)$ ). If  $(a, b) = 1$ , we say that  $a$  and  $b$  are *relatively prime*.

### 0.2.4 Least Common Multiple (l.c.m.)

If  $a, b \in \mathbb{Z} \setminus \{0\}$ , there is a unique positive integer  $l$ , called the *least common multiple* of  $a$  and  $b$  (or l.c.m. of  $a$  and  $b$ ), satisfying:

- (1)  $a \mid l$  and  $b \mid l$  ( $l$  is a common multiple of  $a$  and  $b$ )
- (2) If  $a \mid m$  and  $b \mid m$ , then  $l \leq m$  ( $l$  is the least such multiple)

The l.c.m. of  $a$  and  $b$  will be denoted by  $[a, b]$  (or  $\text{lcm}(a, b)$ ). The connection between the g.c.d.  $d$  and the l.c.m.  $l$  of two integers  $a$  and  $b$  is given by  $dl = ab$ .

### 0.2.5 The Division Algorithm

If  $a, b \in \mathbb{Z} \setminus \{0\}$ , then there exist unique  $q, r \in \mathbb{Z}$  such that

$$a = qb + r \quad \text{and} \quad 0 \leq r < |b|$$

where  $q$  is the *quotient* and  $r$  is the *remainder*.

### 0.2.6 The Euclidean Algorithm

If  $a, b \in \mathbb{Z} \setminus \{0\}$ , then we obtain a sequence of quotients and remainders

$$a = q_0b + r_0 \quad (0)$$

$$b = q_1r_0 + r_1 \quad (1)$$

$$r_0 = q_2r_1 + r_2 \quad (2)$$

$$r_1 = q_3r_2 + r_3 \quad (3)$$

$$\vdots$$

$$r_{n-2} = q_nr_{n-1} + r_n \quad (n)$$

$$r_{n-1} = q_{n+1}r_n \quad (n+1)$$

where  $r_n$  is the last nonzero remainder. Such an  $r_n$  exists since  $|b| > |r_0| > |r_1| > \cdots > |r_n|$  is a decreasing sequence of strictly positive integers if the remainders are nonzero and such a sequence cannot continue indefinitely. Then  $r_n$  is the g.c.d.  $(a, b)$  of  $a$  and  $b$ .

**Example 0.2.6-1** Find the g.c.d. of  $a = 57970$  and  $b = 10353$ .

**Sol.** Applying the Euclidean algorithm, we have

$$57970 = (5)10353 + 6205$$

$$10353 = (1)6205 + 4148$$

$$6205 = (1)4148 + 2057$$

$$4148 = (2)2057 + 34$$

$$2057 = (60)34 + 17$$

$$34 = (2)17$$

Thus, the g.c.d. of 57970 and 10353 is  $(57970, 10353) = 17$ .

### 0.2.7 $\mathbb{Z}$ -linear Combinations

One consequence of the Euclidean Algorithm which we shall use regularly is the following: if  $a, b \in \mathbb{Z} \setminus \{0\}$ , then there exist  $x, y \in \mathbb{Z}$  such that

$$(a, b) = ax + by$$

that is, *the g.c.d. of  $a$  and  $b$  is a  $\mathbb{Z}$ -linear combination of  $a$  and  $b$* . This follows by recursively writing the element  $r_n$  in the Euclidean Algorithm in terms of the previous remainders (namely, use equation (n) above to solve for  $r_n = r_{n-2} - q_nr_{n-1}$  in terms of the remainders  $r_{n-1}$  and  $r_{n-2}$ , then use equation  $(n-1)$  to write  $r_n$  in terms of the remainders  $r_{n-2}$  and  $r_{n-3}$ , etc., eventually writing  $r_n$  in terms of  $a$  and  $b$ ).

**Example 0.2.7-1** Use the Euclidean Algorithm to find integers  $x, y$  such that

$$(57970, 10353) = 57970x + 10353y$$

**Sol.** Based on **Example 0.2.6-1** we know that  $(57970, 10353) = 17$ . Start from the fifth equation in the Euclidean Algorithm,

$$\begin{aligned} 17 &= 2057 - 60 \cdot 34 \\ &= 2057 - 60 \cdot (4148 - (2)2057) = 121 \cdot 2057 - 60 \cdot 4148 \\ &= 121 \cdot (6205 - (1)4148) - 60 \cdot 4148 = 121 \cdot 6205 - 181 \cdot 4148 \\ &= 121 \cdot 6205 - 181 \cdot (10353 - (1)6205) = 302 \cdot 6205 - 181 \cdot 10353 \\ &= 302 \cdot (57970 - (5)10353) - 181 \cdot 10353 \\ &= 302 \cdot 57970 + (-1691) \cdot 10353 \end{aligned}$$

Thus,  $x = 302$  and  $y = -1691$  is a solution of  $(57970, 10353) = 57970x + 10353y$ .

### 0.2.8 Prime and Composite Numbers

An element  $p$  of  $\mathbb{Z}^+$  is called a *prime* if  $p > 1$  and the only positive divisors of  $p$  are 1 and  $p$ . An integer  $n > 1$  which is not prime is called *composite*.

### 0.2.9 The Fundamental Theorem of Arithmetic

If  $n \in \mathbb{Z}$ ,  $n > 1$ , then  $n$  can be factored uniquely into the product of primes, i.e., there are distinct primes  $p_1, p_2, \dots, p_s$  and positive integers  $\alpha_1, \alpha_2, \dots, \alpha_s$  such that

$$n = p_1^{\alpha_1} p_2^{\alpha_2} \dots p_s^{\alpha_s}$$

This factorization is unique in the sense that if  $q_1, q_2, \dots, q_t$  are any distinct primes and positive integers  $\beta_1, \beta_2, \dots, \beta_t$  such that

$$n = q_1^{\beta_1} q_2^{\beta_2} \dots q_t^{\beta_t}$$

then  $s = t$  and if we arrange the two sets of primes in increasing order, then  $q_i = p_i$  and  $\alpha_i = \beta_i$   $1 \leq i \leq s$ .

Suppose the positive integers  $a$  and  $b$  are expressed as products of prime powers:

$$a = p_1^{\alpha_1} p_2^{\alpha_2} \dots p_s^{\alpha_s} \quad b = p_1^{\beta_1} p_2^{\beta_2} \dots p_s^{\beta_s}$$

where  $p_1, p_2, \dots, p_s$  are distinct and the exponents are  $\geq 0$  (we allow the exponents to be 0 here, so that the products are taken over the same set of primes – the exponent will be 0 if that prime is not actually a divisor). Then the g.c.d. of  $a$  and  $b$  is

$$(a, b) = p_1^{\min\{\alpha_1, \beta_1\}} p_2^{\min\{\alpha_2, \beta_2\}} \dots p_s^{\min\{\alpha_s, \beta_s\}}$$

and the l.c.m. of  $a$  and  $b$  is

$$[a, b] = p_1^{\max\{\alpha_1, \beta_1\}} p_2^{\max\{\alpha_2, \beta_2\}} \dots p_s^{\max\{\alpha_s, \beta_s\}}$$

### 0.2.10 Euler $\varphi$ -function

For  $n \in \mathbb{Z}^+$ , let  $\varphi(n)$  be the number of positive integers  $a \leq n$  with  $a$  relatively prime to  $n$ , i.e.,  $(a, n) = 1$ . For example,  $\varphi(12) = 4$  since the positive integers 1, 5, 7, 11 are the only positive integers less than or equal to 12 which have no factors in common with 12. For prime  $p$ ,  $\varphi(p) = p - 1$ , and more generally, for all  $a \geq 1$  we have the formula

$$\varphi(p^a) = p^a - p^{a-1} = p^{a-1}(p - 1)$$

The function  $\varphi$  is *multiplicative* in the sense that

$$\varphi(ab) = \varphi(a)\varphi(b) \quad \text{if } (a, b) = 1$$

(note that it is important here that  $a$  and  $b$  be relatively prime). Together with the formula above this gives a general formula for the values of  $\varphi$ : if  $n = p_1^{\alpha_1} p_2^{\alpha_2} \dots p_s^{\alpha_s}$ , then

$$\begin{aligned} \varphi(n) &= \varphi(p_1^{\alpha_1})\varphi(p_2^{\alpha_2}) \dots \varphi(p_s^{\alpha_s}) \\ &= p_1^{\alpha_1-1}(p_1 - 1)p_2^{\alpha_2-1}(p_2 - 1) \dots p_s^{\alpha_s-1}(p_s - 1) \end{aligned}$$

**Example 0.2.10-1** Find the value of  $\varphi(36)$ .

**Sol.** The prime factorization of 36 is  $36 = 2^2 \cdot 3^2$ , therefore

$$\begin{aligned} \varphi(36) &= \varphi(2^2)\varphi(3^2) \\ &= 2^{2-1}(2 - 1)3^{2-1}(3 - 1) \\ &= 2 \cdot 1 \cdot 3 \cdot 2 = 12 \end{aligned}$$

## 0.3 $\mathbb{Z}/n\mathbb{Z}$ : The integers modulo $n$

Let  $n$  be a fixed positive integer. Define a relation on  $\mathbb{Z}$  by

$$a \sim b \quad \text{if and only if} \quad n \mid (a - b)$$

Clearly  $a \sim a$ , and  $a \sim b$  implies  $b \sim a$  for any integers  $a$  and  $b$ , so this relation is trivially reflexive and symmetric. If  $a \sim b$  and  $b \sim c$ , then  $n$  divides  $a - b$  and  $n$  divides  $b - c$ , so  $n$  also divides the sum of these two integers, i.e.,  $n$  divides  $(a - b) + (b - c) = a - c$ , so  $a \sim c$  and the relation is transitive. Hence, this is an equivalence relation. Write  $a \equiv b \pmod{n}$  (read:  $a$  is *congruent* to  $b$  mod  $n$ ) if  $a \sim b$ . For any  $k \in \mathbb{Z}$  we shall denote the equivalence class of  $a$  by  $\bar{a}$  – this is called the *congruent class* or *residue class* of  $a$  mod  $n$  and consists of the integers which differ from  $a$  by an integral multiple of  $n$ , i.e.,

$$\begin{aligned} \bar{a} &= \{a + kn \mid k \in \mathbb{Z}\} \\ &= \{a, a \pm n, a \pm 2n, a \pm 3n, \dots\} \end{aligned}$$

There are precisely  $n$  distinct equivalence classes mod  $n$ , namely

$$\bar{0}, \bar{1}, \bar{2}, \dots, \overline{n-1}$$



determined by the possible remainders after division by  $n$ , and this residue classes partition the integers  $\mathbb{Z}$ . the set of equivalence classes under this equivalence relation will be denoted by  $\mathbb{Z}/n\mathbb{Z}$ , and called the *integers modulo  $n$*  (or the *integers mod  $n$* ).

The process of finding the equivalence class mod  $n$  of some integer  $a$  is often referred to as *reducing  $a$  mod  $n$* . This terminology also frequently refers to finding the smallest nonnegative integer congruent to  $a$  mod  $n$  (the *least residue* of  $a$  mod  $n$ ).

**Definition 0.3-1** We can define an addition and a multiplication for the elements of  $\mathbb{Z}/n\mathbb{Z}$ , defining *modular arithmetic* as follows: for  $\bar{a}, \bar{b} \in \mathbb{Z}/n\mathbb{Z}$ , define their sum and product by

$$\bar{a} + \bar{b} = \overline{a + b} \quad \text{and} \quad \bar{a} \cdot \bar{b} = \overline{ab}$$

Given any two elements  $\bar{a}$  and  $\bar{b}$  in  $\mathbb{Z}/n\mathbb{Z}$ , to compute their sum (respectively, their product) take *any representative* integer  $a$  in the class  $\bar{a}$  and *any representative* integer  $b$  in the class  $\bar{b}$ , and add (respectively, multiply) the integers  $a$  and  $b$  as usual in  $\mathbb{Z}$ , and then take the equivalence class containing the result.

**Theorem 0.3-1** The operations of addition and multiplication on  $\mathbb{Z}/n\mathbb{Z}$  defined in **Definition 0.3-1** are both well defined, that is, they do not depend on the choices of representatives for the classes involved. More precisely, if  $a_1, a_2 \in \mathbb{Z}$  and  $b_1, b_2 \in \mathbb{Z}$  with  $\bar{a}_1 = \bar{b}_1$  and  $\bar{a}_2 = \bar{b}_2$ , then  $\overline{a_1 + a_2} = \overline{b_1 + b_2}$  and  $\overline{a_1 a_2} = \overline{b_1 b_2}$ , i.e., if

$$a_1 \equiv b_1 \pmod{n} \quad \text{and} \quad a_2 \equiv b_2 \pmod{n}$$

then

$$a_1 + a_2 \equiv b_1 + b_2 \pmod{n} \quad \text{and} \quad a_1 a_2 \equiv b_1 b_2 \pmod{n}$$

**Proof.** Suppose  $a_1 \equiv b_1 \pmod{n}$ , i.e.,  $a_1 - b_1$  is divisible by  $n$ . Then  $a_1 = b_1 + sn$  for some integer  $s$ . Similarly,  $a_2 \equiv b_2 \pmod{n}$  means  $a_2 = b_2 + tn$  for some integer  $t$ . Then  $a_1 + a_2 = (b_1 + b_2) + (s + t)n$ , so  $a_1 + a_2 \equiv b_1 + b_2 \pmod{n}$ , which shows that the sum of the residue classes is independent of the representatives chosen.

Similarly,  $a_1 a_2 = (b_1 + sn)(b_2 + tn) = b_1 b_2 + (b_1 t + b_2 s + stn)n$ , so  $a_1 a_2 \equiv b_1 b_2 \pmod{n}$ , and so the product of the residue classes is also independent of the representatives chosen.

**Example 0.3-1** Find the last two digits in the number  $2^{1000}$ .

**Sol.** First observe that the last two digits give the remainder of  $2^{1000}$  after we divided by 100, so we are interested in the residue class mod 100 containing  $2^{1000}$ . We compute  $2^{10} = 1024 \equiv 24 \pmod{100}$ , so then  $2^{20} = (2^{10})^2 \equiv 24^2 = 576 \equiv 76 \pmod{100}$ . Then  $2^{40} = (2^{20})^2 \equiv 76^2 = 5776 \equiv 76 \pmod{100}$ . Similarly,  $2^{80} \equiv 2^{160} \equiv 2^{320} \equiv 2^{640} \equiv 76 \pmod{100}$ . Finally,  $2^{1000} = 2^{640} \cdot 2^{320} \cdot 2^{40} \equiv 76 \cdot 76 \cdot 76 \equiv 76 \pmod{100}$ . Thus, the last two digits of  $2^{1000}$  are 76.

An important subset of  $\mathbb{Z}/n\mathbb{Z}$  consists of the collection of residue classes which have a multiplicative inverse in  $\mathbb{Z}/n\mathbb{Z}$ :

$$(\mathbb{Z}/n\mathbb{Z})^\times = \{\bar{a} \in \mathbb{Z}/n\mathbb{Z} \mid \text{there exists } \bar{c} \in \mathbb{Z}/n\mathbb{Z} \text{ with } \bar{a} \cdot \bar{c} = \bar{1}\}$$

**Proposition 0.3-1**

$$(\mathbb{Z}/n\mathbb{Z})^\times = \{\bar{a} \in \mathbb{Z}/n\mathbb{Z} \mid (a, n) = 1\}$$

**Proof.** It is easy to see that if any representative of  $\bar{a}$  is relatively prime to  $n$ , then all representatives are relatively prime to  $n$ , so that the set on the right in the proposition is well defined.

If  $a$  is an integer relatively prime to  $n$ , then the Euclidean Algorithm produces integers  $x$  and  $y$  satisfying  $ax + ny = 1$ , hence  $ax \equiv 1 \pmod{n}$ , so that  $\bar{x}$  is the multiplicative inverse of  $\bar{a}$  in  $\mathbb{Z}/n\mathbb{Z}$ . This gives an efficient method for computing multiplicative inverses in  $\mathbb{Z}/n\mathbb{Z}$ .

**Example 0.3-2** Find the multiplicative inverse of  $\overline{17}$  in  $\mathbb{Z}/60\mathbb{Z}$ .

**Sol.** Suppose  $n = 60$  and  $a = 17$ . Applying the Euclidean Algorithm, we obtain

$$60 = (3)17 + 9$$

$$17 = (1)9 + 8$$

$$9 = (1)8 + 1$$

$$8 = (8)1$$

so that  $a$  and  $n$  are relatively prime, and  $(-7)17 + 2 \cdot 60 = 1$ . Hence,  $\overline{-7} = \overline{53}$  is the multiplicative inverse of  $\overline{17}$  in  $\mathbb{Z}/60\mathbb{Z}$ .

## Part I

# Group Theory

## 1 Introduction to Groups

### 1.1 Basic Axioms and Examples

#### Definition 1.1-1

1. A *binary operation*  $\star$  on a set  $G$  is a function  $\star : G \times G \rightarrow G$ . For any  $a, b \in G$ , we shall write  $a \star b$  for  $\star(a, b)$ .
2. A binary operation  $\star$  on a set  $G$  is *associative* if for all  $a, b, c \in G$ , we have  $a \star (b \star c) = (a \star b) \star c$ .
3. If  $\star$  is a binary operation on a set  $G$ , we say elements  $a$  and  $b$  of  $G$  *commute* if  $a \star b = b \star a$ . We say  $\star$  (or  $G$ ) is *commutative* if for all  $a, b \in G$ , we have  $a \star b = b \star a$ .

#### Example 1.1-1

1.  $+$  (usual addition) is a commutative binary operation on  $\mathbb{Z}$  (or on  $\mathbb{Q}, \mathbb{R}, \mathbb{C}$  respectively).
2.  $\times$  (usual multiplication) is a commutative binary operation on  $\mathbb{Z}$  (or on  $\mathbb{Q}, \mathbb{R}, \mathbb{C}$  respectively).
3.  $-$  (usual subtraction) is noncommutative binary operation on  $\mathbb{Z}$ , where  $-(a, b) = a - b$ . It is not a binary operation on  $\mathbb{Z}^+$  (nor  $\mathbb{Q}^+, \mathbb{R}^+$ ) (e.g.  $-(1, 2) = 1 - 2 = -1 \notin \mathbb{Z}^+$ ).
4. Taking the vector cross-product of two vectors in  $\mathbb{R}^3$  is a binary operation which is not associative and not commutative. For example,
  - (1)  $\mathbf{u} = (1, 2, 3), \mathbf{v} = (4, 5, 6) \in \mathbb{R}^3, \mathbf{u} \times \mathbf{v} = (-3, 6, -3)$   
 $\Rightarrow \mathbb{R}^3 \times \mathbb{R}^3 \rightarrow \mathbb{R}^3$
  - (2)  $\mathbf{u} = (1, 2, 3), \mathbf{v} = (4, 5, 6) \in \mathbb{R}^3, \mathbf{u} \times \mathbf{v} = (-3, 6, -3), \mathbf{v} \times \mathbf{u} = (3, -6, 3)$   
 $\Rightarrow$  it is not commutative.
  - (3)  $\mathbf{u} = (1, 2, 3), \mathbf{v} = (4, 5, 6), \mathbf{w} = (7, 8, 9) \in \mathbb{R}^3,$   
 $(\mathbf{u} \times \mathbf{v}) \times \mathbf{w} = (-3, 6, -3) \times (7, 8, 9) = (78, 6, -66)$   
 $\mathbf{u} \times (\mathbf{v} \times \mathbf{w}) = (1, 2, 3) \times (-3, 6, -3) = (-24, -6, 12)$

Suppose that  $\star$  is a binary operation on a set  $G$ , and  $H$  is a subset of  $G$ . If the restriction of  $\star$  to  $H$  is a binary operation on  $H$  ( $\forall a, b \in H, a \star b \in H$ ), we say that  $H$  is *closed* under  $\star$ .

Observe that if  $\star$  is an associative (respectively, commutative) binary operation on a set  $G$ , and  $\star$  restricted to some subset  $H$  of  $G$  is a binary operation on  $H$ , then  $\star$  is automatically associative (respectively, commutative) on  $H$  as well.

**Definition 1.1-2**

1. A *group* is an ordered pair  $(G, \star)$  where  $G$  is a set and  $\star$  is a binary operation on  $G$  satisfying the following axioms:
  - (i) **Associative:**  $(a \star b) \star c = a \star (b \star c)$ , for all  $a, b, c \in G$ .
  - (ii) **Identity:** There exists an element  $e \in G$  such that  $e \star a = a \star e = a$  for all  $a \in G$ .
  - (iii) **Inverses:** For each  $a \in G$ , there exists  $a^{-1} \in G$  such that  $a \star a^{-1} = a^{-1} \star a = e$ .
2. The group  $(G, \star)$  is called *abelian* (or *commutative*) if  $a \star b = b \star a$  for all  $a, b \in G$ .

We say  $G$  is a *finite group* if in addition  $G$  is a finite set.

Note that the axiom (ii) ensures that a group is always nonempty.

**Example 1.1-2**

1.  $\mathbb{Z}, \mathbb{Q}, \mathbb{R}$  and  $\mathbb{C}$  are groups under  $+$  with  $e = 0$  and  $a^{-1} = -a$  for all  $a$ .
2.  $\mathbb{Q} \setminus \{0\}, \mathbb{R} \setminus \{0\}, \mathbb{C} \setminus \{0\}, \mathbb{Q}^+, \mathbb{R}^+$  are groups under  $\times$  with  $e = 1$  and  $a^{-1} = \frac{1}{a}$ .
3. The axioms for a vector space  $V$  which specify that  $(V, +)$  is an abelian group.
4. For  $n \in \mathbb{Z}^+$ ,  $\mathbb{Z}/n\mathbb{Z}$  is an abelian group under the operation  $+$  with the identity element  $\bar{0}$  and the inverse of  $\bar{a}$  is  $\overline{-a}$ .
5. For  $n \in \mathbb{Z}^+$ , the set  $(\mathbb{Z}/n\mathbb{Z})^\times$  of equivalence classes  $\bar{a}$  which have multiplicative inverses mod  $n$  is an abelian group under multiplication with the identity element  $\bar{1}$ .

If  $(A, \star)$  and  $(B, \diamond)$  are groups, we can find a new group  $A \times B$ , called the *direct product*, whose elements are those in the Cartesian product

$$A \times B = \{(a, b) \mid a \in A, b \in B\}$$

and whose operation is defined componentwise:

$$(a_1, b_1)(a_2, b_2) = (a_1 \star a_2, b_1 \diamond b_2)$$

**Proposition 1.1-1** If  $G$  is a group under the operation  $\star$ , then

1. The identity of  $G$  is unique.
2. For each  $a \in G$ ,  $a^{-1}$  is uniquely determined.
3.  $(a^{-1})^{-1} = a$  for all  $a \in G$ .
4.  $(a \star b)^{-1} = (b)^{-1} \star (a)^{-1}$
5. **Generalized Associative Law:** For any  $a_1, a_2, \dots, a_n \in G$ , the value of  $a_1 \star a_2 \star \dots \star a_n$  is independent of how the expression is bracketed.

**Proof.**

1. If  $f$  and  $g$  are both identities, then by axiom (ii) of the **Definition 1.1-2**, we have  $f \star g = f$  and  $g \star f = g$ . Thus  $f = g$ , and the identity is unique.

2. Assume  $b$  and  $c$  are both inverses of  $a$ , and let  $e$  be the identity of  $G$ . By axiom (iii) of the **Definition 1.1-2**,  $a \star b = e$  and  $c \star a = e$ . Thus

$$\begin{aligned}
 c &= c \star e && \text{(Axiom (ii))} \\
 &= c \star (a \star b) && \text{(Since } e = a \star b) \\
 &= (c \star a) \star b && \text{(Axiom (i))} \\
 &= e \star b && \text{(Since } e = c \star a) \\
 &= b && \text{(Axiom (ii))}
 \end{aligned}$$

3. The inverse of  $a$  is  $a^{-1}$ , and the inverse of  $a^{-1}$  is  $(a^{-1})^{-1}$ , by part 2., we know  $a = (a^{-1})^{-1}$ .
4. Let  $c = (a \star b)^{-1}$ , so by definition of  $c$ ,  $(a \star b) \star c = e$ . By the associative law, we have

$$a \star (b \star c) = e$$

Multiply both sides on the left by  $a^{-1}$  to get

$$a^{-1} \star (a \star (b \star c)) = a^{-1} \star e$$

The associative law on the LHS and the definition of  $e$  on the RHS give

$$\begin{aligned}
 (a^{-1} \star a) \star (b \star c) &= a^{-1} \\
 e \star (b \star c) &= a^{-1} \\
 b \star c &= a^{-1}
 \end{aligned}$$

Now, multiply both sides on the left by  $b^{-1}$  to get

$$\begin{aligned}
 b^{-1} \star (b \star c) &= b^{-1} \star a^{-1} \\
 (b^{-1} \star b) \star c &= b^{-1} \star a^{-1} \\
 e \star c &= b^{-1} \star a^{-1} \\
 c &= b^{-1} \star a^{-1}
 \end{aligned}$$

Thus  $(a \star b)^{-1} = b^{-1} \star a^{-1}$ .

5. First show the result is true for  $n = 1, 2$  and 3. Next, assume for any  $k < n$  that any bracketing of a product of  $k$  elements,  $b_1 \star b_2 \star \cdots \star b_k$  can be reduced (without altering the value of the product) to an expression of the form

$$b_1 \star (b_2 \star (b_3 \star (\cdots \star b_k))) \cdots$$

Now argue that an bracketing of the product  $a_1 \star a_2 \star \cdots \star a_n$  must break into 2 subproducts, say  $(a_1 \star a_2 \star \cdots \star a_k) \star (a_{k+1} \star a_{k+2} \star \cdots \star a_n)$ , where each subproduct is bracketed in some fashion. Apply the induction assumption to each of these two subproducts and finally reduce the result to the form  $a_1 \star (a_2 \star (a_3 \star (\cdots \star a_n))) \cdots$  to complete the induction.

For any group  $G$  (operation  $\cdot$  implied) and  $x \in G$  and  $n \in \mathbb{Z}^+$  since the product  $xx \dots x$  ( $n$  terms) does not depend on how it is bracketed, we shall denote it by  $x^n$ . Denote  $x^{-1}x^{-1} \dots x^{-1}$  ( $n$  terms) by  $x^{-n}$ . Let  $x^0 = 1$ , the identity of  $G$ .

When we are dealing with specific groups, we shall use the natural (given) operation. For example, when the operation is  $+$ , the identity will be denoted by  $0$  and for any element  $a$ , the inverse  $a^{-1}$  will be written  $-a$ , and  $a + a + \dots + a$  ( $n > 0$  terms) will be written  $na$ ;  $-a - a - \dots - a$  ( $n$  terms) will be written  $-na$ , and  $0a = 0$ .

**Proposition 1.1-2** Let  $G$  be a group and let  $a, b \in G$ . The equations  $ax = b$  and  $ya = b$  have unique solutions for  $x, y \in G$ . In particular, the left and right cancellation laws hold in  $G$ , i.e.,

1. If  $au = av$ , then  $u = v$ .
2. If  $ub = vb$ , then  $u = v$ .

**Proof.** We can solve  $ax = b$  by multiplying both sides on the left by  $a^{-1}$  and simplifying to get  $x = a^{-1}b$ . The uniqueness of  $x$  follows because  $a^{-1}$  is unique. Similarly, we can solve  $ya = b$  by multiplying both sides on the right by  $a^{-1}$  and simplifying to get  $y = ba^{-1}$ . The uniqueness of  $y$  follows because  $a^{-1}$  is unique.

If  $au = av$ , multiply both sides on the left by  $a^{-1}$ , and simplify to get  $u = v$ . Similarly, if  $ub = vb$ , multiply both sides on the right by  $b^{-1}$ , and simplify to get  $u = v$ .

**Definition 1.1-3** For  $G$  a group and  $x \in G$  define the *order* of  $x$  to be the smallest positive integer  $n$  such that  $x^n = 1$ , and denote this integer by  $|x|$ . In this case  $x$  is said to be of order  $n$ . If no positive power of  $x$  is the identity, the order of  $x$  is defined to be infinity and  $x$  is said to be of infinite order.

### Example 1.1-3

1. An element of a group has order 1 if and only if it is the identity.
2. In the additive groups  $\mathbb{Z}$ ,  $\mathbb{Q}$ ,  $\mathbb{R}$  or  $\mathbb{C}$  every nonzero element has infinite order.
3. In the multiplicative groups  $\mathbb{R} \setminus \{0\}$  or  $\mathbb{Q} \setminus \{0\}$  the element  $-1$  has order 2 and all other nonidentity elements have infinite order.
4. In the additive group  $\mathbb{Z}/9\mathbb{Z}$ , the element  $\bar{6}$  has order 3 since  $\bar{6} \neq \bar{0}$ ,  $\bar{6} + \bar{6} = \bar{12} = \bar{3} \neq \bar{0}$ , but  $\bar{6} + \bar{6} + \bar{6} = \bar{18} = \bar{0}$ , the identity in this group.
5. In the multiplicative group  $(\mathbb{Z}/7\mathbb{Z})^\times$ , the element  $\bar{2}$  has order 3 since  $\bar{2} \neq \bar{1}$ ,  $\bar{2} \times \bar{2} = \bar{4} \neq \bar{1}$ , but  $\bar{2} \times \bar{2} \times \bar{2} = \bar{8} = \bar{1}$ , the identity in this group.

**Definition 1.1-4** Let  $G = \{g_1, g_2, \dots, g_n\}$  be a finite group with  $g_1 = 1$ . The *multiplication table* or *group table* of  $G$  is the  $n \times n$  matrix whose  $i, j$  entry is the group element  $g_i g_j$ .

More about the group table:

1. [Group Multiplication Tables | Cayley Tables \(Abstract Algebra\)](#)
2. [Group Theory Step-by-Step: 1 - 7](#)

## 1.2 Dihedral Groups

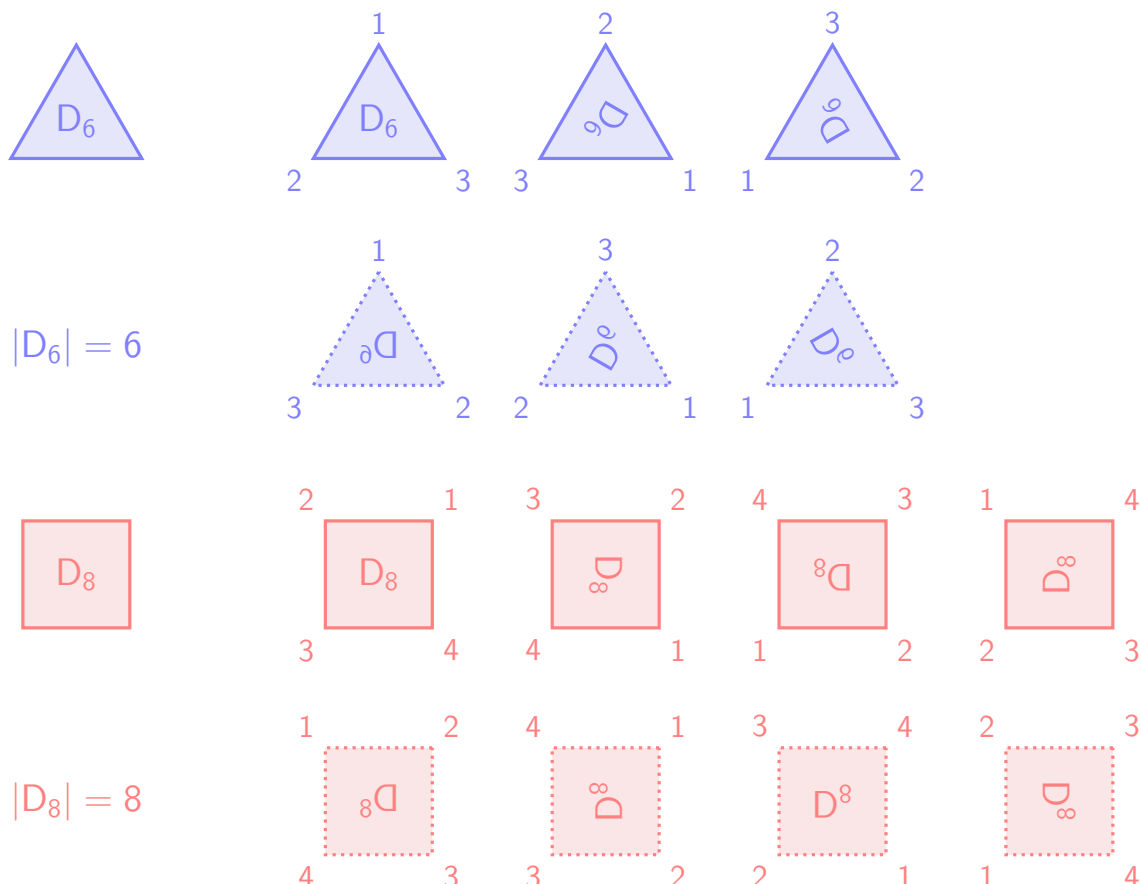
For each  $n \in \mathbb{Z}^+$ ,  $n \geq 3$  let  $D_{2n}$  be the set of symmetries of a regular  $n$ -gon, where a symmetry is any rigid motion of the  $n$ -gon which can be effected by taking a copy of the  $n$ -gon, moving this copy in any fashion in 3-space, then placing the copy back on the original  $n$ -gon so it exactly covers it. Each symmetry  $s$  can be described uniquely by the corresponding permutation  $\sigma$  of  $\{1, 2, 3, \dots, n\}$  where if the symmetry  $s$  puts vertex  $i$  in the place where vertex  $j$  was originally, then  $\sigma$  is the permutation sending  $i$  to  $j$ .

The identity of  $D_{2n}$  is the identity symmetry (which leaves all vertices fixed), denoted by 1, and the inverse of  $s \in D_{2n}$  is the symmetry which reverses all rigid motions of  $s$  (so if  $s$  effects permutation  $\sigma$ , then the inverse of  $s$  effects the permutation  $\sigma^{-1}$ ).

**Proposition 1.2-1** The order of the dihedral group

$$|D_{2n}| = 2n$$

**Proof.** To find the order  $|D_{2n}|$  observe that given any vertex  $i$ , there is a symmetry which sends vertex 1 into position  $i$ . Since vertex 2 is adjacent to vertex 1, vertex 2 must end up in position  $i + 1$  or  $i - 1$  (when  $n + 1$  is 1 and  $1 - 1$  is  $n$ , i.e., the integers labelling the vertices are read mod  $n$ ). Moreover, by following the first symmetry by a reflection about the line through vertex  $i$  and the center of the  $n$ -gon one sees that vertex 2 can be sent to either position  $i + 1$  or  $i - 1$  by some symmetry. Thus there are  $2n$  positions the ordered pair of 1, 2 may be sent to upon applying symmetries.



These symmetries are the  $n$  rotations about the center through  $2\pi/n$  radian,  $0 \leq i \leq n-1$ , and the  $n$  reflections through the  $n$  lines of symmetry. Now, we only need to define two generators to describe the group  $D_{2n}$ .

1. **Rotation**  $r$ : Rotation clockwise about the origin through  $2\pi/n$  radian.
2. **Reflection**  $s$ : Reflection about the line of symmetry through vertex 1 and the origin.

### 1.3 Symmetric Groups

### 1.4 Matrix Groups

### 1.5 The Quaternion Group

### 1.6 Homomorphisms and Isomorphisms

### 1.7 Group Actions

## 2 Subgroups