

# Math 3GR3 - Abstract Algebra

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## Course Outline

- Office hours: Monday 9:30-10:20 and Wednesday 2:30-3:20 (HH 419)

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# 1 Set theory

## 1.1 Reveiw

**Definition 1.1.** *Set is a collection of distinct objects.*

Here are some properties of a set:

- $\{\text{apple}, 2, \{3\}\}$  is a set.
- If  $x$  is in  $A$ , we write  $x \in A$ . If not, we write  $x \notin A$ .
- $\emptyset$  is an empty set.
- Note that order or repeated elements are not important:  $\{1, 2, 3\} = \{3, 1, 2\}$  and  $\{1, 1, 1, 2, 2, 3\} = \{1, 2, 3\}$ .

**Definition 1.2.** *Let  $A$  and  $B$  be sets.  $B$  is a subset of  $A$  if for all  $x \in B$ ,  $x \in A$  and we write  $B \subseteq A$ .  $B$  is a proper subset of  $A$  if  $B$  is a subset of  $A$  but  $B \neq A$  and we write  $B \subset A$ .*

**Theorem 1.1.**  *$A$  and  $B$  are equal if and only if  $B \subseteq A$  and  $A \subseteq B$ .*

**Example 1.1.1.**

- $\mathbb{N}$  is a set of natural numbers:  $\{0, 1, 2, 3, \dots\}$ .
- $\mathbb{Z}$  is a set of integers:  $\{\dots, -2, -1, 0, 1, 2, \dots\}$ .
- $\mathbb{Q}$  is a set of rational numbers.
- $\mathbb{R}$  is a set of real numbers.
- $\mathbb{C}$  is a set of complex numbers.

**Definition 1.3.** *Universal set  $U$  contains all elements.*

Let  $A$  and  $B$  be sets. Then, we can define the following:

**Definition 1.4** (Intersection).  $A \cap B = \{x \mid x \in A \text{ and } x \in B\}$ .

**Definition 1.5** (Union).  $A \cup B = \{x \mid x \in A \text{ or } x \in B\}$ .

**Definition 1.6** (Complement).  $A' = \{x \mid x \in U \text{ and } x \notin A\}$ .

**Definition 1.7** (Set difference).  $A - B = \{x \mid x \in A \text{ but } x \notin B\}$ .

**Definition 1.8** (Cartesian product).  $A \times B = \{(a, b) \mid a \in A, b \in B\}$ .

**Example 1.1.2.** Let  $A = \{0, 1\}$  and  $B = \{\text{dog}, \text{cat}\}$ . Then,

$$A \times B = \{(0, \text{dog}), (0, \text{cat}), (1, \text{dog}), (1, \text{cat})\}$$

**Theorem 1.2** (DeMorgan's Laws). *Let  $A$  and  $B$  be sets. Then,*

- $(A \cup B)' = A' \cap B'$ .
- $(A \cap B)' = A' \cup B'$ .

*Proof.* To show that  $(A \cap B)' = A' \cup B'$ , we want to show that  $(A \cap B)' \subseteq A' \cup B'$  and  $A' \cup B' \subseteq (A \cap B)'$ .

First, let  $x \in (A \cap B)'$ . Then,  $x \notin (A \cap B)$ . So either  $x \notin A$  or  $x \notin B$ . If  $x \notin A$ , then  $x \in A'$ . Since  $A' \subset A' \cup B'$ ,  $x \in A' \cup B'$ . If  $x \in B$ , then  $x \in B' \subset A' \cup B'$ . Therefore,  $x \in A' \cup B'$ .

Now, we want to prove the opposite direction. Take  $x \in A' \cup B'$ . So  $x \in A'$  or  $x \in B'$ . Thus,  $x \notin A$  or  $x \notin B$ . In either case,  $x \notin (A \cap B)$ . Therefore,  $x \in (A \cap B)'$ .  $\square$

## 1.2 Equivalence relation

**Definition 1.9.** Let  $A$  and  $B$  be sets. Then, a relation is any subset  $S \subseteq A \times B$

**Example 1.2.1.** Let  $A = \{0, 1\}$  and  $B = \{\text{dog}, \text{cat}\}$ . Then,

$$S = \{(1, \text{dog}), (2, \text{cat})\} \subseteq A \times B$$

Functions can give you relations:

**Example 1.2.2.** Let  $f : \mathbb{R} \rightarrow \mathbb{R}$  where  $f(x) = x^2$ . Then, the following is a relation:

$$\{(x, f(x)) \mid x \in \mathbb{R}\} \subseteq \mathbb{R} \times \mathbb{R}$$

**Example 1.2.3.** Let  $X$  be a set of all McMaster students. Then,

$$R = \{(x, y) \mid x \text{ has same height as } y\} \subseteq X \times X$$

**Definition 1.10.** Let  $X$  be a set. An equivalence relation on  $X$  is a set  $R \subseteq X \times X$  such that

- $(x, x) \in R$  for all  $x \in X$  (reflexive)
- If  $(x, y) \in R$  and  $(y, x) \in R$  (symmetric)
- If  $(x, y) \in R$  and  $(y, z) \in R$ , then  $(x, z) \in R$  (transitive)

**Example 1.2.4.** Example 1.2.1 is not an equivalence relation since  $A \neq B$ .

**Example 1.2.5.** Example 1.2.2 is not an equivalence relation since  $(2, 2) \notin \{(x, x^2) \mid x \in \mathbb{R}\}$ .

**Example 1.2.6.** Example 1.2.3 is an equivalence relation.

- (reflexive) For any student  $x$  in  $X$ ,  $x$  has the same height as  $x$ , so  $(x, x) \in R$ .
- (symmetric) Suppose  $(x, y) \in R$  so  $x$  and  $y$  have the same height. But  $y$  and  $x$  have the same height so  $(y, x) \in R$ .

- (transitive) if  $(x, y) \in R$  and  $(y, z) \in R$ , then  $x$  and  $y$  have the same height and  $y$  and  $z$  have the same height. So  $x$  and  $z$  have the same height, i.e.  $x, z \in R$ .

*Remark.* Sometimes, we write  $x \sim y$  to mean  $(x, y) \in R$ .

**Example 1.2.7.** Prove that the following is an equivalence relation:

$$R = \{(x, y) \mid x = y\} \subseteq \mathbb{Z} \times \mathbb{Z}$$

*Proof.*

- (reflective) For any  $x \in \mathbb{Z}$ ,  $x = x$  and  $(x, x) \in R$ .
- (symmetric) If  $x \sim y$  then  $x = y$  so  $y = x$ , and  $y \sim x$ .
- (transitive) If  $x \sim y$  and  $y \sim z$ , then  $x = y = z$ , so  $x \sim z$ .

□

**Definition 1.11.** Fix a positive integer  $n > 0$ . We say  $r$  is congruent to  $s$  modulo  $n$  if  $n$  divides  $r - s$ , i.e.  $(r - s) = nl$  for some integer  $l$ . We write

$$r \equiv s \pmod{n}$$

**Example 1.2.8.** Let  $n = 7$ . Then,  $22 \equiv 8 \pmod{7}$  since 7 divides  $22 - 8$ . However,  $22 \not\equiv 10 \pmod{7}$  since 7 does not divide  $22 - 10 = 12$ .

**Example 1.2.9.** Congruent definition is an equivalence relation on  $\mathbb{Z}$ :

$$R = \{(r, s) \mid r \equiv s \pmod{n}\} \subseteq \mathbb{Z} \times \mathbb{Z}$$

*Proof.*

- (reflexive) For all  $r \in \mathbb{Z}$ ,  $n$  divides  $r - r = 0$ . So  $r \equiv r \pmod{n}$  for all  $r$ . So  $(r, r) \in R$ .
- (symmetric) Suppose  $(r, s) \in R$  so  $r - s = nl$  for some  $l$ . We multiply both sides by  $(-1)$  to obtain

$$(s - r) = (-1)(r - s) = (-1)(nl) = n(-l).$$

So  $n$  divides  $s - r$  and  $(s, r) \in R$ .

- (transitive) If  $(r, s) \in R$  and  $(s, t) \in R$ , then  $r - s = nl$  and  $s - t = nk$ . But then

$$(r - t) = (r - s) + (s - t) = nl + nk = n(l + k),$$

so  $(r, t) \in R$ .

□

**Definition 1.12.** If  $R$  is an equivalence relation on  $X$ , and  $x \in X$ , the equivalence class of  $x$  is

$$[x] = \{y \mid (x, y) \in R\}$$

**Example 1.2.10.** Consider

$$R = \{(x, y) \mid x \text{ and } y \text{ have the same height}\}.$$

Then,

$$[\text{Abby}] = \{\text{all people who have same height as Abby}\}.$$

**Example 1.2.11.** Consider

$$R = \{(x, y) \mid x = y\} \subseteq \mathbb{Z} \times \mathbb{Z}.$$

Then,

$$[42] = \{42\}.$$

**Example 1.2.12.** Consider

$$R = \{(r, s) \mid r \equiv s \pmod{5}\} \subseteq \mathbb{Z} \times \mathbb{Z}.$$

Then,

$$[3] = \{\dots, -7, -2, 3, 8, 13, 18, \dots\}.$$

**Definition 1.13.** A partition  $P$  of set  $X$  is a collection of sets,  $X_0, X_1, X_2, \dots$  such that

$$X = \bigcup_i X_i$$

and  $X_i \cap X_j = \emptyset$  for all  $i \neq j$ .

**Example 1.2.13.** In Example 1.2.12, we have

$$\mathbb{Z} = [0] \cup [1] \cup [2] \cup [3] \cup [4]$$

**Theorem 1.3.** If  $R$  is an equivalence relation on  $X$ , then the distinct equivalence classes form a partition of  $X$ .

*Proof.* For any  $x \in X$ ,  $x \sim x$  so  $x \in [x]$ . Thus,

$$X = \bigcup_{x \in X} [x].$$

Given  $x, y \in X$ , we want to show that  $[x] = [y]$  or  $[x] \cap [y] = \emptyset$ . Suppose that  $[x] \cap [y] \neq \emptyset$ . Let  $z \in [x] \cap [y]$ . So  $x \sim z$  and  $y \sim z$ . Let  $a \in [x]$ . Then,  $x \sim a$  so  $a \sim x$ , and  $x \sim z$  and  $z \sim y$ . So  $a \sim y$ . Thus  $y \sim a$ , and thus  $a \in [y]$ . So  $[x] \subseteq [y]$ .

Same argument shows  $[y] \subseteq [x]$ . So have  $[x] \cap [y] = \emptyset$  or  $[x] = [y]$ . So considering only distinct classes, we have a partition:

$$X = [x_0] \cup [x_1] \cup \dots,$$

□

### 1.3 Well ordering principle and division algorithm

**Theorem 1.4.** (First principle of mathematical induction) Set  $S(n)$  be a statement about integer  $n \in \mathbb{N}$  and supposed  $S(n)$  is true for some  $n_0 \geq 1$ . If for all integers  $k \geq 0$ , if  $S(k)$  is true implies  $S(k+1)$  is true, then  $S(n)$  is true for all  $n \geq n_0$ .

**Theorem 1.5** (Second principle of mathematical induction). Let  $S(n)$  be a statement for integers  $n \in \mathbb{N}$  and assume  $S(n_0)$  is true. If  $S(n_0), S(n_0 + 1), \dots, S(k)$  imply that  $S(k+1)$  is true, then  $S(n)$  is true for all  $n \geq n_0$ .

**Definition 1.14** (Well ordering property). Every nonempty set of positive integers has a smallest element.

*Remark.* Well ordering property becomes false once you include negative values.

**Lemma 1.1.** Principle of mathematical induction implies 1 is the smallest integer.

**Theorem 1.6.** Principle of mathematical induction implies well ordering property.

*Proof.* Let  $S$  be a nonempty set of positive integers. If  $1 \in S$ , then by above lemma, the set  $S$  has a smallest element. Assume that if  $S$  is a set that contains  $1 \leq k \leq n$ , then  $S$  satisfies the well ordering property. Let  $S$  be any set that contains an integer  $1 \leq k \leq n+1$ . If  $S$  does not contain any elements smaller than  $n+1$ ,  $n+1$  is the smallest element. If  $S$  does contain an integer  $k < n+1$ , then by induction step, we have already shown that  $S$  has well ordering property. By induction, all  $S$  satisfy well ordering property.  $\square$

*Remark.* Induction and well ordering property are equivalent.

Recall long division. If we divide 304 with 14, we get  $304 = 14(21) + 10$ . Here, we call 304 a dividend, 14 a divisor, 21 a quotient, and 10 a remainder. Now, we want to know whether this process stops and whether the answer is unique:

**Theorem 1.7** (Division algorithm). Let  $A$  and  $B$  be integers with  $b > 0$ . Then, there exists unique integers  $q$  and  $r$  such that

$$a = bq + r \text{ with } 0 \leq r < b$$

*Proof.* To prove that the above theorem is true, we have to show (1) existence and (2) uniqueness.

First, let  $S = \{a - bk \mid a - bk \geq 0\}$ . If  $0 \in S$ , then there is a  $k$  such that  $a - bk = 0 \iff a = bk$ . Then, we can let  $q = k$  and  $r = 0$ . If  $0 \notin S$ , we want to use the well ordering principle. We need to check that  $S \neq \emptyset$ .

- If  $a < 0$ , then  $a - ba = a(1 - b) > 0$ , since  $b > 0$ . So  $S \neq \emptyset$ .
- If  $a = 0$ , then  $0 - b(-1) > 0$ , so  $S \neq \emptyset$ .

- If  $a > 0$ , then  $a - b(0) > 0$ , so  $S \neq \emptyset$ .

By the well ordering property, there exists a smallest element say  $r$  in  $S$ , i.e. there is a  $q$  such that  $a - bq = r$ .

We claim that we also have  $0 \leq r < b$ . If  $r \geq b$ ,

$$r - b = (a - bq) - b = a - b(q + 1) \geq 0.$$

So  $r - b \in S$  and  $r - b$  is smaller than  $r$ , the smallest element of  $S$ . So we must have  $0 \leq r < b$ .

Now, suppose there was  $q, r, q', r'$  such that

$$\begin{cases} a = bq + r, 0 \leq r < b \\ a = bq' + r', 0 \leq r' < b \end{cases}$$

So  $bq + r = bq' + r' \implies bq - bq' = r' - r$ . Note that

$$-b < -r < r' - r < r' < b.$$

Thus,

$$-b < bq - bq' < b.$$

If we divide both sides by  $b$ , we get  $-1 < q - q' < 1$ . So we find that  $q - q' = 0$ .  $\square$

**Definition 1.15.**  $a$  divides  $b$  if there exists  $m$  such that  $b = am$ . We write  $a|b$ .

**Example 1.3.1.**  $3|12$  since  $12 = 3 \cdot 4$ .

**Definition 1.16.**  $d$  is a common divisor of  $a$  and  $b$  if  $d|a$  and  $d|b$ .

**Example 1.3.2.** 2 is a common divisor of 12 and 18.

**Definition 1.17.**  $d$  is the greatest common divisor of  $a$  and  $b$  if (1)  $d$  is a common divisor of  $a$  and  $b$  and (2) if  $d'|a$  and  $d'|b$ , then  $d'|d$ . We write  $d = \gcd(a, b)$ .

**Example 1.3.3.**  $6 = \gcd(12, 18)$ .

**Definition 1.18.**  $a$  and  $b$  are relatively prime if  $\gcd(a, b) = 1$ .

*Remark.* For any integer  $b$ ,  $b|0$  since  $0 = b \cdot 0$ . Furthermore,  $\gcd(b, 0) = |b|$ .

**Theorem 1.8.** Let  $a$  and  $b$  be non-zero integers. Then, there exists  $r$  and  $s$  such that  $\gcd(a, b) = ra + sb$ .

**Example 1.3.4.**  $6 = \gcd(12, 18) = 12(-1) + 18 \cdot 1$

*Proof.* Let  $S = \{am + bn \mid m, n \in \mathbb{Z}, am + bn > 0\}$ . If  $a < 0$ , then  $a(-1) + b(0) > 0$ , so  $S \neq \emptyset$ . If  $a > 0$ , then  $a(1) + b(0) > 0$  so  $S \neq \emptyset$ . By the well ordering property, there exists a smallest element in  $S$ , say  $d$ . So  $d = am + bn$  for some  $m + n$ .

Now, we want to prove that  $d = \gcd(a, b)$ . First, by the division algorithm, there exists  $q$  and  $r$  such that  $a = dq + r$  with  $0 \leq r < d$ . If  $r > 0$ , then,

$$\begin{aligned} r &= a - dq = a - (am + bn)q \\ &= a - amq - bnq \\ &= a(1 - mq) + b(-nq) > 0. \end{aligned}$$

Then  $r \in S$  and  $r < d$  but  $d$  is the smallest element of  $S$ . So  $r = 0$ , i.e.  $a = dq + 0$ . So  $d|a$ . Same proof shows  $d|b$ .

Now, suppose that  $d'|a$  and  $d'|b$ . So  $a = d'a'$  and  $b = d'b'$ . But then

$$\begin{aligned} d &= am + bn \\ &= d'a'm + d'b'n \\ &= d'(a'm + b'n) \end{aligned}$$

So  $d'|d$ . Hence,  $\gcd(a, b) = d$ . □

*Remark.* If  $\gcd(a, b) = 1$ , then  $1 = as + br$  for some  $s$  and  $r$ .

**Lemma 1.2.** Suppose  $a, b, q$  and  $r$  such that  $a = bq + r$ . Then,  $\gcd(a, b) = \gcd(b, r)$ .

*Proof.* Let  $d = \gcd(a, b)$  and  $e = \gcd(b, r)$ . Now,  $d|a$  and  $d|b$ , so  $a = da'$  and  $b = db'$ . Since  $r = a - bq$ , we have  $r = da' - db'q = d(a' - b'q)$ . So  $d|r$  and  $d|b$ , so  $d \leq \gcd(b, r) = e$ .

Now,  $e|b$  and  $e|r$ . So  $b = eb^*$  and  $r = er^*$ . So  $a = bq + r = eb^*q + er^* = e(b^*q + r^*)$ . So  $e|a$  and  $e|b$ . So  $e \leq d$ . Hence  $d \leq e \leq d$ , i.e.  $e = d$ . □

Now, we introduce the *Euclidean algorithm* to find the greatest common divisors of two integers: To compute  $\gcd(a, b)$ , repeatedly apply division algorithm:

$$\begin{aligned} a &= bq_1 + r_1 \\ b &= r_1q_1 + r_2 \\ r_1 &= r_2q_2 + r_3 \\ &\vdots \\ r_{n-2} &= r_{n-1}q_{n-1} + r_n \\ r_{n-1} &= r_nq_n + 0 \end{aligned}$$

Then, the last non-zero remainder,  $r_n$  is the greatest common divisor.

*Remark.* This algorithm is guaranteed to stop because  $r_n$  is a monotonically decreasing sequence, i.e.  $b > r_1 > r_2 > r_3 > \dots \geq 0$ . At some point, we must reach  $r_{n+1} = 0$  for some  $n$ .

**Example 1.3.5.** We want to find  $\gcd(234, 96)$ . Note  $234 = 96 \cdot 2 + 42$ . Note that  $\gcd(234, 96) = \gcd(96, 42)$ . Then, since  $96 = 42 \cdot 2 + 12$ , we have  $\gcd(96, 42) = \gcd(42, 12)$ . Likewise, we can continue to obtain  $\gcd(234, 96) = 6$ .



*Remark.* We can reverse this algorithm to find  $s$  and  $t$  such that  $\gcd(0, b) = sa + bt$ . Notice that

$$\begin{aligned} 234 &= 96(2) + 42 \\ 96 &= 42(2) + 12 \\ 42 &= 12(3) + 6 \\ 42 &= 234 + 96(-2) \quad 12 = 96 + 42(-2) \\ 6 &= 42 + 12(-3) \end{aligned}$$

So

$$\begin{aligned} 6 &= 42 + [96 + 42(-2)](-3) \\ &= 42(7) + 96(-3) \end{aligned}$$

Then,

$$\begin{aligned} 6 &= [234 + 96(-2)](7) + 96(-3) \\ &= (234)(7) + 96(-3) + 96(-3) \\ &= 234(7) + 96(-17) \end{aligned}$$

**Definition 1.19.** A positive integer  $p > 1$  is prime if its only divisions are 1 and  $p$ . Otherwise, a number is composite.

**Example 1.3.6.** 7 is a prime.

**Lemma 1.3.** Let  $a$  and  $b$  be integers and  $p$  a prime. If  $p|ab$ , then  $p|a$  or  $p|b$ . This statement is false when  $p$  is not a prime.

*Proof.* If  $p \nmid a$ , we want to show that  $p|b$ . If  $p \nmid a$ , then  $\gcd(a, p) = 1$ . So there exists  $s$  and  $t$  such that  $1 = as + pt$ . Then, we have  $b = abs + pbt$ . Since  $p|ab$ , we have  $ab = pk$ . So,

$$b = pks + pbt = p(ks + bt).$$

Therefore,  $p|b$ . □

**Theorem 1.9** (Fundamental theorem of arithmetic). Let  $n > 1$  be any integer.

$$n = p_1 p_2 \cdots p_k,$$

where  $p_i$  is a prime (not necessarily distinct). Furthermore, this decomposition is unique in the following sense. If  $n = q_1 \cdots q_l$  is another production of primes, then  $k = l$  and after relabelling,  $p_i = q_i$ .

*Existence.* Let

$$S = \{a \in \mathbb{Z} \mid a > 1 \text{ and } a \text{ does not have a primary decomposition}\}.$$

If  $S \neq \emptyset$ , then by the well ordering principle, there is a smallest  $a \in S$ . Note  $a$  is not a prime because if  $a$  is prime then  $a = a$  is a factorization. So  $a$  is

composite and  $a = bc$  with  $1 < b, c < a$ . However,  $b, c \notin S$  so they have a factorization:

$$\begin{aligned} b &= p_1 \cdots p_l \\ c &= q_1 \cdots q_k \end{aligned}$$

But then  $a = p_1 \cdots p_l q_1 \cdots q_k$ . So  $a \notin S$ , This is a contradiction and  $S = \emptyset$ .

Now, we want to prove the uniqueness. Suppos

$$n = p_1 \cdots p_k = q_1 \cdots q_l$$

Since  $p_1 | n$ ,  $p_1 | q_1 \cdots q_l$ . So  $p_1 | q_i$  for some  $i$  by the Lemma. Since  $q_i$  is prime and  $p_1 > 1$ , then  $p_1 = q_i$ . Then, we do a relabelling so that  $q_i$  is  $q_1$ . So we have

$$\begin{aligned} p_1 p_2 \cdots p_k &= q_1 q_2 \cdots q_l \\ \implies p_2 \cdots p_k &= q_2 \cdots q_l \end{aligned}$$

We repeat the process. If  $k > 1$ , we would end with

$$p_{l+1} p_{l+2} \cdots p_k = 1.$$

Likewise, we would end with a similar equation if  $k < l$ . Both cases are impossible because  $p_i, q_i > 1$ . So  $k = l$  and  $p_i = q_i$  for all  $i$ .  $\square$

**Theorem 1.10.** *There exists an infinite number of primes.*

*Proof.* Suppose only primes are  $p_1, p_2, \dots, p_n$ . Let

$$P = p_1 p_2 \cdots p_n + 1.$$

Since  $P > p_1, \dots, p_n$ ,  $P$  is not a prime. So  $P$  is a composite number by FTA, some  $p_i$  must divide  $P$ . Since  $P - p_1 p_2 \cdots p_n = 1$ , then  $p_i | 1$ , yielding contradiction. So there must be infinite number of primes.  $\square$

**Example 1.3.7.** Prove that if  $\gcd(a, b) = 1$  and  $a | bc$ , then  $a | c$ .

*Proof.* Beacuse  $\gcd(a, b) = 1$ , there exists integers  $s$  and  $t$  such that  $as + bt = 1$ . This follows from theorem 2.10. If we multiply both sides by  $c$ , we get

$$acs + bct = c$$

Since  $a | bc$ ,  $bc = ak$  for some integer  $k$ . After substitution, we have

$$c = acs + akt.$$

But this means

$$c = a(cs + kt).$$

So  $a | c$ , as desired.  $\square$

## 2 Groups and rings

### 2.1 Group theory

Before we begin, we're going to look at sets with *extra structure*.

**Example 2.1.1** (Integer equivalence classes). Let  $n = 6$ . Consider the distinct equivalence classes modulo 6:

$$R = \{(a, b) \mid a \equiv b \pmod{6}\} \subseteq \mathbb{Z} \times \mathbb{Z}$$

Then,

$$[0] = \{\dots, -6, 0, 6, \dots\}$$

$$[1] = \{\dots, -5, 1, 7, \dots\}$$

$$[2] = \{\dots, -4, 2, 8, \dots\}$$

$$[3] = \{\dots, -3, 3, 9, \dots\}$$

$$[4] = \{\dots, -2, 4, 10, \dots\}$$

$$[5] = \{\dots, -1, 5, 11, \dots\}$$

We denote the six distinct equivalence classes by

$$\mathbb{Z}_6 = \{[0], [1], [2], [3], [4], [5]\}.$$

Usually, we write

$$\mathbb{Z}_6 = \{0, 1, 2, 3, 4, 5\}.$$

In general, for any  $n > 1$ , let

$$\mathbb{Z}_n = \{0, 1, 2, \dots, n-1\}.$$

Then, we can add and multiply elements of  $\mathbb{Z}_n$ :

$$a + b = (a + b) \pmod{n}$$

$$ab = (ab) \pmod{n}$$

In fact, for any  $a \in \mathbb{Z}$  and  $n > 1$ , if  $a = nq + r$  with  $0 \leq r < n$ , then  $[a] = [r]$ . Equivalently,  $a \equiv r \pmod{n}$  and  $a \equiv r$  in  $\mathbb{Z}_n$ .

We can look at some other properties of addition and multiplication in  $\mathbb{Z}_n$ :

- Addition and multiplication commute
- Addition and multiplication are associative
- There are additive and multiplicative identities
- For every element in  $\mathbb{Z}_n$ , there exists an additive inverse.
- Multiplication is distributive over addition
- If  $\gcd(a, n) = 1$ , then there exists an integer  $b$  such that  $ab \equiv 1 \pmod{n}$ .

Consider a square cut in the plane. We can flip it, rotate it, and but not stretch it, and then put it back in the original spot. Then, we have 8 operations.

Let  $R_0$  be rotating  $0^\circ$ ,  $R_{90}$  rotating  $90^\circ$ ,  $R_{180}$  rotating  $180^\circ$ , and  $R_{270}$  rotating  $270^\circ$ . Then,  $H$  will be a flip on the horizontal axis,  $V$  on the vertical axis,  $D_1$  on the main-diagonal, and  $D_2$  on the anti-diagonal. Note that you can perform one operation, then followed by another, and end back up with another known operation. For example  $H, R_{270}$  is equivalent to  $D_1$ . Note that order is important.

We want to think of these as functions, i.e., each function maps a square to itself. Let

$$D_4 = \{R_0, R_{90}, R_{180}, R_{270}, V, H, D_1, D_2\}.$$

We call is a dihedral group and it has the following properties:

- Operations of composition is closed.
- $R_0$  is an identity element.
- Each element  $A \in D_4$  has an inverse, i.e., we can reverse it to  $R_0$ .
- The operation is associative.

In fact,  $D_4$  forms a group and those are the four properties that all groups must have.

Now, we want to formally define a group.

**Definition 2.1.** *Given any set  $G$ , a binary operation  $\circ$  is any function*

$$\circ : G \times G \rightarrow G$$

*that maps a pair  $(a, b) \in G \times G$  to an element  $a \circ b$ .*

**Example 2.1.2.**  $+$  on  $\mathbb{Z}$  is a binary operation

$$+ : \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z}$$

. Likewise, multiplication is also a binary operation.

**Example 2.1.3.** Composition of functions on  $D_4$  is a binary operation:

$$\circ_{D_4} : D_4 \times D_4 \rightarrow D_4$$

**Definition 2.2.** *A group  $(G, \circ)$  is a set  $G$  with a binary operation  $\circ$  such that*

- *(associative)  $a \circ (b \circ c) = (a \circ b) \circ c$ .*
- *(identity) there exists an  $e \in G$  such that  $a \circ e = e \circ a = a$  for all  $a \in G$ .*
- *(inverse) for all  $a \in G$  exists  $a^{-1} \in G$  such that  $a \circ a^{-1} = a^{-1} \circ a = e$ .*

**Definition 2.3.** If a group  $G$  satisfies commutativity,

$$a \circ b = b \circ a, \forall a, b \in G,$$

then  $G$  is called abelian.

**Example 2.1.4.**  $D_4$  is a group where the binary operation is composition of functions.  $D_4$  is not abelian since

$$D_1 \circ H \neq H \circ D_1$$

**Example 2.1.5.** Consider

$$\mathbb{Z} = \{\dots, -2, -1, 0, 1, 2, \dots\}.$$

There are two operations on  $\mathbb{Z}$ : addition and multiplication.  $\mathbb{Z}$  with addition is an abelian group with identity 0. However,  $\mathbb{Z}$  with multiplication is not a group because it doesn't have an inverse.

**Example 2.1.6.** Rationals, real numbers, and complex numbers are all groups with operation of  $+$ .

**Example 2.1.7** (Trivial group).  $G = \{e\}$ .

**Example 2.1.8.** Fix  $n > 1$ . Then,  $\mathbb{Z}_n = \{0, 1, 2, \dots, n-1\}$  is a group under addition. However, it's not a group under multiplication.

**Example 2.1.9.**  $\mathbb{R}$  is not a group under multiplication. It satisfies associativity and existence of identity but 0 does not have a multiplicative inverse. However,

$$\mathbb{R}^* = \mathbb{R} \setminus \{0\}$$

is a group under multiplication. Likewise,  $\mathbb{Q}^* = \mathbb{Q} \setminus \{0\}$  and  $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$  are groups under multiplication.

**Example 2.1.10.** Let  $n > 1$  and

$$u(n) = \{a \mid 1 \leq a \leq n-1, \gcd(a, n) = 1\}.$$

For example,

$$u(3) = \{1, 2\} \quad u(5) = \{1, 2, 3, 4\}$$

$$u(4) = \{1, 3\} \quad u(8) = \{1, 3, 5, 7\}$$

For all  $n > 1$ ,  $u(n)$  is a group under multiplication modulo  $n$ .

**Example 2.1.11.** Consider

$$M_2(\mathbb{R}) = \{\text{all } 2 \times 2 \text{ matrices with entries in } \mathbb{R}\}.$$

This set is a group under addition.

**Example 2.1.12.** All vector spaces are groups under addition.

**Example 2.1.13** (General linear group).

$$GL_2(\mathbb{R}) = \{\text{all } 2 \times 2 \text{ matrices that are invertible}\} \\ = \left\{ \begin{bmatrix} a & b \\ c & d \end{bmatrix} \mid ad - cb \neq 0 \right\}$$

This is a group under matrix multiplication.

We want to make new groups from existing groups. Let  $G$  and  $H$  be groups and that let  $\square$  and  $*$  denote their binary operations. Then,

$$G \times H = \{(g, h) \mid g \in G, h \in H\}.$$

This is also a group where

$$(g_1, h_1) \circ (g_2, h_2) = (g_1 \square g_2, h_1 * h_2).$$

**Example 2.1.14.** Consider

$$G = \mathbb{Z}_3 = \{0, 1, 2\}, H = \mathbb{R}^* = \mathbb{R} \setminus \{0\}$$

Then,

$$(2, 4) \circ (2, 6) = (2 + 2, 4 \times 6) = (1, 24) \in G \times H.$$

In this case, the identity of  $\mathbb{Z}_3 \times \mathbb{R}^*$  is  $(0, 1)$ .

**Definition 2.4.** The order of  $G$  refers to number of elements in  $G$  and is denoted by  $|G|$ .  $G$  is finite if  $|G| < \infty$ . Otherwise, it is infinite.

There are many different binary operations used to define groups. Normally, we will use the multiplicative notation. The only exception is when we are proving something about an additive group.

From now on, we will be using the following notations:

$$a^n = \begin{cases} a \cdot a \cdots a & (\text{n times}) \text{ if } n > 0 \\ 1 & n = 0 \\ (a^{-1} \cdots a^{-1}) & n < 0 \end{cases}$$

$$na = \begin{cases} a + a + \cdots + a & (\text{n times}) \text{ if } n > 0 \\ 0 & n = 0 \\ (-a) + (-a) + \cdots + (-a) & n < 0 \end{cases}$$

**Theorem 2.1.** For every group  $G$ , identity is unique.

*Proof.* Suppose  $e$  and  $e'$  are identities of  $G$ . So for any  $a \in G$ , (1)  $ae = a$  and (2)  $e'a = a$ . If  $a = e'$ , (1) implies  $e'e = e'$ . If  $a = e$ , (2) implies  $e'e = e$ . So

$$e' = e'e = e,$$

and  $e' = e$ . □

**Theorem 2.2.** *If  $g \in G$ , then inverse of  $g$  is unique.*

*Proof.* Suppose that  $g'$  and  $g''$  are inverses of  $g$ . So  $g'g = gg' = e$  and  $g''g = gg'' = e$ . So

$$gg' = gg'' = e.$$

If we multiply both sides by  $g'$ ,

$$\begin{aligned} g'(gg') &= g'(gg'') \\ \implies (g'g)g' &= (g'g)g'' \\ \implies eg' &= g' = g'' = eg''. \end{aligned}$$

□

**Theorem 2.3** (Socks-shoes property).  $(ab)^{-1} = b^{-1}a^{-1}$ .

*Proof.* By definition,  $(ab)^{-1}$  is the inverse of  $(ab)$ , i.e.,

$$(ab)(ab)^{-1} = e.$$

But we also have

$$\begin{aligned} (ab)(b^{-1}a^{-1}) &= a(bb^{-1})a^{-1} \\ &= aea^{-1} \\ &= aa^{-1} \\ &= e. \end{aligned}$$

So  $b^{-1}a^{-1}$  is also an inverse of  $(ab)$ . Since inverses are unique, we have

$$(ab)^{-1} = b^{-1}a^{-1}.$$

□

**Theorem 2.4.** *If  $G$ , cancellation works, i.e. if  $ab = bc$ , then  $a = c$ .*

*Proof.* Suppose that  $ab = ac$ . Then,  $a^{-1} \in G$ . So we multiply both sides by  $a^{-1}$  on the left

$$a^{-1}(ab) = a^{-1}(ac).$$

So  $b = c$ .

□

*Remark.* As a consequence, each row and column in a Cayley table (group operation table) has a distinct element. In other words, if  $ab_i = ab_j$  then  $b_i = b_j$

**Theorem 2.5.** *For any  $a, b \in G$ , there exists unique  $x$  and  $y$  such that  $ax = b$  and  $ya = b$ .*

*Proof.* One solution is  $x = a^{-1}b$  since

$$a(a^{-1}b) = (aa^{-1})b = b.$$

This is unique because if  $ax_1 = b = ax_2$ , by cancellation  $x_1 = x_2$ .

□

## 2.2 Subgroups

**Definition 2.5.** A subset  $H$  of a group  $G$  is a group if it is a group under the same operation of  $G$ .

**Example 2.2.1.** If  $G \neq \{e\}$ , the  $G$  has at least two subgroups:

- $\{e\} \subseteq G$ ,
- $G$  itself.

These are trivial groups but we want  $\{e\} \subset H \subset G$ .

**Example 2.2.2.** Consider  $G = \mathbb{Z}$ . Then,

$$E = \{n \in G \mid n \text{ is even}\} = \{-4, -2, 0, 2, 4\}$$

is a subgroup because

- because it is closed under addition.
- $0 \in E$ .
- addition is associative.
- for any  $a \in E$ ,  $-a \in E$  so every element in  $E$  has an inverse.

**Example 2.2.3.** The set of odd integers is not a subgroup because it is not closed under addition and 0 is not an element.

**Example 2.2.4.**  $m\mathbb{Z} = \{mn \mid n \in \mathbb{Z}\}$  is a subgroup.

**Example 2.2.5.** Consider  $D_4$ . Let  $H = \{R_0, R_{90}, R_{180}, R_{270}\}$ . Note  $D_4$  is not abelian but  $H$  is.

**Example 2.2.6.** Consider  $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$ , a group under multiplication. Then,

$$H = \{1, -1, i, -i\}$$

is a finite subgroup of  $\mathbb{C}^*$ :

	1	$i$	$-1$	$-i$
1	1	$i$	$-1$	$-i$
$i$	$i$	$-1$	$-i$	1
$-1$	$-1$	$-i$	1	$i$
$-i$	$-i$	1	$i$	$-1$

**Example 2.2.7.** Show that if  $a^2 = e$  for all  $a \in G$  then  $G$  is abelian.



*Proof.* Given any  $a, b \in G$ , we want to show  $ab = ba$ . Given that  $aa = e$ , since inverses are unique,  $a = a^{-1}$ . Now, consider  $(ab)^2$ . Since  $ab \in G$ ,

$$(ab^2) = (ab)(ab) = e.$$

Now, we multiply  $(ab)(ab) = e$  on the left by  $a$  and on the right by  $b$ :

$$\begin{aligned} a(ab)(ab)b &= aeb \\ (aa)(ba)(bb) &= ab \\ ba &= ab \end{aligned}$$

So  $G$  is abelian. □

**Theorem 2.6.** *A subset  $H$  of a group  $G$  is a subgroup if*

- $e \in H$ .
- $\forall g_1, g_2 \in H, g_1 \circ g_2 \in H$ .
- $\forall g \in H, g^{-1} \in H$

*Proof.* 1 implies that  $H$  has an identity, 2 implies that  $H$  is closed under operation. 3 implies that every  $g \in H$  has an inverse. So we only need to check the associative property.

Let  $a, b, c \in H$ . Now,  $a, b, c \in G$ , so

$$(ab)c = a(bc)$$

holds in  $G$ . But since the operation is closed,  $(ab)$  and  $(bc)$  are in  $H$ , so

$$(ab)c = a(bc)$$

also holds in  $H$ . □

**Definition 2.6** (Center of a group). *For any group  $G$ , the center of  $G$  is defined as*

$$Z(G) = \{a \in G \mid ag = ga, \forall g \in G\}.$$

**Example 2.2.8.** If  $G$  is abelian,  $G = Z(G)$ . If  $G = D_3$ ,  $Z(D_4) = \{R_0, R_{180}\}$ . For all  $G$ ,  $e \in Z(G)$ .

**Theorem 2.7.** *For all  $G$ ,  $Z(G)$  is a subgroup of  $G$ .*

*Proof.* First,  $e \in Z(G)$  since for all  $g \in G$ ,

$$eg = g = ge.$$

Let  $a, b \in Z(G)$ . We want to show that  $ab \in Z(G)$ . So for any  $g \in G$ , we need to show that  $(ab)g = g(ab)$ . To prove this, take any  $g \in G$ . Then,

$$\begin{aligned}(ab)g &= a(bg) \quad (\text{associativity}) \\ &= a(gb) \quad (\text{since } b \in Z(G)) \\ &= (ag)b \quad (\text{associativity}) \\ &= (ga)b \quad (\text{since } a \in Z(G)) \\ &= g(ab) \quad (\text{associativity})\end{aligned}$$

So  $ab \in Z(G)$ .

Now, let  $a \in Z(G)$  and take any  $g \in G$ . So  $g^{-1} \in G$ , and since  $a \in Z(G)$ ,

$$ag^{-1} = g^{-1}a.$$

Taking the inverse of both sides gives

$$ga^{-1} = (ag^{-1})^{-1} = (g^{-1}a)^{-1} = a^{-1}g.$$

So for any  $a \in Z(G)$  and any  $g \in G$ ,

$$a^{-1}g = ga^{-1},$$

i.e.  $a^{-1} \in Z(G)$ . □

**Example 2.2.9.** If every proper subgroup of group  $G$  is abelian, is  $G$  abelian?

*Proof.* No.  $D_4$  is not abelian. However, all proper subgroup are abelian.

$$\begin{aligned}H_1 &= \{R_0, R_{90}, R_{180}, R_{270}\} \\ H_2 &= \{R_0, R_{180}\} \\ H_3 &= \{R_0, D_1\} \\ H_4 &= \{R_0, D_2\} \\ H_5 &= \{R_0, V\} \\ H_6 &= \{R_0, H\} \\ H_7 &= \{R_0, D_{1,2}, H, V\}\end{aligned}$$

□

## 3 Special groups

### 3.1 Cyclic groups

So how do we find subgroups? Here's one way to construct subgroups:

**Definition 3.1.** Fix an  $a \in G$ . Then,  $\langle a \rangle = \{a^n \mid n \in \mathbb{Z}\}$

**Example 3.1.1.** Consider  $G = D_4$ . Then, since  $R_{90} \in G_4$ ,

$$\begin{aligned}\langle R_{90} \rangle &= \{R_{90}^{-1}, R_0, R_{90}, R_{90} \circ R_{90}, \dots\} \\ &= \{R_0, R_{90}, R_{180}, R_{270}\}.\end{aligned}$$

**Example 3.1.2.** If  $G = \mathbb{Z}_6$  and  $2 \in G$ , then

$$\begin{aligned}\langle 2 \rangle &= \{2 - 2 - 2, 2 - 2, 2, 2 + 2, 2 + 2 + 2, \dots\} \\ &= \{2, 4, 0\}.\end{aligned}$$

**Theorem 3.1.** For any  $a \in G$ ,  $\langle a \rangle$  is a subgroup of  $G$  and it is the smallest subgroup of  $G$  that contains  $a$ .

*Proof.* First,  $e \in \langle a \rangle$  since  $e = a^0$ . Now, suppose that  $g_1, g_2 \in \langle a \rangle$ . So  $g_1 = a^{n_1}$  and  $g_2 = a^{n_2}$ . But then,

$$g_1 g_2 = a^{n_1} a^{n_2} = a^{n_1 + n_2} \in \langle a \rangle.$$

Finally, if  $a^n \in \langle a \rangle$  then  $(a^n)^{-1} = a^{-n} \in \langle a \rangle$ . So  $\langle a \rangle$  is a subgroup.

To prove that it is the smallest subgroup, consider a subgroup  $H$  with  $a \in H$ . Then,  $a^1, a^2, a^3$  and  $a^0, a^{-1}, a^{-2}$  are also in  $H$ . So  $\langle a \rangle \subseteq H$ .  $\square$

**Definition 3.2.** If  $G$  contains an element  $a$  such that  $G = \langle a \rangle$ , then we say  $G$  is cyclic and  $a$  is the generator.

**Example 3.1.3.**  $\mathbb{Z}_6$  is cyclic since  $\mathbb{Z}_6 = \langle 5 \rangle$ .

**Definition 3.3.** If  $a \in G$ , then the order of  $a$  is the smallest positive integer such that  $a^n = e$ . We write  $|a| = n$ . If order is not finite,  $|a| = \infty$ .

**Example 3.1.4.** Consider  $G = \mathbb{Z}_6$ . Then,

- $|3| = 2$  since  $3 + 3 = 0$ .
- $|5| = 6$  since  $5 + 5 + 5 + 5 + 5 + 5 = 0$ .

**Example 3.1.5.** Consider  $\mathbb{Z}$  with addition. Then,  $|1| = \infty$ .

**Example 3.1.6.** Consider  $\mathbb{Z}_n$  with addition. Then,  $|1| = n$ .

**Example 3.1.7.** Consider  $u(8) = \{1, 3, 5, 7\}$  under multiplication. Observe that

$$\begin{aligned}|1| &= 1 \\ |3| &= 2 \\ |5| &= 2 \\ |7| &= 2\end{aligned}$$

$u(8)$  is not cyclic because no element with  $|a| = |u(8)| = 4$ .

**Theorem 3.2.** Every cyclic group is abelian.

*Proof.* Let  $g_1, g_2 \in \langle a \rangle$ . So  $g_1 = a^{n_1}$  and  $g_2 = a^{n_2}$  for some  $n_1, n_2$ . Then,

$$g_1 g_2 = a^{n_1} a^{n_2} = a^{n_1+n_2} = a^{n_2+n_1} = a^{n_2} a^{n_1} = g_2 g_1.$$

□

**Theorem 3.3.** *If  $G$  is cyclic, all subgroups are cyclic.*

*Proof.* Let  $H \subseteq G$  be a subgroup of  $G = \langle a \rangle$ . If  $H = \{e\}$  and if  $H = G$ , then  $H$  is cyclic.

So assume that  $\{e\} \subset H \subset G$ . If  $g \in H$ , then  $g = a^n$  for some  $n \in \mathbb{Z}$ . Since  $g^{-1} = a^{-n}$ , we know that at least one of  $n$  or  $-n$  is positive.

Let  $m$  be the smallest positive integer such that  $a^m \in H$ . We claim that  $H = \langle a^m \rangle$ . If  $a^m \in H$ , then  $\langle a^m \rangle \subseteq H$ . Take  $g = a^n \in H$ . Then, we can divide  $n$  by  $m$  using the division algorithm, i.e.,

$$n = mq + r,$$

with  $0 \leq r < m$ . If  $0 < r < m$ , then

$$a^n = a^{mq+r} = a^{mq} a^r.$$

Since  $a^{mq} \in H$ ,  $a^{-mq} \in H$ . So

$$a^n a^{-mq} = a^{n-mq} = a^r \in H.$$

However, this contradicts our assumption that  $m$  is the smallest positive exponent in  $H$ . Therefore,  $r = 0$ . Hence,  $n = mq$ , so  $g = a^n = (a^m)^q \in \langle a^m \rangle$ . So  $H$  is cyclic. □

Recall that the order of  $a \in G$ , denoted  $|a|$ , is smallest positive integer  $n$  such that  $a^n = e$ . The order of  $G$ , denoted  $|G|$ , is number of elements in  $G$ .

**Theorem 3.4.** *Let  $a \in G$ .*

- *If  $|a| = \infty$ , then  $a^i = a^j$  if and only if  $i = j$ .*
- *If  $|a| = n$ , then  $a^i = a^j$  if and only if  $n|(i - j)$ .*
- *If  $|a| = n$ , Then,  $\langle a \rangle = \{a^0, a^1, a^2, \dots, a^{n-1}\}$ . Also,  $|a| = |\langle a \rangle|$ .*

*Proof.* (1) Because  $|a| = \infty$ , all elements of  $\langle a \rangle$  are distinct. Indeed, if  $a^i = a^j$ , then  $a^i a^{-j} = e$ . So  $a^{i-j} = e$ . But  $|a| = \infty$ , so  $a^{i-j} = e$  iff  $i - j = 0$ , i.e.,  $i = j$ .

(2) Suppose that  $a^i = a^j$ . Without loss of generality, we can assume that  $i > j$ . So  $a^i a^{-j} = e$ . Now, we can divide  $(i - j)$  by  $n$  using division algorithm, i.e.,

$$(i - j) = nq + r,$$

with  $0 \leq r < n$ . If  $0 < r < m$ , then

$$a^{i-j} = (a^n)^q a^r = a^r = e.$$

This means  $a^r = e$  with  $r < n$ . However, this contradicts the assumption that  $|a| = n$ . So  $r = 0$  and  $n|(i - j)$ . To prove the other direction, assume that  $n|(i - j)$ . Then,  $(i - j) = nq$  and  $i = nq + j$ . Then,

$$a^i = a^{nq+j} = (a^n)^q a^j = a^q a^j = a^j.$$

(3) We want to show that  $\langle a \rangle = \{a^0, a^1, \dots, a^{n-1}\}$ . Take  $a^k \in \langle a \rangle$ . Then, we divide  $k$  by  $n$  using division algorithm:

$$k = nq + r,$$

with  $0 \leq r < n$ . So

$$a^k = a^{nq+r} = a^r.$$

So  $a^k = a^r \in \{a^0, a^1, \dots, a^{n-1}\}$ . □

**Example 3.1.8.** Consider

$$\mathbb{Z}_5 = \{0, 1, 2, 3, 4\}.$$

This is a cyclic group generated by 1. So  $|1| = 5$ . Note that  $7 \cdot 1 = 2 = 22 \cdot 1$  and  $5|(22 - 7)$ .

**Corollary 3.1.** *For any cyclical group  $G = \langle a \rangle$ , if  $|a| = n$ , and  $a^k = e$ , then  $n|k$ .*

*Proof.* Apply (2) with  $i = k$  and  $j = 0$ . □

**Theorem 3.5.** *If  $|a| = n$ , then  $|a^k| = n/\gcd(n, k)$ .*

**Example 3.1.9.** Consider

$$\mathbb{Z}_6 = \{0, 1, 2, 3, 4, 5\}.$$

Then,

$$\langle 1 \rangle = \{1, 1+1, 1+1+1, 1+1+1+1, 1+1+1+1+1, 1+1+1+1+1+1\}.$$

Then,  $|1| = 6$ . So

$$\langle 1 \rangle = \{1 \cdot 1, 2 \cdot 1, 3 \cdot 1, 4 \cdot 1, 5 \cdot 1, 0 \cdot 1\}.$$

So

$$|2 \cdot 1| = \frac{6}{\gcd(2, 6)} = \frac{6}{2} = 3$$

$$|3 \cdot 1| = \frac{6}{\gcd(3, 6)} = \frac{6}{3} = 2$$

$$|4 \cdot 1| = \frac{6}{\gcd(4, 6)} = \frac{6}{2} = 3$$

**Corollary 3.2.** *For any  $k \in \mathbb{Z}$ ,  $\mathbb{Z}_n = \langle k \rangle$  iff  $\gcd(n, k) = 1$ .*

*Proof.* Observe that

$$k = 1 + 1 + 1 + \cdots + 1 = k \cdot 1$$

with  $|1| = n$ . So

$$|k| = \frac{n}{\gcd(n, k)}.$$

So  $\langle k \rangle = \mathbb{Z}_n$  iff  $|k| = n$  iff  $n = n / \gcd(n, k)$  iff  $\gcd(n, k) = 1$ .  $\square$

Now, recall that  $\mathbb{Q}^* = \mathbb{Q} \setminus \{0\}$ ,  $\mathbb{C}^* = \mathbb{C} \setminus \{0\}$ , and  $\mathbb{R}^* = \mathbb{R} \setminus \{0\}$  are multiplicative groups. We are interested in finding finite multiplicative subgroups.

**Theorem 3.6.** *In  $\mathbb{Q}^*$  and  $\mathbb{R}^*$ , there are only two finite subgroups, which are  $\{1\}$  and  $\{1, -1\}$ .*

*Proof.* Take any  $H \subseteq \mathbb{Q}^*$  be a subgroup with  $|H| < \infty$ . Let  $a \in H$ . Then,  $a^n = 1$  for some  $n$ . So,  $a$  satisfies

$$a^n - 1 = 0 = (a - 1)(a^{n-1} + a^{n-2} + \cdots + a + 1).$$

If  $n = 1$ , then  $a = 1$ . If  $n = 2$ , then  $a^2 = 1$  so  $a = \pm 1$ .

If  $n < 3$ ,  $a$  would have to take a root of

$$x^{n-1} + x^{n-2} + \cdots + x + 1 = 0,$$

or  $(x - 1)$ . But the former equation does not have real or rational roots. So  $a = 1$ .

Therefore,  $H = \{1\}$  or  $H = \{-1, 1\}$ .  $\square$

Recall the following properties of complex numbers:

- $(a + bi)(c + di) = (ac - bd) + (ad + bc)i$ .
- $|a + bi| = \sqrt{a^2 + b^2}$ .
- $(a + bi)^{-1} = (a - bi)/(a^2 + b^2)$ .

We can represent complex numbers using polar coordinates:

$$a + bi = z = |z|(\cos \theta + i \sin \theta),$$

and we denote it by  $r \operatorname{cis} \theta$ . It is convenient to use polar coordinates due to the following property:

**Theorem 3.7.** *If  $z_1 = r_1 \operatorname{cis} \theta_1$  and  $z_2 = r_2 \operatorname{cis} \theta_2$ . Then,*

$$\begin{aligned} z_1 z_2 &= r_1 r_2 (\operatorname{cis}(\theta_1 + \theta_2)) \\ z_1^{-1} &= r_1^{-1} \operatorname{cis}(-\theta) \end{aligned}$$

**Definition 3.4** (Circle subgroup).

$$\mathbb{T} = \{z \in \mathbb{C}^* \mid |z| = 1\}$$

is a subgroup.

*Proof.*

- (identity)  $1 \in \mathbb{T}$  since  $|1| = 1$ .
- (closure) Suppose  $z_1, z_2 \in \mathbb{T}$ . So  $z_1 = 1 \operatorname{cis} \theta_1$  and  $z_2 = 1 \operatorname{cis} \theta_2$ . So  $z_1 z_2 = 1 \cdot 1 \operatorname{cis}(\theta_1 + \theta_2) \in \mathbb{T}$ .
- (inverse) If  $z = 1 \operatorname{cis} \theta \in \mathbb{T}$ , then  $z^{-1} = 1 \operatorname{cis}(-\theta) \in \mathbb{T}$ .

□

**Definition 3.5.** Fix  $n \geq 1$ . The complex numbers that satisfy  $x^n - 1 = 0$  are called  $n$ -th root of unity.

*Remark.*  $x^n - 1$  has  $n$  roots (up to multiplicity) in  $\mathbb{C}$ .

**Example 3.1.10.** Consider  $n = 3$ ,

$$x^3 - 1 = 0.$$

Roots are  $1, w, w^2, \dots$ , where

$$w = \frac{-1 + \sqrt{3}i}{2}, w^2 = \frac{-1 - \sqrt{3}i}{2}.$$

**Theorem 3.8.** The set of  $n$ -th root of unity form a cyclic group of order  $n$  in  $\mathbb{C}^*$ . Furthermore, the  $n$ -th root of unity are

$$z = \operatorname{cis} \left( \frac{2k\pi}{n} \right),$$

for  $k = 0, 1, 2, \dots, n-1$ .

**Definition 3.6.** A generator of the  $n$ -th group of units is called a primitive  $n$ -th root.

**Example 3.1.11.** If  $n = 8$ , primitive roots are

$$w, w^3, w^5, w^7,$$

and the rest are non-primitive roots.

**Example 3.1.12.** Find all cyclic subgroups of  $\mathbb{Z}_8$ .

$$\begin{aligned} \langle 0 \rangle &= \{0\} \\ \langle 1 \rangle &= \langle 3 \rangle = \langle 5 \rangle = \langle 7 \rangle = \mathbb{Z}_8 \\ \langle 4 \rangle &= \{0, 4\} \\ \langle 2 \rangle &= \langle 6 \rangle = \{0, 2, 4, 6\} \end{aligned}$$

**Example 3.1.13.** Find all cyclic subgroups of  $u(9)$ .

$$\begin{aligned}\langle 1 \rangle &= \{1\} \\ \langle 2 \rangle &= u(9) = \langle 5 \rangle \\ \langle 4 \rangle &= \{4, 7, 1\} = \langle 7 \rangle \\ \langle 8 \rangle &= \{1, 8\}.\end{aligned}$$

**Example 3.1.14.** Prove that the order of every element in a cyclic group  $G$  divides  $|G|$ .

**Example 3.1.15.** Suppose  $|G| = p$ , a prime and  $G$  cyclic. Show that every nonidentity element has order  $p$ .

## 3.2 Permutation groups

**Definition 3.7.** A permutation of a set  $X$  is a bijection:

$$\sigma : X \rightarrow X$$

**Definition 3.8.** A permutation group of a set  $X$  is the set of all permutations of  $X$  with binary operation composition of functions.

**Example 3.2.1.** Consider

$$X = \{1, 2, 3, 4, 5\}$$

Then, given

$$\begin{aligned}\sigma : X &\rightarrow X \\ 1 &\rightarrow 1 \\ 2 &\rightarrow 3 \\ 3 &\rightarrow 4 \\ 4 &\rightarrow 2 \\ 5 &\rightarrow 5\end{aligned}$$

and

$$\begin{aligned}\tau : X &\rightarrow X \\ 1 &\rightarrow 2 \\ 2 &\rightarrow 3 \\ 3 &\rightarrow 1 \\ 4 &\rightarrow 5 \\ 5 &\rightarrow 4\end{aligned},$$



we have

$$\begin{aligned}\sigma \cdot \tau : X &\rightarrow X \\ 1 &\rightarrow 3 \\ 2 &\rightarrow 4 \\ 3 &\rightarrow 1 \\ 4 &\rightarrow 5 \\ 5 &\rightarrow 2\end{aligned}$$

To avoid writing like this, we introduce a better notation:

$$\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 1 & 3 & 4 & 2 & 5 \end{pmatrix}, \tau = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 3 & 1 & 5 & 4 \end{pmatrix}.$$

Then,

$$\sigma \cdot \tau = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 1 & 3 & 4 & 2 & 5 \end{pmatrix} \cdot \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 3 & 1 & 5 & 4 \end{pmatrix} = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 3 & 4 & 1 & 5 & 2 \end{pmatrix}$$

Likewise,

$$\tau \cdot \sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 2 & 1 & 5 & 3 & 4 \end{pmatrix}$$

Note that  $\sigma \cdot \tau \neq \tau \cdot \sigma$ . In general, a permutation group is not abelian.

**Definition 3.9.** Fix an integer  $n \geq 1$ . The symmetric group on  $n$  letters, denoted  $S_n$ , is the set of all permutations of  $\{1, 2, 3, \dots, n\}$ .

**Theorem 3.9.**  $S_n$  is a non-abelian group (if  $n \geq 3$ ).

*Proof.*

- $S_n$  has an identity

$$\begin{pmatrix} 1 & 2 & 3 & \cdots & n \\ 1 & 2 & 3 & \cdots & n \end{pmatrix}$$

- Each element has an inverse (reverse the map the permutation)
- Composition is associative

□

*Remark.* Note that there are  $n!$  permutations.

**Example 3.2.2.**

$$S_3 = \left\{ \begin{pmatrix} 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix}, \begin{pmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{pmatrix}, \begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 3 \end{pmatrix}, \begin{pmatrix} 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix}, \begin{pmatrix} 1 & 2 & 3 \\ 3 & 2 & 1 \end{pmatrix} \right\}$$

Now, we introduce a cyclic notation. Consider

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 4 & 3 & 6 & 2 & 5 \end{pmatrix}$$

Note that 1 and 3 map to themselves whereas we have

$$2 \rightarrow 4 \rightarrow 6 \rightarrow 5.$$

So we write

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 4 & 3 & 6 & 2 & 5 \end{pmatrix} = (2465),$$

which means that

- each element is mapped to the one to right
- the last element is mapped to the front
- elements that do not appear are apped to themselves

**Example 3.2.3.**

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 2 & 1 & 4 & 6 & 5 & 3 \end{pmatrix} = (12)(346)$$

**Example 3.2.4.**

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 4 & 2 & 1 & 3 & 5 & 6 \end{pmatrix} = (143) = (314) = (431)$$

**Definition 3.10.** A permutation of form  $(a_1, a_2, \dots, a_k)$  is called a  $k$ -cycle.

**Theorem 3.10.** If two cycles,  $\sigma$  and  $\tau$ , are disjoint cycles, (i.e., they don't share any common values), then  $\sigma \cdot \tau = \tau \cdot \sigma$ .

*Proof.* Let  $\sigma = (a_1, \dots, a_k)$  and  $\tau = (b_1, \dots, b_l)$ . We know that

$$\sigma \cap \tau = \emptyset.$$

Then,

- if  $x \in \{1, 2, \dots, n\}$  but  $x \notin \sigma \cup \tau$ , then  $\sigma(x) = x$  and  $\tau(x) = x$  so  $\sigma(\tau(x)) = x = \tau(\sigma(x))$ .
- suppose  $x \in \sigma$  so  $x = a_i$  for some  $i$  and  $x \notin \tau$ . Now,  $\sigma(x) = \sigma(a_i) = a_{i+1}$ . Also,  $\tau(x) = x$  and  $\tau(a_{i+1}) = a_{i+1}$ . So

$$\sigma(\tau(a_i)) = \sigma(a_i) = a_{i+1} = \tau(a_{i+1}) = \tau(\sigma(a_i))$$

□

**Example 3.2.5.**

$$(12)(346) = (346)(12)$$

*Remark.* Not every permutation can be expressed as a cycle

**Theorem 3.11.** *Every permutation can be expressed as a product of disjoint cycles.*

We will illustrate this with an example, rather than a proof. Consider

$$\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 3 & 7 & 5 & 2 & 1 & 8 & 4 & 6 \end{pmatrix}$$

We start with an element that is not mapped to itself, i.e.,

$$1 \rightarrow 3 \rightarrow 5 \implies (135)$$

Now, take another element not in previous step and is not mapped to itself

$$2 \rightarrow 7 \rightarrow 4 \implies (274)$$

We can do the same thing for the rest and get

$$\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 3 & 7 & 5 & 2 & 1 & 8 & 4 & 6 \end{pmatrix} = (135)(274)(68)$$

The advantage of doing this is that it's easy to compute the order of  $\sigma$ .

**Theorem 3.12.** *Suppose  $\sigma = \sigma_1 \sigma_2 \dots \sigma_t$  is a product of  $t$  disjoint cycles. Then,*

$$|\sigma| = \text{lcm}(|\sigma_1|, |\sigma_2|, \dots, |\sigma_t|)$$

*Remark.* If  $\sigma = (a_1 a_2 a_3 \dots a_k)$  is a  $k$ -cycle,  $|\sigma| = k$ .

*Proof.* Let  $d_i = |\sigma_i|$  and  $d = \text{lcm}(d_1, \dots, d_t)$ . Since the cycles are disjoint,

$$\sigma^d = (\sigma_1 \dots \sigma_t)^d = \sigma_1^d \sigma_2^d \dots \sigma_t^d$$

For each  $i$ ,  $d = d_i m_i$  for some  $m_i$ . So

$$\begin{aligned} \sigma^d &= \sigma_1^{d_1 m_1} \sigma_2^{d_2 m_2} \dots \sigma_t^{d_t m_t} \\ &= \left(\sigma_1^{d_1}\right)^{m_1} \left(\sigma_2^{d_2}\right)^{m_2} \dots \left(\sigma_t^{d_t}\right)^{m_t} \\ &= e^{m_1} e^{m_2} \dots e^{m_t} \\ &= e \end{aligned}$$

So  $|\sigma| \leq d$ .

Now, let  $l = |\sigma|$ . So

$$e = \sigma^l = (\sigma_1 \sigma_2 \dots \sigma_t)^l = \sigma_1^l \dots \sigma_t^l$$

Since the cycles are disjoint, this implies that

$$\sigma_i^l = e$$

for each  $i$ . Since  $|\sigma_i| = d_i$ , we have that  $d_i | l$  for all  $i$ . So  $l$  is a common multiple of  $d_1, d_2, \dots, d_t$ . So

$$\text{lcm}(d_1, \dots, d_t) \leq l.$$

Thus,

$$|\sigma| \leq d = \text{lcm}(d_1, d_2, \dots, d_t) \leq l = |\sigma|.$$

Hence,  $|\sigma| = \text{lcm}(d_1, \dots, d_t)$ . □

**Example 3.2.6.** Going back to the example, since

$$\sigma = (135)(274)(68),$$

we get

$$|\sigma| = \text{lcm}(3, 3, 2) = 6.$$

**Definition 3.11.** A 2-cycle is called a transposition.

**Example 3.2.7.** Consider the cycle (1423). We can write it as a product of transpositions:

$$(1423) = (13)(12)(14)$$

**Theorem 3.13.** Every permutation can be expressed as a product of transpositions.

*Proof.* We only need to verify this for cycles. Consider

$$(a_1 a_2 \cdots a_k) = (a_1 a_k)(a_1 a_{k-1})(a_1 a_{k-2}) \cdots (a_1 a_3)(a_1 a_2)$$

□

**Example 3.2.8.**

$$\begin{aligned} \sigma &= (135)(247)(68) \\ &= (15)(13)(27)(24)(68) \end{aligned}$$

*Remark.* Factorization in the transposition is not unique.

**Example 3.2.9.**

$$\begin{aligned} (123) &= (13)(12) \\ &= (13)(23)(12)(13) \\ (1235) &= (15)(13)(12) \\ &= (13)(24)(35)(14)(24) \end{aligned}$$

Observe that (123) is a product of an even number of transpositions whereas (1235) is a product of an odd number of transpositions. So we want to make this into a theorem but we need to prove a lemma first:

**Lemma 3.1.** If  $(id) = e = \sigma_1 \sigma_2 \cdots \sigma_t$ , then  $t$  is even.

*Proof.* Since no transposition is the identity, we must have  $t > 1$ . If  $t = 2$ , we are done. We can perform induction on  $t$ .

e have the following 4 cases for  $\sigma_{t-1} \sigma_t$ :

	$\sigma_{t-1}\sigma_t$	=	$\sigma'_{t-1}\sigma'_t$
1	$(ab)(ab)$		$e$
2	$(bc)(ab)$		$(ac)(bc)$
3	$(cd)(ab)$		$(ab)(cd)$
4	$(ac)(ab)$		$(ab)(bc)$

In case 1, since  $(ab)(ba) = e$ , we remove  $\sigma_{t-1}\sigma_t$  from  $e = \sigma_1 \cdots \sigma_{t-2}$ , and by inducting  $t-2$  is even, so  $t$  is even.

In cases 2, 3 and 4, we can replace  $\sigma_{t-1}\sigma_t$  with  $\sigma'_{t-1}\sigma'_t$ . In all cases, the last occurrence of  $a$  moves left by 1.

Now, we look at  $\sigma_{t-2}\sigma_{t-1}$ . If in case 1, remove the pair  $\sigma_{t-2}\sigma_{t-1}$  and finish by inducting. Else, use cases 2, 3 and 4 to move left one transpositions. We eventually get into case 1. If not, we end with

$$(id) = (ab')\sigma_2\sigma_3 \cdots \sigma_t,$$

but the right hand side sends  $a$  to  $b'$ , contradicting the fact that this is identity.  $\square$

**Theorem 3.14.** *No permutation can be expressed as both of odd number of transpositions and even number of transpositions*

*Proof.* Suppose

$$\sigma = \sigma_1 \cdots \sigma_t = \tau_1 \cdots \tau_l$$

with  $t$  even and  $l$  odd. Then,

$$\begin{aligned} (id) &= \sigma(\sigma^{-1}) = (\sigma_1 \cdots \sigma_t)(\tau_1 \cdots \tau_l)^{-1} \\ &= \sigma_1 \cdots \sigma_t \tau_1^{-1} \cdots \tau_l^{-1} \\ &= \sigma_1 \cdots \sigma_t \tau_1 \cdots \tau_l \end{aligned}$$

So  $(id)$  is a product of  $t+l$  transpositions. But this is odd, so a contradiction to the lemma.  $\square$

**Definition 3.12.** *A permutation of  $\sigma \in S_n$  is even if it can be written as an even number of transpositions and odd if it can be written as an odd number of transpositions.*

### 3.3 Alternating groups

**Definition 3.13.** *The alternating group  $A_n$  is*

$$A_n = \{\sigma \in S_n \mid \sigma \text{ is even}\}.$$

**Theorem 3.15.**  *$A_n$  is a group and a subgroup of  $S_n$ .*

*Proof.* To prove closure, let  $\sigma, \tau \in A_n$ . So

$$\sigma = \sigma_1 \cdots \sigma_t$$

and

$$\tau = \tau_1 \cdots \tau_l$$

with  $t, l$  even. But then

$$\sigma\tau = \sigma_1 \cdots \sigma_t \tau_1 \cdots \tau_l \in A_n$$

since  $t + l$  is even. Also,  $(id) \in A_n$  by the lemma above.

Finally, if  $\sigma \in A_n$  and  $\sigma = \sigma_1 \cdots \sigma_t$  with  $t$  even, then

$$\begin{aligned} \sigma^{-1} &= (\sigma_1 \cdots \sigma_t)^{-1} \\ &= \sigma_t^{-1} \cdots \sigma_1^{-1} \\ &= \sigma_t \cdots \sigma_1 \in A_n \end{aligned}$$

□

### 3.4 Group of rigid motions

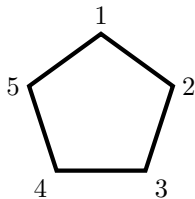
Recall that  $D_4$  is a set of all rigid motions of the square. We can now think of the rotations as permutations

$$\begin{aligned} R_0 &= \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 2 & 3 & 4 \end{pmatrix}, \\ R_{90} &= \begin{pmatrix} 1 & 2 & 3 & 4 \\ 2 & 3 & 4 & 1 \end{pmatrix}, \\ R_{180} &= \begin{pmatrix} 1 & 2 & 3 & 4 \\ 3 & 4 & 1 & 2 \end{pmatrix}, \\ &\vdots \\ D &= \begin{pmatrix} 1 & 2 & 3 & 4 \\ 1 & 4 & 3 & 2 \end{pmatrix} \end{aligned}$$

In fact, we can apply this for any regular polygons:

**Definition 3.14.**  $D_n$  is the group of rigid motions of the regular  $n$ -gon.

Note that we are going to write vertices in clockwise fashion:



A rigid motion is determined by 2 pieces of information:

- where 1 is sent to ( $n$  choices)
- do the numbers go clockwise or counter clockwise (2 choices)

So the total number of rigid motions is  $2n$ .

**Theorem 3.16.**  $D_n$  is a group of order  $2n$ .

*Proof.* We already showed that  $|D_n| = 2n$ . We want to show that it's actually a group:

- Clearly,  $e \in D_n$  since this is the motion where we leave unchanged.
- If  $\sigma, \tau \in D_n$ , they are both rigid motion, but so it  $\sigma\tau \in D_n$ .
- If  $\sigma \in D_n$  is a rigid motion, we can always reverse the motion to back the original configuration. So  $\sigma^{-1} \in D_n$ .

□

*Remark.*  $D_n$  is a subgroup of  $S_n$ .

**Example 3.4.1.**  $D_3 = S_3$

We saw that  $D_4$  is not cyclic. In general,  $D_n$  is not cyclic. However,  $D_n$  can be generated by 2 elements.

**Theorem 3.17.** For  $n \geq 3$ ,  $D_n$  consists of all products of elements  $r$  and  $s$  such that rotation,  $r$ , and reflection,  $s$ , satisfy

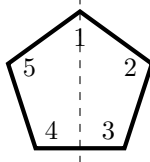
$$r^n = 1 \text{ and } s^n = 1,$$

*Proof.* Notice that any rigid motion is a rotation and/or a reflection.

Let  $r = \frac{2\pi}{n}$ . Then, there are  $n$  rotations:

$$(id), r, r^2 = 2\left(\frac{2\pi}{n}\right), r^3 = 3\left(\frac{2\pi}{n}\right), \dots, r^{n-1} = (n-1)\left(\frac{2\pi}{n}\right)$$

Likewise, there are  $n$  reflections  $s_1, s_2, s_3, \dots, s_n$ , where each  $s_i$  leaves  $i$  fixed. For example,  $s_1$  in  $D_5$  will look like this:



If  $n$  is odd,  $s_i$  only fixes  $i$ , whereas if  $n$  is even,  $s_i$  fixes two or no elements (e.g., reflection of a square along the vertical axis fix no elements).

Let  $s = s_1$ . I claim that every element of  $D_n$  can be written in terms of  $r$  and  $s$ . Recall that a rigid motion is determined by (1) where 1 is sent and (2) whether numbers are clockwise or counter clockwise. If 1 is sent to  $k$  clockwise, the motion is given by  $r^{k-1}$ . If 1 is sent to  $k$  in counter clockwise, the motion is given by  $r^{k-1}s$ . So

$$D_n = \{r^a s^b \mid 0 \leq a \leq n-1, 0 \leq b \leq 1\}.$$

Finally, consider  $rsrs$ . Then,  $rsrs = 1$  so  $r(srs) = 1$  and  $r^{-1} = srs$ .  $\square$

**Example 3.4.2.** Show  $D_n$  is not abelian for all  $n \geq 3$ .

*Proof.* Suppose that  $D_n$  is abelian. We showed that  $rsrs = 1$ . Since  $D_n$  is abelian,  $rs^2r = 1$ . But  $s^2 = 1$ . So  $r^2 = 1$ . But  $n \geq 3$  and  $|r| = 3 > 2$ .  $\square$

**Example 3.4.3.** Use cycle notation to write out all elements of  $D_5$ .