MAT 311 Abstract Algebra

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Contents

1 Sets and Relations

1.0.1 Def. What *is* Abstract Algebra

- Algebra: procedures for performing operations, i.e. $+, -, \times, \div$, and methods for solving equations. It uses bldspecific operations on **specific** objects.
- Abstract Algebra: discuss **general** structures and the relationships between the elements of these structures.

1.1 Sets

1.1.1 Def. Set

A set is a collection of objects. These objects are called "elements". A set is typically uppercase, and elements are typically lowercase.

Set Notation

1. List Notation:

$$B = \{\text{John}, \text{Paul}, \text{Ringo}, \text{George}\}$$
$$\mathbb{N} = \{1, 2, 3, \dots\}$$

2. Set-builder Notation:

$$B = \{b : b \text{ is a Beatle}\}$$

Well-Defined Sets

Sets must be **well-defined**. That is, given set S and any element x, either $x \in S$ or $x \notin S$.

1.1.2 Def. Subset

A set A is a subset of set B, written as $A \subseteq B$, if every element of A is also in B.

Note: every non-empty set has at least two subsets:

- The set itself
- $\emptyset$

1.1.3 Def. Proper Subset

If $A \subseteq B$ but $A \neq B$, then A is a **proper subset** of B, written $A \subset B$ or $A \subsetneq B$.

Note: A set B is an *improper subset* of itself.

1.1.4 Def. Cartesian Product

Let A and B be sets. The set $A \times B = \{(a, b) : a \in A \text{ and } b \in B\}$ is the cartesian product of A and B.

Note: $A \times B = B \times A \iff A = B, \text{ or } A \times B = \emptyset$.

Example

Let $A = \{c : c \text{ is a primary color}\}$ and let $B = \{\epsilon, \delta\}$. Find:

1. $B \times B = \{(\epsilon, \epsilon), (\epsilon, \delta), (\delta, \epsilon), (\delta, \delta)\}$
2. $A \times \emptyset = \emptyset$

1.2 Relations

1.2.1 Def. Relation

A **relation** between sets A and B is a subset $\mathcal{R}$ of $A \times B$. It is a collection of ordered pairs. Note: $(a, b) \in \mathcal{R} \equiv a\mathcal{R}b$ means "a is related to b".

1.2.2 Def. Function

A **function** is a relation in which no two of the ordered pairs have the same first term. Note: if $f : \mathbb{R} \to \mathbb{R}$ is a function, then is passes the vertical-line test.

1.2.3 Def. One-to-One

A function is **one-to-one**, or **injective**, if no two ordered pairs have the same <u>second</u> term.

To prove f is one-to-one, first assume that $f(x_1) = f(x_2)$, then show that $x_1 = x_2$.

1.2.4 Def. Onto

A function $f : X \to Y$ is **onto**, or **surjective**, if the codomain is equal to the range, meaning every element $y \in Y$ has some $x \in X$ such that $f(x) = y$.

1.2.5 Def. One-to-One Correspondence

A function $f : X \to Y$ is a **one-to-one correspondence**, or a **bijection**, if it is both one-to-one and onto.

1.3 Partitions and Equivalence Relations

1.3.1 Def. Partition

A **partition** of a set S is a collection of non-empty subsets of S such that:

1. The union of these subsets is S.
2. These subsets are pairwise disjoint.

Note: these subsets are called **cells** of the partition.

1.3.2 Def. Equivalence Relation

An **equivalence relation** $\mathcal{R}$ on a set S must be:

1. Reflexive, meaning $x\mathcal{R}x \quad \forall\, x \in S$.
2. Symmetric, meaning if $x\mathcal{R}y$, then $y\mathcal{R}x$.
3. Transitive, meaning if $x\mathcal{R}y$ and $y\mathcal{R}z$, then $x\mathcal{R}z$.

1.3.3 Def. Equivalence Class

$$\overline{x} = \{y \in S : x\mathcal{R}y\} \text{ is the equivalence class of } x$$

Example

Let $S = \mathbb{R}$. Define $x\mathcal{R}y$ iff $x \geq y$. Is $\mathcal{R}$ an equivalence relation on S?

1. Is $\mathcal{R}$ reflexive? $\forall x \in S, x\mathcal{R}x$, so YES.
2. Is $\mathcal{R}$ symmetric? Consider 5 and 1: $5 \geq 1$ but $1 \not\geq 5$, so NO.
3. Is $\mathcal{R}$ transitive? If $x \geq y$ and $y \geq z$ then $x \geq z$, so YES.

Since $\mathcal{R}$ is not symmetric, it is not an equivalence relation on S.

Note on Partition Cells and Equivalence Classes

Partitions give rise to equivalence relations and vice versa. The *cells* of the partition are analogous to the *equivalence classes* of the equivalence relation.

2 Binary Operations

2.0.1 Def. Binary Operation

A **binary operation** $*$ on a set S is a function from $S \times S$ into S, $* : S \times S \to S$. That is, $*$ is a rule which assigns to each ordered pair $(a, b) \in S \times S$ exactly one element $a * b \in S$.

Condition 1: Uniquely Defined

For all $a, b \in S \times S$, $a * b$ must be **uniquely defined**. This means that $*$ cannot be undefined for any $a * b$, and each $a * b$ must have exactly one result, not two or more.

Condition 2: Closed under $*$

S must be **closed** under $*$. That is,

$$\forall\ a, b \in S, \qquad a * b \in S.$$

2.0.2 Def. Commutative

A binary operation $*$ on a set S is commutative if

$$\forall\ a, b \in S, \qquad a * b = b * a.$$

2.0.3 Def. Associative

A binary operation $*$ on a set S is associative if

$$\forall\ a, b, c \in S, \qquad a * (b * c) = (a * b) * c.$$

2.1 Finite Sets

Example

Let $S = \{a, b, c, d\}$. Define a binary operation $*$ on S using the following table. Complete the table so that $*$ is commutative.

$*$	a	b	c	d
a	b	d	a	a
b	d	a	c	b
c	a	c	b	b
d	a	b	b	c

Note: $*$ is commutative iff the table is symmetric along the main diagonal.
Is $*$ associative? Why or why not? **No**,

$$a * (b * c) = a * c = a$$
$$(a * b) * c) = d * c = b$$

Example

Suppose that $*$ is associative and commutative operation on a set S. Show that $H = \{a \in S : a * a = a\}$ is closed under $*$. Note that the elements of H are called **idenmptents** of the binary operation $*$.

Proof. Let $a, b \in H$. Show $a * b \in H$.

We know $a * a = a$ and $b * b = b$. Show $(a * b) * (a * b) = a * b$.

$$\begin{aligned} LHS &= (a * b) * (a * b) \\ &= a * (b * a) * b && \text{since } * \text{ is associative} \\ &= a * (a * b) * b && \text{since } * \text{ is commutative} \\ &= (a * a) * (b * b) && \text{since } * \text{ is associative} \\ &= a * b \\ &= RHS \end{aligned}$$

Thus, H is closed under $*$. □

3 Isomorphic Binary Structures

3.0.1 Def. Binary Algebraic Structure

A **binary algebraic structure** $\langle S, * \rangle$ is a set S together with a binary operation $*$.

3.0.2 Def. Isomorphism

Let $\langle S, * \rangle$ and $\langle S', *' \rangle$ be binary structures. An **isomorphism** of S with S' is a *one-to-one* function $\phi : S \mapsto S'$ such that

$$\forall \ \ x, y \in S, \qquad \phi(x * y) = \phi(x) *' \phi(y).$$

Notation: $\langle S, * \rangle \simeq \langle S', *' \rangle$

Example 1

Prove that $\langle \mathbb{R}, + \rangle \simeq \langle \mathbb{R}^+, \cdot \rangle$.

Proof. Consider $\phi : \mathbb{R} \mapsto \mathbb{R}^+,$ where $\phi(x) = e^x$.

1. One-to-one: Assume $\phi(x_1) = \phi(x_2)$ for some $x_1, x_2 \in \mathbb{R}$.

$$\begin{aligned} \phi(x_1) &= \phi(x_2) \\ e^{x_1} &= e^{x_2} \\ \ln e^{x_1} &= \ln e^{x_2} \\ x_1 &= x_2 \end{aligned}$$

   Thus ϕ is one-to-one.

2. Onto: Let $y \in \mathbb{R}^+$. Let us find $x \in \mathbb{R}$ such that $y = \phi(x)$.

$$\begin{aligned} y &= \phi(x) = e^x \\ \ln y &= \ln e^x = x \end{aligned}$$

   Choose $x = \ln y$. Thus ϕ is onto.

3. Operation Preserving: Need to show that $\phi(x + y) = \phi(x) \cdot \phi(y)$.

$$\begin{aligned} \phi(x + y) &= e^{x+y} \\ &= e^x \cdot e^y \\ &= \phi(x) \cdot \phi(y) \end{aligned}$$

   Thus ϕ is operation preserving.

Since ϕ is one-to-one, onto, and operation preserving, thus ϕ is an isomorphism of $\langle \mathbb{R}, + \rangle$ and $\langle \mathbb{R}^+, \cdot \rangle$, and $\langle \mathbb{R}, + \rangle \simeq \langle \mathbb{R}^+, \cdot \rangle$. □

3.0.3 Def. Identity Element

Let $\langle S, * \rangle$ be an algebraic structure. An element $e \in S$ is the identity element **id** for $*$ if for all $s \in S$:

$$\underbrace{\overbrace{e * s}^{\text{left } \textbf{id}} = \overbrace{s * e}^{\text{right } \textbf{id}}}_{\text{two-sided } \textbf{id}} = s$$

3.0.4 Thm. Identity Uniqueness

A binary structure $\langle S, * \rangle$ has at most one identity element.

Proof. Assume e_1 and e_2 are both identity elements for $\langle S, * \rangle$. Thus,

$$\begin{aligned} e_1 * e_2 &= e_1 && \text{since } e_1 \text{ is } \textbf{id} \\ e_1 * e_2 &= e_2 && \text{since } e_2 \text{ is } \textbf{id} \end{aligned}$$

Since binary operations are uniquely defined, $e_1 = e_2$ must be true. $\therefore$ $\langle S, * \rangle$ has at most one identity element. □

3.0.5 Thm. Isomorphism and Identity

Suppose $\langle S, * \rangle$ has identity element e. If $\phi : S \mapsto S'$ is an isomorphism of $\langle S, * \rangle$ with $\langle S', *' \rangle$, then $\phi(e)$ is the identity element for $\langle S', *' \rangle$.

Proof. Assume $\langle S, * \rangle$ has identity e and $\phi : S \mapsto S'$ is an isomorphism. Let $s' \in S'$.

$$\begin{aligned} \phi(e) *' s' &= \phi(e) *' \phi(s) \\ &= \phi(e * s) && \text{since } \phi \text{ is operation preserving} \\ &= \phi(s) = s' \end{aligned}$$

Thus $\phi(e) *' s' = s'$.

$$\begin{aligned} s' *' \phi(e) &= \phi(s) *' \phi(e) \\ &= \phi(s * e) && \text{since } \phi \text{ is operation preserving} \\ &= \phi(s) = s' \end{aligned}$$

Thus $s' *' \phi(e) = s'$. So $\phi(e) *' s' = s' *' \phi(e) = s'$. Thus $\phi(e)$ is the identity of $\langle S', *' \rangle$. □

Showing Two Binary Structure are *not* Isomorphic

To show that two binary structures are *not* isomorphic, you need to show that one binary structure has some property that other does not, meaning they are structurally distinct.

Example

Is $\langle \mathbb{Z}, + \rangle \simeq \langle \mathbb{R}, \cdot \rangle$? **No**, because $\mathbb{Z}$ is countably infinite, whereas $\mathbb{R}$ are uncountably infinite. These two sets have different cardinalities.

4 Groups

4.0.1 Def. Group

A **group** $\langle G, * \rangle$ is a set G *closed* under the binary operation $*$, such that the following axioms are satisfied:

$\mathfrak{G}_1$: For all $a, c, b \in G$, we have

$$(a * b) * c = a * (b * c). \qquad \textbf{associativity of *}$$

$\mathfrak{G}_2$: There is an element e in G such that for all $x \in G$,

$$e * x = x * e = x. \qquad \textbf{identity element } e \textbf{ for *}$$

$\mathfrak{G}_3$: Corresponding to each $a \in G$, there is an element a' in G such that

$$a * a' = a' * a = e. \qquad \textbf{inverse } a' \textbf{ of } a$$

Note: G does not *need* to be commutative.

4.0.2 Def. Abelian Group

A group G is **Abelian** if its binary operation is **commutative**.

4.0.3 Thm. Cancellation Laws

If $\langle G, * \rangle$ is a group, then the left and right cancellation laws hold in G.

- **Left**:

$$\text{if } \; a * b = a * c \; \text{ then } \; b = c$$

- **Right**:

$$\text{if } \; b * a = c * a \; \text{ then } \; b = c$$

Proof for Left. Assume $\langle G, * \rangle$ is a group and $a * b = a * c$:

$$\begin{aligned} a * b &= a * c & & \\ \overline{a} * a * b &= \overline{a} * a * c & & \mathfrak{G}_3 \\ e * b &= e * c & & \mathfrak{G}_3 \\ b &= c & & \mathfrak{G}_2 \end{aligned}$$

□

The proof for right cancellation follows the same structure.

4.0.4 Thm. Unique Solutions

If $\langle G, * \rangle$ is a group and if $a, b \in G$, then $a * x = b$ and $y * a = b$ have unique solutions x and y in G.

Proof. Assume $\langle G, * \rangle$ is a group and consider $a * x = b$ for $a, b \in G$.

$$\begin{aligned} a * x &= b & & \\ \overline{a} * (a * x) &= \overline{a} * b & & \mathfrak{G}_3 \\ (\overline{a} * a) * x &= \overline{a} * b & & \mathfrak{G}_1 \\ e * x &= \overline{a} * b & & \mathfrak{G}_3 \\ x &= \overline{a} * b & & \mathfrak{G}_2 \end{aligned}$$

Assume x_1 and x_2 are both solutions to the above equation.

$$a * x_1 = b \text{ and } a * x_2 = b$$

Thus $a * x_1 = a * x_2$. By left cancellation,

$$x_1 = x_2$$

Thus the solution is unique. □

The $y * a = b$ proof follows the same structure.

4.0.5 Thm. Unique Identity and Inverse

If $\langle G, * \rangle$ is a group, then th identity element and the inverse of each element are unique.

4.0.6 Thm. Inverse of Two Elements

Let $\langle G, * \rangle$ be a group. Then for all $a, b \in G$, we have $(a * b)' = a' * b'$.

Proof.

$$\begin{aligned}
(a * b) * (a * b)' &= e && \text{by definition of } \mathfrak{G}_3 \\
a * b * (a * b)' &= e && \mathfrak{G}_1\text{, associativity} \\
(a' * a) * b * (a * b)' &= a' * e && \mathfrak{G}_1 \\
b * (a * b)' &= a' * e && \mathfrak{G}_3 \\
b' * b(a * b)' &= b' * a' * e && \\
(a * b)' &= b' * a' && \mathfrak{G}_1,\ \mathfrak{G}_3
\end{aligned}$$

□

4.1 Finite Groups and Group Tables

Cayley Tables

Let $\langle G, * \rangle$ be a finite group.

1. If $\|G\| = 1$, then $G = \{e\}$, where e is the identity.

$*$	e
e	e

   This is known as the **trivial group**.

2. If $\|G\| = 2$, then $G = \{e, a\}$.

$*$	e	a
e	e	a
a	a	e

   Note: by $\mathfrak{G}_3$, e must appear in every row and column of a group table, and exactly once.

3. If $\|G\| = 3$, then $G = \{e, a, b\}$

$*$	e	a	b
e	e	a	b
a	a	b	e
b	b	e	a

   Claim: No row or column of a Cayley Table may contain the same element twice.

Proof. Let $a, x, y \in G$ for $\langle G, * \rangle$, where $x \neq y$. Consider the Cayley Table:

$*$	e	a	$\cdots$	x	$\cdots$	y
e	e	a	$\cdots$	x	$\cdots$	y
a	a	$\_$	$\cdots$	$a * x$	$\cdots$	$a * y$

Suppose a row can have the same element twice, say $a * x = a * y$. By left cancellation $x = y$, a contradiction. Thus no row or column can have the same element twice. □

By the pigeon-hole principle, each element of a group must be represented in each row and column exactly once.

5 Subgroups

5.1 Notation

1. Usually we will not use $*$ to denote a binary operation and instead will use *juxtaposition.* That is, we write ab instead of $a * b$. If the binary operation is commutative, $a + b$ is often used.

2. 0 is often used to represent the identity for the operation $+$ and 1 to represent the identity for $\cdot$. We will also continue to use e, and personally I will often use **id**.

3. Instead of a' to represent a's inverse, we will use the more common a^{-1} when the operation is $\cdot$ and $-a$ when the operation is $+$.

4. Exponentiation:

$$\begin{aligned} a^n &= aaa \cdots a \qquad (n \text{ copies}) \\ a^{-n} &= a^{-1}a^{-1} \cdots a^{-1} \qquad (n \text{ copies}) \\ a^0 &= e \end{aligned}$$

5.1.1 Def. Order

If G is a group, then the **order** of G, denoted as $|G|$, is the number of elements in G.

5.1.2 Def. Subgroup

Let H be a subset of a group G. H is a **subgroup** of G if H itself is a group under the operation of G. Notation: $H \leq G$.

5.1.3 Def. Improper and Proper Subgroups

G is an **improper** subgroup of itself. All other subgroups of G are **proper** subgroups, denoted as $H < G$.
Fact: All groups have a trivial subgroup $\{e\}$.

5.1.4 Thm. Proving that a Subset of a Group is a Subgroup

Let H be a subset of a group G. If:

1. H is closed with respect to the operation of G and,

2. H is closed with respect to inverses,

then H is a subgroup of G.

Proof. Let $H \subseteq G$ and assume (1) and (2).

1. By (1), H is closed under the operation of G.

2. Associativity: Let $a, b, c \in H$. Note that $a, b, c \in G$, since $H \subseteq G$. Since G is a group, $a(bc) = (ab)c$. Thus associativity is "*inherited*" from G.

3. Identity: Let $a \in H$. By (2), $a^{-1} \in H$. By (1), $aa^{-1} = e \in H$.

4. Inverse: Let $a \in H$. By (2), $a^{-1} \in H$.

Thus H is a group, and thus also a subgroup of G. □

Example

Prove that $\langle E, +\rangle \leq \langle \mathbb{Z}, +\rangle$.

Proof. Check: Is $E \subseteq \mathbb{Z}$? ✓

1. Is E closed w.r.t. $+$? Let $a, b \in E$. By definition, $\exists\ k, j \in \mathbb{Z}$ such that $a = 2k$ and $b = 2j$. So, $a + b = 2k + 2j = 2(k + j) \in E$. Thus, E is closed w.r.t. E.

2. is E closed w.r.t. inverses? Let $a \in E$. By definition, $\exists\ k \in \mathbb{Z}$ such that $a = 2k$. Multiplying both sides by -1 gives $-a = -2k = 2(-k) \in E$.

$\therefore E \leq \mathbb{Z}$ under $+$. □

5.1.5 Thm. Cyclic Subgroups

Let G be a group and let $a \in G$. Then $H = \{a^n : n \in \mathbb{Z}\}$ is a subgroup of G. This subgroup H is called the **cyclic subgroup** of G generated by a and is denoted $\langle a\rangle$.

5.1.6 Def. Cyclic Group and Generator of a Cylic Group

Let G be a group and let $a \in G$. Then G is **cyclic** if

$$G = \{a^n : n \in \mathbb{Z}\} = \langle a\rangle.$$

'a' is called the **generator** of the cyclic group.

6 Cyclic Groups

Recall

- If G is a group, $a \in G$, and $G = \{a^n : n \in \mathbb{Z}\}$ then $G = \langle a \rangle$ is a *cyclic group* generated by a.
- Every cyclic group is Abelian.
- The *Division Algorithm*: if $m \in \mathbb{Z}^+$ and $n \in \mathbb{Z}$, then there exists unique $q, r \in \mathbb{Z}$ such that

$$n = mq + r \text{ and } 0 \leq r < m.$$

6.0.1 Thm. Cyclic Subgroups are Cyclic

A subgroup of a cyclic group is cyclic.

Proof. Let G be a cyclic group, say $G = \langle a \rangle$, where $a \in G$. Let H be a subgroup of G. Since $H \subseteq G$, every element of H must be a power of a. Consider the *smallest* positive power of a, $a^m \in H$, for $m \in \mathbb{Z}^+$. Let $a^n \in H$ for $n \in \mathbb{Z}$.

By the division algorithm, there exists unique, $\exists! q, r \in \mathbb{Z}$ such that $n = mq + r$ where $0 \leq r < m$. Then,

$$\begin{aligned} a^n &= a^{mq+r} = a^{mq}a^r \\ a^r &= a^{-mq}a^n = (a^m)^{-q}a^n \end{aligned}$$

Since we know that $a^m \in H$, we know that $(a^m)^{-q} \in H$. We also asserted that $a^n \in H$. Thus, we can conclude that $a^r \in H$. But $0 \leq r < m$, and m is the *smallest* positive integer such that $a^m \in H$. Thus $r = 0$. So,

$$\begin{aligned} n &= mq + 0 = mq \\ a^n &= a^{mq} \end{aligned}$$

Thus every element of H takes the form $(a^m)^q$, and H is cyclic, with generator $\langle a^m \rangle$. □

6.0.2 Def. Cyclic Group of Order n

If G is a cyclic group of *order* n, then

$$G = \langle a \rangle = \underbrace{\{e = a^0, a^1, a^2, \ldots, a^{n-1}\}}_{n \text{ elements}} \text{ and } a^n = e.$$

We say the *order of* a *is* n, meaning $a^n = e$. Otherwise, the order of a is infinite, and hence the order of G is infinite.

6.0.3 Thm. Cyclic Groups and the Integer

Let $G = \langle a \rangle$.

1. Every cyclic group of order n is isomorphic to $\langle \mathbb{Z}_n, +_n \rangle$.
2. Every cyclic group of order infinity is isomorphic to $\langle \mathbb{Z}, + \rangle$.

Proof.

1. Let $G = \langle a \rangle$ be a cyclic group of order n. Then

$$G = \{e = a^0, a^1, a^2, \ldots, a^{n-1}\}$$

Consider $\mathbb{Z}_n = \{0, 1, 2, \ldots, n-1\}$. Define $\phi : \mathbb{Z}_n \to G$ by $\phi(x) = a^x$.

(a) One-to-one: assume $a^x = a^y$. Then $x = y$. Thus ϕ is one-to-one.

(b) Onto: let $a^x \in G$. Then choose $x \in \mathbb{Z}_n$, and $\phi(x) = a^x$. Thus, ϕ is onto.

(c) Operation Preserving: $\phi(x + y) = a^{x+y} = a^x a^y = \phi(x)\phi(y)$. Thus ϕ is operation preserving.

Thus ϕ is an isomorphism and $\langle \mathbb{Z}_n, +_n \rangle \simeq G$.

2. Follows nearly identical as above.

□

Note

The above theorem implies that all cyclic groups of order n are isomorphic to each other, and all cyclic groups of order infinity are isomorphic to each other. This is because isomorphism is an equivalence relation.

6.1 Subgroups of Cyclic Groups

6.1.1 Thm. Order of Subgroups of Cyclic Groups

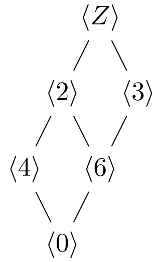
Let $G = \langle a \rangle$ by a cyclic group of order n. Let $b \in G$ and let $b = a^s$ for $s \in \mathbb{Z}$. Then $\langle b \rangle$ is a cyclic subgroup of G containing $\frac{n}{d}$ elements, where $d = \gcd(n, s)$.

6.1.2 Cor. Order of Subgroups of Cyclic Groups

If $G = \langle a \rangle$ is a cyclic group of order n, then the other generators of G are the elements of the form a^r where $\gcd(n, r) = 1$.

Cyclic Subgroup Diagrams

Example cyclic diagram for $\mathbb{Z}_{12} = \langle Z \rangle$.



6.2 Infinite Cyclic Groups

The subgroups of $\langle \mathbb{Z}, + \rangle$ are of the form $\langle n\mathbb{Z}, + \rangle$ for $n \in \mathbb{Z}$. For example,

$$2\mathbb{Z} = \{\ldots, -4, -2, 0, 2, 4, \ldots\}$$
$$5\mathbb{Z} = \{\ldots, -10, -5, 0, 5, 10, \ldots\}$$

7 Generating Sets and Cayley Digraphs

This section is not covered in this course.

8 Groups of Permutations

IDEA: A *permutation* of a set can be thought of as a rearrangement of the elements of the set.

8.0.1 Def. Permutation

A permutation of a set A is a function $\phi : A \to A$ that is both one-to-one and onto. This means ϕ is a bijection from A to itself.

Note: We will use "tabular notation" for ϕ.

Example

Let $A = \{1, 2, 3, 4, 5, 6\}$ and consider two permutations of A:
$f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 6 & 1 & 3 & 5 & 4 & 2 \end{pmatrix}$ and $g = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 2 & 3 & 1 & 6 & 5 & 4 \end{pmatrix}$. Note that the operation of *permutation multiplication* is function composition. That is, $fg = f \circ g$.

1. $fg = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 1 & 3 & 6 & 2 & 4 & 5 \end{pmatrix}$
2. $g^2 f = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 6 & 3 & 2 & 5 & 4 & 1 \end{pmatrix}$
3. $f^{-1} g = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 6 & 3 & 2 & 1 & 4 & 5 \end{pmatrix}$

8.0.2 Thm. Permutations Multiplication and Groups

Let A be a nonempty set and let S_A be the collection of all permutations of A. Then S_A is a group under permutation multiplication.

Proof. Note Permutation Multiplication is a binary operation on S_A.

$\mathfrak{G}_1$ Let $f, g, h \in S_A$. Let $a \in A$

$$\begin{aligned}[f(gh)](a) &= [f \circ (g \circ h)](a) \\ &= f((g \circ h)(a)) \\ &= f(g(h(a))) = (f \circ g)h(a) = [(fg)h](a)\end{aligned}$$

$\therefore \langle S_A, + \rangle$ is associative.

$\mathfrak{G}_2$ Let $i(a) = a$ for all $a \in A$. Then i is the identity permutation.

$\mathfrak{G}_3$ Every permutation in S_A is bijective, so every permutation has an inverse.

$\therefore S_A$ is a group. □

8.0.3 Def. Symmetric Group

Let A be the finite set $A = \{1, 2, 3, \ldots, n\}$. The group of all permutations of A is called the **symmetric group**, denoted S_n.

Note: $|S_n| = n!$

Example

Consider S_3, which would be the group of all permutations of the set $A = \{1, 2, 3\}$. This set is also known as D_3, the group of symmetries of an equilateral triangle, where a symmetry is a movement of a shape to make it coincide with its former position. The letter D is used because this type of group is called a *dihedral group*, which are the groups of symmetries of regular polygons that include rotations and reflections.

Labeling the vertices of the triangle $1, 2,$ and 3, we get the following, where ρ are rotations and μ are reflections.

$$\rho_0 = \begin{pmatrix} 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix} \qquad \mu_1 = \begin{pmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{pmatrix}$$
$$\rho_1 = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix} \qquad \mu_2 = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 2 & 1 \end{pmatrix}$$
$$\rho_2 = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix} \qquad \mu_3 = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 3 \end{pmatrix}$$

However, when we consider D_4, the dihedral group consisting of symmetries of a square, we notice that $S_4 \neq D_4$.

8.0.4 Thm. Cayley's Theorem

Every group is isomorphic to a group of permutations.

Proof. Let G be a group, and let $a \in G$ be fixed. Define $\pi_a : G \to G$ by

$$\pi_a(x) = ax, \qquad \forall\ x \in G$$

First, we prove that π_a is a permutation of G.

Proof. A permutation is one-to-one and onto.

1. One-to-one: Assume $\pi_a(x_1) = \pi_a(x_1)$ for $x_1, x_2 \in G$.

   $$\begin{aligned} \pi_a(x_1) &= \pi_a(x_1) \\ ax_1 &= ax_2 \\ x_1 &= x_2 && \text{by left cancellation} \end{aligned}$$

   Thus π_a is one-to-one.

2. Onto: Let $y \in G$. Show $\exists\ x \in G$ such that $y = \pi_a(x)$.

   $$\begin{aligned} y &= \pi_a(x) = ax \\ a^{-1}y &= x \end{aligned}$$

   Choose $x = a^{-1}y$. Thus π_a is onto.

Thus π_a is a permutation of G. □

Let $G^* = \{\pi_a : a \in G\}$. We must show that G^* is a group (consisting of permutations). It suffices to show that G^* is a subgroup of S_G, the group of all permutations of G. Note: $G^* \subseteq S_G$.

Proof. A subgroup is closed under the operation and inverses.

1. Closed under operation of S_G: Consider $\pi_a, \pi_b \in G^*$ for $a, b \in G$. For $x \in G$,

   $$(\pi_a \circ \pi_b)(x) = \pi_a(bx) = abx = \pi_{ab}(x)$$

   Since $ab \in G$, we know that $\pi_{ab} \in G^*$, so G^* is closed under the operation.

2. Closed under inverses: Let $\pi_a \in G^*$. Since π_a is a bijection, we know π_a has an inverse $(\pi_a)^{-1}$. Note: π_e is the identity of S_G. Consider $(\pi_a)^{-1} = \pi_{a^{-1}}$. For $x \in G$,

$$\begin{aligned}(\pi_{a^{-1}} \circ \pi_a)(x) &= a^{-1}ax = ex = \pi_e(x)\\ (\pi_a \circ \pi_{a^{-1}})(x) &= aa^{-1}x = ex = \pi_e(x)\end{aligned}$$

Thus $(\pi_a)^{-1} = \pi_{a^{-1}} \in G^*$, and G^* is closed under inverses.

Thus $G^* \leq S_G$. □

It remains to be proven that $G \simeq G^*$. Consider $\phi : G \to G6*$, by

$$\pi(a) = \pi_a.$$

Proof. An isomorphism is onto-to-one, onto, and operation preserving.

1. One-to-one: Let $\phi(a) = \phi(b)$ for $a, b \in G$.

$$\begin{aligned}\phi(a) &= \phi(b)\\ \pi_a &= \pi_b\end{aligned}$$

Using $x \in G$,

$$\begin{aligned}\pi_a(x) &= \pi_b(x)\\ ax &= bx\\ a &= b && \text{by right cancellation}\end{aligned}$$

Thus ϕ is one-to-one.

2. Onto: Given any $\pi_a \in G^*$, $\exists\ a \in G$, such that $\phi(a) = \pi_a$. Thus ϕ is onto.

3. Operation Preserving: Show $\phi(ab) = \phi(a) \circ \phi(b)$, $\forall\ a, b \in G$.

$$\begin{aligned}\phi(ab) &= \pi_{ab}\\ &= \pi_a \circ \pi_b\\ &= \phi(a) \circ phi(b)\end{aligned}$$

Thus ϕ is operation preserving.

Thus ϕ is an isomorphism, and $G \simeq G^*$. □

Thus group G is isomorphic to a group of permutations G^*. □

9 Orbits, Cycles, and the Alternating Groups

Consider the set $A = \{1, 2, 3, \ldots, 8\}$ and let $\sigma \in S_8$ be defined by $\sigma = \begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 \\ 3 & 5 & 6 & 4 & 7 & 1 & 2 & 8 \end{pmatrix}$. How does σ "move" elements in A?

$$\begin{gathered} 1 \mapsto 3 \mapsto 6 \mapsto 1 \\ 2 \mapsto 5 \mapsto 7 \mapsto 2 \\ 8 \mapsto 8 \end{gathered}$$

9.0.1 Def. Orbits

The **orbits** of a permutation σ are the equivalence class of A determined by $a \sim b$ if and only if $b = \sigma^n(a)$ for some $n \in \mathbb{Z}$.

9.0.2 Def. Cycle

A permutation is a cycle if it has *at most* **one** orbit containing more than one element.

Example

Writing $\begin{pmatrix} 1 & 2 & 3 & 4 & 5 \\ 3 & 2 & 5 & 1 & 4 \end{pmatrix}$ as a cycle.

$$(1, 3, 5, 4)$$

Note: elements that are not moved by the permutation do **not** appear in the cycle.

Example

In S_8, perform $(1, 3, 6)(2, 8)(4, 7, 5)$ and express the answer as a permutation.

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

In S_6, write $(1, 4, 5, 6)(2, 1, 5)$ as a permutation. Does $(2, 1, 5)(1, 4, 5, 6)$ result in the same permutation? No, they do not.

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

Notes

Disjoint cycles commute. Every permutation σ of a finite set can be expressed asa product of disjoint cycles.

9.0.3 Def. Transposition

A cycle of length two (2) is called a **transposition**.

Note

Every cycle can be expressed as a product of one or more transpositions, although it is *not* unique.

In S_5,

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

9.0.4 Def. Even and Odd Permutations

A permutation is **even** if it can be expressed as a product of an even number of transpositions. A permutation is **odd** if it can be expressed as a product of an odd number of transpositions.

Note

If i is the identity permutation, then i is even.

9.0.5 Thm. Permutations are either Even or Odd

If $\sigma \in S_n$, then σ cannot be both even and odd.

Proof. Let $\sigma \in S_n$ and assume σ can be both even and odd. Note that σ^{-1} is also both even and odd. But, $i = \sigma\sigma^{-1}$ is even, while σ is odd and σ^{-1} is even, or σ is even and σ^{-1} is odd. This would imply that i could be odd, which is a contradiction. □

Recall

S_n is the group of all permutations on $\{1, 2, 3, \ldots, n\}$. Each of these permutations can be expressed as a product of *transpositions*. Even though this breakdown is not unique, the above theorem shows that every breakdown of a particular permutation must either be even or odd. All of the even permutations are given a special designation.

9.0.6 Def. The Alternating Group

The set of all even permutations in S_n is called the **alternating group** on $\{1, 2, \ldots, n\}$, denoted as A_n.

Notes

The alternating group A_n is a subgroup of S_n. Additionally, recall that $|S_n| = n!$. Thus $|A_n| = \frac{n!}{2}$.

10 Cosets and the Theorem of Lagrange

10.0.1 Thm. Relation for Cosets

Let $H \leq G$. Let the relation $\sim_L$ be defined on G by $a \sim_L b$ if and only if $a^{-1}b \in H$ for all $a, b \in G$. Similarly, let the relation $\sim_R$ be defined on G by $a \sim_R b$ if and only if $ab^{-1} \in H$ for all $a, b \in G$. Then $\sim_L$ and $\sim_R$ are both equivalence relations on G.

Proof of $\sim_L$. Let G be a group and $H \leq G$. Define $a \; sim_L b$ by $a^{-1}b \in H$.

1. Reflexive on G:
$$a^{-1}a = e \in H$$
Thus $\sim_L$ is reflexive.

2. Symmetric on G: Assume $a \sim_L b$. Since $a^{-1}b \in H$,
$$\begin{aligned}(a^{-1}b)^{-1} &\in H\\ b^{-1}(a^{-1})^{-1} &\in H\\ b^{-1}a &\in H\end{aligned}$$
Thus $\sim_L$ is symmetric.

3. Transitive on G Assume $a \sim_L b$ and $b \sim_L c$. Since $a^{-1}b \in H$ and $b^{-1}c \in H$,
$$\begin{aligned}(a^{-1}b)(b^{-1}c) &\in H\\ a^{-1}bb^{-1}c &\in H\\ a^{-1}c \in H\end{aligned}$$
Thus $\sim_L$ is transitive.

Therefore, $\sim_L$ is an equivalence relation. □

(The proof for $\sim -R$ is essentially the same.)

Note

Recall that equivalence relations define a partition on a set. Let $a \in G$ be fixed. The partition cell containing a consists of all arbitrary $x \in G$ such that $a \sim_L x$. This implies $a^{-1}x \in H$, so there exists $h \in H$ such that $a^{-1}x = h$. That is, there exists $h \in H$ such that $x = ah$. Therefore, the partition cell containing a is $\{ah : h \in H\}$.

10.0.2 Def. Coset

Let G be a group and $H \leq G$. For any element $a \in G$, the symbol aH denotes the set of all products ah as a remains fixed and h ranges over H. The set aH is called the **left coset** of H in G. Similarly, $Ha = \{ha : h \in H\}$ is the **right coset** of H in G.

Notes

Cosets of G are subsets of G. If G is Abelian, then the left and right cosets are the same. That is, $aH = Ha$ for all $a \in G$.

If $a \in Hb$, then $Ha = Hb$.

Proof. Assume $a \in Hb$. We must show that $Ha \subseteq Hb$ and $Ha \supseteq Hb$.

$Ha \subseteq Hb$. Let $x \in Ha$. We know $\exists \; h_1 \in H$ such that $x = h_1a$.

Since $a \in Hb$, we know $\exists \; h_2 \in H$ such that $a = h_2b$.

So $x = h_1a = h_1(h_2b) = (h_1h_2)b$. $h_1h_2 \in H$, so $x \in Hb$. □

$Ha \supseteq Hb$. Let $y \in Hb$. We know $\exists\ h_3 \in H$ such that $y = h_3 b$.
Since $a \in Hb$, we know $\exists\ h_2 \in H$ such that $a = h_2 b \implies b = h_2^{-1} a$.
So $y = h_3 b = h_3(h_2^{-1} a) = (h_3 h_2^{-1})a$. $h_3 h_2^{-1} \in H$, so $y = Ha$. □

Thus $Ha \subseteq Hb$ and $Ha \supseteq Hb$ and therefore $Ha = Hb$. □

Note

A consequence of above is that a given coset can be written in more than one way. if a coset of H has n elements, say $a_1, a_2, \ldots, a_n$, then it can be written n different ways: $Ha_1, Ha_2, \ldots, Ha_n$.

Example

Consider D_4, the symmetries of a square. Let $H = \{\rho_0, \mu_2\}$. List the right cosets of H in D_4 and the elements of each coset. See table 8.12 (not shown).

$$\begin{aligned} H\rho_0 &= \{\rho_0, \mu_2\} = H\mu_2 \\ H\rho_1 &= \{\rho_1, \delta_1\} = H\delta_1 \\ H\rho_2 &= \{\rho_2, \mu_1\} = H\mu_1 \\ H\rho_3 &= \{\rho_3, \delta_2\} = H\delta_2 \end{aligned}$$

10.0.3 Thm. One-to-one Correspondence of Cosets

If Ha is any coset of H in G, then there is a one-to-one correspondence from H to Ha.

Proof. Define $f : H \to Ha$ by $f(h) = ha$.

1. One-to-one: Let $f(h_1) = f(h_2)$.

$$\begin{aligned} h_1 a &= h_2 a \\ h_1 &= h_2 \end{aligned}$$

   Thus f is one-to-one.

2. Onto: Let $ha \in Ha$. Choose h, and $f(h) = ha$. So f is onto.

Thus f is a one-to-one correspondence from H to Ha. □

Consequence: Any coset Ha of H has the same number of elements as H and thus all cosets of H in G have the same cardinality.

10.0.4 Thm. Lagrange's Theorem

Let G be a finite group and let H be a subgroup of G. The order of G is a multiple of the order of H. Or, the order of H is a divisor of the order of G.

$$|G| = |H| \cdot |G : H|$$

10.0.5 Def. Index of H in G

The **index of** H **in** G, denoted as $(G : H)$ or $|G : H|$, is the number of cosets of H in G.

10.0.6 Cor. Groups of Prime Order

If G is a group with a prime number p elements, then G is a cyclic group. Furthermore, any element $a \neq \mathbf{id}$ in G is a generator in G.

Proof. Let G be a group having p elements, where p is prime. If $a \in G$ but $a \neq \mathbf{id}$, then the order of a is some integer $m \neq 1$.

Then $\langle a \rangle = \{a, a^2, \ldots, a^m = \mathbf{id}\}$ has m elements, $|\langle a \rangle| = m$.

By Lagrange's Theorem, the order of G is a multiple of $|\langle a \rangle|$. But $|G|$ is prime p, and $m \neq 1$, so $p = m$. So $|\langle a \rangle| = |G|$, and thus $\langle a \rangle = G$. □