COMP0147 Discrete Mathematics for Computer Scientists Notes

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Notes adapted from:

- Lecture notes by Max Kanovich and Robin Hirsch [1].
- *A First Course in Abstract Algebra* by Joseph J. Rotman [2].

Contents

1 Set Theory

1.1 Set Notations

- Set definition: $A = \{a, b, c\}$
- Set membership (element-of): $a \in A$
- Set builder notation: $\{x \mid x \in \mathbb{R} \land x^2 = x\}$
- Empty set: $\emptyset$

1.2 Properties

- No structure
- No order
- No copies

For example, a, b, c are references to actual objects in

$$\{a, b, c\} \Leftrightarrow \{c, a, b\} \Leftrightarrow \{a, b, c, b\}$$

1.3 Set Equality

Definition 1.3.1 (Set Equality)**.** Set $A = B$ iff:

1. $A \subseteq B \implies \forall\, x(x \in A \to x \in B)$
2. $B \subseteq A \implies \forall\, y(y \in B \to y \in A)$

Remark. $A = B \Leftrightarrow A \subseteq B \land B \subseteq A$

1.4 Set Operations

- *Union*: $A \cup B \coloneqq \{x \mid x \in A \lor x \in B\}$
- *Intersection*: $A \cap B \coloneqq \{x \mid x \in A \land x \in B\}$
- *Relative Complement*: $A \setminus B \coloneqq \{x \mid x \in A \land x \notin B\}$
- *Absolute Complement*: $A^c \coloneqq U \setminus A \coloneqq \{x \mid x \in U \land x \notin A\}$
- *Symmetric Difference*: $A \Delta B \coloneqq (A \setminus B) \cup (B \setminus A) \coloneqq (A \cup B) \setminus (A \cap B)$
- *Cartesian Product*: $A \times B \coloneqq \{(x, y) \mid x \in A \land y \in B\}$

1.5 Boolean Algebra

Definition 1.5.1 (De Morgan's Laws).

$$\neg(p \lor q) \equiv \neg p \land \neg q \tag{1.1}$$
$$\neg(p \land q) \equiv \neg p \lor \neg q \tag{1.2}$$

Definition 1.5.2 (Idempotent Laws).

$$p \lor p \equiv p \tag{1.3}$$
$$p \land p \equiv p \tag{1.4}$$

Definition 1.5.3 (Commutative Laws).

$$p \lor q \equiv q \lor p \tag{1.5}$$
$$p \land q \equiv q \land p \tag{1.6}$$

Definition 1.5.4 (Associative Laws).

$$p \lor (q \lor r) \equiv (p \lor q) \lor r \tag{1.7}$$
$$p \land (q \land r) \equiv (p \land q) \land r \tag{1.8}$$

Definition 1.5.5 (Distributive Laws).

$$p \land (q \lor r) \equiv (p \land q) \lor (p \land r) \tag{1.9}$$
$$p \lor (q \land r) \equiv (p \lor q) \land (p \lor r) \tag{1.10}$$

Definition 1.5.6 (Identity Laws).

$$p \lor \mathrm{F} \equiv p \tag{1.11}$$
$$p \lor \mathrm{T} \equiv \mathrm{T} \tag{1.12}$$
$$p \land \mathrm{T} \equiv p \tag{1.13}$$
$$p \land \mathrm{F} \equiv \mathrm{F} \tag{1.14}$$

Definition 1.5.7 (Absorption Laws).

$$p \lor (p \land q) \equiv p \tag{1.15}$$
$$p \land (p \lor q) \equiv p \tag{1.16}$$

Definition 1.5.8 (Implication and Negation Laws).

- *Identity*: $p \to q \equiv \neg p \lor q$
- *Counter-example*: $\neg(p \to q) \equiv p \land \neg q$
- *Equivalences*: $p \to q \to r \equiv (p \land q) \to r \equiv q\ to(p \to r)$

- *Absorption*:
  $p \to \mathrm{T} \equiv T$
  $p \to \mathrm{F} \equiv \neg p$
  $\mathrm{T} \to p \equiv p$
  $\mathrm{F} \to p \equiv T$
- *Contrapositive*: $p \to q \equiv \neg q \to \neg p$
- *Law of Excluded Middle*:
  $p \vee \neg p \equiv \mathrm{T}$
  $p \wedge \neg p \equiv \mathrm{F}$
- *Double Negation*: $\neg\neg p \equiv p$
- *Reduction to Absurdity*: $\neg p \to \mathrm{F} \equiv p$

1.6 Set Algebra

Definition 1.6.1 (De Morgan's Laws).

$$(A \cup B)^c \equiv A^c \cap B^c \tag{1.17}$$
$$(A \cap B)^c \equiv A^c \cup B^c \tag{1.18}$$

Definition 1.6.2 (Idempotent Laws).

$$A \cup A \equiv A \tag{1.19}$$
$$A \cap A \equiv A \tag{1.20}$$

Definition 1.6.3 (Commutative Laws).

$$A \cup B \equiv B \cup A \tag{1.21}$$
$$A \cap B \equiv B \cap A \tag{1.22}$$

Definition 1.6.4 (Associativity Laws).

$$A \cup (B \cup C) \equiv (A \cup B) \cup C \tag{1.23}$$
$$A \cap (B \cap C) \equiv (A \cap B) \cap C \tag{1.24}$$

Definition 1.6.5 (Distributive Laws).

$$A \cap (B \cup C) \equiv (A \cap B) \cup (B \cap C) \tag{1.25}$$
$$A \cup (B \cap C) \equiv (A \cup B) \cap (B \cup C) \tag{1.26}$$

Definition 1.6.6 (Identity Laws).

$$A \cup \emptyset \equiv A \tag{1.27}$$
$$A \cap \emptyset \equiv \emptyset \tag{1.28}$$
$$A \cap U \equiv A \tag{1.29}$$
$$A \cup U \equiv U \tag{1.30}$$

Definition 1.6.7 (Absorption Laws).

$$A \cup (A \cap B) \equiv A \tag{1.31}$$
$$A \cap (A \cup B) \equiv A \tag{1.32}$$

Definition 1.6.8 (Difference Identity Laws).

$$C \setminus (A \cup B) \equiv (C \setminus A) \cap (C \setminus B) \tag{1.33}$$
$$C \setminus (A \cap B) \equiv (C \setminus A) \cup (C \setminus B) \tag{1.34}$$

Definition 1.6.9 (Complement-Difference Identity Law).

$$C \setminus D \equiv C \cap D^c \tag{1.35}$$

Definition 1.6.10 (Double Complement Law).

$$(D^c)^c \equiv D \tag{1.36}$$

Definition 1.6.11 (Contraposition).

$$C \subseteq D \Leftrightarrow D^c \subseteq C^c \tag{1.37}$$
$$C = D \Leftrightarrow C^c = D^c \tag{1.38}$$

Definition 1.6.12 (Arbitrary Union).
Given sets $A_1, A_2, \dots, A_n$ where $I = \{1, 2, \dots, n\}$

$$A_1 \cup A_2 \cup \dots \cup A_n := \bigcup_{i \in I} A_i \tag{1.39}$$

Then

$$x \in \bigcup_{i \in I} A_i \Leftrightarrow \exists\, i \in I : x \in A_i \tag{1.40}$$

Definition 1.6.13 (Arbitrary Intersection).
Given sets $A_1, A_2, \dots, A_n$ where $I = \{1, 2, \dots, n\}$

$$A_1 \cap A_2 \cap \dots \cap A_n := \bigcap_{i \in I} A_i \tag{1.41}$$

Then

$$x \in \bigcap_{i \in I} A_i \Leftrightarrow \forall\, i \in I : x \in A_i \tag{1.42}$$

2 Functions

2.1 Function Basics

Definition 2.1.1 (Function)**.** A function f is a mapping from X to Y

$$f\colon X \mapsto Y \tag{2.1}$$

- $\operatorname{domain}(f) = X$
- $\operatorname{image}(f) = f(X)$

Definition 2.1.2 (Total Function)**.** A function is *total* if

$$\operatorname{domain}(f) = X \tag{2.2}$$

Definition 2.1.3 (Partial Function)**.** A function is *partial* if

$$\operatorname{domain}(f) \subseteq X \tag{2.3}$$

Definition 2.1.4 (Surjection)**.** A function $f\colon X \mapsto Y$ is *surjective* iff

$$f(X) = Y \Leftrightarrow \forall\, y \in Y\colon\ \exists\, x \in X\colon\ f(x) = y \tag{2.4}$$

Namely each $y \in Y$ has a corresponding $x \in X$.

Definition 2.1.5 (Injection (Encodings, One-to-one))**.** A function $f\colon X \mapsto Y$ is *injective* iff

$$\forall\, x_1, x_2 \in X\colon\ x_1 \neq x_2 \to f(x_1) \neq f(x_2) \tag{2.5}$$

$$\Leftrightarrow \forall\, x_1, x_2 \in X\colon\ f(x_1) = f(x_2) \to x_1 = x_2 \tag{2.6}$$

Namely each distinct element $x \in X$ maps to a different element in Y.

Definition 2.1.6 (Bijection)**.** A function $f\colon X \mapsto Y$ is *bijective* iff f is both *injective* and *surjective.*

$$\operatorname{Bijective}(f) \coloneqq \operatorname{Injective}(f) \wedge \operatorname{Surjective}(f) \tag{2.7}$$

The *inverse bijection* $f^{-1}\colon Y \mapsto X$ does exist.

2.2 Composition of Injections

Proposition 2.2.1 (Composition of Injection)**.** Given *injections* $f\colon X \mapsto Y$ and $g\colon Y \mapsto Z$, then their *composition* $h\colon X \mapsto Z$ is given by

$$h(x) := g(f(x)) \tag{2.8}$$

Then h is also an *injective* function. Namely $h = g \circ f$ where h is composed from g and f with f applied first.

Proof. Given any $x_1, x_2 \in X$ where $x_1 \neq x_2$, then

$$f(x_1) \neq f(x_2) \tag{2.9}$$

as f is *injective*, and thus

$$h(x_1) = g(f(x_1)) \neq g(f(x_2)) = h(x_2) \tag{2.10}$$

h is *injective* consequently. ■

2.3 Composition of Surjection

Proposition 2.3.1 (Composition of Surjection)**.** Given *surjections* $f\colon X \mapsto Y$ and $g\colon Y \mapsto Z$, then their *composition* $h\colon X \mapsto Z$ is given by

$$h(x) := g(f(x)) \tag{2.11}$$

Then h is also a *surjective* function.

Proof. To prove $h\colon X \mapsto Z$ is *injective*, it is required to prove that

$$\forall\, z \in Z\colon\ \exists\, x \in X\colon h(x) = z \tag{2.12}$$

Where $h(x) \Leftrightarrow (g \circ f)(x) \Leftrightarrow g(f(x))$.

Given any element $z \in Z$ ($\forall\, z \in Z$):

1. That $g\colon Y \mapsto Z$ is *surjective* by definition, then $\exists\, y \in Y\colon g(y) = z$.
2. That $f\colon X \mapsto Y$ is *surjective* by definition, then $\exists\, x \in X\colon f(x) = y$.

Then $\forall\, z \in Z\colon\ \exists\, x \in X\colon h(x) = (g \circ f)(x) = g(f(x)) = g(y) = z$ holds true. ■

2.4 Composition of Bijection

Proposition 2.4.1 (Composition of Bijection)**.** Given *bijections* $f\colon X \mapsto Y$ and $g\colon Y \mapsto Z$, then their composition $h\colon X \mapsto Z$ is given by

$$h(x) := g(f(x)) \tag{2.13}$$

Then h is also a *bijective* function; an *inverse bijection* $h^{-1}\colon Z \mapsto X$ also exists.

2.5 Cardinality of Sets

Definition 2.5.1 (Cardinality)**.** The number of elements in a set X is denoted $|X|$.

Definition 2.5.2 (Equal Cardinality and Bijection)**.**

$$|X| = |Y| \tag{2.14}$$

Holds true if there exists a *bijection* $h\colon X \mapsto Y$ (one-to-one correspondence between X and Y).

Namely, X and Y have the same number of distinct elements, and each distinct element $x \in X$ corresponds to exactly one distinct element $y \in Y$.

Theorem 2.5.1 (Cantor-Bernstein)**.** Given

1. *injective* function $f\colon X \mapsto Y$
2. *injective* function $g\colon Y \mapsto X$

Then there exists a *bijective* function $h\colon X \mapsto Y$.

Equivalently,

$$(|X| \leq |Y|) \wedge (|Y| \leq |X|) \to (|X| = |Y|) \tag{2.15}$$

Remark. Examples include countable sets, enumerable sets

$$|\mathbb{Q}| = |\mathbb{Z}| = |\mathbb{N}| = \aleph_0 \tag{2.16}$$

Where the cardinality of countable sets such as the *rational numbers*, *integers* and the *natural numbers* is denoted as "alpeh-zero" ($\aleph_0$).

On the other hand, continuum such as the *real numbers* are not countable and as such

$$|\mathbb{R}| > \aleph_0 \tag{2.17}$$

3 Permutations

3.1 Permutation Basics

Definition 3.1.1 (Permutation)**.** The bijection – *permutation* – of

$$\begin{array}{ccccc} 1 & 2 & 3 & \cdots & n \\ \downarrow & \downarrow & \downarrow & \cdots & \downarrow \\ \sigma(1) & \sigma(2) & \sigma(3) & \cdots & \sigma(n) \end{array} \tag{3.1}$$

Is denoted as

$$\begin{pmatrix} 1 & 2 & 3 & \cdots & n \\ \sigma(1) & \sigma(2) & \sigma(3) & \cdots & \sigma(n) \end{pmatrix} \tag{3.2}$$

Where $\sigma\colon \{1, \ldots, n\} \to \{1, \ldots, n\}$ is the *permutation* bijection.

Definition 3.1.2 (Counting Permutations)**.**

$$|S_n| := n! \tag{3.3}$$

Which is the number of different ways to permutate n elements $\{1, 2, \ldots, n\} \subset \mathbb{Z}$. Together, the different permutations for n distinct elements is the *symmetric group* S_n.

Remark. For example, with $S_3 = \{1, 2, 3\}$, there are $3! = 6$ different ways to arrange the three distinct elements

$$\begin{array}{ccc} \begin{pmatrix} 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix} & \begin{pmatrix} 1 & 2 & 3 \\ 1 & 3 & 2 \end{pmatrix} & \begin{pmatrix} 1 & 2 & 3 \\ 2 & 1 & 3 \end{pmatrix} \\ \begin{pmatrix} 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix} & \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix} & \begin{pmatrix} 1 & 2 & 3 \\ 3 & 2 & 1 \end{pmatrix} \end{array} \tag{3.4}$$

Definition 3.1.3 (Order of Permutation)**.** The *order* of a permutation σ is the smallest $k \in \mathbb{Z}^+$ such that

$$\sigma^k = \epsilon \tag{3.5}$$

Where ϵ is the *identity permutation*

$$\epsilon(x) = x \tag{3.6}$$

Definition 3.1.4 (Sign of Permutation)**.** The *sign* of a permutation $\operatorname{sgn}\sigma\colon \sigma \to \{-1, +1\}$ where $\sigma \in S_n$ is defined as

$$\operatorname{sgn}(\sigma) = (-1)^k \tag{3.7}$$

Where k is the number of *disorders* within σ, the number of pairs (x, y) such that $x > y \to \sigma(x) < \sigma(y)$ or the converse $x < y \to \sigma(x) > \sigma(y)$. Additionally,

$$\operatorname{sgn}(\sigma) = \begin{cases} +1 & \text{if k is even} \\ -1 & \text{if k is odd} \end{cases} \tag{3.8}$$

Remark. For example, in

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

$1 < 2$ but $\sigma(1) = 2 > \sigma(2) = 1$, hence a disorder.

For each $i \in \{1, \dots, n\}$, starting from $i = 1$, compare $\sigma(i)$ with $\sigma(i+1), \dots, \sigma(n)$ and add the number of disordered pairs, then move on to $i + 1$ and compare $\sigma(i+1)$ with $\sigma(i+2), \dots, \sigma(n)$ and so on.

Theorem 3.1.1 (Composition of Permutation)**.**

$$\operatorname{sgn}(\sigma_1\sigma_2) := \operatorname{sgn}(\sigma_1) \cdot \operatorname{sgn}(\sigma_2) \tag{3.9}$$

Where

$\circ$	even	odd
even	even	odd
odd	odd	even

Table 3.1: Sign Changes on Composition

4 Binary Relations

Definition 4.0.1 (Binary Relation)**.** A binary relation $R(x, y)$ describes some relationship between x and y where $R\colon X \to Y$, $R \subseteq X \times Y$, $x \in X$ and $y \in Y$. This relation can be expressed in infix notation as xRy.

4.1 Equivalence Relations

Definition 4.1.1 (Equivalence Relation)**.** A binary relation $E(x, y)$ is an *equivalence relation* on X iff it satisfies all three conditions:

1. **Reflexivity**
   $\forall\, x \in X\colon E(x, x)$
2. **Symmetry**
   $\forall\, x, y \in X\colon E(x, y) \to E(y, x)$
3. **Transitivity**
   $\forall\, x, y, z \in X\colon E(x, y) \land E(y, z) \to E(x, z)$

4.2 Equivalence Classes

Definition 4.2.1 (Equivalence Class)**.** If $a \in X$, the *equivalence class* $[a]$ is

$$[a] \coloneqq \{x \in X\colon E(x, a)\} \subseteq X \tag{4.1}$$

Definition 4.2.2 (Congruence and Equivalence Class of mod m on $\mathbb{Z}$)**.** For *congruence mod m* on $\mathbb{Z}$, if $a \in \mathbb{Z}$ then the *congruence class* of a is

$$[a]_m \coloneqq \{x \in \mathbb{Z}\colon x = a + km\} \tag{4.2}$$

Where $k \in \mathbb{Z}$. Since $x = a + km \Leftrightarrow x \equiv a \bmod m$, then the *equivalence class* of a is also the *congruence class.*

$$\Leftrightarrow [a]_m \coloneqq \{x \in \mathbb{Z}\colon x \equiv a \bmod m\} \tag{4.3}$$

Definition 4.2.3 (Set of Remainders)**.** Over $\mathbb{Z}$, the *remainder* r from the integer division $k \div m$ is

$$r \bmod m \equiv k \bmod m \tag{4.4}$$

Then the set of remainders G_m from the integer division $k \div m$ is defined by

$$G_m \coloneqq \{0, 1, 2, \dots, m-2, m-1\} \tag{4.5}$$

4.3 Quotient Groups

Definition 4.3.1 (Quotient Group)**.** A *quotient group* is a group constructed via congruence mod m.

Definition 4.3.2 (Congruence Class)**.** If $m \leq 2$ and $a \in \mathbb{Z}$ then the *congruence class* of a mod m is $[a] \subseteq \mathbb{Z}$

$$[a] \coloneqq \{b \in \mathbb{Z} \colon b \equiv a \bmod m\} \tag{4.6}$$
$$\Leftrightarrow \{a + km \colon k \in \mathbb{Z}\} \tag{4.7}$$
$$\Leftrightarrow \{\dots, a - 2m, a - m, a, a + m, a + 2m, \dots\} \tag{4.8}$$

Remark. Let $E(x, y) \coloneqq$ "$x - y \equiv 0 \bmod 2$", that is, $x - y$ is divisible by 2. Then,

$$[k]_2 \coloneqq \{y \colon E(k, y)\} \tag{4.9}$$

Where $[k]_2$ is the congruence class of integers modulo 2.
Computing $[0]_2$ and $[1]_2$ yields

- $[0]_2 = \{0, 2, -2, 4, -4, \dots, 2n, -2n, \dots\}$
- $[1]_2 = \{1, -1, 3, -3, \dots, 2n + 1, \dots\}$

Observe that

$$[1]_2 \oplus [1]_2 \Leftrightarrow [2]_2 \Leftrightarrow [0]_2 \tag{4.10}$$

It can be deduced that $[0]_2$ and $[1]_2$ are two congruence (and equivalence) classes which partition the integers $\mathbb{Z}$ into two disjoint subsets – integers which are odd, and integers which are even. This may be denoted as

$$\mathbb{Z}/E \equiv \{\text{EVEN}, \text{ODD}\} \tag{4.11}$$

Definition 4.3.3 (Congruence Modular Arithmetic (mod m) on $\mathbb{Z}$)**.**

$$[a]_m \oplus [b]_m \equiv [a + b]_m \tag{4.12}$$
$$[a]_m \otimes [b]_m \equiv [a \cdot b]_m \tag{4.13}$$

If $a_1 \equiv a_2 \bmod m$ and $b_1 \equiv b_2 \bmod m$ then

$$a_1 + b_1 \equiv a_2 + b_2 \bmod m \tag{4.14}$$
$$a_1 \cdot b_1 \equiv a_2 \cdot b_2 \bmod m \tag{4.15}$$
$$\tag{4.16}$$

Remark. We may introduce addition $(+)$ and multiplication $(*)$ over the remainders G_m previously defined as

$$G_m \coloneqq \{0, 1, 2, \dots, m - 2, m - 1\} \tag{4.17}$$

For example, given $m = 3$, then the multiplication and addition table of $+ \pmod 3$ and $* \pmod 3$ over G_3 can be computed:

+ (mod 3)	0	1	2
0	0	1	2
1	1	2	0
2	2	0	1

$*$ (mod 3)	0	1	2
0	0	0	0
1	0	1	2
2	0	2	1

Table 4.1: Multiplication and Addition Table of G_3

5 Groups

5.1 Group Basics

A *group* is an abstract collection consisting of:

- A *nonempty set* G.
- A *binary operation* $\star \colon G \times G \to G$.

It has the following properties:

1. **Closure**
$$\forall\, x, y \colon x \in G \wedge y \in G \to x \star y \in G \tag{5.1}$$
2. **Associativity**
$$\forall\, x, y, z \in G \colon (x \star y) \star z \equiv x \star (y \star z) \tag{5.2}$$
3. **Neutral Element**
$$\exists\, \epsilon \in G \colon \; \forall\, x \in G \colon x \star \epsilon \equiv \epsilon \star x \equiv x \tag{5.3}$$
That there exists an unique *neutral* element $\epsilon \in G$.
4. **Invertibility**
$$\forall\, x \in G \colon \; \exists\, y \in G \colon x \star y \equiv y \star x \equiv \epsilon \tag{5.4}$$
That there exists an unique *inverse* element $y := x^{-1} \in G$ where x^{-1} denotes the *inverse* element of x.

Definition 5.1.1 (Commutative Group)**.** An *commutative group* (or *abelian group*) is a *group* for which its operation $\star \colon G \times G \to G$ satisfies the additional *commutative* property:

- **Commutativity**
$$\forall\, x, y \in G \colon x \star y \equiv y \star x \tag{5.5}$$

5.2 Multiplicative Group

Proposition 5.2.1 (Multiplicative Group)**.** A *multiplicative group* is a *group* $(G, *)$ which has the binary operation $* \colon G \times G \to G$:

- **Closure, Associativity**. The multiplication operation $* \colon G \times G \to G$ is closed and is left associative.
- **Neutral Element**. The neutral element ϵ is unique.
- **Invertibility**. The inverse element x^{-1} is unique.

- For all $a, b \in G$ the equation
$$a * x = b \tag{5.6}$$
Has the unique solution
$$x = a^{-1} * b \tag{5.7}$$

Since

$$\begin{aligned}
a * x = b &\Leftrightarrow a^{-1} * (a * x) = a^{-1} * b && \text{(Multiply by inverse element)} && (5.8)\\
&\Leftrightarrow (a^{-1} * a) * x = a^{-1} * b && \text{(Associativity)} && (5.9)\\
&\Leftrightarrow \epsilon * x = a^{-1} * b && \text{(Invertibility)} && (5.10)\\
&\Leftrightarrow x = a^{-1} * b && \text{(Neutral Element)} && (5.11)
\end{aligned}$$

Remark. An example of a multiplicative group is permutations under composition, namely S_n is a group $(G, \circ)$ where $\circ\colon G \times G \to G$.

For example, let G be the set of permutations

$$\epsilon = \begin{pmatrix} 1 & 2 & 3 \\ 1 & 2 & 3 \end{pmatrix} \quad \sigma_1 = \begin{pmatrix} 1 & 2 & 3 \\ 2 & 3 & 1 \end{pmatrix} \quad \sigma_2 = \sigma_1^2 = \begin{pmatrix} 1 & 2 & 3 \\ 3 & 1 & 2 \end{pmatrix} \tag{5.12}$$

To verify that G does form a group with composition $\circ$, one may draw the multiplication table for the group. Note that

$$\sigma_2\sigma_2 = \sigma_1^4 = \sigma_1^3\sigma_1 = \epsilon\sigma_1 = \sigma_1 \tag{5.13}$$

$\circ$	ϵ	σ_1	σ_2
ϵ	ϵ	σ_1	σ_2
σ_1	σ_1	σ_2	ϵ
σ_2	σ_2	ϵ	σ_1

Table 5.1: Multiplication Table of Composition $\circ$ over G

5.3 Additive Group

Definition 5.3.1 (Additive Group)**.** An *additive group* is a *group* $(G, +)$ with the binary operation $+\colon G \times G \to G$. It has the same properties of a general *group*.

1. **Closure**
$$\forall\, x, y\colon x \in G \wedge y \in G \to x + y \in G \tag{5.14}$$
2. **Associativity**
$$\forall\, x, y, z \in G\colon (x + y) + z \equiv x + (y + z) \tag{5.15}$$
3. **Neutral Element**
$$\exists\, \epsilon \in G\colon\ \forall\, x \in G\colon x + \epsilon \equiv \epsilon + x \equiv x \tag{5.16}$$
That there exists an unique *neutral* element $0_G \in G$ (usually denoted simply as 0).

4. **Invertibility**
$$\forall\, x \in G \colon\ \exists\, y \in G \colon x + y \equiv y + x \equiv 0 \tag{5.17}$$
That there exists an unique *inverse* element $y := -x \in G$ where $-x$ denotes the *inverse* element of x.

Remark. An example of an additive group is $(\mathbb{Z}, +)$ (i.e. addition over the integers).
Then for any of such *commutative group* $(G, +)$
- *Neutral element* 0 is unique.
- *Inverse element* $-x$ is unique.
- For any $a, b \in G$ the equation
$$a + x = b \tag{5.18}$$
Has a unique solution
$$x = b + (-a) = b - a \tag{5.19}$$

5.4 Associativity of Sequential Composition of Functions

Definition 5.4.1 (Sequential Composition of Functions)**.** Let $f * g$ denote the sequential composition of functions $f * X \to Y$ and $g \colon Y \to Z$ such that $f * g \colon X \to Z$ where f is applied first then g, i.e. $\forall\, x \in X \colon (f * g)(x) := g(f(x))$.

Proposition 5.4.1 (Associativity of Sequential Composition of Functions)**.** Given sets X, Y and Z and
- *Injection* $f \colon A \to B$
- *Injection* $g \colon B \to C$
- *Injection* $h \colon C \to D$

Then their composition is associative:
$$(f * g) * h \equiv f * (g * h) \tag{5.20}$$

Proof.
Let $s = (f * g)$ and $t = (s * h)$, then $t(x) = h(s(x)) = h(g(f(x)))$.
Let $u = (g * h)$ and $v = (f * u)$, then $v(x) = u(f(x)) = h(g(f(x)))$.
Together they yield the desired equality $t(x) = v(x)$. ∎

5.5 Subgroups

Definition 5.5.1 (Subgroup)**.** Given a *group* $(G, *)$, then the subset $H \subseteq G$ is a *subgroup* of G if it fulfills the properties:
1. **Closure**
$$\forall\, x, y \colon x \in H \land y \in H \to x * y \in H \tag{5.21}$$
2. **Neutral Element**
$$\epsilon \in H \tag{5.22}$$
That is, the *neutral* element ϵ from G is contained within the subset $H \subseteq G$.

3. **Invertibility**

$$\forall\, x \in H \colon x^{-1} \in H \tag{5.23}$$

5.6 Lagrange's Theorem

Theorem 5.6.1 (Lagrange's Theorem)**.** Given a finite *group* of order n $(G, *)$ where

$$G := \{g_1, g_2, \dots, g_n\} \tag{5.24}$$

And its *subgroup* $(H, *)$ of order $k \leq n$

$$H := \{h1_, h_2, \dots, h_k\} \tag{5.25}$$

Then $k|n$ (k divides n).

G can be *partitioned* into ℓ disjoint subsets of the same size k such that

$$n = k\ell \tag{5.26}$$

Definition 5.6.1 (Left Coset)**.** Given $(G, *)$ is a *group*, $(H, *)$ is a *subgroup* of $(G, *)$ and $g \in G$ then the *left coset* gH of H in G with respect to g is defined as

$$gH := \{g * h \colon h \in H\} \tag{5.27}$$

Remark. Visually,

$$G \equiv \left.\begin{array}{c} \boxed{g_1 H} \\ \boxed{g_2 H} \\ \vdots \\ \boxed{g_\ell H} \end{array}\right\} \ell \text{ disjoint subsets} \tag{5.28}$$

To verify that the *left cosets* together do in fact reconstruct G, check the multiplication table

$*$	h_1	h_2	$\cdots$	h_k
$g_1 H$	$g_1 * h_1$	$g_1 * h_2$	$\cdots$	$g_1 * h_k$
$g_2 H$	$g_2 * h_1$	$g_2 * h_2$	$\cdots$	$g_2 * h_k$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
$g_\ell H$	$g_\ell * h_1$	$g_\ell * h_2$	$\cdots$	$g_\ell * h_k$

Table 5.2: Multiplication Table from ℓ Left Cosets, Each of Size $|H| = k$

Proposition 5.6.1. For any $a, b \in G$ from $(G, *)$

$$(a * b)^{-1} \equiv b^{-1} * a^{-1} \tag{5.29}$$

Proof.

$$
\begin{aligned}
(a*b)^{-1} &\Leftrightarrow (a*b)^{-1} * \epsilon && \text{(Neutral element)} && (5.30)\\
&\Leftrightarrow (a*b)^{-1} * (a*a^{-1}) && \text{(Invertibility)} && (5.31)\\
&\Leftrightarrow (a*b)^{-1} * ((a*\epsilon)*a^{-1}) && \text{(Neutral element)} && (5.32)\\
&\Leftrightarrow (a*b)^{-1} * \left[(a*(b*b^{-1}))*a^{-1}\right] && \text{(Invertibility)} && (5.33)\\
&\Leftrightarrow (a*b)^{-1} * \left[(a*b)*(b^{-1}*a^{-1})\right] && \text{(Associativity)} && (5.34)\\
&\Leftrightarrow \left[(a*b)^{-1}*(a*b)\right]*(b^{-1}*a^{-1}) && \text{(Associativity)} && (5.35)\\
&\Leftrightarrow \epsilon*(b^{-1}*a^{-1}) && \text{(Invertibility)} && (5.36)\\
&\Leftrightarrow b^{-1}*a^{-1} && \text{(Neutral Element)} && (5.37)
\end{aligned}
$$

■

Proof. For a constructive proof of Lagrange's Theorem:
Let the binary relation $E(x, y)$ be defined on the *group* $(G, *)$, with its *subgroup* $(H, *)$

$$E(x, y) := x^{-1} * y \in H \tag{5.38}$$

For the equivalence

$$x = y \Leftrightarrow x^{-1} * y = 1 \tag{5.39}$$

Then for each of the required properties:

- **Neutral Element** from *Reflexivity* of $E(x, y)$

$$\forall\, x \in G\colon E(x, x) \tag{5.40}$$

  Since

$$E(x, x) \equiv x^{-1} * x \in H \equiv \epsilon \in H \tag{5.41}$$

  Then this satisfies the *reflexivity* requirement for *equivalence relations*, and proves the *neutral element* requirement for *subgroups*.
- **Invertibility** from *Symmetry* of $E(x, y)$

$$\forall\, x, y \in G\colon E(x, y) \to E(y, x) \tag{5.42}$$

  Let for some $h \in H$, $x^{-1} * y = h$, then by proposition 5.6.1

$$y^{-1} * x \equiv (x^{-1} * y)^{-1} \equiv h^{-1} \in H \tag{5.43}$$

  Which satisfies the *symmetry* requirement for *equivalence relations*, and proves the *invertibility* requirement for *subgroups*.

- **Closure** from *Transitivity* of $E(x, y)$

$$\forall\, x, y, z \in G \colon E(x, y) \wedge E(y, z) \to E(x, z) \tag{5.44}$$

Let for some $h_1, h_2 \in H$, $(x^{-1} * y = h_1) \wedge (y^{-1} * z = h_2)$, then

$$\begin{aligned} x^{-1} * z &\Leftrightarrow x^{-1} * \epsilon * z &(5.45)\\ &\Leftrightarrow (x^{-1} * y) * (y^{-1} * z) &(5.46)\\ &\Leftrightarrow h_1 * h_2 \in H &(5.47)\end{aligned}$$

Which satisfies the *transitivity* requirement for *equivalence relations*, and proves the *closure* requirement for *subgroups*.

■

Remark. To demonstrate Lagrange's Theorem, let the *group* be constructed from $x * y \pmod{10}$.

Let $(G, *)$ be a finite *group* of order $n = 4$ where

$$G = \{1, 3, 7, 9\} \tag{5.48}$$

And $(H, *)$ be its *subgroup* of order $k = 2$.

Constructing the multiplication table yields

$* \pmod{10}$	1	9
$1 * H$	1	9
$3 * H$	3	7
$7 * H$	7	3
$9 * H$	9	1

Table 5.3: Multiplication Table for $(G, *)$

There are only $\ell = 2$ disjoint subsets (unique cosets) gH; G can be partitioned into ℓ disjoint subsets, each of size $|H| = 2$ such that $4 = n = k\ell = 2 \cdot 2$.

Visually,

$$G = \left.\begin{array}{|c|}\hline 1 * H = 9 * H = \{1, 9\} \\ \hline 3 * H = 7 * H = \{3, 7\} \\ \hline \end{array}\right\} \ell = 2 \tag{5.49}$$

5.6.1 Equivalence Classes

Definition 5.6.2 (Equivalence Class)**.** Given *group* $(G, *)$ and its *subgroup* $(H, *)$, then the *equivalence class* $[g]$ is defined as

$$[g] \coloneqq \{y \in G \mid g^{-1} * y \in H\} \tag{5.50}$$

Then

$$\forall\, h \in H\colon g^{-1} * y = h \Leftrightarrow y = g * h \tag{5.51}$$

Which yields the equivalence

$$\{y \in G \mid g^{-1} * y \in H\} \equiv \{y \in G \mid y \in gH\} \tag{5.52}$$

Hence

$$[g] \equiv gH \tag{5.53}$$

That the *equivalence class* $[g]$ is exactly the *left coset* gH.

Let ℓ be the number of disjoint equivalence class $[g]$, then G can be partitioned into ℓ disjoint subsets where visually,

$$G = \left.\begin{array}{c} \boxed{[g_1] \equiv g_1 H} \\ \boxed{[g_2] \equiv g_1 H} \\ \vdots \\ \boxed{[g_\ell] \equiv g_\ell H} \end{array}\right\} \ell \text{ disjoint subsets} \tag{5.54}$$

Proposition 5.6.2.

$$\forall\, g \in G\colon |gH| \equiv |H| \equiv k \tag{5.55}$$

Proof. Let I be the set of indices $I := \{1, \dots, k\}$

$$\forall\, i, j \in I\colon (h_i = h_j) \leftrightarrow (g * h_i = g * h_j) \tag{5.56}$$

$$\Leftrightarrow \forall\, i, j \in I\colon (h_1 \neq h_j) \leftrightarrow (g * h_i \neq g * h_j) \tag{5.57}$$

■

Remark. Let A_n be the set of all *even permutations* and B_n be the set of all *odd permutations.*

Given the *group* $(S_n, *)$, then $(A_n, *)$ is a *subgroup* of S_n.

With the multiplication table

$*$	A_n
$\epsilon * A_n$	A_n
$\epsilon * A_n$	B_n

Table 5.4: Multiplication Table for Group S_n

Since

$$\sigma * A_n \equiv \begin{cases} A_n & \text{if } \sigma \text{ is even} \\ B_n & \text{if } \sigma \text{ is even} \end{cases} \tag{5.58}$$

Hence,

$$|A_n| \equiv \frac{1}{2} \cdot |S_n| \equiv \frac{1}{2} \cdot n! \tag{5.59}$$

5.6.2 Order of an Element in Lagrange's Theorem

Definition 5.6.3 (Order of an Element)**.** Given a *group* $(G, *)$ and element $a \in G$ then the *order* of the element a is the smallest $k \in \mathbb{Z}^+$ such that

$$a^k = \epsilon \tag{5.60}$$

Proposition 5.6.3. Given a *group* $(G, *)$ with *order* n, then for any $a \in G$, should its *order* k exist, then $k|n$ (k divides n).

Proposition 5.6.4. Given *group* $(G, *)$,

$$\forall\, a \in G \colon a^{|G|} \equiv 1 \tag{5.61}$$

Proof. With the *cyclic subgroup* generated by $a \in G$

$$\{a^m \mid m \in \mathbb{Z}\} = \{\epsilon, a, a^2, ...\} \tag{5.62}$$

■

Remark. This may be used to calculate the modulo of integers raised to large exponents. For example, for $2^{20} \pmod{15}$. To compute this, let the *multiplicative group* $(G, *)$ be defined over G of *order* 8 where

$$G = \{1, 2, 4, 7, 8, 11, 13, 14\} \tag{5.63}$$

And the *binary operation* $x * y := x * y \pmod{15}$.

Note that $2^{-1} = 8 \pmod{15}$ and $4^{-1} = 4 \pmod{15}$.

Since $|G| = 8$,

$$2^8 = 1 \pmod{15} \tag{5.64}$$

Then $2^{20} \pmod{15}$ can be calculated by decomposing its exponent:

$$2^{20} = 2^{2 \cdot 8 + 4} = (2^8)^2 * 2^4 = 1 * 16 = 1 \pmod{15} \tag{5.65}$$

6 Euclidean Algorithm

6.1 Euclidean Algorithm Basics

Definition 6.1.1 (Euclidean Algorithm)**.** The *Euclidean Algorithm* can be used to compute the *greatest common divisor* of two integers $a, b \in \mathbb{Z}$, denoted $\gcd(a, b)$.

Its process, given $a \geq b$ is

$$\begin{aligned}
a &= q_0 \cdot b + r_1 && (6.1)\\
b &= q_1 \cdot r_1 + r_2 && (6.2)\\
r_1 &= q_2 \cdot r_2 + r_3 && (6.3)\\
&\vdots\\
r_{k-1} &= q_k \cdot r_k + r_{k+1} && (6.4)\\
r_k &= q_{k+1} \cdot r_{k+1} + r_{k+2} && (6.5)\\
&\vdots\\
r_{n-1} &= q_n \cdot r_n + r_{n+1} && (6.6)\\
r_n &= q_{n+1} \cdot r_{n+1} + 0 && (6.7)
\end{aligned}$$

Such that $\gcd(a, b) := r_{n+1}$.

6.2 gcd(a, b) as a Linear Combination of a and b

Proposition 6.2.1. Given $a, b \in \mathbb{Z}$, then for some $k_1, k_2 \in \mathbb{Z}$, and some $d \in \mathbb{Z}$,

$$d = \gcd(a, b) = k_1 a + k_2 b \tag{6.8}$$

Remark. To solve the congruence $4 * x = 1 \pmod{17}$ for x, find x in the form of $x = 4^{-1} \pmod{17}$.

For instance, to find $\gcd(34, 13)$ as a linear combination $k_1 a + k_2 b$, then first use the Euclidean algorithm to find $\gcd(34, 13)$:

$$\begin{array}{r|r}
34 = 2 \cdot 13 + 8 & a = 2 \cdot b + r_1 \\
13 = 8 + 5 & b = r_1 + r_2 \\
8 = 5 + 3 & r_1 = r_2 + r_3 \\
5 = 3 + 2 & r_2 = r_3 + r_4 \\
3 = 2 + \boxed{1} & r_3 = r_4 + \boxed{r_5} \\
2 = 2 \cdot 1 + 0 & r_4 = 2 \cdot r_5 + 0
\end{array} \tag{6.9}$$

Note that

$$\begin{aligned} a &= 2 \cdot b + r_1 \\ b &= r_1 + r_2 \\ r_1 &= r_2 + r_3 \\ r_2 &= r_3 + r_4 \\ r_3 &= r_4 + \boxed{r_5} \\ r_4 &= 2 \cdot r_5 + 0 \end{aligned} \quad \Leftrightarrow \quad \begin{aligned} r_1 &= a - 2b \\ r_2 &= b - r_1 \\ r_3 &= r_1 - r_2 \\ r_4 &= r_2 + r_3 \\ \boxed{r_5} &= r_3 - r_4 \end{aligned} \tag{6.10}$$

It is now possible to *collect* k_1 and k_2 in a bottom-up manner:

$$\boxed{r_5} = r_3 - r_4 \tag{6.11}$$
$$= r_3 - (r_2 - r_3) \tag{6.12}$$
$$= -r_2 + 2r_3 \tag{6.13}$$
$$= -r_2 - 2(r_1 - r_2) \tag{6.14}$$
$$= 2r_1 - 3r_2 \tag{6.15}$$
$$= 2r_1 - 3(b - r_1) \tag{6.16}$$
$$= -3b + 5r_1 \tag{6.17}$$
$$= -3b + 5(a - 2b) \tag{6.18}$$
$$= 5a - 13b \tag{6.19}$$

Hence $\gcd(34, 13) = gcd(a, b) = 5a - 13b$ for some $a, b \in \mathbb{Z}$. One may verify this by checking that

$$5 \cdot 34 - 13 \cdot 13 = 170 - 169 = 1 \tag{6.20}$$

6.3 Problems for Integers Modulo m

- $\boxed{a * x = b \pmod{m} \Leftrightarrow x = a^{-1} * b \pmod{m}}$
  For $\mathbb{R}^+$, given some $a, b, m \in \mathbb{Z}$

$$a * x = b \pmod{m} \tag{6.21}$$
$$\Leftrightarrow a^{-1} * a * x = a^{-1} * b \pmod{m} \tag{6.22}$$
$$\Leftrightarrow x = a^{-1} * b \pmod{m} \tag{6.23}$$

- $\boxed{a^n \pmod{m} \Leftrightarrow (a \cdot a^2 \cdot a^4 \cdot a^8, \dots) \pmod{m}}$
  That is, to decompose the exponent into smaller equivalences.
- $\boxed{x^a = b \pmod{m} \Leftrightarrow x = b^{a^{-1}} \pmod{m}}$

For $\mathbb{R}^+$, given some $a, b, m \in \mathbb{Z}$

$$x^a = b \pmod{m} \tag{6.24}$$
$$x = \sqrt[a]{b} \pmod{m} \tag{6.25}$$
$$x = b^{\frac{1}{a}} \pmod{m} \tag{6.26}$$
$$x = b^{a^{-1}} \pmod{m} \tag{6.27}$$

- For the discrete logarithm: $\boxed{a^x = b \pmod{m} \Leftrightarrow x = \log_a b \pmod{m}}$

6.4 Multiplicative Group of Integers Modulo m

Definition 6.4.1 (Relatively Prime, Coprime)**.** Two integers $a, b \in \mathbb{Z}$ are *relatively prime* (or *coprime*) if

$$\gcd(a, b) = 1 \tag{6.28}$$

Definition 6.4.2 (Multiplicative Group of mod m)**.** Given $m \in \mathbb{Z}$, then

$$G_m^{\times} := \{a \in \mathbb{Z} \mid (1 \leq a < m) \wedge (\gcd(a, b) = 1)\} \tag{6.29}$$

Forms a group $(G_m^{\times}, * \pmod{m})$ under *multiplicative modulo m*.

1. **Closure**

$$\forall\, a, b, m \in G_m^{\times} \colon (\gcd(a, m) = 1) \wedge (\gcd(b, m) = 1) \to (\gcd(a * b, m) = 1) \tag{6.30}$$

2. **Associativity**

   Given by multiplication on integers modulo m.

3. **Neutral Element**

$$\forall\, m \in G_m^{\times} \colon \gcd(1, m) = 1 \tag{6.31}$$

4. **Invertibility**

$$\forall\, a \in G_m^{\times} \colon \exists\, y \in G_m^{\times} \colon a * y = 1 \pmod{m} \tag{6.32}$$

   For which the inverse element y is denoted a^{-1}, giving

$$\forall\, a \in G_m^{\times} \colon a * a^{-1} = 1 \pmod{m} \tag{6.33}$$

Theorem 6.4.1 (Euler Totient Function)**.** Given the *multiplicative modulo group* $G_m^{\times}$, then

$$\phi(m) := |G_m^{\times}| \tag{6.34}$$

Theorem 6.4.2. If p is a prime and $k \geq 1$ then

$$\phi(p^k) \equiv p^{k-1}(p-1) \tag{6.35}$$

Theorem 6.4.3. If $a, b \in \mathbb{Z}$ and a, b are *relatively prime* (i.e. $\gcd(a, b) = 1$) then

$$\phi(ab) \equiv \phi(a)\phi(b) \tag{6.36}$$

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