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1 Fundamentals

1.1 Sets

1.1.1 Definition

A **set** can be considered as a collection of elements; more intuitively, you can consider something a set if you can determine whether a given object belongs to it. Typically sets are defined as $A = \{1, 2, \dots\}$, by a property $A = \{x \mid x \% 2 = 0\}$, or with an appropriate verbal description.

1.1.2 Set operations

There are a number of ways to “combine” sets:

- **Union:** $A \cup B = \{x \mid x \in A \text{ or } x \in B\}$
- **Intersection:** $A \cap B = \{x \mid x \in A \text{ and } x \in B\}$
- **Difference:** $A \setminus B = \{x \mid x \in A \text{ and } x \notin B\}$

Lemma 1.1.1. $A = (A \setminus B) \cup (A \cap B)$

Proof. To prove set equivalencies, we must prove that both $\text{RHS} \subseteq \text{LHS}$ and $\text{LHS} \subseteq \text{RHS}$; meaning, the LHS and RHS are subsets of each other, and are thus equal.

First, to prove $\text{LHS} \subseteq \text{RHS}$, let $a \in A$. If $a \notin B$, then $a \in A \setminus B$, and $a \in \text{RHS}$. Else, if $a \in B$, then $a \in A \cap B$ and $a \in \text{RHS}$. Thus, $\text{LHS} \subseteq \text{RHS}$.

Next, to prove $\text{RHS} \subseteq \text{LHS}$, let $a \in \text{RHS}$. If $a \in A \setminus B$, then $a \in A = \text{LHS}$. Else, $a \in A \cap B$, and thus $a \in A = \text{LHS}$. Thus, $\text{RHS} \subseteq \text{LHS}$. Since $\text{LHS} \subseteq \text{RHS}$ and $\text{RHS} \subseteq \text{LHS}$, $\text{LHS} = \text{RHS}$. ■

1.1.3 Indexed sets

Let I be a set. If for every $i \in I$, we have a set B_i , we say that we have a *collection* of sets B_i indexed by I . We write $\{B_i : i \in I\}$.

Example 1.1.1. Let $I = \{1, 2, 3\}$, and $B_i = \{1, 2, 3, 4\} \setminus \{i\}$ (B_i is the set of all numbers from 1 to 4, excluding i), for $i \in I$. We thus have $B_1 = \{2, 3, 4\}$ (etc.).

This concept of indexing allows us to introduce repeated unions/intersections. For instance, we can write

$$\bigcup_{i \in I} B_i = B_1 \cup B_2 \cup B_3 = \{1, 2, 3, 4\}.$$

Similarly,

$$\bigcap_{i \in I} B_i = \{4\}.$$
¹

¹You can somewhat consider these “large” unions/intersections as analogous to summations Σ and products Π .

Example 1.1.2. Let $I = \mathbb{R}$, and $B_i = [i, \infty] = \{r \in \mathbb{R} : r \geq i\}$. Then, $\bigcup_{i \in \mathbb{R}} B_i = \mathbb{R}$ and $\bigcap_{i \in \mathbb{R}} B_i = \emptyset$.

1.1.4 Cartesian product

Let A_1, A_2, \dots, A_n be sets. We define the **Cartesian product**

$$A_1 \times A_2 \times \cdots \times A_n = \{(x_1, x_2, \dots, x_n) : x_i \in A_i, \text{ for } 1 \leq i \leq n\}.$$

For instance,

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

Example 1.1.3. Let $A = B = \mathbb{R}$. $A \times B = \{(x, y) : x \in \mathbb{R}, y \in \mathbb{R}\} = \mathbb{R}^2$ is the set of all points in the Cartesian plane.

We can also define Cartesian products over an index set. Let I be an index set, with A_i for all $i \in I$. Then, we can write

$$\prod_{i \in I} A_i = \{(a_i)_{i \in I} : a_i \in A_i\}$$

Example 1.1.4.

$$I = \mathbb{N}, A_0 = \{0, 1, 2, \dots\}, A_1 = \{1, 2, 3, \dots\}, \dots, A_i = \{i, i+1, i+2, \dots\}$$

$$Y := \prod_{i \in I} A_i = \{(a_0, a_1, a_2, \dots) : a_i \in \mathbb{N}, a_i \geq i\}$$

We can say that a particular vector $(b_0, b_1, \dots) \in Y$ if for each b_i , $b_i \geq i$ (and $b_i \in \mathbb{N}$, of course).

In other words, a particular item of the vector must be greater than or equal to its index. Thus, we can say

$$(0, 1, 2, 3, \dots) \in Y$$

while

$$(2, 2, 2, 2, \dots) \notin Y$$

since $a_3 = 2 \implies i = 3$, and $2 \not\geq 3$.

1.2 Methods of Proof**1.2.1 Proving equality via two inequalities**

In short, say $x, y \in \mathbb{R}$. $x = y \iff x \leq y$ and $y \leq x$. Similarly, in the context of sets, we can say that, for two sets X, Y , $X = Y \iff X \subseteq Y$ and $Y \subseteq X$.

1.2.2 Contradiction (bwoc)

Given a statement P , we can prove P true by assuming P false ($\equiv \neg P$), then arriving to a contradiction (this contradiction is often a violated axiom or basic rule of the system at hand.)

Example 1.2.1. Show that there are no solutions to $x^2 - y^2 = 1$ in the positive integers.

Proof (bwoc). Assume there are, so $x, y \in \mathbb{Z}_+$.² We can then write

$$1 = x^2 - y^2 = (x - y)(x + y).$$

$x - y$ and $x + y$ must be integers, and so we have two cases, $\begin{cases} x - y = 1 \\ x + y = 1 \end{cases}$ and

$\begin{cases} x - y = -1 \\ x + y = -1 \end{cases}$. In either case, y must be zero, contradicting our initial assumption and thus proving the statement. ■

² \mathbb{Z}_+ is used to denote positive integers; similarly, \mathbb{Z}_- denotes negative integers.

1.2.3 Proving the contrapositive

Logically, $A \implies B \iff \neg B \implies \neg A^3$.

Example 1.2.2. Let X, Y be sets. Prove $X = X \setminus Y \implies X \cap Y = \emptyset$.

Proof. Prove contrapositive: $X \cap Y \neq \emptyset \implies X \neq X \setminus Y$. $X \cap Y \neq \emptyset \implies \exists t \in X \cap Y \implies t \in X$ and $t \in Y$, thus $t \notin X \setminus Y$, but $t \in X$, so $X \neq X \setminus Y$. ■

³“I am hungry therefore I will eat” \iff “I will *not* eat therefore I am *not* hungry.” Notice too that B need not imply A (“I will eat therefore I am hungry”). If $A \implies B \iff B \implies A$, $A \equiv B$

1.2.4 Induction

Axiom 1.2.1 (Well-Ordering Principle). Every $S \subseteq \mathbb{N}$, where $S \neq \emptyset$, has a minimal element, ie $\exists a \in S$ s.t. $\forall b \in S, a \leq b$.

Theorem 1.2.1 (Principle of Induction). Let $n_0 \in \mathbb{N}$. Say that for every $n \in \mathbb{Z}, n \geq n_0$, we are given a statement P_n . Assume

(a) P_{n_0} is true

(b) if P_n is true, then P_{n+1} is true

then P_n is true for all $n \geq n_0$.

Proof (bwoc). Assume not.⁴ Then, we define $S = \{n \in \mathbb{N} : n \geq n_0, P_n \text{ false}\}$. By the Well-Ordering Principle, there exists a minimal element $a \in S$. By definition, $a \geq n_0$, and as P_{n_0} is taken to be true, then $a > n_0$ since $n_0 \notin S$. Thus, $a - 1 \notin S$, as a is the minimal element of S , and therefore P_{a-1} is true. However, by (b), this implies P_a is also true, and thus $a \notin P$, contradicting our initial assumption. ■

⁴note that (a) and (b) of the Principle of Induction are still taken to be true; it is simply the conclusion that is assumed to be false.

1.2.5 Pigeonhole principle

Axiom 1.2.2. If there are more pigeons than pigeonholes, then at least one pigeonhole must contain more than one pigeon.⁵

⁵Alternatively, you can consider fractional pigeons (though a little gruesome); given $n + 1$ pigeons and n holes, each hole will contain, on average, $1 + \frac{1}{n}$ pigeons.

Example 1.2.3. Consider $n_1, \dots, n_6 \in \mathbb{N}$. There exist at least two of these n 's s.t. $n_i - n_j$ is evenly divisible by 5.

Proof. Let us rewrite each n_i as $n_i = 5k_i + r_i$, where $k_i, r_i \in \mathbb{N}$, k_i is the quotient, and r_i is the residual. $r_i \in \{0, 1, 2, 3, 4\}$ (the only possible remainders when a number is divided by 5), and so there are 5 possible values of r_i , but 6 different n_i . Thus, two n_i must have the same r_i , and we can write:

$$\begin{aligned} n_i &= 5k_i + r; n_j = 5k_j + r \\ n_i - n_j &= (5k_i + r) - (5k_j + r) \\ &= 5(k_i - k_j) \end{aligned}$$

$(k_i - k_j) \in \mathbb{Z}$, and so $n_i - n_j$ is evenly divisible by 5. ■

1.3 Functions

Definition 1.3.1 (Function). Given 2 sets A, B , a function $f : A \rightarrow B$ is a rule such that $\forall a \in A, \exists! f(a) \in B$, where $\exists!$ denotes “there exists a unique”.

Definition 1.3.2 (Graph). Given a function $f : A \rightarrow B$, a graph $\Gamma_f = \{(a, f(a)) : a \in A\} \subseteq A \times B$. We can say that, $\forall a \in A, \exists! b \in B$ such that $(a, b) \in \Gamma_f$.

Example 1.3.1. Consider the Cartesian plane, denoted \mathbb{R}^2 . It is simply a graph Γ_f where $f : \mathbb{R} \rightarrow \mathbb{R}$ is the identity function, $f(x) = x$.

Definition 1.3.3 (Injective). A function is an injection iff $\forall a_1, a_2 \in A, f(a_1) = f(a_2) \implies a_1 = a_2$.

Definition 1.3.4 (Surjective). A function is a surjection iff $\forall b \in B, \exists a \in A$ such that $f(a) = b$. In other words, every element of B is mapped to by at least one element of A ; you can pick any element in the range and it will have a preimage.

Definition 1.3.5 (Bijective). Both.

Definition 1.3.6 (Fibre). The fibre of some $y \in Y$ is $f^{-1}(y) = f^{-1}(y)$

Definition 1.3.7 (Cardinality). *The cardinality of a set A , denoted $|A|$, is the number of elements in A , if A is finite, or a more abstract notion of size if A is infinite.*

We say that two sets A, B have the same cardinality ($|A| = |B|$) if \exists a bijection $f : A \rightarrow B$.⁶ This necessitates the question, however: if two sets are not equal in cardinality, how do we compare their sizes?

We write

$$|A| \leq |B| \iff \exists f : A \rightarrow B \text{ where } f \text{ is injective}$$

and

$$|A| \geq |B| \iff \exists f : A \rightarrow B \text{ where } f \text{ is surjective.}^7$$

Note that $|B| \leq |A|$ if either $A = \emptyset$ or, as above, $\exists f : B \rightarrow A$ surjective.

Definition 1.3.8 (Composition). *Given two functions $f : A \rightarrow B, g : B \rightarrow C$, the composition is the function $g \circ f : A \rightarrow C$*

Proposition 1.3.1. *If $|A| = |B|$ and $|B| = |C|$ then $|A| = |C|$*

Proof. $\exists f : A \rightarrow B$ bijective, and $\exists g : B \rightarrow C$ bijective. We desire to show that $\exists h : A \rightarrow C$ that is bijective. We can write $h = g \circ f$, where $h(a) = g(f(a))$.

To show that h bijective:

- **injective:** Suppose $h(a_1) = h(a_2)$, then $g(f(a_1)) = g(f(a_2))$, and since g is injective, $f(a_1) = f(a_2)$. Since f is injective, $a_1 = a_2$, and thus h is injective.
- **surjective:** Let $c \in C$. Since g is surjective, $\exists b \in B$ such that $g(b) = c$. Since f is surjective, $\exists a \in A$ such that $f(a) = b$. Thus, $h(a) = g(f(a)) = g(b) = c$, and thus h is surjective.

Thus, h is bijective, and $|A| = |C|$. ■

Lemma 1.3.1. *If $g \circ f$ injective, f injective. If $g \circ f$ surjective, g surjective.*

Definition 1.3.9 (Image). *The image of a function $f : A \rightarrow B$ is the set $Im(f) = \{f(a) : a \in A\}$, ie the set of all elements in B that are mapped to by f . Note that $Im(f) \subseteq B$, and $Im(f) = B$ if f is surjective.*

Proposition 1.3.2. $|A| \leq |B|$ if $|B| \geq |A|$

⁶Consider this in the finite case: a bijection indicates that all elements in the domain map uniquely to a single element in the range, and the range is completely “covered” by the function.

⁷Consider this intuitively; if your domain is smaller than your range, then you will “run out” of things to map from the domain to the range before you “run out” of things in the range, hence, you have an injection. Similarly, if your domain is larger than your range, then you will have “leftover” elements in the domain (that will map to “already mapped to” elements in the range), hence, you have a surjection.

Proof. If $A = \emptyset$, $|B| \geq |A|$ clearly.

If $A \neq \emptyset$, we are given $\exists f : A \rightarrow B$ injective. Let us choose some $a_0 \in A$. We define $g : B \rightarrow A$ as

$$g(b) = \begin{cases} a_0 & b \notin \text{Im}(f) \\ a & b = f(a) \in \text{Im}(f)^8 \end{cases}$$

Note that $g(f(a)) = g(b) = a$, so g is surjective. Thus, $|B| \geq |A|$. ■

⁸Note that a is unique in A , as f is injective.

Proposition 1.3.3. $|B| \geq |A|$ if $|A| \leq |B|$

Theorem 1.3.1 (Cantor-Bernstein Theorem). $|A| \leq |B|$ and $|B| \leq |A| \implies |A| = |B|$.⁹

Equivalently, if $\exists f : A \rightarrow B$ injective and $\exists g : B \rightarrow A$ injective, then $\exists h : A \rightarrow B$ bijective.

⁹It is often very difficult to define an arbitrary bijective function between two sets in order to prove their cardinality is equal. The Cantor-Bernstein Theorem allows us to prove that two sets have the same cardinality by proving that there exists an injection from A to B and an injection from B to A , which is typically far easier.

Proposition 1.3.4. If $|A_1| = |A_2|$ and $|B_1| = |B_2|$ then $|A_1 \times B_1| = |A_2 \times B_2|$.

Proof. The first two statements define bijections $f : A_1 \rightarrow A_2$ and $g : B_1 \rightarrow B_2$, and we desire to have $f \times g : A_1 \times B_1 \rightarrow A_2 \times B_2$. We define $f \times g(a_1, b_1) := (f(a_1), g(b_1))$. We must show that $f \times g$ is bijective. ■

Example 1.3.2. Consider A as the set of all points in the unit circle centered at $(0, 0)$ in \mathbb{R}^2 , and B as the set of all points in the square of side length 2 centered at $(0, 0)$ in \mathbb{R}^2 (ie, the circle is inscribed in the square). We wish to prove that $|A| = |B|$.

Proof. Let $f : A \rightarrow B$, $f(x) = x$. f is injective, and thus $|A| \leq |B|$. Let $g : A \rightarrow B$,

$$g(x) = \begin{cases} 0; \sqrt{2}x \notin B \\ \sqrt{2}x; \sqrt{2}x \in B \end{cases} . \text{ In simpler terms, consider this as multiplying points of } A \text{ by}$$

$\sqrt{2}$; any point in this new “expanded” circle that lies within B maps to itself, and any that lies outside maps to 0. This is thus a surjection, and thus $|B| \leq |A|$. By the Cantor-Bernstein Theorem, $|A| = |B|$. ■

Proposition 1.3.5. $A = \{0, 1, 4, 9, \dots\}$. $|A| = |\mathbb{N}|$.

Proof. Define $f : \mathbb{N} \rightarrow A$, $f(n) = n^2$. This is clearly injective¹⁰, and thus $|A| \leq |\mathbb{N}|$. ■

¹⁰Notice that f is only injective if we restrict the domain to \mathbb{N} ; if we were to consider \mathbb{Z} , for instance, $f(-1) = f(1) = 1$.

Proposition 1.3.6. $B = \{p \in \mathbb{N} : p \text{ prime}\}$ is infinite ($|B| = |\mathbb{N}|$).

Proof (Euclid). Let $f : \mathbb{N} \rightarrow B$, $f(n) =$ the n th prime. This is clearly bijective, and is an example of enumerating a set. ■

Definition 1.3.10 (Countable/enumerable). A set A is countable if $|A| = |\mathbb{N}|$, or A is finite.

If A is finite of size n , \exists a bijection $f : \{0, 1, 2, \dots, n-1\} \rightarrow A$.

If A is infinite, \exists a bijection $f : \mathbb{N} \rightarrow A$.

Proposition 1.3.7. $|\mathbb{N}| = |\mathbb{Z}|$

Proof. We aim to find a bijection $f : \mathbb{Z} \rightarrow \mathbb{N}$, ie one that maps integers to natural numbers. Consider the function

$$f(x) = \begin{cases} 2x & x \geq 0 \\ -2x - 1 & x < 0 \end{cases}.$$

This function is an injection because if $f(x_1) = f(x_2)$, then $x_1 = x_2$ (positive case: $2x_1 = 2x_2 \implies x_1 = x_2$, negative case: $-2x_1 - 1 = -2x_2 - 1 \implies x_1 = x_2$, and $2x_1 \neq -2x_2 - 1$ for any integer). It is also a surjection (there is no natural number that cannot be mapped to by an integer). Thus, the function is a bijection and $|\mathbb{N}| = |\mathbb{Z}|$.¹¹ ■

¹¹Note what would happen if f was defined as $-2x$ for $x < 0$; then, f would not be surjective (eg, $f(-1) = 2 = f(1)$.)

Proposition 1.3.8. $|\mathbb{N}| = |\mathbb{N} \times \mathbb{N}|$

Remark 1.3.1. It is possible to construct a bijective $f : \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{N}$; see assignment 1.

Proof. Let $f : \mathbb{N} \rightarrow \mathbb{N} \times \mathbb{N}$, $f(n) = (n, 0)$, clearly an injection ($\implies |\mathbb{N}| \leq |\mathbb{N} \times \mathbb{N}|$)¹². The function $g(m, n) = 2^n 3^m$ is also injective, and thus $|\mathbb{N}| = |\mathbb{N} \times \mathbb{N}|$. ■

¹²Note that this function is *not* surjective!

Corollary 1.3.1. $|\mathbb{Z}| = |\mathbb{Z} \times \mathbb{Z}|$

Proof. Consider $h : \mathbb{N} \rightarrow \mathbb{N} \times \mathbb{N}$, a bijection¹³, and $f : \mathbb{N} \rightarrow \mathbb{Z}$. Let $g = (f, f) : \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{Z} \times \mathbb{Z}$. The composition $g \circ h \circ f^{-1} : \mathbb{Z} \rightarrow \mathbb{N} \rightarrow \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{Z} \times \mathbb{Z}$ is also a bijection, and thus $|\mathbb{Z}| = |\mathbb{Z} \times \mathbb{Z}|$. ■

¹³Which must exist by the proof of the previous proposition.

Example 1.3.3. Show that $|\mathbb{N}| = |\mathbb{Q}|$.

Proof. First, we find an injection $\mathbb{Q} \rightarrow \mathbb{N}$. Let $f : \mathbb{Q} \rightarrow \mathbb{Z} \times \mathbb{Z}$, $f(n) = (p, q)$ where $\frac{p}{q} = n$ (by definition of \mathbb{Q}). Using the same function definitions as in Corollary 1.3.1, the composition $h^{-1} \circ g^{-1} \circ f : \mathbb{Q} \rightarrow \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{N} \times \mathbb{N} \rightarrow \mathbb{N}$. This is a composition of injections, and is thus an injection itself, and thus $|\mathbb{Q}| \leq |\mathbb{N}|$. The identity function $1 : \mathbb{N} \rightarrow \mathbb{Q}$, $1(n) = n$ is clearly an injection as well as all naturals are rationals, and thus $|\mathbb{N}| \leq |\mathbb{Q}|$. By the Cantor-Bernstein Theorem, $|\mathbb{N}| = |\mathbb{Q}|$. ■

Definition 1.3.11. We say $|A| < |B|$ if $|A| \leq |B|$ but $|A| \neq |B|$, ie $\exists f : A \rightarrow B$ is injective, but no such bijective.

Remark 1.3.2. We denote an injective function as $\mathbb{N} \hookrightarrow \mathbb{Z}$, and a surjective function as $\mathbb{Z} \twoheadrightarrow \mathbb{N}$. We say that a particular element n maps to some other element n' by $n \mapsto n'$

Theorem 1.3.2 (Cantor). $|\mathbb{N}| < |\mathbb{R}|$

Proof (Cantor's Diagonal Argument). We clearly have an injection $\mathbb{N} \hookrightarrow \mathbb{R}, n \mapsto n$, thus $|\mathbb{N}| \leq |\mathbb{R}|$.

Now, suppose $|\mathbb{N}| = |\mathbb{R}|$. Then, we can enumerate the real numbers as a_0, a_1, \dots with signs ϵ_i . We denote the decimal expansion of each number as¹⁴

$$a_0 = \epsilon_0 0.a_{00}a_{01}a_{02} \dots$$

$$a_1 = \epsilon_1 0.a_{10}a_{11}a_{12} \dots$$

$$a_2 = \epsilon_2 0.a_{20}a_{21}a_{22} \dots$$

$$\vdots$$

Consider the number $0.e_0e_1e_2\dots$, where $e_i = \begin{cases} 3 & a_{ii} \neq 3 \\ 4 & a_{ii} = 3 \end{cases}$. This number is different than any given a_i at the $i + 1$ -th decimal place, and is thus not in the enumeration, contradicting our initial assumption. ■

Remark 1.3.3 (Continuum Hypothesis). *Cantor claimed that there's no set $|A|$ such that $|\mathbb{N}| < |A| < |\mathbb{R}|$. It has been proven today that this is “undecidable”.*

¹⁴We make the clarification that, despite the fact that $1.000\dots = 0.999\dots$, we will take the “infinite zeroes” interpretation, and thus every real number has a unique decimal expansion. This is an important, if subtle, distinction.

Definition 1.3.12 (Algebra on Cardinalities). *If α, β are cardinalities $\alpha = |A|, \beta = |B|$, Cantor defined:*

$$\alpha + \beta = |A \sqcup B| \text{ (disjoint union)}$$

$$\alpha \cdot \beta = |A \times B|$$

$$\alpha^\beta = |B^A| \text{ (set of all functions from } A \text{ to } B)$$

1.4 Relations

Definition 1.4.1 (Relation). *A relation on a set A is a subset $S \subseteq A \times A (= \{(x, y) : x, y \in A\})$.*

We say that x is related to y if $(x, y) \in S$, where we denote $x \sim y$.

Conversely, if we are given $x \sim y$, we can define an $S = \{(x, y) : x \sim y\}$.

Example 1.4.1. Following are examples of relations on A .

- 1) Let $S = A \times A$; any $x \sim$ any y because $(x, y) \in S$ for all (x, y) .
- 2) Let $S = \emptyset$; no $x \sim$ any y (even to itself).
- 3) $S = \text{diag.} = \{(a, a) : a \in A\}$; $x \sim x \forall x$, but $x \not\sim y$ if $y \neq x$.
- 4) $A = [0, 1](\in \mathbb{R})$. Say $x \sim y$ if $x \leq y$. Thus, $S = \{(x, y) : x \leq y\}$ (the diagonal, and everything above).
- 5) $A = \mathbb{Z}$, $x \sim y$ if $5|(x - y)$, ie x and y have same residue mod 5.¹⁵

¹⁵Where $a|b$ denotes that b divides a .

Definition 1.4.2 (Reflexive). A relation is reflexive if for any $x \in A$, $x \sim x$.

This includes examples 1), 2) (iff A is empty), 3), 4), and 5) above.

Definition 1.4.3 (Symmetric). A relation is symmetric if $x \sim y \implies y \sim x$.

This includes 1), 2), 3), and 5) above.

Definition 1.4.4 (Transitive). A relation is transitive if $x \sim y$ and $y \sim z$ implies $x \sim z$.

This includes 1), 2), 3), 4), and 5) above.

Definition 1.4.5 (Partial Order). A partial order on a set A is a relation $x \sim y$ s.t.

1. $x \sim x$ (reflexive)
2. if $x \sim y$ and $y \sim x$, $x = y$ (antisymmetric)
3. $x \sim y$ and $y \sim z \implies x \sim z$ (transitive)

It is common to use \leq in place of \sim for partial orders.

We call a set on which a partial order exists a partially ordered set (poset).

This is called *partial*, as it is possible that for some $x, y \in A$ we have $x \not\sim y$ and $y \not\sim x$, ie x, y are not comparable. A partial order is called *linear/total* if for every $x, y \in A$, either $x \leq y$ or $y \leq x$, eg., $A = [0, 1], \mathbb{R}, \mathbb{Z}, \dots$, with $x \leq y$. Consider the above examples:

- 1) is not total, if A has at least two element, because $\exists x \neq y$ but both $x \sim y$ and $y \sim x$, and thus not antisymmetric.
- 3) yes
- 5) no, as this is symmetric, since $5|(x - y) \implies 5|(y - x)$, and thus $x \sim y, y \sim x \not\implies y = x$

Example 1.4.2. Let¹⁶ $A = \mathbb{N}_+ = \{1, 2, 3, 4, \dots\}$, and define $a \sim b$ if $a|b$. We verify:

- $a \sim a$ (since $a|a$)
- $a \sim b, b \sim a \implies a = b$, since in \mathbb{N}_+ , $a|b \implies a \leq b$, and we thus have $a \leq b$ and $b \leq a$, and thus $a = b$.
- suppose $a \sim b$ and $b \sim c$, then $a|b$ and $b|c$. We can write $b = a \cdot m$ and $c = b \cdot n$ for $n, m \in \mathbb{N}$. This means that $c = bn = amn = a(mn)$, which means that $a|c$, so $a \sim c$.

Thus, A is a poset. Note that this is not a linear order, as $2 \not\sim 3$, and $3 \not\sim 2$ (not all a, b are comparable).

¹⁶Try this with integers, see where it fails

Definition 1.4.6 (Equivalence Relation). We aim to, abstractly, define some \sim such that if $x \sim x, x \sim y$, then $y \sim x$, and if $x \sim y, y \sim z$, then $x \sim z$.

Specifically, an equivalence relation \sim on the set A is a relation $x \sim y$ s.t. it is

- reflexive;
- symmetric;
- transitive.¹⁷

¹⁷Note that, generally, equivalence and order relations are very different.

Example 1.4.3. 1. Let $n \geq 1$ be an integer. A permutation σ of n elements is a bijection $\sigma : \{1, 2, \dots, n\} \rightarrow \{1, 2, \dots, n\}$. Their number is $n!$, ie there are $n!$ permutations of n elements. The collection of all permutations of n elements is denoted S_n , which we call the “symmetric group” on n elements. We aim to define an equivalence relation on S_n .

Let us define $\sigma \sim \tau$ if $\sigma(1) = \tau(1)$. We verify that this is an equivalence relation:

- (a) $\sigma \sim \sigma, \sigma(1) = \sigma(1)$, so yes
- (b) $\sigma \sim \tau$ means $\sigma(1) = \tau(1)$, so yes
- (c) $\sigma \sim \tau, \tau \sim \rho, \sigma(1) = \tau(1), \tau(1) = \rho(1)$, so $\sigma(1) = \rho(1)$, hence $\sigma \sim \rho$, so yes.

Thus, \sim is an equivalence relation on S_n .

Example 1.4.4. Define a relation on \mathbb{Z} by saying that $x \sim y$ if $x - y$ even, ie $2|(x - y)$. This is reflexive, as $2|(x - x) = 0, x \sim x$, symmetric, since $(y - x) = -(x - y)$, and transitive $x - z = \underbrace{(x - y)}_{\text{even}} + \underbrace{(y - z)}_{\text{even}} \implies x \sim z$.

Example 1.4.5. We say two sets $A \sim B$ if $|A| = |B|$. $1_A = \text{Id} : A \rightarrow A, a \mapsto a$ shows $A \sim A$. $A \sim B \implies \exists f : A \rightarrow B$ bijective, then $f^{-1} : B \rightarrow A$ also bijective so $B \sim A$. If $A \sim B, B \sim A$ then $A \sim C$ (since $|A| = |B|, |B| = |C| \implies |A| = |C|$ as proved earlier).

Definition 1.4.7 (Disjoint Union). Let S be a set, and $S_i, i \in I, \subseteq S$. S is the disjoint union of the S_i 's if $S = \bigcup_{i \in I} S_i$, and for any $i \neq j, S_i \cap S_j = \emptyset$ ¹⁸; we denote $S = \coprod_{i \in I} S_i$. We can say that $\{S_i\}$ for a partition of S .

¹⁸ie, no S_i 's share elements; think of "partitioning" S such that no subsets overlap.

Example 1.4.6. Let $S = \{1, 2\}$. Partitions are $\{1, 2\}$, and $\{1\}, \{2\}$.

Let $S = \{1, 2, 3\}$. Partitions are $\{1, 2, 3\}, \{1\}, \{2\}, \{3\}, \dots$

Definition 1.4.8 (Equivalence Class). Given an equivalence relation \sim of A and some $x \in A$, the equivalence class of x is $[x] = \{y \in A : x \sim y\} \subseteq S$.

Theorem 1.4.1. The following theorems are related to equivalence classes:

- (1) the equivalence classes of A form a partition of A ;
- (2) conversely, any partition of A defines an equivalence relation on A given by the partition.

Lemma 1.4.1. Let X be an equivalence class; $a \in X$, then $X = [a]$.

Proof of Lemma 1.4.1. If X is an equivalence class, $X = [x]$ for some $x \in A$, by definition. Let $a \in X$. If $b \in [a]$ then $b \sim a$ and as $a \in [x]$ then $a \sim x \implies b \sim x \implies b \in [x] \implies [a] \subseteq [x]$.

Otoh, $a \sim x \implies x \in [a]$, so $[x] \subseteq [a]$, and thus $[x] = [a]$. ■

Proof of Theorem 1.4.1. We prove (1), (2) individually.

(1) We aim to show that if the equivalence classes are $\{X_i\}_{i \in I}$ then $A = \coprod_{i \in I} X_i$. We say the following:

1. Every $a \in A$ is in some equivalence class ($a \in [a]$).
2. Two different equivalence classes are disjoint \iff if X, Y equiv. classes s.t. $X \cap Y \neq \emptyset$ then $X = Y$.¹⁹

Let $a \in X \cap Y \xrightarrow{\text{lemma}} [a] = X, [a] = Y \implies X = Y$.

Here, consider the examples above;

- Example 1.4.3; S_n : there are n equiv classes $X_i = \{\sigma \in S_n : \sigma(1) = i\}$. $S_n = X_1 \sqcup X_2 \sqcup \dots X_n$. $\sigma \in S_n$ and $\sigma(1) = i$, then $\sigma \in X_i$.

- Example 1.4.4; \mathbb{Z} : two equiv. classes; $X = \text{even integers} = [0]$, $Y = \text{odd integers} = [1]$, so $\mathbb{Z} = \text{even} \sqcup \text{odd}$
- Example 1.4.5; sets: an equivalence is a cardinality. $n := [\{1, 2, \dots, n\}] = \text{all sets with } n \text{ elements}$. Similarly, we often write that $\aleph_0 := [\mathbb{N}] = \text{inf. countable sets} = \text{sets un bijection with } \mathbb{N}$, and $2^{\aleph_0} := [\mathbb{R}]$.

(2) We are given a partition $A = \sqcup_{i \in I} X_i$. We say $x \sim y$ if $\exists i \in I$ s.t. x and y belong to X_i (noting that such an i is unique if it exists, by definition of an equivalence class).

- $x \sim x$, clearly, since $x \in X_i \implies x \in X_i$
- $x \sim y \implies y \sim x$, by similar logic
- $x \sim y, y \sim z$ means that x and y in some same X_i , and y and z in some same X_j . So, $y \in X_i \cap X_j$, but we are working with a partition so $X_i = X_j$, so $x \sim z$.

Thus, \sim is an equivalence relation.²⁰ ■

²⁰Contrapositive...

Example 1.4.7. Let $A = \text{students in this class}$. $x \sim y$ if x, y have the same birthday. The equivalence classes in this case are the dates s.t. \exists some student with that birthday.

Definition 1.4.9 (Complete set of representatives). If \sim is an equiv. relation on A , a subset $\{a_i : i \in I\} \subseteq A$ is called a complete set of representatives if the equivalence classes are $[a_i], i \in I$ with no repetitions.

You find such a subset by choosing from every equiv class one element. Considering our examples:

- For Example 1.4.3, $S_n = X_1 \sqcup \dots \sqcup X_n$, $X_i = \{\sigma : \sigma(1) = i\}$. We define

$$\sigma_i(j) = \begin{cases} i & j = 1 \\ 1 & j = i \\ j & \text{otherwise} \end{cases} = [\sigma_i]$$

(switch i, j and leave all others intact). $\{\sigma_1, \dots, \sigma_n\}$ are a complete set of representatives.

- For Example 1.4.4 (even/odd in \mathbb{Z}), a complete set of reps could be $\{0, 1\}$, ie $\mathbb{Z} = [0] \sqcup [1]$.

²⁰This whole proof/theorem can sound pretty confusing. Abstractly, and non-rigorously, consider this: we define some “notion” of equivalence. Intuitively, if a set of items in, say, A , are equivalent, then they shouldn’t be equivalent to any other items outside of that set (by our particular definition of equivalence). Thus, no “subsetting” of A into equivalence classes will cause any subset to overlap; thus, we have a partition. This works in reverse through similar logic, where we even more concretely say that the very act of begin in the same partitioning of A is to be equivalent.

1.5 Number Systems

1.5.1 Complex Numbers

Definition 1.5.1 (Complex Numbers). $\mathbb{C} = \{a + bi : a, b \in \mathbb{R}\}$. Equivalently, we can consider complex numbers as the points $(a, b) \in \mathbb{R}^2$.²¹

Given some $z = a + bi$, we can write $\operatorname{Re}(z) = a$, $\operatorname{Im}(z) = b$.

²¹We can define the function $f : \mathbb{C} \rightarrow \mathbb{R}^2$, $f(a + bi) = (a, b)$, a bijection.

Definition 1.5.2 (Algebra on Complex Numbers). Given $z_i = x_i + y_i i$, we define:

- Addition: $z_1 + z_2 = (x_1 + x_2) + (y_1 + y_2)i$. This is associative and commutative.
- Multiplication: $z_1 z_2 = (x_1 x_2 - y_1 y_2) + (x_1 y_2 + x_2 y_1)i$
- Inverse: $z \neq 0$, $\frac{1}{z} := \frac{\bar{z}}{|z|^2}$, noting that $z \cdot \frac{1}{z} = z \cdot \frac{\bar{z}}{|z|^2} = 1$

Definition 1.5.3 (Complex Conjugate). Given $z = a + bi$, the complex conjugate of z is $\bar{z} = a - bi$.

Lemma 1.5.1. The following hold for complex conjugates:²²

- (a) $\bar{\bar{z}} = z$.
- (b) $\overline{z_1 + z_2} = \bar{z}_1 + \bar{z}_2$, $\overline{z_1 \cdot z_2} = \bar{z}_1 \cdot \bar{z}_2$.
- (c) $\operatorname{Re}(z) = \frac{z + \bar{z}}{2}$, $\operatorname{Im}(z) i = \frac{z - \bar{z}}{2}$.
- (d) Given $|z| = \sqrt{a^2 + b^2}$,
 - (i) $|z|^2 = z \cdot \bar{z}$
 - (ii) $|z_1 + z_2| \leq |z_1| + |z_2|$
 - (iii) $|z_1 \cdot z_2| = |z_1| \cdot |z_2|$

Theorem 1.5.1 (Fundamental Theorem of Algebra). Any polynomial $a_n x^n + \dots + a_1 x + a_0$ for $a_i \in \mathbb{C}$, $n > 0$, $a_n \neq 0$, has a root in \mathbb{C} .

²²(a), (b), and (c) are simply algebraic rearrangements of two complex numbers. (d.i) and (d.iii) follow from similar arguments, and finally (ii) is the triangle inequality restated in terms of complex numbers.

Example 1.5.1 (Roots of Unity). Let $n \geq 1$, $n \in \mathbb{Z}$. $x^n = 1$ has n solutions in \mathbb{C} , called the roots of unity of order n . They are given as $(1, \frac{2\pi k}{n})$, $k = 0, 1, 2, \dots, n - 1$ in polar notation.

Theorem 1.5.2. Let $f(x) = a_n x^n + \cdots + a_1 x + a_0$ be a complex polynomial of degree n . Then, there are complex numbers z_1, \dots, z_n s.t.

$$f(x) = a_n \prod_{i=1}^n (x - z_i)$$

each (1) $f(z_j) = 0 \forall j = 1, \dots, n$, and (2) $f(\lambda) = 0 \implies \lambda = z_j$ for some j .

Proof (by induction). If $n = 1$, $f(x) = a_1 x + a_0 = a_1 \left(x - \frac{-a_0}{a_1} \right) = a_1 (x - z_1)$. Clearly, $f(z_1) = 0$.

$$\text{If } 0 = f(\lambda) = a_1 (\lambda - z_1)$$

NB: we claim that $s_1, s_2 \in \mathbb{C}$ and $s_1 \cdot s_2 = 0$, either $s_1 = 0$ or $s_2 = 0$. We have that $|s_1| \cdot |s_2| = |s_1 \cdot s_2| = 0$, but $|s_1|, |s_2|$ real, so $|s_1| = |s_2| = 0$. Say $|s_1| = 0$; we can say $s_1 = x + yi$, then $|s_1|^2 = 0 = x^2 + y^2 \implies x = y = 0$.²³

Assume that true for polynomials of degree $n > 0$ and prove for $n + 1$; let f be a polynomial of degree $n + 1$, $f(x) = a_{n+1} x^{n+1} + \cdots$. Let z_{n+1} be a root of $f : f(z_{n+1}) = 0$. Such exists by the Fund'l Thm. We introduce the following lemma:

Lemma 1.5.2. Let g be a polynomial with complex coefficients. Let $\lambda \in \mathbb{C}$; then we can write $g(x) = (x - \lambda)h(x) + r, r \in \mathbb{C}, h$ a polynomial with complex coefficients as well.

Proof of Sub-Lemma. By induction; we can write $g(x) = a_n x^n + \cdots + a_1 x + a_0$. If $\deg(g) = 0$, then $g = a_0 \implies h(x) = 0, a_0 = r$.

Assume this is true for degrees $\leq n$, and that g has degree $\leq n + 1$.

$$g(x) = (x - \lambda)a_{n+1}x^n + b(x),$$

where $b(x) = g(x) - (x - \lambda)a_{n+1}x^n = a'_n x^n + a'_{n-1} x^{n-1} + \cdots$, for some $a'_n, \dots, a'_0 \in \mathbb{C}$. We can apply induction to $b(x)$ (that has $\deg \leq n$); $b(x) = (x - \lambda)h_1(x) + r$, so

$$g(x) = (x - \lambda) \underbrace{(a_{n+1}x^n + h_1(x))}_{h(x)} + r,$$

as desired. ■

Now, we write our $f(x)$ as

$$f(x) = (x - z_{n+1})h(x) + r,$$

using the lemma. Then,

$$\begin{aligned} 0 &= f(z_{n+1}) = (z_{n+1} - z_{n+1})h(z_{n+1}) + r \\ &= 0 + r + 0 \implies r = 0, \end{aligned}$$

so

$$f(x) = (x - z_{n+1})h(x).$$

Comparing the highest terms:

$$\begin{aligned} a_{n+1}x^{n+1} + \dots &= (x - z_{n+1})(*x^n + \dots) \\ \implies &\text{leading coefficient of } h(x) \text{ also } a_{n+1}. \end{aligned}$$

By induction,

$$\begin{aligned} h(x) &= \underbrace{a_{n+1}}_{\text{lead coef of } h} \cdot \prod_{i=1}^n (x - z_i) \\ \implies f(x) &= a_{n+1} \prod_{i=1}^{n+1} (x - z_i) \quad \text{first "statement"} \end{aligned}$$

Further:

- (1): $f(z_j) = a_{n+1} \prod_{i=1}^{n+1} (z_j - z_i) = 0$ when $i = j$.
- (2): if $f(\lambda) = 0$, then $a_{n+1} \prod_{i=1}^{n+1} (\lambda - z_i) = 0$. But oif a product of two complex numbers is 0, then one of them is 0. $a_{n+1} \neq 0$, so some $\lambda - z_i = 0$, ie $\lambda = z_i$ for some i .

■

Definition 1.5.4 (Complex Exponential). *The complex exponential, $e^z = 1 + \frac{z}{1} + \frac{z^2}{2!} + \dots$ can be Taylor expanded and we have that*

$$e^{i\theta} = \cos \theta + i \sin \theta.$$

²³The same logic can be extended to any number of complex z_i 's; let $z_1 z_2 z_3 = 0 \implies z_1(z_2 z_3)$. As we showed, one of $z_1, (z_2 z_3)$ are zero. If $z_1 \neq 0$, then $z_2 z_3 = 0$. But then, one of z_2, z_3 must be zero, etc..

Example 1.5.2. If $z = e^{x+yi} = e^x \cdot e^{yi} = e^x(\cos y + i \sin y)$, then $z = (e^x, y)$ in polars.

We can apply this idea to prove some trigonometric formulas. Consider $e^{2i\theta}$;

$$\begin{aligned} e^{2i\theta} &= (\cos \theta + i \sin \theta)^2 = \underbrace{\cos^2 \theta - \sin^2 \theta}_{\text{Re}} + \underbrace{2 \sin \theta \cos \theta}_{\text{Im}} i \\ e^{2i\theta} &= \underbrace{\cos(2\theta)}_{\text{Re}} + i \underbrace{\sin(2\theta)}_{\text{Im}} \\ \implies \cos(2\theta) &= \cos^2 \theta - \sin^2 \theta \\ \implies \sin(2\theta) &= 2 \sin \theta \cos \theta \end{aligned}$$

1.6 Rings

Definition 1.6.1 (Ring). A ring R is a set with two operations

- Addition: $R \times R \xrightarrow{+} R, \quad (a, b) \mapsto a + b$
- Multiplication: $R \times R \xrightarrow{\cdot} R, \quad (a, b) \mapsto a \cdot b$

The following hold:

1. (+ is commutative) $a + b = b + a, \forall a, b \in R$.
2. (+ is associative) $a + (b + c) = (a + b) + c, \forall a, b, c \in R$.
3. (0) \exists a zero element, 0, s.t. $0 + a = a + 0 = a, \forall a \in R$.
4. (negative) $\forall a \in R, \exists b \in R$ s.t. $a + b = 0$.
5. (\cdot associative) $a(bc) = (ab)c, \forall a, b, c \in R$.
6. (1) $\exists 1 \in R$ s.t. $1 \cdot a = a \cdot 1 = a, \forall a \in R$.
7. (distributive) $\forall a, b, c \in R, a(b + c) = ab + ac$

Remark 1.6.1. We do not require multiplication to be commutative, nor inverses for multiplication.

$\mathbb{Z}, \mathbb{Q}, \mathbb{R}, \mathbb{C}, \mathbb{R}[i] := \{a + bi : a, b \in \mathbb{Z}\}, M_2(\mathbb{Z}) := \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} : a, b, c, d \in \mathbb{Z} \right\}, \dots$ are all examples of rings.

2 Appendix