

APPLIED MATH BOOT CAMP 2024

1. THE NATURAL NUMBERS AND INDUCTION

What are the natural numbers anyways?

Axiom 1.1 (Peano's Postulates). *The natural numbers are defined as a set \mathbb{N} together with a unary “successor” function $S : \mathbb{N} \rightarrow \mathbb{N}$ and a special element $1 \in \mathbb{N}$ satisfying the following postulates:*

- I. $1 \in \mathbb{N}$.
- II. If $n \in \mathbb{N}$, then $S(n) \in \mathbb{N}$.
- III. There is no $n \in \mathbb{N}$ such that $S(n) = 1$.
- IV. If $n, m \in \mathbb{N}$ and $S(n) = S(m)$, then $n = m$.
- V. If $A \subset \mathbb{N}$ is a subset satisfying the two properties:
 - $1 \in A$
 - if $n \in A$, then $S(n) \in A$,then $A = \mathbb{N}$.

Question 1.2. *Intuitively, what is $S(n)$?*

We take the following theorem for granted (we do not want to get into too much logic...).

Theorem 1.3 (Mathematical Induction). *For each $n \in \mathbb{N}$, let $P(n)$ be a proposition. Suppose the following two results:*

- (A) $P(1)$ is true.
- (B) If $P(n)$ is true, then $P(S(n))$ is true.

Then $P(n)$ is true for all $n \in \mathbb{N}$.

Statement (A) is called the base case and statement (B) is called the inductive step. The assumption that P is true of n is called the inductive hypothesis.

Remark 1.4. *From now on we assume that all the usual properties of \mathbb{N} and \mathbb{Z} hold. A list of properties will be posted.*

When you write a proof, you need to clearly declare what the inductive hypothesis is (if it is not obvious from context) and clearly delineate the parts of the proof relating to the base case and inductive step. Here is an example.

Proposition 1.5. *For every $n \in \mathbb{N}$, we have*

$$(1.1) \quad \sum_{i=0}^n 2^i = 2^{n+1} - 1.$$

Proof. We prove this by induction. For the base case, take $n = 0$. Notice that the left hand side of (1.1) is

$$2^0 = 1,$$

while the right hand side is

$$2^{0+1} - 1 = 2 - 1 = 1.$$

These are equal. Thus, the base case is established.

We now prove the inductive step. Assume that (1.1) holds for n , and we prove it for $n + 1$. By the inductive hypothesis, we have

$$\sum_{i=0}^{n+1} 2^i = 2^{n+1} + \sum_{i=0}^n 2^i = 2^{n+1} + (2^{n+1} - 1) = 2 \cdot 2^{n+1} - 1 = 2^{n+2} - 1.$$

The proof is complete. \square

Exercise 1.6. Show that

$$\sum_{i=1}^n i^2 = \frac{n(2n+1)(n+1)}{6}.$$

2. SETS AND FUNCTIONS

Sets and functions are among the most fundamental objects in mathematics. A formal treatment of set theory was first undertaken at the end of the 19th Century and was finally codified in the form of the Zermelo-Fraenkel axioms. This goes well beyond our purposes here. Thus, we present a simplified version.'

Definition 2.1. A set is an object S with the property that, given any x , we have the dichotomy that precisely one of the following two conditions is true: $x \in S$ or $x \notin S$. In the former case, we say that x is an element of S , and in the latter, we say that x is not an element of S .

A set is often presented in one of the following forms:

- A complete listing of its elements.
Example: the set $S = \{1, 2, 3, 4, 5\}$ contains precisely the five smallest positive integers.
- A listing of some of its elements with ellipses to indicate unnamed elements.
Example 1: the set $S = \{3, 4, 5, \dots, 100\}$ contains the positive integers from 3 to 100, including 6 through 99, even though these latter are not explicitly named.
Example 2: the set $S = \{2, 4, 6, \dots, 2n, \dots\}$ is the set of all positive even integers.
- A two-part indication of the elements of the set by first identifying the source of all elements and then giving additional conditions for membership in the set.
Example 1: $S = \{x \in \mathbb{N} \mid x \text{ is prime}\}$ is the set of primes.
Example 2: $S = \{x \in \mathbb{Z} \mid x^2 < 3\}$ is the set of integers whose squares are less than 3.

Definition 2.2. Two sets A and B are equal if they contain precisely the same elements, that is, $x \in A$ if and only if $x \in B$. When A and B are equal, we denote this by $A = B$.

Definition 2.3. A set A is a subset of a set B if every element of A is also an element of B , that is, if $x \in A$, then $x \in B$. When A is a subset of B , we denote this by $A \subset B$. If $A \subset B$ but $A \neq B$ we say that A is a proper subset of B .

Exercise 2.4. Let $A = \{1, \{2\}\}$. Is $1 \in A$? Is $2 \in A$? Is $\{1\} \subset A$? Is $\{2\} \subset A$? Is $1 \subset A$? Is $\{1\} \in A$? Is $\{2\} \in A$? Is $\{\{2\}\} \subset A$? Explain.

Proof. Yes, $1 \in A$. No, $2 \notin A$. Yes, $\{1\} \subset A$. No, $\{2\} \not\subset A$. No, $1 \not\subset A$. No, $\{1\} \notin A$. Yes, $\{2\} \in A$. Yes, $\{\{2\}\} \subset A$ because $\{2\}$ is the only element of $\{\{2\}\}$ and $\{2\} \in A$. \square

Definition 2.5. Let A and B be two sets. The union of A and B is the set

$$A \cup B = \{x \mid x \in A \text{ or } x \in B\}.$$

Definition 2.6. Let A and B be two sets. The intersection of A and B is the set

$$A \cap B = \{x \mid x \in A \text{ and } x \in B\}.$$

Theorem 2.7 (No proof required). Let A and B be two sets. Then:

- a) $A = B$ if and only if $A \subset B$ and $B \subset A$.
- b) $A \subset A \cup B$.
- c) $A \cap B \subset A$.

A special example of the intersection of two sets is when the two sets have no elements in common. This motivates the following definition.

Definition 2.8. The empty set is the set with no elements, and it is denoted \emptyset . That is, no matter what x is, we have $x \notin \emptyset$.

Definition 2.9. Two sets A and B are disjoint if $A \cap B = \emptyset$.

Exercise 2.10. Show that if A is any set, then $\emptyset \subset A$.

Proof. A set $A \not\subset B$ if there exists $x \in A$ where $x \notin B$. Because there is no $x \in \emptyset$ where $x \notin A$, $\emptyset \subset A$. \square

Definition 2.11. Let A and B be two sets. The difference of B from A is the set

$$A \setminus B = \{x \in A \mid x \notin B\}.$$

The set $A \setminus B$ is also called the *complement* of B relative to A . When the set A is clear from the context, this set is sometimes denoted B^c , but we will try to avoid this imprecise formulation and use it only with warning.

Theorem 2.12. Let X be a set, and let $A, B \subset X$. Then:

- a) $X \setminus (A \cup B) = (X \setminus A) \cap (X \setminus B)$
- b) $X \setminus (A \cap B) = (X \setminus A) \cup (X \setminus B)$

Proof. Start with a proof statement a). Let $x \in X \setminus (A \cup B)$. Then $x \notin A \cup B$, which means that

$$x \in (X \setminus A) \text{ and } x \in (X \setminus B).$$

This is the definition of intersection, so

$$x \in (X \setminus A) \cap (X \setminus B).$$

Therefore

$$X \setminus (A \cup B) \subset (X \setminus A) \cap (X \setminus B).$$

To prove equality it will be shown that $X \setminus (A \cup B) = (X \setminus A) \cap (X \setminus B)$. Let $x \in (X \setminus A) \cap (X \setminus B)$. Then

$$x \in (X \setminus A) \text{ and } x \in (X \setminus B).$$

This means that $x \notin A$ and $x \notin B$. Therefore,

$$x \notin (A \cup B),$$

and so

$$x \in (X \setminus (A \cup B)).$$

As a result

$$(X \setminus A) \cap (X \setminus B) \subset (X \setminus (A \cup B)).$$

Combining the forward and reverse statements gives $X \setminus (A \cup B) = (X \setminus A) \cap (X \setminus B)$.

What follows is a proof of statement b). Let $x \in X \setminus (A \cap B)$. Then

$$x \notin (A \cap B),$$

and by definition of intersection,

$$x \notin A \text{ or } x \notin B.$$

Therefore,

$$x \in (X \setminus A) \cup (X \setminus B),$$

and

$$(X \setminus A \cap B) \subset (X \setminus A) \cup (X \setminus B).$$

Now it will be shown that the right hand side is a subset of the left hand side. Let $x \in (X \setminus A) \cup (X \setminus B)$. Then

$$x \notin A \text{ or } x \notin B.$$

Therefore,

$$x \notin (A \cap B) \text{ and } x \in X \setminus (A \cap B).$$

This means that

$$(X \setminus A) \cup (X \setminus B) \subset X \setminus (A \cap B).$$

Combining the forward and reverse relations gives $X \setminus A \cap B = (X \setminus A) \cup (X \setminus B)$. \square

Sometimes we will encounter families of sets. The definitions of intersection/union can be extended to infinitely many sets.

Definition 2.13. Let $\mathcal{A} = \{A_\lambda \mid \lambda \in I\}$ be a collection of sets indexed by a nonempty set I . Then the intersection and union of \mathcal{A} are the sets

$$\bigcap_{\lambda \in I} A_\lambda = \{x \mid x \in A_\lambda, \text{ for all } \lambda \in I\},$$

and

$$\bigcup_{\lambda \in I} A_\lambda = \{x \mid x \in A_\lambda, \text{ for some } \lambda \in I\}.$$

Note: unions and intersections should almost never be written in-line because doing so causes spacing issues and is difficult to read. Please use display environments.

Exercise 2.14. Give an example of an indexed family of sets.

Example. Let $A_\lambda = \{\lambda\}$, and let $\mathcal{A} = \{A_\lambda \mid \lambda \text{ is prime}\}$ \square

Theorem 2.15. Let X be a set, and let $\mathcal{A} = \{A_\lambda \mid \lambda \in I\}$ be a collection of subsets of X . Then:

$$(1) \quad X \setminus \left(\bigcup_{\lambda \in I} A_\lambda \right) = \bigcap_{\lambda \in I} (X \setminus A_\lambda) \quad \text{and} \quad (2) \quad X \setminus \left(\bigcap_{\lambda \in I} A_\lambda \right) = \bigcup_{\lambda \in I} (X \setminus A_\lambda).$$

Proof. Begin with a proof of statement (1). Let

$$x \in X \setminus \left(\bigcup_{\lambda \in I} A_\lambda \right).$$

This means that

$$x \in (X \setminus A_\lambda) \text{ for all } \lambda \in I.$$

This is the definition of the intersection, so

$$x \in \bigcap_{\lambda \in I} (X \setminus A_\lambda),$$

and

$$X \setminus \left(\bigcup_{\lambda \in I} A_\lambda \right) \subset \bigcap_{\lambda \in I} (X \setminus A_\lambda).$$

To show that the right hand side is a subset of the left hand side, let

$$x \in \bigcap_{\lambda \in I} (X \setminus A_\lambda).$$

This means that

$$x \notin A_\lambda \text{ for all } \lambda \in I,$$

and so

$$x \in (X \setminus (\bigcup_{\lambda \in I} A_\lambda))$$

This gives that

$$\bigcap_{\lambda \in I} (X \setminus A_\lambda) \subset X \setminus (\bigcup_{\lambda \in I} A_\lambda).$$

Combining the forward and reverse statements gives

$$X \setminus (\bigcup_{\lambda \in I} A_\lambda) = \bigcap_{\lambda \in I} (X \setminus A_\lambda).$$

The proof for statement (2) follows. Let

$$x \in (X \setminus (\bigcap_{\lambda \in I} A_\lambda))$$

This means that there must exist

$$\lambda' \in I \text{ where } x \notin A_{\lambda'} \text{ and } x \in X \setminus A_{\lambda'}.$$

Therefore,

$$x \in \bigcup_{\lambda \in I} (X \setminus A_\lambda),$$

and

$$X \setminus (\bigcap_{\lambda \in I} A_\lambda) \subset \bigcup_{\lambda \in I} (X \setminus A_\lambda).$$

To show that the right hand side is a subset of the left hand side, let

$$x \in \bigcup_{\lambda \in I} (X \setminus A_\lambda).$$

By definition of union, there must exist $\lambda' \in I$ such that

$$x \in X \setminus A_{\lambda'} \text{ or } x \notin A_{\lambda'}.$$

This means that

$$x \notin \bigcap_{\lambda \in I} A_\lambda,$$

and

$$x \in (X \setminus \bigcap_{\lambda \in I} A_\lambda).$$

Therefore,

$$\bigcup_{\lambda \in I} (X \setminus A_\lambda) \subset (X \setminus \bigcap_{\lambda \in I} A_\lambda).$$

Combining the forward and reverse statements gives

$$X \setminus (\bigcap_{\lambda \in I} A_\lambda) \subset \bigcup_{\lambda \in I} (X \setminus A_\lambda).$$

□

Definition 2.16. Let A and B be two nonempty sets. The Cartesian product of A and B is the set of ordered pairs

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

If (a, b) and $(a', b') \in A \times B$, we say that (a, b) and (a', b') are equal if and only if $a = a'$ and $b = b'$. In this case, we write $(a, b) = (a', b')$.

Definition 2.17. Let A and B be two nonempty sets. A function f from A to B is a subset $f \subset A \times B$ such that for all $a \in A$ there exists a unique $b \in B$ satisfying $(a, b) \in f$. To express the idea that $(a, b) \in f$, we most often write $f(a) = b$. To express that f is a function from A to B in symbols we write $f: A \rightarrow B$.

Exercise 2.18. Let the function $f: \mathbb{N} \rightarrow \mathbb{N}$ be defined by $f(n) = 2n$. Describe f as a subset of $\mathbb{N} \times \mathbb{N}$ in two ways (see the discussion below Definition 2.1).

Solution. The function $f(n) = 2n$ can be represented as a set either $f = \{(1, 2), (2, 4), (3, 6), \dots\}$ or $f = \{(n, 2n) \mid \text{for all } n \in \mathbb{N}\}$

□

Definition 2.19. Let $f: A \rightarrow B$ be a function. The domain of f is A and the codomain of f is B .

If $X \subset A$, then the image of X under f is the set

$$f(X) = \{f(x) \in B \mid x \in X\}.$$

If $Y \subset B$, then the preimage of Y under f is the set

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

Exercise 2.20. Must $f(f^{-1}(Y)) = Y$ and $f^{-1}(f(X)) = X$? For each, either prove that it always holds or give a counterexample.

Counterexample. No, $f(f^{-1}(Y)) = Y$ is not always true. Let $f: \mathbb{N} \rightarrow \mathbb{N}$ be a function defined as $f(n) = 2n$ and let $Y = \{2, 3\}$. Then

$$f^{-1}(Y) = \{1\}$$

as there is no $n \in \mathbb{N}$ for which $2n = 3$. Taking the image gives

$$f(\{1\}) = \{2\},$$

which is different from Y , so The statement $f(f^{-1}(Y)) = Y$ does not hold.

No, $f^{-1}(f(X)) = X$ is not always true. Let $f: \mathbb{N} \rightarrow \mathbb{N}$ be a function defined as $f(n) = 1$ and let $X = \{2, 3\}$. Then

$$f(X) = \{1\}.$$

However, as $f(n) = 1$ for all $n \in \mathbb{N}$,

$$f^{-1}(\{1\}) = \mathbb{N}.$$

Since $X \neq \mathbb{N}$, $f^{-1}(f(X)) = X$ does not hold.

□

Definition 2.21. A function $f: A \rightarrow B$ is surjective (also known as ‘onto’) if, for every $b \in B$, there is some $a \in A$ such that $f(a) = b$. The function f is injective (also known as ‘one-to-one’) if for all $a, a' \in A$, if $f(a) = f(a')$, then $a = a'$. The function f is bijective, (also known as a bijection or a ‘one-to-one’ correspondence) if it is surjective and injective.

Exercise 2.22. Let $f: \mathbb{N} \rightarrow \mathbb{N}$ be defined by $f(n) = n^2$. Is f injective? Is f surjective?

Solution. The function f is injective. Because f is monotonic and increasing, if

$$n_1 < n_2 \text{ for } n_1, n_2 \in \mathbb{N},$$

then

$$(n_1)^2 < (n_2)^2.$$

Therefore, if

$$(n_1)^2 = (n_2)^2,$$

it must be true that

$$n_1 = n_2.$$

The function f is not surjective because there exists no $n \in \mathbb{N}$ such that $n^2 = 2$.

□

Exercise 2.23. Let $f : \mathbb{N} \rightarrow \mathbb{N}$ be defined by $f(n) = n + 2$. Is f injective? Is f surjective?

Solution. Yes, f is injective. Because f is monotonic and increasing, if

$$n_1 < n_2 \text{ for } n_1, n_2 \in \mathbb{N},$$

it follows that

$$n_1 + 2 < n_2 + 2.$$

Therefore, if

$$n_1 + 2 = n_2 + 2,$$

it must be true that

$$n_1 = n_2.$$

No, f is not surjective because there exists no $n \in \mathbb{N}$ such that $n + 2 = 1$. □

Exercise 2.24. Let $f : \mathbb{Z} \rightarrow \mathbb{Z}$ be defined by $f(x) = x^2$. Is f injective? Is f surjective?

Solution. No, f is not injective because $(-1)^2 = 1$ and $1^2 = 1$. No, f is not surjective because there exists no $z \in \mathbb{Z}$ such that $z^2 = -1$. □

Exercise 2.25. Let $f : \mathbb{Z} \rightarrow \mathbb{Z}$ be defined by $f(x) = x + 2$. Is f injective? Is f surjective?

Solution. Yes, f is injective. f is monotonic and increasing, so if

$$z_1 < z_2 \text{ for } z_1, z_2 \in \mathbb{Z},$$

then

$$z_1 + 2 < z_2 + 2.$$

Therefore, if

$$z_1 + 2 = z_2 + 2,$$

it follows that

$$z_1 = z_2.$$

Yes, f is surjective because for all $z_2 \in \mathbb{Z}$ there exists $z_1 \in \mathbb{Z}$ such that $z_1 + 2 = z_2$. □

Definition 2.26. Let $f : A \rightarrow B$ and $g : B \rightarrow C$. Then the composition $g \circ f : A \rightarrow C$ is defined by $(g \circ f)(x) = g(f(x))$, for all $x \in A$.

Proposition 2.27. Let A , B , and C be sets and suppose that $f : A \rightarrow B$ and $g : B \rightarrow C$. Then $g \circ f : A \rightarrow C$ and

- a) if f and g are both injections, so is $g \circ f$.
- b) if f and g are both surjections, so is $g \circ f$.
- c) if f and g are both bijections, so is $g \circ f$.
- d) if f is an injection and g is not, $g \circ f$ is not injective
- e) if f is not an injection and g is, $g \circ f$ is not injective
- f) if f is a surjection and g is not, $g \circ f$ is not surjective
- g) if f is not a surjection and g is, $g \circ f$ is not surjective

Proof. What follows is a proof of statement a). Fix any $a_1, a_2 \in A$ such that $g(f(a_1)) = g(f(a_2))$. Because g is an injection, $f(a_1) = f(a_2)$, and because f is also an injection, $a_1 = a_2$. Therefore, $g(f(a_1)) = g(f(a_2))$ gives $a_1 = a_2$, and $g \circ f$ is an injection.

What follows is a proof of statement b). Given that g is a surjection, for any $c \in C$, there must exist $b \in B$, such that $g(b) = c$. Similarly, because f is a surjection, for all $b \in B$, there must exist $a \in A$, such that $f(a) = b$. Therefore, for all $c \in C$ we can rewrite $g(b) = c$ as $g(f(a)) = c$, and $g \circ f$ must also be a surjection.

What follows is a proof of statement c). If f and g are both bijections, they are both injections and surjections. By parts (a) and (b), $g \circ f$ must also be both an injection and surjection, and is therefore a bijection.

To show d) is true, let $f : \mathbb{N} \rightarrow \mathbb{N}$ such that $f(x) = x$ for all $x \in \mathbb{N}$, and let $g : \mathbb{N} \rightarrow \mathbb{N}$ such that $g(y) = 1$ for all $y \in \mathbb{N}$. Then

$$\begin{aligned} g(f(1)) &= g(1) \\ &= 1. \end{aligned}$$

Also,

$$\begin{aligned} g(f(2)) &= g(2) \\ &= 1. \end{aligned}$$

Thus $g(f(1)) = g(f(2))$, and $g \circ f$ is not an injection.

To show e) is true, let $f : \mathbb{N} \rightarrow \mathbb{N}$ such that $f(x) = 1$ for all $x \in \mathbb{N}$, and let $g : \mathbb{N} \rightarrow \mathbb{N}$ such that $g(y) = y$ for all $y \in \mathbb{N}$. Then

$$\begin{aligned} g(f(1)) &= g(1) \\ &= 1. \end{aligned}$$

Also,

$$\begin{aligned} g(f(2)) &= g(1) \\ &= 1. \end{aligned}$$

Thus $g(f(1)) = g(f(2))$, and $g \circ f$ is not an injection.

To show that f) is true, let $f : \mathbb{N} \rightarrow \mathbb{N}$ such that $f(x) = 2x$ for all $x \in \mathbb{N}$, and let $g : \mathbb{N} \rightarrow \mathbb{N}$ such that $g(y) = y$ for all $y \in \mathbb{N}$. 3 is in the codomain of g , and has representation $g(3) = 3$. 3 is also in the codomain of f , but there exists no $x \in \mathbb{N}$ such that $2x = 3$, and by extension there exists no $x \in \mathbb{N}$ such that $(g \circ f)(x) = 3$. Therefore, $g \circ f$ is not a surjection.

To show that g) is true, let $g : \mathbb{N} \rightarrow \mathbb{N}$ such that $g(y) = 2y$ for all $y \in \mathbb{N}$. 3 is in the codomain of g , but there exists no $y \in \mathbb{N}$ such that $2y = 3$. Therefore, no matter what $f : A \rightarrow \mathbb{N}$ is, $g \circ f$ is not a surjection. \square

Proposition 2.28. *Suppose that $f : A \rightarrow B$ is bijective. Then there exists a bijection $g : B \rightarrow A$ that satisfies $(g \circ f)(a) = a$ for all $a \in A$, and $(f \circ g)(b) = b$, for all $b \in B$. The function g is often called the inverse of f and denoted f^{-1} . It should not be confused with the preimage.*

Proof. Define $g : B \rightarrow A$ as follows. Fix $b \in B$. By the bijectivity of f , there exists a unique $a \in A$ such that $f(a_b) = b$. Let $g(b) = a_b$. Applying f to both sides of the definition for g gives

$$\begin{aligned} f(g(b)) &= f(a_b) \\ &= b. \end{aligned}$$

Similarly, applying our definition of g to the equation of $f(a_b) = b$ gives

$$\begin{aligned} g(f(a_b)) &= g(b) \\ &= a_b. \end{aligned}$$

To show that g is an injection, fix $b_1, b_2 \in B$, and set $g(b_1) = g(b_2)$. Applying f gives

$$\begin{aligned} f(g(b_1)) &= f(g(b_2)) \\ b_1 &= b_2. \end{aligned}$$

This satisfies the definition of an injection. To show that g must be a surjection, assume for contradiction that g is not a surjection. That would mean that for all $b \in B$, there exists $a \in A$, such that $g(b) \neq a$. Applying f to both sides gives

$$\begin{aligned} f(g(b)) &\neq f(a) \\ b &\neq f(a). \end{aligned}$$

This contradicts f as a bijection, so g must be a surjection, and therefore a bijection as well.

□

Definition 2.29. We say that two sets A and B are in bijective correspondence when there exists a bijection from A to B or, equivalently, from B to A .

3. BUILDING THE REAL NUMBERS

This sheet introduces a continuum C through a series of axioms. We will construct such an object in a bit.

Axiom 3.1. A continuum is a nonempty set C .

We often refer to elements of C as *points*.

Definition 3.2. Let X be a set. An ordering on the set X is a subset $<$ of $X \times X$, with elements $(x, y) \in <$ written as $x < y$, satisfying the following properties:

- (a) (Trichotomy) For all $x, y \in X$ exactly one of the following holds: $x < y$, $y < x$ or $x = y$.
- (b) (Transitivity) For all $x, y, z \in X$, if $x < y$ and $y < z$ then $x < z$.

Remark 3.3. a) In mathematics “or” is understood to be inclusive unless stated otherwise.

So in a) above, the word “exactly” is needed.

b) $x < y$ may also be written as $y > x$.

c) By $x \leq y$, we mean $x < y$ or $x = y$; similarly for $x \geq y$.

Axiom 3.4. A continuum C has an ordering $<$.

Definition 3.5. If $A \subset C$ is a subset of C , then a point $a \in A$ is a first point of A if, for every element $x \in A$, either $a < x$ or $a = x$. Similarly, a point $b \in A$ is called a last point of A if, for every $x \in A$, either $x < b$ or $x = b$.

Definition 3.6. A set A is finite if $A = \emptyset$ or if there exists $n \in \mathbb{N}$ and a bijection $f : A \rightarrow \{1, 2, \dots, n\}$. In the former case, we say that A has no elements, and in the latter case, we say that A has n elements.

Lemma 3.7. Fix $n \in \mathbb{N}$. Suppose that A has $n + 1$ elements and that $a \in A$. Then $A \setminus \{a\}$ has n elements.

Proof. Let $f : \{2, 3, \dots\} \rightarrow \mathbb{N}$ be a function defined as $f(n) = n - 1$. This function is monotonic and increasing, so if

$$n_1 < n_2,$$

it must be true that

$$n_1 - 1 < n_2 - 1.$$

This implies that if

$$f(n_1) = f(n_2),$$

then

$$n_1 = n_2,$$

and f must be an injection.

The function f must also be a surjection because for all $m \in \mathbb{N}$, there exists $n \in \{2, 3, \dots\}$ such that $n - 1 = m$.

This subtraction by one function must be a bijection, and therefore for any $n \in \mathbb{N}$ and set A with $n + 1$ elements, $A \setminus \{a\}$ with $a \in A$, has n elements. □

Lemma 3.8. If A is a nonempty, finite subset of a continuum C , then A has a first and last point.

Proof. What follows is a proof by induction on a set with n elements. The base case is the set which only has 1 element. This element is both the first and last point of the set.

The induction hypothesis is that any set with n elements, where $n \in \mathbb{N}$, has a first point and last point. Consider a set A with $n + 1$ elements. Now define a new set

$$A' = A \setminus \{a\}, \text{ where } a \in A.$$

By Lemma 3.7, A' has n elements, and by the induction hypothesis has a first point $a_f \in A'$ and last point $a_l \in A'$.

If $a < a_f$, then a is the first point of A . Similarly, if $a > a_l$, then a is the last point of A . Otherwise, the a_f and a_l values for $A \setminus \{a\}$ are the a_f and a_l values for A .

Therefore, by induction, every set with $n + 1$ elements has a first and last point. \square

Theorem 3.9. *Suppose that A is a set of n distinct points in a continuum C , or, in other words, $A \subset C$ has cardinality n . Then symbols a_1, \dots, a_n may be assigned to each point of A so that $a_1 < a_2 < \dots < a_n$, i.e. $a_i < a_{i+1}$ for $1 \leq i \leq n - 1$.*

Proof. What follows is a proof by induction on a set with n elements. The base case is the set that only has 1 element. This one element is ordered and can be designated a_1 .

The induction hypothesis is that any set with n elements, where $n \in \mathbb{N}$, has symbols a_1, \dots, a_n that may be assigned to each point of A so that $a_1 < a_2 < \dots < a_n$. Consider a set A with $n + 1$ elements. By Lemma 3.8, A has a last element $a_l \in A$. Define

$$A' = A \setminus \{a_l\}.$$

Since each element is distinct, for all $a \in A$, $a_l > a$. Therefore, for all $a' \in A'$, $a_l > a'$ as well.

Seeing as A' has n elements, by the induction hypothesis its elements have an ordering from least to greatest, terminating at a_n . A has the same ordering as A' but with $a_l = a_{n+1}$.

Therefore, by induction, any set with n elements can have its elements labeled and ordered from least to greatest. \square

Definition 3.10. *If $x, y, z \in C$ and either (i) both $x < y$ and $y < z$ or (ii) both $z < y$ and $y < x$, then we say that y is between x and z .*

Corollary 3.11. *Of three distinct points in a continuum, one must be between the other two.*

Proof. Let $A = \{x, y, z\}$ where $x, y, z \in C$ and are distinct. Then A is a finite subset of C and has a first and last element. Because of the choice of x, y , and z is arbitrary, we can set x as the first point and z as the last point without the loss of generality. By definition 3.10, this must mean that $x < y$ and $y < z$, and can therefore state that y is between x and z . \square

Axiom 3.12. *A continuum C has no first or last point.*

Definition 3.13. *If $a, b \in C$ and $a < b$, then the set of points between a and b is called an interval, denoted by (a, b) .*

Theorem 3.14. *If x is a point of a continuum C , then there exists an interval (a, b) such that $x \in (a, b)$.*

Proof. Because $x \in C$ and C is a continuum, by Axiom 3.12, it is always possible to find $a, b \in C$ such that $a < x$ and $x < b$. By definition 3.10, x is between a and b , and by definition 3.13, (a, b) constitutes an interval. Therefore, $x \in (a, b)$. \square

Definition 3.15. *Let A be a subset of a continuum C . A point p of C is called a limit point of A if every interval I containing p has nonempty intersection with $A \setminus \{p\}$. Explicitly, this means:*

$$\text{for every interval } I \text{ with } p \in I, \text{ we have } I \cap (A \setminus \{p\}) \neq \emptyset.$$

Notice that we do not require that a limit point p of A be an element of A . We will use the notation $LP(A)$ to denote the set of limit points of A .

Theorem 3.16. *If p is a limit point of A and $A \subset B$, then p is a limit point of B .*

Proof. Let I be any interval such that $p \in I$. Since p is a limit point of set A , $I \cap (A \setminus \{p\}) \neq \emptyset$. Let $x \in I \cap (A \setminus \{p\})$, so $x \in I$ and $x \in A \setminus \{p\}$. Because $A \subset B$, $A \setminus \{p\} \subset B \setminus \{p\}$, and $x \in B \setminus \{p\}$. Therefore $x \in I \cap (B \setminus \{p\})$ and x must be a limit point of B . \square

Definition 3.17. *If (a, b) is an interval in a continuum C , then $C \setminus (\{a\} \cup (a, b) \cup \{b\})$ is called the exterior of (a, b) and is denoted by $\text{ext}(a, b)$.*

Lemma 3.18. *If (a, b) is an interval in a continuum C , then*

$$\text{ext}(a, b) = \{x \in C \mid x < a\} \cup \{x \in C \mid b < x\}.$$

Proof. Let $x \in \text{ext}(a, b)$. By definition 3.17, $x \notin (a, b)$, and by definition 3.13, is not between a and b . Therefore, $x \leq a$ or $x \geq b$. However $a, b \notin \text{ext}(a, b)$, so $x < a$ or $x > b$. This as a set gives $\text{ext}(a, b) = \{x \in C \mid x < a\} \cup \{x \in C \mid b < x\}$. \square

Lemma 3.19. *No point in the exterior of an interval is a limit point of that interval. No point of an interval is a limit point of the exterior of that interval.*

Proof. Let $p \in \text{ext}(a, b)$. By lemma 3.18, either $p < a$ or $p > b$.

Consider just the case that $p < a$. Because $\text{ext}(a, b)$ is a subset of a continuum C , by axiom 3.12, there must be $x \in C$ such that $x < p$. By definition 3.10, p is between x and a , and $p \in (x, a)$ by definition 3.13. However, the intersection $(x, a) \cap (a, b) = \emptyset$, so by definition 3.15, p cannot be a limit point of (a, b) .

The justification is very similar for the case where $p > b$, as there must now exist $x \in C$ such that $x > p$. Thus $p \in (b, x)$, and $(b, x) \cap (a, b) = \emptyset$. Therefore, no point of the exterior of an interval can be a limit point of the interval.

To show that no point of an interval can be a limit point of the exterior of that interval, let $p \in (a, b)$, and by definition of the exterior, $\text{ext}(a, b) \cup (a, b) = \emptyset$. This proves the statement. \square

Theorem 3.20. *If two intervals have a point x in common, their intersection is an interval containing x .*

Proof. Let $(a, b), (c, d) \subset C$ with $x \in (a, b)$ and $x \in (c, d)$. This is the definition of the intersection and $x \in (a, b) \cap (c, d)$. By definition 3.10, $x > a$, $x < b$, $x > c$, $x < d$. Let the function $\max(x, y)$ for $x, y \in C$ be defined as

$$\max(x, y) = \begin{cases} x & \text{if } x > y \text{ or } x = y, \\ y & \text{if } x < y, \end{cases}$$

Similarly, let the function $\min(x, y)$ for $x, y \in C$ be defined as

$$\min(x, y) = \begin{cases} x & \text{if } x < y \text{ or } x = y, \\ y & \text{if } x > y, \end{cases}$$

Since $x > a$ and $x > c$, it must be true that $x > \max(a, c)$. Similarly, as $x < b$ and $x < d$, $x < \min(b, d)$. By definition 3.10, x is between $\max(a, c)$ and $\min(b, d)$, and by definition 3.13, the set of all possible values for x describe the interval $(\max(a, c), \min(b, d))$. \square

Corollary 3.21. *If n intervals I_1, \dots, I_n have a point x in common, then their intersection $I_1 \cap \dots \cap I_n$ is an interval containing x .*

Proof. This will be proven by induction on the set of intervals I_n all containing x . Let I_1 be one of those intervals. Because every interval contains x , $x \in I_1$.

The induction hypothesis is that the intersection of n intervals which all contain x , is itself an interval that contains x . Let I_1, \dots, I_n where $x \in I_n$ for all n . Then the intersection,

$$I_{n+1} \cap \bigcap_{i=1}^n I_i = \bigcap_{i=1}^{n+1} I_i$$

is the intersection of two intervals, both of which contain x . By theorem 3.20, the intersection

$$\bigcap_{i=1}^{n+1} I_i$$

is also an interval that contains x .

Therefore, by induction, the intersection of any number of intervals containing a point x must also be an interval that contains x . \square

Exercise 3.22. Is Corollary 3.21 true for infinite intersections of intervals?

Counterexample. Consider the set of nested intervals $I_n = (x - 1/n, x + 1/n)$ where $x \in \mathbb{R}$ and $n \in \mathbb{N}$. Every set contains x . Consider any point $x + a$ where $a \in \mathbb{R}$. Because \mathbb{N} is unbounded, for any choice of a , it must be true that there exists $n \in \mathbb{N}$ such that $1/n < |a|$. Therefore, for any choice of a , there must exist I_n such that $x + a \notin I_n$. Therefore, the infinite intersection of these intervals must not contain anything other than x , and as such, cannot be an interval. \square

Theorem 3.23. Let A, B be subsets of a continuum C . Then p is a limit point of $A \cup B$ if, and only if, p is a limit point of at least one of A or B .

Proof. Let p be a limit point of A . By theorem 2.7, $A \subset A \cap B$, and by theorem 3.16, p is a limit point of $A \cap B$. By the same reasoning, if p is limit point of B , then p is a limit point of $A \cap B$.

The reverse implication will be proven using the contrapositive, which states that if p is not a limit point of both B and A , then it is not a limit point of $A \cup B$. Since p is not a limit point of A and B , there must exist intervals $I_1, I_2 \in C$ such that

$$p \in I_1, I_2, I_1 \cap (A \setminus \{p\}) = \emptyset, \text{ and } I_2 \cap (B \setminus \{p\}) = \emptyset.$$

Since I_1 and I_2 both contain p , by theorem 3.20, there must exist an interval I_3 such that $I_3 = I_1 \cap I_2$ and $p \in I_3$. By theorem 2.7, $I_3 \subset I_1$ and $I_3 \subset I_2$, so

$$I_3 \cap (A \setminus \{p\}) = \emptyset \text{ and } I_3 \cap (B \setminus \{p\}) = \emptyset.$$

Therefore, it must be true that $I_3 \cap ((A \cup B) \setminus \{p\}) = \emptyset$. \square

Corollary 3.24. Let A_1, \dots, A_n be n subsets of a continuum C . Then p is a limit point of $A_1 \cup \dots \cup A_n$ if, and only if, p is a limit point of at least one of the sets A_k .

Proof. Let p be a limit point of some set $A_m \in \{A_1, \dots, A_n\}$. Since

$$A_m \subset \bigcup_{i=1}^n A_i,$$

by theorem 3.16,

$$p \text{ is a limit point of } \bigcup_{i=1}^n A_i.$$

The reverse implication will be proven by the contrapositive and induction on the union of the sets A_n . The contrapositive of this statement is that if p is not a limit point of every set $A_m \in \{A_1, \dots, A_n\}$, then p is not a limit point of

$$\bigcup_{i=1}^n A_i.$$

The base case is for when there is one set A_1 and p is not the limit point of A_1 . The induction hypothesis is that the union of $n - 1$ sets for which p is not a limit point of any individual set, does not have p as its limit point. Let

$$\bigcup_{i=1}^{n-1} A_i$$

be the union of $n - 1$ sets A_i , and that p is not a limit point for each set A_i . Let A_n be a set for which p is not a limit point. By the induction hypothesis, p is not a limit point of $\bigcup_{i=1}^{n-1} A_i$, and since p is not a limit point of A_n , $\bigcup_{i=1}^{n-1} A_i \cup A_n = \bigcup_{i=1}^n A_i$ does not have p as its limit point by theorem 3.23. Therefore, by induction, if p is not a limit point of each set $A_m \in \{A_1, \dots, A_n\}$ it is not a limit point of $\bigcup_{i=1}^n A_i$. \square

Theorem 3.25. *If p and q are distinct points of a continuum C , then there exist disjoint intervals I and J containing p and q , respectively.*

Proof. There are two cases that need to be proven separately: the case in which there exists a distinct element $x \in C$ that is between p and q , and the case in which there does not. Let $p < q$ and thereby the interval (p, q) exists. Consider first the case in which there exists $x \in (p, q)$. By definition 3.10, $x < q$ and $x > p$. Being part of a continuum, by axiom 3.12, there must exist $a, b \in C$ such that $a < p$ and $q < b$. Since $a < p$ and $p < x$, there exists an interval (a, x) with $p \in (a, x)$. Similarly, since $x < q$ and $q < b$, there exists an interval (x, b) with $q \in (x, b)$. As a result, $(a, x) \cap (x, b) = \emptyset$, which proves the result for the nonempty case. Now consider the case in which there exists no $x \in C$ such that $x \in (p, q)$. Define $a, b \in C$ the same as in the first case. Since $a < p$ and $p < q$, there exists interval (a, q) with $p \in (a, q)$. Similarly, since $p < q$ and $q < b$, there exists interval (p, b) with $q \in (p, b)$. The intersection $(a, q) \cap (p, b) = (p, q)$, but we defined this set to be empty, so $(a, q) \cap (p, b) = \emptyset$, thereby proving the result for this case. \square

Corollary 3.26. *A subset of a continuum C consisting of one point has no limit points.*

Proof. Let A be a subset of continuum C with only one element. Consider the possibility that the single element $p \in A$ is the limit point. Then, no matter the choice of I with $p \in I$, $I \cap (A \setminus \{p\}) = \emptyset$. Now consider any point $p \notin A$ as a potential limit point of A . Let $a \in A$. Since a and p are distinct, by theorem 3.25, there must exist disjoint intervals I_1 and I_2 such that $a \in I_1$ and $p \in I_2$. Since $A \setminus \{p\} \subset A$, and because A only has one element which is contained in I_1 , $A \setminus \{p\} \subset A \subset I_1$. Because I_1 and I_2 are disjoint, $A \setminus \{p\} \cap I_2 = \emptyset$, and since $p \in I_2$, p cannot be a limit point of A . \square

Theorem 3.27. *A finite subset A of a continuum C has no limit points.*

Proof.] This will be proven by induction on a set A with n elements. The base case is the case in which A only has one element, and corollary 3.26 ensure that this set cannot have a limit point. The induction hypothesis is that any set with n elements does not have any limit points. Let A have $n + 1$ elements. By theorem 3.9, each element of A can be assigned a symbol a_1, \dots, a_{n+1} . The set A can be rewritten as $A \setminus \{a_{n+1}\} \cup \{a_{n+1}\}$, where $A \setminus \{a_{n+1}\}$ has n elements by lemma 3.7. By the induction hypothesis $A \setminus \{a_{n+1}\}$ cannot have any limit points, and since $\{a_{n+1}\}$ cannot have any limit points by corollary 3.26, by theorem 3.23, $(A \setminus \{a_{n+1}\}) \cup \{a_{n+1}\}$ cannot have any limit points either. Therefore, by induction, no finite set can have limit points. \square

Corollary 3.28. *If A is a finite subset of a continuum C and $x \in A$, then there exists an interval R , containing x , such that $A \cap R = \{x\}$.*

Proof. Consider any point $x \in A$ and some interval I such that $x \in I$. By the definition of intersection, $x \in I \cap A$. Since A is finite, by theorem 3.28, it must not have any limit points. By definition 3.15, this means that $I \cap A \setminus \{x\} = \emptyset$. For $I \cap A \setminus \{x\} = \emptyset$ to be true, there must

be no other element $y \in C$ such that $y \in I$, $y \in A$, and $y \neq x$. It therefore must be true that $I \cap A = \{x\}$. \square

Theorem 3.29. *If p is a limit point of A and I is an interval containing p , then the set $I \cap A$ is infinite.*

Proof. The set A can be rewritten as $A = (A \cap I) \cup (A \setminus I)$. It must be true that $I \cap (A \setminus I) = \emptyset$, and since $p \in I$, p cannot be a limit point of $A \setminus I$. By theorem 3.23, p must be a limit point of $(A \cap I)$, and therefore by theorem 3.27, cannot be finite. \square

3.1. Building a continuum: defining \mathbb{R} . We take it for granted that we have the rational numbers:

$$\mathbb{Q} = \{a/b : a \in \mathbb{Z}, b \in \mathbb{N}\}.$$

This inherits an ordering from the one on \mathbb{Z} :

$$\frac{a}{b} < \frac{c}{d} \quad \text{if and only if} \quad ad < bc.$$

Definition 3.30. *A (Dedekind) cut is a set $A \subset \mathbb{Q}$ such that*

- (i) $A \neq \mathbb{Q}, \emptyset$;
- (ii) *there is no largest point: if $a \in A$, there is a point $a' \in A$ such that $a < a'$;*
- (iii) *if $a \in A$ and $b \in \mathbb{Q}$ satisfies $b < a$, then $b \in A$.*

Let us denote \mathbb{R} to be the set of cuts.

It may seem strange that we are defining \mathbb{R} here. Surely, we already know what it is!? Actually, the more you think about it, the more you will have trouble pinning down an actual definition of the real numbers. This is one approach to it (the other one is related to taking the “completion” of a metric space, which we discuss during the semester). As you go through these exercises, you may find it interesting to think about how real numbers that you “know,” like $\sqrt{2}$ and π , could be defined using cuts.

Theorem 3.31. *For any $A, B \in \mathbb{R}$, we define $<$ by*

$$A < B \quad \text{if and only if} \quad A \subsetneq B.$$

Show that $<$ is an ordering on \mathbb{R} .

Proof. Let $A, B \in \mathbb{R}$ be any cuts. If there exists $b \in B$ such that for all $a \in A$ $a < b$, then by definition 3.30 part (iii), $a \in B$. So for all $a \in A$, $a \in B$, which means $A \subset B$ or $A < B$. Without the loss of generality, it is similarly possible to show that $B \subset A$ or $B < A$.

If it is simultaneously true that for any choice $a \in A$ there exists $b \in B$ such that $a < b$ and that for any choice of $b' \in B$ there exists $a' \in A$ such that $a' > b'$, then by definition 3.30 part (iii) any element of A is also in B and any element of B is also in A . These cuts must therefore be equal.

Together, this shows $<$ satisfies definition 3.2 (a).

Let $A, B, C \in \mathbb{R}$ be cuts with $A < B$ and $B < C$. Therefore, $A \subset B$ and $B \subset C$, and $A \subset C$ as a result, thereby satisfying definition 3.2 (b). Because $<$ contains all properties of an ordering, $<$ is an ordering on \mathbb{R} . \square

Definition 3.32. *If a cut C_a has the form*

$$C_a = \{b \in \mathbb{Q} : b < a\}$$

for some $a \in \mathbb{Q}$, we call C_a a rational cut. Let $C_{\mathbb{Q}}$ be the set of all rational cuts.

Lemma 3.33. *Given $a \in \mathbb{Q}$, show that C_a is a cut; that is, $C_a \in \mathbb{R}$.*

Proof. Let $b, c \in \mathbb{Q}$ with $b < a$ and $c > a$. Then by Definition 3.32, $b \in C_a$ while $c \notin C_a$, so C_a is nonempty and not all of \mathbb{Q} . This satisfies Definition 3.30 part (i) of a cut.

Using the same b defined above, define $a' = (b + a)/2$. Then, $a' \in \mathbb{Q}$ and must be between b and a . Since the choice of b was arbitrary, it is always possible to find a larger value in C_a , thus C_a satisfies Definition 3.30 (ii).

Again using the same b defined above, define $d \in \mathbb{Q}$ such that $d < b$. Since $d < b$ and $b < a$, $d < a$ and by definition of C_a , $d \in C_a$. Therefore, C_a satisfies definition 3.30 (iii).

Since C_a satisfies all properties of a cut, C_a must be a cut. \square

Theorem 3.34. *Show that \mathbb{R} is nonempty and has no first or last point.*

Proof. Fix $a \in \mathbb{Q}$. By Lemma 3.32, for any $q \in \mathbb{Q}$, C_q must exist, so C_a must exist. Therefore \mathbb{R} is nonempty.

To show that \mathbb{R} has no first point, assume for contradiction that it does have first point or first cut. Let this cut be defined as $C_f \in \mathbb{R}$. Since C_f must be nonempty, there must exist some point $p \in C_f$ where $p \in \mathbb{Q}$. Since $p \in \mathbb{Q}$, by Lemma 3.33, we can form a rational cut C_p . Seeing as every $x \in C_p$ must be less than p , and $p \in C_f$, every $x \in C_f$ as well. Since C_f has no largest point, there must also exist $q \in C_f$ where $p < q$, and $q \notin C_p$. Therefore, $C_p \prec C_f$, contradicting that C_f is the first cut of \mathbb{R} , so \mathbb{R} must not have a first point.

To show that \mathbb{R} has no last point, assume for contradiction that it does have a last point or last cut. Let this cut be defined as $C_l \in \mathbb{R}$. Since no cut can be all of \mathbb{Q} , $\mathbb{Q} \setminus C_l$ is nonempty. Let $d \in \mathbb{Q} \setminus C_l$. \square

Exercise 3.35. *Show that*

$$\{C \in \mathbb{R} : C \text{ is a rational cut}\} \subsetneq \mathbb{R}.$$

Think about how the set on the left hand side is a “copy” of \mathbb{Q} . More formally, find $\varphi : \mathbb{Q} \rightarrow C_{\mathbb{Q}}$ that is bijective, increasing (that is, $\varphi(a_1) \prec \varphi(a_2)$ if $a_1 < a_2$), and that $C_{\mathbb{Q}} \neq \mathbb{R}$.

Solution. To show that $\{C \in \mathbb{R} : C \text{ is a rational cut}\} \subsetneq \mathbb{R}$, I claim that $C_{\sqrt{2}} = \{x \in \mathbb{Q} : x < 0 \text{ or } x^2 < 2\}$ is a cut which is distinct from any rational cut.

Consider $-1, 2 \in \mathbb{Q}$. Since $-1 < 0$, $-1 \in C_{\sqrt{2}}$, and $2^2 > 2$ so $2 \notin C_{\sqrt{2}}$. Therefore, $C_{\sqrt{2}}$ is nonempty and not all of \mathbb{Q} , satisfying Definition 3.30 (i).

Consider any $a \in \mathbb{Q}$ and $a < 0$ or $a^2 < 2$. From our definition of $C_{\sqrt{2}}$, $a \in C_{\sqrt{2}}$. Since \mathbb{Q} is unbounded, there must always exist $b \in \mathbb{Q}$ such that $b < a$. Therefore, either $b < 0$ or $b^2 < 2$ so $b \in C_{\sqrt{2}}$, which satisfies Definition 3.30 (iii).

To show that there is no largest element of $C_{\sqrt{2}}$, let $a \in C_{\sqrt{2}}$. Consider $(a + 1/n)$ where n is some $n \in \mathbb{N}$. Squaring gives

$$\begin{aligned} (a + 1/n)^2 &= a^2 + 2a/n + 1/n^2 \\ &< a^2 + 2a/n + 1/n \\ &= a^2 + (2a + 1)/n \end{aligned}$$

I claim that there must exist $n_0 \in \mathbb{N}$ such that $a^2 + (2a + 1)/n_0 < 2$. Rearranging this equality gives

$$(2a + 1)/(2 - a^2) < n_0.$$

This n_0 must exist as $2 - a^2 > 0$ and \mathbb{N} is unbounded.

Since

$$a^2 + (2a + 1)/n_0 < 2,$$

and

$$\begin{aligned} (a + 1/n_0)^2 &< a^2 + (2a + 1)/n_0 \\ (a + 1/n_0)^2 &< 2. \end{aligned}$$

Therefore, there is no largest element of $C_{\sqrt{2}}$, which satisfies Definition 3.30 (ii), and $C_{\sqrt{2}}$ is a cut.

What remains to be shown is that $C_{\sqrt{2}}$ is distinct from any rational cut. Which means there must exist no closest element $q \in \mathbb{Q}$ where for every $b \in \mathbb{Q}$ such that $b < \sqrt{2}$, it is also true that $b < q$.

Let $a \in \mathbb{Q}$ be any element such that $2 < a^2$. Consider some smaller element $(a - 1/n)$ where $n \in \mathbb{N}$. Squaring this smaller element gives

$$\begin{aligned}(a - 1/n)^2 &= a^2 - 2a/n + 1/n^2 \\ &> a^2 - 2a/n.\end{aligned}$$

I claim there must exist $n_0 \in \mathbb{N}$ such that $a^2 - 2a/n_0 > 2$. Rearranging this equality gives

$$n_0 > 2a/(a^2 - 2).$$

Since $a^2 - 2$ must be positive and \mathbb{N} is unbounded, n_0 must exist. Therefore,

$$a^2 - 2a/n_0 > 2.$$

Since

$$(a - 1/n_0)^2 > a^2 - 2a/n_0,$$

it must be true that

$$(a - 1/n_0)^2 > 2.$$

Thus, for every $q \in \mathbb{Q}$ where $q > \sqrt{2}$, there exists $b \in \mathbb{Q}$ such that $b < q$ and $b > \sqrt{2}$. So $b \in C_q$ and $b \notin C_{\sqrt{2}}$. Therefore, $C_{\sqrt{2}} \notin \{C \in \mathbb{R} : C \text{ is a rational cut}\}$, and $\{C \in \mathbb{R} : C \text{ is a rational cut}\} \subsetneq \mathbb{R}$. \square

4. ADDING A TOPOLOGY

In this sheet we give a continuum C a topology. Roughly speaking, this is a way to describe how the points of C are ‘glued together’.

Definition 4.1. A subset of a continuum is closed if it contains all of its limit points.

Theorem 4.2. The sets \emptyset and C are closed.

Proof. Since the empty set has no points, it cannot have any limit points. Therefore, there exists no limit point p where $p \in \emptyset$. The empty set is therefore closed.

Let p be any limit point of a continuum C . By Definition 3.15, $p \in C$. Therefore, C is closed. \square

Theorem 4.3. A subset of C containing a finite number of points is closed.

Proof. Let A be any finite subset of C . By Theorem 3.27, A does not have any limit points. Therefore, there exists no limit point p where $p \notin A$. The empty set is therefore closed. \square

Definition 4.4. Let X be a subset of C . The closure of X is the subset \overline{X} of C defined by:

$$\overline{X} = X \cup LP(X).$$

Theorem 4.5. For any $X \subset C$, X is closed if and only if $X = \overline{X}$.

Proof. Let $X = \overline{X}$. Then by the definition of closure, $LP(X) \subset X$, and X is closed.

Let X be closed. For any point p in $LP(X)$ it must be true that $p \in X$. Therefore, $LP(X) \subset X$ and $X \cup LP(X) = X$. However this is definition of closure, so $X = \overline{X}$.

Since both statements imply the other, the proof is complete. \square

Theorem 4.6. The closure of $X \subset C$ satisfies $\overline{X} = \overline{\overline{X}}$.

Proof. By the definition of closure, $\overline{\overline{X}} = \overline{X} \cup LP(\overline{X})$. To arrive at the desired conclusion, it needs to be shown that $LP(\overline{X}) \subset \overline{X}$, and thereby $\overline{X} \cup LP(\overline{X}) = \overline{X}$.

Since $\overline{X} = X \cup LP(X)$, if $p \in LP(\overline{X})$, p must be a limit point of X or a limit point of $LP(X)$ by Theorem 3.23. Consider any limit point p of $LP(X)$, and assume for contradiction that p is not a limit point of X . By Definition 2.15, there must exist I_p with $p \in I_p$ where

$$I_p \cap (LP(X) \setminus \{p\}) \neq \emptyset \text{ and } I_p \cap (X \setminus \{p\}) = \emptyset.$$

Let $y \in I_p \cap (LP(X) \setminus \{p\})$. It must be true that $y \in I_p$ and $y \in LP(X)$. Therefore, y is a limit point of X and for every interval I where $y \in I$ it is true that

$$I \cap (X \setminus \{y\}) \neq \emptyset.$$

However, $y \in I_p$ so it must be true that

$$I_p \cap (X \setminus \{y\}) = \emptyset,$$

producing a contradiction. Therefore, any limit point of $LP(X)$ must be a limit point of X , and

$$LP(\overline{X}) = LP(X).$$

Hence,

$$LP(\overline{X}) \subset \overline{X},$$

so

$$\begin{aligned} \overline{\overline{X}} &= \overline{X} \cup LP(\overline{X}) \\ \overline{\overline{X}} &= \overline{X}. \end{aligned}$$

□

Corollary 4.7. *Given any subset $X \subset C$, the closure \overline{X} is closed.*

Proof. By Theorem 4.6, $\overline{X} = \overline{\overline{X}}$, so by Theorem 4.5, \overline{X} is closed. □

Definition 4.8. *A subset G of a continuum C is open if its complement $C \setminus G$ is closed.*

Theorem 4.9. *The sets \emptyset and C are open.*

Proof. The complement of C is the empty set. Since C is closed by Theorem 4.2, the \emptyset is open by Definition 4.8. But the complement of the empty set is C . Since by Theorem 4.2, the \emptyset is closed, by Definition 4.8, C is open. □

The following is a very useful criterion to determine whether a set of points is open.

Theorem 4.10. *Let $G \subset C$. Then G is open if and only if for all $x \in G$, there exists an interval I such that $x \in I \subset G$.*

Proof. If G is open, then by Definition 4.8, the complement $C \setminus G$ is closed and contains all of its limit points. Let $x \in G$. Since $x \notin C \setminus G$, there must exist an interval I such that $x \in I$ and $I \cap (C \setminus G) \setminus \{x\} = \emptyset$. Therefore, $I \subset G$, proving the forward relation.

To prove the reverse implication, consider any $x \in G$ and let $x \in I$ where $I \subset G$. It follows that $I \cap (C \setminus G) = \emptyset$. It then must be true that $I \cap ((C \setminus G) \setminus \{x\}) = \emptyset$. Therefore, x cannot be a limit point of $C \setminus G$. Since x is any element of G , no element of G can be a limit point of $C \setminus G$. Therefore, if $C \setminus G$ has any limit points, they must be contained in the set $C \setminus G$ and $C \setminus G$ is closed. By Definition 4.8, G must be open, thus proving the reverse relation. □

Corollary 4.11. *Every interval I is open. Every complement of an interval, $C \setminus I$, is closed.*

Proof. For I to be open, by Theorem 4.10, for every point $x \in I$ there must exist some interval I_x where $x \in I_x$ and $I_x \subset I$. Seeing as $x \in I$ and $I \subset I$, any interval I satisfies this definition, and is open. Therefore, by Definition 4.8, $C \setminus I$ is closed. □

Corollary 4.12. *Let $G \subset C$. Then G is open if and only if for all $x \in G$, there exists a subset $V \subset G$ such that $x \in V$ and V is open.*

Proof. Let G be open. By Theorem 3.10, for every point $x \in G$, there exists an interval I such that $x \in I \subset G$. Since I is an open set by Corollary 4.11, this satisfies the reverse implication condition.

To prove the forward implication, for all $x \in G$, let there exist a subset $V \subset G$ such that $x \in V$ and V is open. Since V is open and $x \in V$, by Definition 4.10, there must exist an interval I_x where $x \in I_x$ and $I_x \subset V$. Since $V \subset G$, it follows that $I_x \subset G$. Therefore for all $x \in G$, there exists an interval I_x where $x \in I_x$ and $I_x \subset G$, and G is open by Definition 4.10. \square

Corollary 4.13. *Let $a \in C$. Then the sets $\{x \mid x < a\}$ and $\{x \mid a < x\}$ are open.*

Proof. Consider any $b \in \{x \mid x < a\}$. It must be true that $b - 1 \in \{x \mid x < a\}$. Therefore, the interval $(b - 1, a)$ exists, with $b \in (b - 1, a)$ and $(b - 1, a) \subset \{x \mid x < a\}$. Since the choice of b can be any element of $\{x \mid x < a\}$, the set is therefore open by Theorem 4.10.

Consider any $b \in \{x \mid x > a\}$. It must be true that $b + 1 \in \{x \mid x > a\}$. Therefore, the interval $(a, b + 1)$ exists, with $b \in (a, b + 1)$ and $(a, b + 1) \subset \{x \mid x > a\}$. Since the choice of b can be any element of $\{x \mid x > a\}$, the set is therefore open by Theorem 4.10. \square

Theorem 4.14. *Let G be a nonempty open set. Then G is the union of a collection of intervals.*

Proof. Since G is open, for every $x \in G$ there exists some interval I_m , where $x \in I_m$ and $I_m \subset G$. Let \mathcal{I} be the family of these sets so

$$\mathcal{I} = \{I_m \subset G \mid x \in G \text{ and } x \in I_m\}.$$

Therefore, the union of every set in \mathcal{I} must contain every element of G , so

$$G \subset \bigcup_m I_m.$$

. Since each set I_m is a subset of G ,

$$\bigcup_m I_m \subset G.$$

Therefore, G is the union of intervals. \square

Exercise 4.15. *Do there exist subsets $X \subset C$ that are neither open nor closed?*

Theorem 4.16. *Let $\{X_\lambda\}$ be an arbitrary collection of closed subsets of a continuum C . Then the intersection*

$$\bigcap_\lambda X_\lambda$$

is closed.

Theorem 4.17. *Let G_1, \dots, G_n be a finite collection of open subsets of a continuum C . Then the intersection $G_1 \cap \dots \cap G_n$ is open.*

Exercise 4.18. *Is it necessarily the case that the intersection of an infinite number of open sets is open? Is it possible to construct an infinite collection of open sets whose intersection is not open? Equivalently, is it possible to construct an infinite collection of closed sets whose union is not closed?*

Corollary 4.19. *Let $\{G_\lambda\}$ be an arbitrary collection of open subsets of a continuum C . Then the union $\bigcup_\lambda G_\lambda$ is open. Let X_1, \dots, X_n be a finite collection of closed subsets of a continuum C . Then the union $X_1 \cup \dots \cup X_n$ is closed.*

Theorem 4.14 says that every nonempty open set is the union of a collection of intervals. This necessary condition for open sets is also sufficient:

Corollary 4.20. *Let $G \subset C$ be nonempty. Then G is open if and only if G is the union of a collection of intervals.*

Corollary 4.21. *If (a, b) is an interval in C , then $\text{ext}(a, b)$ is open.*

Definition 4.22. *Let $X \subset C$. Then X is disconnected if it may be written as $X = A \cup B$, where A and B are disjoint, non-empty open sets in X . We say that X is connected if it is not disconnected.*

Exercise 4.23. *Let C be a continuum and $a \in C$. Prove that $C \setminus \{a\}$ is a disconnected continuum.*

5. CONNECTEDNESS AND BOUNDEDNESS

Axiom 5.1. *A continuum is connected.*

Theorem 5.2. *The only subsets of a continuum C that are both open and closed are \emptyset and C .*

Theorem 5.3. *For all $x, y \in C$, if $x < y$, then there exists $z \in C$ such that z is in between x and y .*

Corollary 5.4. *Every interval is infinite.*

Corollary 5.5. *Every point of C is a limit point of C .*

Corollary 5.6. *Every point of an interval (a, b) is a limit point of (a, b) .*

We will now introduce boundedness. The first definition should be intuitively clear. The second is subtle and powerful.

Definition 5.7. *Let X be a subset of C . A point u is called an upper bound of X if for all $x \in X$, $x \leq u$. A point l is called a lower bound of X if for all $x \in X$, $l \leq x$. If there exists an upper bound of X , then we say that X is bounded above. If there exists a lower bound of X , then we say that X is bounded below. If X is bounded above and below, then we simply say that X is bounded.*

Definition 5.8. *Let X be a subset of C . We say that u is a least upper bound or supremum of X and write $u = \sup X$ if:*

- (1) u is an upper bound of X , and
- (2) if u' is an upper bound of X , then $u \leq u'$.

We say that l is a greatest lower bound or infimum and write $l = \inf X$ if:

- (1) l is a lower bound of X , and
- (2) if l' is a lower bound of X , then $l' \leq l$.

Exercise 5.9. *If $\sup X$ exists, then it is unique, and similarly for $\inf X$.*

The following lemma is extremely useful when dealing with suprema; an analogous statement can be made for infima.

Lemma 5.10. *Suppose that $X \subset C$ and $s = \sup X$. If $p < s$, then there exists an $x \in X$ such that $p < x \leq s$.*

Theorem 5.11. *Let $a < b$. The least upper bound and greatest lower bound of the interval (a, b) are:*

$$\sup(a, b) = b \quad \text{and} \quad \inf(a, b) = a.$$

Lemma 5.12. *Let X be a subset of C . Suppose that $\sup X$ exists and $\sup X \notin X$. Then $\sup X$ is a limit point of X . The same holds for $\inf X$.*

Corollary 5.13. *Both a and b are limit points of the interval (a, b) .*

Let $[a, b]$ denote the closure $\overline{(a, b)}$ of the interval (a, b) .

Corollary 5.14. *The closed interval $[a, b] = \{x \in C \mid a \leq x \leq b\}$.*

Lemma 5.15. *Let $X \subset C$ and define:*

$$\Psi(X) = \{x \in C \mid x \text{ is not an upper bound of } X\}.$$

Then $\Psi(X)$ is open. Define:

$$\Omega(X) = \{x \in C \mid x \text{ is not a lower bound of } X\}.$$

Then $\Omega(X)$ is open.

Theorem 5.16. *Suppose that X is nonempty and bounded above. Then $\sup X$ exists. Similarly, if X is nonempty and bounded below, then $\inf X$ exists.*

Corollary 5.17. *Every nonempty closed and bounded set has a first point and a last point.*

Exercise 5.18. *Is this true for \mathbb{Q} ?*

5.1. Building a continuum: the real numbers are connected.

Exercise 5.19. *Show that \mathbb{Q} is not connected.*

Lemma 5.20. (i) *Suppose that $\mathcal{A} \subset \mathbb{R}$ is bounded from above. Show that \mathcal{A} has a supremum.*
(ii) *Suppose that $\mathcal{A} \subset \mathbb{R}$ is bounded from below. Show that \mathcal{A} has an infimum.*

Lemma 5.21. *Suppose that \mathcal{A} is an open set in \mathbb{R} , and let $A \in \mathcal{A}$. If there is $\underline{B}, \overline{B} \in \mathbb{R}$ such that $\underline{B} < A < \overline{B}$, then there are points $P_1, P_2 \in \mathbb{R} \setminus \mathcal{A}$ such that*

$$A \in (P_1, P_2) \quad \text{and} \quad (P_1, P_2) \subset \mathcal{A}.$$

Theorem 5.22. *Show that \mathbb{R} is connected.*

At this point, we see that \mathbb{R} is a continuum. (Side note: can you think of any other sets that satisfy the axioms of a continuum?) All previous results, thus, apply to it. If you feel inclined, think about how our usual actions of addition, subtraction, multiplication, and division can be defined using the Dedekind cuts. From this point on, we can always imagine C to be \mathbb{R} . This is not necessary, but it may help with intuition.

6. COMPACTNESS

Definition 6.1. *Let X be a subset of C and let $\mathcal{G} = \{G_\lambda\}_{\lambda \in \Lambda}$ be a collection of subsets of C . We say that \mathcal{G} is a cover of X if every point of X is in some G_λ , or in other words:*

$$X \subset \bigcup_{\lambda \in \Lambda} G_\lambda.$$

We say that the collection \mathcal{G} is an open cover if each G_λ is open.

Definition 6.2. *Let X be a subset of C . X is compact if for every open cover \mathcal{G} of X , there exists a finite subset $\mathcal{G}' \subset \mathcal{G}$ that is also an open cover.*

A good summary of the definition of compactness is “every open cover contains a finite subcover”.

Exercise 6.3. *Show that all finite subsets of C are compact.*

Lemma 6.4. *No finite collection of intervals covers C .*

Theorem 6.5. *C is not compact.*

Exercise 6.6. *Show that intervals are not compact.*

Theorem 6.7. *If X is compact, then X is bounded.*

Lemma 6.8. *Let $X \subset C$ and $p \in C \setminus X$. Then*

$$\mathcal{G} = \{\text{ext}(a, b) \mid (a, b) \text{ contains } p\}$$

is an open cover of X .

Theorem 6.9. *If X is compact, then X is closed.*

It will turn out that the two properties of compactness in Theorem 6.7 and Theorem 6.9 characterize compact sets completely (at least in C), meaning that every bounded closed set is compact. The rest of the sheet is concerned with proving this fact.

For the next three results, fix points $a, b \in C$ and suppose \mathcal{G} is an open cover of $[a, b]$.

Lemma 6.10. *For all $s \in [a, b]$, there exist $G \in \mathcal{G}$ and $p, q \in C$ such that $p < s < q$ and $[p, q] \subset G$.*

Definition 6.11. *Fix $\bar{x} \in C$. We say that \bar{x} is reachable from a if there exist $n \in \mathbb{N} \cup \{0\}$, $x_0, \dots, x_n \in C$, and $G_1, \dots, G_n \in \mathcal{G}$ such that*

$$a = x_0 < x_1 < \dots < x_{n-1} < x_n = \bar{x}$$

and

$$[x_{i-1}, x_i] \subset G_i \quad \text{for each } i \in \{1, 2, \dots, n\}.$$

Theorem 6.12. *Let X be the set of all $\bar{x} \in C$ that are reachable from a . Then the point b is not an upper bound for X .*

Corollary 6.13. *There is a finite subset $\mathcal{G}' \subset \mathcal{G}$ that is a cover of $[a, b]$.*

Corollary 6.14. *The set $[a, b]$ is compact.*

This last corollary is the main ingredient for the proof of the Heine-Borel theorem.

Lemma 6.15. *A closed subset Y of a compact set $X \subset C$ is compact.*

Theorem 6.16. *If $X \subset C$, then X is compact if and only if X is closed and bounded.*

Lemma 6.17. *A compact set $X \subset C$ with no limit points must be finite.*

Theorem 6.18. *Every bounded infinite subset of C has at least one limit point.*