

Math 1010: Analysis *Lecture Notes*

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These are lecture notes for “Math 1010: Analysis: Functions of One Variable” taught at BROWN UNIVERSITY by Javi Gómez Serrano in the Spring of 2023.

These notes are taken by Jiahua Chen with gracious help and input from classmates. Please direct any mistakes/errata to me via [email](#), or feel free to pull request the notes repository (<https://github.com/jchen/math1010-notes>).

Notes last updated February 16, 2023.

Contents

§1 January 26, 2023

§1.1 Introductions

Instructor: Javi Gómez Serrano. Email: javier_gomez_serrano@brown.edu.

Text: *Principles of Mathematical Analysis*¹, W. Rudin [?]. We will cover select chapters of this book. If the pace is too fast, bring it up.

Structure: Biweekly HW with problems from the book and extra problems. Homework posted Thursdays. Roughly 6 homework assignments (maybe 5, or 7). Worst homework will be dropped.

Midterm and final, in class (TBA). There will additionally be 2 quizzes (20 minutes each), which should be extremely easy. There are 2 questions from the quizzes: one will literally be a problem from the homework, and one will be a definition.

Grading potentially returned by Tuesday following submission. Grading is as follows: 30% problem sets, 10% quizzes, 25% midterm, 35% final. There will be a curve.

Office Hours: Kassir 314, Monday 5-7pm.

§1.2 Fundamentals

§1.2.1 Sets

Definition 1.1 (Set)

One can think of a set as a collection of objects.

If a is an object, and A is a set. $a \in A$ means that a is a member of A .

Definition 1.2 (Subsets)

If A, B are sets, we say that A is a subset of B (we write $A \subset B$ ²) whenever $a \in A \implies a \in B$.

A is a proper subset of B if $A \subset B$ and $A \neq B$.

Remark 1.3. \emptyset is the set with no elements. \emptyset is a subset of *every* set.

¹Find online using *appropriate channels*.

²Some also write $A \subseteq B$.

Definition 1.4 (Union)

If A, B are sets, $A \cup B$ is the union of A and B .

$$A \cup B \stackrel{\text{def}}{=} \{a \mid a \in A \text{ or } a \in B\}$$

Definition 1.5 (Intersection)

If A, B are sets, $A \cap B$ is the intersection of A and B .

$$A \cap B \stackrel{\text{def}}{=} \{a \mid a \in A \text{ and } a \in B\}$$

We can generalize this to an arbitrary number of sets:

Definition 1.6 (Generalization of Union/Intersection)

If \mathcal{C} is a collection of sets (possibly infinite). Then

$$\bigcup_{A \in \mathcal{C}} A \stackrel{\text{def}}{=} \{a \mid a \in A \text{ for some } A \in \mathcal{C}\}$$

and

$$\bigcap_{A \in \mathcal{C}} A \stackrel{\text{def}}{=} \{a \mid a \in A \text{ for all } A \in \mathcal{C}\}.$$

Definition 1.7 (Disjunction)

We say that A and B are disjoint if $A \cap B = \emptyset$.

Proposition 1.8 (Distribution over intersection and union)

The following is true:

1. $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$
2. $A \cup (B \cap C) = (A \cup B) \cap (A \cup C)$

Proof of statement 1. We prove that the sets on the left are contained in the sets on the right, and the sets on the right are contained on the sets on the left. That is, $X \subset Y$ and $Y \subset X \Rightarrow X = Y$.

Case $A \cap (B \cup C) \subset (A \cap B) \cup (A \cap C)$: Let $a \in A \cap (B \cup C)$. Then $a \in A$ and $a \in (B \cup C)$. So $a \in B$ or $a \in C$.

Suppose $a \in B$, then $a \in A \cap B$ so $a \in (A \cap B) \cup (A \cap C)$. Suppose $a \in C$, then $a \in A \cap C$ so still $a \in (A \cap B) \cup (A \cap C)$.

Regardless, this is precisely the set on the right.

Case $(A \cap B) \cup (A \cap C) \subset A \cap (B \cup C)$: Let $a \in (A \cap B) \cup (A \cap C)$. Then $a \in (A \cap B)$ or $a \in (A \cap C)$.

If $a \in (A \cap B)$, then $a \in A$ and $a \in B$, so $a \in A$ and $a \in B \cup C$, so $a \in A \cap (B \cup C)$.

If $a \in (A \cap C)$, then $a \in A$ and $a \in C$, so $a \in A$ and $a \in B \cup C$, so still $a \in A \cap (B \cup C)$.

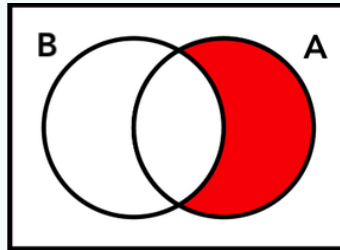
Again, regardless, $a \in A \cap (B \cup C)$.

Having proven containment in both directions, we conclude the sets on the left and right are equal. \square

Definition 1.9 (Set Difference)

We define the difference $A \setminus B$ as

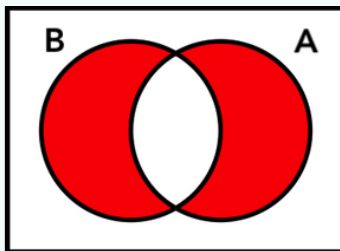
$$A \setminus B = \{a \mid a \in A, a \notin B\}.$$



Definition 1.10 (Symmetric Difference)

We define the symmetric difference

$$A \triangle B = (A \setminus B) \cup (B \setminus A).$$



Definition 1.11 (Set Product)

We define the product of A and B as

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

§1.2.2 Relations**Definition 1.12 (Relations)**

A relation R between sets A and B is any subset of $A \times B$.

If $(a, b) \in R$, we will think of a “being related” to b .

For now, consider $A = B$. We define a special set of relations.

Definition 1.13 (Reflexive/Symmetric/Transitive Relations)

We have the following definitions:

1. R is reflexive iff $(a, a) \in R, \forall a \in A$.³
2. R is symmetric iff whenever $(a_1, a_2) \in R$, then $(a_2, a_1) \in R$.
3. R is transitive iff whenever $(a_1, a_2) \in R$, and $(a_2, a_3) \in R$, then $(a_1, a_3) \in R$.

Definition 1.14 (Equivalence Relation)

A relation R that satisfies all conditions 1-3 in ?? is called an equivalence relation.

Definition 1.15 (Equivalence Class)

Given an element $a \in A$ with relation R , we write

$$[a]_R \stackrel{\text{def}}{=} \{a' \in A \mid (a, a') \in R\}$$

as the equivalence class of a (the set of all elements that are ‘related’ to a).

Remark 1.16. Instead of writing $(a, a') \in R$, we write $a \sim_R a'$ or $a \sim a'$.

³ \forall is to say ‘for all’.

Proposition 1.17 (Distinct Equivalence Classes are Disjoint)

If R be an equivalence relation on A . Suppose $a_1, a_2 \in A$. Then, either

$$[a_1]_R = [a_2]_R \quad \text{or} \quad [a_1]_R \cap [a_2]_R = \emptyset$$

Proof. We show that these statements cannot happen simultaneously, and that one or the other *must* be true.

The former is as follows: notice $a_1 \in [a_1]_R$ because $a_1 \sim a_1$ by R reflexive. Since $[a_1]_R = [a_2]_R$, then $a_1 \in [a_1]_R \cap [a_2]_R$. This implies that the intersection $[a_1]_R \cap [a_2]_R$ is nonempty, which is a contradiction.

We now show that at least one has to happen. If $a_1 \in [a_1]_R \cap [a_2]_R = \emptyset$, we are done. Otherwise, if $a_1 \in [a_1]_R \cap [a_2]_R \neq \emptyset$, then $\exists^4 a \in A$ such that $a \in [a_1]_R$ and $a \in [a_2]_R$.

We claim WLOG $[a]_R = [a_1]_R$. Suppose $a' \in [a]_R$, then $(a, a') \in R$. Since $(a, a') \in R$ and $(a_1, a) \in R$ (due to $a \in [a_1]_R$), transitivity gives $(a_1, a') \in R$ so $a' \in [a_1]_R$. Let's otherwise suppose $a' \in [a_1]_R$, so $(a_1, a') \in R$. Reflexivity gives $(a, a_1) \in R$ ($(a_1, a) \in R$ by $a \in [a_1]_R$), and by transitivity $(a, a_1) \in R$ and $(a_1, a') \in R$ gives $(a, a') \in R$ so $a' \in [a]_R$.⁵

By symmetry, $[a]_R = [a_2]_R$, so $[a_1]_R = [a]_R = [a_2]_R$ which is as desired. \square

Essentially, what we have shown, is that we can partition a set according to equivalence classes. All equivalence classes are either going to be the same or different. This is, equivalence relations form a *partition* of a set. We can construct a set of partitions (disjoint subsets) of a set S . That is, “equivalence classes partition A .”

Definition 1.18 (Partition)

A partition of A is a collection \mathcal{P} of subsets of A such that

1. $A = \bigcap_{S \in \mathcal{P}} S$,
2. $S_i \cap S_j = \emptyset$ if $S_i \neq S_j$ for each $S_i, S_j \in \mathcal{P}$.

With this definition, if R is an equivalence relation, then $\mathcal{C}_R = \{[a]_R \mid a \in A\}$ is a partition of A .

We'll use all of this to define a function (which is the whole purpose of this course).

§1.2.3 Functions

⁴ \exists is to denote ‘there exists’.

⁵Wow, this is quite dense but the idea is to chain reflexivity and transitivity to get everything related to one another.

Definition 1.19 (Function)

Let A, B be sets and f be a relation between A and B .

We say f is a function from A to B and we write $f : A \rightarrow B$ iff the following holds:

1. $\forall a \in A$, there exists *at least* one $b \in B$ s.t. $(a, b) \in f$. (all elements have an image)
2. $\forall a \in A$, there exists *at most* one $b \in B$ s.t. $(a, b) \in f$. (all elements have only one image)

We write $f(a) = b$, and b is the image of a by f . We call A the domain of f , and B the codomain of f ⁶.

⁶I like to denote B the codomain and the actual set of images the *image* of f . And ‘range’ is just ambiguous it seems.

§2 January 31, 2023

§2.1 Properties of Functions

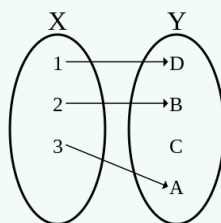
We introduce some properties of functions:

Definition 2.1 (Injectivity)

A function $f : A \rightarrow B$ is injective (one-to-one) if

$$f(a_1) = f(a_2) \implies a_1 = a_2.$$

“No two elements in A map to the same element in B .”



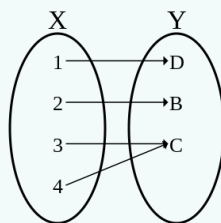
(Using X and Y , injective but not surjective.)

Definition 2.2 (Surjectivity)

A function $f : A \rightarrow B$ is surjective (onto) if

$$\forall b \in B, \exists a \in A, \text{ s.t. } f(a) = b.$$

“Every element in B has a preimage in A .”



(Using X and Y , surjective but not injective.)

Definition 2.3 (Functional Composition)

Suppose $f : A \rightarrow B$ and $g : B \rightarrow C$ are functions, then $(g \circ f) : A \rightarrow C$ with

$$(g \circ f)(a) := g(f(a)).$$

Proposition 2.4

Let $f : A \rightarrow B$, $g : B \rightarrow C$ be functions, then if f, g are both injective, then so is $(g \circ f)$.

The same holds if they are surjective.

Proof of injective part. Let $a, a' \in A$ be such that

$$\begin{aligned}(g \circ f)(a) &= (g \circ f)(a') \\ g(f(a)) &= g(f(a'))\end{aligned}$$

With g injective, therefore

$$f(a) = f(a')$$

With f injective, we then have

$$a = a'$$

Therefore, $(g \circ f)$ is injective. □

Proof of surjective part. We want to show that $\forall c \in C, \exists a \in A$ such that $g(f(a)) = (g \circ f)(a) = c$.

Since g is surjective, $\exists b \in B$ s.t. $g(b) = c$.

Since f is surjective, $\exists a \in A$ such that $f(a) = b$.

Now, plugging in, $g(f(a)) = g(b) = c$. Therefore, exists such a pre-image $a \in A$ for every $c \in C$ under $(g \circ f)$. Hence, $(g \circ f)$ is surjective. □

Definition 2.5 (Bijectivity)

If $f : A \rightarrow B$ is injective and surjective, we call f a bijection.

Theorem 2.6 (Existence of Inverse)

Let $f : A \rightarrow B$, then $\exists f^{-1} : B \rightarrow A$ such that

$$f^{-1} \circ f = \text{id}_A$$

$$f \circ f^{-1} = \text{id}_B$$

where

$$\text{id}_A : A \rightarrow A, \quad \forall a \in A, \text{id}_A(a) = a$$

$$\text{id}_B : B \rightarrow B, \quad \forall b \in B, \text{id}_B(b) = b$$

if and only if f is a bijection.

Proof.

\Leftarrow : Suppose $f : A \rightarrow B$ is a bijection. Then, we define $f^{-1} \subset B \times A$ as

$$f^{-1} = \{(b, a) \mid (a, b) \in f\}$$

It's clear that this is a relation. We check that f^{-1} is a function.

That is, we need to check that $\forall b \in B$, there exists one and only one $a \in A$ such that $(b, a) \in f^{-1}$.

In other words, taking the definition of f^{-1} , we have to check that $\forall b \in B$, $\exists!$ ⁷ $a \in A$ such that $(a, b) \in f$. This is exactly f being bijective.

Let's now show that

$$f^{-1} \circ f = \text{id}_A \tag{2.1}$$

$$f \circ f^{-1} = \text{id}_B \tag{2.2}$$

Let's first show $??$, suffices to show $f^{-1}(f(a)) \stackrel{?}{=} a, \forall a$.

$\forall a \in A, \exists b \in B$ such that $f(a) = b$, so $(a, b) \in f$. By definition, $(b, a) \in f^{-1}$ so $f^{-1}(b) = a$. Then $f^{-1}(f(a)) = f^{-1}(b) = a$.

We do $??$ very similarly.

\Rightarrow : Suppose $f : A \rightarrow B$ and g ⁸ : $B \rightarrow A$ such that $g \circ f = \text{id}_A$ and $f \circ g = \text{id}_B$. We show that f is a bijection.

⁷ $\exists!$ as 'exists exactly one'.

⁸We use g to reduce confusion with f^{-1}

We first show injectivity. Suppose $f(a_1) = f(a_2)$, applying g on both sides gives

$$\begin{aligned} g(f(a_1)) &= g(f(a_2)) \\ \text{id}_A(a_1) &= \text{id}_A(a_2) \\ a_1 &= a_2 \end{aligned}$$

This gives us injectivity.

We then show surjectivity. Let $b \in B$, we claim $\exists a \in A$ such that $f(a) = b$. Take $a := g(b)$, then $f(a) = f(g(b)) = b$. We've found such an a such that $f(a) = b$, giving us surjectivity.

In both directions, this gives us the bijection. □

Remark 2.7. Let $f : A \rightarrow B$ be a bijection, with A and B finite. We have that A has n elements $\iff B$ has n elements. That is, A and B have equal cardinality.

This extends to arguments on infinite sets too, like between \mathbb{Z} and \mathbb{Q} . \mathbb{Q} and \mathbb{R} or \mathbb{Z} and \mathbb{R} have different cardinalities and hence don't have bijections.

If $f : A \rightarrow B$ is not a bijection, we cannot define an inverse in the same way as we did before. But, we can consider the inverse image.

Definition 2.8 (Inverse Image)

Given function $f : A \rightarrow B$, $C \subseteq B$ we define the inverse image of C as

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

“The set of $a \in A$ that take me somewhere in C .”

If $C = \{b\}$, we get all elements mapped to b . That is,

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

§2.2 Cardinality

Definition 2.9 (Cardinality)

If A, B are sets, we say that A and B are equivalent ($A \simeq B$) if there exists a bijective $f : A \rightarrow B$. This is an equivalence relation.

The cardinality of a set A ($\#(A)$) is the equivalence class of A under this relation:

$$\#(A) := \{B \mid A \simeq B\}.$$

Remark 2.10. When A is finite with n elements, this is an abuse of notation. $\#(A)$ is the set of all sets with n elements, or we also say the ‘cardinality’ of A is simply n .

Example 2.11

Consider \mathbb{Z} , the set of integers. Consider $2\mathbb{Z}$, the set of even integers. They belong to the same cardinality. Even though they are infinite sets, they are the ‘same level’ of infinite⁹.

Specifically, we have bijection $f : \mathbb{Z} \rightarrow 2\mathbb{Z}$ with $x \mapsto 2x$.

§2.3 Natural Numbers

We’ll assume the Peano Axioms, which are the following:

A. $\exists \mathbb{N}$, an element $1 \in \mathbb{N}$.

B. a function $s : \mathbb{N} \rightarrow \mathbb{N}$ satisfying

(1) $\forall n \in \mathbb{N}, s(n) \neq 1$,

(2) s is injective,

(3) if $\exists S$, such that $1 \in S \subset \mathbb{N}$, and S satisfies that whenever $n \in S$, then $s(n) \in S$, this implies $S = \mathbb{N}$.

Why do we need condition (3)?

Example 2.12

Picking the half integers

$$\left\{ \frac{n}{2} \mid n \in \mathbb{N} \right\}$$

which satisfies the first two conditions but not the third.

s is called the *successor* function.

Proposition 2.13

For every $n \in \mathbb{N}$, $s(n) \neq n$.

Proof. Let

$$S = \{n \in \mathbb{N} \mid s(n) \neq n\}.$$

⁹Even though we might think that $2\mathbb{Z} \subseteq \mathbb{Z}$.

Clearly, $1 \in S$ by axiom (1). Suppose $n \in S$ for some n . We claim that $s(n) \in S$. By the injectivity of s , $s(n) \neq n$ so $s(s(n)) \neq s(n)$.

By (3), $S = \mathbb{N}$ which gives $s(n) \neq n, \forall n$. We can never loop when we keep applying s . \square

Definition 2.14 (Natural Number)

We'll call $s(1) = 2, s(2) = 3, \dots$. These are the natural numbers.

§3 February 2, 2023

§3.1 Natural Numbers, *continued*

Recall: we defined the natural numbers \mathbb{N} . We had a *successor* function s where $2 = s(1)$, $3 = s(2)$, and so on...

Definition 3.1

We define

- a. For any $n \in \mathbb{N}$, $n + 1 := s(n)$.
- b. For every $m, n \in \mathbb{N}$ $n + s(m) := s(n + m)$.

Proposition 3.2

We can check that

1. $\forall m, n \in \mathbb{N}$, $m + n = n + m$.
2. $\forall n, m, r \in \mathbb{N}$,

$$m + (n + r) = (m + n) + r$$
3. $\forall n, m \in \mathbb{N}$, $n + m \neq N$.¹⁰
4. s is a bijection from \mathbb{N} to $\mathbb{N} \setminus \{1\}$.

Proof of 4. We note that by the Peano axioms, s doesn't map any element to 1. Then, $s : \mathbb{N} \rightarrow \mathbb{N} \setminus \{1\}$.

We show that s is bijective. Consider

$$S = \{1\} \cup \{s(n) \mid n \in \mathbb{N}\}.$$

Suffices to show that $S = \mathbb{N}$. We know that $1 \in S$ by construction, and if $n \in S$, $n \in \mathbb{N}$, $s(n) \in S$ by construction, then by axiom (3), $S = \mathbb{N}$.

Hence if $k \neq 1$, $\exists n$ such that $k = s(n)$. Since s is injective by axiom (2), s is bijective. \square

Now that we have a bijection, we can define predecessors:

¹⁰We note that $0 \notin \mathbb{N}$.

Definition 3.3 (Predecessor)

We can define $n - 1$ for $n \neq 1$ by saying that $n - 1$ is the element such that

$$(n - 1) + 1 = n.$$

Definition 3.4 (Ordering)

We say that $m \leq n$ for $m, n \in \mathbb{N}$ if either $m = n$ or $m + a = n$ for some $a \in \mathbb{N}$.

Moreover, " \leq " is a partial order that satisfies $\forall m, n \in \mathbb{N}$, $m \leq n$ or $n \leq m$ (which makes \leq a total order).

Definition 3.5 (Partial Order)

A partial order R is a relation such that

1. aRa ,
2. $aRb, bRa \Rightarrow a = b$,
3. $aRb, bRc \Rightarrow aRc$.

Definition 3.6 (Multiplication)

We define multiplication by

$$\begin{aligned} \forall n \in \mathbb{N}, \quad n \cdot 1 &= n \\ n \cdot s(m) &= n + n \cdot m. \end{aligned}$$

Proposition 3.7

Our definition of multiplication satisfies the following: $\forall n, m, r, s \in \mathbb{N}$,

1. (*Distributivity*) $n \cdot (m + r) = n \cdot m + n \cdot r$
2. (*Commutativity*) $n \cdot m = m \cdot n$
3. (*Associativity*) $(n \cdot m) \cdot r = n \cdot (m \cdot r)$
4. If $n < m$ and $r \leq s$, then $r \cdot n < s \cdot m$.

§3.2 Cardinality & Natural Numbers

For each $n \in \mathbb{N}$, consider

$$J_n = \{m \in \mathbb{N} \mid m \leq n\}.$$

That is, $J_1 = \{1\}$, $J_2 = \{1, 2\}$.

Proposition 3.8

For $n \geq 1$,

$$J_{n+1} = J_n \cup \{n+1\}.$$

Proof. We prove by showing subset inclusion in both directions:

\supset : Let $k \in J_n \cup \{n+1\}$. If $k = n+1$, $k \in J_{n+1}$. If $k \in J_n$, then $k \leq n$ and since $n \leq n+1 \Rightarrow k \leq n+1 \Rightarrow k \in J_{n+1}$.

\subset : Let $k \in J_{n+1}$. If $k \in J_n$, we are done. If $k \notin J_n$, then $k \not\leq n \Rightarrow k \geq n+1$. But $k \in J_{n+1} \Rightarrow k \leq n+1$. So necessarily, $k = n+1$.

Which is as desired. □

Definition 3.9 (Cardinality, *again*)

We say that a set A has cardinality¹¹ n if

$$A \simeq {}^{12}J_n {}^{13}.$$

In this case, we say A is finite and write $\#(A) = n$.

If A is not related to any J_n , we say that A is infinite.

Lemma 3.10

Let A, B be finite¹⁴ sets. If $A \subset B$, then $\#(A) \leq \#(B)$.

Proof. Define $f : A \rightarrow B$ with $a \mapsto a$. f is injective by definition.

This is a bijection with a subset of B , therefore the cardinality has to satisfy $\#(A) \leq \#(B)$. □

¹¹This is unfortunately an abuse of notation.

¹²We use \sim to denote a relation, and \simeq to denote a bijection.

¹³This is in a model that assumes $0 \in \mathbb{N}$, unfortunately, which is a bit confusing.

¹⁴They don't need to be finite, but then the comparison of cardinalities is a bit wishy-washy.

Theorem 3.11 $\forall n \in \mathbb{N},$

$$\#(J_n) < \#(J_{n+1}) < \#(\mathbb{N})$$

Proof. If we replace the first $<$ by \leq , then this is easy by the previous lemma.

We assume we already know¹⁵

$$\#(J_n) \neq \#(J_{n+1}), \forall n, \quad (3.1)$$

we want to show that $\#(J_n) \neq \#(\mathbb{N}), \forall n$.

Assume there exists some n such that

$$\#(\mathbb{N}) = \#(J_n)$$

Then we have

$$\#(J_{n+1}) \leq \#(\mathbb{N}) = \#(J_n)$$

which is a contradiction. \square

Proof of ??. We induct on n .

Base case $n = 1$. $J_1 = \{1\}$ and $J_2 = \{1, 2\}$. Then $\#(J_1) < \#(J_2)$, since we can't define a bijection.

Inductive step. Suppose that $\#(J_n) \neq \#(J_{n+1})$. We wish to prove $\#(J_{n+1}) \neq \#(J_{n+2})$. By contraposition, assume there exists a bijection $f : J_{n+1} \rightarrow J_{n+2}$. Then, $\exists k \in J_{n+1}$ such that $f(k) = n + 2$. Define $h : J_{n+1} \rightarrow J_{n+1}$ by

$$h(m) := \begin{cases} m & \text{if } m \notin \{k, n+1\} \\ m+1 & \text{if } m = k \\ k & \text{if } m = n+1 \end{cases}$$

Let $\hat{f} = f \circ h : J_{n+1} \rightarrow J_{n+2}$, a bijection. \hat{f} maps $n+1 \mapsto n+2$. Defining $g(x) = \hat{f}(x)$ for $x \in J_n$ (\hat{f} restricted to J_n so $g : J_n \rightarrow J_{n+1}$) completes the contraposition.

Which gives the general statement of ??. \square

Corollary 3.12

If $A \simeq \mathbb{N}$, A is infinite.

We say in this case that A is countable.

If A is infinite and $\#(A) \neq \#(\mathbb{N})$ ¹⁶, then we say that A is uncountable.

¹⁵Note from me: why can't we claim $\#(J_n) = n$ by definition of cardinality?

Proof. If A were finite, then $A \simeq J_n$ for some n which is impossible by ?? □

Example 3.13

\mathbb{N} is countable, \mathbb{Q} is countable, \mathbb{R} is uncountable.

Corollary 3.14

Let S be an infinite subset of \mathbb{N} . Then S is countably infinite.

Definition 3.15 (Countability)

We say that A is countable if A is finite or countable infinite.

¹⁶That is, $A \not\simeq \mathbb{N}$.

§4 February 7, 2023

§4.1 Natural Numbers, *continued*

Theorem 4.1

Let S be an infinite subset of \mathbb{N} . Then S is countably infinite.

Proof. The objective is to construct a bijection between S and \mathbb{N} . We will do this inductively.

Let $f(1)$ be the smallest element¹⁷ of S for $f : \mathbb{N} \rightarrow S$.

Assuming we have defined $f(1), f(2), \dots, f(n)$, we define $f(n+1)$ to be the smallest element of $S \setminus \{f(1), f(2), \dots, f(n)\}$.

By construction, f is bijective. □

Recall ??:

Definition (Countability)

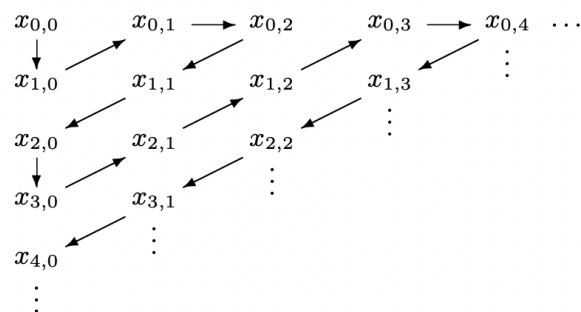
We say that A is countable if it is finite or countably infinite.

Theorem 4.2

Let \mathcal{C} be a countable collection¹⁸ of countable sets.

Then the union $\bigcup_{A \in \mathcal{C}} A$ is countable.

We can do something like this:



¹⁷Within reasonable context, we assume that \mathbb{N} is well-ordered. That is, every subset has a least element.

¹⁸A 'collection' usually refers to a collection of sets.

Proof. Again, we try to construct a bijection f from \mathbb{N} . We list all the elements of $\bigcup_{A \in \mathcal{C}} A$ in a sequence. This will give $f(1), f(2), \dots$ and so on.

Since each A is countable, we may list its elements. The collection \mathcal{C} is also countable. We can arrange every row to be an element of \mathcal{C} .

$$\begin{array}{c|cccc} A_1 & a_1 & a_2 & a_3 & \cdots \\ A_2 & b_1 & b_2 & b_3 & \cdots \\ A_3 & c_1 & c_2 & \cdots & \\ A_4 & d_1 & \cdots & & \\ \vdots & \vdots & \ddots & & \end{array}$$

We then count the elements using diagonals (or a zig-zag), and remove duplicates¹⁹. □

§4.2 Before We Get to the Real Numbers

Let's begin by proving the following theorem.

Theorem 4.3

$\sqrt{2}$ is not rational.

Proof. Assume not, that we can write $\sqrt{2} = \frac{m}{n}$, for $m, n \in \mathbb{Z}$, $n \neq 0$ and m, n coprime.

Then, $2n^2 = m^2$. So, m is even. Writing $m = 2m'$, $2n^2 = 4m'^2$, which in particular implies n is even, which is a contradiction.

It had better be, then, that $\sqrt{2}$ is irrational. □

We now show more, namely that we can get arbitrarily close to irrational numbers by rational numbers²⁰.

Theorem 4.4

If $q \in \mathbb{Q}$ satisfies $0 < q^2 < 2$, then we can find $\bar{q} \in \mathbb{Q}$ such that $q^2 < \bar{q}^2 < 2$. Similarly if $r \in \mathbb{Q}$ satisfies $2 < r^2$, then we can find $\bar{r} \in \mathbb{Q}$ such that $2 < \bar{r}^2 < r^2$.

Proof. We'll just prove the first part; the second part is similar.

¹⁹This is a bit wishy-washy, but we're only removing elements here so we remain in the 'countable' territory.

²⁰This is to say, \mathbb{Q} is *dense* in \mathbb{R} .

Suppose $q > 0$, define

$$\bar{q} = q + \frac{2 - q^2}{2 + q}.$$

then $\bar{q} > q$ and

$$\begin{aligned} \bar{q}^2 - 2 &= q^2 + \left(\frac{2 - q^2}{q + 2}\right)^2 + \frac{2q(2 - q^2)}{2 + q} - 2 \\ &= \frac{(q^2 - 2)(q + 2)^2 + (2 - q^2)^2 + (2 - q^2)2q(2 + q)}{(q + 2)^2} \\ &= \frac{q^2 - 2}{(q + 2)^2} \left[\cancel{q^2} + 4 + \cancel{4q} + \cancel{q^2} - 2 - \cancel{2q(2 + q)} \right] \\ &= \frac{2(q^2 - 2)}{(q + 2)^2} \end{aligned}$$

which is surely negative. □

Corollary 4.5

The set

$$\{q \in \mathbb{Q} \mid q^2 < 2\}$$

does not have a largest element.

Definition 4.6 (Upper Bound)

If A is a set with a partial ordering \leq , we say that $a \in A$ is an upper bound for a subset $B \subset A$ if $b \leq a \forall b \in B$.

We say that a is a least upper bound for B if whenever a' is an upper bound for B , then $a \leq a'$.

Lemma 4.7

If a is a least upper bound for B , then a is unique.

Proof. Assume a, a' are both least upper bounds for B . By definition, both a, a' are upper bounds. WLOG, if a is a least upper bound and a' an upper bound, $a \leq a'$. Similarly, $a' \leq a$. Hence, $a = a'$. □

Now that we have proved uniqueness, we can give a a name:

Definition 4.8 (Supremum & Infimum)

We define $\sup B := a$ when a is the least upper bound of B .

Similarly, $\inf B := a$ when a is the greatest lower bound of B .

Definition 4.9 (Least-Upper-Bound Property)

Let A be a totally ordered set with order \leq . We say that A has the least upper bound property if each nonempty subset of $B \subset A$ with an upper bound in A has a least upper bound in A .

§4.3 The Real Numbers**Definition 4.10**

A field F is a set with two operations: $+$, \cdot .

The $+$ operation satisfies:

Closure. $x, y \in F \Rightarrow x + y \in F$.

Commutativity. $x + y = y + x, \forall x, y \in F$.

Associativity. $(x + y) + z = x + (y + z), \forall x, y, z \in F$.

Identity. $\exists 0$ such that $0 + x = x \forall x \in F$.

Inverses. $\forall x \in F, \exists -x \in F$ such that $x + (-x) = 0$.

And a \cdot operation that satisfies:

Closure. $x, y \in F \Rightarrow x \cdot y \in F$.

Commutativity. $x \cdot y = y \cdot x, \forall x, y \in F$.

Associativity. $(x \cdot y) \cdot z = x \cdot (y \cdot z), \forall x, y, z \in F$.

Identity. $\exists 1 \neq 0$ such that $1 \cdot x = x, \forall x \in F$.

Inverse. $\forall x \neq 0, \exists x^{-1} \in F$ such that $x \cdot x^{-1} = 1$

Together, we also have

Distribution. $\forall x, y, z \in F, x \cdot (y + z) = x \cdot y + x \cdot z$.

In other words, a field F is a commutative ring with multiplicative inverse.

Definition 4.11

An ordered field is a field F which is an ordered set such that

1. $x + y < x + z$ if $x, y, z \in F$ and $y < z$.
2. $x \cdot y > 0$ if $x, y \in F$ and $x > 0, y > 0$.

Example 4.12

\mathbb{Q}, \mathbb{R} are ordered fields. \mathbb{N}, \mathbb{Z} are not fields.

Theorem 4.13 (Archimedian Property)

Given $x, y \in \mathbb{R}, x > 0$. Then $\exists n \in \mathbb{Z}$ such that $nx > y$.

Proof. We argue by contradiction. Assume such n doesn't exist.

Then take set

$$A = \{nx \mid n \in \mathbb{N}\}$$

which is bounded by y .

Therefore, if it has supremum²¹ s , $s - x < s$, so $s - x$ is not an upper bound of A (otherwise s is not a supremum). Then, $\exists a \in A$ (otherwise $s - x$ would have been an upper bound) such that $a \geq s - x$, which means $\exists m \in \mathbb{N}$ such that $mx > s - x$. This implies that $s < (m + 1)x$ but $m + 1 \in A$, which is a contradiction. \square

Corollary 4.14

Let $x, y \in \mathbb{R}$ with $x < y$. Then $\exists q \in \mathbb{Q}$ such that $x < q < y$. This is to say, "in between any two real numbers lies rational numbers."

Proof. By ?? applied to $y - x$ and 1. Then $\exists n \in \mathbb{Z}$ such that

$$n(y - x) > 1$$

and we can also find $m_1, m_2 \in \mathbb{N}$ such that

$$m_1 > nx, m_2 > -nx$$

by the Archimedian property again. which implies

$$-m_2 < nx < m_1$$

²¹ \mathbb{R} has the least upper bound property.

Then, $\exists m \in \mathbb{N}$ such that $m - 1 \leq nx < m$ ²². Which implies that

$$nx < m \leq 1 + nx < ny$$

which then gives

$$x < \frac{m}{n} < y$$

which is as desired. $\frac{m}{n}$ is precisely a rational between real x and y . □

Theorem 4.15

For every $x \in \mathbb{R}$ with $x > 0$, $n > 0 \in \mathbb{N}$, $\exists! y > 0$ such that $y^n = x$.

Proof. We prove uniqueness. Suppose by contradiction that WLOG $y_1 < y_2$ such that $y_1^n = x$ and $y_2^n = x$. Contradiction by $y_1^n < y_2^n$.

We now start the proof for existence. Let

$$E = \{t \mid t^n < x\}$$

If $t = \frac{x}{x+1}$, then $t < x$ and $0 < t < 1$. So $t^n < t < x$ so E is not empty.

If $t > 1 + x$, $t^n \geq t > x$. We've found an upper bound of E . Then, $\exists y = \sup E$.

We'll leave it here that E has a supremum, and continue next time. □

²²By contradiction, if there is no such m we incur the previous statement

§5 February 9, 2023

§5.1 Real Numbers, *continued*

Recall: from last time that we were trying to prove

Theorem

$\forall x \in \mathbb{R}, x > 0$ and $\forall n \in \mathbb{N}, n > 0$,

$$\exists! y > 0 \text{ s.t. } y^n = x.$$

Proof. Define E as

$$E := \{t \mid t^n < x\}.$$

E has an upper bound x and by the least upper bound property, $\exists y = \sup(E)$.

Our objective is to show that $y^n = x$. We use the identity that

$$b^n - a^n = (b - a)(b^{n-1} + ab^{n-2} + a^2b^{n-3} + \cdots + a^{n-1}).$$

Assuming that a, b positive, and bounding $b^{n-1} + ab^{n-2} + \cdots < nb^{n-1}$,

$$b^n - a^n < (b - a)nb^{n-1}$$

if $0 < a < b$.

For the sake of contradiction, first assume $y^n < x$. Choose $0 < h < 1$ such that

$$h < \frac{x - y^n}{n(y + 1)^{n-1}}.$$

Then, $(y + 1)^n - y^n < hn(y + 1)^{n-1}$, this is also bounded by $< hn(y + 1)^{n-1} = x - y^n$ so we have that $(y + h)^n < x$.

Then $y + h \in E$. But we defined y to be the supremum of E , which is a contradiction.

We complete our ‘squeeze’ with assuming (again, for the sake of contradiction) that $y^n > x$. We choose

$$h = \frac{y^n - x}{ny^{n-1}} > 0.$$

Since $y^n - x < ny^n$, $h < y$. Then we can show that

$$y^n - (y - h)^n < hny^{n-1} = y^n - x$$

so $(y - h)^n > x$. This again, contradicts y being a least upper bound since $y - h < y$ and $y - h$ is an upper bound.

Hence the least upper bound of E is the n -th root of x exactly by our two contradictions. \square

§5.2 Metric Spaces

We'll do some topology for the next few classes or so.

Definition 5.1 (Metric Space)

A set X and a function $d : X \times X \rightarrow \mathbb{R}$ is a metric space if we have the following properties:

Nonnegative. $d(x, y) \geq 0$, furthermore $d(x, y) = 0 \iff x = y$.

Symmetric. $d(x, y) = d(y, x)$.

Triangle Inequality. $d(x, y) \leq d(x, z) + d(z, y)$.

We will call d a distance.

Example 5.2

$X = \mathbb{R}^n$ with $d(\vec{a}, \vec{b}) = |\vec{a} - \vec{b}|$ is a metric space.

Example 5.3

X arbitrary, and

$$d(x, y) = \begin{cases} 1 & \text{if } x \neq y \\ 0 & \text{if } x = y \end{cases}$$

is also a metric space.

Example 5.4

$X = \{f \mid f \text{ bounded and } f : [0, 1] \rightarrow \mathbb{R}\}$ with

$$d(f, g) = \sup_{x \in [0, 1]} \{|f(x) - g(x)|\}$$

is a metric space.

§5.2.1 Open and Closed Sets

The mental image for these are open and closed intervals on the real number line.

Definition 5.5 (Neighborhood)

Let $r > 0$. The neighborhood of radius centered at $x \in X$ is

$$B_r(x) = \{y \in X \mid d(x, y) < r\}.$$

Example 5.6

In \mathbb{R} , with $d = |x - y|$, we get the open interval

$$B_r(x) = \{y \mid x - r < y < x + r\}$$

Example 5.7

In \mathbb{R}^n with $d(\vec{x}, \vec{y}) = |\vec{x} - \vec{y}|$, we get the open ball

$$B_r(\vec{x}) = \{\vec{y} = (y_1, \dots, y_n) \mid (x_1 - y_1)^2 + \dots + (x_n - y_n)^2 < r^2\}.$$

Example 5.8

In \mathbb{R} , a neighborhood with radius 0.5 is the point itself, and a neighborhood with radius 2 is the entire space.

Let (X, d) be a metric space.

Definition 5.9 (Open Set)

A set $Y \subset X$ is open if $\forall y \in Y, \exists r > 0$ ²³ such that $B_r(y) \subset Y$.

Proposition 5.10

Any neighborhood is open.

Proof. Let $x \in X, r > 0$. We look at $B_r(x)$.

$\forall y \in B_r(x)$, we want to find s such that

$$B_s(y) \subset B_r(x)$$

Let $s = r - d(x, y)$. Let $z \in B_s(y)$. We wish to show that $z \in B_r(x)$, that is, $d(z, x) < r$.

Invoking the triangle inequality,

$$d(z, x) \leq d(z, y) + d(y, x) < s + d(x, y) = r - d(x, y) + d(x, y).$$

²³This r may depend on our y .

This gives that every point in $B_s(y)$ is in $B_r(x)$, so $B_s(y) \subset B_r(x)$. Hence, every neighborhood is open. \square

Example 5.11

In \mathbb{R} , the only intervals which are open are open intervals²⁴.

Example 5.12

In \mathbb{R}^2 , the set

$$\{(x, y) \mid y > 0\} \cup \{(x, y) \mid y < -1\}$$

is open.

Remark 5.13. Not being open **does not** imply a set is closed.

Proposition 5.14

Let \mathcal{C} be a collection of open sets.

(1) $\bigcup_{O \in \mathcal{C}} O$ is open.

(2) $\bigcap_{O \in \mathcal{C}} O$ is open if \mathcal{C} is finite.

If \mathcal{C} is infinite, (2) might fail.

Example 5.15

For example,

$$O_n = \left(1 - \frac{1}{n}, 1 + \frac{1}{n}\right)$$

Then

$$\bigcap O_n = \{1\}$$

Proof of (1). Let $x \in \bigcup_{O \in \mathcal{C}} O$. Then there exists $O \in \mathcal{C}$ such that $x \in O$, which we denote O_x .

Then, $\exists r$ such that $B_r(x) \subset O_x \subset \bigcup_{O \in \mathcal{C}} O$. Hence, $\bigcup_{O \in \mathcal{C}} O$ is open. \square

Proof of (2). Let $\mathcal{C} = \{O_1, O_2, \dots, O_n\}$. Let $x \in \bigcap_{O \in \mathcal{C}} O$. Then $x \in O_i$ for all i . Since each O_i is open, there exists r_i such that $B_{r_i}(x) \subset O_i$.

²⁴This looks...tautological.

Let $r = \min_i r_i$. Since the \mathcal{C} is finite, the minimum is strictly positive. Then $B_r(x) \subset B_{r_i}(x), \forall i$, so $B_r(x) \subset O_i, \forall i$. Therefore, $B_r(x) \in \bigcap_{O \in \mathcal{C}} O$. \square

Definition 5.16 (Interior Point)

An interior point of $Y \subset X$ is a point $y \in Y$ such that $\exists r > 0$ such that $B_r(y) \subset Y$.

We define

$$\overset{\circ}{Y} := \text{the set of interior points of } Y$$

$$Y \text{ open} \iff Y = \overset{\circ}{Y}.$$

Example 5.17

$$[0, 1] = (0, 1).$$

$$\overset{\circ}{\mathbb{Q}} = \emptyset.$$

Definition 5.18 (Closed Set)

A set Y is closed if $X \setminus Y$ ²⁵ is open.

Remark 5.19. A set can be open *and* closed, or neither.

For example, \emptyset and X are both open and closed.

Proposition 5.20

Let \mathcal{C} be a collection of closed sets. Then

$$(1) \bigcap_{C \in \mathcal{C}} C \text{ is closed.}$$

$$(2) \bigcup_{C \in \mathcal{C}} C \text{ is closed if } \mathcal{C} \text{ is finite.}$$

Proof. Let $C = X - O$ for some open set O .

$$\bigcup_{C \in \mathcal{C}} (X - O) = X - \bigcap_{O \in \mathcal{C}} O$$

Combined with the equivalent proposition for open sets completes this proof. \square

²⁵Sometimes, Y^c is used to denote $X \setminus Y$, the complement of Y in X .

§5.2.2 Limit Points

Definition 5.21 (Limit Point)

Let $Y \subset X$. A point $x \in X$ is a limit point of Y if $\forall r > 0$, $\exists y \in Y$ such that $y \neq x$ and $y \in B_r(x)$. We denote

$$Y' = \{y \mid y \text{ is a limit point of } Y\}.$$

§6 February 14, 2023

The first quiz will definitely be after we get homework 2 back. Definitions on the quiz will come from lecture and the reading. Midterm will be around Spring break.

§6.1 Metric Spaces, *continued*

§6.1.1 Limit Points

Recall that we left off at limit points last lecture.

Example 6.1

The following are examples of sets and limit points:

1. 0 is a limit point of the set

$$\left\{0, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \dots\right\}.$$

2. $\{1, 2, 3\} \subset \mathbb{R}$ has no limit points.

3. In \mathbb{R}^2 ,

$$S = B_1(0) \cup \{(x, 0) \mid x \in \mathbb{R}\} \cup \{(10, 10)\}$$

has limit points

$$S' = \underbrace{\{(x, y) \mid x^2 + y^2 \leq 1\}}_{\text{closed ball}} \cup \{(x, 0) \mid x \in \mathbb{R}\}.$$

We note that nothing can approach $(10, 10)$ thus this is not a limit point. The open ball gives rise to the closed ball, and we also have the axis as well.

Proposition 6.2

$x \in X$ is a limit point of Y iff $\forall r > 0, \exists$ infinitely many points of Y in $B_r(x)$.

Proof.

\Leftarrow : This falls from the definition. In fact, this is a stronger statement than the definition.

Since $\forall r > 0$ there exists infinitely many points in $B_r(x)$, then there exists $y \neq x$ in $B_r(x)$.

\Rightarrow : Suppose otherwise, that there exists some $r > 0$ such that there doesn't exist infinitely many points of Y in $B_r(x)$ (say there are finitely many points of Y in $B_r(x)$). Let us call these points y_1, \dots, y_n . Let $r_0 = \min_{y_i \neq x} \{d(y_i, x)\} > 0$ (we're done if this set is empty).

Then $B_{r_0}(x) \cap Y = \{x\}$, and x is not a limit point of y , which is a contradiction.

Which concludes the bidirectional. \square

§6.1.2 Closedness

Theorem 6.3

Y is closed if and only if $Y' \subset Y$.

Proof.

\Rightarrow : Suppose Y is closed. Let $y \in Y'$, we wish to show that $y \in Y$. We argue by contradiction, suppose $y \notin Y$, then $y \in X \setminus Y$ which is open. So, $\exists r > 0$ such that $B_r(y) \subset X \setminus Y$. Then, $B_r(y) \cap Y = \emptyset$ (since it is in $X \setminus Y$). This is a contradiction with $y \in Y'$.

\Leftarrow : Suppose $Y' \subset Y$. We want to show that $X \setminus Y$ is open.

Let $z \in X \setminus Y$. Since $z \notin Y$, $z \notin Y'$ since $Y' \subset Y$. Then, $\exists r > 0$ such that $B_r(z) \cap Y$ has no points $p \neq z$ such that $p \in Y$. Then $B_r(z) \subset X \setminus Y$ implies $X \setminus Y$ is open.

Which is as desired. \square

Definition 6.4 (Closure)

The closure of Y is $\bar{Y} = Y \cup Y'$.

Theorem 6.5

Let \mathcal{C} be a collection of sets $C \subset X$ such that C is closed and $Y \subset C$. Then

$$\bar{Y} = \bigcap_{C \in \mathcal{C}} C.$$

That is, \bar{Y} is the smallest closed superset of Y .

Proof.

Case \subset : Let $y \in Y$ or $y \in Y'$, we want to show that $y \in \bigcap_{C \in \mathcal{C}} C$. That is to say, it is in every superset of Y .

If $y \in Y$, then $y \in Y \subset C$ by the definition of C .

If $y \in Y'$, we pick arbitrary C . Since y is a limit point of Y , y is also a limit point of C . Since C is closed, $y \in C$ by ???. Since our choice of C was arbitrary, it holds true for all C .

Case \supset : We will show that $\bar{Y} \in \mathcal{C}$. Since $\bar{Y} \supset Y$, we only need to show that \bar{Y} is closed.

If $x \notin \bar{Y}$, then $x \notin Y$ and $x \notin Y'$. So $\exists r > 0$ such that $B_r(x) \cap Y = \emptyset$.

Since $B_r(x)$ is open, each point has a neighborhood centered in $B_r(x)$, this means that the neighborhood doesn't intersect Y ²⁶. For each point in $B_r(x)$, that point is *neither* in Y nor a limit point of Y .

Then, $B_r(x) \subset X \setminus \bar{Y}$, so $X \setminus \bar{Y}$ is open, then \bar{Y} is closed.

Which is as desired. □

Corollary 6.6

$Y = \bar{Y}$ if and only if Y is closed.

Proof.

\implies : Falls from the proof just now.

\impliedby : Y is closed so $Y' \subset Y$ so $\bar{Y} = Y \cup Y' = Y$.

as desired. □

§6.1.3 Compactness

Definition 6.7 (Compactness)

A subset K of a metric space (X, d) is compact if for every collection \mathcal{C} of open sets such that $K \subset \bigcup_{C \in \mathcal{C}} C$, one can extract a finite collection C_1, C_2, \dots, C_n such that $K \subset \bigcup_{i=1}^n C_i$.

\mathcal{C} is referred to as an open cover of K , and C_1, \dots, C_n is referred to as a finite subcover of K .

Definition 6.8 (Boundedness)

A set $E \subset X$ is bounded if $\exists x \in X, R > 0$ such that $E \subset B_R(x)$.

²⁶Assume otherwise, then $z \in B_r(x)$ and $z \in Y'$, but we can squeeze a ball $B_{r'}(z) \subset B_r(x)$ which is disjoint from Y' .

Theorem 6.9

Any compact set $K \subset X$ is bounded.

Proof. Fix arbitrary x . Take collection $\mathcal{C} = \{B_R(x) \mid R = 1, 2, \dots\}$.

We show first that \mathcal{C} is an open cover. \mathcal{C} being open is clear, since each set is open. We show it is a cover. For any $y \in K$, $y \in B_R(x)$ for every $R > d(x, y)$. So \mathcal{C} is an open cover.

Since K is compact, then there exists a finite subcover $B_{R_1}(x), B_{R_2}(x), \dots, B_{R_n}(x)$. Take $R = \max\{R_1, \dots, R_n\}$ which is finite. Then $K \subset \bigcap_{i=1}^n B_{R_i}(x) = B_R(x)$ (we can line up the open balls in order of radius, and have a chain of subset inclusions).

Then, K is bounded. □

We'll state this theorem today without proof.

Theorem 6.10

Any compact set $K \subset X$ is closed.

§7 February 16, 2023

§7.1 Heine-Borel Theorem

Today, we'll work toward proving the Heine-Borel theorem. Informally,

Theorem (Heine-Borel Theorem)

A subset of \mathbb{R}^n is compact \iff it is bounded and closed.

The forward direction holds true in all metric spaces, the backward direction only applies to \mathbb{R}^n .

We stated last time in ?? and ?? that compact implies bounded and closed.

We'll first show that (0) any compact set is closed. Then, our strategy for the reverse direction will be to prove that bounded and closed sets are compact. We'll prove the following:

- (1) If a set A is compact, any closed subset $B \subset A$ is compact too.
- (2) In \mathbb{R}^n , an n -cell $I = \prod_{i=1}^n [a_i, b_i]$ is compact (intervals).
- (3) We can enclose any set K in \mathbb{R}^n with some compact n -cell I such that $K \subset I$.

Theorem (??)

Any compact $K \subset X$ is closed.

Proof. The idea is to show that $K^C = X \setminus K$ is open.

Let $x \in K^C$, suffices to find a radius $r > 0$ such that $B_r(x) \subset K^C$.

Construct²⁷ an open cover of K . For each $y \in K$, we define $B_y = B\left(y, \frac{d(x,y)}{2}\right)$. $\mathcal{C} = \{B_y \mid y \in K\}$ is a cover of K .

\mathcal{C} is an open cover of K since each $y \in B_y \in \mathcal{C}$. Since K is compact, we can extract a finite subcover

$$\{B_{y_1}, B_{y_2}, \dots, B_{y_n}\}$$

We let $r = \min_{i=1, \dots, n} \left\{ \frac{d(x, y_i)}{2} \right\}$. Remains to show that $B_r(x) \subset K^C$.

²⁷This should be a familiar construction we'll revisit, can we find a cover that has a finite subcover?

We fix point $z \in B_r(x)$, so $|z - x| < r$ and $d(z, x) < r$. By the triangle inequality,

$$\begin{aligned} d(y_i, x) &\leq d(z, y_i) + d(z, x) \\ &< d(z, y_i) + r. \end{aligned}$$

Observe that $r \leq \frac{d(x, y_i)}{2} = d(x, y_i) - \frac{d(x, y_i)}{2}$ by our definition of r , which then implies

$$\frac{d(y_i, x)}{2} \leq d(y_i, x) - r < d(z, y_i) \implies \frac{d(x, y_i)}{2} < d(z, y_i), \quad \forall i = 1, \dots, n.$$

which means that $z \in B_{y_i}$. In particular, $z \notin K \Rightarrow B_r(x) \subset K^C$. Which exactly means that K^C is open and K is closed. \square

Summarizing this proof, we're keeping track of balls and their radiuses. This gives us (0).

We'll continue to proving statements (1) through (3).

Theorem 7.1 (Important Statement 1)

Let $K \subset X$ be a compact set and let $L \subset K$ be closed. Then L is compact.

Proof. Let \mathcal{C} be an open cover of L . Then, let $D = \mathcal{C} \cup \{L^C\}$ be open. D is another open cover of K . Since K is compact, let $\{D_1, \dots, D_n\}$ be a finite subcover of K . If all D_i are in \mathcal{C} , we are done, this is a finite subcover of L , we are done.

If not, suppose $D_n = L^C$ (with reordering). Consider $\{D_1, D_2, \dots, D_{n-1}\}$. We claim that this is a finite subcover of L .

If $x \in L$, $\exists i = 1, \dots, n$ such that $x \in D_i$, $i \neq n$ (otherwise we're in the previous statement). Which is as desired, and L is compact. \square

Corollary 7.2

For K compact and F closed, $F \cap K$ is compact.

We discussed earlier that the forward implication comes with all metric spaces but the backward implication does not.

Example 7.3

Consider a space

$$X = \left\{ \frac{1}{n}, n \geq 1 \right\}, d(x, y) = \begin{cases} 0 & \text{if } x = y \\ 1 & \text{otherwise} \end{cases}$$

This is bounded and closed, but not compact.

Theorem 7.4 (Heine-Borel Theorem)

A set $K \subset \mathbb{R}^n$ is compact if and only if it is bounded and closed.

Definition 7.5 (n -cell)

An n -cell is a subset of \mathbb{R}^n of the form

$$[a_1, b_1] \times \cdots \times [a_n, b_n], \quad a_i \leq b_i \quad \forall i$$

where $[a_i, b_i]$ denotes the closed interval $\{x \mid a_i \leq x \leq b_i\}$.

Lemma 7.6

Suppose we have a collection of nested n -cells C_1, C_2, \dots . That is, if

$$C_i = \prod_{k=1}^n [a_k^i, b_k^i] \implies [a_k^i, b_k^i] \supset [a_k^{i+1}, b_k^{i+1}].$$

and

$$C_1 \supset C_2 \supset C_3, \dots$$

Since these are nested, the claim is that $\bigcap_{i=1}^{\infty} C_i$ is then non-empty.

Proof. We do it for $n = 1$, so we can just use scalars. Take $C_i = [a^i, b^i]$ ²⁸. Let $A = \{a^1, a^2, \dots\}$. Take $a = \sup A$. We claim that $a \in \bigcap_{i=1}^{\infty} C_i$.

Note that $a^i \leq b^j$ by our nested property, so we have a chain of inequalities $a^i \leq a^j \leq b^j$ if $i \leq j$. Then also $a^i \leq b^i \leq b^j$ for $i \leq j$.

By change of inequalities, b^j is an upper bound of A . Since a is $\sup A$, then $a \leq b^j$ for all j . Then $a^i \leq a \leq b^i$ so $a \in C_i$ for every i . Then a is in the intersection.

Extend for dimension n greater than 1, consider vectors and take coordinate-wise supremum a_1, a_2, \dots, a_n , such that

$$a_k^i \leq a_k \leq b_k^i$$

for all i, k not dissimilar to above. □

Lemma 7.7 (Important Statement 2)

Every n -cell is compact.

²⁸Here the i s are still indices, not exponents. Recall we needed 2 indices last time

Proof. Let I be a k -cell, $I = \prod_{j=1}^k [a_j, b_j]$. Let

$$\delta = \left(\sum_{j=1}^k (b_j - a_j)^2 \right)^{1/2}$$

If $x, y \in I$, $|x - y| < \delta$. δ can be thought of as the diagonal of the cell. Suppose for the sake of contradiction we have an open cover $\{G_\alpha\}$ *without* a finite subcover of I . Let $c_j = \frac{a_j + b_j}{2}$, so for each dimension we have k -cell $[a_j, c_j]$ and $[c_j, b_j]$. Altogether, we have 2^k k -cells.

One of these cells is not covered by a finite subcover. Let's call that cell I_1 . We split again and get an subset of I_1 , I_2 . We then have construction

$$I_1 \supset I_2 \supset I_3 \supset \dots$$

For all k , I_k is not covered by a finite subcover of $\{G_\alpha\}$. Additionally, $\forall x, y \in I_k$, $|x - y| < 2^{-k}\delta$ (we split k times).

By lemma ??, $\bigcap_{j=1}^\infty I_j$ is nonempty. Let $x^* \in \bigcap_{j=1}^\infty I_j$, and α such that $x^* \in G_\alpha$. Since G_α is open, $\exists r$ such that if $|y - x^*| < r$, $r \in G_\alpha$ (there is a ball in G_α). Taking k large enough (go down the chain) such that $2^{-k}\delta < r$, then $I_k \subset G_\alpha$ which is a contradiction. \square