

FALL 2024 MATH 325 LECTURE NOTES AND WORKSHEETS

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1. MONDAY, AUGUST 26, 2024 §1.1

What is a number? Certainly the things used to count sheep, money, etc. are numbers: $1, 2, 3, \dots$. We will call these the *natural numbers* and write \mathbb{N} for the set of all natural numbers

$$\mathbb{N} = \{1, 2, 3, 4, \dots\}.$$

Since we like to keep track of debts too, we'll allow negatives and 0, which gives us the *integers*:

$$\mathbb{Z} = \{\dots, -3, -2, -1, 0, 1, 2, 3, 4, \dots\}.$$

(The symbol \mathbb{Z} is used since the German word for number is *zahlen*.)

Fractions should count as numbers also, so that we can talk about eating one and two-thirds of a pizza last night. We define a *rational number* to be a number expressible as a quotient of two integers: $\frac{m}{n}$ for $m, n \in \mathbb{Z}$ with $n \neq 0$. For example

$$\frac{5}{3}, \frac{2}{7}, \frac{2019}{2020}$$

are rational numbers. Of course, we often talk about numbers such as “two and a fourth”, but that the same as $\frac{9}{4}$. Every integer is a rational number just by taking 1 for the denominator; for example, $7 = \frac{7}{1}$. The set of all rational numbers is written as \mathbb{Q} (for “quotient”).

You might not have thought about it before, but an expression of the form $\frac{m}{n}$ is really an “equivalence class”: the two numbers $\frac{m}{n}$ and $\frac{a}{b}$ are deemed equal if $mb = na$. For example $\frac{6}{9} = \frac{2}{3}$ because $6 \cdot 3 = 9 \cdot 2$.

We’ll talk more about decimals later on, but recall for now that a decimal that terminates is just another way of representing a rational number. For example, 1.9881 is equal to $\frac{19881}{10000}$. Less obvious is the fact that a decimal that repeats also represents a rational number: For example, $1.333\dots$ is rational (it’s equal to $\frac{4}{3}$) and so is $23.91278278278\dots$. We’ll see why this is true later in the semester.

Are these all the numbers there are? Maybe no one in this class would answer “yes”, but the ancient Greeks believed for a time that every number was rational. Let’s convince ourselves, as the Greeks did eventually, that there must be numbers that are not rational. Imagine a square of side length 1. By the Pythagorean Theorem, the length of its diagonal, call this number c , must satisfy

$$c^2 = 1^2 + 1^2 = 2.$$

That is, there must be a some number whose square is 2 since certainly the length of the diagonal in such a square is representable as a number. Right? Now, let’s convince ourselves that there is no *rational number* with this property. In fact, I’ll make this a theorem.

Theorem 1.1. *There is no rational number whose square is 2.*

Preproof Discussion 1. *Before launching a formal proof, let’s philosophize about how one shows something does not exist. To show something does not exist, one proves that its existence is not possible. For example, I know that there must not be large clump of plutonium sewn into the mattress of my bed. I know this since, if such a clump existed, I’d be dead by now, and yet here I am, alive and well!*

More generally and formally, one way to prove the falsity of a statement P is to argue that if we assume P to be true then we can deduce from that assumption something that is known to be false. If you can do this, then you have proven P is false. In symbols: If one can prove

$$P \implies \text{Contradiction}$$

then the statement P must in fact be false.

In the case at hand, letting P be the statement “there is a rational number whose square is 2”, the Theorem is asserting that P is false. We will prove this by assuming P is true and deriving an impossibility.

This is known as a proof by contradiction.

Proof. By way of contradiction, assume there were a rational number q such that $q^2 = 2$. By definition of “rational number”, we know that q can be written as $\frac{m}{n}$ for some integers m and n such that $n \neq 0$. Moreover, we may assume that we have written q in reduced form so that m and n have no prime factors in common. In particular, we may assume that not both of m and n are even. (If they were both even, then we could simplify the fraction by factoring out common factors of 2’s.) Since $q^2 = 2$, $\frac{m^2}{n^2} = 2$ and hence $m^2 = 2n^2$. In particular, this shows m^2 is even and, since the square of an odd number is odd, it must be that m itself is even. So, $m = 2a$ for some integer a .

But then $(2a)^2 = 2n^2$ and hence $4a^2 = 2n^2$ whence $2a^2 = n^2$. For the same reason as before, this implies that n must be even. But this contradicts the fact that m and n are not both even.

We have reached a contradiction, and so the assumption that there is a rational number q such that $q^2 = 2$ must be false. \square

Thus, if we would like to have a number corresponding to the length of the diagonal of a square with side length one, it must be a number that is real but not rational. Let's record the common name for such a number.

Definition 1.2. A real number is *irrational* if it is not rational.

A version of the previous proof was known even to the ancient Greeks.

Our first major mathematical goal in the class is to make a formal definition of the real numbers. Before we do this, let's record some basic properties of the rational numbers. I'll state this as a Proposition (which is something like a minor version of a Theorem), but we won't prove them; instead, we'll take it for granted to be true based on our own past experience with numbers.

For the rational numbers, we can do arithmetic $(+, -, \times, \div)$ and we also have a notion of size $(<, >)$. The first seven observations below describe the arithmetic, and the last three describe the notion of size.

Proposition 1.3 (Arithmetic and order properties of \mathbb{Q}). *The set of rational numbers form an “ordered field”. This means that the following ten properties hold:*

- (1) *There are operations $+$ and \cdot defined on \mathbb{Q} , so that if p, q are in \mathbb{Q} , then so are $p + q$ and $p \cdot q$.*
- (2) *Each of $+$ and \cdot is a commutative operation (i.e., $p + q = q + p$ and $p \cdot q = q \cdot p$ hold for all rational numbers p and q).*
- (3) *Each of $+$ and \cdot is an associative operation (i.e., $(p + q) + r = p + (q + r)$ and $(p \cdot q) \cdot r = p \cdot (q \cdot r)$ hold for all rational numbers p, q , and r).*
- (4) *The number 0 is an identity element for addition and the number 1 is an identity element for multiplication. This means that $0 + q = q$ and $1 \cdot q = q$ for all $q \in \mathbb{Q}$.*
- (5) *The distributive law holds: $p \cdot (q + r) = p \cdot q + p \cdot r$ for all $p, q, r \in \mathbb{Q}$.*
- (6) *Every number has an additive inverse: For any $p \in \mathbb{Q}$, there is a number $-p$ satisfying $p + (-p) = 0$.*
- (7) *Every nonzero number has a multiplicative inverse: For any $p \in \mathbb{Q}$ such that $p \neq 0$, there is a number p^{-1} satisfying $p \cdot p^{-1} = 1$.*
- (8) *There is a “total ordering” \leq on \mathbb{Q} . This means that*
 - (a) *For all $p, q \in \mathbb{Q}$, either $p \leq q$ or $q \leq p$.*
 - (b) *If $p \leq q$ and $q \leq p$, then $p = q$.*
 - (c) *For all $p, q, r \in \mathbb{Q}$, if $p \leq q$ and $q \leq r$, then $p \leq r$.*
- (9) *The total ordering \leq is compatible with addition: If $p \leq q$ then $p + r \leq q + r$.*
- (10) *The total ordering \leq is compatible with multiplication by non-negative numbers: If $p \leq q$ and $r \geq 0$ then $pr \leq qr$.*

Which of the properties from Proposition 1.3 does \mathbb{N} satisfy?

The commutativity, associativity, distributive law, multiplicative identity, and all of the ordering properties are true for \mathbb{N} .

We expect everything from Proposition 1.3 to be true for the real numbers. We will build them into our definition. To define the real numbers \mathbb{R} , we take the ten properties listed in the Proposition to be axioms. It turns out the set of real numbers satisfies one key additional property, called the *completeness axiom*, which I cannot state yet.

Axioms. *The set of all real numbers, written \mathbb{R} , satisfies the following eleven properties:*

- (Axiom 1) *There are operations $+$ and \cdot defined on \mathbb{R} , so that if $x, y \in \mathbb{R}$, then so are $x + y$ and $x \cdot y$.*
- (Axiom 2) *Each of $+$ and \cdot is a commutative operation.*
- (Axiom 3) *Each of $+$ and \cdot is an associative operation.*
- (Axiom 4) *The real number 0 is an identity element for addition and the real number 1 is an identity element for multiplication. This means that $0 + x = x$ and $1 \cdot x = x$ for all $x \in \mathbb{R}$.*
- (Axiom 5) *The distributive law holds: $x \cdot (y + z) = x \cdot y + x \cdot z$ for all $x, y, z \in \mathbb{R}$.*
- (Axiom 6) *Every real number has an additive inverse: For any $x \in \mathbb{R}$, there is a number $-x$ satisfying $x + (-x) = 0$.*
- (Axiom 7) *Every nonzero real number has a multiplicative inverse: For any $x \in \mathbb{R}$ such that $x \neq 0$, there is a real number x^{-1} satisfying $x^{-1} \cdot x = 1$.*
- (Axiom 8) *There is a “total ordering” \leq on \mathbb{R} . This means that*
 - (a) *For all $x, y \in \mathbb{R}$, either $x \leq y$ or $y \leq x$.*
 - (b) *If $x \leq y$ and $y \leq z$, then $x \leq z$.*
 - (c) *For all $x, y, z \in \mathbb{R}$, if $x \leq y$ and $y \leq z$, then $x \leq z$.*
- (Axiom 9) *The total ordering \leq is compatible with addition: If $x \leq y$ then $x + z \leq y + z$ for all z .*
- (Axiom 10) *The total ordering \leq is compatible with multiplication by nonnegative real numbers: If $x \leq y$ and $z \geq 0$ then $zx \leq zy$.*
- (Axiom 11) *The completeness axiom holds. (I will say what this means later.)*

There are many other familiar properties that are consequences of this list of axioms. As an example we can deduce the following property:

“Cancellation of Addition”: For real numbers, $x, y, z \in \mathbb{R}$, if $x + y = z + y$ then $x = z$.

Let’s prove this carefully, using just the list of axioms: Assume that $x + y = z + y$. Then we can add $-y$ (which exists by Axiom 6) to both sides to get $(x + y) + (-y) = (z + y) + (-y)$. This can be rewritten as $x + (y + (-y)) = z + (y + (-y))$ (Axiom 3) and hence as $x + 0 = z + 0$ (Axiom 6), which gives $x = z$ (Axiom 4 and Axiom 2).

Here is the incredible fact: everything that we know about the real numbers follows from these axioms! In particular, all of the basic facts about arithmetic of real numbers follow from this, like “the product of two negative numbers is positive,” as well as everything you encountered in Calculus, like the Mean Value Theorem.

2. WEDNESDAY, AUGUST 27, 2024 §1.4 & 1.5

Making sense of if-then statements.

- The statement “If P then Q ” is true whenever Q is true or P is false. Equivalently, the statement “If P then Q ” is false whenever Q is false and P is true.
- The **converse** of the statement “If P then Q ” is the statement “If Q then P ”.
- The **contrapositive** of the statement “If P then Q ” is the statement “If not Q then not P ”.
- Any if-then statement is equivalent to its *contrapositive*, but not necessarily to its converse!

- (1) For each of the following statements, write its contrapositive and its converse. Decide if original/contrapositive/converse true or false for real numbers a, b , but don't prove them yet.
- (a) If a is irrational, then $1/a$ is irrational.
 - (b) If a and b are irrational, then ab is irrational.
 - (c) If $a \geq 3$, then $a^2 \geq 9$.

- (a) Contrapositive: If $1/a$ is rational, then a is rational. Converse: If $1/a$ is irrational, then a is irrational. Original, contrapositive, and converse all TRUE.
- (b) Contrapositive: If ab is rational, then a is rational or b is rational. Converse: if ab is irrational, then a and b are irrational. Original, contrapositive, and converse all FALSE.
- (c) Contrapositive: If $a^2 < 9$ then $a < 3$. Converse: $a^2 \geq 9$ then $a \geq 3$. Original and contrapositive are TRUE but converse is FALSE.

Proving if-then statements.

- The general outline of a direct proof of “If P then Q ” goes
 - (1) Assume P .
 - (2) Do some stuff.
 - (3) Conclude Q .
- Often it is easier to prove the contrapositive of an if-then statement than the original, especially when the conclusion is something negative. We sometimes call this an *indirect proof* or a *proof by contraposition*.

- (2) Consider the following proof of the claim “For real numbers x, y, z , if $x + y = z + y$, then $x = z$ ” from the axioms of \mathbb{R} . Match the parts of this proof with the general outline above. Which sentences are *assumptions* and which are

assertions? Is it clear *just from reading each sentence on its own* whether it is an assumption or an assertion? Is it clear *why* each assertion is true?

Proof. Suppose that $x + y = z + y$. Then adding $-y$ (which exists by Axiom 6) we get

$$(x + y) + (-y) = (z + y) + (-y).$$

This can be rewritten (by Axiom 3) as

$$x + (y + (-y)) = z + (y + (-y)),$$

and hence (by Axiom 6) as

$$x + 0 = z + 0,$$

which gives $x = z$ (by Axioms 4 and 2). □

The first sentence is an assumption, while the others are assertions. It is clear that the first is an assumption since it says “Suppose”; another possibility is “Assume”.

- (3) Consider the following purported proof of the true fact “If $2x + 5 \geq 7$ then $x \geq 1$.” Is this a good proof? Is it a correct proof?

Proof.

$$x \geq 1.$$

Multiply both sides by two.

$$2x \geq 2.$$

Add five to both sides.

$$2x + 5 \geq 7.$$

□

No. It is not clear what is an assumption and what is an assertion. From the order of the sentences, it looks like they are assuming the conclusion and deducing the hypothesis! This was OK in this example, but they could have done almost the exact same thing to “prove” the false statement “If $2x^2 + 5 \geq 7$ then $x \geq 1$.”

Proving if-then statements.

- (4) Prove or disprove each of the statements in (1). You might consider a proof by contraposition for some of these!

- (a) TRUE: We proceed by contraposition. Suppose that $1/a$ is rational, so $1/a = p/q$ for some integers p/q . Then $a = q/p$ is rational.
- (b) FALSE: Consider $a = \sqrt{2}$ and $b = \sqrt{2}$. Both a and b are irrational, but $ab = 2$ is rational.

(c) TRUE: If $a \geq 3$ then $a^2 = a \cdot a \geq a \cdot 3 \geq 3 \cdot 3 = 9$, where we used that $a \geq 3 \geq 0$ in the first inequality, and $3 \geq 0$ in the second.

(5) Prove or disprove the *converse* of each of the statements in (1).

(a) TRUE: We proceed by contraposition. Suppose that a is rational, so $a = p/q$ for some integers p/q . Then $1/a = q/p$ is rational.
 (b) FALSE: Consider $a = \sqrt{2}$ and $b = 1$. Then $ab = \sqrt{2}$ is irrational, but b is rational, so it is not true that a and b are irrational.
 (c) FALSE: Consider $a = -3$; for this choice of a , $a \not\geq 3$ but $a^2 = 9 \geq 9$.

Using the axioms of \mathbb{R} to prove basic arithmetic facts.

(6) Let x and y be real numbers. Use the axioms of \mathbb{R} to prove¹ that if $x \geq y$ then $-x \leq -y$.

Let $x \geq y$. Adding $(-x) + (-y)$ to both sides (which exists by Axiom 6), we obtain $-y = x + ((-x) + (-y)) \geq y + ((-x) + (-y)) = -x$ (by Axiom 9 and Axiom 5). Conversely, let $-x \leq -y$. Adding $x + y$ to both sides, we obtain $y = (x + y) + (-x) \leq (x + y) + (-y) = x$ (by Axiom 9 and Axiom 5).

(7) Let x and y be real numbers. Use the axioms of \mathbb{R} to prove that $x \geq y$ if and only if $-x \leq -y$.

We need to prove both directions. The first direction is the previous problem. Conversely, let $-x \leq -y$. Adding $x + y$ to both sides, we obtain $y = (x + y) + (-x) \leq (x + y) + (-y) = x$ (by Axiom 9 and Axiom 5).

(8) Let x, y be real numbers. Use the axioms of \mathbb{R} and facts we have already proven² to prove that if $x \leq 0$ and $y \leq 0$, then $xy \geq 0$.

¹Hint: You may want to add something to both sides.

²Be careful: are you using any facts that we have not already proven?

3. FRIDAY, AUGUST 29, 2024 §1.4 & 1.5

Making sense of quantifier statements.

- The symbol for “**for all**” is \forall and the symbol for “**there exists**” is \exists .
- The negation of “For all $x \in S$, P ” is “There exists $x \in S$ such that not P ”.
- The negation of “There exists $x \in S$ such that P ” is “For all $x \in S$, not P ”.

A prankster has spraypainted the real number line red and blue, so every real number is red or blue (but not both)!

- (1) Match each informal story (i)–(iv) below with a precise quantifier statement (A)–(D).

Informal stories:

- (i) Every number past some point is red.
- (ii) There are arbitrarily big red numbers.
- (iii) All positive numbers are red.
- (iv) There are positive red number(s).

Precise statements:

- (A) For every $y > 0$, y is red.
- (B) There exists $y > 0$ such that y is red.
- (C) For every $x \in \mathbb{R}$, there is some $y > x$ such that y is red.
- (D) There exists $x \in \mathbb{R}$ such that for every $y > x$, y is red.

(i)=(D), (ii)=(C), (iii)=(A), (iv)=(B)

- (2) Draw a picture where (A) is false and (B) is true.

Answers may vary

- (3) Draw a picture where (C) is true and (D) is false.

Answers may vary

- (4) Suppose that (C) is true. Which of the following statements must also be true? Why?

- (a) There is some $y > 1000000000$ such that y is red.
- (b) For every $\mu \in \mathbb{R}$, there is some $\theta > \mu$ such that θ is red.
- (c) For every $x \in \mathbb{R}$, there is some $y > 2x$ such that y is red.

These are ALL TRUE.

The next problem is no longer about a spraypainting of the real number line.

(5) Rewrite each statement with symbols in place of quantifiers, and write its negation. Do you think the original statement is true or false (but don't prove them yet)?

- (a) There exists $x \in \mathbb{Q}$ such that $x^2 = 2$.
- (b) For all $x \in \mathbb{R}$, $x^2 > 0$.
- (c) For all $x \in \mathbb{R}$ such that³ $x \neq 0$, $x^2 > 0$.
- (d) For all $x \in \mathbb{R}$, there exists $y \in \mathbb{R}$ such that $x < y$.
- (e) There exists $x \in \mathbb{R}$ such that for all $y \in \mathbb{R}$, $x < y$.

- (a) $\exists x \in \mathbb{Q} : x^2 = 2$. NEGATION: For all $x \in \mathbb{Q}$, $x^2 \neq 2$.
- (b) $\forall x \in \mathbb{R}, x^2 > 0$. NEGATION: There exists $x \in \mathbb{R}$ such that $x^2 \leq 0$.
- (c) $\forall x \in \mathbb{R} : x \neq 0, x^2 > 0$. NEGATION: There exists $x \in \mathbb{R}$ such that $x \neq 0$ such that $x^2 \leq 0$.
- (d) $\forall x \in \mathbb{R}, \exists y \in \mathbb{R} : x < y$. NEGATION: There exists $x \in \mathbb{R}$ such that for all $y \in \mathbb{R}$, $x \geq y$.
- (e) $\exists x \in \mathbb{R} : \forall y \in \mathbb{R}, x < y$. NEGATION: For all $x \in \mathbb{R}$ there exists $y \in \mathbb{R}$ such that $x \geq y$.

Proving quantifier statements and using the axioms of \mathbb{R} .

- The general outline of a proof of “For all $x \in S$, P ” goes
 - (1) Let $x \in S$ be arbitrary.
 - (2) Do some stuff.
 - (3) Conclude that P holds for x .
- To prove a there exists statement, you just need to give an example. To prove “There exists $x \in S$ such that P ” directly:
 - (1) Consider² $x = [\text{some specific element of } S]$.
 - (2) Do some stuff.
 - (3) Conclude that P holds for x .

Note: explaining *how* you found your example “ x ” is *not* a logically necessary part of the proof.

(6) Circle the correct answer in each of the blanks below:

- To prove a “for all” statement, you need to give a
GENERAL ARGUMENT / SPECIFIC EXAMPLE.
- To *disprove* a “for all” statement, you need to give a
GENERAL ARGUMENT / SPECIFIC EXAMPLE.
- To prove a “there exists” statement, you need to give a
GENERAL ARGUMENT / SPECIFIC EXAMPLE.
- To *disprove* a “there exists” statement, you need to give a
GENERAL ARGUMENT / SPECIFIC EXAMPLE.

³In a statement of the form “For all $x \in S$ such that Q , P ”, the “such that Q ” part is part of the hypothesis: it is restricting the set S that we are “alling” over.

- If you want to *use* a “for all” statement that you know is true, you CAN CHOOSE A SPECIFIC VALUE / MUST USE A MYSTERY VALUE
- If you want to *use* a “there exists” statement that you know is true, you CAN CHOOSE A SPECIFIC VALUE / MUST USE A MYSTERY VALUE

- To prove a “for all” statement, you need to give a GENERAL ARGUMENT.
- To *disprove* a “for all” statement, you need to give a SPECIFIC EXAMPLE.
- To prove a “there exists” statement, you need to give a SPECIFIC EXAMPLE.
- To *disprove* a “there exists” statement, you need to give a GENERAL ARGUMENT.
- If you want to *use* a “for all” statement that you know is true, you CAN CHOOSE A SPECIFIC VALUE
- If you want to *use* a “there exists” statement that you know is true, you MUST USE A MYSTERY VALUE

- (7) Prove or disprove each of the statements in (5) using the axioms of \mathbb{R} and facts we have already proven.

- (a) FALSE: We showed that there is no rational number whose square is two.
- (b) FALSE: Take $x = 0$; then $x^2 = 0$ which is not strictly greater than zero.
- (c) TRUE.
- (d) TRUE: Let $x \in \mathbb{R}$ be given. Then $y = x + 1 > x$.
- (e) FALSE: Suppose that $x \in \mathbb{R}$. We claim that there is some $y \in \mathbb{R}$ such that $y \leq x$; just take x itself!

More practice with quantifier statements. Using the axioms of \mathbb{R} and statements that we’ve already proven (like cancellation of addition, or any problem on the list above the given one), prove the following:

- (8) Prove that there exists some $x \in \mathbb{R}$ such that $2x + 5 = 3$.

Take $x = -1$. Then $2x + 5 = 2(-1) + 5 = 3$.

- (9) Prove⁴ that for any real number r , we have $r \cdot 0 = 0$.

Let r be any real number. We have $0 + 0 = 0$ (Axiom 4) and hence $r \cdot (0 + 0) = r \cdot 0$. But $r \cdot (0 + 0) = r \cdot 0 + r \cdot 0$ (Axiom 5) and so $r \cdot 0 = r \cdot 0 + r \cdot 0$. We can rewrite this as $0 + r \cdot 0 = r \cdot 0 + r \cdot 0$ (Axiom 4). Now apply the

⁴Hint: You might find it useful to write $0 = 0 + 0$ and, in a later step, use cancellation of addition.

Cancellation of Addition property (which we previously deduced from the axioms) to obtain $0 = r \cdot 0$.

- (10) Let x be a real number. Use the axioms of \mathbb{R} and facts we have already proven to show that if there exists a real number y such that $xy = 1$, then $x \neq 0$.

Let x be a real number. Suppose that there exists a real number y such that $xy = 1$. By way of contradiction, suppose that $x = 0$. Then $1 = xy = 0y = 0$, which is a contradiction. Thus, we must have $x \neq 0$. Thus, if there exists a real number y such that $xy = 1$, then $x \neq 0$.

- (11) Prove that⁵ for all $x \in \mathbb{R}$ such that $x \neq 0$, we have $x^2 \neq 0$.

⁵Hint: Use (10).

4. WEDNESDAY, SEPTEMBER 3, 2024 §1.8

I owe you a statement of the very important Completeness Axiom. Before we get there, I want to recall an axiom of \mathbb{N} that we haven't discussed yet. It pertains to minimum elements in sets. Let's be precise and define minimum element.

Definition 4.1. Let S be a set of real numbers. A **minimum** element of S is a real number x such that

- (1) $x \in S$, and
- (2) for all $y \in S$, $x \leq y$.

In this case, we write $x = \min(S)$.

The definition of **maximum** is the same except with the opposite inequality.

Axiom 4.2 (Well-ordering axiom). *Every nonempty subset of \mathbb{N} has a minimum element.*

Example 4.3. If S is the set of even multiples of 7, then S has 14 as its minimum.

We generally like to say *the* minimum, rather than *a* minimum. To justify this, let's prove the following.

Proposition 4.4. *Let S be a set of real numbers. If S has a minimum, then the minimum is unique.*

Preproof Discussion 2. *The proposition has the general form "If a thing with property P exists, then it is unique".*

How do we prove a statement such as "If a thing with property P exists, then it is unique"? We argue that if two things x and y both have property P , then x and y must be the same thing.

Proof of Proposition 4.4. Let S be a set of real numbers, and let x and y be two minima of S . Applying part (1) of the definition of minimum to y , we have $y \in S$. Applying part (2) of the definition of minimum to x and the fact that $y \in S$, we get that $x \leq y$. Switching roles, we get that $y \leq x$. Thus $x = y$.

We conclude that if a minimum exists, it is necessarily unique. \square

The previous proposition plus the Well-Ordering Axiom together imply that every nonempty subset of \mathbb{N} has exactly one minimum element. A similar proof shows that if a maximum exists, it is necessarily unique. Could a set fail to have a maximum or a minimum? Yes!

Example 4.5.

- (1) The empty set \emptyset has no minimum and no maximum element. (There is no $s \in \emptyset$!)
- (2) The set of natural numbers \mathbb{N} has 1 as a minimum, but has no maximum. (Suppose there was: if $n = \max(\mathbb{N})$ was the maximum, then $n < n + 1 \in \mathbb{N}$ gives a contradiction.)
- (3) The open interval $(0, 1) = \{x \in \mathbb{R} \mid 0 < x < 1\}$ has no minimum and no maximum. (Exercise later.)

Definition 4.6. Let S be any subset of \mathbb{R} . A real number b is called an **upper bound** of S provided that for every $s \in S$, we have $s \leq b$.

Definition 4.7. A subset S of \mathbb{R} is called **bounded above** if there exists at least one upper bound for S . That is, S is bounded above provided there is a real number b such that for all $s \in S$ we have $s \leq b$.

For example, the open interval $(0, 1)$ is bounded above, by for example 50.

The subset \mathbb{N} of \mathbb{R} is not bounded above — there is no real number that is larger than every natural number. This fact is surprisingly non-trivial to deduce just using the axioms; in fact, one needs the Completeness Axiom to show it. But of course our intuition tells us that it is obviously true.

Let's give a more interesting example of a subset of \mathbb{R} that is bounded above.

Example 4.8. Define S to be those real numbers whose squares are less than 2:

$$S = \{x \in \mathbb{R} \mid x^2 < 2\}.$$

I claim S is bounded above. In fact, I'll prove 2 is an upper bound: Suppose $x \in S$. If $x > 2$, then $x \cdot x > x \cdot 2$ and $x \cdot 2 > 2 \cdot 2$, and hence $x^2 > 4 > 2$. This contradicts the fact that $x \in S$. So, we must have $x \leq 2$.

A nearly identical argument shows that 1.5 is also an upper bound (since $1.5^2 = 2.25 > 2$) and similarly one can show 1.42 is an upper bound. But 1.41 is not an upper bound. For note that $1.411^2 = 1.99091$ and so $1.41 \in S$ but $1.411 > 1.41$.

Question: What is the smallest (or least) upper bound for this set S ? Clearly, it ought to be $\sqrt{2}$ (i.e., the positive number whose square is equal to exactly 2), but there's a catch: how do we know that such real number exists?

Definition 4.9. Suppose S is subset of \mathbb{R} that is bounded above. A **supremum** (also known as a **least upper bound**) of S is a number ℓ such that

- (1) ℓ is an upper bound of S (i.e., $s \leq \ell$ for all $s \in S$) and
- (2) if b is any upper bound of S , then $\ell \leq b$.

In this case we write $\sup(S) = \ell$.

5. FRIDAY, SEPTEMBER 5, 2024 §1.8

Let S be a set of real numbers.

- A number b is an **upper bound** for S provided for all $x \in S$ we have $b \geq x$.
- The set S is **bounded above** provided there exists at least one upper bound for S .
- A number m is the **maximum** of S provided
 - (1) $m \in S$, and
 - (2) m is an upper bound of S .
- A number ℓ is a **supremum** of S provided
 - (1) ℓ is an upper bound of S , and
 - (2) for any upper bound b for S , we have $\ell \leq b$.

- (1) Write, in simplified form, the negation of the statement “ b is an upper bound for S ”.

There exists some $x \in S$ such that $x > b$.

- (2) Write, in simplified form, the negation of the statement “ S is bounded above”.

For every $b \in \mathbb{R}$, there exists $x \in S$ such that $x > b$.

- (3) Let S be a set of real numbers and suppose that $\ell = \sup(S)$.
- (a) If $x > \ell$, what is the most concrete thing you can say about x and S ?
 - (b) If $x < \ell$, what is the most concrete thing⁶ you can say about x and S ?

- (a) $x \notin S$.
- (b) There exists some $y \in S$ such that $y > x$.

- (4) Let $S = \{x \in \mathbb{R} \mid x^3 + x < 5\}$. Use the definition of supremum to answer the following:
- (a) Is 1 the supremum of S ? Why or why not?
 - (b) Is 2 the supremum of S ? Why or why not?

- (a) No. 1 is not an upper bound for S , because $1.5^3 + 1.5 = 4.875 < 5$, so 1.5 is a larger element of S .
- (b) No. We claim that 1.75 is an upper bound for S , so 2 is not the smallest upper bound of S . Indeed, if $x \in S$ then $x \leq 1.75$; if $x > 1.75$ then $x^3 + x > 1.75^3 + 1.75 = 7.109375 > 5$ so $x \notin S$.

- (5) Consider the open interval $(0, 1) = \{x \in \mathbb{R} \mid 0 < x < 1\}$.

⁶Hint: Use one of the previous problems.

- (a) Prove⁷ that $(0, 1)$ has no maximum element.
 (b) Prove that $\sup((0, 1)) = 1$.

- (a) To obtain a contradiction, suppose that $(0, 1)$ has a maximum element; call it z . Since $z \in (0, 1)$ so $0 < z < 1$. First, we claim that $y = \frac{z+1}{2} \in (0, 1)$. Indeed, $z > 0$ implies $y > \frac{0+1}{2} = \frac{1}{2} > 0$, and $z < 1$ implies $y < \frac{1+1}{2} = 1$, so $y \in (0, 1)$. Now we claim that y is larger than z : $y = \frac{z+1}{2} > \frac{z+z}{2} = z$. But this contradicts that z is an upper bound for $(0, 1)$, so z cannot be the maximum. Since assuming the existence of a maximum element leads to a contradiction, we conclude that no maximum exists.
- (b) We need to show that 1 is an upper bound for $(0, 1)$, and that any other upper bound b for $(0, 1)$ satisfies $b \geq 1$. By definition of the interval $(0, 1)$, the number 1 is an upper bound. Now suppose that b is an upper bound for $(0, 1)$. We claim that $b \geq 1$. Suppose otherwise that $b < 1$ to obtain a contradiction. Consider $y = \frac{b+1}{2}$. Then by the same algebraic argument as the previous part, $y \in (0, 1)$ and $y > b$, so y is not an upper bound for $(0, 1)$. This contradicts the assumption that $b < 1$, so $b \geq 1$. Thus, every upper bound of $(0, 1)$ is at least 1. This shows that 1 is the supremum of $(0, 1)$.

- (6) Let S be a set of real numbers, and let $T = \{2s \mid s \in S\}$. Prove that if S is bounded above, then T is bounded above.

Assume that S is bounded above. Then there is some upper bound b for S , so for every $s \in S$, we have $b \geq s$. We claim that $2b$ is an upper bound for T . Indeed, if $t \in T$, then we can write $t = 2s$ for some $s \in S$, and $s \leq b$ implies $t = 2s \leq 2b$. Thus, T is bounded above.

- (7) Let S be a set of real numbers. Show that if S has a supremum, then it is unique.

Suppose both x and y are both suprema of the same subset S of \mathbb{R} . Then, since y is an upper bound of S and x is a supremum of S , by part (2) of the definition of “supremum” we have $y \geq x$. Likewise, since x is an upper bound of S and y is a supremum of S , we have $x \geq y$ by definition. Since $x \leq y$ and $y \leq x$, we conclude $x = y$.

⁷Hint: Try a proof by contradiction!

Can you think of a set with no supremum?

The subset \mathbb{N} does not have a supremum since, indeed, it does not have any upper bounds at all.

Can you think of an example of a set that is bounded above but has no supremum? There is only one such example and it is rather silly: the empty set is bounded above. Indeed, every real number is an upper bound for the empty set. So, there is no least upper bound.

Having explained the meaning of the term “supremum”, I can finally state the all-important completeness axiom:

Axiom (Completeness Axiom). *Every nonempty, bounded-above subset of \mathbb{R} has a supremum.*

This is an incredibly powerful fact about the real numbers. To give a sense of what it does, recall that we showed that there is no rational number whose square is two; the completeness axiom is what allows us to show that there is a real number whose square is two.

Proposition 5.1. *There is a positive real number whose square is 2.*

In class, let’s just discuss the outline of this proof rather than the algebraic details, so we can see the big picture. You can read the full proof in the lecture notes.

Proof outline.

Step 1: Define S to be the subset $S = \{x \in \mathbb{R} \mid x^2 < 2\}$.

Step 2: Show that S is nonempty and bounded above. Thus, by the Completeness Axiom, there is a real number $\ell = \sup(S)$.

Step 3: Show that $\ell^2 < 2$ leads to a contradiction. (Assuming $\ell^2 < 2$, we can find a number s slightly larger than ℓ that is an element of S , contradicting that ℓ is an upper bound of S .)

Step 4: Show that $\ell^2 > 2$ leads to a contradiction. (Assuming $\ell^2 > 2$, we can find a number b slightly smaller than ℓ that is an upper bound of S , contradicting that ℓ is the smallest upper bound of S .)

Step 5: There’s no other possibility: we must have $\ell^2 = 2$! □

Here is the proof in full detail.

Proof. Define S to be the subset

$$S = \{x \in \mathbb{R} \mid x^2 < 2\}.$$

S is nonempty since, for example, $1 \in S$, and it is bounded above, since, for example, 2 is an upper bound for S , as we showed earlier. So, by the Completeness Axiom, S has a least upper bound, and we know it is unique from the proposition above. Let us call it ℓ . I will prove $\ell^2 = 2$.

We know one of $\ell^2 > 2$, $\ell^2 < 2$ or $\ell^2 = 2$ must hold. We prove $\ell^2 = 2$ by showing that both $\ell^2 > 2$ and $\ell^2 < 2$ are impossible.

We start by observing that $1 \leq \ell \leq 2$. The inequality $1 \leq \ell$ holds since $1 \in S$ and ℓ is an upper bound of S , and the inequality $\ell \leq 2$ holds since 2 is an upper bound of S and ℓ is the least upper bound of S .

Suppose $\ell^2 < 2$. We show this leads to a contradiction by showing that ℓ is not an upper bound of S in this case. We will do this by constructing a number that is ever so slightly bigger than ℓ and belongs to S . Let $\varepsilon = 2 - \ell^2$. Then $0 < \varepsilon \leq 1$ (since $\ell^2 < 2$ and $\ell^2 \geq 1$). We will now show that $\ell + \varepsilon/5$ is in S : We have

$$(\ell + \varepsilon/5)^2 = \ell^2 + \frac{2}{5}\ell\varepsilon + \frac{\varepsilon^2}{25} = \ell^2 + \varepsilon\left(\frac{2\ell}{5} + \frac{\varepsilon}{25}\right).$$

Now, using $\ell \leq 2$ and $0 < \varepsilon \leq 1$, we deduce

$$0 < \frac{2\ell}{5} + \frac{\varepsilon}{25} \leq \frac{4}{5} + \frac{\varepsilon}{25} < 1.$$

Putting these equations and inequalities together yields

$$(\ell + \frac{\varepsilon}{5})^2 < \ell^2 + \varepsilon = 2.$$

So, $\ell + \frac{\varepsilon}{5} \in S$ and yet $\ell + \frac{\varepsilon}{5} > \ell$, contradicting the fact that ℓ is an upper bound of S . We conclude $\ell^2 < 2$ is not possible.

Assume now that $\ell^2 > 2$. Our strategy will be to construct a number ever so slightly smaller than ℓ , which therefore cannot be an upper bound of S , and use this to arrive at a contradiction. Let $\delta = \ell^2 - 2$. Then $0 < \delta \leq 2$ (since $\ell \leq 2$ and hence $\ell^2 - 2 \leq 2$). Since $\delta > 0$, we have $\ell - \frac{\delta}{5} < \ell$. Since ℓ is the least upper bound of S , $\ell - \frac{\delta}{5}$ must not be an upper bound of S . By definition, this means that there is $r \in S$ such that $\ell - \frac{\delta}{5} < r$. Since $\delta \leq 2$ and $\ell \geq 1$, it follows that $\ell - \frac{\delta}{5}$ is positive and hence so is r . We may thus square both sides of $\ell - \frac{\delta}{5} < r$ to obtain

$$(\ell - \frac{\delta}{5})^2 < r^2.$$

Now

$$(\ell - \frac{\delta}{5})^2 = \ell^2 - \frac{2\ell\delta}{5} + \frac{\delta^2}{25} = \delta + 2 - \frac{2\ell\delta}{5} + \frac{\delta^2}{25}$$

since $\ell^2 = \delta + 2$. Moreover,

$$\delta + 2 - \frac{2\ell\delta}{5} + \frac{\delta^2}{25} = 2 + \delta(1 - \frac{2\ell}{5} + \frac{\delta}{25}) \geq 2 + \delta(1 - \frac{4}{5} + \frac{\delta}{25})$$

since $\ell \leq 2$. We deduce that

$$\delta + 2 - \frac{2\ell\delta}{5} + \frac{\delta^2}{25} \geq 2 + \delta(\frac{1}{5}) \geq 2.$$

Putting these inequalities together gives $r^2 > 2$, contrary to the fact that $r \in S$. We conclude that $\ell^2 > 2$ is also not possible.

Since $\ell^2 < 2$ and $\ell^2 > 2$ are impossible, we must have $\ell^2 = 2$. □

6. MONDAY, SEPTEMBER 9, 2024 §1.9

Recall the Completeness Axiom:

COMPLETENESS AXIOM: Every nonempty bounded above set of real numbers has a supremum.

The collection of rational numbers does not satisfy the completeness axiom and indeed it is precisely the completeness axiom that differentiates \mathbb{R} from \mathbb{Q} .

Example 6.1. Within the set \mathbb{Q} the subset $S = \{x \in \mathbb{Q} \mid x^2 < 2\}$ does not have a supremum. That is, no matter which rational number you pick that is an upper bound for S , you may always find an even smaller one that is also an upper bound of S .

It is precisely the completeness axiom that assures us that everything that ought to be a number (like the length of the diagonal of a square with side length 1) really is a number. It gives us that there are “no holes” in the real number line — the real numbers are *complete*.

The completeness axiom is also at the core of the Intermediate Value Theorem and many of the other major theorems we will cover in this class.

We also need the completeness axiom to understand the relationship between \mathbb{N} , \mathbb{Q} , and \mathbb{R} .

Theorem 6.2. *If x is any real number, then there exists a natural number n such that $n > x$.*

This looks really stupid at first. How could it be false? But consider: there are examples of ordered fields, i.e. situations in which Axioms 1–10 hold, in which this Theorem is not true! So, its proof must rely on the Completeness Axiom.

Proof. Let x be any real number. By way of contradiction, suppose there is no natural number n such that $n > x$. That is, suppose that for all $n \in \mathbb{N}$, $n \leq x$. Then \mathbb{N} is a bounded above (by x). Since it is also clearly nonempty, by the Completeness Axiom, \mathbb{N} has a supremum, call it ℓ . Consider the number $y := \ell - 1$. Since $y < \ell$ and ℓ is the supremum of \mathbb{N} , y cannot be an upper bound of \mathbb{N} . So, there must be some $m \in \mathbb{N}$ such that $\ell - 1 < m$. But then by adding 1 to both sides of this inequality we get $\ell < m + 1$ and, since $m + 1 \in \mathbb{N}$, this contradicts that assumption that ℓ is the supremum of \mathbb{N} .

We conclude that, given any real number x , there must exist a natural number n such that $n > x$. \square

Corollary 6.3 (Archimedean Principle). *If $a \in \mathbb{R}$, $a > 0$, and $b \in \mathbb{R}$, then for some natural number n we have $na > b$.*

“No matter how small a is and how large b is, if we add a to itself enough times, we can overtake b .”

Proof. We apply Theorem 6.2 to the real number $x = \frac{b}{a}$. It gives that there is a natural number n such that $n > x = \frac{b}{a}$. Since $a > 0$, upon multiplying both sides by a we get $n \cdot a > b$. \square

Theorem 6.4 (Density of the Rational Numbers). *Between any two distinct real numbers there is a rational number; more precisely, if $x, y \in \mathbb{R}$ and $x < y$, then there exists $q \in \mathbb{Q}$ such that $x < q < y$.*

Proof. We will prove this by consider two cases: $x \geq 0$ and $x < 0$.

Let us first assume $x \geq 0$. We apply the Archimedean Principle using $a = y - x$ and $b = 1$. (The Principle applies as $a > 0$ since $y > x$.) This gives us that there is a natural number $n \in \mathbb{N}$ such that

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

and thus

$$0 < \frac{1}{n} < y - x.$$

Consider the set $S = \{p \in \mathbb{N} \mid p \frac{1}{n} > x\}$. Since $\frac{1}{n} > 0$, using the Archimedean principle again, there is at least one natural number $p \in S$. By the Well Ordering Axiom, there is a smallest natural number $m \in S$.

We claim that $\frac{m-1}{n} \leq x$. Indeed, if $m > 1$, then $m-1 \in \mathbb{N} \setminus S$ (because $m-1$ is less than the minimum), so $\frac{m-1}{n} \leq x$; if $m = 1$, then $m-1 = 0$, so $\frac{m-1}{n} = 0 \leq x$.

So, we have

$$\frac{m-1}{n} \leq x < \frac{m}{n}$$

By adding $\frac{1}{n}$ to both sides of $\frac{m-1}{n} \leq x$ and using that $\frac{1}{n} < y - x$, we get

$$\frac{m}{n} \leq x + \frac{1}{n} < x + (y - x) = y$$

and hence

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

Since $\frac{m}{n}$ is clearly a rational number, this proves the result in this case (when $x \geq 0$).

We now consider the case $x < 0$. The idea here is to simply “shift” up to the case we’ve already proven. By Theorem 6.2, we can find a natural number j such that $j > -x$ and thus $0 < x + j < y + j$. Using the first case, which we have already proven, applied to the number $x + j$ (which is positive), there is a rational number q such that $x + j < q < y + j$. We deduce that $x < q - j < y$, and, since $q - j$ is also rational, this proves the theorem in this case. \square

7. WEDNESDAY, SEPTEMBER 11, 2024 §1.9

DEFINITION: Let S be a set of real numbers. A number ℓ is the **supremum** of S provided

- ℓ is an upper bound of S and
- if b is any upper bound of S , then $\ell \leq b$.

THEOREM 6.3: For every real number r , there is a natural number n such that $n > r$.

COROLLARY 6.4 (ARCHIMEDEAN PRINCIPLE): For every positive real number a and every real number b , there is some natural number n such that $na > b$.

THEOREM 6.5 (DENSITY OF RATIONAL NUMBERS): For any real numbers x, y with $x < y$, there is some rational number q such that $x < q < y$.

- (1) Use the Archimedean Principle to show that for any positive number $\varepsilon > 0$, there is a natural number n such that $0 < \frac{1}{n} < \varepsilon$.

Let $\varepsilon > 0$. We apply the Archimedean Principle with $\varepsilon > 0$ and 1 to obtain that there is some natural number n such that $n\varepsilon > 1$. We claim that this is the n we seek. Indeed, after rearranging, we find that $\varepsilon > \frac{1}{n}$, and $n > 0$ implies $\frac{1}{n} > 0$ as well.

- (2) Prove that the supremum of the set $S = \left\{1 - \frac{1}{n} \mid n \in \mathbb{N}\right\}$ is 1.

First, we show that 1 is an upper bound for S . Indeed, and $s \in S$ can be written as $1 - \frac{1}{n}$ for some $n \in \mathbb{N}$, and since $\frac{1}{n} > 0$, we have $1 - \frac{1}{n} < 1$. Thus 1 is an upper bound.

Now we show that 1 is the smallest upper bound. Suppose that $b < 1$ is an upper bound. Let $\varepsilon = 1 - b$, which by hypothesis is positive. Then by the previous problem, there is some $n \in \mathbb{N}$ such that $\frac{1}{n} < \varepsilon$, so $1 - \frac{1}{n} > 1 - \varepsilon = b$. Thus, b is not an upper bound. It follows that 1 is the smallest upper bound, i.e., the supremum of S .

- (3) Prove the following:

COROLLARY 7.1 (DENSITY OF IRRATIONAL NUMBERS): For any real numbers x, y with $x < y$, there is some irrational number z such that $x < z < y$.

Let $x < y$ be real numbers. Then we have $x - \sqrt{2} < y - \sqrt{2}$. By density of rationals, there is some rational number q such that $x - \sqrt{2} < q < y - \sqrt{2}$. Then $x < q + \sqrt{2} < y$. Since q is rational and $\sqrt{2}$ is irrational, $z = q + \sqrt{2}$ is irrational, and hence the number we seek.

- (4) Let S be a set of real numbers, and suppose that $\sup(S) = \ell$. Let $T = \{s + 7 \mid s \in S\}$. Prove that $\sup(T) = \ell + 7$.

First, we show that $\ell + 7$ is an upper bound of T . Let $t \in T$. Then there is some $s \in S$ such that $t = s + 7$. Since $s \leq \ell$, we have $t = s + 7 < \ell + 7$, so $\ell + 7$ is indeed an upper bound. Next, let b be an upper bound for T . We claim that $b - 7$ is an upper bound for S . Indeed, if $s \in S$, then $s + 7 \in T$ so $s + 7 \leq b$, so $s \leq b - 7$. Then, by definition of supremum, we have $b - 7 \geq \ell$, so $b \geq \ell + 7$.

8. FRIDAY, SEPTEMBER 13, 2024 §1.7 & 1.9

DEFINITION: For a real number x , the **absolute value** of x is

$$|x| := \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{if } x < 0 \end{cases}.$$

THEOREM 8.1 (TRIANGLE INEQUALITY): Let x, y, z be real numbers. Then

$$|x - z| \leq |x - y| + |y - z|.$$

THEOREM 8.2 (REVERSE TRIANGLE INEQUALITY): Let x, y, z be real numbers. Then

$$|x - z| \geq ||x - y| - |y - z||.$$

We often use the Triangle Inequality to show precise versions of “if x is close to y and y is close to z , then x is close to z .” We often use the Reverse triangle Inequality to show precise versions of “if x is far from y and y is close to z , then x is far from z .”

- (1) If x and y are real numbers, what is the geometric meaning of $|x - y|$?

The distance between x and y on the real number line.

- (2) We will often look at conditions like $|x - L| < \varepsilon$, where L and ε are real numbers and x is a variable. Describe $\{x \in \mathbb{R} : |x - L| < \varepsilon\}$ in interval notation. Now draw a picture of this on the real number line, showing the role of L and ε .

$(L - \varepsilon, L + \varepsilon)$.



- (3) Describe $\{x \in \mathbb{R} : |3x + 7| < 4\}$ explicitly in interval notation.

Since $|3x + 7| = |3||x + \frac{7}{3}| = 3|x + \frac{7}{3}|$, we have $|3x + 7| < 4$ if and only if $|x + \frac{7}{3}| < \frac{4}{3}$, so our interval goes from $\frac{-7}{3} - \frac{4}{3} = \frac{-11}{3}$ to $\frac{-7}{3} + \frac{4}{3} = -1$. That is $(\frac{-11}{3}, -1)$.

- (4) Suppose that $|x - 2| < \frac{1}{5}$, $|y - 2| < \frac{2}{5}$.
- Show that $x > \frac{8}{5}$.
 - Show that $|x - y| < \frac{3}{5}$.
 - Use the reverse triangle inequality to show that $|y - 3| > \frac{3}{5}$.

- (a) Since $|x - 2| < \frac{1}{5}$, we have $-(x - 2) \leq |x - 2| < \frac{1}{5}$, so $x - 2 > -\frac{1}{5}$, and $x > 2 - \frac{1}{5} = \frac{9}{5} > \frac{8}{5}$.
- (b) By the triangle inequality, $|x - 2| < \frac{1}{5}$ and $|y - 2| < \frac{2}{5}$ implies $|x - y| < \frac{1}{5} + \frac{2}{5} = \frac{3}{5}$.
- (c) Applying the reverse triangle inequality with y , 2, and 3, we have $|y - 3| \geq ||3 - 2| - |y - 2|| = |1 - |y - 2||$. Since $|y - 2| < \frac{2}{5}$, $1 - |y - 2| > 0$, so $|1 - |y - 2|| = 1 - |y - 2| > 1 - \frac{2}{5} = \frac{3}{5}$.

(5) True or false & justify¹: There is a rational number x such that $|x^2 - 2| = 0$.

False! This would imply that $x^2 = 2$, and there is no such rational number.

(6) True or false & justify⁸: There is a rational number x such that $|x^2 - 2| < \frac{1}{1000000}$.

True! There is a rational number x in the interval $(\sqrt{2} - \frac{1}{4000000}, \sqrt{2} + \frac{1}{4000000})$ by density of rational numbers. In particular, $x < \sqrt{2} + \frac{1}{4000000} < 2$ so $|x + \sqrt{2}| < 2 + 2 = 4$. (This is a crude bound, but good enough.) Then $|x^2 - 2| = |x - \sqrt{2}| \cdot |x + \sqrt{2}| < \frac{1}{4000000} \cdot 4 = \frac{1}{1000000}$.

⁸You can use anything we've proven in class, but don't use things we haven't, like decimal expansions.

9. MONDAY, SEPTEMBER 16, 2024 §2.1

We now turn our attention to the next major topic of this class: sequences of real numbers. We will spend the next few weeks developing their properties carefully and rigorously. Sequences form the foundation for much of what we will cover for the rest of the semester.

Definition 9.1. A **sequence** is an infinite list of real numbers indexed by \mathbb{N} :

$$a_1, a_2, a_3, \dots$$

(Equivalently, a sequence is a function from \mathbb{N} to \mathbb{R} : the value of the function at $n \in \mathbb{N}$ is written as a_n .)

We will usually write $\{a_n\}_{n=1}^{\infty}$ for a sequence.

Example 9.2. To describe sequences, we will typically give a formula for the n -th term, a_n , either an explicit one or a recursive one. On rare occasion we'll just list enough terms to make the pattern clear. Here are some examples:

- (1) $\{5 + (-1)^n \frac{1}{n}\}_{n=1}^{\infty}$ is the sequence that starts

$$4, \frac{11}{2}, \frac{14}{3}, \frac{21}{4}, \frac{24}{5}, \dots$$

- (2) Let $\{a_n\}_{n=1}^{\infty}$ be defined by $a_1 = 1, a_2 = 1$ and $a_n = a_{n-1} + a_{n-2}$ for all $n \geq 2$. This gives the sequence

$$1, 1, 2, 3, 5, 8, 13, 21, 34, \dots$$

This is an example of a recursively defined sequence. It is the famed **Fibonacci sequence**.

- (3) Let $\{c_n\}_{n=1}^{\infty}$ be the sequence whose n -th term is the n -th smallest positive prime integer:

$$2, 3, 5, 7, 11, 13, 17, 19, 23, \dots$$

Note that here I have not really given an explicit formula for the terms of the sequence, but it is possible to describe an algorithm that lists every term of the sequence in order.

You have all probably seen an “intuitive” definition of the limit of a sequence before. For example, you probably believe that

$$5 + (-1)^n \frac{1}{n}$$

converges to 5. Let's give the rigorous definition.

Definition 9.3. Let $\{a_n\}_{n=1}^{\infty}$ be an arbitrary sequence and L a real number. We say $\{a_n\}_{n=1}^{\infty}$ **converges** to L provided the following condition is met:

For every real number $\varepsilon > 0$, there is a real number N such that $|a_n - L| < \varepsilon$ for all natural numbers n such that $n > N$.

This is an extremely important definition for this class. Learn it by heart!
In symbols, the definition is

A sequence $\{a_n\}_{n=1}^{\infty}$ converges to L provided
 $\forall \varepsilon > 0, \exists N \in \mathbb{R} : \forall n \in \mathbb{N} \text{ s.t. } n > N, |a_n - L| < \varepsilon.$

It's a complicated definition — three quantifiers!

Here is what the definition is saying somewhat loosely: No matter how small a number ε you pick, so long as it is positive, if you go far enough out in the sequence, all of the terms from that point on will be within a distance of ε of the limiting value L .

Example 9.4. To say that the sequence $\{a_n\}_{n=1}^{\infty}$ where $a_n = 5 + (-1)^n \frac{1}{n}$ converges to 5 gives us a different statement for every $\varepsilon > 0$. For example:

- Setting $\varepsilon = 3$, there is a number N such that for every natural number $n > N$, $|a_n - 5| < 3$. Namely, we can take $N = 0$, since for *every* term a_n of the sequence, $|a_n - 5| < 3$ holds true.
- Setting $\varepsilon = \frac{1}{3}$, there is a number N such that for every natural number $n > N$, $|a_n - 5| < \frac{1}{3}$. We cannot take $N = 0$ anymore, since $1 > 0$ and $|a_1 - 5| = 1 > \frac{1}{3}$. However, we can take $N = 3$, since for $n > 3$, $|a_n - 5| = \frac{1}{n} < \frac{1}{3}$.
- Setting $\varepsilon = 1/1000000$, there is a number N such that for every natural number $n > N$, $|a_n - 5| < 1/1000000$. We need a bigger N ; now $N = 1000000$ works.

In general, our choice of N may depend on ε , which is OK since our definition is of the form $\forall \varepsilon > 0, \exists N \dots$ rather than $\exists N : \forall \varepsilon > 0 \dots$

Example 9.5. I claim the sequence $\{a_n\}_{n=1}^{\infty}$ where $a_n = 5 + (-1)^n \frac{1}{n}$ converges to 5. I'll give a rigorous proof, along with some commentary and “scratch work” within the parentheses.

Proof. Let $\varepsilon > 0$ be given.

(Scratch work: Given this ε , our goal is to find N so that if $n > N$, then $|5 + (-1)^n \frac{1}{n} - 5| < \varepsilon$. The latter simplifies to $\frac{1}{n} < \varepsilon$, which in turn is equivalent to $\frac{1}{\varepsilon} < n$ since ε and n are both positive. So, it seems we've found the N that “works”. Back to the formal proof....)

Let $N = \frac{1}{\varepsilon}$. Then $\frac{1}{N} = \varepsilon$, since ε is positive.

(Comment: We next show that this is the N that “works” in the definition. Since this involves proving something about every natural number that is bigger than N , we start by picking one.)

Pick any $n \in \mathbb{N}$ such that $n > N$. Then $\frac{1}{n} < \frac{1}{N}$ and hence

$$|a_n - 5| = |5 + (-1)^n \frac{1}{n} - 5| = |(-1)^n \frac{1}{n}| = \frac{1}{n} < \frac{1}{N} = \varepsilon.$$

This proves that $\{5 + (-1)^n \frac{1}{n}\}_{n=1}^{\infty}$ converges to 5. □

Remark 9.6. A direct proof that a certain sequence converges to a certain number follows the general outline:

- Let $\varepsilon > 0$ be given. (or, if your prefer, “Pick $\varepsilon > 0$.”)
- Let $N = [\text{expression in terms of } \varepsilon \text{ from scratch work}]$.
- Let $n \in \mathbb{N}$ be such that $n > N$.
- [Argument that $|a_n - L| < \varepsilon$.]
- Thus $\{a_n\}_{n=1}^{\infty}$ converges to L .

In particular, you usually can't just sit down and write a proof in one fell swoop: you will have to prepare for your proof by figuring out what value of N will beat ε . The work that you use to find N in terms of ε does *not* belong in the final proof.

Example 9.7. I claim that the sequence

$$\left\{ \frac{2n-1}{5n+1} \right\}_{n=1}^{\infty}$$

converges to $\frac{2}{5}$. Again I'll give a proof with commentary and scratch work in parentheses.

Proof. Let $\varepsilon > 0$ be given.

(Scratch work: We need n to be large enough so that

$$\left| \frac{2n-1}{5n+1} - \frac{2}{5} \right| < \varepsilon.$$

This simplifies to $\left| \frac{-7}{25n+5} \right| < \varepsilon$ and thus to $\frac{7}{25n+5} < \varepsilon$, which we can rewrite as $\frac{7}{25\varepsilon} - \frac{1}{5} < n$.)

Let $N = \frac{7}{25\varepsilon} - \frac{1}{5}$. We solve this equation for ε : We get $\frac{7}{25\varepsilon} = \frac{5N+1}{5}$ and hence $\frac{25\varepsilon}{7} = \frac{5}{5N+1}$, which gives finally

$$\varepsilon = \frac{7}{25N+5}.$$

(Next we show this value of N works....)

Now pick any $n \in \mathbb{N}$ is such that $n > N$. Then

$$\left| \frac{2n-1}{5n+1} - \frac{2}{5} \right| = \left| \frac{10n-5-10n-2}{25n+5} \right| = \frac{7}{25n+5}.$$

Since $n > N$, $25n+5 > 25N+5$ and hence

$$\frac{7}{25n+5} < \frac{7}{25N+5} = \varepsilon.$$

We have proven that if $n \in \mathbb{N}$ and $n > N$, then

$$\left| \frac{2n-1}{5n+1} - \frac{2}{5} \right| < \varepsilon.$$

This proves $\left\{ \frac{2n-1}{5n+1} \right\}_{n=1}^{\infty}$ converges to $\frac{2}{5}$. □

10. WEDNESDAY, SEPTEMBER 18, 2024 §2.1

DEFINITION: A sequence $\{a_n\}_{n=1}^{\infty}$ **converges** to a real number L provided for every real number $\varepsilon > 0$, there is a real number N such that $|a_n - L| < \varepsilon$ for all natural numbers n such that $n > N$.

- (1) Consider the sequence $\{a_n\}_{n=1}^{\infty} = \{2 - \frac{50}{n}\}_{n=1}^{\infty}$.
- (a) Write out the first seven terms of this sequence: use a calculator to write the decimal expansions for the numbers.
 - (b) Can you find a point N such that every term in the sequence after N (that is, every a_n for $n > N$) is within 20 of 2 (that is, $|a_n - 2| < 20$)?
 - (c) Can you find a point N such that every term in the sequence after N (that is, every a_n for $n > N$) is within 10 of 2 (that is, $|a_n - 2| < 10$)?
 - (d) Can you find a point N such that every term in the sequence after N (that is, every a_n for $n > N$) is within 1 of 2 (that is, $|a_n - 2| < 1$)?
 - (e) If ε is a positive number, can you find a point N such that every term in the sequence after N (that is, every a_n for $n > N$) is within ε of 2 (that is, $|a_n - 2| < \varepsilon$)?
 - (f) Write a proof that the sequence $\{a_n\}_{n=1}^{\infty} = \{2 - \frac{50}{n}\}_{n=1}^{\infty}$ converges to 2.

- (a) $-48, -23, -14.666, -10.5, -8, -6.333, -5.142$
- (b) after the second term, this is true, so $N = 2$ works
- (c) after the fourth term, this is true, so $N = 4$ works
- (d) Now we have to do a computation: $|a_n - 2| = \frac{50}{n} < 1$ is true when $n > 50$. So $N = 50$ works.
- (e) $|a_n - 2| = \frac{50}{n} < \varepsilon$ is true when $n > \frac{50}{\varepsilon}$ so $N = \frac{50}{\varepsilon}$ works.
- (f) Let $\varepsilon > 0$. Take $N = \frac{50}{\varepsilon}$. Let $n > N$ be a natural number. Then $n > N$ implies

$$|a_n - 2| = \frac{50}{n} < \frac{50}{N} = \varepsilon.$$

This proves that $\{a_n\}_{n=1}^{\infty}$ converges to 2.

- (2) Prove that the sequence $\left\{\frac{1}{\sqrt{n}}\right\}_{n=1}^{\infty}$ converges to 0.
- (3) Let $\{a_n\}_{n=1}^{\infty}$ be a sequence. Suppose we know that $\{a_n\}_{n=1}^{\infty}$ converges to 1. Prove⁹ that there is a natural number $n \in \mathbb{N}$ such that $a_n > 0$.

⁹Hint: If you know that a “for all” statement is true, you can choose any specific value for that variable and get a more specific true statement.

Take $\varepsilon = 1$. By definition of converges to 1, there is some N such that for all $n > N$, $|a_n - 1| < 1$, and in particular $a_n > 0$. So, take any natural number greater than n , and the conclusion follows.

(4) Prove or disprove: The sequence $\left\{ \frac{n+1}{2n} \right\}_{n=1}^{\infty}$ converges to 0.

Take $\varepsilon = 1/2$. We claim that there is no N such that for all $n > N$ we have $|a_n - 0| < 1/2$. Indeed, given N , take any n to be any natural number greater than N . Then $a_n = 1/2 + 1/2n > 1/2$, so $|a_n| > 1/2$. Thus, there is no N satisfying the desired property. This means that the sequence does not converge to 0.

11. MONDAY, SEPTEMBER 23, 2024 §2.1

Definition 11.1. We say that a sequence $\{a_n\}_{n=1}^{\infty}$ is **convergent** if there is a number L such that $\{a_n\}_{n=1}^{\infty}$ converges to L , and **divergent** otherwise.

Example 11.2. Let's prove the sequence $\{(-1)^n\}_{n=1}^{\infty}$ is divergent.

Proof. We proceed by contradiction: Suppose the sequence did converge to some number L . Our strategy will be to derive a contradiction by showing that such an L would have to satisfy mutually exclusive conditions.

By definition, since the sequence converges to L , we have that for every $\varepsilon > 0$ there is a number N such that $|(-1)^n - L| < \varepsilon$ for all natural numbers n such that $n > N$. In particular, this statement is true for the particular value $\varepsilon = \frac{1}{2}$. That is, there is a number N such that $|(-1)^n - L| < \frac{1}{2}$ for all natural numbers n such that $n > N$. Let n be any even natural number that is bigger than N . (Certainly one exists: we know there is an integer bigger than N by Theorem 6.2. Pick one. If it is even, take that to be n . If it is odd, increase it by one to get an even integer n .) Since $(-1)^n = 1$ for an even integer n , we get

$$|1 - L| < \frac{1}{2}$$

and thus $\frac{1}{2} < L < \frac{3}{2}$.

Likewise, let n be an odd natural number bigger than N . Since $(-1)^n = -1$ for an odd integer n , we get

$$|-1 - L| < \frac{1}{2}$$

and thus $-\frac{3}{2} < L < -\frac{1}{2}$. But it cannot be that both $L > \frac{1}{2}$ and $L < -\frac{1}{2}$.

We conclude that no such L exists; that is, this sequence is divergent. \square

Proposition 11.3. *If a sequence converges, then there is a unique number to which it converges.*

Proof. Recall that to show something satisfying certain properties is unique, one assumes there are two such things and argues that they must be equal. So, suppose $\{a_n\}_{n=1}^{\infty}$ is a sequence that converges to L and that also converges to M . We will prove $L = M$.

By way of contradiction, suppose $L \neq M$. Then set $\varepsilon = \frac{|L-M|}{3}$. Since we are assuming $L \neq M$, we have $\varepsilon > 0$. According to the definition of convergence, since the sequence converges to L , there is a real number N_1 such that for $n \in \mathbb{N}$ such that $n > N_1$ we have

$$|a_n - L| < \varepsilon.$$

Also according to the definition, since the sequence converges to M , there is a real number N_2 such that for $n \in \mathbb{N}$ and $n > N_2$ we have

$$|a_n - M| < \varepsilon.$$

Pick n to be any natural number larger than $\max\{N_1, N_2\}$ (which exists by Theorem 6.2). For such an n , both $|a_n - L| < \varepsilon$ and $|a_n - M| < \varepsilon$ hold. Using the triangle

inequality and these two inequalities, we get

$$|L - M| \leq |L - a_n| + |M - a_n| < \varepsilon + \varepsilon.$$

But by the choice of ε , we have $\varepsilon + \varepsilon = \frac{2}{3}|L - M|$. That is, we have deduced that $|L - M| < \frac{2}{3}|L - M|$ which is impossible. We conclude that $L = M$. \square

From now on, given a sequence $\{a_n\}_{n=1}^{\infty}$ and a real number L , will we use the short-hand notation

$$\lim_{n \rightarrow \infty} a_n = L$$

to mean that the given sequence converges to the given number. For example, we showed above that

$$\lim_{n \rightarrow \infty} \frac{2n - 1}{5n + 1} = \frac{2}{5}.$$

But, to be clear, the statement “ $\lim_{n \rightarrow \infty} a_n = L$ ” signifies nothing more and nothing less than the statement “ $\{a_n\}_{n=1}^{\infty}$ converges to L ”.

Here is some terminology we will need:

Definition 11.4. Suppose $\{a_n\}_{n=1}^{\infty}$ is any sequence.

- (1) We say $\{a_n\}_{n=1}^{\infty}$ is **bounded above** if there exists at least one real number M such that $a_n \leq M$ for all $n \in \mathbb{N}$.
- (2) We say $\{a_n\}_{n=1}^{\infty}$ is **bounded below** if there exists at least one real number m such that $a_n \geq m$ for all $n \in \mathbb{N}$.
- (3) We say $\{a_n\}_{n=1}^{\infty}$ is **bounded** if it is both bounded above and bounded below.

Proposition 11.5. *If a sequence $\{a_n\}_{n=1}^{\infty}$ converges then it is bounded.*

Proof. Suppose the sequence $\{a_n\}_{n=1}^{\infty}$ converges to the number L . Applying the definition of “converges to L ” using the particular value $\varepsilon = 1$ gives the following fact: There is a real number N such that if $n \in \mathbb{N}$ and $n > N$, then $|a_n - L| < 1$. The latter inequality is equivalent to $L - 1 < a_n < L + 1$ for all $n > N$.

Let m be any natural number such that $m > N$, and consider the finite list of numbers

$$a_1, a_2, \dots, a_{m-1}, L + 1.$$

Let b be the largest element of this list. I claim the sequence is bounded above by b . For any $n \in \mathbb{N}$, if $1 \leq n \leq m - 1$, then $a_n \leq b$ since in this case a_n is a member of the above list and b is the largest element of this list. If $n \geq m$ then since $m > N$, we have $n > N$ and hence $a_n < L + 1$ from above. We also have $L + 1 \leq b$ (since $L + 1$ is in the list) and thus $a_n < b$. This proves $a_n \leq b$ for all n as claimed.

Now take p to be the smallest number in the list

$$a_1, a_2, \dots, a_{m-1}, L - 1.$$

A similar argument shows that $a_n \geq p$ for all $n \in \mathbb{N}$. \square

12. WEDNESDAY, SEPTEMBER 25, 2024 §2.1

DEFINITION 12.1: Let $\{a_n\}_{n=1}^{\infty}$ be a sequence.

- (1) We say $\{a_n\}_{n=1}^{\infty}$ is **increasing** if for all $n \in \mathbb{N}$ we have $a_n \leq a_{n+1}$.
- (2) We say $\{a_n\}_{n=1}^{\infty}$ is **decreasing** if for all $n \in \mathbb{N}$, we have $a_n \geq a_{n+1}$.
- (3) We say $\{a_n\}_{n=1}^{\infty}$ is **monotone** if it is either decreasing or increasing.
- (4) We say $\{a_n\}_{n=1}^{\infty}$ is **strictly increasing** if for all $n \in \mathbb{N}$, $a_n < a_{n+1}$.

- (1) For each of the following sequences which of the following adjectives apply: bounded above, bounded below, bounded, (strictly) increasing, (strictly) decreasing, (strictly) monotone?
 - (a) $\{\frac{1}{n}\}_{n=1}^{\infty}$
 - (b) The Fibonacci sequence $\{f_n\}_{n=1}^{\infty}$ where $f_1 = f_2 = 1$ and $f_n = f_{n-1} + f_{n-2}$ for $n \geq 3$.
 - (c) $\{(-1)^n\}_{n=1}^{\infty}$
 - (d) $\{5 + (-1)^n \frac{1}{n}\}_{n=1}^{\infty}$.

- (a) bounded, strictly decreasing, strictly monotone
- (b) bounded below, increasing, monotone
- (c) bounded
- (d) bounded

- (2) Prove or disprove: Every increasing sequence is bounded above.

False: the Fibonacci sequence is a counterexample, since we saw above that it is increasing but not bounded above.

- (3) Prove or disprove: Every increasing sequence is bounded below.

True: it follows from the definition that a_1 is a lower bound.

- (4) Prove or disprove: Every bounded sequence is convergent.

The sequence $\{(-1)^n\}_{n=1}^{\infty}$ is bounded but divergent, so this is false.

- (5) Suppose that $\{a_n\}_{n=1}^{\infty}$ is a sequence that is bounded above by 1000 and below by -1000 . Show that the sequence $\left\{\frac{a_n}{n}\right\}_{n=1}^{\infty}$ converges to 0.

Suggestion: First start the way we always do when showing a sequence converges. Then see if you can use the hypothesis that $\{a_n\}_{n=1}^{\infty}$ is bounded in a useful way.

Let $\varepsilon > 0$ be arbitrary. Take $N = \frac{1000}{\varepsilon}$. Then, since $-1000 < a_n < 1000$, we have $|a_n| < 1000$ and $\left|\frac{a_n}{n}\right| < \frac{1000}{n}$ for any $n \in \mathbb{N}$, so for any natural number $n > N$, we have

$$\left|\frac{a_n}{n} - 0\right| < \frac{1000}{n} < \frac{1000}{N} = \varepsilon.$$

This shows that $\left\{\frac{a_n}{n}\right\}_{n=1}^{\infty}$ converges to 0.

13. FRIDAY, SEPTEMBER 27, 2024 §2.2

EXAMPLE 13.1:

- (1) A constant sequence $\{c\}_{n=1}^{\infty}$ converges to c .
- (2) The sequence $\{\frac{1}{n}\}_{n=1}^{\infty}$ converges to 0.

THEOREM 13.2 (LIMITS AND ALGEBRA):

Let $\{a_n\}_{n=1}^{\infty}$ be a sequence that converges to L , and $\{b_n\}_{n=1}^{\infty}$ be a sequence that converges to M .

- (1) If c is any real number, then $\{ca_n\}_{n=1}^{\infty}$ converges to cL .
- (2) The sequence $\{a_n + b_n\}_{n=1}^{\infty}$ converges to $L + M$.
- (3) The sequence $\{a_nb_n\}_{n=1}^{\infty}$ converges to LM .
- (4) If $L \neq 0$ and $a_n \neq 0$ for all $n \in \mathbb{N}$, then $\left\{\frac{1}{a_n}\right\}_{n=1}^{\infty}$ converges to $\frac{1}{L}$.
- (5) If $M \neq 0$ and $b_n \neq 0$ for all $n \in \mathbb{N}$, then $\left\{\frac{a_n}{b_n}\right\}_{n=1}^{\infty}$ converges to $\frac{L}{M}$.

- (1) Use Theorem 13.2 and Example 13.1 to show that the sequence $\{2 + 5/n - 7/n^2\}_{n=1}^{\infty}$ converges to 2. Show every step in your argument.

The constant sequence $\{2\}_{n=1}^{\infty}$ converges to 2 by Ex 10.1 part 1. The sequence $\{5/n\}_{n=1}^{\infty} = \{5 \cdot 1/n\}_{n=1}^{\infty}$ converges to $5 \cdot 0 = 0$ by Ex 10.1 part 2 and Thm 10.2 part 1. The sequence $\{-7/n^2\}_{n=1}^{\infty} = \{-7 \cdot 1/n \cdot 1/n\}_{n=1}^{\infty}$ converges to $-7 \cdot 0 \cdot 0 = 0$ by Ex 10.1 part 2, Thm 10.2 part 1, and Thm 10.2 part 3. Thus, by Thm 10.2 part 2, the sequence $\{2 + 5/n - 7/n^2\}_{n=1}^{\infty}$ converges to $2 + 0 + 0 = 2$ by Thm 10.2 part 2.

- (2) Use Theorem 13.2 and Example 13.1 to show that the sequence $\left\{\frac{2n+3}{3n-4}\right\}_{n=1}^{\infty}$ converges to $\frac{2}{3}$.

- (3) Use Theorem 13.2 to show that if $\{a_n\}_{n=1}^{\infty}$ converges to L , and $\{b_n\}_{n=1}^{\infty}$ converges to M , then $\{a_n - b_n\}_{n=1}^{\infty}$ converges to $L - M$.

By Thm 10.2 part 1, $\{-b_n\}_{n=1}^{\infty}$ converges to $-M$. Then by Thm 10.2 part 2, $\{a_n - b_n\}_{n=1}^{\infty} = \{a_n + (-b_n)\}_{n=1}^{\infty}$ converges $L + (-M) = L - M$.

- (4) Prove or disprove the following converse to part (2): If $\{a_n + b_n\}_{n=1}^{\infty}$ converges to $L + M$ then $\{a_n\}_{n=1}^{\infty}$ converges to L and $\{b_n\}_{n=1}^{\infty}$ converges to M .

Take $\{a_n\}_{n=1}^{\infty} = \{(-1)^n\}_{n=1}^{\infty}$ and $\{b_n\}_{n=1}^{\infty} = \{(-1)^{n+1}\}_{n=1}^{\infty}$. Then $\{a_n + b_n\}_{n=1}^{\infty} = \{0\}_{n=1}^{\infty}$ converges to 0, but neither $\{a_n\}_{n=1}^{\infty}$ nor $\{b_n\}_{n=1}^{\infty}$ converges.

- (5) Prove or disprove: If $\{a_n\}_{n=1}^{\infty}$ is a convergent sequence and $\{b_n\}_{n=1}^{\infty}$ is a divergent sequence, then $\{a_n + b_n\}_{n=1}^{\infty}$ is divergent.

Let $\{a_n\}_{n=1}^{\infty}$ be a convergent sequence and $\{b_n\}_{n=1}^{\infty}$ be a divergent sequence. By way of contradiction, assume that $\{a_n + b_n\}_{n=1}^{\infty}$ converges. Say that $\{a_n\}_{n=1}^{\infty}$ converges to L and $\{a_n + b_n\}_{n=1}^{\infty}$ converges to M . Then since $b_n = (a_n + b_n) - a_n$, from the Theorem 13.2 we conclude that $\{b_n\}_{n=1}^{\infty}$ converges to $M - L$; in particular it is convergent. This is a contradiction. We conclude that $\{a_n + b_n\}_{n=1}^{\infty}$ must diverge.

- (6) Prove part (1) of Theorem 10.2 in the special case $c = 2$ by following the following steps:

- Assume that $\{a_n\}_{n=1}^{\infty}$ converges to L .
- We now want to show that $\{2a_n\}_{n=1}^{\infty}$ converges to something. You know what goes next!
- Now we do some scratchwork: we want an N such that for $n > N$ we have $|2a_n - 2L| < \varepsilon$. Factor this to get some inequality with a_n . How can we use our assumption to get an N that “works”?
- Complete the proof.

Assume that $\{a_n\}_{n=1}^{\infty}$ converges to L . Let $\varepsilon > 0$. Since $\varepsilon/2$ is a positive number, by definition of converges, there is some N such that for all $n > N$ we have $|a_n - L| < \varepsilon/2$. Then, for this N and any $n > N$, we have $|(2a_n) - 2L| = 2|a_n - L| < 2\varepsilon/2 = \varepsilon$. This shows that $\{2a_n\}_{n=1}^{\infty}$ converges to $2L$.

- (7) Prove part (1) of Theorem 10.2.

- (8) Prove part (2) of Theorem 10.2.

- (9) Prove part (3) of Theorem 10.2.

14. MONDAY, SEPTEMBER 30, 2024 §2.2

Last time we looked at:

Theorem 13.2 (Limits and algebra). Let $\{a_n\}_{n=1}^{\infty}$ be a sequence that converges to L , and $\{b_n\}_{n=1}^{\infty}$ be a sequence that converges to M .

- (1) If c is any real number, then $\{ca_n\}_{n=1}^{\infty}$ converges to cL .
- (2) The sequence $\{a_n + b_n\}_{n=1}^{\infty}$ converges to $L + M$.
- (3) The sequence $\{a_nb_n\}_{n=1}^{\infty}$ converges to LM .
- (4) If $L \neq 0$ and $a_n \neq 0$ for all $n \in \mathbb{N}$, then $\left\{\frac{1}{a_n}\right\}_{n=1}^{\infty}$ converges to $\frac{1}{L}$.
- (5) If $M \neq 0$ and $b_n \neq 0$ for all $n \in \mathbb{N}$, then $\left\{\frac{a_n}{b_n}\right\}_{n=1}^{\infty}$ converges to $\frac{L}{M}$.

You will prove part (1) in the homework. Let's prove part (2), and you can read the rest in the notes.

Proof of (2): Let $\{a_n\}_{n=1}^{\infty}$ be a sequence that converges to L , and $\{b_n\}_{n=1}^{\infty}$ be a sequence that converges to M . Let $\varepsilon > 0$. Since $\varepsilon/2 > 0$, by definition of converges, there is some N_1 such that for all $n > N_1$ we have $|a_n - L| < \varepsilon/2$. Likewise, there is some N_2 such that for all $n > N_2$ we have $|b_n - M| < \varepsilon/2$. Let $N = \max\{N_1, N_2\}$. Then for $n > N$, we have

$$|(a_n + b_n) - (L + M)| = |(a_n - L) + (b_n - M)| \leq |a_n - L| + |b_n - M| < \frac{\varepsilon}{2} + \frac{\varepsilon}{2} = \varepsilon.$$

This shows that $\{a_n + b_n\}_{n=1}^{\infty}$ converges to $L + M$. \square

First, we prove (3).

Pick $\varepsilon > 0$.

("Scratch work": The goal is to make $|a_nb_n - LM|$ small and the trick is to use that

$$\begin{aligned} |a_nb_n - LM| &= |a_n(b_n - M) + (a_n - L)M| \\ &\leq |a_n(b_n - M)| + |(a_n - L)M| \\ &= |a_n||b_n - M| + |a_n - L||M|. \end{aligned}$$

Our goal will be to take n to be large enough so that each of $|a_n||b_n - M|$ and $|a_n - L||M|$ is smaller than $\varepsilon/2$. We can make $|a_n - L|$ as small as we like and $|M|$ is just a fixed number. So, we can "take care" of the second term by choosing n big enough so that $|a_n - L| < \frac{\varepsilon}{2|M|}$. A irritating technicality here is that $|M|$ could be 0, and so we will use $\frac{\varepsilon}{2|M|+1}$ instead. The other term $|a_n||b_n - M|$ is harder to deal with since each factor varies with n . Here we use that convergent sequences are bounded so that we can find a real number X so that $|a_n| \leq X$ for all n . Then we choose n large enough so that $|b_n - M| < \frac{\varepsilon}{2X}$. Back to the proof.)

Since $\{a_n\}$ converges, it is bounded by Proposition 11.5, which gives that there is a strictly positive real number X so that $|a_n| \leq X$ for all $n \in \mathbb{N}$. Since $\{b_n\}$ converges to M and $\frac{\varepsilon}{2X} > 0$, there is a number N_1 so that if $n > N_1$ then $|b_n - M| < \frac{\varepsilon}{2X}$.

$\frac{\varepsilon}{2X}$. Since $\{a_n\}$ converges to L and $\frac{\varepsilon}{2|M|+1} > 0$, there is a number N_2 so that if $n \in \mathbb{N}$ and $n > N_2$, then $|a_n - L| < \frac{\varepsilon}{2|M|+1}$. Let $N = \max\{N_1, N_2\}$. For any $n \in \mathbb{N}$ such that $n > N$, we have

$$\begin{aligned} |a_n b_n - LM| &= |a_n(b_n - M) + (a_n - L)M| \\ &\leq |a_n(b_n - M)| + |(a_n - L)M| \\ &= |a_n||b_n - M| + |a_n - L||M| \\ &< X \frac{\varepsilon}{2X} + \frac{\varepsilon}{2|M|+1}|M| \\ &< \varepsilon. \end{aligned}$$

This proves $\{a_n \cdot b_n\}_{n=1}^{\infty}$ converges to $L \cdot M$.

Now we prove (4).

To prove this claim, pick $\varepsilon > 0$.

(Scratch work: We want to show $\left|\frac{1}{a_n} - \frac{1}{L}\right| < \varepsilon$ holds for n sufficiently large. We have

$$\left|\frac{1}{a_n} - \frac{1}{L}\right| = \frac{|L - a_n|}{|a_n||L|}.$$

We can make the top of this fraction as small as we like, but the problem is that the bottom might be very small too since a_n might get very close to 0. But since a_n converges to L and $L \neq 0$ if we go far enough out, it will be close to L . In particular, if a_n is within a distance of $\frac{|L|}{2}$ of M then $|a_n|$ will be at least $\frac{|L|}{2}$. So for n sufficiently large we have $\frac{|a_n - L|}{|a_n||L|} < 2 \frac{|a_n - L|}{|L|^2}$. And then for n sufficiently large we also get $|a_n - L| < \frac{|L|^2}{2\varepsilon}$. Back to the formal proof...

Since $\{a_n\}$ converges to L and $\frac{|L|}{2} > 0$, there is an N_1 such that for $n > N_1$ we have $|a_n - L| < \frac{|L|}{2}$ and hence $|a_n| > \frac{|L|}{2}$. Again using that $\{a_n\}$ converges to M and that $\frac{\varepsilon|L|^2}{2} > 0$, there is an N_2 so that for $n > N_2$ we have $|a_n - L| < \frac{\varepsilon|L|^2}{2}$. Let $N = \max\{N_1, N_2\}$. If $n > N$, then we have

$$\begin{aligned} \left|\frac{1}{a_n} - \frac{1}{L}\right| &= \frac{|a_n - L|}{|a_n||L|} \\ &< \frac{2}{|L|} \frac{|a_n - L|}{|L|} \\ &= 2 \frac{|a_n - L|}{|L|^2} \end{aligned}$$

since $|a_n| > |L|/2$ and hence $\frac{1}{|a_n|} < \frac{2}{|L|}$. But then

$$2 \frac{|a_n - L|}{|L|^2} < 2 \frac{\frac{\varepsilon|L|^2}{2}}{|L|^2} = \varepsilon$$

since $|a_n - L| < \frac{\varepsilon|L|^2}{2}$. Putting these together gives

$$\left| \frac{1}{a_n} - \frac{1}{L} \right| < \varepsilon$$

for all $n > N$. This proves $\{\frac{1}{a_n}\}_{n=1}^{\infty}$ converges to $\frac{1}{L}$.

Finally, part (5) follows from parts (3) and (4).

The following is another useful technique:

Theorem 14.1 (The “squeeze” principle). *Suppose $\{a_n\}_{n=1}^{\infty}$, $\{b_n\}_{n=1}^{\infty}$, and $\{c_n\}_{n=1}^{\infty}$ are three sequences such that $\{a_n\}_{n=1}^{\infty}$ and $\{c_n\}_{n=1}^{\infty}$ both converge to L , and $a_n \leq b_n \leq c_n$ for all n . Then $\{b_n\}_{n=1}^{\infty}$ also converges to L .*

Proof. Assume $\{a_n\}_{n=1}^{\infty}$ and $\{c_n\}_{n=1}^{\infty}$ both converge to L and that $a_n \leq b_n \leq c_n$ for all $n \in \mathbb{N}$. We need to prove $\{b_n\}_{n=1}^{\infty}$ converges to L .

Pick $\varepsilon > 0$. Since $\{a_n\}_{n=1}^{\infty}$ converges to L there is a number N_1 such that if $n \in \mathbb{N}$ and $n > N_1$ then $|a_n - L| < \varepsilon$ and hence $L - \varepsilon < a_n < L + \varepsilon$. Likewise, since $\{c_n\}_{n=1}^{\infty}$ converges to L there is a number N_2 such that if $n \in \mathbb{N}$ and $n > N_2$ then $L - \varepsilon < c_n < L + \varepsilon$. Let

$$N = \max\{N_1, N_2\}.$$

If $n \in \mathbb{N}$ and $n > N$, then $n > N_1$ and hence $L - \varepsilon < a_n$, and $n > N_2$ and hence $c_n < L + \varepsilon$, and also $a_n \leq b_n \leq c_n$. Combining these facts gives that for $n \in \mathbb{N}$ such that $n > N$, we have

$$L - \varepsilon < b_n < L + \varepsilon$$

and hence $|b_n - L| < \varepsilon$. This proves $\{b_n\}_{n=1}^{\infty}$ converges to L . \square

Example 14.2. We can use the Squeeze Theorem to give a short proof that $\{5 + (-1)^n \frac{1}{n}\}_{n=1}^{\infty}$ converges to 5. Note that Theorem 13.2 alone cannot be used in this example. However, from Theorem 13.2, it follows that $\{5 - \frac{1}{n}\}_{n=1}^{\infty}$ and $\{5 + \frac{1}{n}\}_{n=1}^{\infty}$ both converge to 5. Then, since

$$5 - \frac{1}{n} \leq 5 + (-1)^n \frac{1}{n} \leq 5 + \frac{1}{n}$$

for all n , our sequence also converges to 5.

When I introduced the Completeness Axiom, I mentioned that, heuristically, it is what tells us that the real number line doesn't have any holes. The next result makes this a bit more precise:

Theorem 14.3. *Every increasing, bounded above sequence converges.*

Proof. Let $\{a_n\}_{n=1}^{\infty}$ be any sequence that is both bounded above and increasing.

(Commentary: In order to prove it converges, we need to find a candidate number L that it converges to. Since the set of numbers occurring in this sequence is nonempty and bounded above, this number is provided to us by the Completeness Axiom.)

Let S be the set of those real numbers that occur in this sequence. (This is technically different than the sequence itself, since sequences are allowed to have repetitions but

sets are not. Also, sequences have an ordering to them, but sets do not.) The set S is clearly nonempty, and it is bounded above since we assume the sequence is bounded above. Therefore, by the Completeness Axiom, S has a supremum L . We will prove the sequence converges to L .

Pick $\varepsilon > 0$. Then $L - \varepsilon < L$ and, since L is the supremum, $L - \varepsilon$ is not an upper bound of S . This means that there is an element of S that is strictly bigger than $L - \varepsilon$. Every element of S is a member of the sequence, and so we get that there is an $N \in \mathbb{N}$ such that $a_N > L - \varepsilon$.

(We will next show that this is the N that “works”. Note that, in the general definition of convergence of a sequence, N can be any real number, but in this proof it turns out to be a natural number.)

Let n be any natural number such that $n > N$. Since the sequence is increasing, $a_N \leq a_n$ and hence

$$L - \varepsilon < a_N \leq a_n.$$

Also, $a_n \leq L$ since L is an upper bound for the sequence, and thus we have

$$L - \varepsilon < a_n \leq L.$$

It follows that $|a_n - L| < \varepsilon$. We have proven the sequence converges to L . \square

Theorem 14.4 (Monotone Convergence Theorem). *Every bounded monotone sequence converges.*

Proof. If $\{a_n\}_{n=1}^{\infty}$ is increasing, then this is the content of Theorem 14.3. If $\{a_n\}_{n=1}^{\infty}$ is decreasing and bounded, consider the sequence $\{-a_n\}_{n=1}^{\infty}$. If $a_n \leq M$ for all n , then $-a_n \geq -M$ for all n , so $\{-a_n\}_{n=1}^{\infty}$ is bounded below. Also, since $a_n \geq a_{n+1}$ for all n , we have $-a_n \leq -a_{n+1}$ for all n , so $\{-a_n\}_{n=1}^{\infty}$ is increasing. Thus, by Theorem 14.3, $\{-a_n\}_{n=1}^{\infty}$ converges, say to L . Then by Theorem 13.2(1), $\{a_n\}_{n=1}^{\infty} = \{-(-a_n)\}_{n=1}^{\infty}$ converges to $-L$. \square

Example 14.5. Consider the sequence $\{a_n\}_{n=1}^{\infty}$ given by the formula

$$a_n = 1 + \frac{1}{2^2} + \frac{1}{3^2} + \cdots + \frac{1}{n^2}.$$

We will use the Monotone Convergence Theorem to prove that this sequence converges.

First, we need to see that the sequence is increasing. Indeed, for every n we have that $a_{n+1} = a_n + \frac{1}{(n+1)^2} \geq a_n$.

Next, we need to show that it is bounded above. Observe that

$$\begin{aligned} a_n &= 1 + \frac{1}{2^2} + \frac{1}{3^2} + \cdots + \frac{1}{n^2} \\ &\leq 1 + \frac{1}{1 \cdot 2} + \frac{1}{2 \cdot 3} + \cdots + \frac{1}{(n-1)n} \\ &= 1 + \left(\frac{1}{1} - \frac{1}{2}\right) + \left(\frac{1}{2} - \frac{1}{3}\right) + \cdots + \left(\frac{1}{n-1} - \frac{1}{n}\right) \\ &= 1 + 1 - \frac{1}{n}, \end{aligned}$$

so we have $a_n \leq 2$ for all n . This means that $\{a_n\}_{n=1}^{\infty}$ is bounded above by 2.

Hence, by the Monotone Convergence Theorem, $\{a_n\}_{n=1}^{\infty}$ converges. Leonhard Euler was particularly interested in this sequence, and was able to prove that it converges to $\frac{\pi^2}{6}$. This requires some other ideas, so we won't do that here.

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