Real Analysis 1

Forrest Kennedy

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Lecture 1: Complete Analysis Theorems List

Tuesday 28 January 2025

1 The Real Numbers

Definition 1 (Definition of a "function")**.** Given sets A, B a function of $A \to B$ is a mapping that takes ea ch element of A to a single element of B.

Definition 2 (Definition of the "absolute value function")**.** The **absolute value function"** is defined as $|\cdot| : \mathbb{R} \to \mathbb{R}$ such that:

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

Theorem 1 (The Triangle Inequality)**.** With respect to multiplication and division, the absolute value function satisfies:

1. $|ab| = |a| |b|$
2. $|a + b| \leq |a| + |b|$

Proof. We will show the theorem by cases WLOG:

1. $(a = 0)$ $|a + b| = |0 + b| = |b| = |0| + |b| = |a| + |b|$
2. $(a > 0, b > 0)$ By the definition of the absolute value function we have $|a + b| = a + b = |a| + |b|$
3. $(a < 0, b < 0)$ By the definition of the absolute value function we have $|a + b| = -(a + b) = -a + (-b) = |a| + |b|$

4. $(a > 0, b < 0)$ By the definition of the absolute value, we have $|a| = a$ and $|b| = -b$, so $|a|+|b| = a+(-b)$. We want to show that $|a|+|b| = a+(-b) \geq |a+b|$, so again we consider all the possible cases:
   (a) $(a+b=0)$ We have $a + (-b) \overset{?}{\geq} |0| = 0$. Indeed, since $a > 0$ and $b < 0$ we have $a > b$, and our equality holds.
   (b) $(a+b>0)$ We have $a + (-b) \overset{?}{\geq} a + b$. Since $b < 0$, we have $-b > 0$. Comparing the LHS and RHS the equality holds.
   (c) $(a+b<0)$ We have $a+(-b) \overset{?}{\geq} -a+(-b)$. Comparing the LHS and the RHS, the equality holds.

The above considerations exhaust all possible choices for a and b. In all cases. we see that $|a+b| \leq |a| + |b|$ $\square$

Theorem 2 (The ε criteria for equality)**.** Two real numbers a and b are equal if and only if for every real number $\varepsilon > 0$ it follows that $|a-b| < \varepsilon$.

Proof. We will show the theorem in both directions:

- $(\Rightarrow)$ Given $a = b$, we have $a - b = 0 < \varepsilon$ for all $\varepsilon > 0$.
- $(\Leftarrow)$ Assume that for every $\varepsilon > 0$, $|a-b| < \varepsilon$ and, FSOC, that $a \neq b$. Then, let $\varepsilon_0 = a - b$ which we know is nonzero because $a \neq b$. Now, $|a-b| = \varepsilon_0$ and $|a-b| < \varepsilon_0$ by our first assumption. We have reached a contradiction, therefore the reverse implication must hold.

$\square$

Definition 3 (Bounded Above Property of Subsets of $\mathbb{R}$)**.** A set $A \subset \mathbb{R}$ is **bounded above** if there exists a number $b \in \mathbb{R}$ such that $a \leq b$ $\forall a \in A$. The number b is called an **upper bound** for A.

Definition 4 (Bounded Below Property of Subsets of $\mathbb{R}$)**.** A set $A \subset \mathbb{R}$ is **bounded below** if there exists a number $b \in \mathbb{R}$ such that $b \leq a$ $\forall a \in A$. The number b is called a **lower bound** for A.

Definition 5 (The Least Upper Bound)**.** An element $s \in \mathbb{R}$ is called the **least upper bound** for $A \subset \mathbb{R}$ if s meets two conditions:

1. s is an upper bound for A
2. $\forall b$ where b is an upper bound, $s \leq b$.

Definition 6 (The Greatest Lower Bound)**.** An element $l \in \mathbb{R}$ is called the **greatest lower bound** for $A \subset \mathbb{R}$ if l meets two conditions:

1. l is a lower bound for A
2. $\forall b$ where b is an upper bound, $l \geq b$.

Definition 7. A real number a_0 is a **maximum** of the set A if a_0 is an elemnt of A and $a_0 \geq a$ for all $a \in A$. Similarly, a number a_1 is a **minimum** of A if $a_1 \in A$ and $a_1 \leq a$ for all $a \in A$.

Theorem 3 (The ε Characterization of the Supremum)**.** Assume $s \in R$ is an upper bound for a set $A \subset \mathbb{R}$. Then, $s = \sup A$ if and only if, for every choice of $\varepsilon > 0$, there exists an element $a \in A$ satisfying $s - \varepsilon < a$.

Proof. We will show that both the implication and the inverse implication are true:

- $(\Rightarrow)$If s is the *least* upper bound of A, then $s - \varepsilon$ is not an upper bound for A, thus there exists an $a \in A$ such that $s - \varepsilon < a$.
- $(\Leftarrow)$ Assume s is an upper bound of A and that for every $\varepsilon > 0$, $s - \varepsilon < a$. That is, no number smaller than s is an upper bound of A. Thus for all b where b is an upper bound of A, $s \leq b$. Since we assumed that s is an upper bound, s meets both conditions to be the supremum.

□

Theorem 4 (Nested Interval Property of Subsets of $\mathbb{R}$)**.** For each $n \in \mathbb{N}$, assume we are given a closed interval $I_n = [a_n, b_n] = \{x \in R : a_n \leq x \leq b_n\}$. Assume also that each I_n contains I_{n+1}. Then, the resulting nested sequence of closed intervals

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

has a nonempty intersection; that is, $\cap_{n=1}^{\infty} I_n \neq \emptyset$.

Proof. Let $A = \{a_n : n \in \mathbb{N}\}$ and $B = \{b_n : n \in \mathbb{N}\}$, then let $\alpha = \sup A$. From the definition of the supremum, we have $\alpha \geq a_n$ for all $n \in \mathbb{N}$. Because of how we defined our sets, every b_n is an upper bound of A, so we have $\alpha \leq b_n$ for all $n \in \mathbb{N}$. Thus $a_n \leq \alpha \leq b_n$ and $\alpha \in I_n$. Therefore, I_n is nonempty. □

Theorem 5 (Archimedean Property)**.** The theorem has two parts:

1. Given any number $x \in \mathbb{R}$, there exists an $n \in \mathbb{N}$ satisfying $n > x$.
2. Given any real number $y > 0$, there exists an $n \in \mathbb{N}$ satisfying $\frac{1}{n} < y$.

Proof. Statement 1 in the above theorem is equivalent to the statement: $\mathbb{N}$ is not bounded above. FSOC, assume that $\mathbb{N}$ is bounded above, then let $\alpha = \sup \mathbb{N}$. By the definition of the supremum, $\alpha - 1$ is not an upper bound. Thus, $\alpha - 1 < n$ for some $n \in \mathbb{N}$ implies $\alpha < n+1$, but $n+1 \in \mathbb{N}$ by definition so α is less than some natural number and cannot be the supremum, a contradiction! Thus $\mathbb{N}$ is not bounded above, and we have proven statement 1. To prove statement 2, let $x = \frac{1}{y}$ and substitute into the expression in statement 1. □

Definition 8 (Sequence)**.** A **sequence** is a function whose domain is $\mathbb{N}$.

Definition 9 (Convergent Property of a Sequence / Limit of a Sequence)**.** A sequence a_n **converges** to a real number a, if for every $\varepsilon > 0$ there exists $N \in \mathbb{N}$ such that whenever $n \geq N$, we have $|a_n - a| < \varepsilon$. In this case we write

$$\lim_{n \to \infty} a_n = \lim a_n = a \tag{1}$$

Definition 10 (ε-Neighborhood)**.** Given a real number $a \in \mathbb{R}$ and a positive number $\varepsilon > 0$, the set

$$V_\varepsilon(a) = \{x \in \mathbb{R} : |x - a| < \varepsilon\} \tag{2}$$

is called the **ε-neighborhood** of a.

Definition 11 (Topological Definition of the Convergent Property/Limit of a Sequence)**.** A sequence (a_n) converges to a if every ε-neighborhood of a contains all but a finite number of the terms of (a_n).

Theorem 6 (Limit Uniqueness Theorem)**.** The limit of a sequence, when it exists, is unique.

Proof. For the sake of contradiction, let (a_n) be a sequences which converges to both s and t. Then we know that $\exists N_1, N_2 \in \mathbb{N}$ such that for all $\varepsilon > 0$

$$|a_{N_1} - s| < \frac{\varepsilon}{2} \text{ and } |a_{N_2} - t| < \frac{\varepsilon}{2} \tag{3}$$

Now let

$$N = \max\{N_1, N_2\}. \tag{4}$$

And consider $|s - t|$ We can now use the "adding zero" algebraic trick and the triangle inequality:

$$\begin{aligned} |s-t| &= |(s-a_N)+(a_N-t)| && (5)\\ &\leq |a_N-s|+|a_N-t| && (6)\\ &< \frac{\varepsilon}{2}+\frac{\varepsilon}{2} && (7)\\ &= \varepsilon && (8) \end{aligned}$$

Thus $|s-t|<\varepsilon$ for all $\varepsilon>0$, by the ε-Criteria for Equality, $s=t$. □

Definition 12 (Divergent Property of a Sequence)**.** A sequence that does not converge is said to **diverge**.

Definition 13 (Bounded Property of a Sequence)**.** A sequence (x_n) is **bounded** if there exists a number $M>0$ such that $|x_n|\leq M$ for all $n\in\mathbb{N}$.

Theorem 7. Every convergent sequence is bounded.

Proof. □

Theorem 8. Suppose (a_n) is a convergent sequence with $\lim a_n = L$. If $L\neq 0$ and $a_n\neq 0$ for all $n\in\mathbb{N}$, then $\exists\delta>0$ such that $|a_n|\geq\delta>0$ for all $n\in\mathbb{N}$.

Proof. As $L\neq 0$, choose $\varepsilon=\frac{|L|}{2}>0$ $\exists N\in\mathbb{N}$ such that $\forall n\geq N$ we have

$$|a_n-L|<\frac{|L|}{2} \quad (9)$$

$$(10)$$

for $n\geq N$ we have

$$|L|\leq|L-a_n|+|a_n|\leq\frac{|L|}{2}+|a_n| \quad (11)$$

$$(12)$$

Therefore, for all $n\geq N$ we have

$$\frac{|L|}{2}\leq|a_n| \quad (13)$$

$$(14)$$

Define $\delta=\min\{|a_1|,|a_2|,\ldots,|a_{N-1}|,\left|\frac{L}{2}\right|\}>0$. We see that $|a_n|\geq\delta>0$ $\forall n\in\mathbb{N}$. □

Theorem 9. Let $\lim a_n = a$, and $\lim b_n = b$. Then,

1. $\lim ca_n = ca$ for all $c \in \mathbb{R}$;
2. $\lim a_n + b_n = a + b$;
3. $\lim a_n b_n = ab$;
4. $\lim (a_n/b_n) = a/b$, provided $b \neq 0$.

Proof. □

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Theorem 10. Let $a, b \in \mathbb{R}$ and $\lim a_n = a$ and $\lim b_n = b$.

1. If $a_n \geq 0$ $\forall n \in \mathbb{N}$, then $a \geq 0$
2. If $a_n \leq b_n$ $\forall n \in \mathbb{N}$, then $a \leq b$
3. If $\exists c \in \mathbb{R}$ such that $c \leq b_n$ $\forall n \in \mathbb{N}$, then $c \leq b$. Similarly, if $a_n \leq c$ $\forall n \in \mathbb{N}$, then $a \leq c$.

Proof. By contradiction, assume that $a < 0$, therefore $\exists N \in \mathbb{N}$ such that $\forall n \geq N$ we have

$$|a_n - a| < \frac{|a|}{2} \Rightarrow a_n - a < \frac{|a|}{2} \tag{15}$$

$$\Rightarrow a_n < a + \frac{|a|}{2} < 0 \tag{16}$$

$$\Rightarrow a_n < 0 \ \forall n \geq \mathbb{N}. \tag{17}$$

A contradiction! □

Monday 13 January 2025

Lecture 2: Some historical motivations for Analysis

2 The Heat Equation

In 1822, Fourier derived the heat equation. In one dimension:

$$\frac{\partial u}{\partial t} - \frac{\partial^2 u}{\partial x^2} = 0.$$

where $u\,(x,t)$ is the temperature as a function of position and time. A natural problem to solve with the equation is to assume you are given a function $u\,(x,0)$ which represents the initial temperature distribution of the system which we could measure then ask if it is possible to find a general $u\,(x,t)$ given $u\,(x,0)$. Stated another way, if we know the initial temperature distribution, can we find the distribution at an arbitrary time t using only the heat equation. The answer to this question is yes!

If we assume that $u(x,0)$ is a periodic function then:

$$u(x,0) = \sum_{n\in\mathbb{Z}} a_n e^{inx}.$$

Then, rearranging and integrating:

$$a_n = \frac{1}{2\pi}\int_0^{2\pi} u(x,0)\, e^{inx} dx.$$

Then, we will guess that the solution is of the form:

$$u(x,t) = \sum_{n\in\mathbb{Z}} a_n(t)\, e^{inx}.$$

Substituting into the heat equation we get:

$$\frac{\partial u}{\partial t} - \frac{\partial^2 u}{\partial x^2} = \sum_{n\in\mathbb{Z}} a_n'(t)\, e^{inx} - a_n(t)\,(in)^2\, e^{inx} = \sum \left(a_n'(t) + a_n(t)\, n^2\right) e^{inx} = 0.$$

So we have the differential equation:

$$a_n'(t) + a_n(t)\, n^2 = 0.$$

which has the solution:

$$a_n(t) = a_n(0)\, e^{-n^2 t}.$$

We can find $a_n(0)$ with the integral above, so we have our solution! If we check the solution experimentally, we see the right behavior, so what's the problem? The issue is:

$$u(x,0) \neq \sum_{n\in\mathbb{Z}} a_n e^{inx}!$$

At least, when we look at the graph for any specific $n \in \mathbb{N}$ we see that at the extreme points of the function, we get oscilations away from the true value of $u(x,0)$. This affect is called the Gibbs phenomenon. This tells us that the function cannot equal the partial sum. On the other hand, the assumption works, so there must be some kind of notion of equality, but we are not in a position to say what that is right now. This gives us a specific example where Newton's calculus fails. The issue in this example has to do with the definition of "convergence" but there is a deeper issue. When we wrote down $u(x,0) = \sum_{n\in\mathbb{Z}} a_n e^{inx}$, we were writing down nonsense, but we didn't know it. In order to know which statements are valid and which are not, we need to develop an axiomatic system that we can use to build up definitions, theorems, and proofs. This is the buisness of Mathematical Analysis: to provide a rigorous base for analysis to rest upon which contains no nonsense!

Lecture 3

Wednesday 15 January

Once we realize that the we don't know how to add up infinitely many functions, it is easy to see that we don't really know how to add infinitely many **numbers** either! Consider:

$$\begin{aligned} 1 &= 1 \\ 1-1 &= 0 \\ 1-1+1 &= 1 \\ 1-1+1-1 &= 0 \\ &\vdots \\ 1-1+1-1+1+\ldots &= \; ? \end{aligned}$$

Already there seems to be a problem! The series does seem to converge to any number. Of course, we don't know what converge means yet, but there is a deeper problem. Consider the rearrangements:

$$\begin{aligned} 1+(-1+1)+(-1+1)+\ldots &= 1 \\ (1+-1)+(1+-1)+(1+\ldots &= 0 \end{aligned}$$

Clearly, these can't both be right. Again, we have been tricked into writing nonsense because we don't have any axioms to tell us which statements are allowed and which are not. Here, the problem has to do with our adding up of an infinite number of things. When we are properly automatized, we will see that we just don't do that. Instead, we will solve this problem with a "limit," **in order to understand the limit, we will need to develop $\mathbb{R}$, the real number system.** This is the goal of Chapter 1. The point is: adding up infinite things, whether they are functions or just numbers, leads to problems, and whatever formal system we come up with will need to be without these problems if we want it to formalize calculus, which is based around the notion of adding up infinitely many things.

Chapter 1

To motivate the definition of $\mathbb{R}$ let's explore ways in which $\mathbb{R}$ is different to other number systems. Why should we expect the definition of $\mathbb{R}$ to be useful and lead us to a notion of a "continuum?"

Lemma 1. For all $m, n \in \mathbb{Z}$, if $n|m^2$ and n is prime, then $n|m$

Proof. Assume for the sake of contradiction that n does *not* divide m, then n cannot be a prime factor of m, so $m = abcd\ldots$ for some prime numbers

$a, b, c, d, \ldots$, importantly n **cannot be part of the product since** n **does not divide** m. Then $m^2 = (abcd\ldots)^2 = a^2b^2c^2d^2\ldots$ which does not contain n, so $n \nmid m^2$ which contradicts our assumption. Thus it must be the case that $n|m$. $\square$

Theorem 11. There is no rational number whose square is 2

Proof. Assume for contradiction: $\exists r$ s.t. $r = \frac{p}{q}$ where $p, q \in \mathbb{Z}$ and $r^2 = 2$. Also assume, WLOG, that p, q **share no common factors** then:

$$r^2 = \left(\frac{p}{q}\right)^2 = 2 \tag{18}$$
$$\Rightarrow p^2 = 2q^2 \tag{19}$$
$$\Rightarrow 2|p^2 \tag{20}$$
$$\Rightarrow 2|p \text{ (by Lemma 1)} \tag{21}$$
$$\Rightarrow p = 2n \text{ where } n \in \mathbb{Z} \tag{22}$$
$$\Rightarrow (2n)^2 = 4n^2 = 2q^2 \text{ (from Eq. 2)} \tag{23}$$
$$\Rightarrow 2|q^2 \Rightarrow 2|q \tag{24}$$

Thus $2|p$ and $2|q$ which violates our assumption that p, q share no common factors! Thus is must be the case that there is no rational number whose square is 2.

$\square$

Theorem 12. If $n \in N$ and n is **not** a perfect square, then there is no $r \in \mathbb{Q}$ such that $r^2 = n$

Proof. Assume for contradiction: $\exists r$ s.t. $r = \frac{p}{q}$ where $p, q \in \mathbb{Z}$, $gcd\,(p, q) = 1$, $r^2 = n$, and n is not a perfect square.

$$r^2 = \left(\frac{p}{q}\right)^2 = n \tag{25}$$
$$\Rightarrow p^2 = nq^2 \tag{26}$$

Recall that by the Fundamental Theorem of Arithmetic that we can express any number as a product of prime numbers, so:

$$n = k_1^1 \cdot k_2^2 \cdot k_3^3 \cdot k_4^4 \cdot \ldots.$$

Substitute n into Eq. 9:

$$p^2 = \left(k_1^1 \cdot k_2^2 \cdot k_3^3 \cdot k_4^4 \cdot \ldots\right) q^2.$$

Since n is not a perfect square, we know that $\exists j$ s.t. k_j is odd because if this were not the case, n would be a perfect square. From the above, we can see that

$k_j|p^2$. If k_j divides the LHS, it must also divide the RHS, so $k_j|nq^2$. We know that p^2 contains an even number of k_j terms, and we also know that n contains an odd number of k_j terms. For both sides to have the same number of k_j terms, as all equal numbers should, it must be the case that $k_j|q^2$ which implies $k_j|q$ by Lemma 1. Thus, $gcd\,(p,q) = k_j \neq 1$ which contradicts our assumption that $gcd\,(p,q) = 1$. □

After this we talked about "set theory." We did not go into the details.

Theorem 13. The Algebra of Sets exists. $\mathbb{N}$, $\mathbb{Z}$, $\mathbb{Q}$ exist.

Proof. The above is taken as an axiom, but rest assured that their existence can be derived from first-order logic and the ZFC axioms. □

Tuesday 21 January 2025

Lecture 4: Homework 1

1. Prove that there is no rational number, r, such that $r^2 = 8$.

Proof. BWOC, assume there exists a number $r \in \mathbb{Q}$ such that for some $a, b \in \mathbb{Z}$ with $gcd\,(a,b) = 1$:

$$r^2 = \left(\frac{a}{b}\right)^2 = 8.$$

then:

$$\Rightarrow a^2 = 8b^2 \tag{27}$$

$$\Rightarrow 2^2|a^2 \Rightarrow 2|a^2 \Rightarrow 2|a \text{ (by Lemma 1)} \tag{28}$$

so for some $n \in \mathbb{N}$:

$$\left(2^2 n\right)^2 = 8b^2 \tag{29}$$

$$16n^2 = 8b^2 \tag{30}$$

$$2n^2 = b^2 \Rightarrow 2|b \tag{31}$$

Notice $2|a$ and $2|b$ which violates our assumption that $gcd\,(a,b) = 1$. Thus it must be the case that there does not exist a number $r \in \mathbb{Q}$ such that $r^2 = 8$

□

2. Prove that if $a, b \in \mathbb{R}$ then:

$$||\, a \mid - \mid b \,|| \leq |\, a - b \,| \,.$$

Proof. If $a, b \in \mathbb{R}$, then the triangle inequality holds:

$$|\, a + b \,| \leq |\, a \,| + |\, b \,| \,.$$

Now consider:

$$| a |=| a - b + b |\leq| a - b | + | b | \tag{32}$$
$$| b |=| b - a + a |\leq| b - a | + | a | \tag{33}$$
$$\tag{34}$$

Rearranging and using the definition of the absolute value function and the fact that $| a - b |=| b - a |$:

$$| a | - | b |\leq| a - b | \tag{35}$$
$$| b | - | a |\leq| b - a | \tag{36}$$
$$\Rightarrow|| a | - | b ||\leq| a - b | \tag{37}$$

□

3. Let $y_1 = 6$ and for each $n \in \mathbb{N}$ define

$$y_{n+1} = \frac{2}{3}y_n - 2.$$

Prove the following statements:

a. Prove that $y_{n+1} \leq y_n$ for all $n \in \mathbb{N}$.

b. Prove that $y_n > -6$ for all $n \in \mathbb{N}$

Proof. We will show part a by induction. For the base case take $n = 1$, then $y_1 = 6$ and $y_2 = \frac{2}{3}(6) - 2 = 2$, and we have $y_2 \leq y_1$.

For the inductive step, assume $y_{n+1} \leq y_n$ then we need to show that $y_{n+2} \leq y_{n+1}$.

$$y_{n+1} \leq y_n \tag{38}$$
$$\frac{2}{3}y_{n+1} - 2 \leq \frac{2}{3}y_n - 2 \tag{39}$$
$$\Rightarrow y_{n+2} \leq y_{n+1} \tag{40}$$

Thus, we have shown the theorem by induction. □

Proof. We will show part b by induction. For the base case, take $n = 1$, then $y_1 = 6 > -6$.

For the inductive step, assume $y_n > -6$, then $\frac{2}{3}y_n - 2 > \frac{2}{3}(-6) - 2 \Rightarrow y_{n+1} > -6$

Thus, we have shown the theorem by induction. □

4. Prove that if $x \in \mathbb{R}$ and $x > -1$ then for every $n \in \mathbb{N}$ we have $(1 + x)^n \geq 1 + nx$

Proof. We will show the theorem by induction. For the base base, take $n = 1$, then $1 + x \geq 1 + x$, which is true.

For the inductive step, assume $(1 + x)^n \geq 1 + nx$, then multiply both sides by $(1 + x)$ to get:

$$(1 + x)^{n+1} \geq (1 + nx)(1 + x) = 1 + x + nx + nx^2 = 1 + (n + 1)x + nx^2.$$

Since $x > -1$, we know that $nx^2 > 0$, so we have:

$$(1 + x)^{n+1} \geq 1 + (n + 1)x + nx^2 \geq 1 + (n + 1)x.$$

□

5. Prove or give a counterexample for the following statement: Two real numbers satisfy $a < b$ if and only if $a < b + \varepsilon$ for all $\varepsilon > 0$

The statement is false. Take the case where $a = b$ to be the counterexample. We can adjust the statement slightly to make it true.

Theorem 14. Two real numbers satisfy $a \leq b$ if and only if $a \leq b + \varepsilon$ for all $\varepsilon > 0$

1. $(\Rightarrow)$ If $a \leq b$, then $a - b \leq 0$, so $a - b \leq \varepsilon$ for all $\varepsilon > 0$.
2. $(\Leftarrow)$ Assume $a \leq b + \varepsilon$ for all $\varepsilon > 0$. Let $\varepsilon_0 = a - b$, then it must be that $a - b = \varepsilon_0$ and $a - b \leq \varepsilon_0$, a contradiction! Thus, the theorem must be true.

6. Given a function $f\colon C \to D$ and a set $A \subset C$, let $f(A)$ represent the range of f over the set A i.e. $f(A) = \{f(x) | x \in A\}$.

Answer the following questions:

a. Let $f\colon \mathbb{R} \to \mathbb{R}$ given by $f(x) = x^2$. If $A = [0, 2]$ and $B = [1, 4]$, find $f(A)$ and $f(B)$. Does $f(A \cap B) = f(A) \cap f(B)$ in this case? Does $f(A \cup B) = f(A) \cup f(B)$?

   $f(A) = [0, 4], f(B) = [1, 16], f(A \cup B) = [0, 16], f(A \cap B) = [1, 4]$. Yes to both.

b. Find two sets A and B for which $f(A \cap B) \neq f(A) \cap f(B)$.

c. Let $g\colon C \to D$ be any function and let $A, B, C \subset C$ be any two subsets of the domain. Prove that $g(A \cup B) = g(A) \cup g(B)$

   Proof. If $x \in g(A \cup B)$, then $x = a^2$ or $x = b^2$ where $a \in A$ and $b \in B$. $A \cup B$ contains all $a \in A$ and $b \in B$, so $x \in g(A \cup B)$ since it contains all a^2, b^2 where $a, b \in A, B$.

   If $x \in g(A) \cup g(B)$, then either $x \in g(A)$ or $x \in g(B)$. In the first scenario, $x = a^2$ for some $a \in A$ which we know is in $g(A \cup B)$. In the second scenario, $x = b^2$ for some $b \in B$ which we know is in $g(A \cup B)$. □

sday 23 January 2025

Lecture 5: The Definition of Function

Definition 14. Given sets A, B a function of $A \to B$ is a mapping that takes each element of A to a single element of B.

Note:

1. f is the function, $f(x)$ not the function.
2. A is call the **domain**. B is called the **codomain**. $Range(f) = \{y \in B \mid \exists x \in A \text{ and } f(x) = y\}$. $Range(f) \neq$ codomain in general.

Example. Given $f : \mathbb{R} \to \mathbb{R}$ where $f(x) = x^2$, the comain is $\mathbb{R}$ the codomain is $\mathbb{R}$ and the range is $[0, \infty]$.

Note:

1. If $f(x) \neq f(y)$ when $x \neq y$ then f is called **injective** or **one-to-one**.
2. If $Range(f) =$ codomain of f then f is called **surjective** or **onto**.
3. If f is both injective and surjective, then it is called **bijective**.

Example (Dirichlet Function 1829)**.** Define $g : \mathbb{R} \to \mathbb{R}$ by

$$g(x) = \begin{cases} 0 & \text{if } x \notin \mathbb{Q} \\ 1 & \text{if } x \in \mathbb{Q} \end{cases}.$$

The above function definition is important for historical reasons. Dirichlet came up with the definition of a function given above, and it generalizes the concept of a function nicely. Before Dirichlet, function were either thought about as "nice" graphs or as formula, but the new definition generalizes both of these and allows for less traditional function definitions.

Example. The **absolute value function**, $|\cdot| : \mathbb{R} \to \mathbb{R}$, is given below:

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

Theorem 15. Given the above definition of the absolute value function, we have:

1. $|ab| = |a||b|$
2. $|a + b| \leq |a| + |b|$ **(Triangle Inequality)**

Proof. □

Note. A common trick that we will use in Analysis is the "add/subtract" trick. Let $a, b, c \in \mathbb{R}$, then:

$$|a - b| = ||a - c| + |c - b|| \tag{41}$$
$$\Rightarrow |a - b| \leq ||a - c| + |c - b|| \tag{42}$$

Theorem 16. Let $a, b \in R$. Then $a = b \Leftrightarrow |a - b| < \varepsilon$ for all $\varepsilon > 0$.

Proof. ($\Rightarrow$) If $a = b$, then $a - b = 0$ and $a - b < \varepsilon$ for all $\varepsilon > 0$. ($\Leftarrow$) FSOC assume $|a - b| < \varepsilon$ for all $\varepsilon > 0$ and $a \neq b$, then let $\varepsilon_0 = a - b \neq 0$ then we gave $|a - b| < \varepsilon$ and $|a - b| = \varepsilon_0$, a contradiction!

□

Thursday 23 January 2025

Lecture 6: The Axiom of Completeness

We will take an axiomatic approach to Analysis. There are some things which we will just assume are true. Mathematical Formalism is the idea that formal languages with no semantics can serve as the foundation of mathematics. Under this interpretation, the symbols of mathematics do not mean anything at all! They are only symbols and rules for manipulating symbols. Formulating all of mathematics in terms of a formal language allows us to side step assuming the existence of anything. The trade off is that proofs are extraordinarily complex, involve a lot of symbols, and are generally unreadable. For our purposes of writing readable proofs for the most important theorems from Newton's Calculus, we will take a different set of axioms where we do assert the existence of certain mathematical objects. The philosopher should be satisfied with these axioms because they are formally provable within axiomatic set theory. We don't *need* to assume the existence of anything, but we choose to in order to make our lives easier.

Axiom 1 (Algebraic Properties of $\mathbb{R}$)**.** Assume the existence of a set $\mathbb{R}$, called **the Real Numbers**, which is an ordered field.

This axiom gets us most of the way there, however notice that the rational numbers are also an ordered field. We will need to introduce one more axiom to get a unique set for $\mathbb{R}$; but first, we need to define a little bit of mathematical machinery.

Definition 15 (Bounded Above Property of Subsets of $\mathbb{R}$)**.** A set $A \subset \mathbb{R}$ is **bounded above** if there exists a number $b \in \mathbb{R}$ such that $a \leq b \ \forall a \in A$. The number b is called an **upper bound** for A.

Definition 16 (Bounded Below Property of Subsets of $\mathbb{R}$)**.** A set $A \subset \mathbb{R}$ is **bounded below** if there exists a number $b \in \mathbb{R}$ such that $b \leq a \ \forall a \in A$. The number b is called a **lower bound** for A.

Definition 17 (The Least Upper Bound)**.** An element $s \in \mathbb{R}$ is called the **least upper bound** for $A \subset \mathbb{R}$ if s meets two conditions:

1. s is an upper bound for A
2. $\forall b$ where b is an upper bound, $s \leq b$.

Definition 18 (The Greatest Lower Bound)**.** An element $l \in \mathbb{R}$ is called the **greatest lower bound** for $A \subset \mathbb{R}$ if l meets two conditions:

1. l is a lower bound for A
2. $\forall b$ where b is an upper bound, $l \geq b$.

Example. Given the set $A = \{\frac{1}{n} | n \in \mathbb{N}\} = \{1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots\}$, find: upper bounds, the least upper bound, lower bounds, and the greatest lower bound.

1. some upper bounds: $1, 2, 1.1, 3$
2. least upper bound: 1
3. some lower bounds: $0, -1, -100$
4. greatest lower bound $= 0$

Example. There is no upper bound for $\mathbb{N}$

The above arguments were not very rigorous, so now we will do a slightly more rigorous problem just to prove that we can.

Theorem 17. Given the set $A = \{\frac{1}{n} | n \in \mathbb{N}\} = \{1, \frac{1}{2}, \frac{1}{3}, \frac{1}{4}, \ldots\}$, then the least upper bound for A is 1.

Proof. We will prove the two conditions one at a time:

1. Observe that $1 \geq \frac{1}{n}\ \forall n \in \mathbb{N} \Rightarrow 1$ is an upper bound for A.
2. If b is an upper bound, then, because $1 \in A$, $b \geq 1 \Rightarrow 1$ is the upper bound for A.

□

Theorem 18. If some subset of $\mathbb{R}$ has a least upper bound, then it is unique.

Proof. FSOC assume s_1 and s_2 are two distinct greatest upper bounds of some set A, then we have $s_1 \leq s_2$ and $s_2 \leq s_1$ by applying the second condition of the least upper bound property to s_1 and s_2 one at a time. Thus, $s_1 = s_2$. This contradicts our assumption that s_1 and s_2 are distinct. □

Now we are ready to state the Axioms of Completeness:

Axiom 2 (The Axiom of Completeness)**.** Every non-empty set A where $A \subset \mathbb{R}$ which is bounded above has a least upper bound $b \in \mathbb{R}$

Theorem 19. Up to isomorphism, there is one unique complete ordered field.

Proof. The proof of the above theorem is beyond the scope of this course, but it is worth stating because when we work with $\mathbb{R}$ we can be sure that we are working on the right set without having to worry that what we are describing has more interpretations than as real numbers. $\square$

Note. The Axiom of Completeness is not stateable in first-order logic. You can tell because of the "for every nonempty set A." Here, we are quantifying over a set of sets which is not allowed.

Monday 27 January 2025

Lecture 7: Homework 2

1. Compute, without proof, the supremum and infimum (if they exist) of each of the following sets:

2. Let $A \subset \mathbb{R}$ and $B \subset \mathbb{R}$ be two non-empty sets, each of which is bounded above. If $s = \sup\ A$ and $t = \sup\ B$, find and prove a formula for $\sup\ A \cup B$

Proof. We argue that $\sup A \cup B = max\,(s,t)$ by cases:

1. $(s > t)$ WLOG with respect to the $s < t$ case, since $t = \sup B$, we have $t \geq b$ for all $b \in B$, thus by using our case assumption we get $s > t \geq b$ for all $b \in b$ and $s \geq a$ for all $a \in A$ by the definition of the supremum of a set. Therefore, $s \geq u$ for all $u \in A \cup B$ and $\sup A \cup B = s = max\,(s,t)$.
2. $(s = t)$ If $s = t$ by the definition of the supremum we have $s \geq a$ for all $a \in A$ and $t = s \geq b$ for all $b \in B$. Thus $max\,(s,t) = s = t \geq a$ for all $a \in A$ and $max\,(s,t) = s = t \geq b$ for all $b \in B$. Therefore, $\sup A \cup B = max\,(s,t)$.

$\square$

3. Let $A \subset \mathbb{R}$ and $B \subset \mathbb{R}$ be two non-empty sets, each of which is bounded above.

1. If $\sup A < \sup B$, show that there exists $b \in B$ such that b is an upper bound for A.
2. Given an example to show that this is not always the case if we only assume $\sup A \leq \sup B$.

Proof. 1. Combining the definition of the supremum of a set and the given, we get

$$a \leq \sup A < \sup B.$$

Thus $\sup B$ is an upper bound for A, but it cannot be the *least* upper bound because we assumed that $\sup A < \sup B$. Then by negating the ε Characterization of the Supremum we see that $\exists \varepsilon > 0\ \forall a \in A\ (\sup B - \varepsilon \geq a)$. Let ε_0 be the ε such that $\forall a \in A\,(\sup B - \varepsilon_0 \geq a)$. Since $\sup B$ is the least upper bound of B, again we can use the ε Characterization of the supremum, $\forall\ \varepsilon > 0 \exists b \in B\ (\sup B - \varepsilon < b)$ thus $\exists b \in B\,(\sup B - \varepsilon_0 < b)$. Thus, $\exists b \in B\ \forall a \in A\,(b > \sup B - \varepsilon_0 \geq a)$. Therefore, there exists $b \in B$ such that $b \geq a$ for all $a \in A$.

2. Take $A = (1, 2)$ and $B = (0, 2)$. In this case, $\sup A = \sup B$, but there is no element of b which is an upper bound of A.

$\square$

5. Let $A \subset \mathbb{R}$ and $c \in \mathbb{R}$. We define the set cA as:

$$cA = \{ca | a \in A\}.$$

If A is non-empty and bounded above and $c \geq 0$, then prove that *sup* cA = $c \cdot$ *sup* A.

Proof. By the definition of the supremum, we have $\sup cA \geq ca \Rightarrow \frac{1}{c} \sup cA \geq a$. Then $\frac{1}{c} \sup cA$ is an upper bound for A. But $\sup A$ is the *least* upper bound of A, so it must be that $\frac{1}{c} \sup cA \geq \sup A$, thus $\sup cA \geq c \sup A$.

By the definition of the supremum, we have $\sup A \geq a$ for all $a \in A \Rightarrow c \sup A \geq ca \; \forall a \in A$. Thus $c \sup A$ is an upper bound of cA. But $\sup cA$ is the *least* upper bound of cA, so it must be that $c \sup A \geq \sup cA$.

Thus, $\sup cA \geq c \sup A$ and $\sup cA \leq c \sup A$; therefore, $\sup cA = c \sup A$. $\square$

Lecture 8: 1-29-25 Lecture

Wednesday 29 January 2025

- Math Club in MATH350

Definition 19. Let A, B be two sets, we say that A has the **same cardinality** as B if there exists $f : A \to B$ which is a bijection. In the case we write $A \sim B$. Note that $A \sim B \Leftrightarrow B \sim A$

Example. $A = \{1, 2\}$, $B = \{apple, bananana\}$. Then $A \sim B$ since we can define $f : A \to B$ such that:

$$f(x) = \begin{cases} f(1) & = \text{apple} \\ f(2) & = \text{banana} \end{cases}.$$

f is a bijection, so $A \sim B$

Example. let $E = \{2, 4, 6, 8, \ldots\}$. Claim: $\mathbb{N} \sim E$. Define $f : \mathbb{N} \to E$ given by:

$$\begin{cases} f(1) & = 2 \\ f(2) & = 4 \\ f(3) & = 6 \\ \ldots \end{cases}.$$

f is a bijection, so $\mathbb{N} \sim E$

Example. $\mathbb{N} \sim \mathbb{Z}$

Proof. $f : \mathbb{N} \to \mathbb{Z}$ is given by

$$f(n) = \begin{cases} \frac{n-1}{2} & \text{if } n \text{ is odd} \\ \frac{-n}{2} & \text{if } n \text{ is even.} \end{cases}.$$

f is a bijection, so $\mathbb{N} \sim \mathbb{Z}$ □

Theorem 20. Let A, B, C be sets. If $A \sim B$ and $B \sim C$, then $A \sim C$.

Proof. As $A \sim B$, hence there exists a bijection $f : A \to B$. As $B \sim C$, there exists a bijection $g : B \to C$. Therefore, $g \circ f : A \to C$ is a bijection □

Theorem 21. Let X, Y be two sets. If there exists an injective function $f : X \to Y$ and an injective function $g : Y \to X$, then there exists a bijection $h : X \to Y$ and hence $X \sim Y$.

The above will make our lives easier. We no longer need to find an explicit function. Notice no need to check either function for surjectivity. We get it for free.

Theorem 22. $\mathbb{N} \sim \mathbb{Z}^2$ where

$$\mathbb{Z}^2 = \{(m, n) : m, n \in \mathbb{Z}\}.$$

Informal Proof. Take grid of points down to the number line. □

Proof. Let $f : \mathbb{N} \to \mathbb{Z}^2$ given by

$$f(n) = (n, 0).$$

f is clearly injective.As $\mathbb{Z} \sim \mathbb{N} \Rightarrow$ there exists $g : \mathbb{Z} \to \mathbb{N}$ which is a bijection. Define

$$h : \mathbb{Z}^2 \to \mathbb{N}.$$

where $h(m, n) = 2^{g(m)} \cdot 3^{g(n)}$. Now we will show that h is injective. Assume that $h(m_1, n_1) = h(m_2, n_2)$. We want to show that $m_1 = m_2$ and $n_1 = n_2$:

$$2^{g(m_1)} 3^{g(n_1)} = 2^{g(n_1)} 3^{g(n_2)}.$$

As 2 and 3 are prime numbers, by unique factorization:

$$\Rightarrow g(m_1) = g(m_2) \text{ and } g(n_1) = g(n_2)..$$

But $g : \mathbb{Z} \to \mathbb{N}$ is a bijection, hence $m_1 = m_2$ and $n_1 = n_2 \Rightarrow h$ is injective. Thus, by the Cantor-Schroder-Berstein theorem, there exists $z : \mathbb{N} \to \mathbb{Z}^2$ which is a bijection. □

> **Theorem 23.** Show that $\mathbb{N} \to \mathbb{N}^3$ where $\mathbb{N}^3 = \{(a,b,c) : a,b,c \in \mathbb{N}\}$

Proof. Let $f : \mathbb{N} \to \mathbb{N}^2$ be $f(n) = (n,1,1)$. This f is injective. Let $g : \mathbb{N}^3 \to \mathbb{N}$ where $g(a,b,c) = 2^a 3^b 5^c$. This g is injective by the same logic as before. By CSB, then there exists a bijection $z : \mathbb{N} \to \mathbb{N}^3$. □

> **Theorem 24.** A set S is c called **countably infinite** if $S \sim \mathbb{N}$. A set S is called **countable** if either S is finite or countably infinite. S is called **uncountable** if it is not countable. (This definition's slightly different from the textbook).

Example. $A = \{1,2\}$ is finite and countable. $\mathbb{Z} = \{\ldots,-2,-1,0,1,2,\ldots\}$ is countably infinite and countable.

Lecture 9: 1-31-25 Lecture

Friday 31 January 2025

-Recall that a countably infinite set just means that $A \sim \mathbb{N}$.

-Recall that a countable set is either finite or countably infinite.

-Recall that an uncountable set is a set which is not countable. It is not clear a priori that these exist, but they do.

Example. $\mathbb{N} \sim \mathbb{N}^2 \sim \mathbb{Z} \sim Z^2$ are all countable.

> **Theorem 25.** The set $\mathbb{Q}$ is countable (ie it is a countable infinite set).

Proof. Let $f : \mathbb{N} \to \mathbb{Q}$ be $f(n) = \frac{n}{2}$. This is an injective mapping. Every rational number $r \in \mathbb{Q}$ can be uniquely written as $\frac{p}{q}$ where $p \in \mathbb{Z}$, $q \in N$, and $\gcd(p,q) = 1$. Define $g : \mathbb{Q} \to \mathbb{Z}^2$ given by $g(r) = (p,q)$. Clearly this is injective. As $\mathbb{Z}^2 \sim \mathbb{N}$, $\exists h : \mathbb{Z}^2 \to \mathbb{N}$ bijective. Thus $h \circ g : \mathbb{Q} \to \mathbb{N}$ is injective. Therefore, by the Cantor-Schroder-Bernstein theorem. $\mathbb{Q} \sim \mathbb{N}$, and $\mathbb{Q}$ is countable. □

> **Theorem 26.** $\mathbb{R}$ is uncountable.

Proof. We proceed by contradiction. Therefore, $\mathbb{N} \sim \mathbb{R}$ i.e. $f : \mathbb{N} \to \mathbb{R}$ which is a bijection. Therefore, we can write $x_1 = f(1)$, $x_2 = f(2)$, ... We have $\mathbb{R} = \{x_1, x_2, \ldots\}$. Consider a closed interval I_1 which does not contain x_1. Now let I_2 be a closed interval inside I_1 such that $x_2 \notin I_2$. In general, given I_n closed interval, construct a closed interval I_{n+1} such that

1. $I_{n+1} \subset I_n$.
2. $x_{n+1} \notin I_{n+1}$.

Consider the set $\cap_{n=1}^{\infty} I_n$. As $x_n \notin I_n \Rightarrow x_n \notin \cap_{n=1}^{\infty}$. As $f : \mathbb{N} \to \mathbb{R}$ is a bijection (As $\mathbb{R} = \{x_1, x_2, \ldots\}$) we have $\cap_{n=1}^{\infty} I_n = \emptyset$. ☐

But are there any infinities which are small than the cardinality of $\mathbb{N}$

Theorem 27. If B is a countable set and $A \subset B$, then A is countable.

Proof. We will show the theorem by cases:

- (B is a finite set). As $A \subset B$, A is also a finite set and A is countable.
- (B is countably infinite). If A is finite, then obviously A is countable
- Now we assume that A is an infinite set. As B is countably infinite, we gave a bijection $f : \mathbb{N} \to B$. In particular, we can write

  $$B = \{f(1), f(2), \ldots\}.$$

  $A \subset B$ and is infinite. Let $n_1 = \min\{n \in \mathbb{N} : f(n) \in A\}$. More generally given n_k we define n_{k+1} as

  $$n_{k+1} = \min\{n \in \mathbb{N}, n > n_k : f(n) \in A\}.$$

  Define $g : \mathbb{N} \to A$ as $g(k) = f(n_k)$. By construction, g is a bijection; therefore, $A \sim \mathbb{N}$ and A is countable.

☐

Monday 03 February 2025

Lecture 10: 2-3-25 Lecture

Recall from last time

Theorem 28. If $A \subset B$ and B is countable, then A is countable.

Note. if $B = \mathbb{N}$ and $A = \emptyset$. $\emptyset$ is a finite set and thus countable. $\emptyset \subset \mathbb{N}$.

Theorem 29. A set A is countable if and only if there exists an injective function $f : A \to \mathbb{N}$.

Proof. We will prove the forward and backward direction:

- ($\Rightarrow$) Either A is finite or countably infinite. If $A = \emptyset$, then statement is true vacuously. If A is a nonempty finite set, let $|A| = n$, $n \in \mathbb{N}$. Then clearly there exists a bijection between A and $\{1, 2, \ldots, n\}$. Then we just change the function from being $f : A \to \{1, 2, \ldots, n\}$ to $f : A \to \mathbb{N}$. If A is countably infinite, $\exists f : A \to \mathbb{N}$ a bijection. In particular, it is injective.
- ($\Leftarrow$) Let $f : A \to \mathbb{N}$ be injective. Consider $\text{Range}(f) \subset \mathbb{N}$. Observe that $f : A \to \text{Range}(f)$ is a bijection. As $\text{Range}(f) \subset \mathbb{N} \Rightarrow \text{Range}(f)\, is countable$. We also have $A \sim \text{Range}(f) \Rightarrow A$ is countable.

☐

Theorem 30. If A_n is a countable set for each $n \in \mathbb{N}$, then $\cup_{n=1}^{\infty} A_n$ is also countable, i.e. a countable union of countable sets is countable.

INCLUDE GRID OF $\mathbb{N}^2$.

Note. A_ns may not be disjoint! Consider $A_1 = \{1, 2\}$, $A_2 = \{2, 3\}$, $A_3 = \{3, 4, 5\}$. We will try to make these sets disjoint before we get to the proof.

Proof. Define $B_1 = A_1$, $B_2 = A_2 \setminus A_1, \ldots, B_n = A_n \setminus \{A_1 \cup A_2 \sup \ldots\}$ So we have:

$$B_1 = \{1, 2\} \tag{43}$$
$$B_2 = \{3\} \tag{44}$$
$$B_3 = \{4, 5\} \tag{45}$$

Therefore we have $B_1, B_2, B_3, \ldots$ are all disjoint and $\cup_{n=1}^{\infty} A_n = \cup_{n=1}^{\infty} B_n$. As $B_n \subset A_n$ and A_n is countable, B_n is countable. Therefore $\exists f_n : B_n \to \mathbb{N}$ which is injective for all $n \in \mathbb{N}$.

Define $g : \cup_{n=1}^{\infty} N_n \to \mathbb{N}^2$ given as follows if $b \subset \cup_{n=1}^{\infty}$, the as B_n's are all disjoint, there exists a unique $N \in \mathbb{N}$ such $b \in B_n$. Define:

$$g(b) = (f_N(b), N).$$

As f_N is injective $\Rightarrow g$ is injective. As $\mathbb{N}^2$ is countably infinite, $\exists h : \mathbb{N}^2 \to \mathbb{N}$ is a bijection. Therefore, $h \circ g : \cup_{n=1}^{\infty} B_n \to \mathbb{N}$ is injective and $\cup_{n=1}^{\infty} B_n$ is countable.

□

Theorem 31. If $m \in \mathbb{N}$, and $A_1, A_2, \ldots, A_n$ are countable, then $A_1 \cup A_2 \cup \ldots \cup A_m$ is also countable.

Proof. Define $A_n = \emptyset$ for $n \geq m + 1$. Therefore each A_n, $n \in \mathbb{N}$ is countable. By previous theorem $\cup_{n=1}^{\infty} A_n$ is countable. But $\cup_{n=1}^{\infty} A_n = \cup_{n=1}^{\infty} B_n$. □

Theorem 32. Suppose $I = \mathbb{R} \setminus \mathbb{Q}$ is countable which implies $\mathbb{R} = \mathbb{Q} \cup I$ is also countable by the previous corollary, a contradiction!

Lecture 11: Homework 3

Monday 03 February 2025

Proof. From the definitions, we have $\forall n \in \mathbb{N}, \forall a \in A \left(s + \frac{1}{n} \geq a\right)$ and $\forall n \in \mathbb{N}, \exists a \in A \left(s - \frac{1}{n} < a\right)$ Notice that for all $n \in \mathbb{N}$, $s - \frac{1}{n+1} < s - \frac{1}{n}$, so $\forall n \in \mathbb{N}$ $s - \frac{1}{n}$ is a not the least upper bound. Thus we get

$$s - \frac{1}{n} \leq \sup A \leq s + \frac{1}{n} \tag{46}$$
$$-\frac{1}{n} \leq \sup A - s \leq \frac{1}{n} \tag{47}$$

for all $n \in \mathbb{N}$. From here there are 3 cases and we can immediately eliminate two:

- Assume $\sup A - s > 0$, then $\forall n \in \mathbb{N} \left(\sup A - s \leq \frac{1}{n}\right)$ which contradicts the Archimedean Principle since $\sup A - s > 0$.
- Assume $\sup A - s < 0$, then $\forall n \in \mathbb{N} \left(-\left(\sup A - s\right) \leq \frac{1}{n}\right)$ which contradicts the Archimediean Principle since $-\left(\sup A - s\right) > 0$

Therefore, it must be that $\sup A - s = 0 \Rightarrow s = \sup A$. $\square$

2. Prove that $\cap_{n=1}^{\infty} \left(5, 5 + \frac{1}{n}\right) = \emptyset$.

Proof. Assume for the sake of contradiction, that $x \in \cap_{n=1}^{\infty}$, then $5 < x < 5 + \frac{1}{n} \Rightarrow x = 5 + \varepsilon$ for some $\varepsilon > 0 \in \mathbb{R}$. By the archimedean principle, $\exists n \in \mathbb{N} \left(\varepsilon > \frac{1}{n}\right)$, thus $x = 5 + \varepsilon > 5 + \frac{1}{n}$. But then we have $x > 5 + \frac{1}{n}$ from the previous statement and $x < 5 + \frac{1}{n}$ from the given. This is a contradiction, so it must be that $\nexists x \in \mathbb{R} \left(x \in \cap_{n=1}^{\infty} \left(5, 5 + \frac{1}{n}\right)\right)$. Therefore, $\cap_{n=1}^{\infty} \left(5, 5 + \frac{1}{n}\right) = \emptyset$. $\square$

3. Let $a, b \in \mathbb{R}$ with $a < b$. Let $T = \mathbb{Q} \cap [a, b]$. Prove that $\sup T = b$.

Proof. Notice b is the maximum of $[a, b]$, and $\mathbb{Q} \cap [a, b] \subset [a, b]$. Thus $\forall t \in T, t \in [a, b] \Rightarrow b \geq t$. Thus b is an upper bound of T.

To show that b is the supremum of T, assume FSOC that $\exists s$ such that $s < b$ and $\forall t \in T \left(s \geq t\right)$. By the density of the rationals in $\mathbb{R}$, $\exists r \in \mathbb{Q} \left(s < r < b\right)$. Using the fact that rationals are dense in $\mathbb{R}$ again, we know $\exists q \in \mathbb{Q}$ such that $a < q < s < r < b$, thus $r \in T$. Since $r \in T$ and s is an upper bound of T, we have $s \geq r$. Now we have both $s < r$ by the construction of r and $s \geq r$ by assumption, a contradiction! Therefore there is no upper bound s such that $s < b$.

Therefore, we have shown the two conditions for b to be the supremum of T. $\square$

4. For each $n \in \mathbb{N}$ let I_n be a closed bounded interval (the intervals need not be nested). Assume that for any $N \in \mathbb{N}$ we know that $\cap_{n=1}^{N} I_n = \emptyset$. Prove that $\cap_{n=1}^{\infty} I_n \neq \emptyset$.

Proof. $\square$

5. Give an example for each of the following:

   1. Two sets A and B with $A \cap B = \emptyset$, $\sup A = \sup B$, $\sup A \notin A$ and $\sup B \notin B$.

      Take $A = \{x : x \in \mathbb{Q}, 0 < x < 1\}$ and $B = \{x : x \in \mathbb{R} \setminus \mathbb{Q}, 0 < x < 1\}$

   2. A sequence of nested open intervals $J_1 \supset J_2 \supset J_3 \supset \ldots$ with $\cap_{n=1}^{\infty} J_n$ non-empty but containing only a finite number of elements.

      Take $J_n = (-\frac{1}{n}, \frac{1}{n})$

3. A sequence of nested unbounded closed intervals $L_1 \supset L_2 \supset L_3 \supset \ldots$, where each $L_n = [a_n, \infty)$ for some $a_n \in \mathbb{R}$, such that $\cap_{n=1}^{\infty} L_n = \emptyset$.

   Take $L_n = [n, \infty]$ $\forall n \in \mathbb{Z}$. For any $x \in \mathbb{R}$ we know that $x \notin L_{x+1}$, so $\forall x \in \mathbb{R}$, $x \notin \cap_{n=1}^{\infty} L_n$.

6. If $a, b \in \mathbb{R}$ with $a < b$, show that $[a, b] \sim (a, b)$.

Proof. We will use the Cantor-Schroeder-Bernstein theorem to prove the statement. Defining the injective function $f : (a, b) \to [a, b]$ is trivial; let $f(x) = x$ $\forall x \in (a, b)$. Defining the injective function $g : [a, b] \to (a, b)$ requires a little more doing. Intuitively, we will shrink the set from the range down to any closed set that we want which is contained in $[a, b]$, then we will allow the endpoints of the domain to map to the endpoints of the new closed set. Finally, we linearly map the rest of the uncountably many elements of the domain to the uncountably many elements between the endpoints of the new set which is contained in the range. Formally, we will define a linear function such that $g(a) = \frac{b}{4}$ and $g(b) = \frac{3b}{4}$:

$$g(x) = \begin{cases} \frac{b}{4} & x = a \\ \frac{b}{2(b-a)} x + \frac{b}{4} & a < x < b \\ \frac{3b}{4} & x = b \end{cases}.$$

Thus, $f : (a, b) \to [a, b]$ is injective and $g : [a, b] \to (a, b)$ is injective. Therefore, $\exists h : (a, b) \to [a, b]$ which is a bijective, and $[a, b] \sim (a, b)$.

□

Lecture 12: 02-05-25

Tuesday 05 February 2025

-Sequences and series are the most important part of the class. "If you don't understand this, you are going to fail."

Theorem 33. $\mathbb{R} \setminus \mathbb{Q}$ is uncountable: $\mathbb{R} \setminus \mathbb{Q} \sim \mathbb{R}$

Definition 20. Given a set A, the power set $P(A)$ is the set of all subsets of A.

Theorem 34. If A is a finite set with $|A| = n$ then $|P(A)| = 2^n$

This works even for infinite sets!

Theorem 35. $P(\mathbb{N}) \sim \mathbb{R}$

Theorem 36. Given any set A, there does not exist a surjective function $f : A \to P(A)$.

This means that if A is infinite, then $P(A)$ is a "bigger" infinite than A.

Example. $\mathbb{N} \to P(\mathbb{N}) \sim \mathbb{R} \to P(P(\mathbb{N})) \sim P(\mathbb{R}) \to \dots$

Won't be asking too many questions about this stuff.

3 Sequences and Series

Recall from the example given on day 1 that we cannot sum up infinite stiff. Instead, you add up finitely many things and then take a "limit." Now we define what a limit is.

Definition 21. A sequence is a function whose domain is $\mathbb{N}$.

Example. $2, 4, 8, 16, 32, \dots$ is a sequence of natural numbers. $\pi, \pi^2, \pi^3, \dots$ is a sequence of real numbers.

Sequences are not series. Limits apply to sequences, not series.

Example. $\left(1, \frac{1}{2}, \frac{1}{3}, \dots\right)$

Example. $\left(\frac{1+n}{n}{}_{n=1}^{\infty}\right) = \left(2, \frac{3}{2}, \frac{4}{3}, \dots\right)$

Example. $\left(\frac{1+n}{n}\right)$

If you do not write the starting and ending points, it is assume that it is $n = 1$ to ∞.

Example. (a_n), where $a_n = 2^n$ for all $n \in \mathbb{N}$.

Example. (x_n), where $x_1 = 2$ and $\frac{x_n+1}{2}$ for all $n \geq 1$.

Definition 22 (Convergence of a Sequence)**.** A sequence a_n converges to a real number a, if for every $\varepsilon > 0$, there exists $N \in \mathbb{N}$ such that whenever $n \geq N$, we have $|a_n - a| < \varepsilon$. In this case we write

$$\lim_{n\to\infty} a_n = a \Leftrightarrow \lim a_n = a \Leftrightarrow (a_n) \to a.$$

Definition 23 (Conversgence of a Sequence Topological Definition)**.** A sequence (a_n) converges to a, if every ε-neighborhood of a contains all but a finite number of the terms of (a_n).

Definition 24. Given $a \in \mathbb{R}$ and $\varepsilon > 0$, the set

$$V_\varepsilon(a) = \{x \in \mathbb{R} : |x - a| < \varepsilon\}.$$

is called the ε-neighborhood of a

Example. Prove $\lim\left(\frac{1}{\sqrt{n}}\right) = 0$

Proof.

1. Challenge: $\varepsilon = \frac{1}{2}$ Response: let $N = 5$. To confirm, notice $n \geq 5 \Rightarrow \left|\frac{1}{\sqrt{n}} - 0\right| = \frac{1}{\sqrt{n}} < \frac{1}{2}$
2. Challenge: $\varepsilon = \frac{1}{10}$. Response: let $N = 101$. To confirm check $n \geq 101 \Rightarrow \frac{1}{\sqrt{n}} < \frac{1}{10}$

□

Proof. WTS: $\lim\left(\frac{1}{\sqrt{n}}\right) = 0$. If $n \geq N$ we want

$$\left|\frac{1}{\sqrt{n}} - 0\right| < \varepsilon \tag{48}$$

$$\Leftrightarrow \frac{1}{\sqrt{n}} < \varepsilon \tag{49}$$

$$\Leftrightarrow \frac{1}{\varepsilon^2} < n \tag{50}$$

Choose $N \in \mathbb{N}$ such that $\frac{1}{\varepsilon^2} < N \leq n$ □

Proof. Let $\varepsilon > 0$ be given. Let $N \in \mathbb{N}$ be such that

$$N > \frac{1}{\varepsilon^2}.$$

Let $n \geq N$. Then we observe that

$$n > \frac{1}{\varepsilon^2} \Rightarrow \frac{1}{\sqrt{n}} < \varepsilon \Rightarrow \left|\frac{1}{\sqrt{n}} - 0\right| < \varepsilon.$$

Hence, the theorem is proved. □

Lecture 13: 02-07-25 Lecture

Friday 07 February 2025

Example. Template for a proof of ($x_n \to x$):

1. Let $\varepsilon > 0$ be given.
2. Choose N (depending on ε in general). This step takes the most amount of work and this work is not shown and is rough work.
3. let $n \geq N$
4. Now prove that $|x_n - x| < \varepsilon$ for all $n \geq N$. Then the proof is complete.

Example. Prove that $\lim\left(\frac{n+1}{n}\right) = 1$

Rough work:

$x_n = \frac{n+1}{n} = 1 + \frac{1}{n}$

$x = 1$

Now we want:

$$|x_n - x| < \varepsilon \tag{51}$$
$$\left|1 + \frac{1}{n} - 1\right| < \varepsilon \tag{52}$$
$$\left|\frac{1}{n}\right| < \varepsilon \tag{53}$$
$$\frac{1}{n} < \varepsilon \tag{54}$$
$$\frac{1}{\varepsilon} < n \tag{55}$$
$$\tag{56}$$

What I really want: Find N so that $\forall n \geq N$, $\frac{1}{\varepsilon} < n$, so choose $N \in \mathbb{N}$ such that $\frac{1}{\varepsilon} < N$, then if $n \geq N \Rightarrow \frac{1}{\varepsilon} < N < n$.

Proof. Let $\varepsilon > 0$ be given. Choose $N \in \mathbb{N}$ such that $\frac{1}{\varepsilon} < N$. Let $n \geq N$. This implies that

$$\frac{1}{\varepsilon} < N \leq n \tag{57}$$
$$\frac{1}{n} < \varepsilon \tag{58}$$
$$\left|\left(1 + \frac{1}{n}\right) - 1\right| < \varepsilon \tag{59}$$
$$\left|\left(\frac{n+1}{n}\right) - 1\right| < \varepsilon \tag{60}$$
$$\tag{61}$$

Thus we have shown the condition for the proof. □

Example. Prove that $\lim \left(\frac{1}{n^2}\right) = 0$

Proof. Let $\varepsilon > 0$ be given. Choose $N \in \mathbb{N}$ such that

$$N > \frac{1}{\sqrt{\varepsilon}}.$$

Therefore

$$n > \frac{1}{\sqrt{\varepsilon}} \tag{62}$$
$$\frac{1}{n} < \sqrt{\varepsilon} \tag{63}$$
$$\frac{1}{n^2} < \varepsilon \tag{64}$$
$$\left|\frac{1}{n^2} - 0\right| < \varepsilon \tag{65}$$

□

Example. Prove that $\lim \frac{1}{n^2+576n+100{,}002} = 0$

Proof. If $\frac{1}{n^2} < \varepsilon$

$$\left| \frac{1}{n^2 + 576n + 100{,}002} - 0 \right| < \varepsilon \tag{66}$$

□

Note. Do not try to find an "optimal" N, just find one that works!

Lecture 14: 02-10-25 Lecture

Monday 10 February 2025

Theorem 37. The limit of a sequence, when it exists, is unique.

Proof. Let (a_n) be a sequence and assume that $s, t \in \mathbb{R}$ such that $\lim a_n = s$ and $\lim a_n = t$. Let $\varepsilon > 0$ be arbitrary. As $\lim a_n = s$, hence $\exists N_1 \in \mathbb{N}$ such that $\forall n \geq N_1$, we have $|a_n - s| < \frac{\varepsilon}{2}$. Similarly, as $\lim a_n = t$, $\exists N_2 \in \mathbb{N}$ such that $\forall n \geq N_2$, we have $|a_n - t| < \frac{\varepsilon}{2}$. Let

$$N = \max\{N_1, N_2\} \tag{67}$$

hence $|a_N - s| < \frac{\varepsilon}{2}$ and $|a_N - t| < \frac{\varepsilon}{2}$.

$$\begin{aligned} |s - t| &= |(s - a_N) + (a_N - t)| && (68) \\ &\leq |s - a_N| + |a_N - t| && (69) \\ &< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} && (70) \\ &= \varepsilon && (71) \\ &\Rightarrow |s - t| < \varepsilon && (72) \end{aligned}$$

As $\varepsilon > 0$ is arbitrary, this implies that $s = t$ □

Definition 25. A sequence that does not converge is said to diverge.

Example. Prove that the sequence $a_n = (-1)^n$ diverges.

Note. The strategy for these is to assume that it converges, then show that it must converge to two different numbers.

Proof. Suppose by contradiction, let $L \in \mathbb{R}$ be such that $\lim a_n = L$. Therefore, given $\varepsilon = \frac{1}{2}$, there exists $N \in \mathbb{N}$ such that $\forall n \geq N$ we have $|a_n - L| < \frac{1}{2}$. Let $n_1 \geq N$ be odd $\Rightarrow |a_n - L| < \frac{1}{2} \Rightarrow |(-1)^{n_1} - L| < \frac{1}{2} \Rightarrow |(-1) - L| < \frac{1}{2}$ as $n_1 + 1 \geq N$ and is even.

$$\Rightarrow |a_{n_1+1} - L| < \frac{1}{2} \Rightarrow |1 - L| < \frac{1}{2} \Rightarrow 2 < 1 \tag{73}$$

a contradiction! □

Example. Prove that $\lim\left(\frac{1}{n}\right) \neq 1$

Proof. By contradiction, assume that $\lim \frac{1}{n} = 1$. Then for $\varepsilon = \frac{1}{2}$, $\exists N \in \mathbb{N}$ such that $\forall n \geq N$

$$\left|\frac{1}{n} - 1\right| < \frac{1}{2} \tag{74}$$

$$\Rightarrow 1 - \frac{1}{2} < \frac{1}{n} < 1 + \frac{1}{2} \tag{75}$$

$$\Rightarrow \forall n \geq N \left(\frac{1}{2} < \frac{1}{n}\right) \tag{76}$$

By the Archimedean property, $\exists m \in \mathbb{N}$ such that

$$m \geq N \text{ and } \frac{1}{m} < \frac{1}{2} \tag{77}$$

$$\tag{78}$$

This is a contradiction! ☐

Definition 26. A sequence (x_n) is **bounded** if there exists $M > 0$ such that $|x_n| \leq M \ \forall n \in \mathbb{N}$.

Theorem 38. Every convergent sequence is bounded.

This is a standard kind of argument that we will see again and again:

Proof. Let $L \in \mathbb{R}$ be such that $\lim x_n = L$. Hence for $\varepsilon = 1$, $\exists N \in \mathbb{N}$ such that $\forall n \geq N$ we have

$$|x_n - L| < 1 \tag{79}$$

Therefore, $\forall n \geq N$

$$|x_n| = |x_n - L + L| \tag{80}$$

$$\leq |x_n - L| + |L| \tag{81}$$

$$< |L| + 1 \tag{82}$$

Let $M = \max\{|x_1|, |x_2|, \ldots, |x_{N-1}|, |L| + 1\} > 0$. We see that $|x_n| \leq M$ $\forall n \in \mathbb{N}$. Hence (x_n) is bounded. ☐

Monday 10 February 2025

Lecture 15: Homework 4

1. Let $C \subset (0,1]$ be uncountable. Show that there exists $a \in (0,1)$ such that $C \cap [a,1]$ is uncountable.

Proof. ☐

2. Prove the following limits:

1. $\lim \frac{2n+1}{5n+4} = \frac{2}{5}$
2. $\lim \frac{5n^2}{n^3+2n^2+3n+4} = 0$
3. $\lim \frac{\sin(n^2)}{\sqrt{n}} = 0$
4. $\lim \frac{1}{n^2-10} = 0$

Proof. □

3. Let $(a_n)_{n=1}^{\infty}$ be a sequence and let $L \in \mathbb{R}$. Show that $a_n = L$ if and only if the sequence $(a_n - L)_{n=1}^{\infty}$ converges to zero.

Proof. □

4. Prove that $\lim a_n = 0$ if and only if $\lim |a_n| = 0$.

Proof. □

5. If $|a| < 1$, then prove that $\lim a^n = 0$. (Hint: Use the inequality proved in HW1 namely that for $x > -1$ we have $(1+x)^n \geq 1 + nx$, for a suitable chosen x).

Proof. □

Lecture 16: 02-12-25 Lecture

Tuesday 12 February 2025

Example. Prove that (a_n) where $a_n = n^2$ is divergent.

Proof. Assume by contradiction that (a_n) is convergent. Therefore (a_n) is a bounded sequence, so $\exists M > 0$ such that

$$\forall n \in \mathbb{N}(|a_n| \leq M) \tag{83}$$
$$\forall n \in \mathbb{N}\left(n^2 \leq M\right) \tag{84}$$
$$\tag{85}$$

Let $N \in \mathbb{N}$ be such that $N > M$ then

$$N^2 > MN \geq M \tag{86}$$
$$N^2 > M \tag{87}$$

this is a contradiction! □

This next theorem is used all the time.

Theorem 39. Suppose (a_n) is a convergent sequence with $\lim a_n = L$. If $L \neq 0$ and $a_n \neq 0$ for all $n \in \mathbb{N}$, then $\exists \delta > 0$ such that $|a_n| \geq \delta > 0$ for all $n \in \mathbb{N}$.

Proof. As $L \neq 0$, choose $\varepsilon = \frac{|L|}{2} > 0$ $\exists N \in \mathbb{N}$ such that $\forall n \geq N$ we have

$$|a_n - L| < \frac{|L|}{2} \tag{88}$$

$$\tag{89}$$

for $n \geq N$ we have

$$|L| \leq |L - a_n| + |a_n| \leq \frac{|L|}{2} + |a_n| \tag{90}$$

$$\tag{91}$$

Therefore, for all $n \geq N$ we have

$$\frac{|L|}{2} \leq |a_n| \tag{92}$$

$$\tag{93}$$

Define $\delta = \min\{|a_1|, |a_2|, \ldots, |a_{N-1}|, \left|\frac{L}{2}\right|\} > 0$. We see that $|a_n| \geq \delta > 0$ $\forall n \in \mathbb{N}$. □

Theorem 40 (Algebraic limit theorem)**.** Let $a, b \in \mathbb{R}$ and let $\lim a_n = a$ and $\lim b_n = b$. Then

1. $\lim (ca_n) = ca$ for all $c \in \mathbb{R}$
2. $\lim (a_n + b_n) = a + b$
3. $\lim (a_n b_n) = ab$
4. If $b \neq 0$ and $b_n \neq 0$ $\forall n \in \mathbb{N}$, then $\lim \left(\frac{a_n}{b_n}\right) = \frac{a}{b}$

Example. Given $a_n = \frac{3n^2+5}{n^2+10}$. Prove $\lim a_n = 0$

Example.

$$a_n = \frac{n^2\left(3 + \frac{5}{n^2}\right)}{n^3\left(1 + \frac{10}{n^3}\right)} \tag{94}$$

$$\frac{1}{n} \cdot \frac{3 + \frac{5}{n^2}}{1 + \frac{10}{n^3}} \tag{95}$$

We know that $\lim \frac{1}{n} = 0$

$$\Rightarrow \lim \frac{1}{n^2} = 0 \tag{96}$$

$$\Rightarrow \lim \frac{5}{n^2} = 0 \Rightarrow \lim \left(3 + \frac{5}{n^2}\right) = 3 \tag{97}$$

Proof. We will consider each case in turn:

1. If $c = 0$ then $ca_n = 0\ \forall n \in \mathbb{N}$. Clearly $(ca_n) \to 0$ in this case. Let $\varepsilon > 0$ be given. Choose $N = 1$. Therefore, $\forall n \geq N$ we have

$$|ca_n - ca| = |0 - 0| = 0 < \varepsilon \tag{98}$$

Therefore $(ca_n) \to ca$ in this case

Let $c \neq 0$ and let $\varepsilon > 0$ be given. Let $N \in \mathbb{N}$ be such that $\forall n \geq N$ we have

$$|a_n - a| < \frac{\varepsilon}{|c|} \tag{99}$$

Sidebar: we want :

$$ca_n - ca < \varepsilon \tag{100}$$

$$|c|\,|a_n - a| < \varepsilon \tag{101}$$

$$|a_n - a| < \frac{\varepsilon}{|c|} \tag{102}$$

Therefore for $n \geq N$ we have

$$|ca_n - ca| \tag{103}$$

$$= |c|\,|a_n - a| \tag{104}$$

$$< |c|\,\frac{\varepsilon}{|c|} \tag{105}$$

$$= \varepsilon \tag{106}$$

Therefore $|ca_n - ca| < \varepsilon\ \forall n \geq N$ hence proved.

2. Sidebar: WTS

$$|(a_n + b_n) - (a + b)| < \varepsilon \tag{107}$$

$$|(a_n - a) + (b_n - b)| < \varepsilon \tag{108}$$

Now on to the actual proof:

Let $\varepsilon > 0$ be given. Let $N_1 \in \mathbb{N}$ be such that $\forall n \geq N_1$ we have

$$|a_n - a| < \frac{\varepsilon}{2} \tag{109}$$

Let $N_2 \in \mathbb{N}$ be such that $\forall n \geq N_2$ we have

$$|b_n - b| < \frac{\varepsilon}{2} \tag{110}$$

Let $N = \max\{N_1, N_2\}$. Therefore for all $n \geq N$ we have

$$\begin{aligned}
&|(a_n + b_n) - (a + b)| && (111)\\
&= |(a_n - a) + (b_n - b)| && (112)\\
&\leq |a_n - a| + |b_n - b| && (113)\\
&< \frac{\varepsilon}{2} + \frac{\varepsilon}{2} && (114)\\
&= \varepsilon && (115)
\end{aligned}$$

Therefore, $|ca_n - ca| < \varepsilon \ \forall n \geq N$ hence proved.

□

Friday 14 February 2025

Lecture 17: 02-14-25 Lecture

Example. $a_n = \frac{1}{n^2+10}$ and $\lim a_n = 0$

$$a_n = \frac{1}{n^2\left(1 + \frac{10}{n^2}\right)} \tag{116}$$

$$\left(\frac{1}{n^2}\right)\frac{1}{\left(1 + \frac{10}{n^2}\right)} \tag{117}$$

We know that $\lim \frac{1}{n} = 0$ so

$$\text{(By ALT)} \ \lim \frac{1}{n^2} = 0 \tag{118}$$

$$\lim\left(1 + \frac{1}{n^2}\right) = 1 \tag{119}$$

$$\lim \frac{1}{1 + \frac{10}{n^2}} = 1 \tag{120}$$

$$\lim \frac{1}{n^2} \cdot \frac{1}{\left(1 + \frac{10}{n^2}\right)} = 0. \tag{121}$$

Hence proved.

Theorem 41. Let $a, b \in \mathbb{R}$ and $\lim a_n = a$ and $\lim b_n = b$.

1. If $a_n \geq 0 \ \forall n \in \mathbb{N}$, then $a \geq 0$
2. If $a_n \leq b_n \ \forall n \in \mathbb{N}$, then $a \leq b$
3. If $\exists c \in \mathbb{R}$ such that $c \leq b_n \ \forall n \in \mathbb{N}$, then $c \leq b$. Similarly, if $a_n \leq c$ $\forall n \in \mathbb{N}$, then $a \leq c$.

Proof. By contradiction, assume that $a < 0$, therefore $\exists N \in \mathbb{N}$ such that $\forall n \geq N$

we have

$$|a_n - a| < \frac{|a|}{2} \Rightarrow a_n - a < \frac{|a|}{2} \tag{122}$$
$$\Rightarrow a_n < a + \frac{|a|}{2} < 0 \tag{123}$$
$$\Rightarrow a_n < 0 \ \forall n \geq \mathbb{N}. \tag{124}$$

A contradiction! □

Lecture 18: 02-17-25 Lecture

Monday 17 February 2025

- DeLong Lecture today 3:30 - 4:30pm in Kitt Multipurpose room. Speaker: Prof. Laura DeMarco (Harvard)

Definition 27. A sequence (a_n) is called **increasing** if $a_n \leq a_{n+1}$ for all $n \in N$. It is called **decreasing** if $a_n \geq a_{n+1}$ for all $n \in \mathbb{N}$. A sequence is called monotone if it is either increasing or decreasing.

Example. $1, 1, 2, 2, 3, 3, 4, 4, \ldots$ is increasing.

Example. $1, 1, 0, 0, -1, -1, \ldots$ is decreasing

Example. $1, 1, 1, 1, 1, \ldots$ is constant and monotone.

Example. $1, 0, 1, 0, 1, 0, 1, \ldots$ is *not* monotone.

Theorem 42 (Monotone Convergence Theorem)**.** If a sequence is monotone and bounded, then it converges.

Note. There are two enemies of convergence:

1. Oscillations (killed by monotone)
2. Growth (killed by boundedness)

Proof. Let (a_n) be monotone and bounded. Let us assume that (a_n) is increasing (the case for decreasing is proved similarly). Define the set

$$S = \{a_n | n \in \mathbb{N}\} \tag{125}$$

As (a_n) is bounded, this means that the set S is bounded above. Let $x = \sup S$ Now we just need to show that $\lim a_n = x$ to prove the statement. Let $\varepsilon > 0$ be given. As x is the least upper bound, $x - \varepsilon$ is not an upper bound for S. Then there exists $n \in \mathbb{N}$ such that $x - \varepsilon < a_N$. Therefore, for all $n \geq N$ we have

$$x - \varepsilon < a_N \leq a_n \leq x \tag{126}$$
$$x - \varepsilon < a_n < x + \varepsilon \tag{127}$$
$$|a_n - x| < \varepsilon \tag{128}$$

Hence proved. □

Definition 28. Let (b_n) be a sequence. An **infinite series** is a formal expression of the form

$$\sum_{n=1}^{\infty} b_n = b_1 + b_2 + b_3 + \dots \tag{129}$$

We define the corresponding **sequence of partial sums**, (S_m) by

$$S_m = b_1 + b_2 + \dots + b_m \tag{130}$$

we say that the series $\sum_{n=1}^{\infty} b_n$ **converges to B** if the sequence (S_m) converges to B. In this case, we write $\sum_{n=1}^{\infty} = B$.

Note. When we write the first sum, we are literally just writing symbols. If we want to assign meaning to this, we need to construct a sequence of partial sums $b_1, b_1 + b_2, b_1 + b_2 + b_3, \dots$.

Example. Recall from day 1:

$$\begin{align}
b_n &= (-1)^n \tag{131}\\
S_1 &= b_1 = -1 \tag{132}\\
S_2 &= b_1 + b_2 = 0 \tag{133}\\
S_2 &= b_1 + b_2 + b_3 = -1 \tag{134}\\
&\dots \tag{135}
\end{align}$$

Then construct the sequence:

$$(S_1, S_2, S_3, \dots) = (-1, 0, -1, 0, -1, \dots) \tag{136}$$

The sequence does not converge, therefore the series doesn't converge.

Example. Consider

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{1}{1} + \frac{1}{2^2} + \frac{1}{3^2} + \dots \tag{137}$$

As all the terms in the series are positive, we observe that the sequence (S_m) is an increasing sequence. Now we will apply a trick

$$\begin{align}
S_m &= 1 + \frac{1}{2^2} + \frac{1}{3^2} + \dots + \frac{1}{m^2} \tag{138}\\
&< 1 + \frac{1}{1\cdot 2} + \frac{1}{2\cdot 3} + \frac{1}{3\cdot 4} + \dots + \frac{1}{(m-1)\,m} \tag{139}\\
&= 1 + \left(\frac{1}{1} - \frac{1}{2}\right) + \left(\frac{1}{2} - \frac{1}{3}\right) + \left(\frac{1}{3} - \frac{1}{4}\right) + \dots + \left(\frac{1}{m-1} - \frac{1}{m}\right) \tag{140}\\
&= 1 + 1 - \frac{1}{m} \tag{141}\\
&< 2 \tag{142}
\end{align}$$

Therefore $S_m < 2$ for all $M \in \mathbb{N}$. Hence the sequence (S_m) is bounded. As (S_m) is an increasing bounded sequence, by the monotone convergence theorem, it converges.

Note. The above is the Basel Problem. The value that it converges to was found by Euler in 1734 and surprisingly is $\frac{\pi^2}{6}$. This is connected to the Riemann Zeta function.

Lecture 19: Homework 5

Monday 17 February 2025

1. Let $(a_n) \to 0$. Use the Algebraic limit theorem to compute each of the following limits (assuming the functions are always defined). Justify all of your actions.

1. $\lim \left(\frac{1+2a_n}{1+3a_n-4a_n^2}\right)$

$$\begin{aligned}
&= \frac{\lim (1+2a_n)}{\lim (1+3a_n-4a_n^2)} && (143)\\
&= \frac{\lim 1 + \lim 2 \cdot \lim a_n}{\lim 1 + \lim 3 \cdot \lim a_n - \lim 4 \cdot \lim a_n \cdot \lim a_n} && (144)\\
&= 1 && (145)
\end{aligned}$$

2. $\lim \left(\frac{(a_n+2)^2-4}{a_n}\right)$

$$\begin{aligned}
&= \frac{\lim (a_n+2) \cdot \lim (a_n+2) - \lim 4}{\lim a_n} && (146)\\
&= \frac{\left(\lim a_n + \lim 2\right)\left(\lim a_n + \lim 2\right) - \lim 4}{\lim a_n} && (147)\\
&= \frac{\left(\lim a_n + 2\right)\left(\lim a_n + 2\right) - 4}{\lim a_n} && (148)\\
&= \frac{\left(\lim a_n\right)^2 + 4\lim a_n + 4 - 4}{\lim a_n} && (149)\\
&= \lim a_n + 4 = 4 && (150)
\end{aligned}$$

3. $\lim\left(\frac{\frac{2}{a_n}+3}{\frac{1}{a_n}+5}\right)$

$$= \frac{\lim\left(\frac{2}{a_n}+3\right)}{\lim\left(\frac{1}{a_n}+5\right)} \tag{151}$$

$$= \frac{\lim\frac{2}{a_n}+\lim 3}{\lim\frac{1}{a_n}+\lim 5} \tag{152}$$

$$= \frac{\frac{\lim 2}{\lim a_n}+3}{\frac{\lim 1}{\lim a_n}+5}\cdot\frac{\lim a_n}{\lim a_n} \tag{153}$$

$$= \frac{\lim 2+3\lim a_n}{\lim 1+5\lim a_n} = 2 \tag{154}$$

2. Prove that the following sequences diverge:

1. The sequence (a_n) where

$$a_n = (-1)^n n^2 + 1 \tag{155}$$

Proof. Assume for the sake of contradiction that (a_n) converges. Since (a_n) converges, it is bounded. Therefore $\exists M > 0$ such that

$$\forall n \in \mathbb{N}\left(|a_n| \leq M\right) \tag{156}$$
$$\forall n \in \mathbb{N}\left(\left|(-1)^n n^2 + 1\right| \leq M\right) \tag{157}$$

If we force n to be even, then

$$\forall n \in \mathbb{N}\left(n^2 + 1 \leq M\right) \tag{158}$$

But by the Archimedean principle, we can always pick N such that N is even and $N > \sqrt{M-1}$. Then we have

$$N > \sqrt{M-1} \Rightarrow N^2 + 1 > M \tag{159}$$

Which contradicts our assumption that (a_n) converges. Thus (a_n) must diverge.

□

2. The sequence (a_n) where

$$a_n = (-1)^n + \frac{1}{n} \tag{160}$$

Proof. Assume for the sake of contradiction that (a_n) converges. Let $a =$

$\lim a_n$. Then pick $\varepsilon < a$; and, by the definition of convergence, we have:

$$|a_n - a| \leq \varepsilon \tag{161}$$

$$\left|(-1)^n + \frac{1}{n} - a\right| \leq \varepsilon \tag{162}$$

$$-\varepsilon \leq (-1)^n + \frac{1}{n} - a \leq \varepsilon \tag{163}$$

$$a - \varepsilon \leq (-1)^n + \frac{1}{n} \leq \varepsilon + a \tag{164}$$

If we force n to be even and consider the left side of the inequality, then for all even n we have

$$a - \varepsilon \leq \frac{1}{n} \tag{165}$$

But notice that because of how we picked ε, we know that $a - \varepsilon > 0$. Then, by the Archimedean property of $\mathbb{N}$, there exists an $N \in \mathbb{N}$ such that N is even and

$$a - \varepsilon > \frac{1}{N}. \tag{166}$$

Thus, we have reached a contradiction. Therefore, the sequence must diverge. □

3. (Squeeze Theorem). Show that if $x_n \leq y_n \leq z_n$ for all $n \in \mathbb{N}$ and if $\lim x_n = \lim z_n = l$, then $\lim y_n = l$ as well.

Proof. Take the first given statement, and subtract l from everything:

$$x_n - l \leq y_n - l \leq z_n - l \tag{167}$$

Since we are given that $\lim x_n = \lim z_n = l$, we can say that for all $\varepsilon > 0$ there exists $n_1, n_2 \in \mathbb{N}$ such that, if $N_1 \geq n_1$ and $N_2 \geq n_2$

$$|x_{N_1} - l| < \varepsilon \Rightarrow -\varepsilon < x_{N_1} - l < \varepsilon \tag{168}$$

$$|z_{N_2} - l| < \varepsilon \Rightarrow -\varepsilon < z_{N_2} - l < \varepsilon \tag{169}$$

Therefore, if we let $p = \max\{n_1, n_2\}$ we can say that for all $P > p$

$$-\varepsilon < x_P - l \leq y_P - l \leq z_P - l < \varepsilon \tag{170}$$

Thus for all $\varepsilon > 0$ there exists a $P \in \mathbb{N}$ such that

$$|y_P - l| < \varepsilon \tag{171}$$

Therefore, $\lim y_n = l$

□

4. Let $x_n \geq 0$ for all $n \in \mathbb{N}$.

   1. If $(x_n) \to 0$, show that $\sqrt{x_n} \to 0$.

Proof. We know that if $\lim x_n = 0$ that for all $\varepsilon > 0$ there exists an $N \in \mathbb{N}$ such that if $n > N$ then $|x_n - 0| < \varepsilon$. Therefore $x_n < \varepsilon^2 \Rightarrow \left|\sqrt{x_n} - 0\right| < \varepsilon$. $\square$

2. If $(x_n) \to x$, show that $\left(\sqrt{x_n}\right) \to \sqrt{x}$.

Proof. Consider the following equation and apply the fact that $x_n \geq 0$ and $\sqrt{x_n} + \sqrt{x} > \sqrt{x}$, and then the definition of convergence to show the identity:

$$\left|\sqrt{x_n} - \sqrt{x}\right| \tag{172}$$

$$= \left|\sqrt{x_n} - \sqrt{x}\right| \cdot \frac{\sqrt{x_n} + \sqrt{x}}{\sqrt{x_n} + \sqrt{x}} \tag{173}$$

$$= \frac{|x_n - x|}{\sqrt{x_n} + \sqrt{x}} < \frac{|x_n - x|}{\sqrt{x}} < \frac{\varepsilon}{\sqrt{x}} \tag{174}$$

Therefore, $|x_n - x| < \varepsilon$, hence proved. $\square$

5. Consider the sequence (b_n) where $b_n = \sqrt{n^2 + 2n} - n$. Prove that (b_n) is convergent and find its limit.

6. Give an example of each of the following:

1. Sequences (a_n) and (b_n), which both diverge, but whose sum $(a_n + b_n)$ converges.

   Consider $(a_n) = n$ and $(b_n) = -n$

2. Sequences (a_n) and (b_n), which both diverge, but whose product $(a_n b_n)$ converges.

   Consider $(a_n) = (-1)^n$ and $(b_n) = (-1)^{n+2}$

3. Convergent sequences (a_n) and (b_n) with $a_n < b_n$ for all $n \in \mathbb{N}$ such that $\lim (a_n) = \lim (b_n)$.

   Consider $(a_n) = \left(\frac{1}{4}\right)^n$ and $(b_n) = \left(\frac{1}{2}\right)^n$

4. A convergent sequence (b_n) with $b_n \neq 0$ for all $n \in \mathbb{N}$, such that $(1/b_n)$ diverges.

   Consider $(b_n) = \frac{1}{n}$

5. Two sequence (a_n) and (b_n) so that (a_n) is unbounded, (b_n) is bounded, and $(a_n b_n)$ converges.

   Consider $(a_n) = n$ and $(b_n) = \frac{1}{n}$

6. Two sequences (a_n) and (b_n), where $(a_n b_n)$ and (a_n) converge but (b_n) does not.

   Consider $(a_n) = \frac{1}{n}$ and $(b_n) = n$

7. Let (a_n) be a bounded (not necessarily convergent) sequence, and assume that $\lim b_n = 0$. Show that $\lim a_n b_n = 0$. Why are we not allowed to use the Algebraic limit theorem to prove this?

Proof. From the triangle inequality, we have

$$|a_n b_n - 0| = |a_n|\,|b_n| = |a_n|\,|b_n - 0| \tag{175}$$

Since a_n is bounded, we know that there exists an M such that $a_n \leq M$ for all $n \in \mathbb{N}$. Therefore

$$|a_n b_n - 0| = |a_n|\,|b_n - 0| < M\,|b_n - 0| \tag{176}$$

Finally, we know that for all $\varepsilon > 0$, $|b_n - 0| < \varepsilon$, so, from the definition of convergence, $|b_n - 0| < \frac{\varepsilon}{M}$ and

$$|a_n b_n - 0| = |a_n|\,|b_n - 0| < M\,|b_n - 0| < M\frac{\varepsilon}{M} = \varepsilon \tag{177}$$

Therefore, $\lim a_n b_n = 0$. Notice that we could not use the Algebraic limit theorem because that theorem requires both a_n and b_n to converge. We know that b_n converges, but we are only given that a_n is bounded, so it is not necessarily convergent. □

Lecture 20: 02-19-25 Lecture

Tuesday 19 February 2025

Last time we showed that

$$\sum_{n=1}^{\infty} \frac{1}{n^2} \tag{178}$$

converges. Now we will do a slightly different problem.

Example. $\sum_{n=1}^{\infty} \frac{1}{n}$

The partial sums are

$$S_m = 1 + \frac{1}{2} + \frac{1}{3} + \ldots + \frac{1}{m} \tag{179}$$

Observe that (S_m) is an increasing sequence. To prove the statement, we will show that (S_m) is *not* bounded.

$$S_4 = 1 + \frac{1}{2} + \left(\frac{1}{3} + \frac{1}{4}\right) > 1 + \frac{1}{2} + \left(\frac{1}{4} + \frac{1}{4}\right) \tag{180}$$

$$S_8 \tag{181}$$

$$S_{16} \tag{182}$$

$$S_{32} \tag{183}$$

$$S_{2^k} \tag{184}$$

for $k \in \mathbb{N}$ we have

$$S_{2^k} = 1 + \frac{1}{2} + \left(\frac{1}{3} + \frac{1}{4}\right) + \left(\frac{1}{5} + \ldots + \frac{1}{8}\right) + \ldots + \left(\frac{1}{2^{k-1}+1} + \ldots + \frac{1}{2^k}\right) \tag{185}$$

$$S_{2^k} > 1 + \frac{1}{2} + \left(\frac{1}{4} + \frac{1}{4}\right) + \left(\frac{1}{8} + \ldots + \frac{1}{8}\right) + \ldots + \left(\frac{1}{2^k} + \ldots + \frac{1}{2^k}\right) \tag{186}$$

$$= 1 + \frac{1}{2} + 2\left(\frac{1}{4}\right) + 4\left(\frac{1}{8}\right) + \ldots + 2^{k-1}\frac{1}{2^k} \tag{187}$$

$$= 1 + \frac{1}{2} + \frac{1}{2} + \frac{1}{2} + \ldots + \frac{1}{2} \tag{188}$$

$$= 1 + k\left(\frac{1}{2}\right) \tag{189}$$

$$\Rightarrow S_{2^k} > 1 + \frac{k}{2} \tag{190}$$

As the sequence $\left(1 + \frac{k}{2}\right)_{k=1}^{\infty}$ is not bounded. Therefore $(S_m)_{m=1}^{\infty}$ is not bounded. Therefore $(S_m)_{m=1}^{\infty}$ is not convergent. Therefore $\sum_{n=1}^{\infty} \frac{1}{n}$ diverges.

Theorem 43. The series

$$\sum_{n=1}^{\infty} \frac{1}{n^2} \tag{191}$$

converges for $p > 1$ and diverges for $p \leq 1$

Proof. See textbook. □

Bolzano was a priest who first came up with the definition of the limit that we have been using. We will see some theorems named after him in this section.

Definition 29. Let (a_n) j be a sequence of real numbers and let $n_1 < n_2 < n_3 < \ldots$ be an increasing sequence of natural numbers, then the sequence

$$(a_{n_1}, a_{n_2}, a_{n_3}, \ldots) \tag{192}$$

is called a **subsequence** of (a_n) and is denoted by (a_{n_k}) where $k \in \mathbb{N}$ indexes the subsequence.

Example. Let $a_n = n^2$ i.e.

$$(a_n) = (1, 4, 9, 16, 25, \ldots) \tag{193}$$

Let $a_{n_k} = (2k)^2$

$$(a_{n_k}) = (4, 16, 36, \ldots) \tag{194}$$

(a_{n_k}) is a subsequence of (a_n). Here $n_k = 2k$

$$\left(6^2, 11^2, 16^2, 21^2, \ldots\right) \text{ is also a subsequence} \tag{195}$$

$$\left(2^2, 2^2, 2^2, 3^2, 4^2, 5^2, \ldots\right) \text{ is } \textit{not} \text{ a subsequence.} \tag{196}$$

The original sequence is

$$(1, 2, 2, 2, 3, 4, 5, 6, \ldots) \tag{197}$$

then

$$(2, 2, 2, 3, 4, 5, 6, \ldots) \tag{198}$$

is a subsequence.

Theorem 44. All sub sequences of a convergent sequence converge to the same limit as the original sequence.

Proof. Assume that $\lim a_n = a$ and let (a_{n_k}) be a subsequence. Let $\varepsilon > 0$ be given, then $\exists N \in \mathbb{N}$ such that $\forall n \geq N$ we have

$$|a_n - a| < \varepsilon \tag{199}$$

For $k \geq N$ we observe that $n_k \geq k \geq N$. Therefore

$$|a_{n_k} - a| < \varepsilon \tag{200}$$

□

Note. The crucial thing to realize in the above is that a_{n_k} is indexed by k the n_k is just there for emphasis.

Example. Let $0 < b < 1$, then $\lim b^n = 0$

Proof. Observe that

$$b > b^2 > b^3 > \ldots > 0 \tag{201}$$

Therefore, (b^n) is a decreasing sequence which is bounded. Then, by MCT, this sequence converges. Let $L \in \mathbb{R}$ such that $\lim_{n\to\infty} b_n = L$ Observe that for all $n \in \mathbb{N}\, (b \geq b^n)$. Therefore, by order limit theorem

$$1 > b \geq L \tag{202}$$

Similarly, $b^n \geq 0\ \forall n \in \mathbb{N}$. Therefore $L \geq 0$. Therefore $0 \leq L \leq 1$ Look at the subsequence $\left(b^{2n}\right) = \left(b^2, b^4, b^6, \ldots\right)$. Therefore, $\lim_{n\to\infty} b^{2n} = L$. Notice

$$b^n b^n = b^{2n} \tag{203}$$

$$a_n \cdot b_n \tag{204}$$

Therefore, by the ALT we have

$$L \cdot L = L \tag{205}$$
$$L^2 = L \tag{206}$$
$$L = 0 \text{ or } L = 1 \tag{207}$$

But as $0 \leq L < 1$. Therefore, $L = 0$ and $\lim_{n\to\infty} b^n = 0$ ☐

Friday 21 February 2025

Lecture 21: 02-21-25 Lecture

Example. Let $a_n = (-1)^n$. Prove that (a_n) diverges.

Proof. Already done once in class. Now we present a second proof.

$$(a_n) = (-1, 1, -1, 1, -1, 1, \ldots). \tag{208}$$

Observe that $(1, -1, 1, -1, 1, -1, \ldots)$ is a subsequence of (a_n) and this subsequence has a limit of 1. We also observe that $(-1, 1, -1, 1, -1, \ldots)$ is a subsequence of (a_n) and this subsequence has limit -1. We have found that the sequence has subsequences which converge to different limits, therefore (a_n) diverges. ☐

Very fundamental theorem:

Theorem 45 (Bolzano-Weirstrass Theorem)**.** Every bounded sequence contains a convergent subsequence.

Proof. Let (a_n) be a bounded sequence. Hence there exists $M > 0$ such that $|a_n| \leq M \ \forall n \in \mathbb{N}$. Let $a_{n_1} = a_1$ and let $I_1 = [-M, M]$. Now, we sketch the plan for the rest of the proof:

1. We divinde I_1 into two intervals $[-M, 0]$ and $[0, M]$
2. At least one of these closed intervals must contain an infinite number of terms in the sequence (a_n). Call this interval I_2.
3. Let a_{n_2} be such that $a_{n_2} \in I_2$ and $n_2 > n_1 = 1$

We repeat this procedure inductively, so if $a_{n_k} \in I_k$, then

1. Divide the interval I_k into two equal closed intervals.
2. Let I_{k+1} be a closed interval such that it contains infinite number of terms of the sequence (a_n).
3. Let $a_{n_{k+1}}$ be such that $a_{n_{k+1}} \in I_{k+1}$ and $n_{k+1} > n_k$

This gives us a subsequence a_{n_k} with $a_{n_k} \in I_k$ and

$$I_1 \subset I_2 \subset I_3 \subset \ldots \text{(FIX DIRECTION OF SUBSET)} \tag{209}$$

By the nester interval property, $\exists x \in \cap_{k=1}^{\infty} I_k$

Claim: $\lim_{k\to\infty} a_{n_k} = x$

Proof. Let $\varepsilon > 0$ be given. Observe from construction the length of I_k is $(2M) \cdot 2^{-(k-1)}$. We know that $\lim_{k\to\infty} (2M)\, 2^{-(k+1)} = 0$ by the ALT since

$$\lim_{k\to\infty} \left(\frac{2M}{2^k \cdot 2^{-1}} \right) \tag{210}$$

$$\frac{1}{2^n} \to 0 \tag{211}$$

□

So choose $N \in \mathbb{N}$ such that the lenth of I_N is less than ε. Therefore, for all $k \geq N$ we observe that $a_{n_k} \in I_N$ and hence $x \in I_N$. Therefore for all $k \geq N$

$$|a_{n_k} - x| < \varepsilon \tag{212}$$

Hence proved. □