

MAT 2125 Lecture Notes

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Lecture 1

The Real Numbers \mathbb{R}

TBC.

Lecture 2

Completeness of \mathbb{R} , Absolute Value, Sequences

TBC.

Lecture 3

Convergence of Sequences

TBC.

Lecture 4

Properties of Convergence, Squeeze Theorem, Monotone Sequences

TBC.

Lecture 5

Subsequences, Cauchy Sequences

TBC.

Lecture 6

Limsup and Liminf

TBC.

Lecture 7

Series

Recall:

$$\sum_{n=1}^{\infty} a_n = \lim_{N \rightarrow \infty} \sum_{n=1}^N a_n$$

$\sum_{n=1}^{\infty} a_n$ "diverges" if above limit does not exist.

Proposition 7.0.1. Suppose $(a_n)_{n=1}^{\infty}, (b_n)_{n=1}^{\infty}$ converges. Then

(i)

$$\sum_{n=1}^{\infty} a_n + b_n = \sum_{n=1}^{\infty} a_n + \sum_{n=1}^{\infty} b_n$$

(ii)

$$\sum_{n=1}^{\infty} cb_n = c \sum_{n=1}^{\infty} b_n \quad \forall c \in \mathbb{R}$$

This says

$$V := \{(a_n)_{n=1}^{\infty} : \sum_{n=1}^{\infty} a_n \text{ converges}\}$$

is a vector space over \mathbb{R} .

Note:

$$\left(\sum_{n=1}^N a_n \right) \left(\sum_{n=1}^N b_n \right) \neq \sum_{n=1}^{\infty} a_n b_n$$

Proof. **Exercise.**

□

Proposition 7.0.2. $\sum_{n=1}^{\infty} a_n$ converges iff $\sum_{n=k}^{\infty} a_k$ converges.

Proof. **Exercise.**

□

Example: TBC.

Proposition 7.0.3. If $\sum_{n=1}^{\infty} a_n$ converges, then $a_n \rightarrow 0$.

7.1 Divergence Test

Proposition 7.1.1 (Divergence Test). *If $a_n \not\rightarrow 0$, then $\sum_{n=1}^{\infty} a_n$ diverges.*

Proof. $\sum_{n=1}^{\infty} a_n$ converges $\implies S_n \rightarrow L$ for some L , where

$$S_n := \sum_{n=1}^N a_n$$

So,

$$a_n = S_n - S_{n-1}$$

By the Algebra of Limits,

$$\begin{aligned} \lim_{n \rightarrow \infty} a_n &= \lim_{n \rightarrow \infty} S_n - \lim_{n \rightarrow \infty} S_{n-1} \\ &= L - L = 0 \end{aligned}$$

□

Example: TBC.

7.2 Convergence Tests

Proposition 7.2.1 (Boundedness Test). *Let $(a_n)_{n=1}^{\infty}$ be a sequence, if*

(i) $a_n \geq 0$

(ii) There is an upper bound on the partial sums

$$\exists M > 0 \text{ s.t. } \sum_{n=1}^N a_n \leq M$$

Then $\sum_{n=1}^{\infty} a_n$ converges.

Proof. Let

$$S_N := \sum_{n=1}^N a_n$$

Then

$$\begin{aligned} S_{N+1} &= S_N + a_{N+1} \\ &\geq S_N \end{aligned}$$

So by the Monotone Convergence Criterion, $(S_N)_{N=1}^{\infty}$ converges \iff it is bounded above. By (ii), it is bounded. □

Proposition 7.2.2 (Comparison Test).

Lecture 8

Ratio, Root, Alternating Series, and Integral Test, Cauchy Convergence, Topology of \mathbb{R}^d

8.1 Ratio Test

Proposition 8.1.1 (Ratio Test). *Let $(a_n)_{n=1}^{\infty}$ be a sequence of nonzero elements.*

(i) *If*

$$\limsup_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| < 1$$

then $\sum_{n=1}^{\infty} a_n$ converges absolutely.

(ii) *If*

$$\liminf_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| > 1$$

then $\sum_{n=1}^{\infty} a_n$ diverges.

Proof.

(i) Let

$$q = \limsup_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right|$$

where $q < 1$, $\exists r \in (q, 1)$. By the definition of \limsup ,

$$\left| \frac{a_{n+1}}{a_n} \right| \leq r \quad \forall n \geq n_0$$

for some $n_0 \in \mathbb{N}$.

$$\begin{aligned} \left| \frac{a_{n_0+1}}{a_{n_0}} \right| &\leq r \\ |a_{n_0+1}| &\leq r|a_{n_0}| \\ |a_{n_0+2}| &\leq r|a_{n_0+1}| \leq r^2|a_{n_0}| \end{aligned}$$

By induction, we have

$$0 \leq |a_{n_0+k}| \leq r^k |a_{n_0}|$$

By the comparison test,

$$\sum_{k=1}^{\infty} |a_{n_0+k}|$$

converges since

$$\sum_{k=1}^{\infty} r^k |a_{n_0}|$$

is a geometric sequence and $0 \leq r < 1$.

$$\sum_{n=1}^{\infty} |a_n|$$

Converges, thus $\sum_{n=1}^{\infty} a_n$ converges absolutely.

(ii) Let

$$q = \liminf_{n \rightarrow \infty} \left| \frac{a_{n+1}}{a_n} \right| > 1$$

so $\exists n_0$ such that

$$\left| \frac{a_{n+1}}{a_n} \right| > 1$$

for all $n \geq n_0$. Then

$$|a_{n_0+k}| \geq |a_{n_0}| \quad \forall k \geq 0$$

So $a_n \not\rightarrow 0$ as $n \rightarrow \infty$, thus by the divergence test. $\sum_{n=1}^{\infty} a_n$ diverges.

□

Note: The ratio test does not tell us anything when the limit is 1.

For example:

$$\sum_{n \geq 1} \frac{1}{n}$$

diverges, but

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

But on the other hand,

$$\sum_{n \geq 1} \frac{1}{n+1}$$

converges, and

$$\frac{\frac{1}{n+1(n+2)}}{\frac{1}{n(n+1)}} = \frac{n+1}{n+2} \rightarrow 1$$

8.2 Root Test

Proposition 8.2.1 (Root Test). *Let $(a_n)_{n=1}^{\infty}$ be a sequence of real numbers.*

(i) *If*

$$\limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|} < 1$$

then $\sum_{n=1}^{\infty} a_n$ converges absolutely.

(ii) *If*

$$\limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|} > 1$$

then $\sum_{n=1}^{\infty} a_n$ diverges.

Proof.

(i) Let

$$q = \limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|} < 1$$

Then there exists $r \in (q, 1)$ such that $\exists n_0$

$$\sqrt[n]{|a_n|} \leq r$$

for all $n \geq n_0$. Then,

$$0 \leq |a_n| \leq r^n$$

Therefore $\sum_{n=n_0}^{\infty} r^n$ converges since $0 < r < 1$. Then by the comparison test, $\sum_{n=n_0}^{\infty} |a_n|$ converges.

(ii) Let

$$q = \limsup_{n \rightarrow \infty} \sqrt[n]{|a_n|} > 1$$

From exercise 2.7.3, there are infinitely many

$$\sqrt[n]{|a_n|} \geq 1 \implies |a_n| \geq 1$$

Thus $a_n \not\rightarrow 0$ as $n \rightarrow \infty$, thus by the divergence test, $\sum_{n=1}^{\infty} a_n$ diverges.

□

Examples:

•

$$\sum_{n=1}^{\infty} \left(\frac{1}{2}\right)^n$$

$$\sqrt[n]{\left(\frac{1}{2}\right)^2} = \frac{1}{2}$$

•

$$\sum_{n=1}^{\infty} \left(\frac{n}{2n+1}\right)_n$$

$$\sqrt[n]{\left(\frac{n}{2n+1}\right)^n} = \frac{1}{2^{n+1}} \rightarrow \frac{1}{2}$$

•

$$\sum_{n=1}^{\infty} \frac{1}{n_n}$$

$$\sqrt[n]{\frac{1}{n}} = \frac{1}{n^{\frac{1}{n}}} = \frac{1}{e^{\frac{\ln n}{n}}} \rightarrow 0$$

8.3 Alternating Series Test

Proposition 8.3.1 (Alternating Series Test). *Let $(a_n)_{n=1}^{\infty}$ be a sequence of real numbers. Suppose*

(i) $(a_n)_{n=1}^{\infty}$ *is decreasing*

(ii) $\lim_{n \rightarrow \infty} a_n = 0$

Then

$$\sum_{n=1}^{\infty} (-1)^{n+1} a_n$$

converges. Moreover, for any N ,

$$\sum_{n=1}^{2N} (-1)^{n+1} a_n \leq \sum_{n=1}^{\infty} (-1)^{n+1} a_n \leq \sum_{n=1}^{2N-1} (-1)^{n+1} a_n$$

Proof. $a_n \geq 0 \forall n$, since $a_n \rightarrow 0$ as $n \rightarrow \infty$, and $(a_n)_{n=1}^{\infty}$ is decreasing. Let

$$S_N := \sum_{n=1}^N (-1)^{n+1} a_n$$

If N is even,

$$S_{N+2} = S_N + a_{N+1} - a_{N+2} \geq S_N$$

Since

$$a_{N+2} \leq a_{N+1}$$

So $(S_{2N})_{N=1}^{\infty}$ is an increasing sequence and $(S_{2N-1})_{N=1}^{\infty}$ is a decreasing sequence. So by the monotone convergence criterion, both sequence converge.

$$S_{2N-1} + a_{2N} = S_{2N}$$

$$a_{2N} \xrightarrow{N \rightarrow \infty} 0$$

So,

$$\lim_{n \rightarrow \infty} S_{2N-1} = \lim_{N \rightarrow \infty} S_{2N} = L \implies \lim_{N \rightarrow \infty} S_N = L$$

$(S_{2N})_{N=1}^{\infty}$ is increasing, so

$$L = \sup\{(S_{2N})_{N=1}^{\infty}\} \implies S_{2N} \leq L$$

Similarly, $(S_{2N-1})_{N=1}^{\infty}$ is decreasing, so

$$L = \inf\{(S_{2N-1})_{N=1}^{\infty}\} \implies S_{2N-1} \geq L$$

□

8.4 Integral Test

Proposition 8.4.1. Let $f : [1, \infty) \rightarrow \mathbb{R}$. Suppose that

(i) $f(x) \geq 0 \forall x \in [1, \infty)$

(ii) f is decreasing

Then

$\sum_{n=1}^{\infty} f(n)$ converges \iff the improper integral $\int_1^{\infty} f(x) dx$ converges.

8.5 Cauchy Convergence Criterion for Series

Proposition 8.5.1. Let $(a_n)_{n=1}^{\infty}$ be a sequence of real numbers. Then

$\sum_{n=1}^{\infty} a_n$ converges $\iff \forall \epsilon > 0 \exists N_0$ such that $N \leq M \leq N_0, |\sum_{n=M}^N a_n| < \epsilon$.

Proof. Let

$$S_N := \sum_{n=1}^N a_n$$

Then $\sum_{n=1}^{\infty} a_n$ converges $\iff (S_N)_{N=1}^{\infty}$ converges. Cauchy convergence criterion for sequences says that

$(S_N)_{n=1}^{\infty}$ converges \iff it is Cauchy.

$\iff \forall \epsilon > 0 \exists N_0$ s, t $|S_N - S_M| < \epsilon \forall N, M \geq N_0$

□

8.6 Topology of \mathbb{R}^d

8.6.1 Norms

Definition 8.6.1. A norm on \mathbb{R}^d is a function $\|\cdot\| : \mathbb{R}^d \rightarrow [0, \infty)$ satisfying the following properties:

- (i) $\|a\| = 0 \iff a = (0, \dots, 0)$
- (ii) $\|ca\| = |c| \cdot \|a\| \quad \forall c \in \mathbb{R}, a \in \mathbb{R}^d$
- (iii) $\|a + b\| \leq \|a\| + \|b\| \quad \forall a, b \in \mathbb{R}^d$

The euclidean norm of \mathbb{R}^d is given by

$$\|a, \dots, a_d\|_2 = \sqrt{\sum_{i=1}^d a_i^2}$$

The dot product on \mathbb{R}^d is given by

$$(a_1, \dots, a_n) \cdot (b_1, \dots, b_n) = \sum_{i=1}^d a_i b_i$$

We also have the l_1 -norm

$$\|(a_1, \dots, a_n)\|_1 = \sum_{i=1}^d |a_i|$$

And the l_∞ -norm

$$\|(a_1, \dots, a_d)\|_\infty = \max\{|a_1|, \dots, |a_d|\}$$

Proposition 8.6.1. Let $a, b \in \mathbb{R}^d$, write $\|\cdot\|$ for the euclidean norm on \mathbb{R}^d . Then

(i) **Cauchy Schwarz Inequality:**

$$|a \cdot b| \leq \|a\| \cdot \|b\|$$

(ii) **Triangle Inequality:**

$$\|a + b\| \leq \|a\| + \|b\|$$

(iii) $\|\cdot\|$ is a norm on \mathbb{R}^d

Proof.

(i) Consider the quadratic function

$$\begin{aligned}P(t) &= \|a + tb\|^2 \\&= (a + tb) \cdot (a + tb) \\&= a \cdot a + 2a \cdot tb + tb \cdot tb \\&= \|a\|^2 + 2t(a \cdot b) + t^2\|b\|^2\end{aligned}$$

The discriminant of $P(t)$ is less than or equal to 0,

$$\begin{aligned}(2a \cdot b)^2 - 4\|a\|^2\|b\|^2 &\leq 0 \\(a \cdot b)^2 &\leq \|a\|^2\|b\|^2 \\|a \cdot b| &\leq \|a\| \cdot \|b\|\end{aligned}$$

(ii)

$$\begin{aligned}\|a + b\|^2 &= \|a\|^2 + 2a \cdot b + \|b\|^2 \\&\leq \|a\|^2 + 2|a \cdot b| + \|b\|^2 \\&\leq \|a\|^2 + 2\|a\| \cdot \|b\| + \|b\|^2 \\&= (\|a\| + \|b\|)^2\end{aligned}$$

$$\|a + b\|^2 \leq (\|a\| + \|b\|)^2 \implies \|a + b\| \leq \|a\| + \|b\|$$

(iii) **Exercise.** We want to prove $\|a\| = 0 \iff a = 0$ and $\|ca\| = |c| \cdot \|a\|$.

□

Lecture 9

\mathbb{R}^d

Recall: $\|(x_1, \dots, x_d)\| := \sqrt{x_1^2 + \dots + x_d^2}$. This is a norm. i.e.

$$\|a + b\| \leq \|a\|_2 + \|b\|_2 \quad \forall a, b \in \mathbb{R}^d$$

$$\|ca\| = |c| \cdot \|a\|_2, \quad c \in \mathbb{R}, \quad a \in \mathbb{R}^d$$

$$\|a\|_2 > 0, \quad \forall a \in \mathbb{R}^d \setminus \{(0, \dots, 0)\}$$

$$\|(0, \dots, 0)\|_2 = 0$$

Other examples of norms:

- $\|(x_1, \dots, x_d)\|_1 := |x_1| + \dots + |x_d|$
- $\|(x_1, \dots, x_d)\|_\infty := \max\{|x_1|, \dots, |x_d|\}$

Exercise: For $a \in \mathbb{R}^d$,

$$\|a\|_\infty \leq \|a\|_2 \leq \|a\|_1 \leq d\|a\|_\infty (\leq d\|a\|_2)$$

Interesting Fact: There are other norms. but they are all equivalent in the sense that if $\|\cdot\|, \|\cdot\|'$ are norms on \mathbb{R}^d , then $\exists v, R > 0$ such that

$$r\|a\| \leq \|a\|' \leq R\|a\|$$

9.1 Convergence

Definition 9.1.1. Let $(a_n)_{n=1}^\infty$ be a sequence in \mathbb{R}^d and let $L \in \mathbb{R}^d$, we say $(a_n)_{n=1}^\infty$ **converges** to L , and write $\lim_{n \rightarrow \infty} a_n = L$ or $a_n \rightarrow \infty$, if

$$\lim_{n \rightarrow \infty} \|a_n - L\|_2 = 0$$

Note: We could define convergence instead using some other norm, say $\|\cdot\|_1$.

If $\|a_n - L\|_2 \rightarrow 0$, then $\|a_n - L\|_1 \leq d\|a_n - L\|_2 \rightarrow 0$. If $\|a_n - L\|_1 \rightarrow 0$, then $\|a_n - L\|_2 \leq d\|a_n - L\|_1 \rightarrow 0$.

in general, if $\|\cdot\|$ is any norm, then since $\|\cdot\|$ and $\|\cdot\|_2$ are equivalent.

$$\|a_n - L\|_2 \rightarrow 0 \iff \|a_n - L\| \rightarrow 0$$

Example: Say $a_n = (\frac{1}{n}, \frac{1}{n}, \dots, \frac{1}{n})$, then

$$\|a_n - L\|_2 = \sqrt{1/n^2 + \dots + 1/n^2} = \sqrt{\frac{d}{n^2}} = \frac{\sqrt{d}}{n} \rightarrow 0$$

$$\therefore a_n \rightarrow L$$

Given a sequence $(a_n)_{n=1}^\infty$ in \mathbb{R}^d , we write $a_1 = (a_1^{(1)}, a_1^{(2)}, \dots, a_1^{(d)})$ where $a_1^{(1)}, a_1^{(2)}, \dots, a_1^{(d)} \in \mathbb{R}$. Similarly,

$$a_1 = (a_1^{(1)}, a_1^{(2)}, \dots, a_1^{(d)})$$

$$a_2 = (a_2^{(1)}, a_2^{(2)}, \dots, a_2^{(d)})$$

$$a_3 = (a_3^{(1)}, a_3^{(2)}, \dots, a_3^{(d)})$$

$$\vdots$$

$$L = (L^{(1)}, L^{(2)}, \dots, L^{(d)}) \in \mathbb{R}^d$$

We get d sequences in \mathbb{R} , and d possible limit points $L^{(1)}, \dots, L^{(d)} \in \mathbb{R}$

Proposition 9.1.1. *Given $(a_n)_{n=1}^\infty$ and L as above, $a_n \rightarrow L$ as $n \rightarrow \infty \iff a_n^{(i)} \rightarrow L^{(i)}$ in \mathbb{R} as $n \rightarrow \infty$, for $i = 1, \dots, d$.*

Proof. \implies : Suppose $a_n \rightarrow L$, i.e.

$$\|a_n - L\|_2 \rightarrow 0$$

For $x = (x_1, \dots, x_d) \in \mathbb{R}^d$

$$\|x\|_2^2 = x_1^2 + \dots + x_d^2 \geq x_i^2 = |x_i|^2 \therefore |x_i| \leq \|x\|_2$$

Applying this to (*), we get

$$0 \leq |a_n^{(i)} - L^{(i)}| \leq \|a_n - L\|_2 \rightarrow 0$$

So by the squeeze theorem,

$$|a_n^{(i)} - L^{(i)}| \rightarrow 0$$

\implies : Suppose $a_n^{(i)} \rightarrow L^{(i)}$ for $i = 1, \dots, d$.

$$\|a_n - L\|_2^2 = (a_n^{(1)} - L^{(1)})^2 + \dots + (a_n^{(d)} - L^{(d)})^2 \rightarrow 0$$

By algebra of limits,

$$\therefore \|a_n - L\|_2 \rightarrow 0$$

□

Example: $a^n = ((-1)^n, \frac{1}{n}) \in \mathbb{R}^2$. Does (a_n) converge? No, since $(-1)^n$ does not converge.

Definition 9.1.2. A sequence $(a_n)_{n=1}^\infty$ in \mathbb{R}^d is **Cauchy** if $\forall \epsilon > 0, \exists n_0 \in \mathbb{N}_{\geq 1}$ such that

$$\|a_n - a_m\|_2 < \epsilon \quad \forall m, n \geq n_0$$

Theorem 9.1.1 (Cauchy Convergence Criterion for \mathbb{R}^d). Let $(a_n)_{n=1}^\infty$ be a sequence in \mathbb{R}^d . It converges \iff it is Cauchy.

Proof. \implies : Suppose $a_n \rightarrow L \in \mathbb{R}^d$. To show it is Cauchy, let $\epsilon > 0$. $\|a_n - L\|_2 \rightarrow 0$, so $\exists n_0 \in \mathbb{N}_{\geq 1}$ such that

$$\|a_n - L\|_2 < \frac{\epsilon}{2} \quad \forall n \geq n_0$$

Then if $m, n \geq n_0$,

$$\begin{aligned} \|a_m - a_n\|_2 &= \|a_m - L + L - a_n\|_2 \\ &\leq \|a_m - L\|_2 + \|L - a_n\|_2 \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon \end{aligned}$$

$\therefore (a_n)_{n=1}^\infty$ is Cauchy. \implies : Suppose $(a_n)_{n=1}^\infty$ is Cauchy, write

$$a_n = (a_n^{(1)}, \dots, a_n^{(d)})$$

For any $m, n \in \mathbb{N}_{\geq 1}$,

$$|a_n^{(i)} - a_m^{(i)}| \leq \|a_n - a_m\|_2$$

$\therefore (a_n^{(i)})_{n=1}^\infty$ is Cauchy in \mathbb{R} . So by the Cauchy Convergence Criterion, $\exists L^{(i)} \in \mathbb{R}$, such that $a_n^{(i)} \rightarrow L^{(i)}$. By the previous proposition,

$$a_n \rightarrow (L^{(1)}, \dots, L^{(d)})$$

□

Definition 9.1.3. $S \subseteq \mathbb{R}^d$ is **bounded** if $\exists M > 0$ such that

$$\|x\| \leq M \quad \forall x \in S$$

A sequence $(a_n)_{n=1}^\infty$ in \mathbb{R}^d is bound if $\{a_n : n \in \mathbb{N}_{\geq 1}\}$ is a bounded set.

Theorem 9.1.2 (Bolzano-Weierstrass for \mathbb{R}^d). *If $(a_n)_{n=1}^\infty$ is a bounded sequence in \mathbb{R}^d , then it has a subsequence $(a_{n_k})_{n=1}^\infty$ that converges.*

Proof. Write $a_n = (a_n^{(1)}, \dots, a_n^{(d)})$.

We will prove it by induction on d . For $d = 1$, this is the Bolzano-Weierstrass theorem for \mathbb{R} . For $d > 1$ write

$$b_n := (a_n^{(1)}, \dots, a_n^{(d-1)}) \in \mathbb{R}^{d-1}$$

By the induction hypothesis, b_n has a subsequence $(b_{n_k})_{k=1}^\infty$ that converges. Let $L \in \mathbb{R}^{d-1}$ be the limit of this subsequence. Then $L \in \mathbb{R}^{d-1}$ is the limit of b_n . $(a_{n_k}^{(d)})_{k=1}^\infty$ is a bounded sequence in \mathbb{R} , so it has a subsequence $(a_{n_{k_j}}^{(d)})_{j=1}^\infty$ that converges. Let $L^{(d)} \in \mathbb{R}$ be the limit of this subsequence. Then $L = (L^{(1)}, \dots, L^{(d-1)}, L^{(d)})$ is the limit of a_n . \square

Lecture 10

Open and Closed Sets in \mathbb{R}^d

Roughly, an open set is one that we draw with dotted lines. The line represents a "boundary" that is not in the set. This is not a rigorous definition.

Definition 10.0.1 (Open Ball). *Let $a \in \mathbb{R}^d$, $r > 0$. The **open ball** of radius r centered at a is*

$$B(a; r) := \{x \in \mathbb{R}^d : \|x - a\|_2 < r\}$$

Relation to Convergence: If $a_n \rightarrow L$, then this means that $\|a_n - L\|_2 < \epsilon$ for all n large. So, $a_n \in B(L; \epsilon)$

Definition 10.0.2 (Open Sets). *A set $U \subseteq \mathbb{R}^d$ is **open** if $\forall a \in U, \exists r > 0$, such that $B(a; r) \subseteq U$*

Idea: If $a \in U$, then a is not on the boundary but it is truly "inside" the set, so we can fit a ball containing a in the set.

Definition 10.0.3 (Closed Sets). *A set $k \in \mathbb{R}^d$ is **closed** if its complement $\mathbb{R}^d \setminus k$ is open.*

Example: $U \subseteq (0, 1)$. Is this open? Yes.

Proof. Let $a \in U$. We let $r := \min\{|a - 0|, |a - 1|\}$ (We do this so that r is at most the distance to the closest bound, i.e. if a is closer to 0, then the radius r cannot be $|a - 1|$) then

$$B(a; r) = (a - r, a + r) \subseteq (0, 1) = U$$

□

Example: $U := [0, 1]$. Is this open? No.

Proof. Let $a := 0 \in U$. The for any $r > 0$, $\exists z \in B(a; r) = (-r, r)$ s.t $z < 0$, so $z \notin U$. Therefore $B(a; r) \not\subseteq U$ □

Is U closed? This is the same as asking if $\mathbb{R} \setminus U = (-\infty, 0) \cup (1, \infty)$ is open. This is open.

Proof. Let $a \in (-\infty, 0) \cup (1, \infty)$.

- **Case 1:** $a \in (-\infty, 0)$. Set $r := |a|$, so

$$B(a; r) = (a - r, a + r) = (2a, 0) \subseteq U$$

- **Case 2:** $a \in (1, \infty)$ similar.

□

Therefore $U = [0, 1]$ is closed.

Example: Is $U := (0, 1]$ open? No, for any $r > 0$

$$B(1; r) \not\subseteq U$$

Therefore, it is not open.

Note: Sets are not always open or closed. Most sets are neither open nor closed.

This set U is one such example U is not closed since $\mathbb{R} \setminus U = (-\infty, 0] \cup (1, \infty)$
 $0 \in \mathbb{R} \setminus U$ but $\forall r > 0, B(0; r) \not\subseteq \mathbb{R} \setminus U$

Example: For any $a \in \mathbb{R}^d, r > 0$ $B(a; r)$ is an open set.

Proof. Let $x \in B(a; r)$, so $\|x - a\|_2 < r$. Set

$$r_0 := r - \|x - a\|_2 > 0$$

Claim: $B(x; r_0) \subseteq B(a; r)$ To see this, let $y \in B(x; r_0)$ so $\|y - x\|_2 < r_0$. So,

$$\begin{aligned} \|y - a\|_2 &\leq \|y - x\|_2 + \|x - a\|_2 && (\triangle\text{-inequality}) \\ &< r_0 + \|x - a\|_2 \\ &= r \end{aligned}$$

□

Proposition 10.0.1. (i) \emptyset, \mathbb{R}^d are both open in \mathbb{R}^d

(ii) If $U_1, U_2, \dots, U_n \subseteq \mathbb{R}^d$ are all open, then so is $U_1 \cap U_2 \cap \dots \cap U_n$.

(iii) If $U_\alpha \subseteq \mathbb{R}^d$ is an open set for all $\alpha \in I$, (I is some index set) then

$$\bigcup_{\alpha \in I} U_\alpha$$

is open.

Proof. (i),(ii) are exercises.

(iii): Set

$$V := \bigcup_{\alpha \in I} U_{\alpha}$$

Let $a \in V$. This means $\exists \alpha \in I$ such that $a \in U_{\alpha}$. U_{α} is open so $\exists r > 0$ s.t. $B(a; r) \subseteq U_{\alpha}$. $U_{\alpha} \subseteq \bigcup_{\alpha \in I} U_{\alpha} = V$ So $B(a; r) \subseteq V$ as required. \square

Example: For any $n \in \mathbb{N}_{\geq 1}$.

$$\left(\frac{-1}{n}, \frac{1}{n} \right) = B(0; \frac{1}{n})$$

is open in \mathbb{R} . The intersection of these open sets is

$$\bigcap_{n=1}^{\infty} \left(\frac{1}{n}, \frac{-1}{n} \right) = \{0\}$$

which is not open. This shows that openness is not preserved by infinite intersections.

Example: Let

$$U := \{(x, y) \in \mathbb{R}^2 : x > 0, y > 0\}$$

U is open but not closed.

$$U = V \cap W$$

where

$$V := \{(x, y) : x > 0\} \quad W := \{(x, y) : y > 0\}$$

To show V is open, let $a = (x, y) \in V$. Set $r := x > 0$. Then if $(w, z) \in B(a; r)$. Then

$$|w - z| \leq \|(w, z) - a\|_2 < r = x$$

$$\therefore w > x - x = 0$$

So $(w, z) \in U$. Similarly, W is open. Therefore U is open.

Not Closed: Exercise.

Proposition 10.0.2. Let $K \subseteq \mathbb{R}^d$. K is closed \iff for any subsequence $(a_n)_{n=1}^{\infty}$ in K , If it converges, then

$$\lim_{n \rightarrow \infty} a_n \in K$$

Proof. (\implies) Suppose K is closed. Let $(a_n)_{n=1}^\infty$ be a sequence in K s.t

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

exists. Suppose for a contradiction $L \notin K$. This means $L \in \mathbb{R}^d \setminus K$, which is open. So $\exists r > 0$ such that

$$B(L; r) \subseteq \mathbb{R}^d \setminus K$$

Since $a_n \rightarrow L$, we must have $a_n \in B(L; r)$ for some n (in fact, for all n sufficiently large). So $a_n \in B(L; r) \subseteq \mathbb{R}^d \setminus K$. Therefore $a_n \notin K$, which is a contradiction.

(\impliedby) Suppose K is not closed, and we'll prove $\exists (a_n)_{n=1}^\infty$ in K such that $a_n \rightarrow L \notin K$. Since K is not closed, $\mathbb{R}^d \setminus K$ is not open. So $\exists L \in \mathbb{R}^d \setminus K$ such that $\forall r > 0$

$$B(L; r) \not\subseteq \mathbb{R}^d \setminus K$$

For each $n \in \mathbb{N}_{\geq 1}$, we can find $a_n \in B(L; \frac{1}{n})$ such that $a_n \notin \mathbb{R}^d \setminus K$. So $a_n \in K$. This gives a sequence $(a_n)_{n=1}^\infty$ in K and

$$\|a_n - L\|_2 < \frac{1}{n} \rightarrow 0$$

Therefore by the Squeeze Theorem,

$$\|a_n - L\|_2 \rightarrow 0 \implies a_n \rightarrow L$$

$L \in \mathbb{R}^d \setminus K$, so $L \notin K$. □

Definition 10.0.4. Let $A \subseteq \mathbb{R}^d$ and let $a \in \mathbb{R}^d$, a is:

- (i) an **interior point** if $\exists r > 0$ s.t $B(a; r) \subseteq A$
- (ii) an **accumulation point** if \exists a sequence $(a_n)_{n=1}^\infty$ in A s.t $a_n \rightarrow a$
- (iii) a **boundary point** if it is an accumulation point and it is not an interior point.

$$A^\circ := \{\text{All interior points}\}$$

$$\bar{A} := \{\text{All accumulation points}\}$$

$$\partial A := \{\text{All boundary points}\} = \bar{A} \setminus A^\circ$$

Note: The set of interior points, accumulation points, and boundary points are referred to as the **interior** of A , the **closure** of A , and the **boundary** of A respectively

Example: $A := (0, 1] \cup \{2\}$

$$A^\circ = (0, 1)$$

$$\bar{A} = [0, 1] \cup \{2\}$$

$$\partial A = \{0, 1, 2\}$$

Example: $A := \mathbb{Q}$

Since any open interval contains irrational numbers, we have

$$A^\circ = \text{set}$$

Proposition from chapter 2,

$$\bar{A} = \mathbb{R}$$

$$\partial A = \mathbb{R}$$

Lecture 11

Compactness

Definition 11.0.1. A set $A \subseteq \mathbb{R}^d$ is (sequentially) compact if every sequence $(a_n)_{n=1}^\infty$ in A has a subsequence $(a_{n_k})_{k=1}^\infty$ that converges to a point in A .

Example 1: Is $[0,1]$ compact? Yes.

Proof. Recall: Bolzano-Weierstrass theorem states bounded sequence has a convergent subsequence.

Therefore, every sequence $(a_n)_{n=1}^\infty$ in $[0,1]$ has a subsequence $(a_{n_k})_{k=1}^\infty$ that converges. So

$$0 \leq a_{n_k} \leq 1 \implies 0 \leq \lim_{k \rightarrow \infty} a_{n_k} \leq 1 \\ \therefore L \in [0,1]$$

□

Example 2: Is $(0,1)$ compact? No.

Proof. By counter example, let $a_n := \frac{1}{n+1}$, so $a_n \rightarrow 0$. Therefore for all subsequences of a_n , $a_{n_k} \rightarrow 0$. So there exists no subsequence which converges to a point in $(0,1)$. □

Example 3: Is $[0, \infty)$ compact? No.

Proof. The Bolzano-Weierstrass theorem does not apply since $[0, \infty)$ is unbounded. Set $a_n := n$, then $a_n \rightarrow \infty$, so it has no bounded subsequence and therefore no convergent subsequences. □

Theorem 11.0.1 (Heine-Borel). Let $A \subseteq \mathbb{R}^d$. A is compact $\iff A$ is closed and not bounded.

Proof. (\implies) Similar to example 1. Assume A is closed and bounded. Let $(a_n)_{n=1}^\infty$ be a sequence in A . The sequence is bounded since A is, so by the Bolzano-Weierstrass theorem for \mathbb{R}^d , it has a subsequence $(a_{n_k})_{k=1}^\infty$ that converges to some $L \in \mathbb{R}^d$. $a_{n_k} \in A \forall k$ and $a_{n_k} \rightarrow L$ and A is closed, so by the

sequential characterization of closedness, $L \in A$, therefore A is compact.

(\Leftarrow) Assume A is compact. To show A is closed, assume for a contradiction that A is not closed. Therefore there exists a sequence $(a_n)_{n=1}^\infty$ in A such that $a_n \rightarrow L \notin A$. Then for any subsequence $(a_{n_k})_{k=1}^\infty$, we have

$$a_{n_k} \rightarrow L \notin A$$

This contradicts that A is compact, therefore A is closed.

To show A is bounded, assume for a contradiction that A is not bounded. Then $\forall n \in \mathbb{N}_{\geq 1}$, there exists $a_n \in A$ such that $\|a_n\|_2 \geq n$. This gives a sequence $(a_n)_{n=1}^\infty$. Since A is compact, it has a subsequence $(a_{n_k})_{k=1}^\infty$ that converges. But

$$\|a_{n_k}\|_2 \geq n_k \rightarrow \infty$$

So $(a_{n_k})_{k=1}^\infty$ is unbounded, which is a contradiction. \square

Proposition 11.0.1.

(i) If $k_1, \dots, k_n \subseteq \mathbb{R}^d$ are compact, then $\bigcup_{i=1}^n k_i$ is compact.

(ii) If $k_1, \dots, k_n \subseteq \mathbb{R}^d$ are compact, then $\bigcap_{i=1}^n k_i$ is compact.

Proof. Exercise:

(i) Assume $A := \bigcup_{i=1}^n k_i$. Let $(a_n)_{n=1}^\infty$ be a sequence in A . Then there exists $i \in \{1, \dots, n\}$ such that $a_n \in k_i$. Since k_i is compact, it has a subsequence $(a_{n_k})_{k=1}^\infty$ that converges to some $L \in \mathbb{R}^d$. $L \in k_i$ and $k_i \subseteq A$, so $L \in A$. Therefore A is compact.

(ii) Assume $A := \bigcap_{i=1}^n k_i$. Let $(a_n)_{n=1}^\infty$ be a sequence in A . Then $a_n \in k_i$ $\forall i \in \{1, \dots, n\}$. Since k_i is compact, it has a subsequence $(a_{n_k})_{k=1}^\infty$ that converges to some $L \in \mathbb{R}^d$. $L \in k_i$ $\forall i \in \{1, \dots, n\}$ and $k_i \subseteq A$, so $L \in A$. Therefore A is compact. \square

Definition 11.0.2. $A \subseteq \mathbb{R}^d$ is **compact** if for any collection

$$U_\alpha : \alpha \in I$$

of open sets such that

$$A \subseteq \bigcup_{\alpha \in I} U_\alpha$$

There exists finitely many indices $\alpha_1, \dots, \alpha_n$ such that

$$A \subseteq \bigcup_{i=1}^n U_{\alpha_i}$$

Lecture 12

Limits of a Function of Continuous Variables

A sequence is a function $\mathbb{N} \rightarrow \mathbb{R}$. Here, we'll consider function that are going from $\mathbb{R} \rightarrow \mathbb{R}$ (or $\mathbb{R}^d \rightarrow \mathbb{R}^m$).

Definition 12.0.1. Let $X \subseteq \mathbb{R}^d$, $a \in \mathbb{R}^d$ a limit point of X . $f : X \rightarrow \mathbb{R}^m$, $L \in \mathbb{R}^m$. We say the limit of f as X approaches a is L if

$$\forall \epsilon > 0, \exists \delta > 0 \text{ s.t. } \forall x \in X$$

$$x \in B(a; \delta) \wedge x \neq a \implies \|f(x) - L\|_2 < \epsilon$$

The idea is like the definition of convergence of a sequence, except we replace $n \geq n_0$ (which captures "n is sufficiently large") with $x \in B(a; \delta)$, $x \neq a$ (which captures "x is close to, but not equal to a"). In other words, the definition says that if x is close to (but not equal to) a then $f(x)$ is close to L .

Why "not equal to"?: Often we consider the limit as x approaches a when $f(a)$ is not defined. Other times we compare the limit to $f(a)$. So we do not want to use $f(a)$ in the definition of the limit.

Notation: We write

$$\lim_{x \rightarrow a} f(x) = L$$

or

$$f(x) \rightarrow L \text{ as } x \rightarrow a$$

to mean that the limit of f is L as x approaches a .

Example: $f : \mathbb{R} \rightarrow \mathbb{R}$. $f(x) := 3x - 2$. Let $a \in \mathbb{R}$. Claim

$$\lim_{x \rightarrow a} f(x) = 3a - 2$$

Proof. Let $\epsilon > 0$. Consider

$$\begin{aligned} |f(x) - (3a - 2)| &= |3x - 2 - 3a + 2| \\ &= 3|x - a| \end{aligned}$$

We want this $< \epsilon$, set $\delta := \frac{\epsilon}{3}$. Then if $x \in B(a; \delta) = (a - \delta, a + \delta)$ (i.e. $|x - a| < \delta$) then

$$|f(x) - (3a - 2)| = 3|x - a| < 3\delta = \frac{3\epsilon}{3} = \epsilon$$

□

Example: $g : \mathbb{R} \rightarrow \mathbb{R}$. $g(x) := x^2$. Claim:

$$\lim_{x \rightarrow a} g(x) = a^2$$

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

$$\begin{aligned} |g(x) - a^2| &= |x^2 - a^2| \\ &= |x - a||x + a| \end{aligned}$$

What happens if x is close to a ? Intuitively, $|x + a|$ is close to $|a + a|$ and $|x - a|$ is small.

$$\begin{aligned} |x + a| &= |x - a + a + a| \leq |x - a| + |a + a| \\ &< 2|a| + \delta && (\text{if } |x - a| < \delta) \\ &\leq 2|a| + 1 && (\delta \leq 1) \end{aligned}$$

Then,

$$\begin{aligned} |x^2 - a^2| &= |x - a||x + a| \leq |x - a|(2|a| + 1) \\ &< \delta(2|a| + 1) && (\text{if } |x - a| < \delta) \\ &\leq \epsilon && (\text{if } \delta \leq \frac{\epsilon}{2|a|+1}) \end{aligned}$$

Important: Do not define δ in terms of x or δ ! We can use a here since a is constant

So we set $\delta := \min\{1, \frac{\epsilon}{2|a|+1}\}$ Then $\delta \leq \frac{\epsilon}{2|a|+1}$ and $\delta \leq 1$. So if $|x - a| < \delta$. Then from the work above, $|x^2 - a^2| < \epsilon$ as required. □

Note: In proofs where we have $\delta - \epsilon$, we often use

$$\delta := \min\{\dots\}$$

In proofs where we have $n_0 - \epsilon$, we often use

$$n_0 := \max\{\dots\}$$

Proposition 12.0.1 (Uniqueness of Limits). *Let $f : X \rightarrow \mathbb{R}^m$ ($X \subseteq \mathbb{R}^d$), $a \in \mathbb{R}^d$ a limit point of X , $L, L' \in \mathbb{R}^m$. If the limit of f as $x \rightarrow a$ is L and the limit of f as $x \rightarrow a$ is L' , then $L = L'$*

Proof. By contradiction. Suppose $L \neq L'$. So

$$\|L - L'\|_2 > 0$$

Set

$$\epsilon := \frac{\|L - L'\|_2}{2} > 0$$

Since $f(x) \rightarrow L$ as $x \rightarrow a$, $\exists \delta > 0$ such that if $x \in X \cap B(a; \delta) \setminus \{a\}$, then

$$\|f(x) - L\|_2 < \epsilon$$

Since $f(x) \rightarrow L'$ as $x \rightarrow a$, $\exists \delta' > 0$ such that

$$x \in X \cap B(a; \delta') \setminus \{a\} \implies \|f(x) - L'\|_2 < \epsilon$$

Let $\delta_0 \neq \min\{\delta, \delta'\}$. Let

$$x \in X \cap B(a; \delta_0) \setminus \{a\}$$

Then

$$x \in X \cap B(a; \delta) \setminus \{a\}$$

So,

$$\begin{aligned} \|f(x) - L\|_2 &< \epsilon \\ \|f(x) - L'\|_2 &< \epsilon \end{aligned}$$

So,

$$\begin{aligned} \|L - L'\|_2 &\leq \|L - f(x)\|_2 + \|f(x) - L'\|_2 < \epsilon + \epsilon \\ &= \|L - L'\|_2 \end{aligned}$$

And thus, a contradiction. □

Proposition 12.0.2 (Sequential Characterization of Limits). *Let $X \subseteq \mathbb{R}^d$, $a \in \mathbb{R}^d$, a limit point of X . $f : X \rightarrow \mathbb{R}^m$, $L \in \mathbb{R}^m$.*

$\lim_{x \rightarrow a} f(x) = L \iff$ for every sequence $(x_n)_{n=1}^\infty$ in X such that $x_n \rightarrow a$, we have

$$\lim_{n \rightarrow \infty} f(x_n) = L$$

Proof. (\implies) Suppose $\lim_{x \rightarrow a} f(x) = L$. Let $(x_n)_{n=1}^\infty$ be a sequence in $X \setminus \{a\}$ such that $x_n \rightarrow a$. We must show that $f(x_n) \rightarrow L$.

Let $\epsilon > 0$ be given. Since $f(x) \rightarrow L$ as $x \rightarrow a$, $\exists \delta$ such that

$$x \in X \cap B(a; \delta) \setminus \{a\} \implies \|f(x) - L\|_2 < \epsilon$$

Since $x_n \rightarrow a$, using δ in place of ϵ , $\exists n_0$ such that $\forall n \geq n_0$, $\|x_n - a\|_2 < \delta$. i.e. $x_n \in B(a, \delta)$. Also $x_n \in X \setminus \{a\}$. Therefore,

$$\|f(x_n) - L\|_2 < \epsilon$$

(\Leftarrow) Suppose \forall sequences $(x_n)_{n=1}^\infty$ in $X \setminus \{a\}$ converging to a , $f(x_n) \rightarrow L$, and for a contradiction, suppose

$$f(x) \not\rightarrow L$$

We negate " $f(x) \rightarrow L$ " to get that $\exists \epsilon > 0$ such that $\forall \gamma > 0$, $\exists x \in X \cap B(a; \gamma) \setminus \{a\}$ such that $\|f(x) - L\|_2 \geq \epsilon$.

This gives a sequence $(x_n)_{n=1}^\infty$ in $X \setminus \{a\}$, $\|x_n - a\|_2 \leq \frac{1}{n} \forall n$, so by the squeeze theorem

$$\|x_n - a\|_2 \rightarrow 0$$

Since $\|f(x_n) - L\|_2 \geq \epsilon$, $f(x_n) \not\rightarrow L$. This is a contradiction. \square

Note: if $\lim_{n \rightarrow \infty} f(x_n) = L$ for *some* sequence $(x_n)_{n=1}^\infty$ in $X \setminus \{a\}$ converging to a , it *does not* follow that $\lim_{x \rightarrow a} f(x) = L$

Example:

$$f(x) := \begin{cases} 0 & \text{if } x = \frac{1}{n}, n \in \mathbb{N}_{\geq 1} \\ 1 & \text{otherwise} \end{cases}$$

$\lim_{x \rightarrow 0} f(x)$ does not exist but $\lim_{n \rightarrow \infty} f(\frac{1}{n}) = 0$

Proposition 12.0.3 (Algebra of Limits). *Let $x \subseteq \mathbb{R}^d$, $a \in \mathbb{R}^d$ a limit point of X , $f : X \rightarrow \mathbb{R}^m$, $g : X \rightarrow \mathbb{R}^m$, $L, K \in \mathbb{R}^m$. Suppose $\lim_{x \rightarrow a} f(x) = L$, $\lim_{x \rightarrow a} g(x) = K$*

(i)

$$\lim_{x \rightarrow a} f(x) + g(x) = L + K$$

(ii)

$$\lim_{cf(x)} = cL$$

(iii) If $m = 1$,

$$\lim_{x \rightarrow a} f(x)g(x) = LK$$

(iv) If $m = 1$, $g(x) \neq 0 \forall x \in X$, $K \neq 0$. Then

$$\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \frac{L}{K}$$

Proof. (i) Use Sequential Characterization: Let $(x_n)_{n=1}^\infty$ be in $X \setminus \{a\}$ such that $x_n \rightarrow a$. Then $f(x_n) \rightarrow L$ and $g(x_n) \rightarrow K$. So by algebra of limits for sequences,

$$f(x_n) + g(x_n) \rightarrow L + K$$

$$\therefore f(x) + g(x) \rightarrow L + K$$

(ii) **Exercise.**

(iii) **Exercise.**

(iv) **Exercise.**

□

Theorem 12.0.1 (Squeeze Theorem). *Let $X \subseteq \mathbb{R}^d$, $a \in \mathbb{R}^d$ a limit point of X , $f, g, h : X \rightarrow \mathbb{R}$*

$$f(x) \leq g(x) \leq h(x) \quad \forall x \in X$$

and

$$\lim_{x \rightarrow a} f(x) = \lim_{x \rightarrow a} h(x) = L$$

Then

$$\lim_{x \rightarrow a} g(x) = L$$

Proof. **Exercise**

□

If $f : X \rightarrow \mathbb{R}_m$, We can define functions

$$f_1, \dots, f_m : X \rightarrow \mathbb{R}$$

by

$$(f_1(x), \dots, f_m(x)) = f(x)$$

f_1, \dots, f_m are called the *component functions* of f .

Proposition 12.0.4. *Let $X \subseteq \mathbb{R}^d$, $a \in \mathbb{R}^d$ a limit point of X , $f : X \rightarrow \mathbb{R}^m$, f_1, \dots, f_m its component functions. $L = (L_1, \dots, L_m) \in \mathbb{R}^m$. Then*

$$\lim_{x \rightarrow a} f(x) = L \iff \lim_{x \rightarrow a} f_i(x) = L_i \quad \forall 1 \leq i \leq m$$

Proof. **Exercise.**

□

Definition 12.0.2. *Let $X \subseteq \mathbb{R}$, $a \in \mathbb{R}$, $f : X \rightarrow \mathbb{R}^d$.*

- *If a is a limit point of $X \cap (a, \infty)$ then we write $\lim_{x \rightarrow a^+} f(x) = L$ to mean that*

$$\lim_{x \rightarrow a} g(x) = L$$

where

$$g = f|_{X \cap (a, \infty)}$$

- *If a is a limit point of $X \cap (-\infty, a)$ then we write $\lim_{x \rightarrow a^-} f(x) = L$ to mean that*

$$\lim_{x \rightarrow a} g(x) = L$$

where

$$g = f|_{X \cap (-\infty, a)}$$

Example:

$$f(x) := \begin{cases} -1, & x < 0 \\ 0, & x = 0 \\ 1, & x > 0 \end{cases}$$

$$\lim_{x \rightarrow 0^+} f(x) = 1 \neq \lim_{x \rightarrow 0^-} f(x) = -1$$