

richardwu.ca

MATH 247 COURSE NOTES

CALCULUS 3 (ADVANCED)

SPIRO KARIGIANNIS • WINTER 2018 • UNIVERSITY OF WATERLOO

Last Revision: January 30, 2018

Table of Contents

1	January 3, 2018	1
1.1	Euclidean space \mathbb{R}^n	1
1.2	Euclidean inner product	1
1.3	Triangle inequality	2
1.4	Norms	3
1.5	Angle between two vectors	4
2	January 5, 2018	4
2.1	Linear maps	4
2.2	Operator norm	6
3	January 8, 2018	8
3.1	Topology of \mathbb{R}^n	8
3.2	Open and closed balls	8
3.3	Open sets	8
3.4	Properties of open sets	10
3.5	Closed sets	10
3.6	Properties of closed sets	11
3.7	Neither open nor closed	12
3.8	Interior	12
3.9	Closure	12
4	January 10, 2018	13
4.1	Closure of open ball is closed ball	13
4.2	Boundary	14
4.3	Characterization of boundary	14
4.4	Sequences and limits	15
4.5	Uniqueness of limits	16
4.6	Neighbourhood	17

5	January 12, 2018	17
5.1	Relations between convergent sequences and open/closed sets	17
5.2	Bounded and Cauchy sequences	18
5.3	Convergent \iff Cauchy	18
5.4	Convergence implies bounded	18
5.5	Subsequences	19
5.6	Bolzano-Weierstrass (B-W) Theorem	19
6	January 15, 2017	22
6.1	Connectedness	22
6.2	Is R^n connected?	23
6.3	$[0, 1]$ is connected	23
7	January 17, 2017	25
7.1	Convex sets	25
7.2	Convex \Rightarrow connected	25
7.3	Open cover and compactness	27
8	January 19, 2018	27
8.1	Heine-Borel theorem	27
9	January 22, 2018	32
9.1	Limits of functions	32
9.2	Uniqueness of limits	34
9.3	Sequential characterization of limits of functions	34
9.4	Properties of limits of functions	35
10	January 24, 2018	35
10.1	Component functions	35
10.2	Squeeze theorem	36
10.3	Norm properties of limits	36
10.4	Continuity	36
10.5	Continuity on a set	37
10.6	Composition of continuous functions is continuous	37
10.7	Dot product of continuous functions is continuous	37
10.8	Inverse image	37
11	January 26, 2018	38
11.1	Continuity and open/closed sets	38
11.2	Continuity and compact sets	40
11.3	Extreme value theorem (EVT)	42
12	January 29, 2018	43
12.1	Continuity and connected sets	43
12.2	Intermediate value theorem (IVT)	44
12.3	Uniform continuity	45
12.4	Uniform continuity and compact sets	46
12.5	Differentiability	47

Abstract

These notes are intended as a resource for myself; past, present, or future students of this course, and anyone interested in the material. The goal is to provide an end-to-end resource that covers all material discussed in the course displayed in an organized manner. If you spot any errors or would like to contribute, please contact me directly.

1 January 3, 2018

1.1 Euclidean space \mathbb{R}^n

Most postulates and theorems apply to any n -dimensional real vector space with a positive-definite inner product.

$$\mathbb{R}^n = \{x = (x_1, x_2, \dots, x_n); x_j \in \mathbb{R}, j = 1, \dots, n\}$$

Some properties of vectors in \mathbb{R}^n where $x = (x_1, \dots, x_n)$, $y = (y_1, \dots, y_n)$, and $t \in \mathbb{R}$:

$$x + y = (x_1 + y_1, \dots, x_n + y_n)$$

$$tx = (tx_1, \dots, tx_n)$$

$$x + y = y + x$$

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

$$s(tx) = (st)x$$

$$t\vec{0} = \vec{0}$$

$$\vec{0}x = \vec{0}$$

$$(t + s)x = tx + sx$$

$$t(x + y) = tx + ty$$

1.2 Euclidean inner product

An important additional structure on \mathbb{R}^n is the natural **Euclidean inner product** (aka the *dot product*).

$$\cdot : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}$$

which can be written as $x \cdot y \in \mathbb{R}$.

Dot products are **bilinear**, **symmetric**, and **positive-definite**. **Bilinear forms** satisfy

$$(x + y) \cdot z = x \cdot z + y \cdot z$$

$$x \cdot (y + z) = x \cdot y + x \cdot z$$

$$(tx) \cdot y = x \cdot (ty) = t(x \cdot y)$$

symmetric denotes

$$x \cdot y = y \cdot x$$

and **positive-definiteness** means $x \cdot x \geq 0$ with equality $\iff x = \vec{0}$.

Definition 1.1. The dot product is defined for $y = (y_1, \dots, y_n)$ and $y = (y_1, \dots, y_n)$

$$x \cdot y := \sum_{k=1}^n x_k y_k$$

Definition 1.2. The norm $\|x\|$ of $x \in \mathbb{R}^n$ (induced by some inner product $\langle x, x \rangle = x \cdot x$) is defined as

$$\begin{aligned}\|x\|^2 &= x \cdot x \\ \|x\| &= \sqrt{x \cdot x}\end{aligned}$$

1.3 Triangle inequality

Proposition 1.1. Triangle inequality states

$$\|x + y\| \leq \|x\| + \|y\| \quad \forall x, y \in \mathbb{R}^n$$

To prove the above, we need the **Cauchy-Schwarz Inequality**.

Theorem 1.1. The Cauchy-Schwarz inequality states that

$$|x \cdot y| \leq \|x\| \|y\|$$

with equality iff $x = ty$ or $y = tx$ for some $t \in \mathbb{R}$.

Proof. For the equality case, WLOG if $x = ty$

$$\begin{aligned}x \cdot y &= ty \cdot y = t\|y\|^2 \\ &= |t|\|y\|^2 \\ &= \|x\|\|y\|\end{aligned}$$

Let $t \in \mathbb{R}$. Note for all t

$$\begin{aligned}0 &\leq \|x - ty\|^2 = (x - ty) \cdot (x - ty) \\ &= x \cdot x - ty \cdot x - tx \cdot y + t^2 y \cdot y \\ &= \|x\|^2 + t^2 \|y\|^2 - 2t(x \cdot y)\end{aligned}$$

Thus we have

$$at^2 + bt + c \geq 0 \quad \forall t \in \mathbb{R}$$

where $a = \|y\|^2$, $b = -2x \cdot y$ and $c = \|x\|^2$. Note there can exist at most one root (positive parabola where all values are non-negative). For $at^2 + bt + c = 0$ to have at most one real root (such that t exists), we need $b^2 - 4ac \leq 0$ (from the quadratic formula).

$$\begin{aligned}4(x \cdot y)^2 &\leq 4\|x\|^2\|y\|^2 \\ |x \cdot y| &\leq \|x\|\|y\|\end{aligned}$$

If we have equality $\exists t_0$ such that $at_0^2 + bt_0 + c = 0$ or $\|x - t_0 y\|^2 = 0$ so $x = t_0 y$. □

Corollary 1.1. The triangle inequality

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

where the last line follows from the Cauchy-Schwarz inequality.

Definition 1.3. The **distance** between two points $x, y \in \mathbb{R}^n$ is defined to be

$$d(x, y) = \|x - y\|$$

which satisfies the properties

$$\begin{aligned}d(x, y) &= d(y, x) \\ d(x, x) &= 0 \\ d(x, y) &\geq 0 \quad \text{with equality iff } x = y\end{aligned}$$

so we can restate the triangle inequality as $d(x, y) \leq d(x, z) + d(z, x) \quad \forall x, y, z \in \mathbb{R}^n$.

1.4 Norms

There exists different "natural" norms on \mathbb{R}^n

Definition 1.4. A norm $\|\cdot\|$ on \mathbb{R}^n is a map

$$\|\cdot\| : \mathbb{R}^n \rightarrow \mathbb{R}^{\geq 0}$$

such that

1. $\|x\| = 0 \iff x = \vec{0}$
2. $\|tx\| = |t|\|x\|$
3. $\|x + y\| \leq \|x\| + \|y\|$

All inner products determine a norm but not all norms are from inner products. We saw that the dot product determines a norm called the Euclidean norm.

$$l^1 \text{ norm } \|x\|_1 = \sum_{k=1}^n |x_k|$$

$$l^p \text{ norm } \|x\|_p = \left(\sum_{k=1}^n |x_k|^p\right)^{\frac{1}{p}}$$

$$\text{sup norm (aka } l^\infty \text{ norm)} \quad \|x\|_\infty = \max\{|x_1|, \dots, |x_n|\}$$

One can see that l^∞ norm is a "limit" of l^p norms as $p \rightarrow \infty$.

Note the l^2 norm is the Euclidean norm.

Why are norms important? **A norm determines a distance.** For example

$$d(x, y) = \|x - y\|$$

(all norms determine a distance but not all distances are from norms).

Distance is important to define a **limit** which is crucial for differentiability/integrability.

1.5 Angle between two vectors

A corollary to C-S for $x, y \neq \vec{0}$

$$-1 \leq \frac{x \cdot y}{\|x\| \|y\|} \leq 1$$

Define the angle $\theta \in [0, \pi]$ between x and y to be

$$\cos \theta = \frac{x \cdot y}{\|x\| \|y\|}$$

so we have another definition of the dot product

$$x \cdot y = \|x\| \|y\| \cos \theta$$

We say x, y are **orthogonal** if $\theta = \frac{\pi}{2} \iff x \cdot y = 0$.

Why is this the correct definition?

$$\begin{aligned} \|y - x\|^2 &= (y - x) \cdot (y - x) \\ &= \|x\|^2 + \|y\|^2 - 2x \cdot y \\ &= \|x\|^2 + \|y\|^2 - 2\|x\| \|y\| \cos \theta \end{aligned}$$

This aligns with the Law of Cosines $c^2 = a^2 + b^2 - 2ab \cos \theta$.

2 January 5, 2018

2.1 Linear maps

Definition 2.1. A map $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is linear if T takes linear combinations to linear combinations i.e.

$$T\left(\sum_{k=1}^N t_k v_k\right) = \sum_{k=1}^N T(v_k) \quad t_i \in \mathbb{R} \quad v_j \in \mathbb{R}^n$$

We will see linear maps are closely related to **differentiability**.

Some facts about linear maps: let e_1, \dots, e_n be the standard basis.

$$x \in \mathbb{R}^n = (x_1, \dots, x_n) = \sum_{k=1}^n x_k e_k$$

Let f_1, \dots, f_m be the standard basis of \mathbb{R}^m where $f_j = (0, \dots, 1, \dots, 0) \in \mathbb{R}^m$.

$$y \in \mathbb{R}^m = (y_1, \dots, y_m) = \sum_{k=1}^m y_k f_k$$

Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be linear and let

$$\begin{aligned} y = \sum_{l=1}^m y_l f_l &= T(x) = T\left(\sum_{k=1}^n x_k e_k\right) \\ &= \sum_{k=1}^n x_k T(e_k) \\ &= \sum_{k=1}^n x_k \left(\sum_{l=1}^m A_{lk} f_l\right) \\ &= \sum_{k=1}^n \left(\sum_{l=1}^m A_{lk} x_k\right) f_l \end{aligned}$$

By uniqueness of the expansion of a vector in terms of a basis (f_j s) we conclude that

$$y_l = \sum_{k=1}^n A_{lk} x_k \quad l = 1, \dots, m$$

or in matrix form

$$\begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} A_{11} & \dots & A_{1n} \\ \vdots & & \vdots \\ A_{m1} & \dots & A_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$$

We've shown that any linear map $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is necessarily **matrix multiplication**

$$y = T(x) = A \cdot x$$

for some unique $m \times n$ matrix A (with respect to some bases in \mathbb{R}^n and \mathbb{R}^m).

The rule of matrix multiplication is automatic from the composition of linear maps. Let

$$\begin{aligned} T : \mathbb{R}^n &\rightarrow \mathbb{R}^m \\ S : \mathbb{R}^m &\rightarrow \mathbb{R}^p \\ y = T(x) &= A \cdot x \quad m \times n \\ z = S(y) &= B \cdot y \quad p \times m \end{aligned}$$

Therefore $S \circ T : \mathbb{R}^n \rightarrow \mathbb{R}^p$ is linear.

$$\begin{aligned} (S \circ T)\left(\sum_k t_k v_k\right) &= S\left(T\left(\sum_k t_k v_k\right)\right) \\ &= S\left(\sum_k x_k T(v_k)\right) \\ &= \sum_k x_k S(T(v_k)) \\ &= \sum_k t_k (S \circ T)(v_k) \end{aligned}$$

So we have

$$\begin{aligned} z_l &= \sum_{j=1}^m B_{lj} y_j = \sum_{j=1}^m B_{lj} \left(\sum_{i=1}^n A_{ji} x_i \right) \\ &= \sum_{i=1}^n \left(\sum_{j=1}^m B_{lj} A_{ji} \right) x_i \\ &= \sum_{i=1}^n C_{li} x_i \end{aligned}$$

where

$$z = (S \circ T)(x) = C \cdot x \quad p \times n$$

Recall the space $L(\mathbb{R}^n, \mathbb{R}^m)$ of linear maps from \mathbb{R}^n to \mathbb{R}^m is itself a finite dimensional real vector space of dimension nm (isomorphic to \mathbb{R}^{nm}).

$$T \in L(\mathbb{R}^n, \mathbb{R}^m) \iff A \in M_{m \times n}(\mathbb{R})$$

where $M_{m \times n}(\mathbb{R})$ is the space of real $m \times n$ matrices. There is a unique 1-1 correspondence between T and A (as shown before).

2.2 Operator norm

Note one can define norm on matrices. The natural Euclidean norm for matrix A can be defined as

$$\|A\|_2 = \sqrt{\sum_{i=1, \dots, m; j=1, \dots, n} (A_{ij})^2}$$

Definition 2.2. The **operator norm** is defined for a $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ linear map as

$$\|T\|_{op} = \inf\{C > 0, \|T(x)\| \leq C\|x\| \quad \forall x \in \mathbb{R}^n\}$$

We need to show this norm is

1. Well-defined
2. $\|\cdot\|_{op}$ is a norm
1. Show well-defined

$$\begin{aligned} T(x) &= A \cdot x \quad A \quad m \times n \\ \begin{bmatrix} A_{11} & \dots & A_{1n} \\ \vdots & & \vdots \\ A_{m1} & \dots & A_{mn} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} &= \begin{bmatrix} A_1 \cdot x \\ \vdots \\ A_m \cdot x \end{bmatrix} = T(x) \end{aligned}$$

So the norm is

$$\begin{aligned} \|T(x)\|^2 &= (A_1 \cdot x)^2 + \dots + (A_m \cdot x)^2 \\ &\leq \|A_1\|^2 \|x\|^2 + \dots + \|A_m\|^2 \|x\|^2 \\ &= (\|A_1\|^2 + \dots + \|A_m\|^2) \|x\|^2 \end{aligned} \quad \text{C-S}$$

Case 1 Assume $\|A_1\|^2 + \dots + \|A_m\|^2 = 0$.

$$\begin{aligned}\|A_1\|^2 + \dots + \|A_m\|^2 = 0 &\iff A = 0_{m \times n} \\ &\iff T = 0 \in L(\mathbb{R}^n, \mathbb{R}^m)\end{aligned}$$

Then $T(x) = 0 \quad \forall x$ so $\|T(x)\| \leq C\|x\|$ holds $\forall C > 0$, thus the infimum of positive real numbers (0) implies $\|T\|_{op} = 0$.

Case 2 Assume $\|A_1\|^2 + \dots + \|A_m\|^2 > 0$.

$\{C > 0, \|T(x)\| \leq C\|x\| \quad \forall x \in \mathbb{R}^n\}$ is non-empty because $\sqrt{\|A_1\|^2 + \dots + \|A_m\|^2}$ is in there. By the completeness of \mathbb{R} , $\|T\|_{op}$ exists and is ≥ 0 .

2. We've shown $\|T\|_{op}$ exists and is ≥ 0 for all $T \in L(\mathbb{R}^n, \mathbb{R}^m)$. It remains to shown $\|T\|_{op}$ is a norm:

- (a) $\|T\|_{op} = 0$ only for the zero map
- (b) $\|\lambda T\|_{op} = |\lambda| \|T\|_{op} \quad \forall \lambda \in \mathbb{R}$
- (c) $\|T + S\|_{op} \leq \|T\|_{op} + \|S\|_{op}$

To see this, we note that since

$$\|T\|_{op} = \inf\{C > 0, \|T(x)\| \leq C\|x\| \quad \forall x \in \mathbb{R}^n\}$$

\exists a **decreasing sequence** $c_k \geq 0$ such that $\|T(x)\| \leq c_k\|x\| \quad \forall x \in \mathbb{R}^n$ and $\lim_{k \rightarrow \infty} c_k = \|T\|_{op}$.

Take limit as $k \rightarrow \infty$ of the predicate in $\|T\|_{op}$.

$$\begin{aligned}\|T(x)\| &\leq (\lim_{k \rightarrow \infty} c_k) \|x\| \\ \|T(x)\| &\leq \|T\|_{op} \|x\|\end{aligned}$$

So we have

$$\begin{aligned}\|T\|_{op} = 0 &\Rightarrow \|T(x)\| \leq 0 \quad \forall x \\ &\Rightarrow T(x) = 0 \quad \forall x \\ &\Rightarrow T = 0 \in L(\mathbb{R}^n, \mathbb{R}^m)\end{aligned}$$

which proves (a).

$$\|\lambda T\|_{op} = |\lambda| \|T\|_{op}$$

follows from

$$\begin{aligned}\|(\lambda T)(x)\| &= \|\lambda(T(x))\| \\ &= |\lambda| \|T(x)\| \quad \forall x\end{aligned}$$

If $\lambda = 0$, $\lambda T = 0 \Rightarrow \|\lambda T\|_{op} = 0 = |\lambda| \|T\|_{op}$.

If $\lambda \neq 0$

$$\begin{aligned}
 \|\lambda T\|_{op} &= \inf\{C > 0, \|(\lambda T)(x)\| \leq C\|x\|\} \\
 &= \inf\{C > 0, |\lambda|\|T(x)\| \leq C\|x\|\} \\
 &= \inf\{C > 0, \|T(x)\| \leq \frac{C}{|\lambda|}\|x\|\} \\
 &= |\lambda| \inf\{\tilde{C} > 0, \|T(x)\| \leq \tilde{C}\|x\|\} \\
 &= |\lambda|\|T\|_{op}
 \end{aligned}
 \qquad \tilde{C} = \frac{C}{\lambda}$$

which proves (b). (c) is similar.

3 January 8, 2018

3.1 Topology of \mathbb{R}^n

Topology is the study of **closeness** in a space.

3.2 Open and closed balls

Definition 3.1. Let $x \in \mathbb{R}^n$ and $r > 0$. The **open ball** at radius r centred at x is denoted

$$B_r(x) = \{y \in \mathbb{R}^n \mid \|x - y\| < r\}$$

It consists of all points in \mathbb{R}^n whose distance from x is *strictly less than* r .

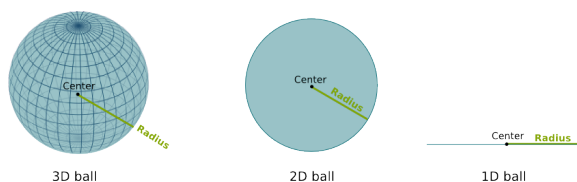


Figure 3.1: Open balls in \mathbb{R} , \mathbb{R}^2 , and \mathbb{R}^3 .

In \mathbb{R} , $B_r(x) = (x - r, x + r)$. In \mathbb{R}^3 , $B_r(x)$ is the *interior* of a sphere of radius r centred at x .

Definition 3.2. Let $x \in \mathbb{R}^n$, $r > 0$. The **closed ball** of radius $r > 0$ centred at x is denoted

$$\overline{B_r(x)} = \{y \in \mathbb{R}^n \mid \|x - y\| \leq r\}$$

Remark 3.1. The notation will be explained in the following class/section. Note that

$$\overline{B_r(x)} = B_r(x) \cup \{\text{points exactly at distance } r\}$$

For $n = 1$, $\overline{B_r(x)} = [x - r, x + r]$.

3.3 Open sets

Definition 3.3. A subset $U \subseteq \mathbb{R}^n$ is called an **open set** (or open) iff $\forall x \in U$, $\exists r > 0$ (r depends on x) such that $B_r(x) \subseteq U$.

(Informally: a subset U is open if for every $x \in U$, all points sufficiently close to x are *also* in U).

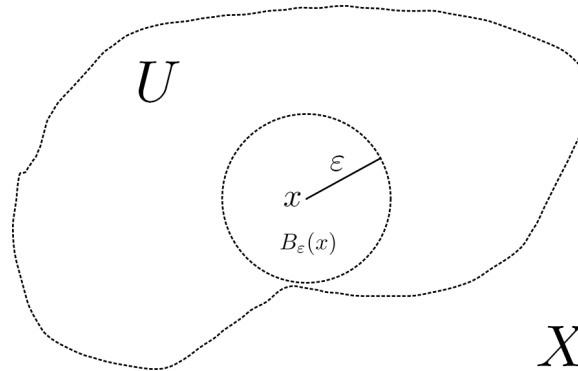


Figure 3.2: One can form an open ball for every point x in an open set U .

Example 3.1. Set that is not open

- $[0, 1] \subseteq \mathbb{R}$. Note: $\nexists r > 0$ for $x = 1$ such that $B_r(x) \subseteq [0, 1]$.

Sets that are open

- \mathbb{R}^n since $x + \epsilon \in \mathbb{R}^n$ by definition.
- \emptyset (vacuous: satisfied trivially \emptyset has no points).

Proposition 3.1. An open ball is an open set.

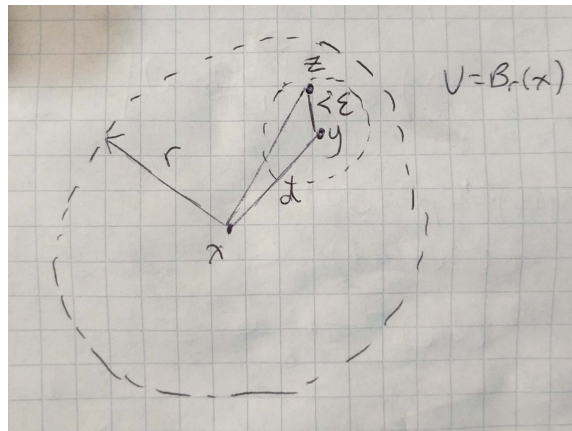


Figure 3.3: An open ball is an open set (see proof below).

Proof. Let $U = B_r(x)$ and $y \in U = B_r(x)$. We need to find some $\epsilon > 0$ such that $B_\epsilon(y) \subseteq U$.

Let $d = \|x - y\| < r$ since $y \in U = B_r(x)$.

Let $\epsilon = r - d > 0$.

Suppose $z \in B_\epsilon(y)$ thus $\|y - z\| < \epsilon$.

We thus have

$$\|z - x\| \stackrel{\Delta}{\leq} \|z - y\| + \|y - x\| < \epsilon + d = r$$

So $B_\epsilon(y) \subseteq U$ hence U is open. □

We can construct more from open sets.

3.4 Properties of open sets

Lemma 3.1. 1. Let $U_\alpha \subseteq \mathbb{R}^n$ be open $\forall \alpha \in A$ (countably or uncountably many), then

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

is open.

2. Let U_1, \dots, U_k be open (**must be finite** number of sets). Then

$$\bigcap_{j=1}^k U_j$$

is open.

Informally, *arbitrary unions* of open sets are open. *Finite intersections* of open sets are open.

Proof.

1. We want to show $\bigcup_{\alpha \in A} U_\alpha$ is open.

Let $x \in \bigcup_{\alpha \in A} U_\alpha$ so \exists some $\alpha_0 \in A$ such that $x \in U_{\alpha_0}$ (holds since union of sets).

But U_{α_0} is open so $\exists r > 0$ such that $B_r(x) \subseteq U_{\alpha_0} \subseteq \bigcup_{\alpha \in A} U_\alpha$.

2. Show $x \in \bigcap_{j=1}^k U_j$ so $x \in U_j$ for all $j = 1, \dots, k$. Each U_j is open so $\forall j, \exists \epsilon_j > 0$ such that $B_{\epsilon_j}(x) \subseteq U_j$.

Let $\epsilon = \min\{\epsilon_1, \dots, \epsilon_k\} > 0$. $\forall j$ we have $B_\epsilon(x) \subseteq B_{\epsilon_j}(x) \subseteq U_j$ hence $B_\epsilon(x) \subseteq \bigcap_{j=1}^k U_j$.

Remark 3.2. Arbitrary (e.g. nonfinite) intersections of open sets need not be open (the min. of infinite numbers is not well defined. An infimum of positive numbers need not be > 0 i.e. it could be 0).

Even intersection of countably infinite sets may not be open. Suppose $U_k = (0, 1 + \frac{1}{k}) \subseteq \mathbb{R} \quad \forall k \in \mathbb{N}$. Note that $\bigcap_{k=1}^{\infty} U_k = (0, 1]$ is not open.

□

3.5 Closed sets

Definition 3.4. A subset $F \subseteq \mathbb{R}^n$ is called **closed** if $F^c = \mathbb{R} \setminus F$ is open (note: this definition is based on open's definition).

Proposition 3.2. A closed ball $\overline{B_r(x)} = \{y \in \mathbb{R}^n \mid \|y - x\| \leq r\}$ is a closed set.

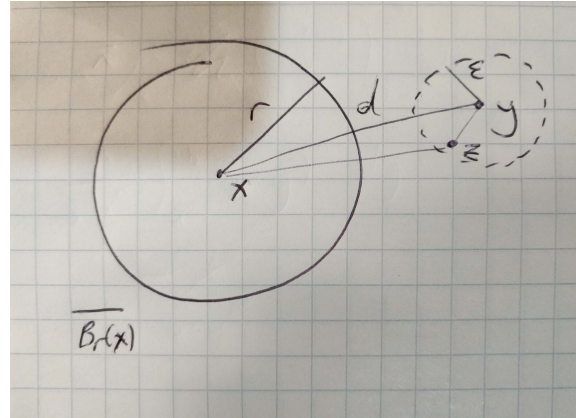


Figure 3.4: A closed ball is a closed set (see proof below).

Proof. Let $F = B_r(x)$ and

$$F^c = (\overline{B_r(x)})^c = \{y \in \mathbb{R}^n \mid \|y - x\| > r\}$$

Let $y \in \overline{B_r(x)}^c$: need to find $\epsilon > 0$ such that $B_\epsilon(y) \subseteq F^c$.

Let $d = \|x - y\| > r$ and let $\epsilon = d - r > 0$.

If $z \in B_\epsilon(y)$, then

$$\begin{aligned} \|x - y\| &\stackrel{\Delta}{\leq} \|x - z\| + \|z - y\| \\ d &\leq \|x - z\| + \|z - y\| \\ \|x - z\| &\geq d - \|z - y\| \\ &> d - \epsilon = r \end{aligned}$$

Hence $z \in F^c$ so $B_\epsilon(y) \subseteq F^c$, thus F^c is open and by definition F is closed. □

3.6 Properties of closed sets

Lemma 3.2. Note: this lemma is the inverse of the equivalent for open sets.

1. If F_1, \dots, F_k is closed, then $\bigcup_{j=1}^k F_j$ is closed.
2. If F_α is closed $\forall \alpha \in A$, then $\bigcap_{\alpha \in A} F_\alpha$ is closed.

Finite unions of closed sets are closed. Arbitrary intersections of closed sets are closed.

Proof. By De Morgan's laws

$$\begin{aligned} \left(\bigcup_{j=1}^k F_j\right)^c &= \bigcap_{j=1}^k (F_j)^c \\ \left(\bigcap_{\alpha \in A} F_\alpha\right)^c &= \bigcup_{\alpha \in A} (F_\alpha)^c \end{aligned}$$

□

3.7 Neither open nor closed

A subset V of \mathbb{R}^n need not be either open or closed. It can be open, closed, neither or both!

Example 3.2. Examples of non-exclusive open or closed sets are

- $(0, 1] \subseteq \mathbb{R}$ - neither
- \mathbb{R}^n, \emptyset are *open and closed*

3.8 Interior

Sometimes a set is neither open or closed, but there are always **natural open (interior) and closed (closure) sets** which can be associated to any subset of \mathbb{R}^n .

Definition 3.5. Let $A \subseteq \mathbb{R}^n$ (could be \emptyset).

$$\begin{aligned} A^o &= \bigcup_{\substack{V \subseteq A \\ V \text{ open in } \mathbb{R}^n}} V && \text{interior of } A \\ &= \bigcup_{\substack{V \subseteq A \\ V \text{ open in } \mathbb{R}^n}} V && \text{union of **all** open subsets of } \mathbb{R}^n \text{ that are contained in } A \end{aligned}$$

Remark 3.3. 1. A^o is open (arbitrary union of open sets) and $A^o \subseteq A$

2. if V is any open subset of \mathbb{R}^n that is contained in A , then $V \subseteq A^o$ (A^o is the largest open subset of \mathbb{R}^n that is contained in A)
3. A is open iff $A^o = A$

Proof. Forwards:

A is open and $A \subseteq A$ thus A must be a V in the union, but since all $V \subseteq A$ then $A^o = A$.

Backwards:

$A^o = A$. Since A^o is open, A is open. □

3.9 Closure

Definition 3.6.

$$\begin{aligned} \overline{A} &= cl(A) && \text{closure of } A \\ &= \bigcap_{\substack{F \supseteq A \\ F \text{ closed in } \mathbb{R}^n}} F && \text{intersection of **all** closed subsets of } \mathbb{R}^n \text{ that contains } A \end{aligned}$$

Remark 3.4. 1. \overline{A} is closed (arbitrary intersection of closed sets) and $\overline{A} \supseteq A$

2. if F is any closed subset of \mathbb{R}^n that contains A , then $F \supseteq \overline{A}$ (\overline{A} is the smallest closed set of \mathbb{R}^n containing A)
3. A is closed iff $\overline{A} = A$

4 January 10, 2018

4.1 Closure of open ball is closed ball

Proposition 4.1. The closure of the open ball $B_\epsilon(x)$ is the closed ball $\overline{B_\epsilon(x)}$ (hence the notation).

Proof. Remember

$$\overline{B_\epsilon(x)} = \{y \in \mathbb{R}^n \mid \|y - x\| \leq \epsilon\}$$

Let $A =$ is closure of $B_\epsilon(x)$.

Let $F = \{y \in \mathbb{R}^n \mid \|x - y\| \leq \epsilon\}$.

We want to show $A = F$.

We know F is closed and $F \supset B_\epsilon(x)$, so F contains $A =$ the closure of $B_\epsilon(x)$ (any closed set containing another set is in the intersection of the closure) or

$$F \supset A \supset B_\epsilon(x)$$

Suppose $F \neq A$, then $\exists y \in F$ with $y \notin A \Rightarrow y \notin B_\epsilon(x)$ so

$$\|x - y\| = \epsilon$$

(it's sandwiched between the closed ball ($\leq \epsilon$) and the open ball ($< \epsilon$), so it must hold with equality with ϵ).

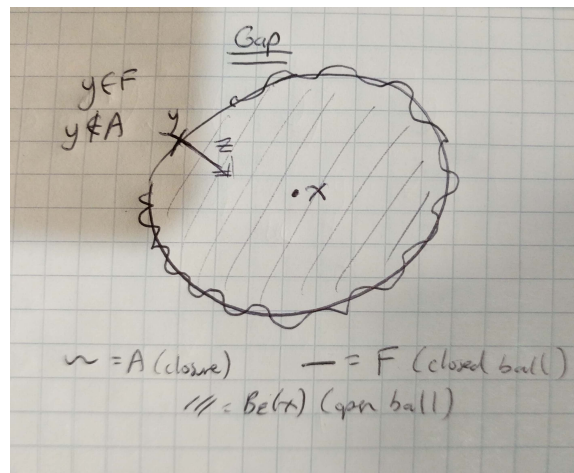


Figure 4.1: The closure of an open ball is the corresponding closed ball.

A is closed and $y \notin A$ so A^c is open and $y \in A^c$. So $\exists \delta > 0$ such that $B_\delta(y) \subseteq A^c$.

Let $t > 0$ with $t < \min\{\delta, \epsilon\}$.

Let

$$z = y + t \frac{(x - y)}{\|x - y\|}$$

(add t unit vectors from y to x). Note that

$$\|z - y\| = t < \delta$$

so $z \in B_\delta(y) \subseteq A^c$.

Also

$$\begin{aligned} x - z &= x - y - t \frac{(x - y)}{\|x - y\|} \\ &= (\|x - y\| - t) \frac{(x - y)}{\|x - y\|} \end{aligned}$$

where the left term is the norm of the vector and the right term is the unit vector.

Thus

$$\|x - z\| = \|\|x - y\| - t\| = |\epsilon - t| = \epsilon - t < \epsilon$$

So $z \in B_\epsilon(x) \subseteq A$, but we assumed $z \in A^c$ which is a contradiction.

So we must have $F = A$.

Remark 4.1. There is a much simpler proof of this using sequences and limit points.

□

4.2 Boundary

Definition 4.1. Let $A \subseteq \mathbb{R}^n$. We define the **boundary** of A denoted $\partial A = bd(A)$ to be

$$\partial A = bd(A) = \{x \in \mathbb{R}^n \mid B_\epsilon(x) \cap A \neq \emptyset, B_\epsilon(x) \cap A^c \neq \emptyset \quad \forall \epsilon > 0\}$$

That is, $x \in \partial A$ iff every open ball centred at x contains a point in A **and** a point in A^c .

Clearly

$$\begin{aligned} \partial B_\epsilon(x) &= \{y \in \mathbb{R}^n \mid \|y - x\| = \epsilon\} \\ &= \partial(\overline{B_\epsilon(x)}) \end{aligned}$$

4.3 Characterization of boundary

Proposition 4.2. Let $A \subseteq \mathbb{R}^n$: then

$$\begin{aligned} \partial A &= \overline{A} \setminus A^\circ \\ &= cl(A) \setminus int(A) \end{aligned}$$

Proof. The following two claims and proofs revolve around complements of sets and how if set A intersect a set B is the empty set, then A is a subset of B^c .

Claim 1

$$x \in \overline{A} \iff B_\epsilon(x) \cap A \neq \emptyset \quad \forall \epsilon > 0$$

Proof. Forwards:

Suppose $x \in \overline{A}$ but $\exists \epsilon_0 > 0$ $B_{\epsilon_0}(x) \cap A = \emptyset$.

So $B_{\epsilon_0}(x) \subseteq A^c \Rightarrow (B_{\epsilon_0}(x))^c \supset A$.

Since $(B_{\epsilon_0}(x))^c$ is closed, then $(B_{\epsilon_0}(x))^c \supset \overline{A}$ (by remark (2) after closure definition).

So $\overline{A} \cap B_{\epsilon_0}(x) = \emptyset$, but $x \in B_{\epsilon_0}(x) \Rightarrow x \notin \overline{A}$, which is a contradiction.

Backwards:

We prove the contrapositive

$$x \notin \bar{A} \Rightarrow B_\epsilon(x) \cap A = \emptyset \quad \forall \epsilon > 0$$

Assume $x \notin \bar{A} \Rightarrow x \in (\bar{A})^c$ which is open, so $\exists \epsilon_0 > 0$ such that $B_{\epsilon_0}(x) \subseteq (\bar{A})^c$. Therefore $B_{\epsilon_0}(x) \cap \bar{A} = \emptyset$ (where $\bar{A} \supset A$), which proves our claim. \square

Claim 2

$$x \notin A^\circ \iff B_\epsilon(x) \cap A^c \neq \emptyset \quad \forall \epsilon > 0$$

Proof. Forwards:

Suppose $x \notin A^\circ$. Assume (for contradiction) $\exists \epsilon_0 > 0$ such that

$$B_{\epsilon_0}(x) \cap A^c = \emptyset \Rightarrow B_{\epsilon_0}(x) \subseteq A$$

(nothing in A^c , thus all in A).

Ergo $x \in (A^\circ)^c$ and $B_{\epsilon_0}(x) \subseteq A^\circ$ (since $B_{\epsilon_0}(x)$ is a closed set contained in A - remark (2) after interior definition).

So $B_{\epsilon_0}(x) \cap (A^\circ)^c = \emptyset$ but $x \in B_{\epsilon_0}(x) \cap (A^\circ)^c$ which is a contradiction.

Backwards:

(Contrapositive): suppose $x \in A^\circ$. A° is open so $\exists \epsilon > 0$ such that

$$B_\epsilon(x) \subseteq A^\circ \subseteq A$$

so $B_\epsilon(x) \cap A^c = \emptyset$. \square

Putting the claims together:

$$x \in \bar{A} \iff B_\epsilon(x) \cap A \neq \emptyset \quad \forall \epsilon > 0 \tag{1}$$

$$x \in (A^\circ)^c \iff B_\epsilon(x) \cap A \neq \emptyset \quad \forall \epsilon > 0 \tag{2}$$

$$x \in \partial A \iff (1) + (2)$$

$$\iff x \in \bar{A} \cap (A^\circ)^c = \bar{A} \setminus A^\circ$$

\square

4.4 Sequences and limits

Definition 4.2. Let (x_k) be a sequence of points in \mathbb{R}^n , $k \in \mathbb{N}$. We say (x_k) **converges** to a point $x \in \mathbb{R}^n$ **iff** for any $\epsilon > 0$, $\exists N \in \mathbb{N}$ (N depends on ϵ in general)

$$k \geq N \Rightarrow \|x_k - x\| < \epsilon$$

(i.e. for any $\epsilon > 0$, **all** the elements of sequence x_k after some $k = N$ are within ϵ of x).

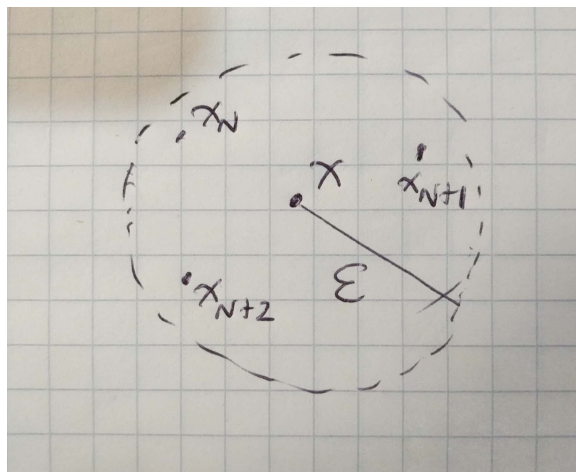


Figure 4.2: All points after $k = N$ for a converging sequence is within ϵ .

If (x_k) converges to x , we denote

$$\lim_{k \rightarrow \infty} x_k = x$$

where x is **the limit** of x_k .

4.5 Uniqueness of limits

Lemma 4.1. Suppose $\lim_{k \rightarrow \infty} x_k = x$ and $\lim_{k \rightarrow \infty} x_k = y$. Then $x = y$ (i.e. a sequence may not converge, but if it does the limit is unique).

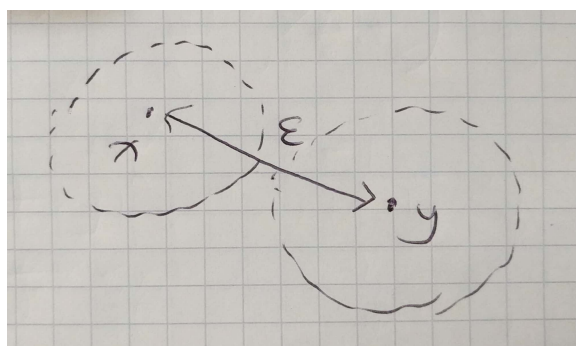


Figure 4.3: Sketch of proof with $x \neq y$ (see below).

Proof. Suppose $x \neq y$, so $\|x - y\| = \epsilon > 0$.

Since (x_k) converges to x , $\exists N_1 \in \mathbb{N}$ such that $k \geq N_1$ and

$$\|x_k - x\| < \frac{\epsilon}{2}$$

Similarly for $y \exists k \geq N_2$.

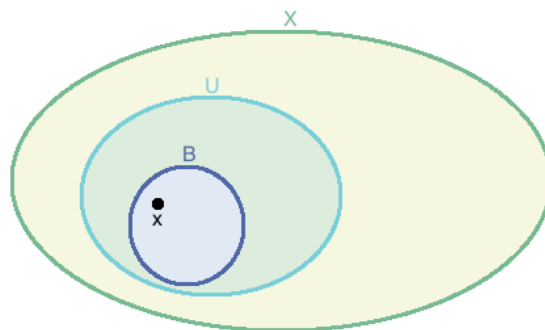
Suppose $k \geq \max\{N_1, N_2\}$. Then

$$\begin{aligned} \|x - y\| &\stackrel{\Delta}{\leq} \|x - x_k\| + \|x_k - y\| \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon \end{aligned}$$

So $x = y$ by contradiction. □

4.6 Neighbourhood

Definition 4.3. Let $x \in \mathbb{R}^n$. A subset $U \subseteq \mathbb{R}^n$ is called a **neighbourhood (n'h'd)** of x if $\exists \epsilon_0 > 0$ such that $B_{\epsilon_0}(x) \subseteq U$.



For every open neighbourhood U of x , there should exist an open set B of x such that B is contained in U .

Figure 4.4: U is a neighbourhood of x since there exists an open set B of x contained in U .

(Equivalently, U is a n'h'd of $x \iff U$ contains an open set containing x .)

Definition 4.4. An open n'h'd of x is any open set containing x . (A set is an open n'h'd of x if it contains x **and** all points sufficiently close to x).

Lemma 4.2. Let (x_k) be a sequence in \mathbb{R}^n . Suppose $\lim_{k \rightarrow \infty} x_k$ exists and equal $x \in \mathbb{R}^n$. Then any n'h'd of x contains all x_k 's for k sufficiently large, i.e. if U is a n'h'd of x , $\exists N \in \mathbb{N}$ (N depends on U) such that

$$k \geq N \Rightarrow x_k \in U$$

Proof. U is a n'h'd of x so $\exists \epsilon_0 > 0$ such that $B_{\epsilon_0}(x) \subseteq U$.

Since $\lim_{k \rightarrow \infty} x_k = x$, $\exists N \in \mathbb{N}$ such that $k \geq N \Rightarrow \|x_k - x\| < \epsilon_0$ so $x_k \in B_{\epsilon_0}(x) \subseteq U \quad \forall k \geq N$. □

5 January 12, 2018

5.1 Relations between convergent sequences and open/closed sets

Recall: $x \in \overline{A} \iff B_\epsilon(x) \cap A \neq \emptyset \quad \forall \epsilon > 0$.

Proposition 5.1. Suppose $x \in \overline{A}$. Take $\frac{1}{k} > 0$. From above: $\exists x_k \in A$ such that $\|x_k - x\| < \frac{1}{k}$, then $\lim_{k \rightarrow \infty} x_k = x$.

Proof. Let $\epsilon > 0$ so $\exists N \in \mathbb{N}$ such that $\frac{1}{N} < \epsilon$ (Archimedean Principle). $\forall k \geq N$, $\frac{1}{k} \leq \frac{1}{N} < \epsilon$ so $\|x_k - x\| < \frac{1}{k} < \epsilon$. □

To summarize, if $x \in \overline{A}$, then \exists a sequence (x_k) such that $\lim_{k \rightarrow \infty} x_k = x$ **and** $x_k \in A \quad \forall k \in \mathbb{N}$.

What about the converse?

Proposition 5.2. Suppose $x_k \in A \quad \forall k$ and $\lim_{k \rightarrow \infty} x_k = x$ **and** $x_k \in A \quad \forall k \in \mathbb{N}$. Then $x \in \overline{A}$.

Proof. If not, $x \in (\overline{A})^c$ so $\exists \epsilon > 0$ such that $B_\epsilon(x) \subseteq (\overline{A})^c$. But $\exists N \in \mathbb{N}$ such that

$$k \geq N \Rightarrow x_k \in B_\epsilon(x)$$

and by hypothesis $x_k \in A \subseteq \overline{A}$.

So $k \geq N \Rightarrow x_k \in \overline{A}$ but we assumed $x_k \in (\overline{A})^c$ which is a contradiction. \square

(i.e. whenever (x_k) is a convergent sequence of points all of whose elements are in A , then the limit is in \overline{A}).

Special case: If A is closed ($\overline{A} = A$) then if $(x_k) \rightarrow x$ and $x_k \in A \forall k$ then $x \in A$; this is **not** true for open sets A .

5.2 Bounded and Cauchy sequences

Definition 5.1. A sequence (x_k) in \mathbb{R}^n is called **bounded** if $\exists M > 0$ such that

$$\|x_k\| \leq M \quad \forall k \in \mathbb{N}$$

(that is: all the x_k 's lie in some closed ball $\overline{B_\epsilon(x)}$ centred at 0).

Definition 5.2. A sequence (x_k) is called **Cauchy** if for any $\epsilon > 0$ there exists an $N \in \mathbb{N}$ such that

$$k, l \geq N \Rightarrow \|x_k - x_l\| < \epsilon$$

(eventually all points in the sequence are close to each other).

5.3 Convergent \iff Cauchy

Proposition 5.3. Let (x_k) be a convergent sequence. Then (x_k) is Cauchy.

Proof. Let $x = \lim_{k \rightarrow \infty} x_k$. Let $\epsilon > 0$, then $\exists N$ such that

$$\|x_k - x\| < \frac{\epsilon}{2}$$

If $k, l \geq N$ then

$$\|x_k - x_l\| \stackrel{\Delta}{\leq} \|x_k - x\| + \|x - x_l\| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$$

\square

Recall from MATH 147: In \mathbb{R} every Cauchy sequence converges (equivalent to **completeness** of \mathbb{R} or the real line). We show Cauchy converges in \mathbb{R}^n in assignment 2 by showing that each j -th component $x^{(j)}$ converges then by the completeness of \mathbb{R} this follows for \mathbb{R}^n .

5.4 Convergence implies bounded

Lemma 5.1. Every convergent sequence is bounded.

Proof. Let $x = \lim_{k \rightarrow \infty} x_k$. Let $M_0 = \|x\| + \epsilon$ for $\epsilon > 0$. Then $\exists N$ such that

$$k \geq N \Rightarrow \|x_k - x\| < \epsilon$$

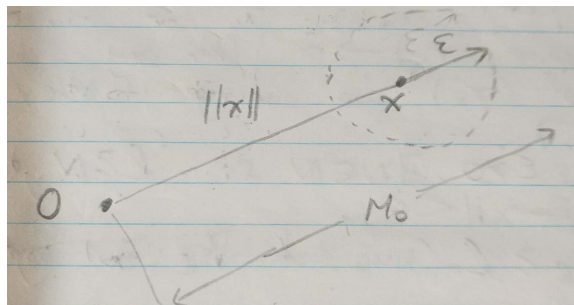


Figure 5.1: Convergent sequences can be bounded by the limit and ϵ and finite points in the sequence.

Note that

$$k \geq N \Rightarrow \|x_k\| \stackrel{\Delta}{\leq} \|x_k - x\| + \|x\| < \epsilon + \|x\| = M_0$$

Thus we let $M = \max\{\|x_1\|, \dots, \|x_{N-1}\|, M_0\}$ then $\|x_k\| \leq M \quad \forall k \in \mathbb{N}$. □

Note: not every bounded sequence is Cauchy. Consider $x_k = (-1)^{k+1}$ in \mathbb{R} , which is bounded but not convergent. Can we find a weaker statement that's true i.e. given a bounded sequence, can we somehow obtain from it a convergent sequence?

5.5 Subsequences

Let (x_k) be a sequence in \mathbb{R}^n . Let $1 \leq k_1 < k_2 < \dots < k_e < k_{e+1} < \dots$ be a sequence of $1, 2, 3, 4, \dots$. Then the corresponding sequence (y_l) (or (x_{k_l})) in \mathbb{R}^n given by $y_l = x_{k_l}$ is called a **subsequence** of (x_k) .

Example 5.1. The subsequence given by $k_l = 2l - 1$ (odd numbers) is

$$(x_{2l-1}) = x_1, x_3, x_5, \dots$$

Proposition 5.4. Suppose $(x_k) \rightarrow x$. Then any subsequence (x_{k_l}) of (x_k) also converges to the same limit x .

Proof. Let $\epsilon > 0$. $\exists N \in \mathbb{N}$ such that $l \geq N$ then $\|x_l - x\| < \epsilon$, but $k_l \geq l$ (since each k_e must be strictly larger $> k_{e-1}$), so $\|x_{k_l} - x\| < \epsilon \quad \forall l \geq N$ hence $\lim_{k_l \rightarrow \infty} x_{k_l} = x$. □

Note: A sequence (x_k) that does not converge can have

1. Subsequences that don't converge (e.g. $k_l = l$ so $x_{k_l} = x_l$).
2. Distinct subsequences with different limits.

For example, $x_k = (-1)^{k+1}$ which is $1, -1, 1, -1, \dots$, we can have two subsequences

$$\begin{aligned} x_{2l-1} &= (-1)^{2l} = 1, 1, 1, \dots & (x_{2l-1}) &\rightarrow 1 \\ x_{2l} &= (-1)^{2l-1} = -1, -1, -1, \dots & (x_{2l}) &\rightarrow -1 \end{aligned}$$

5.6 Bolzano-Weierstrass (B-W) Theorem

Theorem 5.1. In \mathbb{R}^n , every bounded sequence has a convergent subsequence.

Remark 5.1. This convergent subsequence is **not** unique. We'll see in the proof that we make many arbitrary choices.

Proof. By induction on n .

Case $n = 1$: Let (x_k) be a sequence in \mathbb{R} that is **bounded**. So $\exists M > 0$ such that $|x_k| \leq M \quad \forall k \in \mathbb{N} \iff x_k \in [-M, M]$.

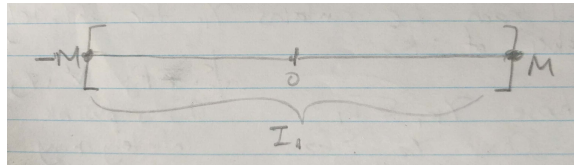


Figure 5.2: I_1 is the interval of our bounded sequence in \mathbb{R} .

Define

$$I_1 = [-M, M] = [-M, 0] \cup [0, M]$$

At least one (maybe both) of $[-M, 0]$ and $[0, M]$ contains x_k for infinite many values of k (the x_k 's could initially be all in one side then infinitely many in the other, or the x_k 's could jump back and forth so both would have infinitely many).

Let I_2 denote the one with infinitely many. That is $x_k \in I_2$ for infinitely many x_k 's. Note that

$$I_2 \subseteq I_1$$

$$I_2 = [a, b] = [a, \frac{a+b}{2}] \cup [\frac{a+b}{2}, b]$$

Again, at least one of these halves contains infinitely many x_k 's. Let I_3 be that one.

Keep subdividing in this way and choosing a half which contains x_k for infinitely many k 's. We have

$$\text{length } I_1 = 2M$$

$$\text{length } I_2 = M$$

$$\text{length } I_3 = \frac{M}{2}$$

$$\vdots$$

$$\text{length } I_l = \frac{2M}{2^{l-1}}$$

moreover,

$$I_1 \supseteq I_2 \supseteq \dots \supseteq I_e \supseteq I_{e+1} \supseteq \dots$$

and each I_l contains x_k for infinitely many values of k .

We can thus choose some $x_{k_1} \in I_1, x_{k_2} \in I_2, \dots, x_{k_l} \in I_l \quad \forall l \in \mathbb{N}$ where $1 \leq k_1 < k_2 < \dots < k_e < k_{e+1} < \dots$. This is possible since there are infinitely many x_k 's in each interval.

We claim:

1.

$$\bigcap_{l=1}^{\infty} I_l \neq \emptyset$$

and in fact contains **exactly one point** x .

Note that

$$I_l = [a_l, b_l] \quad \text{for some } a_l < b_l$$

and also

$$I_l \supset I_{l+1} \Rightarrow a_1 \leq a_l \leq a_{l+1} < b_{l+1} \leq b_l \leq b_1 \quad \forall l$$

(i.e. either endpoints move inwards for each successive interval).

So (a_l) is an increasing sequence bounded by b_1 , therefore $\exists a$ such that $\lim_{l \rightarrow \infty} a_l = a$ and $a_l \leq a \leq b_1 \quad \forall l$.

Similarly (b_l) is a decreasing sequence bounded by a_1 , so $\exists b$ such that $\lim_{l \rightarrow \infty} b_l = b$ and $a_1 \leq b \leq b_l \quad \forall l$.

We have $a_l < b_l \quad \forall l$. Taking the limit we have $a \leq b$ (limit can only be guaranteed with potential for equality).

$$a_1 \leq a_l \leq a_{l+1} \leq a \leq b \leq b_{l+1} \leq b_l \leq b_1$$

Note that

$$\begin{aligned} 0 \leq b - a \leq b_l - a_l &= \text{length}(I_l) \\ &= \frac{2M}{2^{l-1}} \rightarrow 0 \text{ as } l \rightarrow \infty \end{aligned}$$

hence $a = b$ (call this x).

By construction $x = a = b \in [a_l, b_l] = I_l \quad \forall l$ so

$$x \in \bigcap_{l=1}^{\infty} I_l$$

so there exists an element. Suppose $y \in \bigcap_{l=1}^{\infty} I_l$ then $x, y \in I_l \quad \forall l$ and

$$|x - y| \leq \frac{2M}{2^{l-1}} \quad \forall l \Rightarrow x = y \text{ (as } l \rightarrow \infty)$$

2.

$$\lim_{l \rightarrow \infty} x_{k_l} = x$$

Assume $x_{k_l} \in I_l$ and $x \in I_l \quad \forall l$ (from claim 1). So

$$|x_{k_l} - x| \leq \frac{2M}{2^{l-1}} \rightarrow 0 \text{ as } l \rightarrow \infty$$

thus $\lim_{l \rightarrow \infty} x_{k_l} = x$.

The above two claims prove the theorem for $n = 1$.

Now suppose the theorem is true for n , we show it is true for $n + 1$.

Let (x_k) be a bounded sequence in \mathbb{R}^{n+1} , so $\exists M$ such that $\|x_k\| \leq M \quad \forall k$.

We write $x_k = (x_k^1, x_k^2, \dots, x_k^{n+1})$ where x_k^j is the j -th component of vector $x_k \in \mathbb{R}^{n+1}$.

So

$$\|x_k\|^2 = |x_k^1|^2 + |x_k^2|^2 + \dots + |x_k^n|^2 + |x_k^{n+1}|^2 \leq M^2 \quad (5.1)$$

Define a sequence (y_k) in \mathbb{R}^n as the first n components of x_k

$$y_k = (x_k^1, \dots, x_k^n)$$

therefore $\|y_k\| \leq M \quad \forall k$ by equation 5.1.

By the inductive hypothesis, \exists a subsequence (y_{k_l}) of (y_k) that converges to some point $x = (x^1, \dots, x^n) \in \mathbb{R}^n$.

Consider the sequence $(x_{k_l}^{n+1})$ in \mathbb{R}^1 (**TODO(richardwu): why can't we just use (x_k^{n+1}) here instead?**). By equation 5.1, $|x_{k_l}^{n+1}| \leq M \quad \forall l$, so $(x_{k_l}^{n+1})$ is a bounded sequence in \mathbb{R} . By B-W for $n = 1$, \exists subsequence $(x_{k_{l_j}}^{n+1})$ that converges to some $x^{n+1} \in \mathbb{R}$.

Consider the subsequence $(y_{k_{l_j}})$ of (y_{k_l}) , which also converges to $(x^1, \dots, x^n) \in \mathbb{R}^n$.

So $x_{k_{l_j}}^a \rightarrow x^a$ as $j \rightarrow \infty$ for $a = 1, \dots, n$ and $a = n+1$.

Thus the sequence $x_{k_{l_j}} \rightarrow x$ as $j \rightarrow \infty$.

Remark 5.2. We used the IH/B-W on the first n components and then the $n+1$ component to find corresponding convergent subsequences. In order to “meld” them together, we needed to take the subsequence of either subsequence (to have a 2-level subsequence) to ensure it converges for the same k_{l_j} 's as the other 1-level subsequence.

TODO(richardwu): see the above TODO for why we don't just take k_l 's instead of k_{l_j} 's.

□

6 January 15, 2017

6.1 Connectedness

Definition 6.1. Let E be a non-empty subset of \mathbb{R}^n .

We say E is **disconnected** if there exists a **separation** for E . A separation of E is a pair U, V open sets in \mathbb{R}^n such that

1. $E \cap U \neq \emptyset$
2. $E \cap V \neq \emptyset$
3. $E \cap U \cap V = \emptyset$
4. $E \subseteq U \cup V$

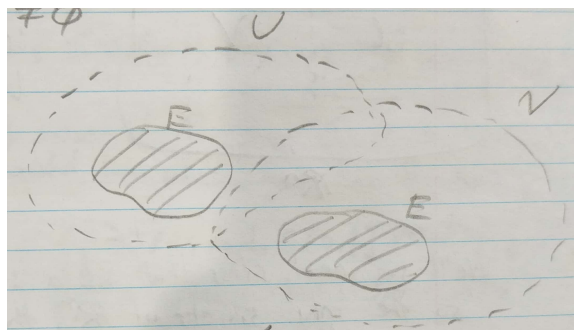


Figure 6.1: E is disconnected since there are open sets U, V that form a separation.

Note that $U \cap V$ need not be empty, but it must be disjoint from E . (intuitively a set is disconnected if it is more than one piece).

Definition 6.2. E is **connected** if \nexists any separation of E .

Remark 6.1. Connectedness and disconnectedness do not apply to \emptyset .

6.2 Is \mathbb{R}^n connected?

(Yes it is).

Suppose \exists a separation of \mathbb{R}^n of open sets U, V such that

1.

$$\emptyset \neq U \cap \mathbb{R}^n = U$$

$$\emptyset \neq V \cap \mathbb{R}^n = V$$

which implies U, V both non-empty. Furthermore

2.

$$U \cap V \cap \mathbb{R}^n = U \cap V = \emptyset$$

which implies U, V are disjoint.

3.

$$\mathbb{R}^n \subseteq U \cup V \subseteq \mathbb{R}^n$$

so $\mathbb{R}^n = U \cup V$. Since $U \cap V = \emptyset$, then $U^c = V$ and $V^c = U$.

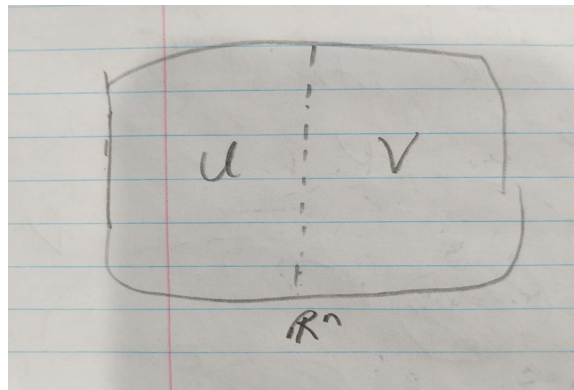


Figure 6.2: Sketch of what disconnected \mathbb{R}^n would look like.

This would mean U, V are both **non-empty** subsets that are **both open and closed** and $U, V \neq \mathbb{R}^n$ (since they are non-empty disjoint).

In other words, if $\exists U$ such that $U \neq \emptyset, U \neq \mathbb{R}^n$ and U is both open and closed, then $U, V = U^c$ gives a separation of \mathbb{R}^n .

We'll see (next class) that \nexists a separation of \mathbb{R}^n for any n , so the only subsets of \mathbb{R}^n that are both open and closed are \emptyset, \mathbb{R}^n .

6.3 $[0, 1]$ is connected

This is an example of a connected subset in \mathbb{R} and will be used next time to prove \mathbb{R}^n is connected and *more*.

Theorem 6.1. Let $E = [0, 1] \subseteq \mathbb{R}$. Then E is connected.

(Aside: in fact: *any* interval $[a, b], [a, b), (a, b], (a, b)$ in \mathbb{R} is connected and these are the **only** connected subsets in \mathbb{R} i.e. connectedness \Rightarrow interval).

Proof. By contradiction.

Suppose $[0, 1]$ is not connected. \exists a separation U, V open subsets of $[0, 1]$ where

1. $U \cap [0, 1] \neq \emptyset$
2. $V \cap [0, 1] \neq \emptyset$
3. $U \cap V \cap [0, 1] = \emptyset$
4. $[0, 1] \subseteq U \cup V$

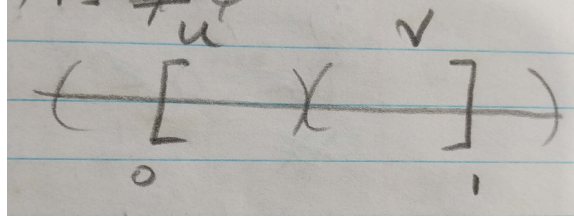


Figure 6.3: Sketch of U, V open sets as (potential) separation for $[0, 1]$.

WLOG $0 \in U$. Since U is open and $0 \in U$, $\exists \epsilon_0 > 0$ such that $B_{\epsilon_0}(0) = (-\epsilon_0, \epsilon_0) \subseteq U$.

WLOG, $\epsilon_0 < 1$ so $[0, \epsilon_0) \subseteq U \cap [0, 1]$.

Define t_0 as

$$\sup\{\epsilon \in (0, 1) \mid [0, \epsilon) \subseteq U \cap [0, 1]\}$$

note: the above is a non-empty subset of \mathbb{R} since ϵ_0 is in the set. It's bounded above by 1, so the supremum or t_0 must exist.

We have $0 < \epsilon_0 \leq t_0 \leq 1$ so $t_0 \in (0, 1]$, thus $t_0 \in U$ or $t_0 \in V$.

Case 1: $t_0 \in U$ Since U is open (all open sets have some open ball around every point) $\exists \delta > 0$ such that

$$(t_0 - \delta, t_0 + \delta) \subseteq U \tag{6.1}$$

WLOG $\delta < t_0$ but $0 < t_0 - \delta < t_0$ so by definition of t_0 (as supremum), $\exists \hat{\epsilon} > 0$ with $t_0 - \delta < \hat{\epsilon} < t_0$ such that

$$[0, \hat{\epsilon}) \subseteq U \cap [0, 1] \tag{6.2}$$

Combining equation 6.1 and 6.2 (joining the two intervals together since we do not know if either separately are in U), we have

$$[0, t_0 + \delta) \subseteq U \cap [0, 1] \tag{6.3}$$

We have two subcases:

$t_0 < 1$ Then we can shrink $\delta > 0$ further to ensure $t_0 + \delta < 1$ ($\delta < 1 - t_0$).

Then $0 < t_0 + \delta < 1$ and $[0, t_0 + \delta) \subseteq U \cap [0, 1]$ which contradicts t_0 as the supremum.

$t_0 = 1$ This implies $U \cap [0, 1] = [0, 1]$ by equation 6.3 but then $V \cap [0, 1] = \emptyset$ (since $U \cap V \cap [0, 1] = \emptyset$), which is a contradiction since V must be non-empty.

Case 2: $t_0 \in V$ Since V is open $\exists \zeta > 0$ such that

$$(t_0 - \zeta, t_0 + \zeta) \subseteq V \tag{6.4}$$

WLOG $\zeta < t_0$ but $0 < t_0 - \zeta < t_0$ so by definition of t_0 (as supremum) $\exists \tilde{\epsilon} > 0$ with $t_0 - \zeta < \tilde{\epsilon} \leq t_0$ such that

$$[0, \tilde{\epsilon}] \subseteq U \cap [0, 1]$$

(it's U since that was the set t_0 was defined with).

Pick $s \in (t_0 - \zeta, \tilde{\epsilon})$. Then $s \in U \cap [0, 1]$ by equation 6.1 but also $s \in V \cap [0, 1]$ by equation 6.4, which is a contradiction.

By the contradiction of the two cases above, $[0, 1]$ is connected. □

7 January 17, 2017

7.1 Convex sets

Definition 7.1. A non-empty subset E of \mathbb{R}^n is called **convex** if whenever $x, y \in E$ then

$$tx + (1 - t)y \in E \quad \forall t \in [0, 1]$$

i.e. the line segment between any 2 points in E is contained in E .

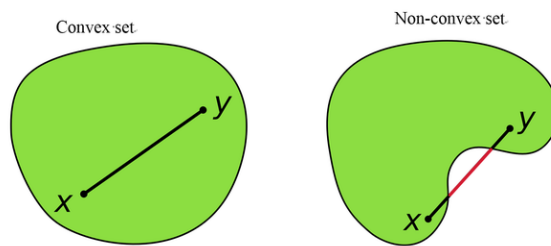


Figure 7.1: Convex and non-convex sets in \mathbb{R}^2 .

7.2 Convex \Rightarrow connected

Corollary 7.1. Any convex subset E of \mathbb{R}^n is connected. This implies two corollaries:

Corollary 7.2. \mathbb{R}^n is connected $\forall n$ since \mathbb{R}^n is trivially connected.

Corollary 7.3. The only subsets of \mathbb{R}^n that are both open and closed are \emptyset, \mathbb{R}^n (see the remark about \mathbb{R}^n connectedness from above).

Proof. Let E be convex and suppose E is *not* connected. \exists open subsets U, V such that

1. $U \cap E \neq \emptyset$
2. $V \cap E \neq \emptyset$
3. $U \cap V \cap E = \emptyset$
4. $E \subseteq U \cup V$

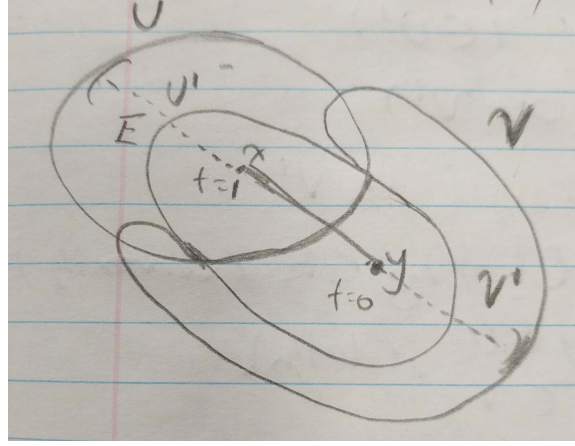


Figure 7.2: Suppose convex E is not connected and there exists a separation U, V .

Let $x \in U \cap E$ and $y \in V \cap E$ (therefore $x \neq y$ since $U \cap V \cap E = \emptyset$). Since E is convex,

$$tx + (1 - t)y \in E \quad \forall t \in [0, 1]$$

Define U', V' subsets of \mathbb{R}^n by

$$U' = \{t \in \mathbb{R} : tx + (1 - t)y \in U\}$$

$$V' = \{t \in \mathbb{R} : tx + (1 - t)y \in V\}$$

(note: U', V' is not restricted to elements $[0, 1]$: t could extend arbitrarily into E^c).

Claim: U', V' are open subsets of \mathbb{R} . Let $t_0 \in U'$ so $x_0 = t_0x + (1 - t_0)y \in U$. Since U is open in \mathbb{R}^n $\exists \epsilon_0 > 0$ such that $B_{\epsilon_0}(x_0) \in U$. We pick $t \in \mathbb{R}$ such that

$$|t - t_0| < \frac{\epsilon_0}{\|x\| + \|y\|}$$

then

$$\begin{aligned} B_{\epsilon_0}(x_0) \Rightarrow \|(tx + (1 - t)y) - x_0\| &= \|tx + (1 - t)y - t_0x - (1 - t_0)y\| \\ &= \|(t - t_0)x + (t_0 - t)y\| \\ &\triangleq \\ &\leq |t - t_0|(\|x\| + \|y\|) \\ &< \epsilon_0 \end{aligned}$$

But $B_{\epsilon_0}(x_0) \subseteq U$ so if $|t - t_0| < \frac{\epsilon_0}{\|x\| + \|y\|}$ then $t \in U'$ (we want our choice of t to imply $t \in U'$).

So $\frac{B_{\epsilon_0}(t_0)}{\|x\| + \|y\|} \subseteq U'$ so U' is open.

Similarly, V' is open.

Thus here are the properties of U', V' . They are both open in \mathbb{R} and

1. $U' \cap [0, 1] \neq \emptyset$ (since $1 \in U'$)
2. $V' \cap [0, 1] \neq \emptyset$ (since $0 \in V'$)
3. $U' \cap V' \cap [0, 1] = \emptyset$ (since $0 \in V'$)

Given some $t \in [0, 1]$ (since $tx + (1 - t)y \in E$ from convexity), note that either $t \in U'$ from $tx + (1 - t)y \in U$ or $t \in V'$ from $tx + (1 - t)y \in V$ (we know from before that $U \cap V \cap E = \emptyset$ thus this must hold for the subsets

$U', V')$.

4. $[0, 1] \subseteq U' \cup V'$

If $t \in [0, 1]$, then $z = tx + (1 - t)y \in E$ so $z \in U \cup V$ from before, so $z \in U$ or $z \in V$, thus by their definitions $t \in U'$ or $t \in V'$.

Then U', V' is a separation for $[0, 1]$, which is a contradiction. Thus E is connected. \square

Remark 7.1. In general, to prove a set E is connected it is generally easier to assume it is *not* connected and there exists a separation, then derive a contradiction.

7.3 Open cover and compactness

Definition 7.2. Let E be a subset of \mathbb{R}^n . An **open cover** of E is a collection of open subsets U_α $\alpha \in A$ of \mathbb{R}^n such that

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

(finite or infinite union of open subsets).

Definition 7.3. The subset E is called **compact** iff every open cover of E admits a **finite subcover**. That is: if $\bigcup U_\alpha$ $\alpha \in A$ is an open cover of E , then \exists a finite subset A_0 of A such that

$$E \subseteq \bigcup_{\alpha \in A_0} U_\alpha$$

Informally, whenever a compact E is covered by a collection of open sets, it is actually covered by just finitely many of those open sets.

Remark 7.2. This definition is not very useful for checking if a subset is compact (because you would have to check every open cover of E).

Definition 7.4. A subset $E \subseteq \mathbb{R}^n$ is called **bounded** if $\exists M > 0$ such that $E \subseteq B_M(0)$. That is $\|x\| < M \forall x \in E$.

8 January 19, 2018

8.1 Heine-Borel theorem

Theorem 8.1. Let E be a subset of \mathbb{R}^n . E is **compact** iff E is both **closed** and **bounded**. The following proof uses the *density of rationals*.

Proof. Step 1: Suppose E is *compact*. We want to show that E is *bounded*.

Let $U_k = B_k(0) = \{x \in \mathbb{R}^n \mid \|x\| < k\}$. U_k is open $\forall k$, thus $U_k \subseteq U_{k+1} \forall k \in \mathbb{N}$. Therefore

$$E \subseteq \bigcup_{k=1}^{\infty} U_k = \mathbb{R}^n$$

$\{U_k, k \in \mathbb{N}\}$ is an open cover of E . Since E is compact, \exists a finite subcover so $\exists k_1 < k_2 < \dots < k_N \in \mathbb{N}$ such that

$$E \subseteq \bigcup_{j=1}^N U_{k_j} = U_{k_N} = B_{k_N}(0)$$

since they're nested so E is bounded.

Corollary 8.1. \mathbb{R}^n is not compact because it is not bounded.

Step 2: Let E be *compact*, we show it is *closed*.

To do this: we show E^c is open (aside if $E^c = \emptyset$ then we are done. This never happens since E is not \mathbb{R}^n).

Let $x \in E^c$. We need to find an open ball centred at x lying completely in E^c . Note $E \subseteq \mathbb{R}^n \setminus \{x\}$ since $x \notin E$.

Let (different U_k from before)

$$U_k = (\overline{B_{\frac{1}{k}}(x)})^c = \{x \in \mathbb{R}^n \mid \|x - y\| > \frac{1}{k}\}$$

which is open (complement of closed ball). We can use this as covers.

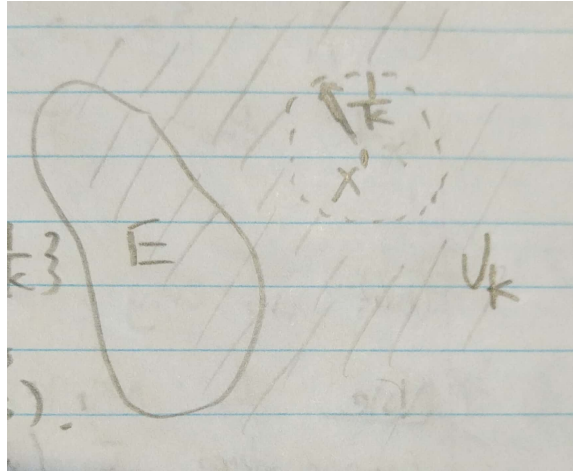


Figure 8.1: U_k is the complement of the closed ball centred at $x \in E^c$ with radius $\frac{1}{k}$ for some $k \in \mathbb{N}$.

If $l > k$, then $\frac{1}{l} < \frac{1}{k}$. Thus if $y \in U_k$, then $\|y - x\| > \frac{1}{k} > \frac{1}{l}$ so $y \in U_l$. That is

$$U_k \subseteq U_l \quad k < l$$

Note that we have

$$E \subseteq \mathbb{R}^n \setminus \{x\} = \bigcup_{k=1}^{\infty} U_k$$

where the infinite union of U_k is an open cover of E . Since E is compact, we have a finite subcover U_{k_1}, \dots, U_{k_N} such that

$$\begin{aligned} E &\subseteq \bigcup_{j=1}^N U_{k_j} \\ &= U_{k_N} \\ &= (\overline{B_{\frac{1}{k_N}}(x)})^c \end{aligned} \quad \text{equation 8.1}$$

Take complements (from $A \subseteq B \Rightarrow B^c \subseteq A^c$)

$$x \in B_{\frac{1}{k_N}}(x) \subseteq \overline{B_{\frac{1}{k_N}}(x)} \subseteq E^c$$

So \exists an open ball for x thus E^c is open and E is closed.

Before we prove the converse:

Lemma 8.1. Let E be any subset of \mathbb{R}^n . Let $\{U_\alpha \mid \alpha \in A\}$ be an open cover of E (so U_α open $\forall \alpha \in A$). That is

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

Thus \exists a countable subset \tilde{A} of A

$$\tilde{A} = \{\alpha_1, \alpha_2, \dots\} = \{\alpha_k \mid k \in \mathbb{N}\}$$

such that $E \subseteq \bigcup_{k=1}^{\infty} U_{\alpha_k}$.

That is: **every open cover admits a countable subcover**. (Note: an infinite set is countable **iff** \exists bijective correspondence with \mathbb{N} . Rational numbers are countable whereas \mathbb{R} is not).

Proof. Assume $E \subseteq \bigcup_{\alpha \in A} U_\alpha$.

Let $x \in E$. Then $\exists \alpha(x) \in A$ such that $x \in U_{\alpha(x)}$.

Since $U_{\alpha(x)}$ is open $\exists \epsilon(x) > 0$ such that

$$B_{\epsilon(x)}(x) \subseteq U_{\alpha(x)}$$

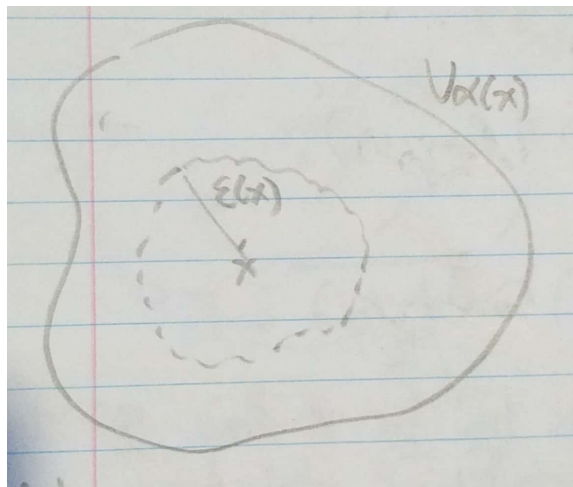


Figure 8.2: We can construct an open ball $B_{\epsilon(x)}(x)$ within some $U_{\alpha(x)}$ for every $x \in E$.

Then $E \subseteq \bigcup_{x \in E} B_{\epsilon(x)}(x)$ (all x). Since the rational numbers \mathbb{Q} are dense in \mathbb{R} , $\exists q(x) \in \mathbb{Q}^n$ and $\zeta(x) \in \mathbb{Q}$ such that

$$\begin{aligned} \|x - q(x)\| &< \frac{\epsilon(x)}{4} \\ \frac{\epsilon(x)}{4} &< \zeta(x) < \frac{\epsilon(x)}{2} \end{aligned}$$

Therefore

$$\|x - q(x)\| < \frac{\epsilon(x)}{4} < \zeta(x)$$

So $x \in B_{\zeta(x)}(q(x))$.

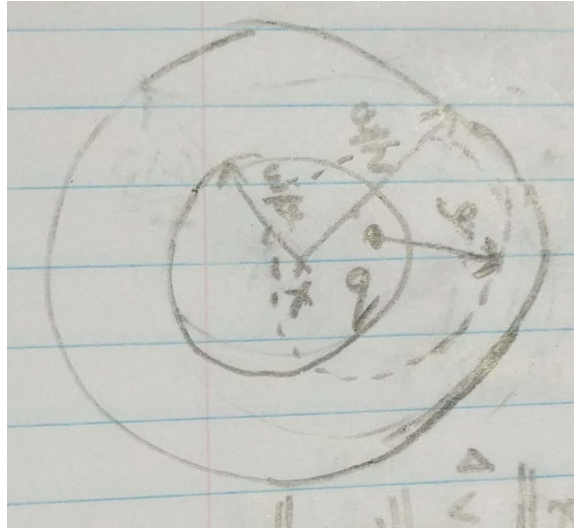


Figure 8.3: We find some open ball centred at $\zeta(x) \in \mathbb{Q}$ with radius $q(x) \in \mathbb{Q}^n$ that contains x .

Suppose $y \in B_{\zeta(x)}(q(x))$, then we have

$$\begin{aligned} \|x - y\| &\stackrel{\Delta}{\leq} \|x - q(x)\| + \|q(x) - y\| \\ &< \frac{\epsilon(x)}{4} + \zeta(x) \\ &< \frac{\epsilon(x)}{4} + \frac{\epsilon(x)}{2} \\ &< \epsilon(x) \end{aligned}$$

So $y \in B_{\epsilon(x)}(x)$ therefore $B_{\zeta(x)}(q(x)) \subseteq B_{\epsilon(x)}(x)$.

We have shown for every $x \in E$, $\exists q(x) \in \mathbb{Q}^n$ and $\zeta(x) \in \mathbb{Q}$ such that

$$x \in B_{\zeta(x)}(q(x)) \subseteq B_{\epsilon(x)}(x)$$

So $E \subseteq \bigcup_{x \in E} B_{\zeta(x)}(q(x))$ but \mathbb{Q} and \mathbb{Q}^n are countable so $\exists q_j \in \mathbb{Q}^n$ and $\zeta_j \in \mathbb{Q}$ where $j \in \mathbb{N}$ such that

$$\begin{aligned} E &\subseteq \bigcup_{j=1}^{\infty} B_{\zeta_j}(q_j) \\ &\subseteq \bigcup_{j=1}^{\infty} B_{\epsilon(x_j)}(x_j) \\ &\subseteq \bigcup_{j=1}^{\infty} U_{\alpha}(x_j) \end{aligned} \quad \text{by equation 8.1}$$

so we have a countable subcover. □

Back to proving the converse: **Step 3:** Let E be *closed and bounded*. We want to show E is *compact*.

Let $\{U_{\alpha} \mid \alpha \in A\}$ be an open cover of E . We showed in the above lemma that $\exists q_j \in \mathbb{Q}^n$, $\zeta_j \in \mathbb{Q}$ where $j \in \mathbb{N}$ such

that

$$E \subseteq \bigcup_{j=1}^{\infty} B_{\zeta_j}(q_j)$$

Claim: $\exists N \in \mathbb{N}$ such that $E \subseteq \bigcup_{j=1}^N B_{\zeta_j}(q_j)$. (i.e. we need only need finitely many of these balls).
If the claim is true, then

$$\begin{aligned} E &\subseteq \bigcup_{j=1}^N B_{\zeta_j}(q_j) \\ &\subseteq \bigcup_{j=1}^N B_{\epsilon(x_j)}(x_j) \\ &\subseteq \bigcup_{j=1}^N U_{\alpha}(x_j) \end{aligned}$$

so we would have a finite subcover.

It remains to prove the claim. Suppose the claim is false (proof by contradiction). Then for every $k \in \mathbb{N}$, we have $E \setminus \bigcup_{j=1}^k B_{\zeta_j}(q_j) \neq \emptyset$.

We choose $x_k \in E \setminus \bigcup_{j=1}^k B_{\zeta_j}(q_j)$. Note that (x_k) is a sequence in E and E is bounded, so (x_k) is a bounded sequence.

By Bolzano-Weierstrass, there exists a subsequence (x_{k_l}) that converges.

$(x_{k_l}) \in E \forall l \in \mathbb{N}$ and E is closed so $x = \lim_{l \rightarrow \infty} x_{k_l} \in E$ as well.

$x \in E$, so \exists some $J \in \mathbb{N}$ such that

$$x \in B_{\zeta_J}(q_J)$$

from our lemma.

But since $\lim_{l \rightarrow \infty} x_{k_l} = x$ then $\exists N \in \mathbb{N}$ such that $\forall l \geq N$

$$x_{k_l} \in B_{\zeta_J}(q_J)$$

(definition of convergent sequence).

But by construction of our sequence

$$x_{k_l} \notin \bigcup_{j=1}^M B_{\zeta_j}(q_j)$$

for any $k_l \geq M$.

So if $k_l > J$, then

$$x_k \notin B_{\zeta_J}(q_J)$$

for $l \geq \max(N, J) \Rightarrow k_l \geq \max(N, J)$.

From equation 8.1 and equation 8.1, we have a contradiction.

(The idea of this proof revolves around showing that all $x \in E$ must be in some open ball with rational parameters. By assuming the contrary of the claim that there is a finite subcover, we choose some sequence outside of all finite subcovers (made of the rational parameters) and show that it is not in an open ball with rational parameters. Thus we have a contradiction so there must be some finite subcover with the open balls of rational parameters). \square

9 January 22, 2018

9.1 Limits of functions

Let $V \subseteq \mathbb{R}^n$ be an *open set* with $x_0 \in V$. Let $f : V \setminus \{x_0\} \rightarrow \mathbb{R}^m$ for some m (i.e. f is defined at all points of V except *possibly* at x_0).

Definition 9.1. We say $\lim_{x \rightarrow x_0} f(x)$ exists and equals $L \in \mathbb{R}^m$ **iff** $\forall \epsilon > 0, \exists \delta > 0$ such that

$$0 < \|x - x_0\| < \delta \Rightarrow \|f(x) - L\| < \epsilon$$

(note that $B_\delta(x_0) \subseteq V$ must hold). In general, δ depends on both ϵ and x_0 (and on f as well if suppose it has a different domain).

Remark 9.1. When $n > 1$, things get more complicated since in $n = 1$, there exists only 2 ways to approach x_0 : from left or right (i.e. $\lim_{x \rightarrow x_0} f(x)$ exists *iff* both left and right limits exist and are equal in $n = 1$).

In $n > 1$, \exists *infinitely many ways* to approach x_0 . This is what makes establishment of the existence of limits harder for $n > 1$.

Example 9.1. Example where different linear paths result in a different limit:

Let $n = 2, m = 1$ ($f : \mathbb{R}^2 \rightarrow \mathbb{R}$) where we denote $(x, y) \in \mathbb{R}^2$.

Suppose we wish to find

$$\lim_{(x,y) \rightarrow (2,3)} \frac{(x-2)^2}{(x-2)^2 + (y-3)^2}$$

where $f(x, y)$ defined everywhere except $(2, 3)$.

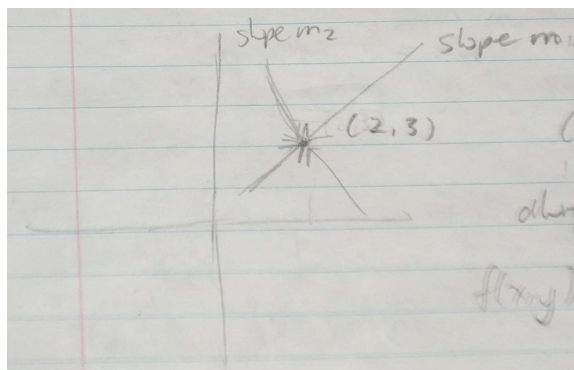


Figure 9.1: There exists many paths to approach $x_0 = (2, 3)$ in f , $m_1 \neq m_2$.

Suppose we have paths/lines with slope m where $(y - 3) = m(x - 2)$. Along this line we have

$$\begin{aligned} f(x, y) &= \frac{(x-2)^2}{(x-2)^2 + (y-3)^2} \\ &= \frac{1}{1 + m^2} \end{aligned}$$

So f is a constant function which depends on the slope of the line/path (it depends on m). Since we found at least 2 paths towards $(2, 3)$ along which f approaches different limiting values, then the limit **DNE**.

Example 9.2. Example where linear paths converge but quadratic paths do not:

We wish to find

$$\lim_{(x,y) \rightarrow (0,0)} \frac{xy^2}{x^2 + y^4}$$

where the domain is $\mathbb{R}^2 \setminus \{0,0\}$.

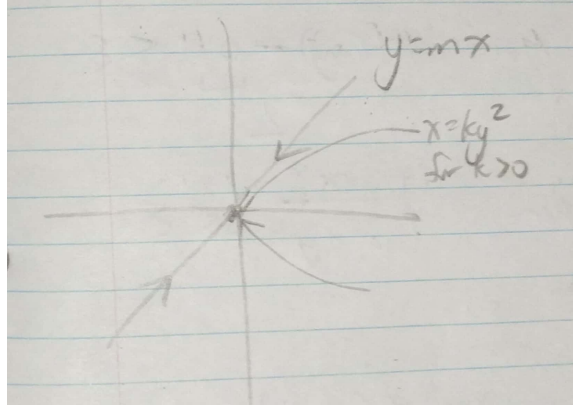


Figure 9.2: There are linear and non-linear paths that approaches $x_0 = (0,0)$.

Note that unlike previously, linear paths $y = mx$ do converge

$$\begin{aligned} f(x, y) &= \frac{x(mx)^2}{x^2 + (mx)^4} \\ &= \frac{m^2 x^3}{x^2 + m^4 x^4} \\ &= \frac{m^2 x}{1 + m^4 x^2} \end{aligned}$$

So as $x \rightarrow 0$, then $\frac{m^2 x}{1 + m^4 x^2} \rightarrow 0$ for any m .

Along $x = 0$ we still have

$$f(x, y) = \frac{0 \cdot y^2}{0^2 + y^4} = 0 \quad \forall y \neq 0$$

(this is important since a vertical line is not explicit). So f approaches 0 as $(x, y) \rightarrow (0, 0)$ for linear paths. We must consider other non-linear paths as well e.g. along $x = ky^2$ we have

$$f(x, y) = \frac{(ky^2)y^2}{(ky^2)^2 + y^4} = \frac{k}{k^2 + 1}$$

which is a constant that depends on k , thus the limit **DNE**.

Example 9.3. Example where the limit does exist in $n > 1$ space:

We wish to find

$$\lim_{(x,y) \rightarrow (0,0)} \frac{x^4}{x^2 + y^2}$$

We *expect the limit to converge* since the degree of the numerator is $>$ degree of denominator, thus numerator $\rightarrow 0$ “much faster” than the denominator so the quotient should go to zero.

Let $\epsilon > 0$. We want to find $\delta > 0$ (depends on ϵ) such that if

$$\|(x, y) - (0, 0)\| < \delta \Rightarrow \|f(x, y) - 0\| < \epsilon$$

where $L = 0$.

Rewriting the above: we have if $x^2 + y^2 < \delta^2$, then

$$\left| \frac{x^4}{x^2 + y^2} \right| < \epsilon$$

Observe that $x^2 \leq x^2 + y^2$ so

$$\frac{x^2}{x^2 + y^2} \leq 1 \quad (x, y) \neq (0, 0)$$

Furthermore note

$$\begin{aligned} \left| \frac{x^4}{x^2 + y^2} \right| &= \frac{x^4}{x^2 + y^2} = x^2 \left(\frac{x^2}{x^2 + y^2} \right) \\ &\leq x^2 \\ &\leq x^2 + y^2 \\ &< \delta^2 = \epsilon \end{aligned} \qquad \frac{x^2}{x^2 + y^2} \leq 1$$

Thus we can take $\delta = \sqrt{\epsilon}$ such that

$$x^2 + y^2 < \delta^2 = \epsilon \Rightarrow |f(x, y) - 0| < \epsilon$$

9.2 Uniqueness of limits

Remark 9.2. A given limit may not exist, but if it does it's **unique** (same proof as uniqueness of limits of sequences).

9.3 Sequential characterization of limits of functions

Proposition 9.1. For $f : V \setminus \{x_0\} \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, $\lim_{x \rightarrow x_0} f(x) = L$ **iff** the sequence $f(x_k)$ converges to L for every sequence (x_k) in $V \setminus \{x_0\}$ converging to x_0 .

i.e. this states the path heuristic from before works formally with sequences too.

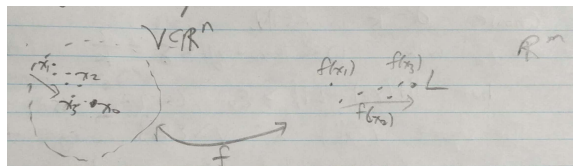


Figure 9.3: Any given sequence (x_k) in V that converges to x_0 must have $f(x_k)$ converge to l in \mathbb{R}^m .

Proof. Forwards: Suppose $\lim_{x \rightarrow x_0} f(x) = L$.

Let (x_k) be a sequence in \mathbb{R}^n with $x_k \in V \setminus \{x_0\} \forall k$ and $\lim_{k \rightarrow \infty} x_k = x_0$.

We need to show $\lim_{k \rightarrow \infty} f(x_k) = L$.

Let $\epsilon > 0$. From our premise $\exists \delta > 0$ such that

$$\|x - x_0\| < \delta \Rightarrow \|f(x) - L\| < \epsilon$$

Since $x_k \rightarrow x_0$ as $k \rightarrow \infty$, $\exists N \in \mathbb{N}$ such that

$$k \geq N \Rightarrow 0 < \|x_k - x_0\| < \delta$$

(definition of convergence).

So $k \geq N \Rightarrow \|f(x_k) - L\| < \epsilon$ so the forwards direction holds.

Backwards: Conversely, suppose the sequence $f(x_k)$ converges to L for every (x_k) in $V \setminus \{x_0\}$ converging to x_0 .

We want to show $\lim_{x \rightarrow x_0} f(x) = L$.

Suppose the limit does not converge to L (contradiction). Negation of the statement is: $\exists \epsilon_0 > 0$ such that $\forall \delta > 0$, $\exists x_\delta$ such that

$$0 < \|x_\delta - x_0\| < \delta \text{ but } \|f(x_\delta) - L\| \geq \epsilon_0$$

(this is the negation of 1) $\forall \epsilon > 0$, 2) $\exists \delta > 0$, and 3) $\forall x \|x - x_0\| < \delta \Rightarrow \|f(x) - L\| < \epsilon$).

Choose $\delta = \frac{1}{k}$, $k \in \mathbb{N}$. $\exists x_k$ with

$$0 < \|x_k - x_0\| < \delta = \frac{1}{k}$$

but $\|f(x_k) - L\| \geq \epsilon_0$ (4).

The sequence (x_k) in $V \setminus \{x_0\}$ converges to x_0 by the premise but $f(x_k) \not\rightarrow L$ by equation 9.1. This contradicts the premise. \square

9.4 Properties of limits of functions

Let $f, g : V \setminus \{x_0\} \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ and suppose

$$\lim_{x \rightarrow x_0} f(x) = L \quad \lim_{x \rightarrow x_0} g(x) = M$$

Then

$$\lim_{x \rightarrow x_0} (f(x) + g(x)) = L + M \quad (\text{additive})$$

$$\lim_{x \rightarrow x_0} cf(x) = cL \quad (\text{scalar multiplicative})$$

$$\lim_{x \rightarrow x_0} \frac{f(x)}{g(x)} = \frac{L}{M} \quad \text{if } m = 1, M \neq 0$$

$$\lim_{x \rightarrow x_0} (f(x)g(x)) = LM \quad \text{if } m = 1 \text{ (same proof as for } n = 1)$$

Proofs are left as exercises.

10 January 24, 2018

10.1 Component functions

Definition 10.1. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, U is open. Then for $x \in U$

$$f(x) = (f_1(x), \dots, f_m(x)) \in \mathbb{R}^m$$

$f_i : U \rightarrow \mathbb{R}$, $1 \leq i \leq m$ are the **component functions** of f (real-valued).

Lemma 10.1. $x_0 \in U$ open in \mathbb{R}^n . Let $f : U \setminus \{x_0\} \rightarrow \mathbb{R}^m$. Then $\lim_{x \rightarrow x_0} f(x) = L = (L_1, \dots, L_m)$ iff $\lim_{x \rightarrow x_0} f_i(x) = L_i \forall i = 1, 2, \dots, m$.

Proof. By property of convergence of limits of sequences in assignment 3 and sequence characterization of limits of functions. That is

$$\lim_{x \rightarrow x_0} f(x) = L \xLeftrightarrow{\text{seq.char.}} \lim_{k \rightarrow \infty} (x_k) = L \xLeftrightarrow{a3\#2} \lim_{k \rightarrow \infty} f_i(x_k) = L_i \xLeftrightarrow{\text{seq.char.}} \lim_{x \rightarrow x_0} f_i(x) = L_i$$

We can also prove this using $\epsilon - \delta$. □

10.2 Squeeze theorem

Theorem 10.1. Suppose $f, g, h : V \setminus \{x_0\} \rightarrow \mathbb{R}$ ($m = 1!$). If $f(x) \leq g(x) \leq h(x) \forall x \in V \setminus \{x_0\}$ (this only really needs to hold in the n'h'd of x_0) and $\lim_{x \rightarrow x_0} f(x) = \lim_{x \rightarrow x_0} h(x) = L \in \mathbb{R}$, then

$$\lim_{x \rightarrow x_0} g(x) = L$$

Proof. Same as proof in $n = 1$ case. □

10.3 Norm properties of limits

Proposition 10.1. Suppose $f : V \setminus \{x_0\} \rightarrow \mathbb{R}^m$ and $\lim_{x \rightarrow x_0} f(x) = L$ then

$$\lim_{x \rightarrow x_0} \|f(x)\| = \left\| \lim_{x \rightarrow x_0} f(x) \right\| = \|L\|$$

Proof. Let $\epsilon > 0$, $\exists \delta > 0$ such that

$$0 < \|x - x_0\| < \delta \Rightarrow \|f(x) - L\| < \epsilon$$

Note that

$$\begin{aligned} \|f(x)\| &\stackrel{\Delta}{\leq} \|f(x) - L\| + \|L\| \\ \|L\| &\stackrel{\Delta}{\leq} \|L - f(x)\| + \|f(x)\| \end{aligned}$$

So rearranging each of the inequalities above and using the premise we see that

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

if $0 < \|x - x_0\| < \delta$ so $\lim_{x \rightarrow x_0} \|f(x)\| = \|L\|$. □

10.4 Continuity

Definition 10.2. Let $U \subseteq \mathbb{R}^n$ be *open* and $f : U \rightarrow \mathbb{R}^m$.

Let $x_0 \in U$. We say f is **continuous at x_0** if

1. $\lim_{x \rightarrow x_0} f(x)$ exists
2. The limit equals $f(x_0)$

Explicitly, f is **cts (continuous)** at x_0 **iff** $\forall \epsilon > 0 \exists \delta > 0$ such that

$$\|x - x_0\| < \delta \Rightarrow \|f(x) - f(x_0)\| < \epsilon$$

Equivalently, by the sequential characterization of limits, f is cts at x_0 iff whenever (x_k) is a sequence in U converging to x_0 , then $f(x_k)$ is a sequence in \mathbb{R}^m converging to $f(x_0)$.

10.5 Continuity on a set

Definition 10.3. f is **continuous on** U (an open set) if it is continuous at every $x \in U$.

Example 10.1. $n = m$ and $U = \mathbb{R}^n$ and $f(x) = x$ (identity map). Then $\forall \epsilon > 0$, let $\delta = \epsilon > 0$ such that

$$\|x - x_0\| < \delta \Rightarrow \|f(x) - f(x_0)\| = \|x - x_0\| < \delta = \epsilon$$

Example 10.2. Let $c \in \mathbb{R}^m$ be fixed, $U = \mathbb{R}^n$. Then $f(x) = c$ is a constant function and is cts on \mathbb{R}^n since $\forall \epsilon > 0$, take *any* $\delta > 0$ we have

$$\|x - x_0\| < \delta \Rightarrow \|f(x) - f(x_0)\| = \|c - c\| = 0 < \epsilon$$

Example 10.3. Let $m = 1$, $U = \mathbb{R}^n$, and $f(x, y) = xy$ for $x = (x_1, x_2) = (x, y) \in \mathbb{R}^2$.

We claim $f(x)$ is cts on \mathbb{R}^n .

Before we prove this example, for the *component functions*:

Remark 10.1. If $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, f is cts at $x_0 \in U$ iff $f_i : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ is cts at x_0 for all $i = 1, \dots, n$.

Proof. Let $h(x, y) = (x, y)$ (identity map, cts. on \mathbb{R}^2 by example 10.1).

So $h_1(x, y) = x$ and $h_2(x, y) = y$ are cts on \mathbb{R}^2 .

$f(x, y) = xy = h_1(x, y)h_2(x, y)$ is cts on \mathbb{R}^2 because limits of product equals products of limits. □

10.6 Composition of continuous functions is continuous

Proposition 10.2. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ be cts on U . Let $g : V \subseteq \mathbb{R}^m \rightarrow \mathbb{R}^p$ be cts on V . Suppose $f(U) = \{f(x) \mid x \in U\} \subseteq V$ so the composition

$$h = g \circ f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^p$$

is defined $h(g(x))$. Then $h = g \circ f$ is cts on U .

Proof. Assignment 4. □

More generally, if f is cts at $x_0 \in U$, $f(x_0) \in V$ and g is cts at $f(x_0)$ then $h = g \circ f$ is cts at x_0 .

10.7 Dot product of continuous functions is continuous

Suppose $f, g : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$. Define $f \cdot g : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$ by

$$(f \cdot g)(x) = f(x) \cdot g(x) = f_1(x)g_1(x) + f_2(x)g_2(x) + \dots + f_m(x)g_m(x)$$

If f, g cts at x_0 , then $f \cdot g$ is cts at x_0 (by addition and product of cts functions on \mathbb{R}).

10.8 Inverse image

Definition 10.4. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, U is open. Let $A \subseteq \mathbb{R}^m$.

The **inverse image** of A under f is denoted $f^{-1}(A)$ and is defined to be

$$f^{-1}(A) = \{x \in U \mid f(x) \in A\}$$

(i.e. the domain of f which maps to the image A).

Remark 10.2. The notation is a bit ambiguous. Suppose we *restrict* f to be a proper subset $V \subset U$ that is still open.

Call this $f|_V : V \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$. So $f|_V(x) = f(x) \forall x \in V$ then if $A \subseteq \mathbb{R}^m$

$$f|_V^{-1}(A) = \{x \in V \mid f(x) \in A\} = f^{-1}(A) \cap V$$

Remark 10.3. Note: $f^{-1}(A)$ could be **empty**.

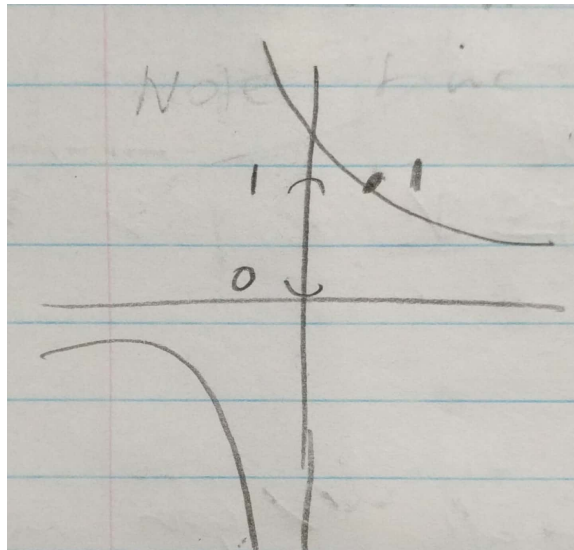


Figure 10.1: Inverse images of $f(x) = \frac{1}{x}$ may be empty.

Let $f : \mathbb{R} \setminus \{0\} \rightarrow \mathbb{R}$, $f(x) = \frac{1}{x}$. Note that

$$f^{-1}((0, 1)) = (1, \infty)$$

$$f^{-1}(\{0\}) = \emptyset$$

11 January 26, 2018

11.1 Continuity and open/closed sets

Proposition 11.1. $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, U is open. Then f is continuous on U **iff** $f^{-1}(V)$ is open in \mathbb{R}^n whenever V is open in \mathbb{R}^m .

(that is: cts iff the inverse image of any open set is open).

Proof. Forwards: Suppose f is cts on U . Let $V \subseteq \mathbb{R}^m$ be open. WLOG $f^{-1}(V) \neq \emptyset$. Let $x_0 \in f^{-1}(V) \subseteq U \Rightarrow f(x_0) \in V$.

Since V is open, $\exists \epsilon > 0$ such that $B_\epsilon(f(x_0)) \subseteq V$. But f is cts at x_0 so $\exists \delta > 0$ such that

$$\|x - x_0\| < \delta \Rightarrow \|f(x) - f(x_0)\| < \epsilon$$

(we take δ small enough such that $B_\delta(x_0) \subseteq U$).

Thus $f(B_\delta(x_0)) \subseteq B_\epsilon(f(x_0)) \subseteq V$. So $B_\delta(x_0) \subseteq f^{-1}(V)$ hence $\forall x_0 \in f^{-1}(V) \exists \delta > 0$ such that $B_\delta(x_0) \subseteq f^{-1}(V)$ so $f^{-1}(V)$ is open.

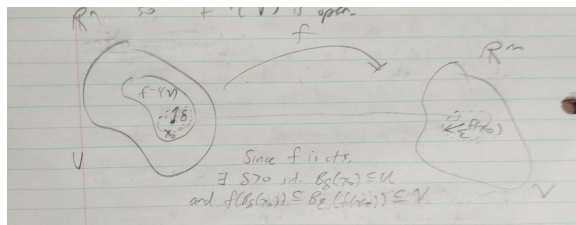


Figure 11.1: Inverse images of $f(x) = \frac{1}{x}$ may be empty.

Backwards: Suppose $f^{-1}(V)$ is open in \mathbb{R}^n for all V open in \mathbb{R}^m . We need to show that f is cts on U . Let $x_0 \in U$. Let $\epsilon > 0$, $B_\epsilon(f(x_0))$ is open in \mathbb{R}^m so by our assumption

$$f^{-1}(V) = f^{-1}(B_\epsilon(f(x_0)))$$

is open in \mathbb{R}^n .

Also $x_0 \in f^{-1}(V)$ since $f(x_0) \in V = B_\epsilon(f(x_0))$ so $\exists \delta > 0$ such that

$$B_\delta(x_0) \subseteq f^{-1}(V)$$

(since $f^{-1}(V)$ is open).

Hence $f(B_\delta(x_0)) \subseteq V = B_\epsilon(f(x_0))$ so f is cts at x_0 . □

Remark 11.1. One can also show that $f^{-1}(\text{closed}) = \text{closed}$ is also equivalent to continuity (on assignment 4).

Remark 11.2. Question: Is the reverse the open set property true? That is, suppose $F : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ U open, f cts on U . Let $V \subseteq U$ defined $f(V) = \{f(x) \mid x \in V\}$ the image of V under f . If V is open in \mathbb{R}^n , is $f(V)$ necessarily open in \mathbb{R}^m ?

No: here's a counter-example.

Example 11.1. $n = m = 1$, $U = \mathbb{R}$. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ where $f(x) = x^2$ (cts on \mathbb{R}). Take $V = (-1, 1)$ open in \mathbb{R} . Then $f(V) = [0, 1]$ which is not open in \mathbb{R} .

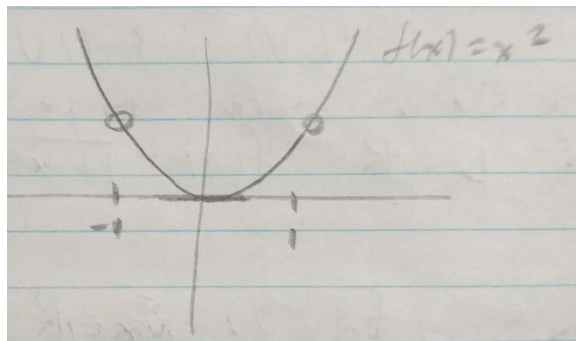


Figure 11.2: An open domain on a cts $f(x) = x^2$ may not admit an open image.

Similarly, if V is closed in \mathbb{R}^n , $f(V)$ need not be closed in \mathbb{R}^m .

Example 11.2. $n = m = 1$, $U = \mathbb{R} \setminus \{0\}$, and $f(x) = \frac{1}{x}$.

Let $V = [1, \infty)$ which is closed on \mathbb{R} (although this is unbounded there is a closed boundary so this is still closed). Then $f(V) = (0, 1]$ is not closed.

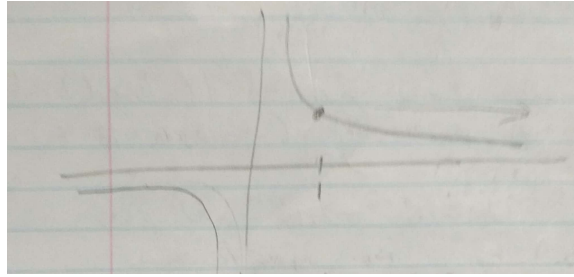


Figure 11.3: A closed domain on a cts $f(x) = \frac{1}{x}$ may not admit a closed image.

Two other types of subsets were **compact and connected**.

11.2 Continuity and compact sets

Suppose $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ cts on U , U open.

Does the same property hold for compact/connected sets as it did for open/closed sets?

That is, if $V \subseteq \mathbb{R}^m$ is **compact**, is $f^{-1}(V)$ tbfcompact on \mathbb{R}^n ? If $V \subseteq \mathbb{R}^m$ is **connected**, is $f^{-1}(V)$ tbfconnected on \mathbb{R}^n ?

No to both!

Example 11.3. Counter-example for compact set:

$n = m = 1$, $U = \mathbb{R}$, and $f(x) = \frac{1}{1+x^2}$. Let $V = [0, 1]$ which is compact. Then $f^{-1}(V) = \{x \in \mathbb{R} \mid \frac{1}{1+x^2} \in [0, 1]\} = \mathbb{R}$ is not compact.

Graph for $1/(1+x^2)$

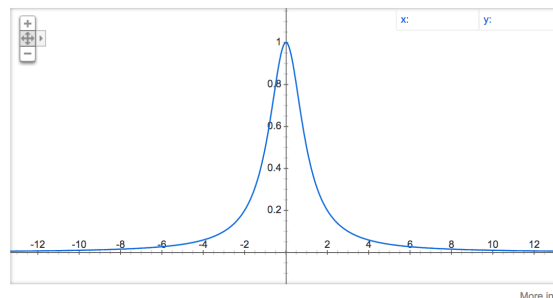


Figure 11.4: A compact image on a cts $f(x) = \frac{1}{1+x^2}$ may not admit a compact inverse image.

Example 11.4. Counter-example for connected set:

$n = m = 1$, $U = \mathbb{R}$, and $f(x) = x^2$. Let $V = (1, 9)$ which is connected. Then $f^{-1}(V) = (-3, -1) \cup (1, 3)$ is not connected.

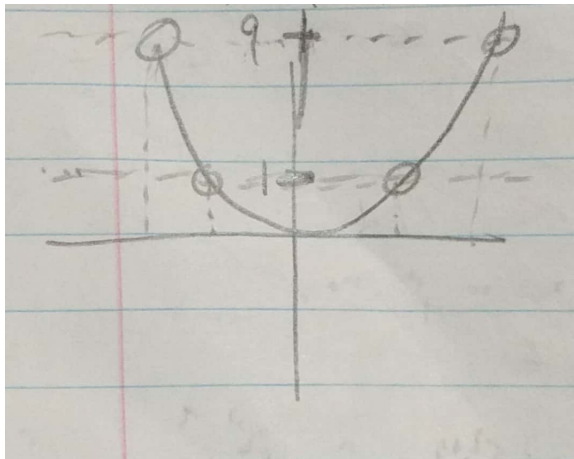


Figure 11.5: A connected image on a cts $f(x) = x^2$ may not admit a connected inverse image.

Proposition 11.2. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, U is open. Let $K \subseteq U$ be **compact**. Then $f(K) = \{f(x) \mid x \in K\}$ is **compact** in \mathbb{R}^m .

Proof. Let $\{U_\alpha \mid \alpha \in A\}$ be an open cover of $f(K)$ i.e. $U_\alpha \subseteq \mathbb{R}^m$ is open $\forall \alpha \in A$ and

$$f(K) \subseteq \bigcup_{\alpha \in A} U_\alpha$$

Claim: $K \subseteq \bigcup_{\alpha \in A} f^{-1}(U_\alpha)$.

If $x \in K$, then $f(x) \in f(K)$ so $f(x) \in U_\alpha$ for some $\alpha \Rightarrow x \in f^{-1}(U_\alpha)$.

Since f is cts, U_α open $\Rightarrow f^{-1}(U_\alpha)$ open in $\mathbb{R}^n \forall \alpha$ (by previous propositions).

So $\{f^{-1}(U_\alpha) \mid \alpha \in A\}$ is an open cover of K which is compact.

So $\exists \alpha_1, \dots, \alpha_n \in A$ such that

$$K \subseteq \bigcup_{j=1}^N f^{-1}(U_{\alpha_j})$$

Then $f(K) \subseteq \bigcup_{j=1}^N U_{\alpha_j}$ because if $y \in f(K)$ where $y = f(x)$ for some $x \in K$ where $x \in f^{-1}(U_{\alpha_j})$ for some $j \in \{1, \dots, N\}$ so $f(x) \in U_{\alpha_j}$.

So $f(K)$ is compact. □

Remark 11.3. By Heine-Borel, compact \iff closed and bounded. But we've seen that if f is cts $f(\text{closed}) \neq \text{closed}$ in general. This implies the additional bounded property makes it valid.

What about $f(\text{bounded}) = \text{bounded}$ for a cts f ? **No:** see this counter-example:

Example 11.5. $U = (0, \infty) \subseteq \mathbb{R}$ for $n = m = 1$ and $f(x) = \log x$.

Let $V = (0, 1)$ which is bounded. Then $f(V) = (-\infty, 0)$ which is not bounded.

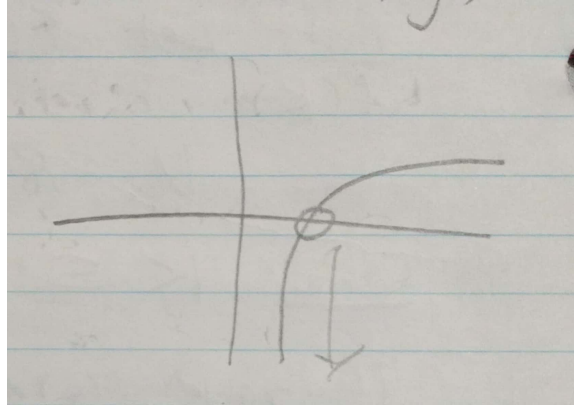


Figure 11.6: A bounded domain on a cts $f(x) = \log x$ may not admit a bounded image.

But as we proved before, $f(\text{closed and bound}) = \text{closed and bounded}$ so both conditions are sufficient.

11.3 Extreme value theorem (EVT)

Corollary 11.1. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, U is open ($m = 1!$) and f is cts on U . Let $K \subseteq U$ be **compact**. Then $\exists x_1, x_2$ in K

$$f(x_1) \leq f(x) \leq f(x_2) \quad \forall x \in K$$

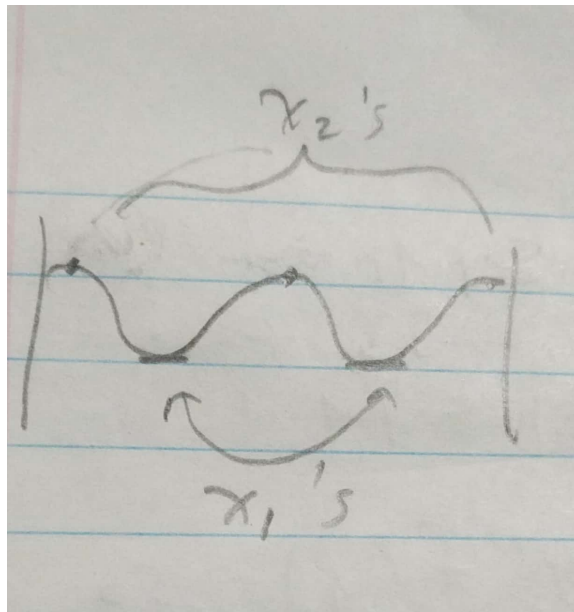


Figure 11.7: x_1, x_2 may not be unique in the Extreme Value Theorem.

This means a cts. real-valued function on a compact set attains a global maximum value and global minimum value. Clearly this wouldn't work in \mathbb{R}^m , $m > 1$ since there is no notion of min/max of vectors).

Proof. Assume K compact, f is cts on U so $f(K)$ is a compact subset of \mathbb{R} (by previous proposition).

By Heine-Borel $f(K)$ is **closed and bounded** in \mathbb{R} , so

$$\begin{aligned} //M &= \sup_{x \in K} f(x) \\ //m &= \inf_{x \in K} f(x) \end{aligned}$$

both exists and is finite (bounded intervals has an infima and suprema).

Let $k \in \mathbb{N}$ such that $M - \frac{1}{k} < M$ so $\exists x_k \in K$ such that

$$M - \frac{1}{k} < f(x_k) \leq M$$

K is bounded so (x_k) is a bounded sequence in \mathbb{R} , so by Bolzano-Weierstrass \exists convergent subsequence $(x_{k_l}) \rightarrow x$ as $l \rightarrow \infty$.

But K is closed so $\lim_{l \rightarrow \infty} x_{k_l} = x \in K$.

Since f is cts, so

$$\lim_{l \rightarrow \infty} f(x_{k_l}) = f(\lim_{l \rightarrow \infty} (x_{k_l})) = f(x) \in f(K)$$

since $x \in K$. Thus

$$M - \frac{1}{k_l} < f(x_{k_l}) \leq M$$

then as $l \rightarrow \infty$, we have $M \leq f(x) \leq M$.

So $x \in K$ and $f(x) = \sup_{y \in K} f(y)$ (some y) so global max is attained.

For global min, similarly $m \leq f(x_k) < m + \frac{1}{k}$.

Remark 11.4. The non-uniqueness of extreme values come from choosing an arbitrary convergent subsequence from (x_k) . □

This generalizes EVT from 147: if f is cts on $[a, b]$ then f attains a global max/min.

Remark 11.5. Note that f must be cts for this to hold. Otherwise we could have

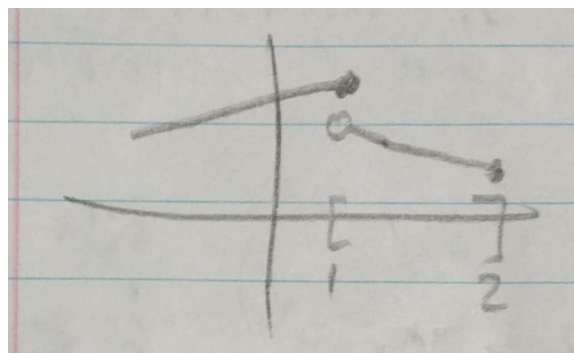


Figure 11.8: There is a global min on $[1, 2]$ but no global max.

12 January 29, 2018

12.1 Continuity and connected sets

(See above for connected image does not imply connected inverse image example.)

Proposition 12.1. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ cts on U which is open.

Let $E \subseteq U$ be **connected** on \mathbb{R}^n . Then $f(E)$ is **connected** in \mathbb{R}^m (i.e. cts image of connected set is connected).

Proof. Suppose $f(E)$ is not connected. Let $V_1, V_2 \in \mathbb{R}^m$ open sets be a separation of $f(E)$

1. $f(E) \subseteq V_1 \cup V_2$
2. $f(E) \cap V_1 \neq \emptyset$
3. $f(E) \cap V_2 \neq \emptyset$
4. $f(E) \cap V_1 \cap V_2 = \emptyset$

Since f is cts, $f^{-1}(V_1), f^{-1}(V_2)$ are open in \mathbb{R}^n . If $x \in E$, $f(x) \in f(E) \subseteq V_1 \cup V_2$. So $f(x) \in V_1$ or $f(x) \in V_2$ which implies $x \in f^{-1}(V_1) \cup f^{-1}(V_2)$, that is

$$E \subseteq f^{-1}(V_1) \cup f^{-1}(V_2)$$

Let $y \in f(E) \cap V_1 \neq \emptyset$. So $\exists x \in E$ such that $y = f(x) \in V$, that is

$$x \in f^{-1}(V) \cap E \neq \emptyset$$

Similarly $f^{-1}(V_2) \cap E \neq \emptyset$.

If $x \in E \cap f^{-1}(V_1) \cap f^{-1}(V_2)$ then $f(x) \in f(E) \cap V_1 \cap V_2 \neq \emptyset$ which is a contradiction of our initial assumptions that V_1, V_2 is a separation.

So $f^{-1}(V_1) \cap f^{-1}(V_2) \cap E = \emptyset$, which means $\{f^{-1}(V_1), f^{-1}(V_2)\}$ is a separation of R which is a contradiction since E is connected.

Thus $f(E)$ must be connected. □

12.2 Intermediate value theorem (IVT)

Corollary 12.1. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}$, where U open ($m = 1!$).

Suppose f is cts on U and let $E \subseteq U$ be connected. Let $x, y \in E$ such that $f(x) < f(y)$. Then for **each** $w \in (f(x), f(y))$, $\exists z \in E$ such that $f(z) = w$.

(i.e. a cts real-valued fn on a connected set admits all values between any two of its values).

Proof. Assume the contrary: that is $\exists w_0 \in (f(x), f(y))$ such that $w_0 \notin f(E)$.

Let

$$V_1 = \{w \in \mathbb{R} \mid w < w_0\} = (-\infty, w_0)$$

$$V_2 = \{w \in \mathbb{R} \mid w > w_0\} = (w_0, \infty)$$

then V_1, V_2 is a separation of $f(E)$ but $f(E)$ is connected by previous proposition, which is a contradiction. □

Aside: If $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ for U open is cts on U then

$$\|f\| : U \rightarrow \mathbb{R}$$

where $\|f\|(x) = \|f(x)\|$ is cts. real-valued so we can apply EVT or IVT to $\|f\|$.

12.3 Uniform continuity

Definition 12.1. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, U is open, and let $D \subseteq U$.

We say that f is **uniformly continuous on D** iff $\forall \epsilon > 0 \exists \delta > 0$ such that

$$x, y \in D \quad \|x - y\| < \delta \Rightarrow \|f(x) - f(y)\| < \epsilon$$

Remark 12.1. 1. Uniformly continuous only makes sense with respect to a particular subset D of U . f may be unif. cts on $D_1 \subseteq U$ but not unif. cts on $D_2 \subseteq U$.

2. If f is unif cts on D , this means given any $\epsilon > 0$, we can find **a single** $\delta > 0$ depending only on ϵ that works to establish continuity of $f|_D$ at $x \in D$ for all $x \in D$.

3. If f is unif cts on D , then $f|_D$ is cts at $x \in D \forall x \in D$ (but the converse is not necessarily true).

Example 12.1. Let $f : \mathbb{R} \setminus \{0\} \rightarrow \mathbb{R}$ and $f(x) = \frac{1}{x}$ (f is cts).

Let $D = (0, 1]$.

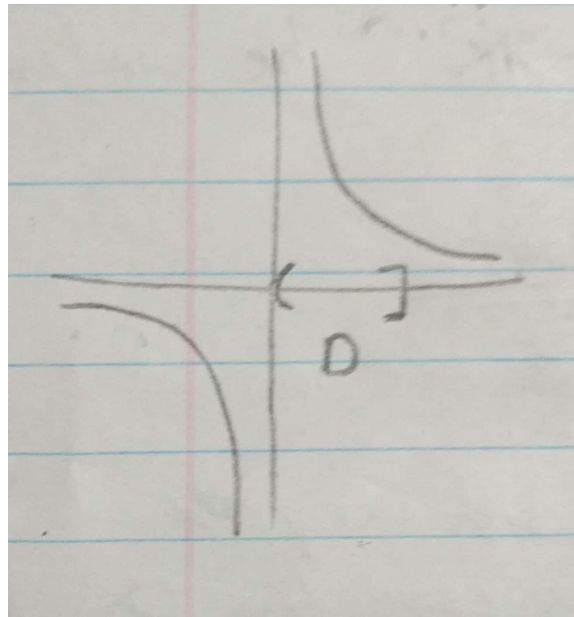


Figure 12.1: For the subdomain $D = (0, 1]$, $f(x) = \frac{1}{x}$ is not uniformly continuous on D . We can find x, y arbitrary close to 0 such that for a given $\epsilon > 0$, there is not single $\delta > 0$.

Claim: f is NOT unif cts on D (so we find an ϵ where no single δ works).

Let $\epsilon = \frac{1}{2}$. Let $\delta > 0$ be arbitrary. Let $n \in \mathbb{N}$ be large enough so that

$$\frac{1}{n(n+1)} < \delta$$

Let $x = \frac{1}{n}$ and $y = \frac{1}{n+1} \in D$. So we have

$$|x - y| = \left| \frac{1}{n} - \frac{1}{n+1} \right| = \frac{1}{n(n+1)} < \delta$$

but we have

$$|f(x) - f(y)| = |n - (n + 1)| = 1 > \epsilon$$

Example 12.2. Let $f : \mathbb{R} \rightarrow \mathbb{R}$ and $f(x) = x^2$ (f is cts).

Let $D = [0, \infty)$.

Claim: f is not unif cts on D .

Let $\epsilon = 1$, let $\delta > 0$ be arbitrary. Let $x = \frac{2}{\delta}$ and $y = \frac{2}{\delta} + \frac{\delta}{2} \in D$ (close to each other).

Note

$$|x - y| = \left| \frac{2}{\delta} - \left(\frac{2}{\delta} + \frac{\delta}{2} \right) \right| = \frac{\delta}{2} < \delta$$

and

$$|f(x) - f(y)| = |x - y|x + y = \frac{\delta}{2} \left(\frac{4}{\delta} + \frac{\delta}{2} \right) = 2 + \frac{\delta^2}{4} > 2 > \epsilon$$

12.4 Uniform continuity and compact sets

Theorem 12.1. Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$ be cts on U open. Let $K \subseteq U$ be **compact**.

Then f is unif cts on K .

Remark 12.2. Aside: In example 12.1, we chose $D = (0, 1]$ and a proof with a counter n when x, y gets arbitrarily close to 0.

If $D = [\zeta, 1]$ such that is compact, our counter argument with n would fail because we can't get arbitrarily close to 0.

Proof. Let $\epsilon > 0$ and let $x \in K$. Since f is cts at x , $\exists \delta(x) > 0$ such that

$$\|y - x\| < \delta(x) \Rightarrow \|f(y) - f(x)\| < \frac{\epsilon}{2}$$

i.e. $f(B_{\delta(x)}(x)) \subseteq B_{\frac{\epsilon}{2}}(f(x))$.

Also $K \subseteq \bigcup_{x \in K} B_{\frac{\delta(x)}{2}}(x)$ (this is an arbitrary union for every point in K).

By compactness of K , \exists finite set $x_1, \dots, x_N \in K$ such that

$$K \subseteq \bigcup_{j=1}^N B_{\frac{\delta(x_j)}{2}}(x_j)$$

Let $\delta = \min\{\frac{\delta(x_1)}{2}, \dots, \frac{\delta(x_N)}{2}\} > 0$.

Suppose $x, y \in K$ and $\|x - y\| < \delta$, and $x \in B_{\frac{\delta(x_j)}{2}}(x_j)$ for some $j \in [1, \dots, N]$ by equation ??.

Then we have

$$\begin{aligned} \|y - x_j\| &\stackrel{\Delta}{\leq} \|y - x\| + \|x - x_j\| \\ &< \delta + \frac{\delta(x_j)}{2} \\ &< \frac{\delta(x_j)}{2} + \frac{\delta(x_j)}{2} \\ &= \delta(x_j) \end{aligned}$$

That is $\|y - x_j\| < \delta(x_j)$ so $y \in B_{\delta(x_j)}(x_j)$, thus we have

$$\begin{aligned} \|f(x) - f(y)\| &\stackrel{\Delta}{\leq} \|f(x) - f(x_j)\| + \|f(x_j) - f(y)\| \\ &< \frac{\epsilon}{2} + \frac{\epsilon}{2} \\ &= \epsilon \end{aligned}$$

so we found a $\delta > 0$ (single δ) such that $x, y \in K$ where $\|x - y\| < \delta \Rightarrow \|f(x) - f(y)\| < \epsilon$. □

12.5 Differentiability

Let $f : U \subseteq \mathbb{R}^n \rightarrow \mathbb{R}^m$, U open and let $a \in U$. We want to define what it means for f to be differentiable at a and what is the derivative of f at a (denoted $(Df)_a$).

We'll see soon that if f is differentiable at a , then $(Df)_a$ is a linear map from \mathbb{R}^n to \mathbb{R}^m ($m \times n$ matrix).

Remark 12.3. Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map. Choose basis β of \mathbb{R}^n , basis γ of \mathbb{R}^m . Then T is represented wrt these two bases by an $m \times n$ basis $[T]_{\gamma, \beta}$.

If $\tilde{\beta}$ is another basis of \mathbb{R}^n and $\tilde{\gamma}$ is another basis of \mathbb{R}^m , then let P (invertible $n \times n$) and Q (invertible $m \times m$) be the change of bases matrices from basis β to $\tilde{\beta}$ and from basis γ to $\tilde{\gamma}$, respectively. Thus

$$[T]_{\tilde{\gamma}, \tilde{\beta}} = Q^{-1}[T]_{\gamma, \beta}P$$

If $n = m$ and we choose $\beta = \gamma$ and $\tilde{\beta} = \tilde{\gamma}$ then

$$[T]_{\tilde{\beta}} = P^{-1}[T]_{\beta}P$$

If $n = m = 1$ such that $\beta = \gamma, \tilde{\beta} = \tilde{\gamma}$ we have

$$[T]_{\tilde{\beta}} = [T]_{\beta} \quad \text{since the } 1 \times 1 \text{ matrices commute}$$

i.e. the matrices representing a linear map $\mathbb{R} \rightarrow \mathbb{R}$ is **unique** (doesn't depend on β).