POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Notes of

Real and Functional Analysis

for the Master in Mathematical Engineering
held by Prof. G. Verzini
a.a. 2023/2024

Edited by
Teo Bonfa

© Gli autori, alcuni diritti riservati.

Disclaimer In questo testo sono raccolti gli appunti tratti dalle lezioni e dalle esercitazioni del corso di AAnalisi Reale e Funzionale, tenuto dal Professor Ginamaria Verzini e dall'esercitatrice Giulia Cavagnari per la LM in Mathematical Engineering, al Politecnico di Milano, nell'Anno Accademico 2023/24.

La proprietà intellettuale rimane ai docenti sopracitati, i quali non hanno revisionato la seguente opera, che si presenta unicamente come un supporto ulteriore alle lezioni, fatta da studenti per studenti, senza pretese di sostituire libri di testo ufficiali o la frequenza delle lezioni.

Quest'opera è rilasciata sotto licenza CC BY-NC-SA 4.0.
`http://creativecommons.org/licenses/by-nc-sa/4.0/`

In sintesi: potete condividere i contenuti del libro, in tutto o in parte, e apportare le vostre modifiche, a patto di citare la fonte, di condividere le modifiche con la stessa licenza, e di non usare il materiale per scopi commerciali (non è permesso stampare il libro per rivenderlo).

Questo riassunto della licenza è parziale e non la sostituisce, ma serve a darvi l'idea.

Il codice sorgente LaTeX è disponibile su
`https://github.com/BonfaTex/My-RFA-23`

Developed by:
Teo Bonfa - `math11235813piday@gmail.com`

Per segnalare eventuali errori o suggerimenti potete contattare gli autori o fare una Pull Request.

Contents

I Introduction **1**

0 Course structure **3**

1 Set Theory **5**

1.1 Equipotent, finite/infinite, countable/uncountable sets, cardinality of continuoum . . . 5
1.2 Families of subsets . . . 6
1.3 Sequences of sets . . . 7
1.4 Charateristic functions . . . 8
1.5 Relations, Equivalence relations . . . 8

II Real Analysis **9**

2 Measure Theory **11**

2.1 Measure spaces . . . 11
2.2 Borel sets . . . 12
2.3 Measures . . . 12

3 **13**

4 **15**

5 **17**

6 **19**

7 **21**

8 **23**

9 **25**

10 **27**

III Functional Analysis **29**

11 **31**

12 **33**

13 **35**

14 **37**

15 **39**

16 **41**

17 **43**

18 **45**

IV Esercitazioni **47**

19 Exercise session 18/09 **49**
19.1 Recall on $\mathbb{R}^n$ 49
19.2 Recall on metric spaces 50
19.3 Topology in metric spaces 53

20 **55**

21 **57**

22 **59**

23 **61**

24 **63**

25 **65**

26 **67**

27 **69**

28 **71**

Part I

Introduction

Chapter 0

Course structure

This course is splitted in two parts:

1. Real Analysis $\rightsquigarrow$ measure and integration theory, in particular:
   - Collections and sequences of sets
   - Measurable space, measure, outer measure
   - Generation of an outer measure
   - Carathéodory's condition, measure induced by an outer measure
   - Lebesgue's measure on $\mathbb{R}^n$
   - Measurable functions
   - The Lebesgue integral
   - Abstract integration
   - Monotone convergence theorem, Fatou's Lemma, Lebesgue's dominated convergence theorem
   - Comparison between the Lebesgue and Riemann integrals
   - Different types of convergence
   - Derivative of a measure and the Radon-Nikodym theorem
   - Product measures and the Fubini-Tonelli theorem
   - Functions of bounded variation and absolutely continuous functions
2. Functional Analysis $\rightsquigarrow$ infinte dimensional linear algebra, in particular:
   - Metric spaces, completeness, separability, compactness
   - Normed spaces and Banach spaces
   - Spaces of integrable functions
   - Linear operators
   - Uniform boundedness theorem, open mapping theorem, closed graph theorem
   - Dual spaces and the Hahn-Banach theorem
   - Reflexivity
   - Weak and weak* convergences
   - Banach-Alaoglu theorem
   - Compact operators
   - Hilbert spaces
   - Projection theorem, Riesz representation theorem
   - Orthonormal basis, abstract Fourier series
   - Spectral theorem for compact symmetric operators

- Fredholm alternativ

The foundation of this theory is the *Set Theory*, that is going to be explained in the next chapter. Enjoy!

NB: this page will be updated with more details and maybe the list of proofs.

Chapter 1

Set Theory

1.1 Equipotent, finite/infinite, countable/uncountable sets, cardinality of continuoum

Let X, Y be sets.

Def — Equipotent sets.
X, Y are equipotent if there exists a bijection $f : X \to Y$ (1-1 injective + onto surjective).

If X, Y are equipotent, then they have the same cardinality. On the other hand, X has cardinality $\geq$ than Y if there exists $f : X \to Y$ onto. For example, for

$$X = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} \qquad Y = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$$

exists $f : X \to Y$ s.t. $\forall y \in Y \; \exists x \in X$ s.t. $f(x) = y$ (f *takes* all the elements of the codomain), but doesn't exist $g : Y \to X$ s.t. $\forall x \in X \; \exists y \in Y$ s.t. $g(y) = x$ (g doesn't *take* all the elements of the codomain).

Def — Finite/infinite sets.
X is finite if it is equipotent to $Y = \{1, 2, ..., k\}$ for some $k \in \mathbb{N}$. X is infinite otherwise.

Prop. X is infinite iff it is equipotent to a proper subset, i.e. if exists a bijection between X and one of his subsets.

For example, between the integers set $\mathbb{Z} = \{0, \pm 1, \pm 2, ...\}$ and the even integers set $\{0, \pm 2, \pm 4, ...\}$ there exists f s.t. $f(z) = 2z$ which is a bijection.

Def — Countable/uncountable (infinite) sets.
X inifinite is countable if it is equipotent to $\mathbb{N}$. It is uncountable otherwise, in which case is more than countable (countable sets are the "smallest" among infinite sets).

Def — Cardinality of continuoum.
X has the cardinality of continuoum if it is equipotent to $\mathbb{R}$. Any such set is uncountable.

For example:

- $\mathbb{N}, \mathbb{Z}, \mathbb{Q}$ are countable
- $\mathbb{R}, \mathbb{R}^N, (0, 1), (0, 1)^N$ have the cardinality of continuoum
- countable unions of countable sets are countable

1.2 Families of subsets

Let X be a set.

Def — Power set.
The power set of X, i.e. the set of all subsets of X, is

$$\mathcal{P}(X) = \{Y : Y \subset X\}$$

It is sometimes denoted as 2^X.

The power set has cardinality strictly bigger than X. For example, $\mathcal{P}(\mathbb{N})$ has the cardinality of continuoum.

Def — Family of subsets.
A family, or collection, of subsets of X is just $\mathcal{C} \subset \mathcal{P}(X)$. Tipically, a family of subsets (induced by $I \subset \mathbb{R}$ set of indexes) is $\mathcal{C} = \{E_i\}_{i\in I}$ where $E_i \subset X\ \forall\, i \in I$.

For example, $\{E_1, E_2, E_3\}$ is a family of subsets.

Def — Union and intersection.
Given a family of sets $\{E_i\}_{i\in I} \subset \mathcal{P}(X)$, will often be considered

$$\bigcup_{i\in I} E_i = \{x \in X : \exists\, i \in I \text{ s.t. } x \in E_i\}$$
$$\bigcap_{i\in I} E_i = \{x \in X : x \in E_i\ \forall\, i \in I\}$$

$\{E_i\}$ is said to be (pairwise) disjoint if $E_i \cap E_j = \varnothing\ \forall\, i \neq j$.

Ex — Standard topology of $\mathbb{R}$.
Given $X = \mathbb{R}$ $\left(\text{or } \mathbb{R}^N\right)$, the standard/euclidian topology of $\mathbb{R}$ $\left(\text{or } \mathbb{R}^N\right)$ is $\mathcal{T} = \{E \subset X : E \text{ is open}\}$, i.e. it is the family of all open subsets of X.
More generally, this can be defined in metric spaces (X, d) where X is a set and d a distance between $x, y \in X$.

Some properties of $\mathcal{T}$:

- $\varnothing, X \in \mathcal{T}$
- finite intersection of open sets is open [$\circledast$]
- any (finite/infinite, countable/uncountable, ...) union of open sets is open [$\circledcirc$]

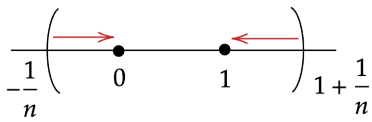
Def — Covering and subcovering.
$\{E_i\}_{i\in I}$ is a covering of X if $X = \bigcup_{i\in I} E_i$. Any subfamily $\{E_i\}_{i\in J, J\subset I}$ is a subcovering if it is a covering.

1.3 Sequences of sets

A sequence is just a family of subsets where $I \equiv \mathbb{N}$, e.g. $\{E_n\}_{n\in\mathbb{N}}$.

Def — Monotone sequences.
$\{E_n\}$ is increasing (not decreasing), $\{E_n\} \nearrow$, if $E_n \subset E_{n+1}\ \forall\, n \in \mathbb{N}$. On the other hand, $\{E_n\}$ is decreasing (not increasing), $\{E_n\} \searrow$, if $E_{n+1} \subset E_n\ \forall\, n \in \mathbb{N}$. If $\{E_n\}$ is increasing/decreasing then it is monotone.

For example, given $X = \mathbb{R}$ and $E_n = \left(-\frac{1}{n}, 1 + \frac{1}{n}\right)$ for $n \geq 1$, we can say that E_n is a monotone decreasing sequence:



But what is $\bigcap_{n=1}^{\infty} E_n$? We know that

$$\bigcap_{n=1}^{\infty} E_n = [0,1]$$

and this is an infinite intersection of open sets (this does not disagree with the prop ⊛). This type of intersection is called "Gδ-set": a countable intersection of open sets.

Similarly, $E_n = \left[a + \frac{1}{n}, b - \frac{1}{n}\right]$, a<b, is increasing and

$$\bigcup_{n=1}^{\infty} E_n = (a,b)$$

is called "Fσ-set": a countable union of closed sets (doesn't disagree with ⊚).

Def — lim sup and lim inf.
Let $\{E_n\}_{n\in\mathbb{N}} \subset \mathcal{P}$. We define

$$\limsup_n E_n := \bigcap_{n=1}^{\infty}\left(\bigcup_{k=n}^{\infty} E_k\right) \qquad \liminf_n E_n := \bigcup_{n=1}^{\infty}\left(\bigcap_{k=n}^{\infty} E_k\right)$$

If these two sets are equal

$$\limsup_n E_n = \liminf_n E_n = \lim_n E_n = F$$

then F is the limit of the succession.

Take note that $\{E_n\} \nearrow$ (resp. $\searrow$) $\Longrightarrow \exists \lim_n E_n = \bigcup_n E_n$ (resp. $\bigcap_n E_n$).

Exer. Looking at the previous definition of lim sup, we can easily proof that

$$x \in \limsup_n E_n \iff x \in \bigcup_{n=k}^{\infty} E_n\ \forall\, k \iff x \in E_n \text{ for } \infty\text{-ly many } n$$

A property that is true for infinitely many n is said to be true *frequently*. Similarly:

$$x \in \liminf_n E_n \iff x \in \bigcap_{n=k}^{\infty} E_n \text{ for at least one } \overline{k} \iff x \in E_n\ \forall\, n \geq \overline{k}$$

A property that is only true after n large enough is said to be true *eventually*.

1.4 Charateristic functions

Let X be a set.

Def — Charateristic function.
Given $E \subset X$, we define the charateristic (or indicator) function

$$\chi_E : X \to \mathbb{R} \quad \text{s.t.} \quad \chi_E(x) = \begin{cases} 1 & x \in E \\ 0 & x \notin E \ \ (\text{or } x \in E^c = X \setminus E) \end{cases}$$

(another notation: $\mathbb{1}_E(x)$)

Prop.

- $\chi_{E_1 \bigcap E_2} = \chi_{E_1} \cdot \chi_{E_2}$
- $\chi_{E_1 \bigcup E_2} = \chi_{E_1} + \chi_{E_2} - \chi_{E_1} \cdot \chi_{E_2}$
- $\chi_{\limsup_n E_n} = \limsup_n \chi_{E_n}$ and likewise $\chi_{\liminf_n E_n} = \liminf_n \chi_{E_n}$

! Take note that the first lim sup/inf refers to sets, the second one to (real) numbers.

1.5 Relations, Equivalence relations

Def — Cartesian product and Relations.
If X and Y are sets, their Cartesian product $X \times Y$ is the set of all ordered pairs (x, y) such that $x \in X$ and $y \in Y$. A relation from X to Y is a subset of $X \times Y$. If R is a relation from X to Y, we shall sometimes write xRy to mean that $(x, y) \in R$.
If $Y = X$, we speak of a relation <u>on</u> X. For example, $xRy \iff y = x^2$.

The most important types of relations are the following:

Def — Equivalence relations.
An equivalence relation is a relation R s.t.

i) $xRx \ \forall x \in X$ (reflexive)
ii) $xRy \iff yRx \ \forall x, y$ (symmetric)
iii) $xRy,\ yRz \implies xRz \ \forall x, y, z$ (transitive)

Equivalence relations allow us to introduce the following constructs which will be useful later on:

- **Equivalence class** of an element x: $E_x = \{y \in X \, : \, yRx\}$
- **Quotient set**: ${}^{X}\!/_{R} = \{E_x \, : \, x \in X\}$

For example, to define $\mathbb{Q}$ in a precise way we take the following relation R

$$\frac{1}{2} = \frac{2}{4} = \frac{3}{6} = \dots$$

i.e. the pairs $(1, 2), (2, 4), (3, 6), \dots \in \mathbb{Z} \times \mathbb{Z}_0$ (without zero), therefore $\mathbb{Q} = {}^{\mathbb{Z} \times \mathbb{Z}_0}\!/_{R}$.

Part II

Real Analysis

Chapter 2

Measure Theory

2.1 Measure spaces

Let X be a set.

Def — σ-algebras.
A family $\mathcal{M} \subset \mathcal{P}(x)$ is called a σ-algebra if

i) $\varnothing \in \mathcal{M}$

ii) $E \subset \mathcal{M} \implies E^c = X \setminus E \in \mathcal{M}$

iii) $\{E_n\}_{n\in\mathbb{N}} \subset \mathcal{M} \Longrightarrow \bigcup_{n=1}^{\infty} E_n \in \mathcal{M}$ (infinite countable union)

If (iii) is replaced by "$E_1, E_2 \in \mathcal{M} \Longrightarrow E_1 \bigcup E_2 \in \mathcal{M}$" then $\mathcal{M}$ is just an algebra (finite union).

Trivial examples: $\mathcal{M} = \mathcal{P}(X)$ is the biggest σ-algebra, $\mathcal{M} = \{\varnothing, X\}$ is the smallest σ-algebra.

We say that

- $\mathcal{M}$ σ-algebra $\rightsquigarrow (X, \mathcal{M})$ is a **measurable space**
- $E \in \mathcal{M}$ are **measurable sets**

Basic properties of $\mathcal{M}$:

1. $X = \varnothing^c \in \mathcal{M}$ (by (i)+(ii))
2. $\mathcal{M}$ is an algebra (σ-alg. $\implies$ alg. but not the viceversa)

   To prove this you can take a finite union (e.g. $E_1 \cup E_2$) and then make infinite unions with $\varnothing$ to have an infinite union that still belongs to $\mathcal{M}$:

$$E_1 \cup E_2 = \underbrace{E_1 \cup E_2 \underbrace{\cup \varnothing \cup \ldots \cup \varnothing \cup \ldots}_{\in \mathcal{M} \text{ by (i)}}}_{\in \mathcal{M} \text{ by (iii)}}$$

3. $\{E_n\}_n \subset \mathcal{M} \Longrightarrow \bigcap_{n\in\mathbb{N}} E_n \in \mathcal{M}$
4. $E, F \in \mathcal{M} \Longrightarrow E \setminus F \in \mathcal{M}$

Now, we want to understand how to generate a σ-algebra.

Th 2.1. Take $\mathcal{S} \subset \mathcal{P}(X)$ any family. Then it is well defined $\sigma_0(\mathcal{S})$, the σ-algebra generated by $\mathcal{S}$ (the smallest σ-algebra containing $\mathcal{S}$):

i) $\sigma_0(\mathcal{S})$ is a σ-algebra

ii) $\mathcal{S} \subset \sigma_0(\mathcal{S})$

iii) if $\mathcal{M}$ is a σ-alg. and $\mathcal{S} \subset \mathcal{M}$ then $\sigma_0(\mathcal{S}) \subset \mathcal{M}$

PROOF (Sketch).
We introduce a collection of collection of sets (we should be more strict)

$$\mathcal{V} = \{\mathcal{M} \subset \mathcal{P}(X) \,:\, \mathcal{M} \text{ is a } \sigma\text{-alg. and } \mathcal{S} \subset \mathcal{M}\}$$

(notice that $\mathcal{V}$ is not empty since $\mathcal{P}(X) \in \mathcal{V}$)

Then $\sigma_0(\mathcal{S}) = \bigcap \{\mathcal{M} \,:\, \mathcal{M} \in \mathcal{V}\}$ (to generate the smallest take the intersection of all).

■

2.2 Borel sets

2.3 Measures

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 9

Chapter 10

Part III

Functional Analysis

Chapter 11

Chapter 12

Chapter 13

Chapter 14

Chapter 15

Chapter 16

Chapter 17

Chapter 18

Part IV

Esercitazioni

Chapter 19

Exercise session 18/09

Today's **aim**: we want to get the essence of the notion of "being closed" in order to deal with continuity (so this lesson will be a little more theoretical than the following ones).

19.1 Recall on $\mathbb{R}^n$

Given $x, y \in \mathbb{R}$ a possible distance between x and y is

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

(we will analyze its properties in a moment)

Given $x, y \in \mathbb{R}^2$ a possible distance between $x = (x_1, x_2)$ and $y = (y_1, y_2)$ is

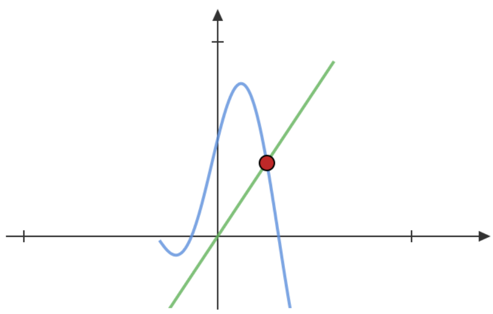
$$d_E(x,y) := \sqrt{\sum_{i=1}^{2} |x_i - y_i|^2}$$

the **Euclidian/canonical distance**. For $\mathbb{R}^n$ is just the same.

Given $f, g \in \mathcal{C}^0([a,b])$, i.e. $f, g : [a,b] \to \mathbb{R}$ continuous, the distance

$$d(f,g) := \min_{x \in [a,b]} |f(x) - g(x)|$$

cannot be a proper distance because $d = 0 \not\Longrightarrow f = g$ (see the definition of distance below).



19.2 Recall on metric spaces

Let X be a nonempty set (no need of any algebraic structure such as vector spaces).

Def. A function $d : X \times X \to [0, +\infty)$ is said to be a **metric/distance** on X if all the followings are satisfied:

(a) $d(x, y) \geq 0$ and $d(x, y) = 0$ iff $x = y$

(b) $d(x, y) = d(y, x)$ (symmetry)

(c) $d(x, y) \leq d(x, z) + d(z, y)$ (**triangular inequality**)

$\forall\, x, y, z \in X$. If d is a distance on X, then (X, d) is called **metric space**.

Examples:

1. $(\mathbb{R}^n, d_E)$ is a metric space

Homework. Prove it.

Hint: in order to prove the tr. inequality use the **Cauchy-Schwarz inequality**

$$\left|\sum_{i=1}^{n} a_i b_i\right| \leq \sqrt{\sum_{i=1}^{n} |a_i|^2} \cdot \sqrt{\sum_{i=1}^{n} |b_i|^2}$$

2. in $\mathbb{R}^n$ $(n \geq 2)$ we can also define

$d_1(x, y) = \sum_{i=1}^{n} |x_i - y_i|$ **Manhattan distance**

$d_\infty(x, y) = \max_{i=1,\dots,n} |x_i - y_i|$ **uniform/maximum distance**

Homework. Prove that both d_1 and d_∞ are distances on $\mathbb{R}^n$.

Hint: use that for $a, b \in \mathbb{R}$, $d(a, b) := |a - b|$ is a distance on $\mathbb{R}$ and so $|a - b| \leq |a - c| + |c - b|$ $\forall\, a, b, c \in \mathbb{R}$

3. for $p > 1$ (but also for $0 < p < 1$)

$$d_p(x, y) = \left(\sum_{i=1}^{n} |x_i - y_i|^p\right)^{1/p}$$

is a metric on $\mathbb{R}^n$ $(p = 2 \rightsquigarrow d_E)$

4. let X be a nonempty set. Can we also define a distance on X? Yes, with the **discrete distance**

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

Homework. Prove that is a metric on X.

Def. Given (X, d) metric space, $x_0 \in X$, $r > 0$,

$$B_r(x_0) = B_d(x_0, r) := \{x \in X \ : \ d(x, x_0) < r\}$$

is a **open ball** of center x_0 and radius r, or a open spherical neighborhood of x_0.

Balls can have different shapes. For examples, let be $X = \mathbb{R}^n$ ($n = 2$ for drawing purposes):

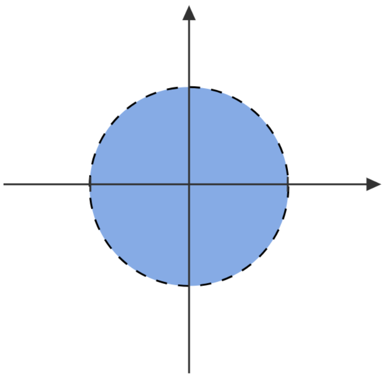
(a) with d_E we have that $B_{d_E}(x_0, r)$ is the open disk of center x_0 and radius r

(b) with d_1 we have

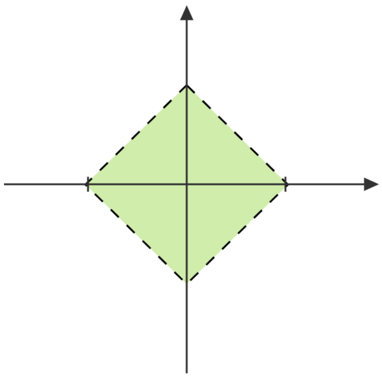
$$\begin{aligned} B_{d_1}(0, r) &= \left\{(x, y) \in \mathbb{R}^2 \ : \ d_1\left((x, y), (0, 0)\right) < r\right\} \\ &= \left\{(x, y) \in \mathbb{R}^2 \ : \ |x| + |y| < r\right\} \end{aligned}$$

(c) with d_∞ we have

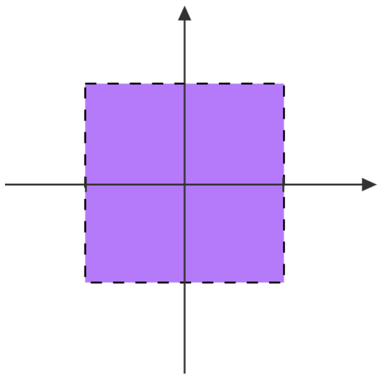
$$\begin{aligned} B_{d_\infty}(0, r) &= \left\{(x, y) \in \mathbb{R}^2 \ : \ d_\infty\left((x, y), (0, 0)\right) < r\right\} \\ &= \left\{(x, y) \in \mathbb{R}^2 \ : \ \max\{|x| + |y|\} < r\right\} \end{aligned}$$



(a) *Ball in* $(\mathbb{R}^n, d_E)$

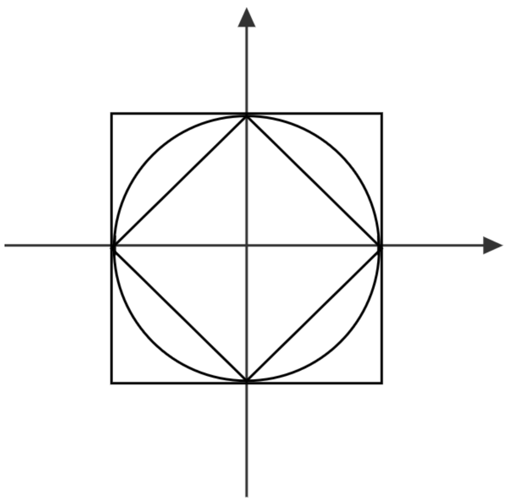


(b) *Ball in* $(\mathbb{R}^n, d_1)$

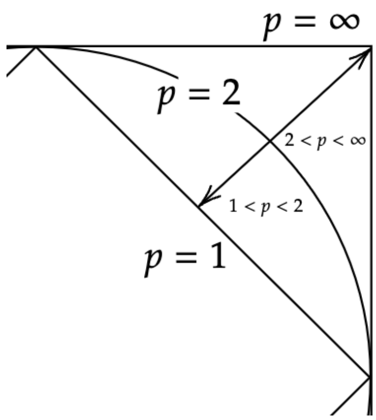


(c) *Ball in* $(\mathbb{R}^n, d_\infty)$

It is remarkable that these balls are equivalent (we will explain it better in due time).



If you generalize to every p, you could say that



$$d_{p,\,p\to\infty} \to d_\infty$$
$$d_{p,\,p=2} \equiv d_E$$
$$d_{p,\,p\to 1} \to d_1$$

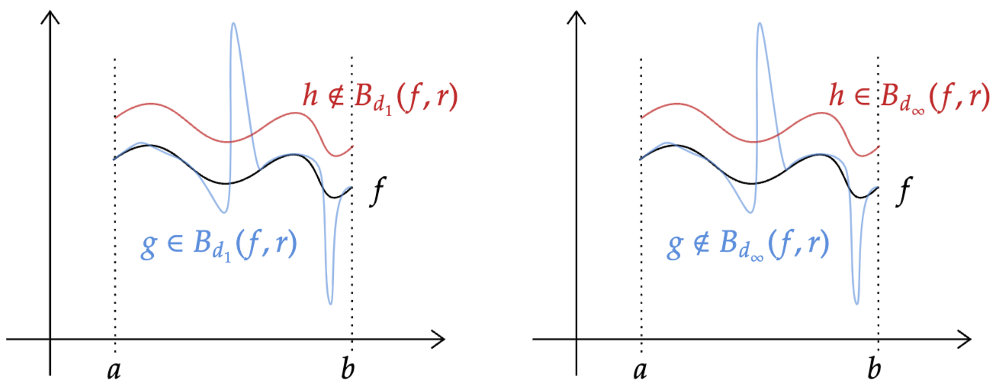
Furthermore, with (X, d) where d is the discrete metric, we have

$$B_d(x_0, r) = \begin{cases} \{x_0\}, & \text{if } r \le 1 \\ X, & \text{if } r > 1 \end{cases}$$

Therefore, many possible distances can be introduced on a set. In some cases they lead to the same *structure* but not in genersal. For example, on $X = \mathcal{C}^0([a,b])$, $f, g \in X$, we have:

- discrete distance (we've got it folks)
- $d_1(f,g) := \displaystyle\int_a^b |f(x) - g(x)| \, \mathrm{d}x$
- $d_\infty(f,g) := \displaystyle\max_{x\in[a,b]} |f(x) - g(x)|$

They are both distances on $\mathcal{C}^0([a,b])$ but they lead to different structures:



19.3 Topology in metric spaces

Chapter 20

Chapter 21

Chapter 22

Chapter 23

Chapter 24

Chapter 25

Chapter 26

Chapter 27

Chapter 28