PMATH351 - Real Analysis (Class Notes)

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Chapter 1

Lecture 1: Sep 8, 2017

1.1 Logistics

Course Website: http://www.math.uwaterloo.ca/~nspronk/math351/math351.html

1.2 Brief Introduction to the Course

1.2.1 Set Theory (Naive, for Real Analysis)

Sets whose existence that we shall take for granted:

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

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

$\mathbb{Q} = \{\frac{m}{n} : m \in \mathbb{Z}, n \in \mathbb{N}, \gcd(m, n) = 1\}$

Definition 1.2.1 (Inclusion)
Given two sets A, B, write

$$A \subseteq B, \quad A \subset B \text{ or } B \supseteq A, \quad \text{etc.} \tag{1.1}$$

for "B contains A", i.e. $\forall x \in A \implies x \in B$. We shall write

$$A \subsetneq B \text{ if } A \subset B \wedge A \neq B \tag{1.2}$$

Definition 1.2.2 (Power Set)
Let X be a set. Let

$$\mathcal{P}(X) := \{A : A \subseteq X\} \tag{1.3}$$

Note that if $X = \{1, ..., n\}$, notice that $\mathcal{P}(X)$ has 2^n elements.

Definition 1.2.3 (Unions and Intersections)
Let $A, B \in \mathcal{P}(X)$ where X is the universe, and $\{A_i\}_{i \in I} \subseteq \mathcal{P}(X)$ where $I \neq \emptyset$.

$$A \cup B = \{x \in X : x \in A \vee x \in B\} \qquad \bigcup_{i \in I} A = \{x \in X : x \in A \textit{ for some } u \in I\}$$
$$A \cap B = \{x \in X : x \in A \wedge x \in B\} \qquad \bigcap_{i \in I} A = \{x \in X : x \in A \forall i \in I\}$$

If we do not have A, B in a common universe, we let the "external union" be

$$A \sqcup B = \{x : x \in A \veebar x \in B\} \tag{1.4}$$

Example 1.2.1
Suppose $I \neq \emptyset$. What is the meaning of

$$\bigcup_{i \in I} A_i, \quad \bigcap_{i \in I} A_i? \tag{1.5}$$

Definition 1.2.4 (Difference Set)
If $A, b \in \mathcal{P}(X)$. Let

$$A \backslash B = \{x \in X : x \in A \wedge x \notin B\} \tag{1.6}$$

In particular

$$X \backslash B = \{x \in X : x \notin B\} \textit{ (complement)} \tag{1.7}$$

Proposition 1.2.1 (De Morgan's Laws)
If X is a set, with $\{A_i\} \in \mathcal{P}(X)$, then

$$X \backslash \bigcup_{i \in I} A_i = \bigcap_{i \in I} (X \backslash A_i), \quad X \backslash \bigcap_{i \in I} A_i = \bigcup_{i \in I} (X \backslash A_i) \tag{1.8}$$

The proof is straightforward and should be done in two lines.

Definition 1.2.5 (Product Sets)
Let A, B be sets.

$$A \times B = \{(a, b) : a \in A, b \in B\} \quad \textit{(ordered pairs)} \tag{1.9}$$

Definition 1.2.6 (Function)
$f \subseteq A \times B$ is called a function if

$$\forall a \in A \quad \exists! b = f(a) \in B \tag{1.10}$$

so that $(a, b) \in f$.

In practice, we write $f : A \to B$ and the ordered pairs are all denoted $(a, f(a))$.

If $X_1, ..., X_n$ are sets, where $n \in \mathbb{N}$, then

$$X_1 \times \ldots \times X_n = \prod_{j=1}^{n} X_j = \{(x_1, ..., x_n) : x_j \in X_j \forall j \in \{1, ..., n\}\} \tag{1.11}$$

is called the n-tuples of X.

IF $\{X_i\}_{i \in I, I \neq \varnothing}$, is a (or an infinite) family of sets

$$\prod_{i \in I} X_i \{(x_i)_{i \in I} : x_i \in X \forall i \in I\} \tag{1.12}$$

Axiom 1.2.1 (Axiom of Choice)
Given any non empty collection of nonempty sets $\{A_i\}_{i \in I}$, we have $\prod_{i \in I} A_i \neq \varnothing$.

Remark (B. Russell)

1. *$\forall n \in \mathbb{N}$, let $S_n = \{l_n, r_n\}$ be a pair of shoes. Surely, $\prod_{i \in I}^{\infty} S_n \neq \varnothing$.*
2. *$\forall n \in \mathbb{N}$, let $T_n = \{s_n, s'_n\}$ be a pair of socks. Why do we expect $\prod_{i \in I}^{\infty} T_n \neq \varnothing$?*

Proposition 1.2.2 (AC')
The AC is equivalent to (AC') given any nonempty set A,

$$\exists f : \mathcal{P}(A) \backslash \{\varnothing\} \to A \qquad \forall B \in P(A) \backslash \{\varnothing\} \quad f(B) \in B \tag{1.13}$$

Proof
$(AC) \implies (AC')$

We assume there is

$$(x_B)_{B \in P(A)\backslash\{\varnothing\}} \in \prod_{B \in P(A)\backslash\{\varnothing\}} B \tag{1.14}$$

(which is nonempty by assumption).

Then we simply have to let $f(B) = x_B$ *for each* B.

$(AC') \implies (AC)$

Given a non-empty collection of nonempty sets $\{A_i\}_{i \in I}$, *let*

$$A = \bigsqcup_{i \in I} A_i \quad \textit{(external product)} \tag{1.15}$$

We have a choice function $f : \mathcal{P}(A)\backslash\{\varnothing\} \to A, f(B) \in B$ *for each* B. *Then*

$$\big(f(A_i)\big)_{i \in I} \in \prod_{i \in I} A_i \tag{1.16}$$

1.3 Relations, Ordering and Zorn

Definition 1.3.1 (Relation)
Let X *be a nonempty set. A relation on* X *is any subset*

$$R \subseteq X \times X \tag{1.17}$$

We write xRy *provided that* $(x, y) \in R$.

Example 1.3.1

1. *A function* $f \subseteq X \times X$ *is a relation.*
2. *In* $\mathbb{N} \times \mathbb{N}$, *consider*
$$mRn \iff \exists p \in \{0\} \cup \mathbb{N} \quad n = m + p \tag{1.18}$$
We write $m \leqslant n \iff mRn$.
3. *On* $\mathbb{Z}$, $m \leqslant n \iff n - m \in \{0\} \cup \mathbb{N}$.
4. *On* $\mathbb{Q}$, $\frac{m}{n} \leqslant \frac{\mu}{\nu} \iff m\nu \leqslant \mu n$ *in* $(\mathbb{Z}, \leqslant)$.
5. *On* $\mathcal{P}(X)$, *we have relations*
$$A \subseteq B$$
$$A \supseteq B$$

Chapter 2

Lecture 2: Sep 11, 2017

2.1 More on Relations

Definition 2.1.1 (More on Relations)
A relation R on X is

1. ***Symmetric*** *if* $xRy \implies yRx$.
2. ***Reflexive*** *if* $\forall x \in X\ xRx$
3. ***Transitive*** *if* $xRy \wedge yRz \implies xRz$
4. ***Anti-Symmetric*** *if* $xRy \wedge yRx \implies x = y \in X$

(i), (ii) and (iii) makes up the ***Equivalence Relation****. We usually use notations like* $\sim, \approx$.

(ii), (iii) and (iv) makes up the ***Partial Order*** *definition. We usually use notations like* $\leqslant, \geqslant$

In Example 1.3.1, (ii), (iii), (iv) and (v) are all partial orders. In (i), f is an equivalence relation only if f is an identity function.

Definition 2.1.2 (Total Order)
A total order is a partial order where for x, y we have at least one of

$$x \leqslant y \quad or \quad y \leqslant x \tag{2.1}$$

holds.

Notice that in Example 1.3.1, (ii), (iii) and (iv) are total orders. However, (v) is not if X has at least two elements.

If $\sim$ is an equivalence relation on X, then we denote the equivalence class by $[x] = \{y \in X : y \sim x\}$

Example 2.1.1
On $\mathbb{Z} \times \mathbb{N}$, let $(m, n) \sim (\mu, v)$ if $m\nu = \mu n$ in $\mathbb{Z}$. Then equivalence classes $[(m, n)]$ are elements of $\mathbb{Q}$. Generally,

$$\frac{m}{n} = [(m, n)] \tag{2.2}$$

2.2 Construction of the Real Numbers

We provide a sketch of Cantor's construction:

Notation: On $\mathbb{Q}$, define $\left|\frac{m}{n}\right| = \begin{cases} \frac{m}{n} & m > 0 \\ -\frac{m}{n} & m < 0 \end{cases}, n \in \mathbb{Z}$

We have the usual properties (triangle inequalities): for $p, q \in \mathbb{Q}$

$$|p + q| \leqslant |p| + |q| \tag{2.3}$$

$$\big||p| - |q|\big| \leqslant |p - q| \tag{2.4}$$

Let $\mathbb{Q}_+ = \{q \in \mathbb{Q} : q > 0\}$

$X = \{(q_n) = (q_n)_{n=1}^{\infty} \in \mathbb{Q}^{\mathbb{N}} : \forall \epsilon \in \mathbb{Q}_+ \ \exists n_\epsilon \in \mathbb{N} \ \forall n, m \geqslant n_\epsilon \ |q_n - q_m| < \epsilon\}$

(X is set of Cauchy sequences of rationals)

On X we define

$$(q_n) \sim (r_n) \text{ if } \forall \epsilon \in \mathbb{Q} \ \exists n_\epsilon \in \mathbb{N} \ |q_n - r_n| < \epsilon \text{ whenever } n \geqslant n_\epsilon \tag{2.5}$$

(tails become closer together)

Then $\sim$ is an equivalence relation (verify yourselves).

We let

$$\mathbb{R} = \{[(q_n)] : (q_n) \in X\} \tag{2.6}$$

Note
$\mathbb{R}$ *is a field.*

$$(q_n) \sim (s_n), (r_n) \sim (t_n) \implies (q_n + r_n) \sim (s_n + t_n), (q_n r_n) \sim (s_n t_n) \tag{2.7}$$

(Check! To check for multiplication, observe that elements of X form bounded sets in $\mathbb{Q}$*).*

$(r_n) \nsim (0, 0, ...) \implies r_n = 0$ *for at most finitely many n*

$\implies$ *define*

$$t_n = \begin{cases} 1 & \text{if } r_n = 0 \\ \frac{1}{r_n} & \text{otherwise} \end{cases}$$

$\implies (r_n)(t_n) \sim (1, 1, 1, ...)$

We can define mutliplication, addition, etc. on $\mathbb{R}$ and it follows that $\mathbb{R}$ is a field.

Note (Properties)

1. $\mathbb{Q}$ *is a subfield:*

$$\mathbb{Q} \hookrightarrow \mathbb{R}, \quad q \mapsto [(q, q, ...)] \tag{2.8}$$

   (eq. class of const. seq.)

2. *Total order: On X let* $(q_n) \leqslant (r_n)$ *if*

$$\forall \epsilon \in \mathbb{Q}_+ \; \exists n_\epsilon \in \mathbb{N} \; \forall n \geqslant n_\epsilon \; q_n \leqslant r_n + \epsilon \tag{2.9}$$

   (Eq. $(1 - \frac{1}{n}) \leqslant (1, 1, ...)$*)*

   Then $(q_n) \leqslant (r_n), (q_n) \sim (s_n), (r_n) \sim (t_n) \implies (s_n) \leqslant (t_n)$ *(check)*

   Hence, let

   $[(q_n)] \leqslant [(r_n)]$ *if* $(q_n) \leqslant (r_n)$.

3. *Density of* $\mathbb{Q}$*: (HW 1)*

   If $[(q_n)] < [(r_n)]$ *then there is q in* $\mathbb{Q}$ *s.t.*

$$[(q_n)] < [(q, q, ...)] < [(r_n)] \tag{2.10}$$

4. *Absolute value:* $|[(q_n)]| = [(|q_n|)]$

   This is the usual absolute value (check)

2.3 Dyadic representation of $\mathbb{R}$

Like the density of $\mathbb{Q} \in \mathbb{R}$, we can show that for $[(q_n)] \in \mathbb{R}$ there is q in $\mathbb{Q}$ s.t. $[(q_n)] \leqslant [(q, q, ...)]$ (HW 1).

Let $X = [(q_n)] \in \mathbb{R}$. Suppose $x \geqslant 0$. Then there is unique $m \in \mathbb{N}$ s.t.

$$[(m, m, ...)] \leqslant x < [(m+1, m+1, ...)] \tag{2.11}$$

Call $m = \lfloor x \rfloor$.

Define

$$x_1 = \begin{cases} 0 & \text{if } x - \lfloor x \rfloor < \frac{1}{2} = [(\frac{1}{2})] \\ 1 & \text{if } x - \lfloor x \rfloor \geqslant \frac{1}{2} \end{cases} \tag{2.12}$$

$$\vdots \tag{2.13}$$

$$x_{n+1} = \begin{cases} 0 & \text{if } x - \left(\lfloor x \rfloor - \sum_{k=1}^{n} \frac{x_k}{2^k} < \frac{1}{2^{k+1}}\right) \\ 1 & \text{if } x - \left(\lfloor x \rfloor - \sum_{k=1}^{n} \frac{x_k}{2^k} \geqslant \frac{1}{2^{k+1}}\right) \end{cases} \tag{2.14}$$

Then, check that

$$x \sim \left(\lfloor x \rfloor + \sum_{k=1}^{2^n} \frac{x_k}{2^k} \right)_{n=1}^{\infty} \tag{2.15}$$

Write $x = \lfloor x \rfloor . x_1 x_2 x_3 ...$

Similarly, we have decimal (base 10) or ternary representation (base 3).

Chapter 3

Lecture 3: Sep 13, 2017

3.1 Last Time

Definition 3.1.1 (Partial Order)
A partial order is a relation $\leqslant$ on X which is

- *reflexive*
- *transitive*
- *anti-symmetric*

We write $(X, \leqslant)$ as a "partially ordered set" or a poset.

3.2 Bounds and Completeness

Definition 3.2.1 (Upper Bound, Supremum)
Let $X, \leqslant)$ be a partially ordered set (aka poset). Given $A \subset X$,

- *an upper bound is any $u \in X$ s.t. $\forall x \in A$ $x \leqslant u$*
- *a supremum (aka least lower bound) is an upper bound s s.t. $s \leqslant u$ for any upper bound u.*

Note

1. *A supremum need not exist.*

   For example, in $(\mathbb{Q}, \leqslant)$,

   - $\mathbb{N}$ *is not bounded above*

- *$A = \{q \in \mathbb{Q} : q^2 \leqslant 2\}$ is bounded above (e.g. 2 is an upper bound) but admits so supremum.*

2. *If a supremum exists, then it is unique (appeal to the anti-symmetry property of $\leqslant$), so we write $s = \sup A$.*

Definition 3.2.2 (Complete)
We say that $(X, \leqslant)$ is complete if any set $A \subset X$ which admits an upper bound has a supremum, $\sup A$.

Example 3.2.1

1. *$X \neq \varnothing$, consider $(\mathcal{P}(X), \subseteq)$. Given $A = \{A_i\}_{i\in I} \subseteq \mathcal{P}(X)$, we have $\sup A = \bigcup_{i\in I} A_i$, so $\mathcal{P}(X), \subseteq)$ is complete.*

2. *$(\mathbb{R}, \leqslant)$ is complete.*

   (Sketch proof) Suppose $\varnothing \neq A \subset \mathbb{R}$ is bounded above. Based on (HW1), we can find $q_0, r_0 \in \mathbb{Q}$ $[\mathbb{Q} \hookrightarrow \mathbb{R}, q \hookrightarrow [(q, q, ...)]$ s.t.

   - *q_0 is not an upper bound for A*
   - *r_0 is an upper bound for A*

   Inductively, define for $n \in \{0\} \cup \mathbb{N}, (q_{n+1}, r_{n+1}) \in \mathbb{Q}^2$.

$$(q_{n+1}, r_{n+1}) = \begin{cases} (q_n, \frac{1}{2}(q_n + r_n)) & \frac{1}{2}(q_n + r_n) \text{ is an upper bound for } A \\ (\frac{1}{2}(q_n + r_n), r_n) & \text{otherwise} \end{cases} \tag{3.1}$$

   Fact (check): $[(q_n)_{n=1}^{\infty}] = [(r_n)_{n=1}^{\infty}]$ and is $\sup A$.

Definition 3.2.3 (Maximum)
Further, we call $m \in A(A \subset X, (X, \leqslant)$ poset a maximum of A if

- *$m = \sup A$*
- *$m \in A$*

Definition 3.2.4 (Lower Bound, Infimum, Minimum)
We have symmetric defnintion for lower bounds, infimums (greatest lower bound) and minimums.

Note: The infimum of A is unique if it exists, denoted as $\inf A$

Proposition 3.2.1 (Infimum of a subset of a space)
If $(X, \leqslant)$ is a complete partially ordered space, then any $A \subseteq X$ which is bounded below, admits an infimum.

Proof
Let $L = \{x \in X : \forall a \in A\ x \leqslant a\}$. Notice that $L \neq \varnothing$ (by assumption on A). Also, L is bounded above, since any element of A is an upper bound.

Then $\sup L = \inf A$.

3.3 Chains and Zorn's Lemma

Definition 3.3.1 (Chain)
Let $(X, \leqslant)$ be a poset. A chain is any subset $C \subseteq X$ s.t. $(C, \leqslant)$ is totally ordered.

(Note: Strictly, we should have $(C, \leqslant \restriction_{C \times C})$.

Definition 3.3.2 (Maximal)
We say an element $m \in X$ is maximal if we have that $\forall x \in X\ m \leqslant x \implies x = m$.

Axiom 3.3.1 (Zorn's Lemma)
Suppose in a poset $(X, \leqslant)$ every chain $C \subseteq X$ admits an upper bound, i.e.

$$\exists u \in X\ \forall x \in C\ x \leqslant u \tag{3.2}$$

Then $(X, \leqslant)$ admits a maximal element.

Definition 3.3.3 (Linearly Independent, Spanning, Basis)
*Let V be a vector space over a field $\mathbb{K}$ ($\mathbb{K} = \mathbb{R}$ or $\mathbb{Q}$). A subset $L \subseteq V$ is **linearly independent (aka lin. ind.)** if for each finite $\{v_1, ..., v_n\} \subseteq L$,*

$$\forall \alpha_n \in \mathbb{K}\ \ 0 = \sum_{i=1}^{n} \alpha_i v_i \implies \alpha_1 = \alpha_2 = \ldots = \alpha_n = 0$$

*A subset $S \subset V$ is **spanning** if for each $v \in V$ there are finite $\{v_1, ..., v_n\} \subseteq S, \{\alpha_1, ..., \alpha_n\} \subseteq \mathbb{K}$ s.t.*

$$v = \sum_{i=1}^{n} \alpha_i v_i$$

*A **basis** is a set $B \subset V$ which is both linearly independent and spanning.*

Theorem 3.3.1 (Vector space over $\mathbb{K}$ has a basis)
A vector space V over $\mathbb{K}$ always admits a basis.

Proof
Let $\mathcal{L} = \{L \subset V : L$ is linearly independent$\}$. We note that $(\mathcal{L}, \subseteq)$ is a poset.

Furthermore, $\big\{\{v\} : v \in V\backslash\{0\}\big\} \subseteq \mathcal{L}$. *So* $\mathcal{L} \neq \varnothing$.

Let $\mathcal{C} = \{L_i\}_{i\in I}$ *be a chain in* $\mathcal{L}$, *and consider* $L = \bigcup_{i\in I} L_i$. *If* $\{v_1, ...v_n\} \subseteq L$, *we have* $v_k \in L_{i_k}$ *for some* $k \in [0, n]$, *and since* $\mathcal{C}$ *is a chain, we may relate so* $L_{i_1} \subseteq L_{i_2} \subseteq \ldots \subseteq L_{i_k}$. *Thus* $\{v_1, ..., v_n\} \subseteq L_{i_n}$ *and is lin. ind. It follows* L *is lin. ind. Hence, Axiom 3.3.1 tells us that* $\mathcal{L}$ *admits a maximal element* B.

WTP B *is spanning. Suppose* B *is not spanning. Then there is* $v_o \in V$ *which cannot be written as a linear combination of finitely many vectors from* B. *Consider*

$$0 = \alpha_0 v_0 + \sum_{i=1}^{n} \alpha_i v_i \tag{3.3}$$

for $\{v_1, ..., v_n\} \subseteq B$, *and* $\alpha_1, ..., \alpha_n \in \mathbb{K}$. *If we can have* $\alpha_n \neq 0$, *then*

$$v_0 = \sum_{i=1}^{n} \left(-\frac{\alpha_i}{\alpha_n} v_i\right) \tag{3.4}$$

which contradicts our assumption on v_o. *Hence* $\alpha_n = 0$, *and thus* $0 = \sum_{i=1}^{n} \alpha_i v_i$, *so* $\alpha_1 = \ldots = \alpha_n = 0$, *as well. Hence* $B \cup \{v_o\} \in \mathcal{L}$. *But* $B \subseteq B \cup \{v_0\}$, *contradicting maximality.*

Remark
An easy modification of the proof shows that any $L = \mathcal{L}$ *is a subset of a basis.*

Chapter 4

Lecture 4: Sep 15, 2017

4.1 Logistics

Office Hours

- today: 1430 - 1520
- Wed, next week: 1430 - 1630

4.2 Cardinal arithmetic

Definition 4.2.1 (Injection, Surjection, Bijection)
Given nonempty sets X, Y, a function $f : X \to Y$ is called a(n)

- ***injection*** $x_1 \neq x_2 \in X \implies f(x_1) \neq f(x_2)$
- ***surjection*** $\forall y \in Y \; \exists x \in X \; f(x) = y$
- ***bijection*** *if it is both an injection and a surjection (aka invertible)*

Of course, if $f : X \to Y$ is a bijection then we can define $f^{-1} : Y \to X$ by $f^{-1}(f(x)) = x$.

We write $X \sim Y$ if there exists a bijection $f : X \to Y$.

Sometimes, we write

$$X \underset{f}{\sim} Y$$

Note ($\sim$ as an equivalence relation)

- *(reflexitivity)* $X \underset{id}{\sim} X$ *($id : X \to X$ is the identity function)*

- *(symmetry)* $X \underset{f}{\sim} Y \implies Y \underset{f^{-1}}{\sim} X$
- *(transitivity)* $X \underset{f}{\sim} Y \wedge Y \underset{g}{\sim} Z \implies X \underset{gf}{\sim} Z$

Hence $\sim$ is an equivalence relation on any given family of sets. We let $|X|$ denote the equivalence class. We call this cardinality of X.

Note: $|\varnothing| = 0,\ \ |\{1, ..., n\}| = n \in \mathbb{N}$

Example 4.2.1

1.
$$\mathbb{N} \sim \mathbb{Z} \quad \because f(n) = \begin{cases} \frac{n}{2} & n \text{ is even} \\ \frac{1}{n}(1-n) & n \text{ is odd} \end{cases}$$

2.
$$\mathbb{R} \underset{f}{\sim} (-1,1) \quad \because f(x) = \frac{x}{|x|+1}$$

   Execise: exhibit f^{-1}

   Answer: $f^{-1}(x) = \frac{x}{1-|x|}$

3. $a < b \in \mathbb{R}\ (0,1) \underset{g}{\sim} (a,b),\ g(x) = a + x(b-a)$

Note (Notation)

$$\aleph_0 = |\mathbb{N}| \ \text{(“aleph-naught”)} \quad c = |\mathbb{R}| \ \text{(“continuum”)}$$

Note (Arithmetic)
Let A, B be sets.

$$|A| + |B| = |A \sqcup B|$$
$$|A||B| = |A \times B|$$
$$|A|^{|B|} = |A^B| \quad (B \neq \varnothing,\ A^B = \{f : B \to A \mid f \text{ is a fucntion}\})$$

Note (Properties)
- *(commutativity)*

$$|A| + |B| = |B| + |A|$$
$$|A||B| = |B||A|$$

- *(distributivity)*

$$|A|(|B| + |C|) = |A||B| + |A||C|$$
$$(A \times (B \sqcup C) \sim (A \times B) \sqcup (A \times C))$$

- *(exponential laws)*

$$(B \neq \varnothing \neq C)$$
$$(1) \quad |A|^{|B|+|C|} = |A|^{|B|}|A|^{|C|} \qquad (2) \quad |A|^{|B||C|} = \left(|A|^{|B|}\right)^{|C|}$$

$$(1) \quad \left(A^{B \sqcup C} \sim A^B \times A^C \text{ via } \phi \mapsto (\phi|_B,\ \phi|_C)\right)$$
$$(2) \quad A^{B \times C} \sim (A^B)^C \text{ via } \phi \mapsto (\phi(b, \cdot) : C \to A)_{b \in B}$$

Definition 4.2.2 (Precedence)
For sets A, B, define

$$A \preceq B \text{ if there is an injection } f : A \to B$$

We sometimes write the above as $A \underset{f}{\preceq} B$.

- *(reflexivity) $A \preceq A$*
- *(transitivity) $A \preceq B,\ B \preceq C \implies A \preceq C$*

We are one property short of making $\preceq$ as an order relation.

Note
It seems reasonable to write $|A| \leqslant |B|$, in this case, our question is: Is $\leqslant$ in cardinal numbers anti-symmetric?

Theorem 4.2.1 (Cantor-Bernstein-Schröder)
If, for non-empty set A, B, we have

$$A \preceq B \ \wedge \ B \preceq A \implies A \sim B \tag{4.1}$$

i.e.

$$|A| \leqslant |B| \wedge |B| \leqslant |B| \implies |A| = |B| \tag{4.2}$$

Proof
Our assumption is that we have injections

$$A \underset{\phi}{\preceq} B, \quad B \underset{\psi}{\preceq} A \tag{4.3}$$

To avoid triviality, let us suppose that neither ϕ or ψ is surjective. Thus

$$\phi(A) \subsetneq B \quad \psi \circ \phi(A) \subsetneq \psi(B) \subsetneq A \tag{4.4}$$

Let $A_0 = A,\ A_1 = \psi(B),\ A_2 = \psi \circ \phi(A)$ and we inductively define

$$A_{n+1} = g(A_n) \text{ where } g = \psi \circ \phi \tag{4.5}$$

Then $A_2 \subsetneq A_1 \subsetneq A_0$, so by applying injection g,

$$\begin{gathered} A_4 \subsetneq A_3 \subsetneq A_2 \\ \vdots \\ A_{n+1} \subsetneq A_n \subsetneq A_{n-1} \end{gathered}$$

Hence, we may decompose

$$\begin{aligned} A = A_0 &= (A_0 \backslash A_1) \cup A_1 \\ &= (A_0 \backslash A_1) \cup (A_1 \backslash A_2) \cup A_2 \\ &\vdots \\ &= \bigcup_{n=1}^{\infty} (A_{n-1} \backslash A_n) \cup A_\infty \end{aligned}$$

where $A_\infty = \bigcap_{n=1}^{\infty} A_n = \bigcap_{n=2}^{\infty} A_n$, we likewise observe

$$A_i = \bigcup_{n=2}^{\infty} (A_{n-1} \backslash A_n) \cup A_\infty$$

Using definitions of the sets A_n $(n \geqslant 2)$ we have

$$g(A_{n=1} \backslash A_n) = A_{n+1} \backslash A_{n+2}$$

Define

$$h : A_0 \to A_1 \quad h(x) = \begin{cases} g(x) & x \in A_{n-1} \backslash A_n \text{ is odd} \\ x & \text{otherwise} \end{cases} \tag{4.6}$$

Then h is a bijection.

Thus $A = A_0 \underset{h}{\sim} A_1 - \phi(B),\ B \underset{\phi}{\sim} \psi(B)$ so we conclude that $A \sim B$. □

Example 4.2.2

1. *Let* $a < b \in \mathbb{R}$. *Then*

$$[a, b) \preceq \mathbb{R} \qquad \textit{obvious}$$
$$\mathbb{R} \sim (-1, 1) \sim (0, 1) \sim (a, b) \preceq [a, b)$$

i.e. $[a, b) \preceq \mathbb{R}$ *and* $\mathbb{R} \preceq [a, b)$ *so* $\mathbb{R} \sim [a, b)$.

Chapter 5

Lecture 5: Sep 18, 2017

5.1 Continuing CBS with examples

Example 5.1.1

2. $\mathcal{P}(\mathbb{N}) \sim \mathbb{R}$, *i.e.* $|\mathcal{P}(\mathbb{N})| = c$

$$\mathcal{P}(\mathbb{N}) \sim \{0,1\}^{\mathbb{N}} \text{ via } A \mapsto \chi(A) \tag{5.1}$$

where

$$\chi_A(n) = \begin{cases} 1 & n \in A \\ 0 & n \notin A \end{cases} \tag{5.2}$$

is the "characteristic indicator".

$$\{0,1\}^{\mathbb{N}} \preceq [0,1) \text{ via } (x_k)_{k=1}^{\infty} \mapsto \sum_{k=1}^{\infty} \frac{x_k}{3^k} = 0.x_1x_2x_3... \quad \text{is the ternary rep'n} \tag{5.3}$$

which is injective.

Claim $[0,1) \preceq \{0,1\}^{\mathbb{N}}$, $\quad 0.x_1x_2x_3... = \sum_{k=1}^{\infty} \frac{x_k}{2^k} \mapsto (x_k)_{k=1}^{\infty}$ *which is the binary rep'n. Note that this representation doesn't allow* $0.1111... = 1$ *(see Lecture 2).*

$\mathcal{P}(\mathbb{N}) \sim \{0,1\}^{\mathbb{N}} \preceq [0,1) \preceq \{0,1\}^{\mathbb{N}} \sim \mathcal{P}(\mathbb{N})$

Thus by Theorem 4.2.1,

$$|\mathcal{P}(\mathbb{N})| = |[0,1)| = c = |\mathbb{R}| \tag{5.4}$$

3. $\mathbb{N} \sim \mathbb{Q} \sim \mathbb{N}^2$

- $\mathbb{N} \preceq \mathbb{Q}$ *(obvious)*

- $\mathbb{Q} \preceq \mathbb{Z} \times \mathbb{N}$, *which we pick* $\frac{m}{n} \mapsto (m, n)$ *with* $\gcd(m, n) = 1$ *where* $m \in \mathbb{Z}, n \in \mathbb{N}$.
- $\mathbb{Z} \times \mathbb{N} \sim \mathbb{N}^2 = \mathbb{N} \times \mathbb{N}$ *as* $\mathbb{Z} \sim \mathbb{N}$
- $\mathbb{N}^2 \sim \mathbb{N}$ *via* $(m, n) \mapsto 2^m 3^n$

Therefore

$$\mathbb{N} \preceq \mathbb{Q} \preceq \mathbb{Z} \times \mathbb{N} \sim \mathbb{N}^2 \preceq \mathbb{N} \tag{5.5}$$

Thus by Theorem 4.2.1, $\mathbb{N} \sim \mathbb{Q} \sim \mathbb{N}^2$.

Note (Notation)
We say that a set A is

- ***countable*** *if* $A \preceq \mathbb{N}$, *i.e.* $|A| \leqslant \aleph_0$
- ***denumerable*** *if* $A \sim \mathbb{N}$, *i.e.* $|A| = \aleph_0$

5.2 Comparison Theorem

Proposition 5.2.1 (Surjectivity)
Suppose X and Y are non-empty sets and there is a surjection $g : X \to Y$. Then $Y \preceq X$.

Proof
Let $f : \mathcal{P}(X)\backslash\{\varnothing\} \to X$ be a choice function (by Axiom 1.2.1 AC). For each $y \in Y$, we have $g^{-1}(\{y\}) = \{x \in X : g(x) = y\} \neq \varnothing$, as g is surjective. Define $h : Y \to X$ be given by $h(y) = f(g^{-1}(\{y\})$ and h is injective, as if $y_1 \neq y_2, \{y_1\} \cap \{y_2\} = \varnothing$, so we see that

$$g^{-1}(\{y_1\}) \cap g^{-1}(\{y_2\}) = \varnothing \tag{5.6}$$

too. □

Theorem 5.2.1 (Comparison Theorem)
Let X and Y be sets. Then either $X \preceq Y$ or $Y \preceq X$.

Proof
If $X = \varnothing$ then $X \preceq Y$; likewise if $Y = \varnothing$. Hence, assume $X \neq \varnothing \neq Y$. Let

$$\Delta = \{(A, f) : A \in \mathcal{P}(X)\backslash\{\varnothing\},\ f \in Y^A \text{ is an injection}\} \tag{5.7}$$

We observe that $\Delta \neq \varnothing$. If $x \in X, y \in Y$, then $(\{x\},\ x \mapsto y) \in \Delta$.

On Δ let

$$(A, f) \preceq (B, g) \iff {}^{A \subseteq B \subseteq X}_{g|_A = f} \tag{5.8}$$

Notice that $\preceq$ is reflexive, anti-symmetric, and transitive. Thus $\preceq$ is a partial order on Δ.

Let $\Gamma = \{(A_i, f_i)\}_{i\in I}$ be a chain in $(\Delta, \preceq)$. We let

$$A = \bigcup_{i\in I} A_i \tag{5.9}$$

and $f \in Y^A$ be given by $f(x) = f_i(x)$ provided $x \in A_i$.

Notice that f is well-defined. Say $x \in A_i$ and $x \in A_j$, then since Γ is a chain, without loss of generality, $A_i \subseteq A_j$, and $f_j|_{A_i} = f_i$.

Furthermore, if $x_1 \neq x_2 \in A$, then $x_1 \in A_{i_1}, x_2 \in A_{i_2}$, and we may suppose $A_{i_1} \subseteq A_{i_2}$. Then $f(x_1) = f_{i_1}(x_1) = f_{i_2}(x_1) \neq f_{i_2}(x_2) = f(x_2)$.

So f is an injection. Thus $(A, f) \in \Delta$ and is an upper bound for Γ.

Thus there is a maximal element $(M, g) \in \Delta$, by Axiom 3.3.1 Zorn's Lemma.

1. *Case 1: $M = X$. Then $X = M \underset{g}{\preceq} Y$.*
2. *Case 2: $M \subsetneq X$. We wish to see that g is surjective.*

   Suppose not, i.e. $\exists y_0 \in Y \backslash g(M)$. Since $M \subsetneq X$, $\exists x_0 \in X \backslash M$. Define $h : M \cup \{x_0\} \to Y$ by

   $$h(x) = \begin{cases} g(x) & x \in M \\ y_0 & x = x_0 \end{cases} \tag{5.10}$$

   which is injective.

   Then $(M \cup \{x_0\}, h) \in \Delta$, and $(M, g) \precneq (M \cup \{x_0\}, h)$, contradicting the maximality of $(M, g) \in \Delta$. Thus g is surjective as desired.

Therefore, $Y \underset{g^{-1}}{\preceq} X$. □

Proposition 5.2.2 (Alternative Definitions of an Infinite Set)
Let A be a set. Then TFAE:

1. *$n \leqslant |A|$ for all $n \in \mathbb{N}$.*
2. *$\aleph_0 \leqslant |A|$, i.e. A is infinite*
3. *$\exists B \subsetneq A$ s.t. $|B| = |A|$.*
4. *$1 + |A| = |A|$ (Hilbert hotel)*
5. *$\aleph_0 + |A| = |A|$*

Chapter 6

Lecture 6: Sep 20, 2017

6.1 Continuing ordinal arithmetic

Proof

1. $1 \implies 2$

We have that for each $n \in \mathbb{N}$ *there is an injection* $\phi_n : \{1, ..., n\} \to A$*. Inductively, define* $f : \mathbb{N} \to A$ *by*

$$\begin{aligned} f(1) &= \phi_1(1) \\ &\vdots \\ f(n+1) &= \phi_{n+1}(k) \quad \textit{where } k = \min\{j \in \{1, ..., n+1\} : \phi_{n+1}(j) \notin \{f(1), ..., f(n)\}\} \end{aligned}$$

The f *is injective by construction, i.e.* $\mathbb{N} \underset{f}{\preceq} A$ *or* $\aleph_0 \leqslant |A|$

2. $2 \implies 3$

We have $\mathbb{N} \underset{f}{\preceq} A$*. Let* $B = A \backslash \{f(1)\}$*.*

Define $g : A \to B$ *by*

$$g(x) = \begin{cases} f(n+1) & x = f(n),\ n \in \mathbb{N} \\ x & \textit{otherwise} \end{cases} \tag{6.1}$$

Then $A \underset{g}{\sim} B$*, i.e.* $|A| = |B|$*.*

3. $3 \implies 4$

We suppose that there is $x_0 \in A \backslash B$ *and* $B \sim A$. *Thus,*

$$A \sim B \preceq B \cup \{x_0\} \preceq A \tag{6.2}$$

Then by Theorem 4.2.1, $A \sim B$ *and furthermore* $A \sim B \cup \{x_0\} \sim A \sqcup \{1\}$, *i.e.* $|A| = |A| + 1$.

4. $4 \implies 5$

   We have $\{1\} \sqcup A \underset{\phi}{\sim} A$. *Then* $\phi(A) \subsetneq A$. *Thus* $\phi \circ \phi(A) \subsetneq \phi(A) \subsetneq A$, *and by induction*

$$\underbrace{\phi^{\circ n}}_{\phi \text{ composed with itself } n \text{ times}}(A) \subsetneq \phi^{\circ(n-1)}(A) \subsetneq \ldots \subsetneq A \tag{6.3}$$

   Hence $|A| \geqslant |A \backslash \phi^{\circ n}(A)| \geqslant n$ *(at each stage above, we gain at least one point).*

5. $2 \implies 5$

   We have $\mathbb{N} \underset{f}{\preceq} A$. *Let*

$$g : \mathbb{N} \sqcup A \to A,\ g(x) = \begin{cases} f(2n) & x = n,\ n \in \mathbb{N} \\ f(2n+1) & x = f(n) \in A,\ n \in \mathbb{N} \\ x & \textit{otherwise} \end{cases} \tag{6.4}$$

6. $5 \implies 2$

   $\aleph_0 \leqslant \aleph_0 + |A| \underset{\textit{by assumption}}{=} |A|$.

Note
Any set satisfying 1 to 5 of the above is called infinite.

Corollary 6.1.1 (A set is either finite or denumerable)
If $A \in \mathcal{P}(\mathbb{N})$, *then either* A *is finite or denumerable.*

Proof
Either $n \leqslant |A|$ *for all* $n \in \mathbb{N}$, *or* $|A| < n$ *for some* $n \in \mathbb{N}$.

Theorem 6.1.1 (Cantor)
For any set X

$$|X| \leqslant |\mathcal{P}(X)|,\ \textit{i.e. } X \preceq \mathcal{P}(X) \wedge X \nsim \mathcal{P}(X) \tag{6.5}$$

Proof
If $X = \varnothing, 0 = |\varnothing| \leqslant 1 = |\{\varnothing\}|$.

If $X \neq \varnothing$*, then* $x \mapsto \{x\} : X \to \mathcal{P}(X)$ *shows* $X \preceq \mathcal{P}(X)$*.*

Now suppose $X \neq \varnothing$*,* $f : X \to \mathcal{P}(X)$*. We will show that f cannot be surjective. Let*

$$E = \{x \in X : x \notin f(x)\} \tag{6.6}$$

i.e. E is a set that is not in the range of f.

If we had $E \subseteq f(X)$*, i.e.* $E = f(x)$ *for some* $x \in X$*, then either*

- $x \in E$*, i.e.* $x \notin f(x)$*, which means that* $E \neq f(x)$*, or*
- $x \notin E = f(x)$*, so* $x \in E$*.*

These contradictions show that $E \nsubseteq f(X)$*.*

Hence there is no surjection $f : X \to \mathcal{P}(X)$*.*

Example 6.1.1
$\aleph_0 = |\mathbb{N}| < |\mathcal{P}(bbN)| = |\mathbb{R}| = c$

Theorem 6.1.2 (Cantor's Continuum Hypothesis)
This is no set A such that

$$\aleph_0 < |A| < c \tag{6.7}$$

Remark
This theorem has recently been proven (about a month ago from Sep 20, 2017). This theorem is independent of ordinary set theory.

Theorem 6.1.3 (Generalized Continuum Hypothesis)
Given an infinite set C, there is no set A such that

$$|C| < |A| < |\mathcal{P}(C)| \tag{6.8}$$

Theorem 6.1.4 (Cantor's Paradox)
There is no "set" of all sets.

Suppose there was a universal set $\mathcal{U}$*, i.e. any set* $A \subseteq \mathcal{U}$*. But then,*

$$|\mathcal{U}| < |\mathcal{P}(\mathcal{U})|, \text{ so } \mathcal{P}(\mathcal{U}) \nsubseteq \mathcal{U} \tag{6.9}$$

so $\mathcal{U}$ *cannot exist.*

Axiom 6.1.1 (Well-Ordering)
Given a non-empty set X, a ***well-order*** *is a partial order on X such that any* $\varnothing \neq A \subseteq X$ *admits a minimal element, i.e.*

$$\exists m_A \in A \; \forall a \in A \; m_A \leqslant a \tag{6.10}$$

Remark
Well-order VS total order: $x, y \in X$ *consider* $A = \{x, y\}$.

Example 6.1.2

1. $(\mathbb{N}, \leqslant)$ *is well-ordered (principle of mathematical induction).*
2. $\mathbb{N}^2$. *Let us consider two well-orders.*

   (pyramid) $(m, n) \leqslant (\mu, \nu) \iff$

   $$\begin{cases} \text{either } m + n < \mu + \nu \\ m + n = \mu + \nu \text{ and } m \leqslant \mu \end{cases} \tag{6.11}$$

   (lexicographic) $(m, n) \underset{l}{\leqslant} (\mu, \nu) \iff$

   $$\begin{cases} \text{either } m < \mu \text{ or} \\ m = \mu \text{ and } n \leqslant \nu \end{cases} \tag{6.12}$$

   Notice that $(m, n) \underset{l}{\leqslant} (\mu, \nu) \iff 2m - \frac{1}{n} \leqslant 2\mu - \frac{2}{\nu} \in (\mathbb{Q}, \leqslant)$

Chapter 7

Lecture 7: Sep 22, 2017

7.1 Metric Spaces

Note
We can use $\mathbb{R}$ in any reasonable manner.

Definition 7.1.1 (Metric and Metric Space)
Let X be a nonempty set. A metric $d : X \times X \to \mathbb{R}$ is a function which satisfies, for $x, y, z \in X$

- ***(non-negativity)*** $d(x, y) \geqslant 0$
- ***(non-degeneracy)*** $d(x, y) = 0 \iff x = y$
- ***(symmetry)*** $d(x, y) = d(y, x)$
- ***(triangle inequality)*** $d(x, z) \leqslant d(x, y) + d(y, z)$

We often call the pair (X, d) a metric space.

Example 7.1.1

1. *On* $\mathbb{R}, d(x, y) = |x - y|$
2. *Let* $X \neq \varnothing$ *any set. Define the "discrete" metric*

$$d : X \times X \to \{0, 1\} \subseteq \mathbb{R}, \;\; d(x, y) = \begin{cases} 0 & x = y \\ 1 & x \neq y \end{cases} \tag{7.1}$$

Note that non-degeneracy and symmetry are obvious. The triangle inequality is sat-

isfied since

$$\textit{Case: } x \neq y \neq z \neq x$$
$$1 = d(x,z) \leqslant 2 = d(x,y) + d(y,z)$$

3. *Let* $f : \mathbb{R} \to \mathbb{R}$ *be strictly increasing. Let*

$$d_f : \mathbb{R}^2 \to [0,\infty) \;\; d_f(x,y) = |f(x) - f(y)| \tag{7.2}$$

E.g. $f(x) = \frac{x}{|x|+1}$.

Exercise: check for its properties.

Proof
By definition of d_f, *it is non-negative and symmetric.*
If $x = y$, *then* $d_f(x,y) = |f(x) - f(y)| = |f(x) - f(x)| = 0$. *Suppose* $x \neq y$. *Since* f *is strictly increasing, without loss of generality, suppose* $f(x) < f(y)$. *Then* $d_f(x,y) > 0$ *since* $f(y) - f(x) > 0$. *Thus* d_f *is non-degenerate.*
Let $x, y, z \in \mathbb{R}^2$.

$$\begin{aligned} d_f(x,z) &= |f(x) - f(z)| \\ &= |f(x) - f(y) + f(y) - f(z)| \\ &\leqslant |f(x) - f(y)| + |f(y) - f(z)| \\ &= d_f(x,y) + d_f(y,z) \end{aligned}$$

4. *(French railroad metric) Suppose we have a set* $X \neq \varnothing$, *and a function* $f : X \to [0,\infty)$ *which satisfies* $f^{-1}(\{0\}) = \{p_0\}$. *Notice that* $f(x) > 0$ *if* $x \in X \backslash \{p_0\}$.

$$d_f : X \times X \to [0,\infty) \;\; d_f(x,y) = \begin{cases} 0 & x = y \\ f(x) + f(y) & x \neq y \end{cases} \tag{7.3}$$

Easy exercise: This is a metric.

Proof

Non-negativity and non-degeneracy are embeded in the function, since $\forall x, y \in X$*, since* $f(x), f(y) \in [0, \infty)$*, we have that* $d_f(x,y) = f(x) + f(y) \geqslant 0$*, and if* $x = y$*,* $d_f(x,y) = 0$*.*

The function is also symmetric, since

$$\begin{aligned} &\forall x, y \in X \\ x \neq y &\implies d_f(x,y) = f(x) + f(y) = f(y) + f(x) = d_f(y,x) \\ x = y &\implies d_f(x,y) = 0 = d_f(y,x) \end{aligned}$$

To prove the triangle inequality, let $x, y, z \in X$*. If* $x = y = z$*,* d_f *is trivially a metric. Without loss of generality, suppose* $x = y \neq z$*, then* $d(x,z) = f(x) + f(z) \overset{(1)}{=} f(y) + f(z) = d(x,y) + d(y,z)$*, where (1) is since* $f(x) = f(y)$*, and* $d(x,y) = 0$*. Suppose* $x \neq y \neq z$*, then*

$$\begin{aligned} d_f(x,z) &= f(x) + f(z) \\ &\leqslant f(x) + f(y) + f(y) + f(z) \quad \text{since } f(y) \geqslant 0 \\ &= d_f(x,y) + d_f(y,z) \end{aligned}$$

Definition 7.1.2 (Norm, Normed Vector Space)

Let V *be a vector space over* $\mathbb{R}$*. A* ***norm*** *is a function* $\|\cdot\| : V \to \mathbb{R}$ *which satisfies, for* $x, y \in V$*,* $\alpha \in \mathbb{R}$

1. ***(non-negativity)*** $\|x\| \geqslant 0$
2. ***(non-degeneracy)*** $\|x\| = 0 \iff x = 0$
3. ***($\|\cdot\|$-homogeneity)*** $\|\alpha x\| = |\alpha| \, \|x\|$
4. ***(subadditivity)*** $\|x + y\| \leqslant \|x\| + \|y\|$

We call the pair $(V, ||\cdot||)$ *a* ***normed vector space****.*

Note

If $(V, \|\cdot\|)$*is a normed vector space, then*

$$d : V \times V \to [0, \infty) \;\; d(x,y) = \|x - y\| \tag{7.4}$$

is always a metric on V*. Everything is easy to check; subadditivity of* $\|\cdot\| \implies$ *triangle inequality of* d*.*

Example 7.1.2

1. $(\mathbb{R}, |\cdot|)$ *is a normed vector space.*

2. *On $\mathbb{R}^n$, for $x = (x_1, ..., x_n)$*

$$\|x\|_2 = \sqrt{x_1^2 + \ldots + x_n^2} \tag{7.5}$$

This is the Euclidean norm.

Consider, also

$$\|x\|_1 = |x_1| + \ldots + |x_n|$$
$$\|x\|_\infty = \max\{|x_1|, ..., |x_n|\}$$

Note
non-degeneracy and $|\cdot|$-homogeneity are obvious for $\|\cdot\|_1,\ \|\cdot\|_\infty$

Let us consider subadditivity

$$\begin{aligned}\|x+y\|_1 &= |x_1+y_1| + \ldots + |x_n+y_n| \\ &\leqslant |x_1| + |y_1| + \ldots + |x_n| + |y_n| \\ &= |x_1| + \ldots + |x_n| + |y_1| + \ldots + |y_n| \\ &= \|x\|_1 + \|y\|_1\end{aligned}$$

$$\begin{aligned}\|x+y\|_\infty &= \max\{|x_i+y_i| : i = 1, ..., n\} \\ &= \max\{|x_i| + |y_i| : i = 1, ..., n\} \\ &= \max\{|x_i| + |y_j| : i, j = 1, ..., n\} \\ &= \max\{|x_i| : i = 1, ..., n\} + \max\{|y_j| : j = 1, ..., n\} \\ &= \|x\|_\infty + \|y\|_\infty\end{aligned}$$

Now for $1 < p < \infty$ consider

$$x^p = \begin{cases} e^{p\log x} & x > 0 \\ 0 & x = 0 \end{cases} \tag{7.6}$$

$$\|x\|_p = (|x_1|^p + \ldots + |x_n|^p)^{\frac{1}{p}}$$

Remark (Cauchy-Bunyakovsky-Schwartz)
$|x \cdot y| \leqslant \|x\|_2\|y\|_2$

Lemma 7.1.1 ($\alpha\beta \leqslant \frac{\alpha^p}{p} + \frac{\beta^q}{q}$)
Let $\alpha, \beta \leqslant 0 \in \mathbb{R},\ 1 < p < \infty$ and q is chosen such that $\frac{1}{p} + \frac{1}{q} = 1$ (i.e. $q = \frac{p}{p-1}$) then

$$\alpha\beta \leqslant \frac{\alpha^p}{p} + \frac{\beta^q}{q} \tag{7.7}$$

with the equality when $\alpha^p = \beta^q$.

Proof
Consider the graph of $y = x^{p-1}$ *(assume* $p \geqslant 2$*). Then*

$$\begin{aligned}\alpha\beta &\leqslant \int_0^\alpha x^{p-1}dx + \int_0^b y^{q-1}dy \\ &= \frac{\alpha^p}{p}\frac{\beta^q}{q}\end{aligned}$$

Equality holds only if $\beta = \alpha^{p-1} \implies \beta^{\frac{1}{p-1}} = \alpha \implies \beta^q = \alpha^p$

Theorem 7.1.1 (Holder's Inequality)
Let $x, y \in \mathbb{R}^n,\ 1 < p < \infty$ *and* q *be so* $\frac{1}{p} + \frac{1}{q} = 1$, *then*

$$\left|\sum_{j=1}^n x_j y_j\right| \leqslant \sum_{j=1}^n |x_j||y_j| \leqslant \left(\sum_{j=1}^n |x_j|^p\right)^{\frac{1}{p}} \left(\sum_{j=1}^n |y_j|^q\right)^{\frac{1}{q}} = \|x\|_p\|y\|_q \tag{7.8}$$

Chapter 8

Lecture 8: Sep 25, 2017

8.1 Logistics

Expect assignment 2 to be up tonight!

8.2 Continuing Normed Vector Space

Proof (Holder's Inequality)
$\|x\|_p \|y\|_q = 0 \implies (x = 0 \vee y = 0) \wedge$ *the inequality is trivial. Let us assume* $\|x\|_p \|y\|_q \neq 0$.
For $j = 1, ..., n$

$$\alpha_j = \frac{|x_j|}{\|x\|_p}, \quad \beta_j = \frac{|y_j|}{\|y\|_q}$$

Then

$$\begin{aligned}
\frac{1}{\|x\|_p \|y\|_q} \sum_{j=1}^{n} |x_j||y_j| = \sum_{j=1}^{n} \alpha_j \beta_j &\overset{(1)}{\leqslant} \sum_{j=1}^{n} \left(\frac{\alpha_j^p}{p} + \frac{\beta_j^q}{q} \right) \\
&= \frac{1}{p} \sum_{j=1}^{n} \alpha_j^p + \frac{1}{q} \sum_{j=1}^{n} \beta_j^q \\
&= \frac{1}{p\|x\|_p^p} \sum_{j=1}^{n} |x_j|^p + \frac{1}{q\|y\|_q^q} \sum_{j=1}^{n} |y_j|^q \\
&= \frac{1}{p\|x\|_p^p} \|x\|_p^p + \frac{1}{q\|y\|_q^q} \|y\|_q^q = \frac{1}{p} + \frac{1}{q} \overset{(2)}{=} 1
\end{aligned}$$

where (1) is by Lemma 7.1.1 and (2) is by choice of q.

Hence, we multiply by $\|x\|_p\|y\|_q$ and see that

$$\sum_{j=1}^{n} |x_j||y_j| \leqslant \|x\|_p\|y\|_q \tag{8.1}$$

□

Theorem 8.2.1 (Minkowski's Inequality)
Let $x, y \in \mathbb{R}^n$ and $1 < p < \infty$. Then

$$\|x+y\|_p \leqslant \|x\|_p + \|y\|_p \tag{8.2}$$

Proof
If $x + y = 0$, this is trivial, hence suppose $x + y \neq 0$. Compute

$$\begin{aligned}
\|x+y\|_p^p = \sum_{j=1}^{n} |x_j+y_j|^p &= \sum_{j=1}^{n} |x_j+y_j||x_j+y_j|^{p-1} \\
&= \sum_{j=1}^{n} (|x_j|+|y_j|)\,|x_j+y_j|^{p-1} \\
&= \sum_{j=1}^{n} |x_j||x_j+y_j|^{p-1} + \sum_{j=1}^{n} |y_j||x_j+y_J|^{p-1} \\
&\leqslant \left(\sum_{j=1}^{n} |x_j|^p\right)^{\frac{1}{p}} \left(\sum_{j=1}^{n} |x_j+y_j|^{(p-1)q}\right)^{\frac{1}{q}} \\
&\quad + \left(\sum_{j=1}^{n} |y_j|^p\right)^{\frac{1}{p}} \left(\sum_{j=1}^{n} |x_j+y_j|^{(p-1)q}\right)^{\frac{1}{q}} \\
&= (\|x\|_p + \|y\|_p) \left(\sum_{j=1}^{n} |x_j+y_j|^{(p-1)q}\right)^{\frac{1}{q}}
\end{aligned}$$

We have $\frac{1}{p} + \frac{1}{q} = 1 \implies \frac{1}{q} = 1 - \frac{1}{p} = \frac{p-1}{p} \implies p = q(p-1)$, and thus

$$\begin{aligned}
\|x+y\|_p^p &\leqslant (\|x\|_p + \|y\|_p) \left(\sum_{j=1}^{n} |x_j+y_j|^p\right)^{\frac{1}{q}} \\
&= (\|x\|_p + \|y\|_p)\|x+y\|_p^{\frac{p}{q}}
\end{aligned}$$

Now divide $\|x+y\|_p^{\frac{p}{q}} \neq 0$*, we get*

$$\|x+y\|_p = \|x+y\|_p^{p-\frac{p}{q}} \leqslant \|x\|_p + \|y\|_p \quad (\textit{since } p - \frac{p}{q} = p(1-\frac{1}{q}) = \frac{p}{p} = 1) \tag{8.3}$$

Corollary 8.2.1 ($\|\cdot\|_p$ is a norm)
Given $1 < p < \infty, \|\cdot\|_p$ *is a norm on* $\mathbb{R}^n$*.*

Proof
Clearly, $\|\cdot\|_p$ *is non-negative and non-degenerate. If* $\alpha \in \mathbb{R}, x \in \mathbb{R}^n$ *then*

$$\begin{aligned}\|\alpha x\|_p = \left(\sum_{j=1}^n |\alpha x_j|_p^p\right)^{\frac{1}{p}} &= \left(\sum_{j=1}^n |\alpha|^p |x_j|^p\right)^{\frac{1}{p}} \\ &= |\alpha| \left(\sum_{j=1}^n |x_)j|^p\right)^{\frac{1}{p}} = |\alpha|\|x\|_p\end{aligned}$$

Finally, subadditivity is provided by Theorem 8.2.1.

8.3 ℓ_p-spaces

Consider $\mathbb{R}^n = \{x = (x_k)_{k=1}^\infty \ : \ x_k \in \mathbb{R}\}$ which is a $\mathbb{R}$-vector space:

$$(x_k)_{k=1}^\infty + (y_k)_{k=1}^\infty = (x_k + y_k)_{k=1}^\infty, \quad \alpha(x_k)k = 1^\infty = (\alpha x_k)k = 1^\infty \tag{8.4}$$

We let, for $1 \leqslant p < \infty$,

- $\ell_p = \{x = (x_k)_{k=1}^\infty \in \mathbb{R}^\mathbb{N} : \sum_{k=1}^\infty |x_k|^p = \lim_{n\to\infty} \sum_{k=1}^n |x_k|^p < \infty\}$

  and

  $\ell_\infty = \{x = (x_k)_{k=1}^\infty : \sup_{k\in\mathbb{N}} |x_k| < \infty\}$

  On ℓ_p we define

$$\|x\|_p = \begin{cases} \left(\sum_{k=1}^\infty |x_k|^p\right)^{\frac{1}{p}} & 1 \leqslant p < \infty \\ \sup_{k\in\mathbb{N}} |x_k| & p = \infty \end{cases} \tag{8.5}$$

Theorem 8.3.1 (ℓ_p is a $\mathbb{R}$-subspace)
Let $1 \leqslant p < \infty$*. Then* ℓ_p *is a* $\mathbb{R}$*-subspace of* $\mathbb{R}^\mathbb{N}$ *and* $\|\cdot\|_p$ *is a norm.*

Proof
We shall prove these statements together. Suppose that $x, y \in \ell_p$. Then

$$\begin{aligned}
\|x+y\|_p &= \left(\sum_{k=1}^{\infty} |x_k + y_k|^p\right)^{\frac{1}{p}} \qquad \textit{(may be } \infty, \infty^{\frac{1}{p}} = \infty\textit{)} \\
&= \left(\lim_{n\to\infty} \sum_{k=1}^{n} |x_k + y_k|^p\right)^{\frac{1}{p}} \\
&= \lim_{n\to\infty} \left(\sum_{k=1}^{n} |x_k + y_k|^p\right)^{\frac{1}{p}} \qquad \left(\substack{x\mapsto x^{\frac{1}{p}} \textit{ is cts on } [0,\infty) \\ x\to\infty \implies x^{\frac{1}{p}} \to \infty}\right) \\
&\leqslant \lim_{n\to\infty} \left[\left(\sum_{k=1}^{n} |x_k|^p\right)^{\frac{1}{p}} + \left(\sum_{k=1}^{n} |y_k|^p\right)^{\frac{1}{p}}\right] \qquad \textit{by Theorem 8.2.1 on each } n \\
&= \left(\lim_{n\to\infty} \sum_{k=1}^{n} |x_k|^p\right)^{\frac{1}{p}} + \left(\lim_{n\to\infty} \sum_{k=1}^{n} |y_k|^p\right)^{\frac{1}{p}} \qquad \textit{cty again} \\
&= \left(\sum_{k=1}^{\infty} |x_k|^p\right)^{\frac{1}{p}} + \left(\sum_{k=1}^{\infty} |y_k|^p\right)^{\frac{1}{p}} = \|x\|_p + \|y\|_p < \infty
\end{aligned}$$

Thus $x + y \in \ell_p$, and we get subaddivity of $\|\cdot\|_p$.

We note that non-negativity and non-degeneracy of $\|\cdot\|_p$ are obvious properties. Liekwise, the $|\cdot|$-homogeneity is straightforward. □

Theorem 8.3.2 (($\ell_\infty, \|\cdot\|_\infty$) is a normed vector space)
$(\ell_\infty, \|\cdot\|_\infty)$ is a normed vector space.

Proof
$x, y \in \ell_\infty \implies$

$$\begin{aligned}
\|x+y\|_\infty = \sup_{k\in\mathbb{N}} |x_k + y_k| &\leqslant \sup_{k\in\mathbb{N}} (|x_k| + y_k|) \\
&\leqslant \sup_{j,k\in\mathbb{N}} (|x_j| + |y_k|) \\
&= \sup_{j\in\mathbb{N}} |x_j| + \sup_{k\in\mathbb{N}} |y_k| = \|x\|_\infty + \|y\|_\infty
\end{aligned}$$

Other properties are easy (exercise).

Note that the norm must be non-negative since $\forall x \in \ell_\infty, \|x\|_\infty = \max\{|x_1|, |x_2|, ..., |x_n|\} > 0$.
The norm is also non-degenerate, since if $x = 0$*, then* $\|x\|_\infty$ *is trivially zero, and if* $\|x\|_\infty = 0$*, then each* $|x_k| = 0$ *for all* k*, thus* $x = 0$.
The norm is clearly $\|\cdot\|$*-homogenous, since given* $\alpha x \in \ell_\infty$,

$$\begin{aligned}\|\alpha x\|_\infty &= \max\{|\alpha x_1|, |\alpha x_2|, ..., |\alpha x_n|\} \\ &= \alpha \max\{|x_1|, |x_2|, ..., |x_n|\} \\ &= \alpha\|x\|_\infty\end{aligned}$$

$\square$

Chapter 9

Lecture 9: Sep 27, 2017

9.1 Last Time

Note

$$1 \leqslant p < \infty$$

$$\ell_p = \left\{ x = (x_k)_{k=1}^{\infty} \in \mathbb{R}^{\mathbb{N}} : \|x\|_p = \left(\sum_{k=1}^{n} |x_k|^p \right)^{\frac{1}{p}} \right\}$$

$$\ell_\infty = \left\{ x = (x_k)_{k=1}^{\infty} \in \mathbb{R}^{\mathbb{N}} : \|x\|_\infty = \sup_{k \in \mathbb{N}} |x_k| \right\}$$

9.2 Continuing with ℓ_p

Define

$$c_0 = \{x = (x_k)_{k=1}^{\infty} \in \mathbb{R}^{\mathbb{N}} : \lim_{k \to \infty} x_k = 0\}$$

Note that c_0 is a $\mathbb{R}$-subspace of $\mathbb{R}^{\mathbb{N}}$: $x, y \in c_0$ and $\alpha \in \mathbb{R}$, then

$$x + y = (x_k + y_k)_{k=1}^{\infty} \in c_0 \left[x_k + y_k \overset{k \to \infty}{\to} 0 \right], \ \alpha x \in c_0$$

Also $(0) = (0, 0, ...) \in c_0$. Also, $c_l \subset \ell_\infty$. Indeed, let $n_1 \in \mathbb{N}$ such that

$$n \geqslant n_1 \implies |x_n - 0| = |x_k| < 1 \quad \text{(here, } \epsilon = 1)$$

Then for $h \in \mathbb{N}$,

$$|x_k| \leqslant \max\{x_1|, ..., |x_{n_1-1}|, 1\} = M$$

i.e. $\|x\|_\infty = \sup_{h\in\mathbb{N}} |x_k| \leqslant M$.

Definition 9.2.1 (The space $C[a,b]$)
Let $a < b \in \mathbb{R}$, and

$$C[a,b] = \{f \in \mathbb{R}^{[a,b]} : f \text{ is continuous } \} \tag{9.1}$$

Note that $C[a,b]$ is a $\mathbb{R}$-vector space $f, g \in C[a,b]$, $\alpha \in \mathbb{R}$, define $f + g, \alpha f \in \mathbb{R}^{[a,b]}$ by

$$(f + g)(t) = f(t) + g(t),\ (\alpha f)(t) = \alpha f(t) \tag{9.2}$$

for all $t \in [a,b]$

Theorem 9.2.1 (Extreme Value Theorem)
if $f \in C[a,b]$ then there exists $t_{\min}, t_{\max} \in [a,b]$ for which

$$f(t_{\min}) \leqslant f(t) \leqslant f(t_{\max}) \quad \text{for all} t \in [a,b] \tag{9.3}$$

Consequently from the Extreme Value Theorem (Theorem 9.2.1), if $f \in C[a,b]$, $|f(\cdot)| \in C[a,b]$ and there is $t_{\max} \in [a,b]$ for which $|f(t)| \leqslant |f(t_{\max})|$ for $r \in [a,b]$. Define, for $f \in C[a,b]$, $\|f\|_\infty = \max_{t\in[a,b]} |f(t)|$.

Just like for $(\ell_\infty, \|\cdot\|_\infty)$, we have that $(C[a,b], \|\cdot\|_\infty)$ is a normed vector space.

We note that $\|\cdot\|_\infty$ is not the only norm on $C[a,b]$. Let $1 \leqslant p < \infty$ and let, for $f \in C[a,b]$

$$\|f\|_p = \left(\int_a^b |f(t)|^p dt\right)^{\frac{1}{p}} \quad \text{(good ol' Riemann integral)} \tag{9.4}$$

Theorem 9.2.2 ($(C[a,b], \|\cdot\|_p)$ as a normed vector space)
$(C[a,b], \|\cdot\|_p)$, $(1 \leqslant p < \infty)$ is a normed vector space.

Proof
First, let us recall right endpoint Riemann sums: $f, g \in C[a,b]$, then

$$\int_a^b g(t)dt = \lim_{n\to\infty} \sum_{k=1}^{n} g\left(a + \frac{k}{n}(b-a)\right) \frac{b-a}{n} \tag{9.5}$$

Hence if $f \in C[a,b]$, then

$$\|f\|_p = \left(\lim_{n\to\infty} \sum_{k=1}^{n} |f(b_k)|^p \frac{b-a}{n} \right) \quad \textit{where } b_k = a + \frac{k}{n}(b-a)$$

$$= \lim_{n\to\infty} \left(\sum_{k=1}^{n} |f(b_k)|^p \right)^{\frac{1}{p}} \left(\frac{b-a}{n} \right)^{\frac{1}{p}}$$

Now, suppose, $f, g \in C[a,b]$

$$\begin{aligned}
\|f+g\|_p &= \lim_{n\to\infty} \left(\sum_{k=1}^{n} |f(b_k)+g(b_k)|^p \right) \left(\frac{b-a}{n} \right)^{\frac{1}{p}} \\
&\leqslant \lim_{n\to\infty} \Bigg[\left(\sum_{k=1}^{n} |f(b_k)|^p \right)^{\frac{1}{p}} \\
&\qquad + \left(\sum_{k=1}^{n} |g(b_k)|^p \right)^{\frac{1}{p}} \Bigg] \left(\frac{b-s}{n} \right)^{\frac{1}{p}} \quad \textit{Minkowski's Theorem 8.2.1} \\
&= \lim_{n\to\infty} \left(\sum_{k=1}^{n} |f(b_k)|^p \right)^{\frac{1}{p}} \left(\frac{b-a}{n} \right)^{\frac{1}{p}} + \lim_{n\to\infty} \left(\sum_{k=1}^{n} |g(b_k)|^p \right)^{\frac{1}{p}} \left(\frac{b-a}{n} \right)^{\frac{1}{p}} \\
&= \|f\|_p + \|g\|_p
\end{aligned}$$

hence we have subadditivity of $\|\cdot\|_p$. It is routine to verify that for $\alpha \in \mathbb{R}$, $f \in C[a,b]$ we have

$$\|\alpha f\|_p = |\alpha| \|f\|_p \tag{9.6}$$

and $\|f\|_p \geqslant 0$ as $|f(\cdot)|^p \geqslant 0$ and finally

$$\|f\|_p = 0 \iff \int_a^b |f(t)|^p dx = 0 \overset{(1)}{\iff} |f(t)|^p = 0 \textit{ for all } t \in [a,b] \iff f = 0 \tag{9.7}$$

((1) as $|f(t)|^p \geqslant 0$ for all t).

Note (Summary thus far about Normed Vector Spaces)

$$\begin{gathered}
(\mathbb{R}, |\cdot|) \\
(\mathbb{R}^{\mathbb{N}}, \|\cdot\|_p),\ 1 \leqslant p < \infty \\
(\ell_p, \|\cdot\|_p),\ 1 \leqslant p < \infty \\
(c_0, \|\cdot\|_\infty) \\
(C[a,b], \|\cdot\|_p),\ 1 \leqslant p < \infty
\end{gathered}$$

9.3 Topology of metric spaces

Definition 9.3.1 (Open and Closed Balls)
Let (X, d) be a metric space, $x_0 \in X$, and $\epsilon > 0$. We define

- *(open ball)* $B(x_0, \epsilon) = \{x \in X : d(x_0, x) < \epsilon\}$
- *(closed ball)* $B[x, \epsilon] = \{x \in X : d(x_0, x) \leqslant \epsilon\}$

Example 9.3.1
In $\mathbb{R}$ we have for $a < b$

$$(a, b) = B\left(\frac{1}{2}(a+b), \frac{1}{2}(b-a)\right)$$
$$[a, b] = B\left[\frac{1}{2}(a+b), \frac{1}{2}(b-a)\right]$$

Definition 9.3.2 (Open and Closed Sets)
Let X, d be a metric space.

- *A set $U \subseteq X$ is open if*

$$\forall x \in U \; \exists \epsilon_x > 0 \; B(x, \epsilon_x) \subseteq U \tag{9.8}$$

- *A set $F \subseteq X$ is closed if $X \backslash F$ is open.*

Proposition 9.3.1 (Open/Closed Balls are Open/Closed Sets)
Let $(X, d), x_0, \epsilon$ as above.

1. $B(x_0, \epsilon)$ *is open.*
2. $B[x_0, \epsilon]$ *is closed.*

Proof

1. *Let $x \in B(x_0, \epsilon)$. Let $\epsilon_x = \epsilon - d(x_0, x) > 0$. Then for $y \in B(x, \epsilon_x)$ and we have*

$$\begin{aligned} d(x_0, y) \leqslant d(x_0, x) + d(y, x) &< d(x_0, x) + \epsilon_x \\ &= d(x_0, x) + \epsilon - d(x_0, x) = \epsilon \end{aligned}$$

   So $y \in B(x_0, \epsilon)$, i.e. $B(x, \epsilon_x) \subseteq B(x_0, \epsilon)$.

2. *Let* $x \in X \backslash B[x_0, \epsilon]$, *and let* $\epsilon_x = d(x, x_0) - \epsilon > 0$. *Now if* $y \in B(x, \epsilon_x)$ *then*

$$\begin{aligned} d(x, x_0) &\leqslant d(x, y) + d(y, x_0) \\ &< \epsilon_x + d(y, x_0) \\ &= d(x, x_0) - \epsilon + d(y, x_0) \end{aligned}$$

$\implies \epsilon < d(y, x_0)$, *i.e.* $y \notin B[x_0, \epsilon]$, *i.e.* $y \in X \backslash b[x_0, \epsilon]$, *so* $B(x, \epsilon_x) \subseteq X \backslash B[x_0, \epsilon]$.

Remark
We may let

$$B[x_0, 0] = \{x \in X : d(x_0, x) \leqslant 0\} = \{x_0\} \tag{9.9}$$

As above, singleton sets $\{x_0\}$ *are closed.*

Chapter 10

Lecture 10: Sep 27, 2017

10.1 Continuing with Balls

Note (Recall)
(X, d) be a metric space, $x_0 \in X$, $\epsilon > 0$

$$B(x_0, \epsilon) = \{x \in X : d(x_0, x) < \epsilon\}$$
$$B[x_0, \epsilon] = \{x \in X : d(x_0, x) \leqslant \epsilon\}$$

Example 10.1.1

1. *$X \neq \varnothing$, $|X| \geqslant 2$, the discrete metric*

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

We have for $x_0 \in X$,

$$B(x_0\epsilon) = \begin{cases} \{x_0\} & 0 < \epsilon \leqslant 1 \\ X & \epsilon > 1 \end{cases}$$
$$B[x_0, \epsilon] = \begin{cases} \{x_0\} & 0 < \epsilon < 1 \\ X & \epsilon \geqslant 1 \end{cases}$$

2. *(Geometry of balls in $\mathbb{R}^2$)*

$$1 \leqslant p < \infty,\ B_p(0, 1) = \{x \in \mathbb{R}^2, d_p(0, x) = ||x||_p < 1\}$$

Pictures

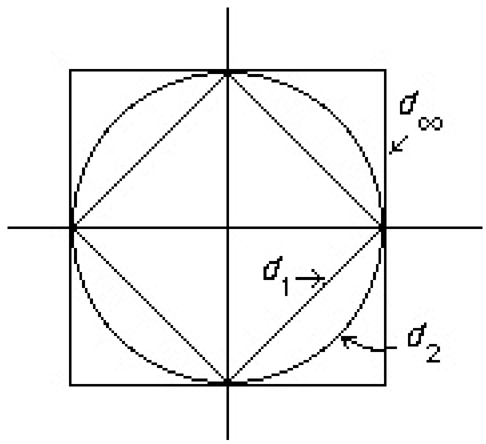
$B_1(0,1) : x_1 + x_2 = 1$ *is a diamond-shaped "ball"*

$B_2(0,1)$ *is a round "ball"*

$B_\infty(0,1)$ *is a squared "ball"*

$B_p(0,1)$ $1 < p < 2$ *the "ball" is inscribed inside the circle*

$B_p(0,1)$ $2 < p < \infty$ *: circle is inscribed within (a square with rounded corners)*



Proposition 10.1.1
Let (X, d) be a metric space.

1. *$X, \varnothing$ are both open and closed.*
2. *If $\{U\}_{i\in I}$ is a family of open sets, then*

$$\bigcup_{i\in I} U_i \quad \text{is open} \tag{10.1}$$

3. *If $\{U_1, ..., U_n\}$ is a finite family of open sets, then*

$$\bigcap_{i=1}^{n} U_i \quad \text{is open} \tag{10.2}$$

4. *If $\{F_i\}_{i\in I}$ is a family of closed sets, then*

$$\bigcap_{i\in I} F_i \quad \text{is closed} \tag{10.3}$$

5. *Of* $\{F_1, ..., F_n\}$ *is a finite family of closed sets, then*

$$\bigcup_{i=1}^{n} F_i \quad \textit{is closed} \tag{10.4}$$

[Recall that singleton sets are closed, hence (5) implies that finite sets are closed]

Proof

1. *Let* $x \in X$. *Then* $x \in B(x, 1) \subseteq X$, *so* X *is open. The test for openness of* $\varnothing$ *is vacuously true (i.e. there are no points to speak of: there are no* $x \in \varnothing$ *at all, hence for any such* x, *we have* x *is "contained" in a ball in* $\varnothing$*).*

   We have $\varnothing = X \backslash X$, $X = X \backslash \varnothing$ *are closed.*

2. *Let* $x \in U = \bigcup_{i \in I} U_i$. *Then there is some* $i_0 \in I$ *so* $x \in U_{i_0}$, *which is open, so there is an* $\epsilon_x > 0$ *such that*

$$x \in B(x, \epsilon_x) \subseteq U_{i_0} \subseteq U \tag{10.5}$$

3. *Let* $x \in V = \bigcap_{i=1}^{n} U_i$. *Then for each* $i = 1, ..., n$, *there is* $\epsilon_i > 0$ *so* $B(x, \epsilon_i) \subseteq U_i$. *Let* $\epsilon = \min\{\epsilon_1, ..., \epsilon_n\} > 0$ *and* $B(x, \epsilon) \subseteq \bigcap_{i=1}^{n} B(x, \epsilon_i) \subseteq V$

For (4) and (5), use De Morgan's Laws and (2) & (3) from above.

Definition 10.1.1 (Boundary)
Given a metric space (X, d), $A \subseteq X$, *we define the boundary of* A *as*

$$\partial A = \{x \in X : \forall \epsilon > 0 \; B(x, \epsilon) \cap A \neq \varnothing, \; \underbrace{B(x, \epsilon) \backslash A}_{B(x,\epsilon) \cap (X \backslash A)} \neq \varnothing\} \tag{10.6}$$

Remark
$\partial A = \partial(X \backslash A)$

Definition 10.1.2 (Interior)
We let the interior of A

$$A^\circ = \bigcup \{U \subseteq X : U \subseteq A \wedge U \textit{ is open}\} \tag{10.7}$$

Proposition 10.1.2 (Characterizations of the Interior)
If (X, d), A *are as above, then*

$$A^\circ = \{x \in X : \exists \epsilon_x > 0 \; B(x, \epsilon_x) \subseteq A\} \tag{10.8}$$

$$= A \backslash \partial A \tag{10.9}$$

Proof
Let $x \in A$. Then we have either

- *for some* $\epsilon_x > 0,\ x \in \underbrace{B(x, \epsilon_x)}_{open} \subseteq A \implies x \in A^\circ$*; or*
- $\forall \epsilon > 0,\ B(x.\epsilon) \backslash A \neq \varnothing \implies$ *since* $x \in A \cap B(x, \epsilon)$*, we have* $x \in \partial A$*. Since* $A^\circ \subseteq A$*, we see that the the two equalities in Equation 10.9 coincide.*

Definition 10.1.3 (Convergence)
Let (X, d) be a metric space, $(x_n)_{n=1}^\infty \subseteq X$ and $x_0 \in X$. Then we say that $(x_n)_{n=1}^\infty$ converges to the limit x_0, written

$$x_0 = \lim_{n\to\infty} x_n \tag{10.10}$$

or

$$x_n \underset{n\to\infty}{\to} x_0 \tag{10.11}$$

if

$$\forall \epsilon > 0\ \exists n_\epsilon \in \mathbb{N}$$
$$n \geqslant n_\epsilon \implies d(x_0, x_n) < \epsilon$$

Remark
The limit, if it exists, is unique. Indeed, since

$$x_0 = \lim_{n\to\infty} x_n \wedge y_0 = \lim_{n\to\infty} x_n$$

then

$$\forall \epsilon > 0\ \exists n_\epsilon, n'_\epsilon \in \mathbb{N}$$
$$n \geqslant n_\epsilon \implies d(x_0, x_n) < \frac{\epsilon}{2}$$
$$n \geqslant n'_\epsilon \implies d(y_0, x_n) < \frac{\epsilon}{2}$$

But then if $n \geqslant \max\{n_\epsilon, n'_\epsilon\}$ we have

$$d(x_0, y_0) \leqslant d(x_0, x_n) + d(x_n, y_0) < \epsilon$$

If this holds for all $\epsilon > 0,\ d(x_0, y_0) = 0$ so $x_0 = y_0$.

Example 10.1.2
Let $(V, \|\cdot\|)$ be a normed vector space. A subset $\{e_n\}_{n=1}^\infty \subseteq V$ is a ***Schauder basis*** *provided that*

$$\forall x \in V\ \exists! \{x_n\}_{n=1}^\infty$$
$$x = \lim_{n\to\infty} \sum_{k=1}^{n} x_k e_k \quad \in V$$

Example: In ℓ_p $(1 \leqslant p < \infty)$*, let* $e_n = (0, ..., 0, \underset{n\text{-}th\ place}{1}, 0, ..)$

Definition 10.1.4 (Accumulation points/Cluster Points and Isolated Points)
We let (X, d) *is a metric space,* $A \subseteq X$ *as above, the set of accumulation points (or cluster points) be given*

$$A' = \{x \in X : \forall \epsilon > 0 \ (B(x, \epsilon)\backslash\{x\}) \cap A \neq \varnothing\} \tag{10.12}$$

(aka a punctured ball).

Furthermore, we call elements of $A\backslash A'$ *as isolated points.*

Proposition 10.1.3
Given (X, d) *as a metric space,* $A \subseteq X$ *as above, the set of all accumulation points*

$$A' = \{x \in X : x = \lim_{n\to\infty} x_n, \ \textit{where } (x_n)_{n=1}^{\infty} \subseteq A\backslash\{x\}\}$$

Proof
If $x \in A'$*, let* $x_1 \in (B(x, 1)\backslash\{x\}) \cap A$*, and inductively let*

$$x_{n+1} \in (B(x, \epsilon_n)\backslash\{x\}) \cap A$$

where $\epsilon + m = \min\{\frac{1}{n}, d(x, x_n)$.

Then we have (exercise) that $x = \lim_{n\to\infty} x_n$*, while* $(x_n)_{n=1}^{\infty} \subseteq A\backslash\{x\}$*. [Notice the points* $x_1, x_2, ..., x_n$ *are distinct]*

The converse inclusion just uses the definition of limits. □

Chapter 11

Lecture 11: Oct 2, 2017

11.1 Last time

Note (3 Descriptions of interior A°)

$$\bigcup\{U \subseteq A : U \textit{ open in } X\}, \{x \in X : \exists \epsilon_x > 0,\ B(x, \epsilon_x) \subseteq A\}$$

11.2 Continuing with Accumulation Points

$$A' = \{x \in X : \forall \epsilon > 0, (B(x\epsilon)\backslash\{x\}) \cap A \neq \varnothing\}$$
$$\text{Also } A' = \{x \in X : x = \lim_{n\to\infty} x_n,\ (x_n)_{n=1}^{\infty} \subset A\backslash\{x\}\}$$

Definition 11.2.1 (Closure)
Given a metric space (X, d) and $A \subseteq X$, define the closure of A by

$$\bar{A} = \cap\{F \subseteq X : A \subseteq F,\ F \textit{ is closed in } X\} \tag{11.1}$$

Of course, $A^\circ \subseteq A \subseteq \bar{A}$.

Theorem 11.2.1 (Characterization of the Closure)
Given a metric space (X, d), $A \subseteq X$, the following sets are the same

$$\bar{A} \quad A \cup \partial A \quad A \cup A' \tag{11.2}$$

("meet" set) $A_m = \{x \in X : \forall \epsilon > 0,\ B(x, \epsilon) \cap A \neq \varnothing\}$.

("limit" set) $A_L = \{x \in X : x = \lim_{n\to\infty} x_n, \quad \text{where } (x_n)_{n=1}^{\infty} \subseteq A\}$

[The notations A_L, A_m will not be used afterwards, we shall use $\bar{A}$.]

Proof
We have

$$\begin{aligned}
\bar{A} &= \bigcap\{F \subseteq X : A \subseteq F,\ F \text{ closed}\} \\
&= \bigcap\{X\backslash U : U \subseteq X\backslash A,\ U \text{ open in } X\} \\
&= X\backslash \bigcup\{U : U \subseteq X\backslash A\ U \text{ open in } X\} \quad \text{De Morgon's Law} \\
&= X\backslash[(X\backslash A)^\circ] \quad \text{(complement of interior)} \\
&= X\backslash[(X\backslash A)\backslash\partial(X\backslash A)] \quad \text{(definition of } (X\backslash A)^\circ) \\
&= X\backslash[(X\backslash A)\backslash\partial A] \\
&= A \cup \partial A
\end{aligned}$$

We thus have that $\bar{A} = A \cup \partial A$.

Now if $x \in A \cup \partial A$, then $\forall\epsilon > 0, B(x,\epsilon) \cap A \neq \varnothing$ [i.e. either $x \in A \cap B(x,\epsilon)$, or $x \in \partial A$, so that $B(x,\epsilon) \cap A \neq \varnothing$]. Thus $A \cup \partial A \subseteq A_m$. Conversely, if $x \in A_m$, then, either

- $\exists\epsilon > 0,\ B(x,\epsilon) \subset A \implies x \in A^\circ \subseteq A$, *or*
- $\forall\epsilon > 0,\ B(x,\epsilon) \cap A \neq \varnothing$, *in which case $x \in \partial A$.*

Hence, $x \in A_m \implies x \in A \cup \partial A$ so $A_m \subseteq A \cup \partial A$.

If $x \in A \cup A'$, then $\forall\epsilon > 0,\ B(x,\epsilon) \cap A \neq \varnothing$. Indeed, as above, either $x \in A$, so $\forall\epsilon > 0, x \in B(x,\epsilon) \cap A$, or $x \in A'$ so that $B(x,\epsilon) \cap A \supseteq (B(x,\epsilon)\backslash\{x\}) \cap A \neq \varnothing$. Hence $A \cup A' \subseteq A_m$.

The definition of a limit of a sequence shows that $A_m = A_L$.

Finally, consider

$$\begin{aligned}
X\backslash(A \cup A') &\subseteq \{x \in X : \exists\epsilon_x > 0,\ B(x,\epsilon_x) \cap A = \varnothing(\implies B(x,\epsilon_x) \subseteq X\backslash A)\} \\
&= (X\backslash A)^\circ \implies X\backslash[(X\backslash A)^\circ] \subseteq X\backslash[X\backslash(A \cup A')]
\end{aligned}$$

Hence

$$\begin{aligned}
\bar{A} = X\backslash[(X\backslash A)^\circ] &\subseteq X\backslash[X\backslash(A \cup A')] \\
&= A \cup A'
\end{aligned}$$

Hence $\bar{A} \subseteq A \cup A' \subseteq A_m = \bar{A}$, so $\bar{A} = A \cup A'$. □

Note
The "limit" set is going to help in A2

11.3 Continuous Functions

Definition 11.3.1 (Continuity)
Let (X, d_X) and (Y, d_Y) be metric spaces. Let $f : X \to Y$ and $x_0 \in X$. We say that f is continuous at x_0 if

$$\forall \epsilon > 0 \quad \delta > 0$$
$$d_X(x, x_0) < \delta \implies d_Y(f(x), f(x_0)) < \epsilon \tag{11.3}$$

We say that f is continuous at the domain X if it is continuous at each point in X.

Note

$$\begin{aligned} \text{Equation 11.3} &\iff f(B(x,\delta) \subseteq B(f(x),\epsilon)) \\ &\iff B(x,\delta) \subseteq f^{-1}B((f(x),\epsilon)) \end{aligned}$$

Definition 11.3.2 (Neighbourhood)
In a metric space, a set N is a ***neighbourhood*** *of a point x_0, if $x_0 \in N^\circ$ (interior).*

Theorem 11.3.1 (Characterization of continuity at a point)
If $(X, d_X), (Y, d_Y), f : X \to Y, x \in X$ are as above, then TFAE:

1. *f is continuous at x_0*
2. *$\forall N$ of $f(x_0) \in (Y, d_Y)$, we have $f^{-1}(N)$ is a neighbourhood of x_0 in (X, d_X).*
3. *$x_0 = \lim_{n\to\infty} x_n \in (X, d_X) \implies f(x_0) = \lim_{n\to\infty} f(x_n) \in (Y, d_Y)$*

Proof
(1) $\implies$ (2)

Given a neighbourhood N of $f(x_0)$, $\exists \epsilon > 0,\ B(f(x_0), \epsilon) \subseteq N$. By assumption of (1), $\exists \delta > 0,\ B(x_0, \delta) \subseteq f^{-1}(B(f(x_0), \epsilon) \subseteq f^{-1}(N)$. Thus $f^{-1}(N)$ is a neighbourhood of x_0.

(2) $\implies$ (1) $\implies$ (3)

Given $\epsilon > 0$, $B(f(x_0), \epsilon)$ is a neighbourhood of $f(x_0)$, so $f^{-1}(B(f(x_0), \epsilon))$ is a neighbourhood of x_0, and hence $\exists \delta > 0,\ B(x_0, \delta) \subseteq f^{-1}(B(f(x_0), \epsilon))$, which proves (1).

Now if $x_0 = \lim_{n\to\infty} x_n \in (X, d_X)$, then by definition, $\exists n_\delta \in \mathbb{N}$ such that if $n \geqslant n_\delta$, $x_n \in B(x_0, \delta)$. But then for $n \geqslant n_\delta$, we have

$$f(x_n) \in f(B(x, \delta)) \subseteq B(f(x_0), \epsilon)$$

and hence $f(x_0) = \lim_{n\to\infty} f(x_n)$.

(3) $\implies$ (1) *which we shall prove by contrapositive, i.e.* $\neg(1) \implies \neg(3)$

If $\neg(1)$*, then* $\exists\epsilon > 0,\ \forall\delta > 0$

$$B(x_0, \delta) \not\subset f^{-1}(B(f(x_0), \epsilon)).$$

Hence for each $n \in \mathbb{N}$*, we may find*

$$x_n \in B(x_0, \frac{1}{n}) \backslash f^{-1}(B(f(x_0), \epsilon)$$

Given $\epsilon' > 0,\ \exists n_{\epsilon'} \in \mathbb{N},\ \forall n_{\epsilon'} \geqslant \frac{1}{\epsilon'}$*. Then for* $n \geqslant n_{\epsilon'},\ x_n \in B(x_0, \epsilon')$ *thus* $\lim_{n\to\infty} x_n = x_0$*. However, each* $f(x_n) \notin B(f(x_0), \epsilon)$*, so* $f(x_n) \underset{n\to\infty}{\not\to} f(x_0)$*.*