Lecture 1, 4/4/23

We use the following two books:

1. Linear Analysis, by B. Bolobás

2. Analysis, by E. Lieb and M. Loss

We begin with metric spaces

Definition 0.1. Let X be a nonempty set and let $\rho : X \times X \to [0, \infty)$. Then $\rho(x, y)$ is called <u>a metric on X</u> if

(i) $\rho(x, y) \geq 0$ for all $x, y \in X$ and $\rho(x, y) = 0$ iff $x = y$.

(ii) $\rho(x, y) = \rho(y, x)$ for all $x, y \in X$

(iii) $\rho(x, y) \leq \rho(x, z) + \rho(z, y)$ for any $x, y, z \in X$. This is called the <u>triangle inequality</u>

ρ is also called a <u>distance</u>. As in, $\rho(x, y)$ is the <u>distance between x and y</u>.

Example 0.1. Let $X = \mathbb{R}^n$, and define $\rho(x, y) = \left(\sum_{i=1}^n (x_i - y_i)^2\right)^{\frac{1}{2}}$. We can in fact replace 2 in this expression with any real $r \geq 1$, or with ∞ (in which case we just take the maximum)

Example 0.2. Let $X = C[a, b]$, the set of continuous $f : [a, b] \to \mathbb{R}$, and define $\rho(x, y) = \max_{x \in [a,b]} |f(x) - g(x)|$

Definition 0.2. Let (X, ρ) be a metric space. For all $x \in X$ and $r > 0$, we defined the <u>open ball centered at x and having radius r</u> as

$$B_r(x) \stackrel{\text{def}}{=} \{y \in X \mid \rho(x, y) < r\}$$

The closed ball is

$$\overline{B_r}(x) \stackrel{\text{def}}{=} \{y \in X \mid \rho(x, y) \leq r\}$$

Definition 0.3. Let (X, ρ) be a metric space and let $A \subseteq X$. Then $a \in A$ is

(i) an <u>interior point</u> of A if there is some $r > 0$ such that $B_r(a) \subseteq A$

(ii) The set of all interior points of A is called the <u>interior of A</u> and is denoted by $\operatorname{int} A$, or A°

(iii) A set A is said to be <u>*open*</u> if $A = A^\circ$

Example 0.3. Let $X = \mathbb{R}^3$, $A = \{(x, y, 0) \mid x, y \in \mathbb{R}\}$. We can see that $A^\circ = \varnothing$.

Proposition 1. *For any x, r, $B_r(x)$ is open.*

Proof. Let $y \in B_r(x)$. Let $r_1 = r - \rho(x, y) > 0$.
Consider $z \in B_{r_1}(y)$. By the triangle inequality, $\rho(x, z) \leq \rho(z, y) + \rho(y, x) < r_1 + \rho(x, y) = r$. So $z \in B_r(x)$, so $B_{r_1}(y) \subseteq B_r(x)$, so y is an interior point. y was arbitrary, so we are done. ∎

Definition 0.4. $A \subseteq X$ is closed if $A^c = X \setminus A$ is open.

Definition 0.5. The point $x \in X$ is a limit point of A if there exists a sequence $\{x_n\}_{n=1}^\infty \subseteq A$ such that $\rho(x, x_n) \to 0$ as $n \to \infty$

Definition 0.6. Let $\{x_n\} \subseteq X$, $x \in X$. Then we we say x_n converges to x, or $x_n \to x$, if $\rho(x_n, x) \to 0$ as $n \to \infty$. In this case, $\{x_n\}_{n=1}^\infty$ is said to be convergent, with limit x.

Theorem 0.1. *If a limit of a sequence $\{x_n\} \subseteq X$ exists, then it is unique.*

Proof. Think ∎

Definition 0.7. A sequence $\{x_n\}_{n=1}^\infty \subseteq X$ is called a Cauchy sequence if $\rho(x_n, x_m) \to 0$ as $n, m \to \infty$. That is, for any $\varepsilon > 0$, there exists an $N \in \mathbb{N}$, such that if $n, m \geq N$, then $\rho(x_n, x_m) < \varepsilon$

Theorem 0.2. *Any convergent sequence is Cauchy*

Proof. Think ∎

Definition 0.8. A metric space (X, ρ) is called complete if every Cauchy sequence converges to some point in X. A metric space which is not complete is called incomplete.

Example 0.4. $X = \mathbb{R}^n$ or $X = C[a, b]$ with the metrics above are complete.

Example 0.5. $\mathbb{Q}$ is incomplete.

Definition 0.9. Let (X, ρ) and $(Y, \tilde{\rho})$ be metric spaces. Then X and Y are isometric if there exist a bijection $f : X \to Y$ such that $\rho(x_1, x_2) = \tilde{\rho}(f(x_1), f(x_2))$ for all $x_1, x_2 \in X$.

Definition 0.10. Let (X, ρ) be a metric space and let $A, B \subseteq X$. Then we say that A is dense in B if $B \subseteq \overline{A}$, where $\overline{A} = \{\text{all limit points of } A\}$

Definition 0.11. Let (X, ρ) and $(\tilde{X}, \tilde{\rho})$ be metric spaces. Then $(\tilde{X}, \tilde{\rho})$ is a completion of $(X,$ if

(i) $X \subseteq \tilde{X}$, and $\tilde{\rho}(x, y) = \rho(x, y)$ for any $x, y \in X$

(ii) X is dense in $\tilde{X}$ in the $\tilde{\rho}$ metric

(iii) $(\tilde{X}, \tilde{\rho})$ is complete

Theorem 0.3. *Any incomplete metric space (X, ρ) admits a completion which is unique up to isometry.*

Proof. Think

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Theorem 0.4. *(The nested ball theorem)*
Let (X, ρ) be a complete metric space, and let $\overline{B_n} = \overline{B_{r_n}}(x_n) \subseteq X$ be a sequence of nested closed balls (meaning $\overline{B_{n+1}} \subseteq \overline{B_n}$) such that $r_n \to 0$. Then $\bigcap_{n=1}^{\infty} \overline{B_n} \neq \varnothing$.

Proof. Consider the centers $\{x_n\}_{n=1}^{\infty} \subseteq X$.

Claim. *$\{x_n\}$ is Cauchy*

Proof. If $m \geq n$, then $\overline{B_m} \subseteq \overline{B_m}$, so $x_m \in \overline{B_m}$, so $\rho(x_m, x_n) \leq r_n$, so $\rho(x_n, x_m) \to 0$ as $m, n \to \infty$.

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Lecture 2, 4/6/23

Definition 0.12. Let (X, ρ) be a metric space, and let $A \subseteq X$. Then A is <u>nowhere dense</u> if $\text{int}(\overline{A}) = \varnothing$

Definition 0.13. Let (X, ρ) be a metric space, and A a set. $A \subseteq X$ is <u>of Baire first category</u> if $A = \bigcup_{n=1}^{\infty} A_n$, where A_n are nowhere dense. Otherwise, A is <u>of Baire second category</u>

Theorem 0.5. *(Baire Category Theorem)*
A complete space is of Baire second category.

Proof. Towards contradiction, assume $X = \bigcup_{n=1}^{\infty} A_n$, where $A_n \subseteq X$ are nowhere dense.
Let $B_1 = B(X_1, 1)$ be a ball in X.
Since A_1 is nowhere dense, there exists $\overline{B}_2 = \overline{B}(x_2, r_2) \subseteq \overline{B}_1$ such that $\overline{B}_2 \cap A_1 = \varnothing$.
Without loss of generality, assume $r_2 < \frac{1}{2}$. Now there exists $\overline{B}_3 = \overline{B}(x_3, r_3) \subseteq \overline{B}_2$ such that $\overline{B}_2 \cap A_1 = \varnothing$.
Without loss of generality, assume $r_3 < \frac{1}{3}$.
At the kth step, there exists $\overline{B}_{k+1} = \overline{B}(x_{k+1}, r_{k+1}) \subseteq \overline{B}_k$ such that $\overline{B}_{k+1} \cap A_k = \varnothing$, $r_{k+1} \leq \frac{1}{k+1}$.
By the nested balls theorem, $\bigcap_{n=1}^{\infty} \overline{B}_n = \{x\}$. By construction, $x \notin A_n$ for all $n \in \mathbb{N}$.
So $X \neq \bigcup_{n=1}^{\infty} A_n$, a contradiction.

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Definition 0.14. Let (X, ρ) be a metric space and let $A \subseteq X$. A collection $\{U_\alpha\}_{\alpha \in A}$ of open subsets of X is an open cover of A if $A \subseteq \bigcup_{\alpha \in A} U_\alpha$
A set $K \subseteq X$ is called compact if any open cover of K has a finite subcover.
Equivalently, $K \subseteq X$ is compact if any sequence $\{x_n\} \subseteq K$ has a limit point $x \in K$.

Theorem 0.6. *(Nested compact set theorem)*
Let (X, ρ) be a metric space and let $\{K_n\}_{n=1}^\infty$ be a sequence of nonempty and nested compact sets. Then $\bigcap_{n=1}^\infty K_n \neq \varnothing$.

Proof. Consider $\{x_n\}_{n=1}^\infty$ with $x_n \in K_n$.
Note for all $n, x_n \in K_1$. Thus there exists a subsequence $\{x_{n_k}\}$ converging to some $x \in K_1$.
We claim that $x \in \bigcap_{n=1}^\infty K_n$.
Fix $m \in \mathbb{N}$. $x_{n_m}, x_{n_{m+1}}, x_{n_{m+2}}, \cdots \in K_m$.
The only limit point is x, thus $x \in K_m$.

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Definition 0.15. Let (X, ρ) be a metric space and let $A \subseteq X$. Then A is bounded if $A \subseteq B(x, r)$ for some $x \in X, r > 0$.

Theorem 0.7. *A compact set in (X, ρ) is closed and bounded.*

Proof. think

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Normed Spaces

Definition 0.16. Let X be a vector space. A function $\|\cdot\| : X \to \mathbb{R}$ is called a norm on X if

(i) $\|x\| \geq 0$ for all $x \in X$. Further, $\|x\| = 0 \iff x = 0$

(ii) $\|\alpha x\| = |\alpha| \|x\|$ for all $x \in X, \alpha \in \mathbb{C}$.

(iii) $\|x + y\| \leq \|x\| + \|y\|$

$(X, \|\cdot\|)$ is called a normed space
Remark:
If one defines $\rho(x, y) = \|x - y\|$, then (X, ρ) is a metric space.

Lecture 3, 4/11/23

Return to metric spaces

Definition 0.17. Let (X, d) be a metric space. Let $T : X \to X$ be a mapping. Then T is said to be a contraction if there exists $\alpha \in (0, 1)$ such that $\rho(Tx, Ty) \leq \alpha\rho(x, y)$ for all $x, y \in X$.

Theorem 0.8. *(Contraction mapping principle)*
Let (X, ρ) be a complete metric space and let $T : X \to X$ be a contraction. Then T has a unique fixed point, i.e. there exists a unique $x \in X$ such that $Tx = x$.

Proof. Proven in 221A

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Claim. $(0, 1) \neq \bigcup_{n=1}^{\infty} [a_n, b_n]$, $[a_n, b_n]$ *are disjoint.*

Proof. Assume $(0, 1) = \bigcup_{n=1}^{\infty} [a_n, b_n]$
We claim the set $X = \bigcup_{n=1}^{\infty} \{a_n, b_n\} \cup \{0\} \cup \{1\}$ is closed. Thus X is a complete metric space. Next, we claim that $\{a_n\}, \{b_n\}, \{0\}, \{1\}$
Alternative proof:
Assume $(0, 1) = \bigcup_{n=1}^{\infty} [a_n, b_n]$.
We construct a function $f : (0, 1) \to \mathbb{R}$ continuous that takes countably many values.
blah blah blah

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Return to normed spaces

Definition 0.18. A complete normed space is called a Banach Space

Definition 0.19. Let X, Y be normed spaces on $K = \mathbb{R}$ or $\mathbb{C}$. A mapping $T : X \to Y$ is linear if $T(\alpha x_1 + \beta x_2) = \alpha Tx_1 + \beta Tx_2$ for all $x_1, x_2 \in X$ and all $\alpha, \beta \in K$.

Definition 0.20. Let X, Y be normed spaces on $K = \mathbb{R}$ or $\mathbb{C}$. Let $T : X \to Y$ be linear. Then

1. T is bounded if there exists $M > 0$ such that for all $x \in X$, $\|Tx\| \leq M\|x\|$

2. The operator norm is

$$\|T\| \stackrel{\text{def}}{=} \sup_{x \in X, x \neq 0} \frac{\|Tx\|}{\|x\|}$$

If T is bounded, then $\|T\| \leq M$

Definition 0.21. Let X and Y be normed spaces on $K = \mathbb{R}$ or $\mathbb{C}$. Let $T : X \to Y$ be linear. T is continuous at $x_0 \in X$ if $x \to x_0$ implies $Tx \to Tx_0$.

Theorem 0.9. *Let X, Y be normed spaces on $K = \mathbb{R}$ or $\mathbb{C}$. Let $T : X \to Y$ be linear. Then the following are equivalent:*

1. *T is continuous at some $x_0 \in X$.*

2. *T is continuous at 0*

3. *T is continuous on X*

4. *T is bounded*

5. *T is Lipschitz*

Proof.

$(3) \Rightarrow (1), (2)$

This is obvious

$(1) \Rightarrow (3)$

Assume T is continuous at some x_0. We want to show continuity at y_0.
Suppose $(y_n) \to y$. Define $x_n = y_n - y_0 + x_0$.
Note $x_n \to x_0$. So $Tx_n \to Tx_0$. Thus

$$\|Ty_n - Ty_0\| = \|Tx_n + Ty_0 - Tx_0 - Ty_0\| \to 0$$

Letting $x_0 = 0$, we get $(2) \Rightarrow (3)$

$(4) \Rightarrow (2)$

Suppose $\|Tx\| \leq M\|x\|$ for all $x \in X$.
Then as $x \to 0$, $\|Tx - T0\| = \|Tx\| \leq M\|x\| \to M\|0\| = 0$.

$(2) \Rightarrow (4)$

For all $\varepsilon > 0$, there exists $\delta > 0$ such that $\|x\| < \delta \implies \|Tx\| < \varepsilon$.
Choose $\varepsilon = 1$. Then there exists $\delta > 0$ such that $\|x\| < \delta \Rightarrow \|Tx\| < 1$
For any $x \in X, x \neq 0 \implies Tx = \frac{\|x\|}{\delta} T(\frac{x}{\|x\|}\delta)$
Set $\overline{x} = \frac{x}{\|x\|}\delta$.
Thus $\|Tx\| = \frac{\|x\|}{\delta}\|T\overline{x}\| \leq \frac{\|x\|}{\delta} = \frac{1}{\delta}\|x\|$
So $\|Tx\| \leq \frac{1}{\delta}\|x\|$ for all $x \in X$, i.e. $M = \frac{1}{\delta}$.

Lecture 4, 4/13/23

(4) $\Rightarrow$ (5)

$\|Tx_1 - Tx_2\| = \|T(x_1 - x_2)\| \leq M\|x_1 - x_2\|$. Thus T is Lipshitz.
Clearly, (5) $\Rightarrow$ (3).

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Definition 0.22. For X, Y normed spaces, the set of all bounded linear operators $T : X \to Y$ is denoted by $B(X, Y)$.

Theorem 0.10. *Let X, Y be normed spaces and let $T \in B(X, Y)$. Then*

$$\|T\| = \sup_{\|x\| \leq 1} \|Tx\| = \sup_{\|x\|=1} \|Tx\| = \sup_{\|x\|<1} \|Tx\|$$

Proof. $\|T\| = \sup_{x \in X, x \neq 0} \frac{\|Tx\|}{\|x\|} = \sup_{x \in X, x \neq 0} \|T(\frac{x}{\|x\|})\|$.
So, letting $\overline{x} = \frac{x}{\|x\|}$, $\|T\| = \sup_{x \in X, x \neq 0} \|T\overline{x}\| \leq \sup_{\|x\|=1} \|Tx\|$
Similarly, $\|T\| \leq \sup_{\|x\| \leq 1} \|Tx\|$
$\|T\| = \sup_{x \in X, x \neq 0} \frac{\|Tx\|}{\|x\|} \geq \sup_{x \in X, \|x\|=1} \frac{\|Tx\|}{\|x\|}$, so we get equality.
We could prove $<$ using limits.

Theorem 0.11. *Let X and Y be normed spaces and let $T : X \to Y$ be linear. Then T is bounded iff T maps bounded sets to bounded sets.*

Proof. Later

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Note: $\|Tx\| \leq \|T\|\|x\|$. Also, a convergent sequence in a metric space is bounded.

Theorem 0.12. *Let X and Y be normed spaces. Then $B(X, Y)$ is a normed space endowed with the operator norm $\|T\|$. Moreover, if Y is Banach, then $B(X, Y)$ is Banach.*

Proof. $B(X, Y)$ is a vector space:
Choose $\alpha, \beta \in K, T_1, T_2 \in B(X, Y)$. Then $\alpha T_1 + \beta T_2$ is linear and continuous. Hence, $\alpha T_1 + \beta T_2 \in B(X, Y)$.
Now we show that $(B(X, Y), \|T\|)$ is a normed space.

1. $\|T\| \geq 0$ for all $T \in B(X, Y)$ clearly, and $\|T\| = 0$ means $Tx = 0$ for any $x \in X$, so $T = 0$.

2. $\|\alpha T\| = |\alpha|\|T\|$

3. Triangle inequality: Choose $x \in B(X, Y)$. Then

$$\begin{aligned}\|(T_1 + T_2)x\| &= \|T_1x + T_2x\| \\ &\leq \|T_1x\| + \|T_2x\| \\ &\leq \|T_1\|\|x\| + \|T_2\|\|x\| \\ &= \|x\|(\|T_1\| + \|T_2\|)\end{aligned}$$

Thus, $\|T_1+T_2\| = \sup_{x\in X, x\neq 0}\|(T_1+T_2)x\| \leq \sup_{\|x\|\leq 1}(\|T_1\|+\|T_2\|)\|x\| \leq \|T_1\|+\|T_2\|$

Now assume Y is a Banach space.
Let $\{T_n\} \subseteq B(X, Y)$ be a Cauchy sequence.
We construct an operator $T : X \to Y$ as follows.
For all $x \in X$, $\{T_nx\}$ is a Cauchy sequence in Y.
Since Y is complete, $\{T_nx\}$ converges to some Tx
We want to show T is linear and bounded.
For all $n \in \mathbb{N}$, $\alpha, \beta \in K$, $x_1, x_2 \in X, T_n(\alpha x_1 + \beta x_2) = \alpha Tx_1 + \beta Tx_2$.
Thus $T(\alpha x_1 + \beta x_2) = \alpha Tx_1 + \beta Tx_2$
Now we show T is bounded.
Since a Cauchy sequence in a metric space is bounded, $\|T_n\| \leq M$ for all $n \in \mathbb{N}$.
For all $x \in \overline{B(0, 1)}, (T_nx) \to Tx$.
Thus $\|Tx\| = \lim_{n\to\infty}\|T_nx\| \leq \lim_{n\to\infty} M\|x\| \leq M$.
Hence $\|T\| \leq M$.

Finally, we show $(T_n) \to T$.
Choose $\varepsilon > 0$. There exists N such that for all $n \geq N$, for all $k \in \mathbb{N}$, $\|T_n - T_{n+k}\| < \varepsilon$.
For all $x \in \overline{B(0, 1)}$, $\|T_nx - T_{n+k}x\| \leq \varepsilon\|x\|$.
Fix $n \geq N$, and let $k \to \infty$ to get $\|T_nx - Tx\| \leq \varepsilon\|x\|$. Thus, $\|T_n - T\| \leq \varepsilon$ for all $n \in \mathbb{N}$¿
So $(T_n) \to T$ in $B(X, Y)$

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Definition 0.23. Let X be a normed space over a field $K = \mathbb{R}$ or $\mathbb{C}$. Then $B(X, K) = X^\star$ is called <u>the dual space of X</u>. $T \in X^\star$ is called a <u>functional</u>.
Special case: $X = L^p(\Omega)$, we will characterize $X^\star$.
When $1 \leq p < \infty$, then $(L^p(\Omega))^\star = L^q(\Omega)$, where $\frac{1}{p} + \frac{1}{q} = 1$ (when $p = 1, q = \infty$)

Theorem 0.13. *Let X be a normed space and Y a Banach space. Assume $A \subseteq X$ is a dense subspace of X and $T \in B(A, Y)$. Then T admits a unique extension $\overline{T} \in B(X, Y)$. Moreover, $\|\overline{T}\| = \|T\|$.*

Proof. Chose $x \in X \setminus A$.
There exists $\{a_n\} \in A$ converging to x because A is dense. Define $Tx = \lim_{n\to\infty} Ta_n$.

First we show this limit exists.
Note $\{Ta_n\}$ is Cauchy, since $\|Ta_n - Ta_m\| \leq \|T\|\|a_n - a_m\| \to 0$.
Since Y is Banach, $\{Ta_n\}$ conveges.
Now we show the limit does not depend on choice of sequence $\{a_n\}$.
Assume $\{b_n\} \to X$. Then

$$\|Ta_n - Tb_n\| = \|T\|\|a_n - b_n\| \leq \|T\|(\|a_n - x\| + \|b_n - x\|) \to 0$$

Thus $\lim_{n\to\infty} Ta_n = \lim_{n\to\infty} Tb_n$
Next we show $\overline{T}$ is linear.

Choose $\alpha, \beta \in K, x_1, x_2 \in X$.
Let $\{a_n\} \to x_1, \{b_n\} \to x_2$ where $\{a_n\}, \{b_n\} \subseteq A$.
$\alpha a_n \to \alpha x_1, \beta b_n \to \beta x_2$
Thus $\alpha a_n + \beta b_n \to \alpha x_1 + \beta x_2$
So

$$\overline{T}(\alpha x_1 + \beta x_2) = \lim_{n\to\infty} T(\alpha x_1 + \beta x_2) = lim_{n\to\infty} T(\alpha x_n) + \lim_{n\to\infty} T(\beta b_n) = \alpha\overline{T}x_1 + \beta\overline{T}x_2$$

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