Analysis III

Homework

Exercises (homework) can be found in the script at the end of each Chapter.
Chapter I: # 3 (only for convex sets), # 4 due Th 4-25
Chapter II: # 2,4,5,6 due Th 5-2
Chapter III: # 3c, 4 due Th 5-9
Chapter IV: # 2b, 3, 4, 6 due Th 5-16
Chapter V: # 2,4,6 due Th 5-25
Chapter VI: # 2,3,4 due Th 6-1

Key Dates

Instruction begins: Mo, April 1
Instruction ends: Fr, June 7
Final's week: June 10-13 (Mo-Th)
Holiday: Mo, May 27

April 2, 2024

No class Thursday, April 04.
Makeup class (tentatively) on Friday, April 12 at 10:30.
Discussion sections on Fridays (tentatively) at 11:40.

Topological Vector Spaces

Definition: Vector Spaces

V over a field $\mathbb{F}$ ($\mathbb{R}$ or $\mathbb{C}$).

Definition: Topological Spaces

(X, τ) where $\tau \subseteq \mathcal{P}(X)$ satisfying

1. $\varnothing, X \in \tau$
2. $A, B \in \tau \implies A \cap B \in \tau$
3. $A_\omega \in \tau \implies \bigcup_\omega A_\omega \in \tau$

Recall: $A \in \tau \iff A$ open $\iff X \setminus A$ closed.
$A^\circ = \bigcup_{\substack{U \subseteq A \\ U \text{ open}}} U$ the set of interior points of A.
$\overline{A} = \bigcap_{\substack{F \supseteq A \\ F \text{ closed}}}$ the closure of A.
A' limit points of A.
Compact sets.
Locally compact sets.
Recall: X is Hausdorff iff $\forall x, y \in X$, $\exists U, V \in \tau$ such that $x \in U$, $y \in V$ and $U \cap V = \varnothing$.

Definition: Bases for Topological Spaces

Definition: Let (X, τ) be a topological space. $\sigma \subseteq \tau$ is called a base for topology τ if $\forall x \in X$, $\forall U \in \tau$, $x \in U$, $\exists W \in \sigma$ such that $x \in W \subseteq U$.

Proposition

$\sigma \subseteq \tau$ is a base for τ if and only if every $U \in \tau$ is the union of certain sets taken from σ.

$$(*) \quad \tau = \left\{ \bigcup_{\omega \subset \Omega} W_\omega \,:\, \{W_\omega\}_{\omega \in \Omega} \subseteq \sigma,\, \Omega \right\}$$

Proof

$(\Longleftarrow)$ ✓
$(\Longrightarrow)$ Take $U \in \tau$ and let $x \in U$, $\rightsquigarrow$ find $W_x \in \sigma$, $x \in W_x \subseteq U$.

$$U = \bigcup_{x \in U} \{x\} \subseteq \bigcup_{x \in U} W_x \subseteq U$$

Therefore $\bigcup_{x \in U} W_x = U$.

Proposition

If σ is a base for some topology τ on X, then

1. $\forall x \in X$, $\exists W \in \sigma$ such that $x \in W$.
2. $\forall U, V \in \sigma$, $\forall x \in U \cap V$, $\exists W \in \sigma$ such that $x \in W \subseteq U \cap V$.

Conversely, if $\sigma \in \mathcal{P}(X)$ ($\varnothing \notin \sigma$) satisfies (1) and (2), then σ is the base for a topology τ (and τ is given by $(*)$).
Note that $U, V \in \tau \implies U \cap V \in \tau$ (requires (2)).
If $U = \bigcup U_\alpha$ and $V = \bigcup V_\beta$, then $U \cap V = \bigcup_{\alpha,\beta} (U_\alpha \cap V_\beta) = \bigcup_{\alpha,\beta} \bigcup_{x \in U} W_{\alpha,\beta,x}$.

Example: Metric Spaces

(X, d) is a metric space if $d : X \times X \to [0, +\infty)$ satisfies

1. $d(x, y) = 0$ if and only if $x = y$.
2. $d(x, y) = d(y, x)$.
3. $d(x, z) \leq d(x, y) + d(y, z)$ (triangle inequality).

Definition: Epsilon Neighborhoods

$$B_\varepsilon(x) = \{y \in x \,:\, d(x, y) < \varepsilon\}$$

$A \subseteq X$ is open if and only if $\forall x \in A$, $\exists \varepsilon > 0$ such that $B_\varepsilon(x) \subseteq A$. $x \in B_\varepsilon(x)$.
τ = set of all open sets.

$$\sigma_1 = \{B_\varepsilon(x) \,:\, x \in X, ; \varepsilon > 0\}$$

is a base for the topology τ.

$$\sigma_2 = \left\{B_{1/n}(x) \,:\, x \in X,\ n \in \mathbb{N}\right\}$$

is also a base for τ.

Definition: Direct Product - Product Topology

Let (X_1, τ_1) and (X_2, τ_2) be topological spaces.
Consider $X = X_1 \times X_2$. The product topology τ on X is given by the base

$$\sigma = \{U_1 \times U_2 \,:\, U_1 \in \tau_1,\ U_2 \in \tau_2\}$$

More explicitly,

$$\tau = \left\{\bigcup_\omega U_{1,\omega} \times U_{2,\omega} \,:\, U_{i,\omega} \in \tau_i\right\}$$

(X_ω, τ_ω) topological spaces $(\omega \in \Omega)$

$$X = \prod_{\omega \in \Omega} = \{(x_\omega)_{\omega \in \Omega} \,:\, x_\omega \in X_\omega\}$$

Formally, $f \cong (x_\omega)_{\omega \in \Omega}$, $x_\omega = f(\omega)$, $f : \Omega \to \bigcup_{\omega \in \Omega} X_\omega$ such that $f(\omega) \in X_\omega$.
[$x \neq \varnothing \Longleftarrow X_\omega \neq \varnothing$ axiom of choice]

$$\sigma = \left\{\prod_{\omega \in \Omega} U_\omega \,:\, U_\omega \in \tau_\omega \text{ and all but finitely many } U_\omega = X_\omega\right\}$$

Definition: Subspace Topology

Given (X, τ) and $Y \subseteq X$, then (Y, τ_Y) is also a topological space where

$$\tau_Y \{U \cap Y \,:\, U \in \tau\}$$

Definition: Local Bases for Topological Spaces

A collection $\gamma \subseteq \tau$ is called a local base at $x \in X$ if

1. $\forall U \in \tau$, $x \in U$, $\exists W \in \gamma$ such that $x \in W \subseteq U$.

2. $\forall W \in \gamma$, $x \in W$

Example

Let (X, d) be a metric space.

$$\gamma_x = \{B_\varepsilon(x) \,:\, \varepsilon > 0\}$$

is a local base at x. Similarly,

$$\tilde{\gamma}_x = \left\{B_{1/n} \,:\, n \in \mathbb{N}\right\}$$

is a countable local base.

Proposition

If γ_x $(x \in X)$ are local bases for τ at X, then

$$\sigma = \bigcup_{x \in X} \gamma_x$$

is a bse for τ.

Proposition

$\{\gamma_x\}_{x \in X}$ are local bases at x for some topology τ if and only if

1. $\forall x \in X$, γ_x is a non-empty collection of subsets containing x.
2. If $U \in \gamma_x$, $V \in \gamma_y$, and $z \in U \cap V$, then $\exists W \in \gamma_z$ such that $z \in W \subseteq U \cap V$.

Definition: Topological Vector Spaces

Suppose V is a vector space over $\mathbb{F} = \mathbb{R}$, $\mathbb{C}$ and let τ be a topology on V.
Then V is a topological vector space (TVS) if

1. $\forall x \in V$, $\{x\}$ is closed.
2. The functions f, g (i.e. algebraic operations) are continuous.

   $f : V \times V \to V,\ f(x, y) = x + y$
   $g : \mathbb{F} \times V \to V,\ g(\lambda, x) = \lambda \cdot x$

Notation

For $A_1, A_2 \subseteq V$ and $B \subseteq \mathbb{F}$,

$$\begin{aligned} A_1 + A_2 &= \{a_1 + a_2 \,:\, a_1 \in A_1,\ a_2 \in A_2\} \\ a + A_1 &= \{a + \alpha \,:\, \alpha \in A\} \\ B \cdot A &= \{\beta \cdot a \,:\, \beta \in B,\ a \in A\} \\ \alpha \cdot A &= \{\alpha \cdot a \,:\, a \in A\} \end{aligned}$$

Lemma

Let V be a TVS. Then

1. $\forall x, y \in V$, $\forall$ open $U_{x+y} \ni x+y$, $\exists$ open $U_x \ni x$, open $U_y \ni y$ such that $U_x + U_y \subseteq U_{x+y}$.
2. $\forall x \in V$, $\alpha \in \mathbb{F}$, $\forall$ open $U_{\alpha x} \ni \alpha x$, $\exists$ open $U_x \ni x$, $U_\alpha \ni \alpha$ such that $U_\alpha \cdot U_x \subseteq U_{\alpha x}$.

Proof of 1

Given $x, y \in X$, $x + y \in U_{x+y}$ open.

$$f(x, y) = x + y \in U_{x+y}$$

and $(x, y) \in f^{-1}(U_{x+y})$ open. In the product topology

$$(x, y) \in U_x \times U_y \subseteq f^{-1}(U_{x+y})$$

which implies $x \in U_x$ and $y \in U_y$, both open, and $U_x + U_y \leq U_{x+y}$.

April 9, 2024

Office Hours: Th 11:30 AM - 1:00 PM
Makeup Class: Friday, April 12 at 11:00 AM.

Lemma

Let V be a TVS

1. $\forall x, y \in V$, $\forall U_{x+y} \ni x+y$ open, $\exists U_x \ni x, U_y \ni y$ such that $U_x + U_y \subseteq U_{x+y}$.
2. $\forall \alpha \in F$, $\forall U_{\alpha x} \ni \alpha x$ open, $\exists U_\alpha \ni \alpha$ open in F, $U_x \ni x$ such that $U_\alpha \cdot U_x \subseteq U_{\alpha x}$.

For 2. with $\alpha = 0$, $\forall x \in X$, $\forall U \ni 0$ open, $\exists \delta > 0$, $U_x \ni x$ open such that $B_\delta(0) \cdot U_x \subseteq U$. That is, $\beta U_x \subseteq U$, $\forall |\beta| < \delta$.

Proposition

In a TVS, the maps

1. Translation: $T_a : x \in V \mapsto X + a \in V \ (a \in V)$
2. Multiplication: $M_\lambda : x \in V \mapsto \lambda \cdot x \in V$ $(\lambda \in \mathbb{F},\ \lambda \neq 0)$

are continuous (in fact, homeomorphic).

Proof

We know $(x, y) \mapsto x + y$ and $(\lambda, x) \mapsto \lambda \cdot x$ are continuous.

Inversions

$T_a \circ T_{-a} = \mathrm{id}$, $T_{-a} \circ T_a = \mathrm{id}$, $M_\lambda \circ M_{1/\lambda} = \mathrm{id}$, and $M_{1/\lambda} \circ M_\lambda = \mathrm{id}$.
Therefore they are bijective and the inverses are continuous.

Remark

If U is open, then $a + U$ is also open.
If γ_0 is a local base at 0, then $\gamma_x = \{x + U \,:\, U \in \gamma_0\} = x + \gamma_0$ is a local base at x.
Recall that γ_x is a local base at x if $\forall W \ni x$ open, $\exists U \in \gamma_x$ such that $x \in U \subseteq W$.
That is, in a TVS only local bses at 0 are needed. We may interpret “local base” as “local base at 0”.

$$\sigma = \bigcup_{x \in V} (x + \gamma_0)$$

is a base for the TVS.

Types of Topologial Vector Spaces

Normed Spaces / Banach Spaces

A normed space is a vector space over $\mathbb{F}$ together with a norm $||\cdot||$, i.e. a map $||\cdot|| : x \in V \mapsto ||x|| \in [0, \infty)$ such that

1. $||x|| = 0 \iff x = 0$.
2. $||x + y|| \leq ||x|| + ||y||$.
3. $||\lambda x|| = |\lambda| \cdot ||x||$.

Remarks

A normed space is a metric space with $d(x, y) = ||x - y||$.
A local base (at 0) is given by ε-neighborhoods:

$$\gamma_0 = \{B_\varepsilon(0) \,:\, \varepsilon > 0\}$$

where

$$B_\varepsilon(0) = \{x \in V \,:\, ||x|| < \varepsilon\}$$

(open ball with radius $\varepsilon > 0$).

Convergence in Normed Space

A sequence $\{x_n\}$ ($x_n \in V$) converges to $\lambda \in V$ if $\lim_{n \to \infty} ||x_n - x|| = 0$.
A sequence $\{x_n\}$ is Cauchy if $\forall \varepsilon > 0$, $\exists N$ such that $\forall j, k \geq N$, $||x_j - x_k|| < \varepsilon$.
A normed space is complete if $\{x_n\}$ Cauchy implies $\exists x \in V$ such that $x_n \to x$.
Complete normed spaces are called Banach spaces.

Example 1

$\ell^p(\mathbb{N})$, $1 \leq p < \infty$, the set of all sequences $\{x_n\}_{n=1}^{\infty} = x$ such that

$$||x|| = \left(\sum_{n=1}^{\infty} |x_n|^p \right)^{1/p} < +\infty$$

Recall $\{x_n\} + \{y_n\} = \{x_n + y_n\}$ and $\lambda\{x_n\} = \{\lambda x_n\}$.
ℓ^p spaces are complete and therefore Banach.
If $\{x_n\} \in \ell^p$ and $\{y_n\} \in \ell^q$, then $\{x_n y_n\} \in \ell^r$, $\frac{1}{p} + \frac{1}{q} = \frac{1}{r} \in [0,1]$ (e.g. $\ell^2 \cdot \ell^2 \leq \ell^1$)

Example 2

$\ell^\infty(\mathbb{N})$, the set of all bounded sequences

$$||x|| = \sup_{n\in\mathbb{N}} |x_n| < +\infty$$

Example 3

$C_0(\mathbb{N}) \subseteq \ell^p(\mathbb{N})$, the set of all sequences $\{x_n\}$

$$\lim_{n\to\infty} x_n = 0$$

C_0 is a closed subspace, and both are Banach.

Example 4

$L^p(\Omega)$, $1 \leq p < \infty$, $\Omega \subseteq \mathbb{R}^d$ a Lebesgue measurable set with $m(\Omega) > 0$, the space of all equivalence classes of Lebesgue measurable functions $f : \Omega \to \mathbb{F}$ such that

$$||f|| = \left(\int_\Omega |f(x)|^p \, dx \right)^{1/p} < +\infty$$

Example 5

$L^\infty(\Omega)$, the measurable and essentially bounded functions

$$\begin{aligned} ||f|| &= \inf_{\substack{N\subseteq\Omega \\ m(N)=0}} \sup_{X\in\Omega\setminus N} |f(x)| < +\infty \\ &= \text{ess sup}_{x\in\Omega} |f(x)| \end{aligned}$$

$L^p(\Omega)$ spaces, $1 \leq p \leq \infty$, are Banach.

Example 6

For $\Omega \neq \varnothing$, let $B(\Omega)$ the set of all bounded functions $f : \Omega \to \mathbb{F}$ with

$$||f|| = \sup_{x\in\Omega} |f(x)|$$

is a Banach space.
$f_n \to f$ in $B(\Omega)$ if and only if f_n converges uniformly on Ω to f.

Example 7

Let Ω be a topological space and $BC(\Omega)$ the set of all bounded, continuous functions $f : \Omega \to \mathbb{F}$.
Then $BC(\Omega) \subseteq B(\Omega)$ is a closed Banach subspace under the same norm.
That is, the uniform limit of continuous functions is a continuous function.

$$\underset{f_n \in BC(\Omega)}{f_n \to f} \implies f \in B(\Omega)$$

Example 8

Let K be a compact, Hausdorff space.
Then $C(K)$ is the set of all continous functions $f : K \to \mathbb{F}$ and $C(K) = BC(K)$.

F Spaces / pre-F Spaces

A pre-F-space is a TVS where the topology is given by some invariant metric $d(x+z, y+z) = d(x, y)$ or $d(x, y) = d(x-y, 0)$.
An F-space is a complete pre-F-space.
A local base (at 0) is given by

$$\gamma_0 = \{B_\varepsilon(0) \,:\, \varepsilon > 0\}, \quad B_\varepsilon(x) = \{y \in V \,:\, d(x, y) < \varepsilon\}$$

Example 1

$\ell^p(\mathbb{N})$, $0 < p < 1$, the set of all $\{x_n\}_{n=1}^{\infty}$ such that

$$\sum_{n=1}^{\infty} |x_n|^p < +\infty$$

with

$$d(x, y) = \sum_{n=1}^{\infty} |x_n - y_n|^p$$

Note that this obeys the triangle inequality specifically because it has not been raised to $1/p$.

$$d(\lambda x, \lambda y) = |\lambda|^p \cdot d(x, y)$$

means that $d(z, 0)$ is not a norm.
Here, $B_\varepsilon(x)$ are not convex sets.

Side Remark

Given $\mathbb{R}^2$, the ℓ^p norm for $1 \leq p \leq \infty$ is given by

$$||(x_1, x_2)|| = \left(|x_1|^p + |x_2|^p\right)^{1/p}$$

and the distance for $0 < p < 1$ by

$$d((x_1, x_2))) = |x_1|^p + |x_2|^p$$

The ε neighborhoods for $p = 1$ are diamonds, $p = 2$ circles, $p = \infty$ squares with smooth transition between them. However, for $0 < p < 1$, we have concave diamond shapes.
These norms and metrics are all equivalent on $\mathbb{R}^2$ in the sense that they give the same topology.

Locally Convex TVS

A TVS which has a local base γ at 0 consisting of open neighborhoods of 0 which are all convex.

Definition: Convex Set

A set $A \subseteq V$ is convex if $\forall\, x, y \in A,\ \lambda \in [0, 1]$, then $\lambda x + (1 - \lambda) y \in A$
Alternatively, the line segment between x and y is contained in A ($[x, y] \subseteq A$).

Fréchet Spaces and pre-Fréchet Spaces

A pre-Fréchet space is locally convex.
A Fréchet space is a locally convex F-space.