Functional analysis

Luka Horjak (luka1.horjak@gmail.com)

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Introduction

These are my lecture notes on the course Functional analysis in the year 2023/24. The lecturer that year was prof. dr. Igor Klep.

The notes are not perfect. I did not write down most of the examples that help with understanding the course material. I also did not formally prove every theorem and may have labeled some as trivial or only wrote down the main ideas.

I have most likely made some mistakes when writing these notes – feel free to correct them.

1 Convexity

1.1 Locally convex spaces

Definition 1.1.1. *A topological vector space*[1] V is an $\mathbb{F}$-vector space that is also a topological space, such both addition and scalar multiplication are continuous.

Definition 1.1.2. Let V be an $\mathbb{F}$-vectors pace. A map $p\colon V \to \mathbb{R}$ is a *seminorm* if the following holds:

i) $\forall x \in V\colon p(x) \geq 0$,

ii) $\forall \lambda \in \mathbb{F}, x \in V\colon p(\lambda x) = |\lambda|\, p(x)$,

iii) $\forall x, y \in V\colon p(x+y) \leq p(x) + p(y)$.

Definition 1.1.3. Let V be an $\mathbb{F}$-vector space and $\mathcal{P}$ a family of seminorms on V. We define a topology $\mathcal{T}$ on V with the sets

$$U(x_0, p, \varepsilon) = \{x \in V \mid p(x - x_0) < \varepsilon\}$$

as a subbasis.

Definition 1.1.4. A topological vector space X is a *locally convex space* if its topology is generated by a family of seminorms $\mathcal{P}$ satisfying

$$\bigcap_{p \in \mathcal{P}} \{x \in X \mid p(x) = 0\} = \{0\}\,.$$

Proposition 1.1.5. A locally convex space X is Hausdorff.

Proof. Let $x, y \in X$ be distinct points. Let $p \in \mathcal{P}$ be a seminorm such that $p(x-y) \neq 0$. Then the sets

$$U = \left\{z \in X \;\middle|\; p(z - x) < \frac{\varepsilon}{2}\right\} \quad \text{and} \quad V = \left\{z \in X \;\middle|\; p(z - y) < \frac{\varepsilon}{2}\right\}$$

split the points x and y. $\square$

Remark 1.1.5.1. The converse is also true.

Definition 1.1.6. A partially ordered set I is *upward directed* if for all $i', i'' \in I$ there exists some $i \in I$ such that $i \geq i'$ and $i \geq i''$.

Definition 1.1.7. A *net* is a pair $((I, \leq), x)$, where $(I, \leq)$ is an upward directed set and $x\colon I \to X$ is a function. We usually write $(x_i)_{i \in I}$.

Remark 1.1.7.1. Let $(X, \mathcal{T})$ be a topological space and $x_0 \in X$. Partially order the set

$$\mathcal{U} = \{U \subseteq X \mid x_0 \in U \land U \text{ is open}\}$$

with reverse inclusion. Then any choice function defines a net $(x_U)_{U \in \mathcal{U}}$.

[1] Also linear topological space.

Definition 1.1.8. Let X be a topological space. A net $(x_i)_{i\in I}$ *converges* so $x \in X$ if for all open sets $U \subseteq X$ with $x \in U$ there exists some index $i_0 \in I$ such that for all $i \geq i_0$ we have $x_i \in U$. We write

$$\lim_{i\in I} x_i = x.$$

Definition 1.1.9. A point $x \in X$ is a *cluster point* of a net $(x_i)_{i\in I}$ if for all open sets $U \subseteq X$ with $x \in U$ and index $i_0 \in I$ there exists some index $i \geq i_0$ such that $x_i \in U$.

Proposition 1.1.10. Let X be a topological space and $A \subseteq X$. Then $x \in \overline{A}$ if and only if there exists a net $(a_i)_{i\in I}$ in A such that

$$\lim_{i\in I} a_i = x.$$

Proof. Suppose a net $(a_i)_{i\in I}$ converges to x. For any neighbourhood U of x and some $i_0 \in I$ we have $a_{i_0} \in U$. Therefore, $U \cap A \neq \emptyset$.

Assume now that $x \in \overline{A}$. Again, define

$$\mathcal{U} = \{U \subseteq X \mid x_0 \in U \land U \text{ is open}\}.$$

There is a choice function a such that $a_U \in A$ for all U. The net $(a_U)_{U\in\mathcal{U}}$ then converges to x. ☐

Proposition 1.1.11. Let X and Y be topological spaces and $f \colon X \to Y$ a map. Then, f is continuous in $x_0 \in X$ if and only if

$$\lim_{i\in I} f(x_i) = f(x_0)$$

for all nets $(x_i)_{i\in I}$ that converge to x_0.

Proof. Suppose that f is continuous at x_0. Take an open neighbourhood U of $f(x_0)$. Then there must exist some $i_0 \in I$ such that for all $i \geq i_0$ we have $x_i \in f^{-1}(U)$, therefore $f(x_i) \in U$.

Now suppose f is discontinuous at x_0. Let

$$\mathcal{U} = \{U \subseteq X \mid x_0 \in U \land U \text{ is open}\}$$

and $V \subseteq Y$ be an open set such that $f(x_0) \in V$ and x_0 is not an interior point of $f^{-1}(V)$. Now using the discontinuity of f, for all $U \in \mathcal{U}$ choose $x_U \in U$ such that $f(x_U) \notin V$. Trivially the net $(x_V)_{V\in\mathcal{V}}$ converges to x_0, but

$$\lim_{V\in\mathcal{V}} f(x_V) \neq f(x_0).$$

☐

Proposition 1.1.12. The following statements are true:

i) A net $(x_i)_{i\in I}$ in a locally convex space converges to x_0 if and only if the net $(p(x_i - x_0))_{i\in I}$ converges to 0 for all $p \in \mathcal{P}$.

ii) The topology in a locally convex space X is the coarsest topology in which all the maps $x \mapsto p(x - x_0)$ are continuous for all $x_0 \in X$ and $p \in \mathcal{P}$.

Proof.

i) If $(x_i)_{i\in I}$ converges to x_0, just apply the proposition 1.1.11. Suppose that all the nets $(p(x_i - x_0))_{i\in I}$ converge to 0. Choose an open set from the local basis of x_0. It is given by
$$U = \{x \in X \mid \forall k \leq n \colon p_k(x - x_0) < \varepsilon\}.$$
But as all nets $(p_k(x_i - x_0))_{i\in I}$ converge to 0, there is some index $i_k \in I$ such that for all $i \geq i_k$ we have $p_k(x_i - x_0) < \varepsilon$. Now just take i_0 to be an upper bound of i_k. For all $i \geq i_0$ we then have $x_i \in U$.

ii) Obvious. □

Definition 1.1.13. For all $f \in X^*$ define a seminorm $p_f \colon X \to \mathbb{R}$ as $p_f(x) = |f(x)|$. The family $\mathcal{P} = \{p_f \mid f \in X^*\}$ induces the *weak topology* on X. We denote the weak topology with $\sigma(X, X^*)$.

Remark 1.1.13.1. The space X with the topology $\sigma(X, X^*)$ is a locally convex space by the Hahn-Banach theorem.[2]

Definition 1.1.14. Let X be a normed space. For all $x \in X$ we define a seminorm $p_x \colon X^* \to \mathbb{R}$ as $p_x(f) = |f(x)|$. The family $\mathcal{P} = \{p_x \mid x \in X\}$ induces the *weak-* topology* on X^*. We denote the weak-* topology with $\sigma(X^*, X)$.

Remark 1.1.14.1. The weak topology on X^* is finer than the weak-* topology, as X can be isometrically mapped into X^{**} with the map $x \mapsto (f \mapsto f(x))$.

[2] Introduction to functional analysis, corollary 2.2.5.2.

1.2 Banach-Alaoglu theorem

Theorem 1.2.1 (Banach-Alaoglu)**.** Let X be a normed space. Then the closed unit ball in X^*

$$(X^*)_1 = \{f \in X^* \mid \|f\| \leq 1\}$$

is compact in the weak-* topology on X^*.

Proof. Assign a disk to all $x \in X$ as $D_x = \{z \in \mathbb{F} \mid |z| \leq \|x\|\}$ with the euclidean topology. Define

$$P = \prod_{x \in X} D_x$$

with the product topology. The space P is then compact by Tychonoff's theorem. Now define the map $\Phi \colon (X^*)_1 \to P$ with $\Phi(f) = (f(x))_{x \in X}$. This map is injective.

Let $(f_i)_{i \in I}$ be a net in $(X^*)_1$ that weak-* converges to $f \in X^*$. Equivalently, we have

$$\lim_{i \in I} f_i(x) = f(x)$$

for all $x \in X$. By the definition of the product topology we have

$$\lim_{i \in I} \Phi(f_i) = \Phi(f).$$

Therefore, Φ is continuous. Analogously, $\Phi^{-1} \colon \operatorname{im} \Phi \to (X^*)_1$ is continuous.

Suppose that $(\Phi(f_i))_{i \in I}$ converges to some $p \in P$. By the definition of the product topology this means that $f_i(x)$ converges to p_x for all $x \in X$. Define a map $f \colon X \to \mathbb{F}$ given by $f(x) = p_x$. Then, f is linear and bounded with $\|f\| \leq 1$. Thus $p = \Phi(f) \in \operatorname{im}(\Phi)$, therefore, $\Phi((X^*)_1)$ is closed. As $(X^*)_1$ is homeomorphic to its image which is compact, it is also compact. □

Corollary 1.2.1.1. Every Banach space X is isometrically isomorphic to a closed subspace $\mathcal{C}(K)$ for some compact Hausdorff space K.

Proof. Choose $K = (X^*)_1$ with the weak-* topology. By Banach-Alaoglu, K is compact and Hausdorff. Now define the map $\Delta \colon X \to K$ with $\Delta(x) = (f \mapsto f(x))$. Now observe that

$$\|\Delta(x)\|_\infty = \sup_{g \in K} |\Delta(x)(g)| = \sup_{g \in K} |g(x)| = \|x\|$$

by Hahn-Banach.[3] □

[3] Introduction to functional analysis, corollary 2.2.5.1.

1.3 Minkowski gauge

Definition 1.3.1. Let X be a $\mathbb{F}$-vector space. A set $A \subseteq$ is

i) *balanced*, if for all $x \in A$ and $\alpha \in \mathbb{F}$ with $|\alpha| \leq 1$ we have $\alpha x \in A$,

ii) *absorbing*, if for all $x \in A$ there exists some $\varepsilon > 0$ such that for all $t \in (0, \varepsilon)$ we have $tx \in A$,

iii) *absorbing in* $a \in A$ if $A - a$ is absorbing.

Theorem 1.3.2. Let X be a $\mathbb{F}$-vector space and $V \subseteq X$ a convex, balanced and absorbing in each of its points. Then there exists a unique seminorm p such that

$$V = \{x \in X \mid p(x) < 1\}.$$

Proof. As A is convex, we can define the *Minkowski gauge*

$$p_V(x) = \inf \{t \geq 0 \mid x \in tV\}.$$

It is of course well defined, as A is absorbing. We can check that

$$\begin{aligned} p_V(\alpha x) &= \inf \left\{ t \geq 0 \,\middle|\, x \in \frac{t}{\alpha} V \right\} \\ &= \inf \left\{ t \geq 0 \,\middle|\, x \in \frac{t}{|\alpha|} V \right\} \\ &= |\alpha| \cdot \inf \left\{ \frac{t}{|\alpha|} \geq 0 \,\middle|\, x \in \frac{t}{|\alpha|} V \right\} \\ &= |\alpha| \, p_V(x) \end{aligned}$$

as A is balanced. Therefore, p_V is homogeneous. As p_V is sublinear,[4] it is a seminorm. It follows that[5]

$$V = \{x \in X \mid p_V(x) < 1\}.$$

Suppose that

$$V = \{x \in X \mid q(x) < 1\}$$

for some seminorm $q \neq p_V$. But then we have $p_V(x) \neq q(x)$ for some $x \in X$, therefore there exists some $t \in \mathbb{R}$ such that $p_V(tx) > 1 > q(tx)$ or $q(tx) > 1 > p_V(tx)$. □

[4] Introduction to functional analysis, proposition 2.3.3.

[5] Introduction to functional analysis, remark 2.3.4.1.

1.4 Applications of the Hahn-Banach theorem

Theorem 1.4.1 (Hahn-Banach)**.** Suppose X is a locally convex space and $A, B \subseteq X$ are disjoint convex sets. If B is compact, there exists a functional $f \in X^*$ that separates A from B – there exist $\alpha, \beta \in \mathbb{R}$ such that for all $a \in A$ and $b \in B$ we have

$$\operatorname{Re} f(a) \leq \alpha < \beta \leq \operatorname{Re} f(b).$$

Theorem 1.4.2. Suppose X is a locally convex space and $A \subseteq X$ is a convex space. Then the closure of A is the same as the closure in the weak topology.

Proof. The set $\overline{A}$ is of course a subset of the closure of A in the weak topology. Now choose a point $x \notin \overline{A}$. There exists a functional $f \in X^*$ and numbers $\alpha, \beta \in \mathbb{R}$ such that

$$\operatorname{Re} f(a) \leq \alpha < \beta \leq \operatorname{Re} f(x)$$

for all $a \in \overline{A}$. But then

$$\overline{A} \subseteq \{y \in X \mid \operatorname{Re} f(y) < \alpha\} = (\operatorname{Re} f)^{-1}((-\infty, \alpha]) = C,$$

where C is closed in the weak topology. It follows that the closure of A in the weak topology is a subset of C. As $x \notin C$, we get the desired equality. $\square$

Corollary 1.4.2.1. A convex set is a locally convex space if and only if it is weakly closed.

Proposition 1.4.3. Let X be a topological vector space and $f \colon X \to \mathbb{F}$ a linear functional. The following statements are equivalent:

i) The functional f is continuous.

ii) The functional f is continuous in 0.

iii) The functional f is continuous in some point $x_0 \in X$.

iv) The set $\ker f$ is closed.

v) The function $x \mapsto |f(x)|$ is a continuous seminorm.

If X is a locally compact space and $\mathcal{P}$ is the family of seminorms defining the topology on X, the above conditions are also equivalent to

$$|f(x)| \leq \sum_{k=1}^{r} \alpha_k p_k(x)$$

for some $\alpha_k \in \mathbb{R}^+$ and $p_k \in \mathcal{P}$.

Proof. The proof of the equivalence of the first 5 statements is the same as for normed spaces. Suppose now that

$$|f(x)| \leq \sum_{k=1}^{r} \alpha_k p_k(x).$$

Let $(x_i)_{i \in I}$ be a net in X that converges to 0. Then

$$0 \leq |f(x_i)| \leq \sum_{k=1}^{r} \alpha_k p_k(x_i),$$

which converges to 0. It follows that f is continuous at 0.

Now suppose that f is continuous at 0. The set

$$f^{-1}\left(\mathring{\mathcal{B}}(0,1)\right) = \{x \in X \mid |f(x)| < 1\}$$

contains an open neighbourhood B of the point 0. We can write

$$B = \bigcap_{j=1}^{r} U(0, p_j, \varepsilon).$$

Take $x \in X$. For $\delta > 0$ be such that

$$p_j\left(x \cdot \frac{\varepsilon}{\delta + \sum p_j(x)}\right) = \frac{\varepsilon}{\delta + \sum p_j(x)} \cdot p_j(x) < \varepsilon,$$

therefore,

$$\left|f\left(x \cdot \frac{\varepsilon}{\delta + \sum p_j(x)}\right)\right| < 1,$$

which can be rearranged to

$$|f(x)| < \frac{1}{\varepsilon} \cdot \sum_{j=1}^{r} p_j(x) + \frac{\delta}{\varepsilon}.$$

Taking a limit, we get the desired inequality. □

Theorem 1.4.4 (Riesz-Markov)**.** Let X be a compact Hausdorff space and $\Phi \in \mathcal{C}(X)$Ă∗. Then there exists a unique regular Borel measure μ such that

$$\Phi(f) = \int_X f \, d\mu$$

for all $f \in \mathcal{C}(X)$. Furthermore, we have $\|\Phi\| = \|\mu\| = |\mu|(X)$.

Proposition 1.4.5. Let X be a completely regular space. Endow the space $\mathcal{C}(X)$ with the topology induced by the seminorms $\{p_K \mid K \subseteq X \text{ is compact}\}$. If $L \in \mathcal{C}(X)^*$, then there exists a compact set $K \subseteq X$ and a regular Borel measure on K such that

$$L(f) = \int_K f \, d\mu$$

for all $f \in \mathcal{C}(X)$. Conversely, every such (K, μ) defines a functional $L \in \mathcal{C}(X)^*$.

Proof. Suppose that

$$L(f) = \int_K f \, d\mu$$

for some compact set K and measure μ. Then we have

$$|L(f)| = \left|\int_K f \, d\mu\right| \le \|\mu\| \cdot \sup_K |f| = \|\mu\| \cdot p_K(f),$$

so L is continuous.

Let now $L \in \mathcal{C}(X)^*$. We can therefore write

$$|L(f)| \leq \sum_{k=1}^{r} \alpha_k p_{K_j}(f)$$

for some compact sets K_j. We can simplify the above to

$$|L(f)| \leq \alpha \cdot p_K(f),$$

where

$$K = \bigcup_{j=1}^{r} K_j.$$

Note that if we have $f \in \mathcal{C}(X)$ and $f|_K = 0$, it follows that $L(f) = 0$. Now define $F \colon \mathcal{C} \to \mathbb{F}$ as follows; for any $g \in \mathcal{C}$ choose an extension $\widetilde{g} \in \mathcal{C}(X)$ of g and set

$$F(g) = L\left(\widetilde{g}\right).$$

This map is well defined by the above observation. We can check that F is indeed linear. Note that

$$|F(g)| = |L\left(\widetilde{g}\right)| \leq \alpha \cdot p_K\left(\widetilde{g}\right) = \alpha \cdot \|g\|_{\infty,K},$$

therefore, F is continuous. By the Riesz-Markov theorem there exists a regular Borel measure μ on K such that

$$F(g) = \int_K g \, d\mu.$$

If $f \in \mathcal{C}(X)$, we have $g = f|_K \in \mathcal{C}(K)$, so

$$L(f) = F(g) = \int_K g \, d\mu. \qquad \square$$

1.5 Krein-Milman theorem

Definition 1.5.1. Let X be a vector space and $C \subseteq X$ a convex subset.

i) A non-empty convex subset $F \subseteq C$ is a *face* if for all $t \in (0,1)$ and $x, y \in C$ satisfying $tx + (1-t)x \in F$, we also have $x, y \in F$.

ii) A point $x \in C$ is an *extreme point* if $\{x\} \subseteq C$ is a face. We denote the set of extreme points of C by $\operatorname{ext} C$.

Definition 1.5.2. For a vector space X and $A \subseteq X$ define the *convex hull* of A as

$$\operatorname{co} A = \left\{ \sum_{i=1}^{n} \alpha_i x_i \;\middle|\; n \in \mathbb{N} \wedge \alpha_j \in \mathbb{R}_{\geq 0} \wedge \sum_{i=1}^{n} \alpha_i = 1 \wedge x_i \in A \right\}.$$

If X is a topological vector space, define the *closed convex hull* as

$$\overline{\operatorname{co}}\, A = \overline{\operatorname{co} A}.$$

Proposition 1.5.3. The set $\operatorname{co} A$ is the smallest convex set that contains A. The set $\overline{\operatorname{co}}\, A$ is the smallest closed set that contains A.

Proof. The only nontrivial part of the proof is convexity of the set $\overline{\operatorname{co}}\, A$. Let $(x_i)_{i \in I}$ and $(y_i)_{i \in I}$ be two nets that converge to x and y, where $x, y \in \overline{\operatorname{co}}\, A$. For any $t \in (0,1)$ we have

$$tx + (1-t)y = \lim_{i \in I} (tx_i + (1-t)y_i) \in \overline{\operatorname{co}}\, A. \qquad \square$$

Lemma 1.5.4. Let X be a topological vector space and $C \subseteq X$ be a non-empty compact convex subset. Then for any $\phi \in X^*$ the set

$$F = \left\{ x \in C \;\middle|\; \operatorname{Re} \phi(x) = \min_C \operatorname{Re} \phi \right\}$$

is a closed face of C.

Proof. As C is a compact set, the set F is obviously non-empty. Also note that, as a preimage of a closed point, F is a closed set. Convexity of F follows from linearity of ϕ. Suppose that $tx + (1-t)y \in F$. As

$$\min_C \operatorname{Re} \phi = \operatorname{Re} \phi(tx + (1-t)y) = t\phi(x) + (1-t)\phi(y) \geq \min_C \operatorname{Re} \phi,$$

it follows that $x, y \in F$. By definition, F is a face. $\square$

Theorem 1.5.5 (Krein-Milman)**.** Let X be a locally convex space and $C \subseteq X$ a non-empty convex compact subset. Then

$$C = \overline{\operatorname{co}}\, (\operatorname{ext} C).$$

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