Functional Analysis

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Part I

Topological vector spaces

Chapter 1

Locally convex spaces

1.1 Vector topologies

1.1 (Canonical uniformity and bornology).

1.2 (Metrizability). Birkhoff-Kakutani

1.3 (Boundedness of linear operators).

1.2 Seminorms and convex sets

1.4 (Seminorms).

$$\bigcap_{i=1}^{m}\{: p() < 1\}$$

Equivalent conditions on the continuity of seminorms

Proof. □

boundedness by seminorms, normability

1.3 Continuous linear functionals

1.5. Let $(x_i^*) \in X^{*n}$. We can define $(x_i^*) : X \to \mathbb{F}^n$. If $x^* \in X^*$ vanishes on $\bigcap_{i=1}^n \ker x_i^*$, then x^* is a linear combination of $\{x_i^*\}$.

1.6 (Hahn-Banach extension). Let $Y \le X$ be real vector spaces. Suppose $l_0 : Y \to \mathbb{R}$ is a linear functional dominated by a sublinear functional $q : X \to \mathbb{R}$ in the sense that $l_0(y) \le q(y)$ for $y \in Y$.

(a) There is a linear functional $l : X \to \mathbb{R}$ that extends l_0 and is dominated by q in the sense that $l \le q$ on X.

(b) There is a linear functional $l : X \to \mathbb{C}$ that extends l_0 and is dominated by p in the sense that $|l| \le p$ on X.

(c) Let X be a locally convex space and $l_0 : Y \to \mathbb{F}$ be a bounded linear functional. Then, it admits a bounded linear extension $l : X \to \mathbb{F}$. If X is normed, then we can take $\|l\| = \|l_0\|$.

Proof. (a) Consider a partially ordered set of all linear functionals which extend l_0 and are dominated by q. Precisely, we consider

$$\{l : V \to \mathbb{R} \mid Y \le V \le X,\ l_0 = l|_Y,\ l \le q|_V\},$$

on which the partial order is given such that for $l : V \to \mathbb{R}$ and $l' : V' \to \mathbb{R}$ we have $l \prec l'$ if and only if $V \le V'$ and $l'|_V = l$. The nonemptyness and the chain condition is easily satisfied, so the partially ordered set has a maximal element $l : V \to \mathbb{R}$ by the Zorn lemma.

Suppose $V \neq X$ and let $e \in X \setminus V$. The inequality

$$l(v) + l(w) = l(v + w) \le q(v + w) \le q(v - e) + q(w + e), \qquad v, w \in V$$

implies the existence of $r \in \mathbb{R}$ such that

$$\sup_{v \in V}(l(v) - q(v - e)) \le r \le \inf_{v \in V}(-l(v) + q(v + e)).$$

If we define $\widetilde{V} := V + \mathbb{R}e$ and $\widetilde{l} : \widetilde{V} \to \mathbb{R}$ such that $\widetilde{l}(v + te) := l(v) + tr$ for $t \in \mathbb{R}$, then $\widetilde{l}(v) = l(v)$ and

$$\widetilde{l}(v + te) = l(v) + tr \le \begin{cases} l(v) + t(-l(t^{-1}v) + q(t^{-1}v + e)) & , t \ge 0 \\ l(v) + t(l(-t^{-1}v) - q(-t^{-1}v - e)) & , t \le 0 \end{cases} = q(v + te)$$

for $v \in V$ and $t \in \mathbb{R}$ lead a contradiction to the maximality of l, which concludes $V = X$.

(b) The real part map $\mathrm{Re} : \mathrm{Hom}_{\mathbb{C}}(X, \mathbb{C}) \to \mathrm{Hom}_{\mathbb{R}}(X, \mathbb{R})$ is bijective. Let p be a seminorm on X and l a complex linear functional on X. We have $|l| \le p$ if and only if $\mathrm{Re}\, l \le p$ because for λ such that $|\lambda| = 1$ and $l(\lambda x) \ge 0$ we have

$$|l(x)| = |\lambda^{-1} l(\lambda x)| = l(\lambda x) = \mathrm{Re}\, l(\lambda x) \le p(\lambda x) = p(x).$$

□

1.7 (Hahn-Banach separation).

Exercises

1.8 (Topology of compact convergence).

Chapter 2

Barreled spaces

2.1 Uniform boundedness principle

2.1 (Barreled spaces)**.** Let X be a topological vector space. A *barrel* is a balanced convex subset of X which is absorbing and closed. A *barreled space* is a topological space in which every barrel is a neighborhood of zero.

2.2 (Uniform boundedness principle)**.** Let X and Y be topological vector spaces. Let $\mathcal{F}$ be a family of continuous linear operator from X to Y. Suppose $\bigcup_{T\in\mathcal{F}} Tx$ is bounded for each $x \in D$, where $D \subset X$.

(a) If D is dense in X, then $\bigcap_{T\in\mathcal{F}} T^{-1}\overline{U}$ is absorbing.

(b) If X is barreled, then $\mathcal{F}$ is equicontinuous.

2.2 Baire category theorem

2.3 (Baire spaces)**.** A topological space is called a *Baire space* if the countable intersection of open dense subsets is always dense.

(a) If a topological vector space is Baire, then it is barreled.

(b) A Baire space is second category in itself.

(c) A topological group that is second category in itself is Baire.

2.4 (Absorbing sets)**.** Let X be a topological vector space that is Baire. A subset $U \subset X$ is said to be *absorbing* if for every $x \in X$ there is a sufficiently large $t > 0$ such that $x \in tU$. Let $U \subset X$.

(a) If U is closed and absorbing, then U has a non-empty open subset.

(b) If U is closed and absorbing, then $U - U$ is a neighborhood of zero.

(c) If U is closed, convex, and absorbing, then U is a neighborhood of zero.

2.5 (Baire category theorem)**.** The Baire category theorem proves many exmples of topological vector space are Baire, in particular barreled.

(a) A complete metric space is Baire.

(b) A locally compact Hausdorff space is Baire.

2.3 Open mapping theorem

2.6 (Open mapping theorem)**.** Let X be a F-space and Y a barreled space. Suppose $T : X \to Y$ is a continuous and surjective linear operator.

(a) $\overline{TU}$ is a neighborhood of zero.

(b) TU is a neighborhood of zero.

Proof. (a) Let U' be a neighborhood of zero such that $U \supset U' - U'$. Because T is surjective, the set $\overline{TU'}$ is a closed absorbing set, so it contains a non-empty open subset, since Y is barreled. Thus, $\overline{TU} \supset \overline{TU'} - \overline{TU'}$ is a neighborhood of zero.

(b) We claim $\overline{TU_{2^{-1}}} \subset TU_1$. Take $y_1 \in \overline{TU_{2^{-1}}}$.

Assume $y_n \in \overline{TU_{2^{-n}}}$. Since $\overline{TU_{2^{-(n+1)}}}$ is a neighborhood of zero, we have

$$(y_n + \overline{TU_{2^{-(n+1)}}}) \cap TU_{2^{-n}} \neq \varnothing.$$

Then, there is $x_n \in U_{2^{-n}}$ such that $Tx_n \in y_n + \overline{TU_{2^{-(n+1)}}}$. Define

$$y_{n+1} := y_n - Tx_n.$$

Then, $\sum_{n=1}^{\infty} x_n$ clearly converges to $x \in U_1$. Therefore,

$$Tx = \sum_{n=1}^{\infty} Tx_n = \sum_{n=1}^{\infty}(y_n - y_{n+1}) = y_1. \qquad \square$$

Exercises

2.7. Let (T_n) be a sequence in $B(X,Y)$. If T_n coverges strongly then $\|T_n\|$ is bounded by the uniform boundedness principle.

2.8. There is a closed absorbing set in $\ell^2(\mathbb{Z}_{\geq 0})$ that is not a neighborhood of zero;

$$\overline{B}(0,1) \setminus \bigcup_{i=2}^{\infty} B(i^{-1}e_i, i^{-2})$$

is a counterexample.

2.9. There is no metric d on $C([0,1])$ such that $d(f_n, f) \to 0$ if and only if $f_n \to f$ pointwise as $n \to \infty$ for every sequence f_n. Note that this problem is slightly different to the non-metrizability of the topology of pointwise convergence.

2.10. We show that there is no projection from ℓ^∞ onto c_0.

2.11 (Schur property)**.** ℓ^1

2.12. Let $\varphi : L^\infty([0,1]) \to \ell^\infty(\mathbb{N})$ be an isometric isomorphism. Suppose φ is realised as a sequence of bounded linear functionals on L^∞.

(a) Show that $\varphi^*(\ell^1) \subset L^1$ where ℓ^1 and L^1 are considered as closed linear subspaces of $(\ell^\infty)^*$ and $(L^\infty)^*$ respectively.

(b) Show that φ^* is indeed an isometric isomorphism, and deduce φ cannot be realised as bounded linear functionals on L^∞.

2.13 (Daugavet property)**.** (a) The real Banach space $C([0,1])$ satisfies the Daugavet property.

Proof. Let T be a finite rank operator on $C([0,1])$, and e_i be a basis of $\operatorname{im} T$. Then, for some measures μ_i,

$$Tf(t) = \sum_{i=1}^{n} \int_0^1 f \, d\mu_i e_i(t).$$

Let $M := \max \|e_i\|$.

Take f_0 such that $\|f_0\| = 1$ and $\|Tf_0\| > \|T\| - \frac{\varepsilon}{2}$. Reversing the sign of f_0 if necessary, take an open interval Δ such that $Tf_0(t) \geq \|T\| - \frac{\varepsilon}{2}$ and $|\mu_i|(\Delta) \leq \frac{\varepsilon}{4nM}$ for all i. Define f_1 such that $f_0 = f_1$ on Δ^c, $f_1(t_0) = 1$ for some $t_0 \in \Delta$, and $\|f_1\| = 1$. Then, $\|Tf_1 - Tf_0\| \leq \frac{\varepsilon}{2}$ shows $Tf_1 \geq \|T\| - \varepsilon$ on Δ. Therefore,

$$\|1 + T\| \geq \|f_1 + Tf_1\| \geq f_1(t_0) + Tf_1(t_0) \leq 1 + \|T\| - \varepsilon.$$

$\square$

2.14 (Bartle-Graves theorem)**.** Let E be a Banach space and N a closed subspace. For $\varepsilon > 0$, there is a continuous homogeneous map $\rho : E/N \to E$ such that $\pi\rho(y) = y$ and $\|\rho(y)\| \leq (1+\varepsilon)\|y\|$ for all $y \in E/N$.

Proof. We want to construct a continuous map $\psi : S_{E/N} \to E$ with $\|\psi(y)\| \leq 1 + \varepsilon$ for all $y \in S_{E/N}$. If then, ρ can be made from ψ.

For each $y_0 \in S_{E/N}$, choose $x_0 \in \pi^{-1}(y_0) \cap B_{1+\varepsilon}$. There is a neighborhood $V_{y_0} \subset S_{E/N}$ of y_0 such that $y \in V_{y_0}$ implies x_0 belongs to $(\pi^{-1}(y) \cap B_{1+\varepsilon}) + U_{2^{-1}}$, which is convex. With a locally finite subcover V_{y_α} and a partition of unity $\eta_\alpha(y)$, define $\psi_1(y) = \sum_\alpha \eta_\alpha(y) x_\alpha$. Then, $\psi_1(y) \in (\pi^{-1}(y) \cap B_{1+\varepsilon}) + U_{2^{-1}}$.

For $i \leq 2$, choose for each y_0 the element x_0 in $\pi^{-1}(y_0) \cap B_{1+\varepsilon} \cap (\psi_{i-1}(y_0) + U_{2^{-i-1}})$. Then, we obtain

$$\psi_i(y) \in \left(\pi^{-1}(y) \cap B_{1+\varepsilon} \cap (\psi_{i-1}(y_0) + U_{2^{-i-1}})\right) + U_{2^{-i}}.$$

Therefore, $\|\psi_i(y) - \psi_{i-1}(y)\| < 2^{-i-2}$, so it converges uniformly to ψ such that $\psi(y) \in \pi^{-1}(y) \cap B_{1+\varepsilon}$. $\square$

Problems

2.15. Let T be an invertible linear operator on a normed space. Then, $T^{-2} + \|T\|^{-2}$ is injective if it is surjective.

Chapter 3

Weak topologies

3.1 Polar topologies

3.1 (Bidual).

3.2. Let X be a locally convex space. The *weak topology* is the topology w on X defined by the family of seminorms $\{x \mapsto |\langle x, \xi\rangle|\}_{\xi\in X^*}$. The *weak* topology* is the topology w^* on X^* defined by the family of seminorms $\{\xi \mapsto |\langle x, \xi\rangle|\}_{x\in X}$. Let $J : X \to X^{**}$ be the canonical embedding.

(a) (X, w) and (X^*, w^*) are locally convex.

(b) $(X, w)^* = X^*$.

(c) $(X^*, w^*)^* = X$. Every locally convex space is a dual of a locally convex space.

Proof. (a) The Hahn-Banach theorem implies the Hausdorffness.

(c) We will only show $(X^*, w^*)^* \subset X$. If $u \in (X^*, w^*)^*$, then there are $x_1, \cdots, x_m \in X$ such that

$$|\langle u, \xi\rangle| \le \sum_{i=1}^{m} |\langle x_i, \xi\rangle|$$

for all $\xi \in X^*$. If we let $\ker\vec{x} := \bigcap_{i=1}^m \ker x_i$, then it is a closed subspace of X^* such that $\ker\vec{x} \subset \ker u$, so we have $u \in \operatorname{span}\vec{x} \subset X$. □

3.3. closure and weak closure of convex subsets

Proof. Hahn-Banach □

3.4 (Polar topologies). A *dual pair* is a pair (X, F) of a vector space X and a subspace F of $X^\#$ which separates points of X. For a topological vector space X and a subspace $F \subset X^*$, (X, F) is a dual pair if and only if F is weakly* dense in X^*, because the weak* density of F is equivalent to that F separates points of X by the Hahn-Banach separation. Note that if X is discrete, then $X^* = X^\#$. If (X, F) is a dual pair, then (F, X) is also a dual pair. A dual pair is never a topological notion. When we consider a canonical dual pair (X, X^*), we forget the topologies on X and X^* after defining X^* as the continuous dual.

For a vector space X and a subspace $X^* \subset X^\#$, the Mackey topology $\tau(X, X^*)$ on X is the topology of uniform convergence on weakly* compact balanced convex subsets of X^*. We can show $X^* = (X_\tau)^*$, i.e. τ is a dual topology.

Let α is a polar topology on X generated by $\mathcal{G} \subset \mathcal{P}(X^*)$. If $x^* \in (X_\alpha)^*$, then there is $\sigma(X, X^*)$-closed balanced convex $C \in \mathcal{G}$ such that $|x^*| \le 1$ on C°.

$X_\sigma, X_\sigma^*, X_\tau, X_\tau^*, X_\beta, X_\beta^*$. $(X^*)_\sigma =: X_\sigma^*$, $(X_\sigma)^* = X^*$.

(a) If a locally convex space X is barreled or metrizable, then X is Mackey, i.e. $X_\tau = X_\beta$.

(b) The Mackey topology is the finest topology such that $(X_\tau)^* = X^*$.

Mackey-Arens
boundedness, incompleteness

3.5 (Weak convergence by dense set)**.** Let X be a Banach space, D^* a subset of X^*, and $\overline{D^*}$ the norm closure of D^*. For example, if X has a predual $X_* \subset X^*$ and D^* is dense in X_*, then $\sigma(X, \overline{D^*})$ is the weak* topology.

(a) There is a squence $x_n \in X$ converges to zero in $\sigma(X, D^*)$ but not in $\sigma(X, \overline{D^*})$.

(b) A bounded sequence $x_n \in X$ converges to zero in $\sigma(X, \overline{D^*})$ if in $\sigma(X, D^*)$.

Proof. (b) Let $\xi \in \overline{D^*}$ and choose $\eta \in D^*$ such that $\|\xi - \eta\| < \varepsilon$. Then,

$$|\langle x_n, \xi\rangle| \le \|x_n\|\|\xi - \eta\| + |\langle x_n, \eta\rangle| \lesssim \varepsilon + |\langle x_n, \eta\rangle| \to \varepsilon.$$

□

3.2 Weak compactness

3.6 (Banach-Alaoglu theorem)**.**

Proof. Consider

$$B_{X^*} \to \prod_{x \in X} \|x\| B : l \mapsto (l(x))_{x\in X}.$$

Since it is an embedding into a compact space, it suffices to show the closedness of image: for $l(x) := \lim_\alpha l_\alpha(x)$, we have

$$\|l(x)\| \le \|l(x) - l_\alpha(x)\| + \|x\| \xrightarrow{\alpha\to\infty} \|x\|,$$

so l is contained in the range. □

3.7 (Eberlein-Šmulian theorem)**.**

3.8 (James' theorem)**.**

3.3 Weak density

Bishop-Phelps theorem

3.9 (Goldstine theorem)**.** Let X be a normed space. Then, B_X is weakly* dense in $B_{X^{**}}$.

Proof. Take $x^{**} \in B_{X^{**}} \setminus \overline{B_X}^{w*}$. By the Hahn-Banach separation, there is $x^* \in X^*$ such that

$$\sup_{x \in B_X} \mathrm{Re}\langle x, x^*\rangle < \mathrm{Re}\langle x^{**}, x^*\rangle.$$

Since the left hand side is equal to $\|x^*\|$, we obtain a contradiction. □

3.4 Compact convex sets

Krein-Milman theorem Choquet theory

Exercises

3.10 (James' space)**.** not reflexive but isometrically isomorphic to bidual

3.11 (Preduals)**.** Let X be a Banach space. A *predual* of X is a Banach space F together with an isometric isomorphism $\varphi : X \to F^*$. Two preduals $\varphi_1 : X \to F_1^*$ and $\varphi_2 : X \to F_2^*$ are said to be equivalent if there is an isometric isomorphism $\theta : F_1 \to F_2$ such that $\theta^* = \varphi_1 \varphi_2^{-1}$.

(a) There is a one-to-one correspondence between the equivalence class of preduals of X and the set of closed subspaces X_* of X^* such that B_X is compact and Hausdorff in $(X, \sigma(X, X_*))$. Such a subspace X_* is also called a predual of X.

(b) If X admits a predual $X_* \subset X^*$, then a $\sigma(X, X_*)$-closed subspace V of X also admits a predual $X_*|_V$.

Proof. (a) Goldstine theorem for surjectivity.

(b) It is easy if we apply the part (a). We can show more directly. If we let $V_* := X_*|_V$ the image of X_* under the map $X^* \to V^*$, then we have isometric injections $V \to (V_*)^* \to X$. We can show V is $\sigma(X, X_*)$ dense in $(V_*)^*$, hence the closedness proves the bijectivity of $V \to (V_*)^*$. $\square$

3.12 (Mazur's lemma)**.**

Part II

Banach spaces

Chapter 4

Operators on Banach spaces

4.1 Bounded operators

4.1 (Bounded belowness in Banach spaces)**.** Let $T \in B(X,Y)$ for Banach spaces X and Y. The following statements are equivalent:

(a) T is bounded below.

(b) T is injective and has closed range.

(c) T is a topological isomorphism onto its image.

4.2 (Bounded belowness in Hilbert spaces)**.** Let $T \in B(H,K)$ for Hilbert spaces H and K. The following statements are equivalent:

(a) T is bounded below.

(b) T is left invertible.

(c) T^* is right invertible.

(d) T^*T is invertible.

4.3 (Injectivity and surjectivity of adjoint)**.** Let $T \in B(X,Y)$ for Banach spaces X and Y.

(a) T^* is injective if and only if T has dense range.

(b) T^* is surjective if and only if T is bounded below.

4.2 Compact operators

$K(X,Y)$ is closed in $B(X,Y)$. $K(X)$ is an ideal of $B(X)$. adjoint is $K(X,Y) \to K(Y^*,X^*)$. integral operators are compact. riesz operator, quasi-nilpotent operator.

4.3 Fredholm operators

4.4. A bounded linear operator $T : X \to Y$ between Banach spaces is called a *Fredholm* operator if its kernel is finite dimensional and its range is finite codimensional.

(a) A Fredholm operator T has closed range.

Proof. (a) Let C be a finite dimensional subsapce of Y such that $\operatorname{im} T \oplus C = Y$. Let $\widetilde{T} : X/\ker T \to Y$ be the induced operator of T. Define $S : (X/\ker T) \oplus C \to Y$ such that $S(x+\ker T, c) := \widetilde{T}(x+\ker T) + c$. Then, S is an topological isomorhpism between Banach spaces by the open mapping theorem, so $S(X/\ker T \oplus \{0\}) = \operatorname{im} \widetilde{T} = \operatorname{im} T$ is closed. □

4.5 (Atkinson's theorem)**.** An operator $T \in B(X,Y)$ is Fredholm if and only if there is $S \in B(Y,X)$ such that $TS - I$ and $ST - I$ is finite rank.

4.6 (Fredholm index)**.** locally constant, in particular, continuous. composition makes the addition of indices.

4.4 Nuclear operators

tensor products

Exercises

4.7 (Completely continuous operators)**.** On reflexive spaces, completely continuous operators are same with compact operators.

4.8 (Dunford-Pettis property)**.** A Banach space X is said to have the *Dunford-Pettis property* if all weakly compact operators $T : X \to Y$ to any Banach space Y is completely continuous.

(a) X has the Dunford-Pettis property if and only if for every sequences $x_n \in X$ and $x_n^* \in X^*$ that converge to x and x^* weakly we have $x_n^*(x_n) \to x^*(x)$.

(b) $C(\Omega)$ for a compact Hausdorff space Ω has the Dunford-Pettis property.

(c) $L^1(\Omega)$ for a probability space Ω has the Dunford-Pettis property.

(d) Infinite dimensional reflexive Banach space does not have the Dunfor-Pettis property.

4.9.

(a) (Mazur-Ulam, 1932) A surjective isometry $T : X \to Y$ between normed spaces is affine.

(b) (Mankiewicz, 1972) Let U, V be open sets in X, Y, normed spaces. A surjective isometry $U \to V$ is uniquely extended to a surjective isometry $X \to Y$.

(c) (Mori) A surjective local isometry $T : X \to Y$ between Banach spaces is an isometry, if X is separable. (Use the Baire category)

Solution. (a) T is continuous. It is easy to see for continuous map T that it is affine if and only if T preserves the midpoint. For $x_1 \neq x_2 \in X$ let x_0 be the midpoint. Define inductively

$$C_1 := \{x \in X : \|x - x_1\| = \|x - x_2\| = \frac{1}{2}\|x_1 - x_2\|\}, \qquad C_k := \{x \in C_{k-1} : \sup_{x' \in C_{k-1}} \|x - x'\| \le \frac{1}{2} \operatorname{diam} C_{k-1}\}.$$

Since $x_0 \in C_{k-1}$ and $x' \in C_{k-1}$ imply $x_0 \in C_k$ by $\|x_0 - x'\| = \frac{1}{2}\|(2x_0 - x') - x'\| \le \frac{1}{2} \operatorname{diam} C_{k-1}$, and since $\operatorname{diam} C_k \le \frac{1}{2} \operatorname{diam} C_{k-1}$, we have $\{x_0\} = \bigcup_{k=1}^{\infty} C_k$. It follows that the midpoint can be detected from the metric structure of X, not depending on the linear structure of X. □

Problems

1. If $T \in B(L^2([0,1]))$ is a compact operator, then for any $\varepsilon > 0$ there is a constant $C_\varepsilon > 0$ such that

$$\|Tf\|_{L^2} \leq \varepsilon \|f\|_{L^2} + C_\varepsilon \|f\|_{L^1}.$$

Proof. 1. Suppose there is $\varepsilon > 0$ such that we have sequence $f_n \in L^2$ satisfying $\|f_n\|_2 = 1$ and

$$\|Tf_n\|_2 > \varepsilon + n\|f_n\|_1.$$

By the compactness of T, there is a subsequence Tf_{n_k} converges to $g \neq 0$ in L^2. Then, $\|f_{n_k}\|_1 \to 0$ implies $f_{n_k} \to 0$ weakly in L^2, hence also for Tf_{n_k}. It means $g = 0$, which contradicts to the assumption. □

Chapter 5

Tensor products of Banach spaces

5.1 Injective and projective tensor products

5.1 (Realizations)**.** For Banach spaces X and Y, $\mathcal{L}(X,Y)$ and $\mathcal{B}(X,Y)=\mathcal{L}(X,Y^*)$ are naturally Banach spaces. Also we have a natural algebraic inclusions of $X\otimes Y$ into $\mathcal{L}(X^*,Y)\le\mathcal{B}(X^*,Y^*)$, and $\mathcal{B}(X,Y)^*$. Also we have a natural algebraic inclusions of $X^*\otimes Y$ into $\mathcal{L}(X,Y)\le\mathcal{B}(X,Y^*)$.

5.2. Let X and Y be a Banach spaces, and α be a norm on $X\otimes Y$. We say α is a *cross norm* if

$$\alpha(x\otimes y)=\|x\|\|y\|,\qquad x\in X,\ y\in Y,$$

and a cross norm is *reasonable* if the *dual norm* α^* on $X^*\otimes Y^*\subset(X\otimes Y,\alpha)^*$ of α is also a cross norm.

$$\varepsilon(u):=\|u\|_{\mathcal{B}(X^*,Y^*)},\qquad \pi(u):=\|u\|_{\mathcal{B}(X,Y)^*}.$$

5.3 (Type C and type L spaces)**.**

5.4 (Duals of tensor products)**.**

$$\mathcal{L}(X\widehat{\otimes}_\pi Y,Z)\cong\mathcal{B}(X,Y,Z)=\mathcal{L}(\mathcal{L}(X,Y^*),Z).$$

$$\mathcal{J}(X,Y)=(X\widehat{\otimes}_\varepsilon Y)^*\hookrightarrow(X\widehat{\otimes}_\pi Y)^*=\mathcal{B}(X,Y).$$

$$\mathcal{K}(X,Y)\hookrightarrow X^*\widehat{\otimes}_\varepsilon Y\leftarrow X^*\widehat{\otimes}_\pi Y\twoheadrightarrow\mathcal{N}(X,Y).$$

5.2 Vector-valued integrals

harmonic and complex analysis

5.5 (Pettis measurability theorem)**.** Let (Ω,μ) be a measure space and X a Banach space. Let $f:\Omega\to X$ be a function. We say f is *strongly measurable* or *Bochner measurable* if it is a pointwise limit of a sequence of simple functions.

If μ is complete, then all the pointwise convergence discussed here can be relaxed to the almost everywhere convergence.

(a) If f is strongly measurable, then f is Borel measurable.

(b) If f is Borel measurable, then f is weakly measurable.

(c) If f is weakly measurable and separably valued, then f is strongly measurable.

5.6 (Pettis integrals).
$$L^1\widehat{\otimes}_\varepsilon X \hookrightarrow \mathcal{L}(X^*, L^1) \overset{*}{\hookrightarrow} \mathcal{L}(L^\infty, X^{**}).$$

- Pettis integrable: $L^1\widehat{\otimes}_\varepsilon X$,
- weakly integrable: $\mathcal{L}(X^*, L^1)$,
- Dunford integrable: $\mathcal{L}(L^\infty, X^{**})$,
- Pettis integral: $L^1\widehat{\otimes}_\varepsilon X \cong *^{-1}\mathcal{L}(L^\infty, X) \subset \mathcal{L}(X^*, L^1)$. It defines $L^1\widehat{\otimes}_\varepsilon X \hookrightarrow \mathcal{K}(L^\infty, X_\sigma)$.

(a) The close graph theorem and the existence of an a.e. convergent subsequence of an L^1 convergent sequence proves a weakly integrable function defines an operator in $\mathcal{L}(X^*, L^1)$.

5.7 (Bochner integrals). Let (Ω, μ) be a measure space and X a Banach space. Let $f : \Omega \to X$ be a strongly measurable function. The function f is said to be *Bochner integrable* if there is a net of simple functions $(s_\alpha)_{\alpha\in\mathcal{A}}$ such that
$$\int_\Omega \|f(\omega) - s_\alpha(\omega)\|\, d\mu(\omega) \to 0$$
for $\alpha \in \mathcal{A}$.

For $T \in \mathcal{L}(X, Y)$ and $\mu : L^1(\mu) \to \mathbb{C}$, the commutative diagram for $\alpha \in \{\varepsilon, \pi\}$
$$\begin{array}{ccc} L^1(\mu)\widehat{\otimes}_\alpha X & \xrightarrow{\mu\otimes\mathrm{id}} & X \\ {\scriptstyle \mathrm{id}\otimes T}\downarrow & & \downarrow{\scriptstyle T} \\ L^1(\mu)\widehat{\otimes}_\alpha Y & \xrightarrow{\mu\otimes\mathrm{id}} & Y, \end{array}$$
which is shown with approximation by simple tensors, justifies that T commutes with the integral:
$$T\int f\, d\mu = \int Tf\, d\mu.$$
The space of Bochner integrable functions $L^1\widehat{\otimes}_\pi X$, factoring through $L^1\widehat{\otimes}_\varepsilon X$, is naturally mapped to the space of Pettis integrals $\mathcal{K}(L^\infty, X_\sigma)$.

(a) f is Bochner integrable if and only if $\int \|f(\omega)\|\, d\mu(\omega) < \infty$.

(b) If f is Bochner integrable, then it is Pettis integrable and the integrals coincides.

Bochner integrable => Pettis integrable => weakly(scalarly) integrable

5.8 (Vector measures). If an element of the Dunford integral $\mathcal{L}(L^\infty, X^{**})$, or the Pettis integral $\mathcal{K}(L^\infty, X_\sigma)$, defines a σ-weakly continuous linear operator $L^\infty \to X$, then it is called a vector measure?

5.3 Approximation property

dual is Banach. Basis problem, Mazur' duck.

5.9 (Approximation property). Every compact operator is a limit of finite-rank operators.

(a) An Hilbert space has the AP.

(b)

Proof. (a) Let H be a Hilbert space and $K \in K(H)$. Since $\overline{KB_H}$ is a compact metric space, it is separable, which means $\overline{KH}$ is separable. Let $(e_i)_{i=1}^\infty$ be an orthonormal basis of $\overline{KH}$, and let P_n be the orthogonal projection on the space spanned by $(e_i)_{i=1}^n$. If we let $K_n := P_nK$, then $K_n \to K$ strongly and K_n has finite rank. Take any $\varepsilon > 0$ and find, using the totally boundedness of KB_H, a finite subset $\{x_j\} \subset B_H$ such that for any $x \in B_H$ there is x_j satisfying $\|Kx - Kx_j\| < \frac{\varepsilon}{2}$. Then,

$$\begin{aligned}\|Kx - K_n x\| &\leq \|Kx - Kx_j\| + \|Kx_j - K_n x_j\| + \|P_n(Kx_j - Kx)\| \\ &\leq \frac{\varepsilon}{2} + \|Kx_j - K_n x_j\| + \frac{\varepsilon}{2}.\end{aligned}$$

By taking the supremum on $x \in B_H$, we have

$$\|K - K_n\| \leq \max_j \|Kx_j - K_n x_j\| + \varepsilon,$$

which deduces $K_n \to K$ in norm.

$\square$

Exercises

Tingley problem

Chapter 6

Geometry of Banach spaces

Part III

Spectral theory

Chapter 7

Operators on Hilbert spaces

7.1 Operator topologies

Projections. Reducing subspaces. Hilbert space classification by cardinal. Riesz representation theorem.

7.1. (a) A Banach space X is isometrically isomorphic to a Hilbert space if there is a bounded linear projection on every closed subspace of X.

7.2 (Riesz representation theorem)**.** Let H be a Hilbert space over a field $\mathbb{K}$, which is either $\mathbb{R}$ of $\mathbb{C}$.

We use the bilinear form $\langle -,- \rangle : X \times X^* \to \mathbb{K}$ of canonical duality. The Riesz representation theorem states that a continuous linear functional on a Hilbert space is represented by the inner product with a vector.

(a) For each $x^* \in H^*$, there is a unique $x \in H$ such that $\langle y, x^* \rangle = \langle y, x \rangle$ for every $y \in H$.

(b) $H \to H^* : x \mapsto \langle -, x \rangle$ is a natural linear and anti-linear isomorphism if $\mathbb{K} = \mathbb{R}$ and $\mathbb{C}$, respectively.

Let H be a separable Hilbert space. Find a positive sequence a_n such that every sequence x_n of unit vectors of H satisfying $|\langle x_i, x_j \rangle| \le a_j$ for all $i < j$ converges weakly to zero.

7.3 (Normal operators)**.** For $T \in B(H)$, we have an obvious fact $(\operatorname{im} T)^\perp = \ker T^*$. Suppose T is normal.

(a) $\ker T = \ker T^*$.

(b) T is bounded below if and only if T is invertible.

(c) If T is surjective, then T is invertible.

7.4 (Invariant and Reducing subsapces)**.** Let K be a closed subspace of H.

(a) K is reducing for T if and only if K is invariant for T and T^*.

(b) K is reducing for T if and only if $TP = PT$, where P is the orthogonal projection on K.

7.5 (Trace class operators)**.** Let $K \in B(H)$. The *trace* of K is

$$\operatorname{Tr}(K) := \sum_i \langle Ke_i, e_i \rangle,$$

where $(e_i) \subset H$ is an orthonormal basis. The operator K is said to be in the *trace-class* if $\operatorname{Tr}(|K|) < \infty$.

(a) The trace does not depend on the choice of (e_i).

(b) K is a trace class if and only if $K = \sum_i \lambda_i \theta_{e_i, e_i'}$ for some $(\lambda_i) \in \ell^1(\mathbb{N})$ and orthonormal sequences $(e_i), (e_i') \subset H$.

(c) $B(H) \to L^1(H)^* : T \mapsto \mathrm{Tr}(T\cdot)$ is an isometric isomorphism.

Proof. (b) Applying the polar decomposition and diagonalizing the compact operator $|K|$, we are done. Conversely, we can check the diagonalization $K^*K = \sum_i |\lambda_i|^2 \theta_{y_i}$, which implies $|K| = \sum_i |\lambda_i| \theta_{y_i}$. Thus,

$$Tr(|K|) = \sum_j \langle |K| y_j, y_j \rangle = \sum_i |\lambda_i| < \infty.$$

□

7.6 (Six locally convex topologies)**.** Let H be a Hilbert space.

$$T \mapsto (\|Tx\|^2 + \|T^*x\|^2)^{\frac{1}{2}}, \qquad T \mapsto \|Tx\|, \qquad T \mapsto \langle Tx, x \rangle$$

for $x \in H$.

$$T \mapsto \Big(\sum_{i=1}^{\infty} \|Tx_i\|^2 + \|T^*x_i\|^2\Big)^{\frac{1}{2}}, \qquad T \mapsto \Big(\sum_{i=1}^{\infty} \|Tx_i\|^2\Big)^{\frac{1}{2}}, \qquad T \mapsto \Big|\sum_{i=1}^{\infty} \langle Tx_i, x_i \rangle\Big|$$

for $(x_i) \in \ell^2(\mathbb{N}, H)$.

(a) A net T_α converges to T strongly in $B(H)$ if and only if $\|(T_\alpha - T)^{\oplus n} \overline{\xi}\| \to 0$ for all $\overline{\xi} \in H^{\oplus n}$.

(b) A net T_α converges to T σ-strongly in $B(H)$ if and only if $\|(T_\alpha - T)^{\oplus \infty} \overline{\xi}\| \to 0$ for all $\overline{\xi} \in H^{\oplus \infty}$.

7.7 (Continuity of linear functionals)**.** Let l be a linear functional on $B(H)$ for a Hilbert space H.

(a) l is weakly continuous if and only if it is strongly* continuous, and in this case we have

$$l = \sum_i \lambda_i \omega_{e_i, e_i'}, \qquad (\lambda_i) \in c_c, \quad (e_i), (e_i') \subset H \text{ orthonormal.}$$

or equivalently,

$$l = \sum_i \omega_{x_i, y_i}, \qquad (x_i), (y_i) \in c_c(\mathbb{N}, H)$$

(b) l is σ-weakly continuous if and only if it is σ-strongly* continuous, and in this case we have

$$l = \sum_i \lambda_i \omega_{e_i, e_i'}, \qquad (\lambda_i) \in \ell^1, \quad (e_i), (e_i') \subset H \text{ orthonormal.}$$

or equivalently,

$$l = \sum_i \omega_{x_i, y_i}, \qquad (x_i), (y_i) \in \ell^2(\mathbb{N}, H)$$

(c) For a convex subset of $B(H)$ is (σ-)weakly closed if and only if (σ-)strongly* closed.

Proof. Suppose l is strongly continuous. There exists $\overline{x} \in H^{\oplus n}$ such that

$$|l(T)| \le \|T^{\oplus n} \overline{x}\|.$$

The functional $l : A \to \mathbb{C}$ factors through $H^{\oplus n}$ such that

$$A \xrightarrow{\overline{x}} H^{\oplus n} \to \mathbb{C}.$$

□

7.8.

(a) On a bounded subset of $B(H)$, the weak, strong, strong* topologies coincide with the σ-weak, σ-strong, σ-strong* topologies, respectively.

7.2 Spectral theorems

7.9 (Spectral measure)**.** Let $(\Omega, \mathcal{A})$ be a measurable space and H a Hilbert space. A *projection-valued measure* on Ω for H is a map $E : \mathcal{A} \to B(H)$ with $E(\varnothing) = 0$ such that $E(A)$ is a projection for every $A \in \mathcal{A}$, and one of the following equivalent conditions hold:

(i) the set function $E_{x,y} : \mathcal{A} \to \mathbb{C} : A \mapsto \langle E(A)x, y\rangle$ is a complex measure on Ω for each $x, y \in H$.

(ii) the countable additivity holds, i.e. $E(\bigsqcup_{i=1}^\infty A_i) = \sum_{i=1}^\infty E(A_i)$ in the strong operator topology of $B(H)$ for $(A_i)_{i=1}^\infty \subset \mathcal{M}$.

(a) $E(A \cap B) = E(A)E(B)$ for $A, B \in \mathcal{M}$.

Kato-Rellich theorem

For a densely defined closed operator $T : H \to H$, $\sigma(T^*) = \overline{\sigma(T)}$.

A multiplication operator by any Borel measurable function $\Omega \to \mathbb{C}$ always defines a densely defined closed normal operator.

7.10 (Bounded Borel functions)**.** Let Ω be a compact Hausdorff space and denote by $B^\infty(\Omega)$ the space of bounded Borel functions on Ω. The linear combinations of projections in $B^\infty(\Omega)$ are called *simple functions*.

(a) There are natural inclusions $C(\Omega) \subset B^\infty(\Omega) \subset C(\Omega)^{**}$ among C*-algebras. (Every bounded Borel function defines a bounded linear functional on $M(\Omega)$.)

(b) $B^\infty(\Omega)$ is the norm closure of simple functions.

(c) $B^\infty(\Omega)$ factors through all $L^\infty(\mu) := M(\pi_\mu)$ for GNS-representations π_μ of $C(\Omega)$.

(d) The topology of pointwise bounded convergence on $B^\infty(\Omega)$ is stronger than the induced σ-weak topology. (It is the bounded convergence theorem.)

7.11 (Borel functional calculus for bounded normal operators)**.** Let $x \in B(H)$ be a normal operator. Consider

$$\begin{tikzcd}
C(\sigma(T))^{**} \arrow[ddddr, bend left, "\widetilde{\pi}"] & & & \\
\cup & & & \\
B^\infty(\sigma(T)) & & & \\
\cup & & & \\
C(\sigma(T)) \arrow[r, "\pi"] & W^*(T) & \subset & B(H).
\end{tikzcd}$$

(a) If we endow the topology of pointwise convergence on $B^\infty(\sigma(a))$, then the Borel functional calculus $\widetilde{\pi} : B^\infty(\sigma(T)) \to B(H)$ is strongly continuous.

(b) Every von Neumann algebra is the norm closed span of projections.

Proof. (a) By the bounded convergence theorem.

(b) This is because $\sigma(a) \subset \mathbb{C}$ is compact so that it is separable and metrizable; every bounded measurable function is a pointwise limit of simple functions. $\square$

7.12 (Spectral representation)**.** A *projection-valued measure* on a compact Hausdorff space Ω is nothing but a faithful non-degenerate representation $E : C(\Omega) \to B(H)$. For a bounded normal operator $T \in B(H)$, there is a natural projection valued measure $\pi : C(\sigma(T)) \to B(H)$, called the *spectral measure*. We now decompose $\pi = \bigoplus_\alpha \pi_\alpha$ to cyclic representations $\pi_\alpha : C(\sigma(T)) \to B(H_\alpha)$ with cyclic unit vectors

ψ_α, which are not unique. Each vector state ψ_α induces a probability measure μ_α on $\sigma(T)$. It is called the spectral measure associated to the cyclic vector ψ_α. We can check that the GNS-representation $C(\sigma(T)) \to B(L^2(\mu_\alpha))$ of μ_α, also called a *multiplication operator representation* of $C(\sigma(T))$, is unitarily equivalent to π_α, so the direct sum $C(\sigma(T)) \to \bigoplus_\alpha B(L^2(\mu_\alpha))$ of GNS representations can be defined. Then, we can show the bounded normal operator T is always unitarily equivalent to the multiplication operator on a finite measure space.

Multiplicity theory: For a faithful non-degenerate representation π of a separable abelian unital C*-algebra A on a separable (maybe?) Hilbert space, there is a unique canonical cyclic decomposition (up to unitary equivalence)

$$\pi \approx \bigoplus_{m=1}^{\infty} \pi_m^{\oplus m} : A \to \bigoplus_{m=1}^{\infty} B(L^2(\mu_m))^{\oplus m},$$

such that the sequence μ_m measures has disjoint supports. Also we can show that if the measure classes of μ_m, which corresponds to the equivalence classes of cyclic representations without cyclic vectors, are same, then two such representations are unitarily equivalent. (I don't know the detailed proofs yet, for example, where to define support of a measure)

To show the correspondence between the measure-theoretic spectral measure and the operator-algebraic spectral measure, note that a projection-valued measure defines a "normal" unital $*$-homomorphism

$$\operatorname{span} P(B^\infty(X)) \to B(H).$$

Then, mimick the definition of Lebesgue integral to construct a unital $*$-homomorphism $C(X) \to B(H)$.

Chapter 8

Unbounded operators

8.1 Closed operators

8.1 (Closed operators). (a) a

8.2 (Adjoint operators). Let $T : \operatorname{dom} T \subset X \to Y$ be a densely defined linear operator between Banach spaces. Define an unbounded operator $T^* : \operatorname{dom} T^* \subset Y^* \to X^*$ such that $\langle x, T^* y^* \rangle := \langle Tx, y^* \rangle$ for all $x \in \operatorname{dom} T$ and $y^* \in \operatorname{dom} T^*$, where

$$\operatorname{dom} T^* := \{y^* \in Y^* \mid \operatorname{dom} T \to \mathbb{C} : x \mapsto \langle Tx, y^* \rangle \text{ is bounded}\}.$$

(a) If $T \subset S$, then $S^* \subset T^*$.

(b) T^* is always closed.

(c) T is closable if and only if T^* is densely defined. If it is, then T^{**} is the closure of T. (Only on reflexive spaces?)

(d) T^* is injective if and only if T has dense range, and surjective if and only if T is bounded below.

Proof. (d) Suppose T is bounded below. Fix $x^* \in X^*$. Since T is bounded below, x^* defines a bounded linear functional on $\operatorname{dom} T$ with respect to $\|x\| + \|Tx\|$, which is embedded in Y as a closed subspace. By the Hahn-Banach extension, we have an element $y^* \in Y^*$ such that $\langle Tx, y^* \rangle = \langle x, x^* \rangle$ for all $x \in X$, which is contained in $\operatorname{dom} T^*$ by the definition of $\operatorname{dom} T^*$. This implies that T is surjective because $T^* y^* = x^*$.

Conversely, suppose T^* is surjective. Let $F := \{x \in \operatorname{dom} T : \|Tx\| \leq 1\}$. Since for every $x^* \in X^*$ we have for some $y^* \in \operatorname{dom} T^*$ such that

$$\sup_{x \in F} |\langle x, x^* \rangle| = \sup_{x \in F} |\langle x, T^* y^* \rangle| = \sup_{x \in F} |\langle Tx, y^* \rangle| \leq \|y^*\|.$$

By the uniform boundedness principle, we have $\sup_{x \in F}(\|x\| + \|Tx\|)$ is bounded, we are done. □

8.3 (Operations of unbounded operators). inverse, composition, addition

8.4 (Symmetric operators). A densely defined operator $T : \operatorname{dom} T \to H$ is called *symmetric* if

$$\langle Tx, y \rangle = \langle x, Ty \rangle, \qquad x, y \in \operatorname{dom} T.$$

Let T be a densely defined symmetric operator. If the closure of T is self-adjoint, then it is called *essentially self-adjoint*.

(a) T has the closed and densely defined closure.

(b) Every symmetric extension of T is a restriction of T^*, which is not symmetric in general. In particular, T has a maximal symmetric extension.

(c) A maximal symmetric operator is closed since the closure of a .

(d) A self-adjoint operator is maximal.

(e) A densely defined closed symmetric operator is essentially self-adjoint if and only if it is indeed the unique self-adjoint extension if and only if the adjoint is symmetric.

8.5 (Cayley transform)**.** There is a one-to-one correspondence between the unitary operators from K_+ to K_-, the deficiency subspaces.

If T is a closed densely defined symmetric operator, then

$$Ux := \begin{cases} 0 & \text{if } x \in L^+, \\ (T-i)(T+i)^{-1}x & \text{if } x \in (L^+)^\perp, \end{cases}$$

is a partial isometry with initial and final spaces $(L^+)^\perp$ to $(L^-)^\perp$ such that $\operatorname{dom} T = (1-U)(L^+)^\perp$.

(a) If T is self-adjoint, then $1-U$ is injective and $\operatorname{dom} T = \operatorname{ran}(1-U)$.

(b) The Cayley transform provides a one-to-one correspondence between self-adjoint operators T and unitary operators U satisfying $\ker(1-U) = 0$.

(c)

Let T be a symmetric operator on a Hilbert space H. We will always assume that T is densely defined and closed. We want to ask the following questions: Is T self-adjoint? If not, does T admit self-adjoint extensions? Which self-adjoint extension generate the appropriate quantum dynamics?

Example. Let $T := i\,d/dx$ on $L^2([0,1])$ with

$$\operatorname{dom} T = H_0^1((0,1)).$$

It is densely defined and closed. Then,

$$\operatorname{dom} T^* = H^1((0,1)) \subset C([0,1])$$

and T^* is not self-adjoint since... The set of self-adjoint extensions is $\{T_\alpha : \alpha \in \mathbb{T}\}$, where

$$\operatorname{dom} T_\alpha = \{f \in H^1((0,1)) : \alpha f(0) = f(1)\}.$$

8.2 Spectral theorems

8.6 (Borel functional calculus for self-adjoint operators)**.** Let T be a self-adjoint operator on H and let $U := (T-i)/(T+i)$ be its Cayley transform. Then, the continuous functional calculus for U defines a faithful non-degenerate representation of $C_0(\mathbb{R})$ by

$$C_0(\mathbb{R}) \to C(\mathbb{T}) \to C(\sigma(U)) \to B(H).$$

The first map is $f \mapsto (s \mapsto f(i\frac{s+1}{s-1})) = f \circ C^{-1}$, and the second map is the restriction. Now obtain a normal extension of it to the universal von Neumann algebra of $C_0(\mathbb{R})$, which contains $B^\infty(\mathbb{R})$. The restriction $B^\infty(\mathbb{R}) \to B(H)$ is the bounded Borel functional calculus for T.

(a)

8.7. Let $f \in B^\infty(\mathbb{R})$.

(a) If $f = 1_{\mathbb{C}\setminus\{0\}}$, then $f(T) = s(T)$.

(b) $f(T)$ is approximated in norm by projections: an argument on $\langle E(\lambda)\xi, \xi\rangle$ works.

(c) $f(VTV^*) = Vf(T)V^*$ for $V^*Vs(T) = s(T)V^*V = s(T)$. It follows from the commutative diagram

$$\begin{tikzcd} C_0(\mathbb{R}) \arrow[r, "\pi_T"] \arrow[d, equal] & B(H) \arrow[d, "V\cdot V^*"] \\ C_0(\mathbb{R}) \arrow[r, "\pi_{VTV^*}"] & B(H). \end{tikzcd}$$

8.8. Let T be a self-adjoint operator on H and U be its Cayley transform.

$$U = C(T) = \frac{T-i}{T+i}, \qquad T = C^{-1}(U) = i\frac{1+U}{1-U}.$$

$e^{-it} = C(\cot(t/2))$.

(a) Note that $C^{-1} : \mathbb{T}\setminus\{1\} \to \mathbb{R}$ is unbounded, and $C - 1 \in C_0(\mathbb{R})$.

(b) unbounded functional calculus: even if f is an unbounded real-valued Borel function on $\mathbb{R}$, the unbounded operator $f(T)$ can be defined by the Cayley transform $g(f(T)) := g\circ f\circ g^{-1}(U)$, because $g\circ f\circ g^{-1}$ is bounded Borel on $\mathbb{T}$. If f is bounded, then it coincides the above bounded Borel functional calculus.

8.9 (Polar decomposition)**.** polar decomposition polar decomposition of symmetric operator? polar decomopsition changes spectrum or domains?

support projection

8.10 (Stone theorem)**.**

8.11 (Analytic vectors)**.** (a) If T is symmetric and D_0 is dense, then $T|_{D_0}$ is essentially self-adjoint.

8.12 (Resolvent convergence)**.**

8.3 Polar decomposition

8.13 (Support projections of operators)**.** Let x be an element of a von Neumenna algebra M. The *left support projection* of x is the minimal projection $p \in M$ such that $x = px$, denoted by $s_l(x)$. The *right support projection* of x is defined as the left support projection of x^*. The projections $s_l(x)$ and $1-s_r(x)$ are also called the *range* and *kernel* projections of x, respectively.

Riesz refinement?

(a) Support projections of x uniquely exist.

(b) $x^*yx = 0$ if and only if $s_l(x)ys_l(x) = 0$ for every $y \in M$.

(c) We have $s_r(x) = s_r(x^*x) = s_r(|x|)$. In particular, $s_l(x) = s_r(x)$ if x is normal.

(d) If $x^*x \le y^*y$, then there is a unique $v \in M$ such that $x = vy$ and $s_r(v) \le s_l(y)$.

(e) There is unique $v \in M$ such that the polar decomposition $x = v|x|$ holds and that $s_r(x) = v^*v$. Moreover, $x^* = v^*|x^*|$ and $s_l(x) = vv^*$. In particular, $s_l(x)$ and $s_r(x)$ are Murray-von Neumann equivalent.

Proof. (a) Let $x \in M$. Since $\operatorname{im} x = \operatorname{im}(xx^*)^{\frac{1}{2}}$, we may assume $0 \le x \le 1$. Then, $x^{2^{-n}}$ is an increasing sequence in M bounded by one, so it converges strongly to some $p \in M_+$. We can check $p^2 = p$ by... We can check p is the range projection of x by...

(d) Suppose $\mathrm{id}_H \in M \subset B(H)$. The operator $v_0 : \overline{yH} \to \overline{xH} : y\xi \mapsto x\xi$ is well defined because

$$\|x\xi\|^2 = \langle x^*x\xi, \xi\rangle \le \langle y^*y\xi, \xi\rangle = \|y\xi\|^2.$$

Let $v := v_0 s_l(y)$. Then, $x\xi = vy\xi$ for all $\xi \in H$. If $v' \in B(H)$ satisfies $y = v'x$ and $v' = v's_l(y)$, then $y^*(v-v')^*(v-v')y = (x-x)^*(x-x) = 0$ implies $0 = s_l(y)(v-v')^*(v-v')s_l(y) = (v-v')^*(v-v')$, so v is unique in $B(H)$. If $u \in M'$ is unitary, then uvu^* satisfies the same property $y = uvu^*x$ and $uvu^* = uvu^*s_l(y)$, so $uvu^* = v$. Since unitaries span M', we have $v \in M'' = M$.

(e) Since $x^*x \le |x|^*|x|$, there is a unique $v \in M$ such that $x = v|x|$ and $v = vs_l(|x|) = vs_r(x)$. Then, $s_r(x) - v^*v = s_r(x)(1-v^*v)s_r(x) = 0$ from $|x|(1-v^*v)|x| = |x|^2 - |x|^2 = 0$, and $s_l(x) - vv^* = s_l(x)(1-vv^*)s_l(x) = 0$ from $x^*(1-vv^*)x = |x|^2 - |x|^2 = 0$. The partial isometry v is unique since $s_r(x) = v^*v$ implies $s_r(v) = s_r(v^*v) = s_r(s_r(x)) = s_r(x)$. Similarly, $s_l(v) = s_l(x)$. The equality $xv^* = |x^*|$ follows from $xv^* = v|x|v^* \ge 0$ and $|xv^*|^2 = vx^*xv^* = v|x|^2v^* = xx^* = |x^*|^2$. □

8.4 Decomposition of spectrum

$$\begin{aligned}\sigma &= \sigma_p \cup \sigma_c \cup \sigma_r \\ &= \sigma_{ess} \cup \sigma_d \\ &= \overline{\sigma_{pp}} \cup \sigma_{ac} \cup \sigma_{sc}.\end{aligned}$$

$$\sigma = \sigma_p \sqcup \sigma_c \sqcup \sigma_r = \overline{\sigma_{pp}} \cup \sigma_{ac}\sigma_{sc} = \sigma_d \sqcup \sigma_{ess,5}.$$

Exercises

8.14 (Strict topology)**.** Let H be a Hilbert space. Let $(T_\alpha) \subset B(H)$ and $K \in K(H)$.

(a) The strong* topology and the strict topology agree on bounded sets of $B(H)$.

8.15 (Unitary group)**.** Let H be a Hilbert space.

(a) The weak topology and the strict topology agree on $U(H)$.

8.16 (Bounded increasing nets)**.** Let T_α be a bounded increasing net of bounded self-adjoint operators on H.

(a) T_α converges strictly. In particular, $T_\alpha \to T$ strictly iff $T_\alpha \to T$ weakly.

Proof. Define T such that

$$\langle Tx, y\rangle := \lim_\alpha \sum_{k=0}^{3} i^k \langle T_\alpha(x + i^k y), x + i^k y\rangle.$$

The convergence is due to the monotone convergence in $\mathbb{R}$. We can check it is a well-defined bounded linear operator by considering the bounded sesquilinear form. Then, $T_\alpha \to T$ weakly by definition, and σ-strongly because the net is increasing. □

8.17 (Distributional operators)**.** (a) Every continuous linear operator $T : \mathcal{D}(\mathbb{R}) \to \mathcal{D}'(\mathbb{R})$ naturally defines a closable densely defined operator $T : \mathrm{dom}\, T \to L^2(\mathbb{R})$ with $\mathrm{dom}\, T := \mathcal{D}(\mathbb{R})$.

8.18 (Hydrogen atom)**.** For $V \in L^\infty(\mathbb{R}^d)$, the operator

$$H\psi(x) := -\frac{\hbar^2}{2m}\Delta\psi(x) - V(x)\psi(x), \qquad x \in \mathbb{R}^d$$

is called the *Schrödinger operator*, and simply we write $H = -\Delta + V$. The eigenvectors associated to the discrete spectrum is called *bound eigenstates*.

Consider the Schrödinger operator $H := -\Delta - |x|^{-1}$ on $L^2(\mathbb{R}^3)$. We want to investigate the spectral decomposition of H by diagonalization.

(a) H is self-adjoint.

(b) $\sigma_d(H) = \{\}$

The orbital comes from the diagonalization of the Laplace-Beltrami operator on the unit sphere.

The periodic Schrödinger operator is diagonalized to the direct integral of elliptic operators defined on the Brillouin torus.

Chapter 9

Operator theory

9.1 Toeplitz operators

invariant subspace problem Beurling theorem Hardy and Bergman and Bloch spaces JB* triple

Part IV

Operator algebras

Chapter 10

Banach algebras

10.1 Spectra of elements

10.1 (Banach algebras)**.** For a Banach algebra A with multiplicative unit, there is a complete renorming such that $\|1\| = 1$, i.e. we can always assume $\|1\| = 1$. It provides a definition of *unital Banach algebra*.

Let A be a unital Banach algebra.

(a) If $\|a\| < 1$, then $1 - a$ is invertible. So $A^\times$ is open.

(b) $A^\times \to A^\times : a \mapsto a^{-1}$ is continuous.

(c) $A^\times \to A^\times : a \mapsto a^{-1}$ is differentiable.

Proof. (a) We can show

$$(1-a)^{-1} = \sum_{k=0}^{\infty} a^k.$$

If a is invertible, then $a + h = a(1 + a^{-1}h)$ has the inverse $(1 + a^{-1}h)^{-1}a^{-1}$ if h is sufficiently small such that $\|a^{-1}h\| < 1$.

(b) Clear from

$$b^{-1} - a^{-1} = b^{-1}(a-b)a^{-1}.$$

(c)

$$\begin{aligned}\frac{\|b^{-1} - a^{-1} - (-a^{-1}(b-a)a^{-1})\|}{\|b-a\|} &= \frac{\|(a^{-1} - b^{-1})(b-a)a^{-1}\|}{\|b-a\|} \\ &\le \|a^{-1} - b^{-1}\|\|a^{-1}\| \xrightarrow{b \to a} 0.\end{aligned}$$

□

10.2 (Vector-valued complex analysis)**.** Let X be a complex Banach space (it is known that Fréchet is also possible. See Rudin p.82). If a function $f : \Omega \subset \mathbb{C} \to X$ on a domain is weakly holomorphic, i.e. f defines an operator $X^* \to \mathrm{Hol}(\Omega)$, then f is clearly Bochner integrable on every contour $\gamma \subset \Omega$, and the Cauchy theorem and the Cauchy formula holds, and f is strongly holomorphic, i.e. complex differentible in norm.

10.3 (Spectrum and resolvent)**.** Let a be an element of a unital Banach algebra A. The *spectrum* of a in A is defined to be the set

$$\sigma_A(a) := \{\lambda \in \mathbb{C} : \lambda - a \text{ is not invertible in } A\},$$

and the *resolvent* of a in A is defined to be its complement $\rho_A(a) := \mathbb{C} \setminus \sigma_A(a)$. We can now define the *resolvent map* $R : \rho_A(a) \to A$ such that

$$R(\lambda) = R(\lambda; a) := (\lambda - a)^{-1}.$$

If A is clear in its context, we omit it to just write $\sigma(a)$ and $\rho(a)$.

(a) $\sigma(a)$ is compact.

(b) $\sigma(a)$ is non-empty.

(c) If A is a division ring, then $A \cong \mathbb{C}$. This result is called the *Gelfand-Mazur theorem*.

Proof. (a) If $|\lambda| > \|a\|$, then $\lambda - a$ is always invertible, so the spectrum is bounded. Closedness follows from the fact that the set of invertibles is open.

(b) Suppose the spectrum $\sigma(a) = \varnothing$ so that the resolvent function $R : \mathbb{C} \to A$ is well-defined on the entire $\mathbb{C}$. Note that $a \neq 0$. Since R is continuous and since

$$\|(\lambda - a)^{-1}\| = \|\lambda^{-1}(1 - \lambda^{-1}a)^{-1}\| = \left\|\lambda^{-1}\sum_{k=0}^{\infty}(\lambda^{-1}a)^k\right\| < (2\|a\|)^{-1}\sum_{k=0}^{\infty}2^{-k} = \|a\|^{-1}$$

on $\{\lambda \in \mathbb{C} : |\lambda| > 2\|a\|\}$, the function R is bounded. Also, for every $l \in A^*$ we have that the function $\mathbb{C} \to \mathbb{C} : \lambda \mapsto \langle R(\lambda), l\rangle$ is holomorphic since $a \mapsto a^{-1}$ is differentiable.

Therefore, by the Liouville theorem, the bounded entire function $\lambda \mapsto \langle R(\lambda), l\rangle$ is constant for all $l \in A^*$. Because A^* separates points of A, the function R is constant, which implies $a \in \mathbb{C}$ and contradicts to $\sigma(a) = \varnothing$.

(c) For any $a \in A$, by the part (b), there must be λ such that $\lambda - a$ is not invertible. In a division ring, zero is the only non-invertible element, so $\lambda = a$. $\square$

10.4 (Spectral radius)**.** Let a be an element of a unital Banach algebra A. The *spectral radius* of a in A is defined to be

$$r(a) := \sup_{\lambda \in \sigma(a)} |\lambda|.$$

(a) $r(a) \le \inf_n \|a^n\|^{\frac{1}{n}}$.

(b) $\limsup_n \|a^n\|^{\frac{1}{n}} \le r(a)$, i.e. $r(a) = \lim_n \|a^n\|^{\frac{1}{n}}$.

Proof. (a) Since $(\lambda - a)^{-1} = \lambda^{-1}(1 - \lambda^{-1}a)^{-1}$ exists if $|\lambda| > \|a\|$, we have $r(a) \le \|a\|$ for all $a \in \mathcal{A}$. For every $\lambda \in \sigma(a)$ and every integer $n \ge 1$ we have

$$|\lambda|^n = |\lambda^n| \le r(a^n) \le \|a^n\|,$$

and it proves $r(a) \le \inf_n \|a^n\|^{\frac{1}{n}}$.

(b) Consider a holomorphic function

$$f : \{\lambda \in \mathbb{C} : |\lambda| > r(a)\} \to \mathbb{C} : \lambda \mapsto \langle R(\lambda), l\rangle$$

for each $l \in A^*$. Since on a smaller domain $\{\lambda \in \mathbb{C} : |\lambda| > \|a\|\}$, the function f can be given by

$$f(\lambda) = \left\langle \lambda^{-1}\sum_{k=0}^{\infty}(\lambda^{-1}a)^k, l\right\rangle,$$

we can determine the coefficients of the Laurent series of f at infinity as

$$f(\lambda) = \sum_{k=0}^{\infty}\langle a^k, l\rangle\lambda^{-k-1}$$

on $\{\lambda \in \mathbb{C} : |\lambda| > r(a)\}$.

Take λ such that $|\lambda| > r(a)$. Then, the sequence $(a^k\lambda^{-k-1})_k \in \mathcal{A}$ is weakly bounded, hence is bounded in norm by the uniform boundedness principle. Let $\|a^n\| \le C_\lambda|\lambda^{n+1}|$ for all $n \ge 1$. Then,

$$\limsup_{n\to\infty} \|a^n\|^{\frac{1}{n}} \le \limsup_{n\to\infty} C_\lambda^{\frac{1}{n}} |\lambda^{n+1}|^{\frac{1}{n}} = |\lambda|.$$

If we limit $|\lambda| \downarrow r(a)$, we are done. □

10.5 (Spectrum in closed subalgebras)**.** For fixed element, smaller the ambient algebra, less "holes" in the spectrum. Let $A \subset B$ be a closed subalgebra containing 1_A. Note that A may be unital even for $1_B \notin A$.

(a) $B^\times$ is clopen in $A^\times \cap B$.

10.2 Ideals

10.6 (Ideals)**.** (a) If I is a left ideal, then A/I is a left A-module.

10.7 (Modular left ideals)**.** A left ideal I is called *modular* if there is $e \in \mathcal{A}$ such that $a - ae \in I$ for all $a \in A$. The element e is called a *right modular unit* for I.

(a) I is modular if and only if A/I is unital(?).

(b) A proper modular left ideal is contained in a maximal left ideal.

(c) I is a maximal modular left ideal if and only if I is a modular maximal left ideal.

(d) There is a non-modular maximal ideal in the disk algebra.

10.8 (Closed ideals)**.** (a) closure of proper left ideal is proper left.

(b) maximal modular left ideal is closed.

10.9 (Unitization)**.** Let A be an algebra. Recall that we always assume algebras are associative. Consider an embedding $A \to B(A) : a \mapsto L_a$, where $L_a(b) = ab$. Define

$$\widetilde{A} := \{\, L_a + \lambda\, \mathrm{id}_{B(A)} : a \in A, \lambda \in \mathbb{C}\,\}.$$

Note that this construction is available even for unital A.

(a) If A is normed, then $\widetilde{A}$ is a normed algebra such that there is an isometric embedding $A \to \widetilde{A}$.

(b) If A is Banach, then $\widetilde{A}$ is a Banach algebra.

(c) $A \oplus \mathbb{C}$ is topologically isomorphic to $\widetilde{A}$ as normed spaces.

Proof. (a) The space of bounded operators $B(A)$ is a normd algebra. Then, $\widetilde{A}$ is a normed $*$-algebra with induced norm

$$\|L_a + \lambda\, \mathrm{id}_{B(A)}\| = \sup_{b\in A} \frac{\|ab + \lambda b\|}{\|b\|}$$

Then, A is a normed $*$-subalgebra of $\widetilde{A}$ because the norm and involution of A agree with $\widetilde{A}$.

(b) Suppose (x_n, λ_n) is Cauchy in $\widetilde{A}$. Since A is complete so that it is closed in $\widetilde{A}$, we can induce a norm on the quotient $\widetilde{A}/A$ so that the canonical projection is (uniformly) continuous so that λ_n is Cauchy. Also, the inequality $\|x\| \le \|(x,\lambda)\| + |\lambda|$ shows that x_n is Cauchy in A.

Since a finite dimensional normed space is always Banach and A is Banach, λ_n and x_n converge. Finally, the inequality $\|(x,\lambda)\| \le \|x\| + |\lambda|$ implies that (x_n, λ_n) converges.

(c) Check the topology on $A \oplus \mathbb{C}$ in detail... □

unitization, homomorphisms, category(direct sum, product, etc.)

$B(\mathbb{C}^n) = M_n(\mathbb{C})$ is simple, but $B(H)$ is not simple.

10.3 Holomorphic functional calculus

10.10 (Holomorphic functional calculus)**.** Let a be an element of a unital Banach algebra A. Let f be a holomorphic function on a neighborhood U of $\sigma(a)$. Let γ be any positively oriented smooth simple closed curve in U enclosing $\sigma(a)$. Define $f(a) \in A$ by the Bochner integral

$$f(a) := \int_\gamma f(\lambda)(\lambda - a)^{-1}\, d\lambda.$$

Let $\mathrm{Hol}(\sigma(a))$ be the Fréchet algebra of all holomorphic functions on a neighborhood of $\sigma(a)$ endowed with the topology of compact convergence. We define the *holomorphic functional calculus* or the *Dunford-Riesz calculus* by the map

$$\Phi : \mathrm{Hol}(\sigma(a)) \to A : f \mapsto f(a).$$

(a) $f(a)$ is independent of the choice of γ.

(b) The functional calculus is an algebra homomorphism.

(c) The functional calculus is bounded.

(d) injective.

(e) unital and $\mathrm{id}_{\mathbb{C}} \mapsto a$.

(f) spectral mapping.

(g) power series.

Proof. (a)

□

10.4 Gelfand theory

Banach algebra of single generator semisimplicity and symmetricity

10.11 (Spectrum of a Banach algebra)**.** Let A be a commutative Banach algbera. A *character* of A is a non-trivial algebra homomorphism $\pi : A \to \mathbb{C}$. Denote by $\sigma(A)$ the set of all characters of A and endow with the weak* topology on $\sigma(A) \subset A^*$. We call this space as the *spectrum* of A.

(a) If A is unital, $\sigma(A)$ is contained in the unit sphere of A^*.

(b) $\sigma(A)$ is locally compact and Hausdorff.

Proof. □

10.12 (Gelfand transform)**.** Let A be a commutative Banach algebra. The *Gelfand transform* or the *Gelfand representation* is the following algebra homomorphism

$$\Gamma : A \to C_0(\sigma(A)) : a \mapsto (\pi \mapsto \pi(a)).$$

(a) Γ has the image separating points by definition.

(b) Γ has closed range if A is a symmetric Banach $*$-algebra.

(c) Γ is injective if and only if A is semisimple.

(d) Γ is isometric if and only if $r(a) = \|a\|$ for all $a \in A$.

Exercises

10.13 (Basic properties of spectrum)**.** Let A be a unital algebra.

(a) $\sigma(ab)\setminus\{0\}=\sigma(ba)\setminus\{0\}$.

(b) If $\sigma(a)$ is non-empty, then $\sigma(p(a))=p(\sigma(a))$.

Proof. (a) Intuitively, the inverse of $1-ab$ is $c=1+ab+abab+\cdots$. Then, $1+bca=1+ba+baba+\cdots$ is the inverse of $1-ba$. □

$C_b(\Omega)$ $\ell^\infty(S)$ $L^\infty(\Omega)$ $B_b(\Omega)$ $A(\mathbb{D})$ $B(X)$

10.14. In $C(\mathbb{R})$, the modular ideals correspond to compact sets.

10.15 (Disk algebra)**.** (a) Every continuous homomorphism is an evaluation.

10.16 (Polynomial convexity)**.** (See Conway)

10.17 (Inclusion relation on spectra)**.** (a) $\sigma(a+b)\subset\sigma(a)+\sigma(b)$ and $\sigma(ab)\subset\sigma(a)\sigma(b)$ for unital cases.

(b) $\sigma(a^{-1})=\sigma(a)^{-1}$ for unital cases.

(c) $r(a)^n=r(a^n)$.

10.18 (Spectral radius function)**.** (a) upper semi-continuous

10.19 (Vector-valued complex function theory)**.** Let Ω be an open subset of $\mathbb{C}$ and X a Banach space. For a vector-valued function $f:\Omega\to X$, we say f is *differentiable* if the limit

$$\lim_{\lambda\to\lambda_0}(\lambda-\lambda_0)^{-1}(f(\lambda)-f(\lambda_0))$$

exists in X for every $\lambda\in\Omega$, and *weakly differentiable* if the limit

$$\lim_{\lambda\to\lambda_0}(\lambda-\lambda_0)^{-1}\langle f(\lambda)-f(\lambda_0),x^*\rangle$$

exists in $\mathbb{C}$ for each $x^*\in X^*$ and every $\lambda\in\Omega$. Then, the followings are all equivalent.

(a) f is differentiable.

(b) f is weakly differentiable.

(c) For each $\lambda_0\in\Omega$, there is a sequence $(x_k)_{k=0}^\infty$ such that we have the power series expansion

$$f(\lambda)=\sum_{k=0}^\infty(\lambda-\lambda_0)^kx_k,$$

where the series on the right hand side converges absolutely and uniformly on any closed ball in Ω centered at λ_0.

10.20 (Exponential of an operator)**.**

Chapter 11

C*-algebras

11.1 C* identity

11.1 ($*$-algebras)**.** normed?

11.2 (C*-identity)**.** A *C*-algebra* is a Banach $*$-algebra A satisfying the C*-identity $\|a^*a\| = \|a\|^2$ for all $a \in A$.

11.3 (Unitization)**.**

$$(L_a + \lambda\,\mathrm{id}_{B(A)})^* = L_{a^*} + \overline{\lambda}\,\mathrm{id}_{B(A)}.$$

Proof. The C*-identity easily follows from the following inequality:

$$\begin{aligned}
\|(a,\lambda)\|^2 &= \sup_{\|b\|=1} \|ab + \lambda b\|^2 \\
&= \sup_{\|b\|=1} \|(ab+\lambda b)^*(ab+\lambda b)\| \\
&= \sup_{\|b\|=1} \|b^*((a^*a + \lambda a^* + \overline{\lambda} a)b + |\lambda|^2 y)\| \\
&\le \sup_{\|b\|=1} \|(a^*a + \lambda a^* + \overline{\lambda} a)b + |\lambda|^2 b\| \\
&= \|(a,\lambda)^*(a,\lambda)\|.
\end{aligned}$$

□

11.2 Continuous functional calculus

11.4 (Gelfand-Naimark representation for C*-algebras)**.** For a commutative C*-algebra A, consider the Gelfand transform $\Gamma : A \to C_0(\sigma(A))$.

(a) Γ is a $*$-homomorphism.

(b) Γ is an isometry.

(c) Γ is a $*$-isomorphism.

Proof. (a)

(b) Note that we have

$$\|\Gamma a\| = \sup_{\varphi\in\sigma(A)} |\Gamma a(\varphi)| = \sup_{\varphi\in\sigma(A)} |\varphi(a)| = r(a)$$

for all $a \in A$. If we assume a is self-adjoint, then since $\|a\|^2 = \|a^*a\| = \|a^2\|$, the spectral radius coincides with the norm by the Beurling formula for spectral radius in Banach algebras:

$$\|\Gamma a\| = r(a) = \lim_{n\to\infty} \|a^{2^n}\|^{1/2^n} = \|a\|.$$

Hence we have for all $a \in A$ that

$$\|a\|^2 = \|a^*a\| = \|\Gamma(a^*a)\| = \|(\Gamma a)^*(\Gamma a)\| = \|\Gamma a\|^2.$$

(c) By the part (a) and (b), the image $\Gamma(A)$ is a closed unital $*$-subalgebra of $C(\sigma(A))$, and it separates points by definition. Then, $\Gamma(A)$ is dense in $C(\sigma(A))$ by the Stone-Weierstrass theorem, which implies $\Gamma(A) = C(\sigma(A)$. $\square$

11.5 (Generators of a C*-algebra)**.** joint spectrum.

11.6 (Continuous functional calculus)**.** Let A be a unital C*-algebra, and $a \in A$ a normal element. Then, we have a $*$-isomorphism

$$C(\sigma(a)) \to \widetilde{C}^*(1,a) : \mathrm{id}_{\sigma(a)} \mapsto a$$

defined by the inverse of the Gelfand transform, which we call the *continuous functional calculus*.

(a) spectral mapping: $\lambda \in \sigma_p(a)$ implies $f(\lambda) \in \sigma_p(f(a))$, $\lambda \in \sigma(a)$ iff $f(\lambda) \in \sigma(f(a))$, composition, ...

11.7 (Normal elements)**.** Let a be an element of a unital C*-algebra A. We say a is *normal*, *unitary*, and *self-adjoint* if $a^*a = aa^*$, $a^*a = aa^* = e$, and $a^* = a$ respectively. For normality and self-adjointness, the definitions can be extended to non-unital C*-algebras.

(a) If a is normal, then a is unitary if and only if $\sigma(a) \subset \mathbb{T}$.

(b) If a is normal, then a is self-adjoint if and only if $\sigma(a) \subset \mathbb{R}$.

Proof. (a)

(b) We may assume A is unital. By the holomorphic functional calculus, we have

$$e^{ia} = \sum_{n=1}^{\infty} \frac{(ia)^n}{n!} \in A,$$

and the inverse of e^{ia} is e^{-ia}. Since the involution on A is continuous, we can check e^{ia} is unitary by

$$(e^{ia})^* = \sum_{n=1}^{\infty} \frac{(-ia)^n}{n!} = e^{-ia}.$$

For every $\varphi \in \sigma(A)$, then by the part (a) the equality

$$e^{-\operatorname{Im}\varphi(a)} = |e^{i\varphi(a)}| = |\varphi(e^{ia})| = 1$$

proves $\varphi(a) \in \mathbb{R}$, hence $\sigma(a) \subset \mathbb{R}$. $\square$

11.8 ($*$-homomorphism)**.** Let $\varphi : A \to B$ be a $*$-homomorphism between C*-algerbas.

(a) φ is determined by self-adjoint elements.

(b) $\|\varphi\| = 1$ if φ is non-trivial.

(c) The iamge of φ is closed.

(d) The induced map $A/\ker\varphi \to B$ is an isometry.

11.3 Positive elements

11.9 (Positive elements)**.** Let a, b be elements of a C*-algebra A. We say a is *positive* and write $a \geq 0$ if it is normal and $\sigma(a) \subset \mathbb{R}_{\geq 0}$. If we define a relation $a \leq b$ as $b - a \geq 0$, then we can see that it is a partial order on A.

(a) $a \geq 0$ if and only if $\|\lambda - a\| \leq \lambda$ for some $\lambda \geq \|a\|$.

(b) If $a \geq 0$ and $\sigma(b) \subset \mathbb{R}_{\geq 0}$, then $\sigma(a+b) \subset \mathbb{R}_{\geq 0}$.

(c) $a \geq 0$ if and only if $a = b^*b$ for some $b \in A$.

Proof. Let $a := b^*b$. Let $a = a_+ - a_-$. Then we have $(ba_-)^*(ba_-) = a_-aa_- = -a_-^3 \leq 0$, which also implies $(ba_-)(ba_-)^* \leq 0$ and

$$0 \leq (ba_-)^*(ba_-) + (ba_-)(ba_-)^* \leq 0.$$

Thus we have $ba_- = 0$ and $a_-^3 = 0$.

□

11.10 (Operator monotone operations)**.** (a) If $0 \leq a \leq b$, then $a^{-1} \geq b^{-1}$.

(b) If $a \leq b$, then $cac^* \leq cbc^*$.

11.11 (Approximate identity)**.** Let e_α be an approximate identity of A.

(a) Exists.

(b)

(c)

(d) separable.

11.12 (Positive linear functionals)**.** Let A be a C*-algebra. A *state* of A is a positive linear functional ω such that $\|\omega\| = 1$.

(a) For $\omega \in A^*$, ω is positive if and only if $\lim_\alpha \omega(e_\alpha) = \|\omega\|$.

(b) For a normal element $a \in A$ there is a state ω such that $|\omega(a)| = \|a\|$.

(c) A self-adjoint linear functional is the difference of two positive linear functional. It is called the *Jordan decomposition*.

Proof. (a)

(b) We may assume A is unital. Since $\sigma(a) \cup \{0\}$ is compact, there is $\lambda \in \sigma(a)$ such that $|\lambda| = \|a\|$. The Dirac measure δ_λ induces a state ω_0 of $C^*(1, a)$ such that $\omega_0(a) = \lambda$. By the Hahn-Banach extension, there is extension $\omega \in A^*$ of ω_0 with $\|\omega\| = 1$. Since $\omega(1) = \omega_0(1) = 1$, ω is positive by the part (a), and $|\omega(a)| = |\omega_0(a)| = |\lambda| = \|a\|$.

(c) We first show the real dual $(A^{sa})^*$ can be identified with the self adjoint part $(A^*)^{sa}$ of the complex dual. By this identification, we can describe the weak* topology on $(A^*)^{sa}$ as $\sigma((A^*)^{sa}, A^{sa})$.

We may assume A is unital. The closed unit ball of the real Banach space $(A^*)^{sa}$ is weakly* compact. We are enough to show

$$(A^*)^{sa}_1 = \overline{\mathrm{conv}}(S(A) \cup -S(A)),$$

where the closure is taken in the weak* topology, because $S(A)$ and $-S(A)$ are weakly* compact and convex due to the unit of A, the closure on the right-hand side is not necessary. Suppose not and take $l \in (A^*)^{sa}_1$ which is not approximated weakly* by $\mathrm{conv}(S(A) \cup -S(A))$. By the Hahn-Banach separation, there is $a \in A^{sa}$ such that

$$\sup_{\omega \in S(A) \cup -S(A)} \omega(a) < l(a).$$

If we take $\omega \in S(A)$ such that $|\omega(a)| = \|a\|$ using the part (b), then we get a contradiction to the bound $\|l\| \le 1$.

□

11.4 Representations of C*-algebras

11.13 (Non-degenerate representations). Let A be a C*-algebra. A *representation* of A on a Hilbert space H is a $*$-homomorphism $\pi : A \to B(H)$. We say a representation $\pi : A \to B(H)$ is *non-degenerate* if $\pi(A)H$ is dense in H.

(a) Every representation has a unique non-degenerate subrepresentation.

(b) The following statements are equivalent:

  (i) π is non-degenerate.
  (ii) For each $\xi \in H$ there is $a \in A$ such that $\pi(a)\xi \neq 0$.
  (iii) $\pi(e_\alpha) \to \mathrm{id}_H$ strongly for an approximate identity e_α of A.

11.14 (Cyclic representations). *cyclic* if there is a vector $\psi \in H$ such that $A\psi$ is dense in H. Cyclic decomposition

11.15 (Irreducible representations). *irreducible* if there is no proper closed subspace $K \subset H$ such that $\pi(A)K \subset K$. The following statements are equivalent:

(i) π is irreducible.
(ii) $\pi(A)' = \mathbb{C}\,\mathrm{id}_H$.
(iii) $\pi(A)$ is strongly dense in $B(H)$.
(iv) Every non-zero vector in H is cyclic.

11.16 (Gelfand-Naimark-Segal representation). Let A be a C*-algebra, and ω be a state on A. The *left kernel* of ω is defined to be

$$N_\omega := \{a \in A : \omega(a^*a) = 0\}.$$

(a) N_ω is a left ideal of A.
(b) $\langle a + N, b + N\rangle := \omega(b^*a)$ is an inner product on A/N_ω.
(c) There is a unique representation $\pi_\omega : A \to B(H_\omega)$ such that $\pi_\omega(a)(b+N_\omega) := ab+N_\omega$ for $a, b \in A$.
(d) $\pi_\omega : A \to B(H_\omega)$ is a cyclic representation.

Exercises

11.17 (Projections in $M_2(\mathbb{C})$). The space of self-adjoint elements in $M_2(\mathbb{C})$ is a real vector space spanned by

$$1 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \qquad p := \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \qquad q := \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}.$$

(a) $(p-q)^2 = \frac{1}{2}$.
(b) If we let $\lambda_\pm$ be the eigenvalues of $ap + bq$, then $\lambda_+ + \lambda_- = a + b$ and $\lambda_+ - \lambda_- = \sqrt{a^2 + b^2}$.
(c) Every functional calculus $f(x)$ of self-adjoint x is a linear combination of x and 1.
(d) $ap + bq + c \ge 0$ if and only if $a + b + 2c \ge \sqrt{a^2 + b^2}$.

(e) Every projection of rank one is given by $ap + bq + (1-a-b)/2$ for $a^2 + b^2 = 1$.

11.18 (Operator monotone square). Let A be a C*-algebra in which the square function is operator monotone, that is, $0 \le a \le b$ implies $a^2 \le b^2$ for any positive elements a and b in A. We are going to show that A is necessarily commutative. Let a and b denote arbitrary positive elements of A.

(a) Show that $ab + ba \ge 0$.

(b) Let $ab = c + id$ where c and d are self adjoints. Show that $d^2 \le c^2$.

(c) Suppose $\lambda > 0$ satisfies $\lambda d^2 \le c^2$. Show that $c^2 d^2 + d^2 c^2 - 2\lambda d^4 \ge 0$.

(d) Show that $\lambda(cd + dc)^2 \le (c^2 - d^2)^2$.

(e) Show that $\sqrt{\lambda^2 + 2\lambda - 1} \cdot d^2 \le c^2$ and deduce $d = 0$.

(f) Extend the result for general exponent: A is commitative if $f(x) = x^\beta$ is operator monotone for $\beta > 1$.

11.19 (States on unitization). Let A be a non-unital C*-algebra and $\widetilde{A}$ be its unitization. Let $\widetilde{\omega} = \omega \oplus \lambda$ be a bounded linear functional on $\widetilde{A}$, where $\omega \in A^*$ and $\lambda \in \mathbb{C}^* = \mathbb{C}$.

Since A is hereditary in $\widetilde{A}$, the extension defines a well-defined injective map $S(A) \to S(\widetilde{A})$. We can identify $PS(A)$ as a subset of $PS(\widetilde{A})$ whose complement is a singleton.

(a) $\widetilde{\rho}$ is positive if and only if $\lambda \ge 0$ and $0 \le \rho \le \lambda$.

(b) $\widetilde{\omega}$ is a state if and only if $\lambda = 1$ and $0 \le \omega \le 1$.

(c) $\widetilde{\omega}$ is a pure state if and only if $\lambda = 1$ and ω is either a pure state or zero.

11.20 (Representations of $C_0(X)$). Let $A = C_0(X)$ and μ be a state on A, a regular Borel probability measure on a locally compact Hausdorff space X.

(a) The left kernel of μ is $N_\mu = \{f \in A : f|_{\operatorname{supp}\mu} = 0\}$.

(b) $H_\mu = L^2(X, \mu)$.

(c) The canonical cyclic vector is the unity function on X.

11.21 (Representations of $K(H)$).

11.22 (Automorphism group of $K(H)$ and $B(H)$).

11.23 (Approximate eigenvectors).

11.24 (Kadison transitivity theorem).

11.25 (Hereditary C*-algebras).

11.26 (Extreme points of the ball). Let A be a C*-algebra and let B_A be the closed unit ball of A.

(a) Extreme points of $A_+ \cap B_A$ is the projections in A.

(b) Extreme points of $A_{sa} \cap B_A$ is the self-adjoint unitaries in A.

(c) Every extreme point of B_A is a partial isometry.

Problems

1. A C-algebra is commutative if and only if a function $f(x) = x(1+x)^{-1}$ is operator subadditive.

Chapter 12

Von Neumann algebras

12.1 Normal states

12.1 (Von Neumann algebras). A *von Neumann algebra* on a Hilbert space H is a σ-weakly closed non-degenerate $*$-subalgebra M of $B(H)$. Two von Neumann algebras M_1 and M_2 on H_1 and H_2 are said to be isomorphic if there is a $*$-isomorphism $M_1 \to M_2$.

(a) Every von Neumann algebra contains the identity of $B(H)$.

(b) A positive map φ between von Neumann algebras is order continuous if and only if it is continuous between σ-weak topologies.

(c) image of normal $*$-homomorphism is σ-weakly closed.

12.2 (Normal states). Let $N \subset M \subset B(H)$ be von Neumann algebras. The space of σ-weakly continuous linear functionals on M is denoted by M_*.

(a) M_* is a predual of M.

(b) The restriction of a normal state of M on N is normal.

(c) A normal state of N is extended to a normal state of M.

(d) A state ω of M is normal if and only if $\omega(x) = \sum_{i=1}^{\infty} \langle x\xi_i, \xi_i \rangle$ for some $(\xi_i) \in \ell^2(\mathbb{N}, H)$.

(e) M_* is a closed subspace of M^*.

12.3 (Support projections). p, Mp, pM_*.

(a) projections of M, σ-closed left ideals of M, closed right invariant subspaces of M_*.

(b) For a normal state ω of M, its left hull kernel $\mathfrak{n}_\omega := \{x \in M : \varphi(x^*x) = 0\}$ is a σ-weakly closed left ideal of M, so there is a projection $s(\omega)$ such that $\mathfrak{n}_\omega = Ms(\omega)$. This projection is called the *support* or the *carrier* projection of ω.

Proof. Let $\mathfrak{n}$ be a σ-strongly* closed left ideal of M. Then, $\mathfrak{a} := \mathfrak{n}^* \cap \mathfrak{n}$ is a σ-strongly* closed $*$-subalgebra of M, whose unit is a projection $p \in M$. If $xp \in Mp$, since $p \in \mathfrak{n}$ and $\mathfrak{n}$ is a left ideal, we have $xp \in \mathfrak{n}$. Conversely, if $x \in \mathfrak{n}$, then $x^*x \in \mathfrak{a}$ implies $|x| \in \mathfrak{a}$ so that $|x| = |x|p$ since p is the unit of $\mathfrak{a}$, and by the polar decomposition $x = v|x|$, we have $x = v|x| = v|x|p \in Mp$. Therefore, $\mathfrak{n} = Mp$. If two projections p and q in M satisfy $Mp = Mq$, then since there is a unique unit in a σ-strongly* closed $*$-algebra $pMp = qMq$, hence $p = q$ and the uniqueness follows.

□

12.4 (Normal cyclic representations). (a) The GNS representation of a normal state is normal.

(b) faithful normal states

(c) closedness of $x \mapsto \Omega$?

(d) sufficiently large representation, dependence of weak and strong topologies

An action admits a separating vector if and only if it admits a cyclic separating vector, which is equivalent to that the action can be realized as a cyclic representation associated to a faithful normal state, so every normal state is a vector state by the Connes cocycle.

12.2 Density theorems

12.5 (Double commutant theorem)**.** The *commutant* of a subset $S \subset B(H)$ is the set S' of all elements of $B(H)$ that commute every $a \in S$. Let A be a non-degenerate $*$-subalgebra of $B(H)$. One can describe the von Neumann algebra generated by A in $B(H)$ purely algebraically in terms of commutants.

(a) The double commutant A'' is weakly closed $*$-algebra.

(b) If $x \in A''$, for any $\varepsilon > 0$ and $\xi \in H$ there is $a \in A$ such that $\|(x-a)\xi\| < \varepsilon$.

(c) A is σ-strongly* dense in A''. In particular, if A is σ-strongly* closed, then it is weakly closed.

Proof. (a) Suppose a net $x_\alpha \in A''$ weakly converges to $x \in B(H)$. For any $y \in A'$,

$$\langle xy\xi, \eta\rangle = \lim_\alpha \langle x_\alpha y\xi, \eta\rangle = \lim_\alpha \langle y x_\alpha \xi, \eta\rangle = \langle yx\xi, \eta\rangle, \qquad \xi, \eta \in H.$$

Hence $x \in A''$.

(b) We claim $x\xi \in \overline{A\xi}$ for each $\xi \in H$. Let p be the projection onto $\overline{A\xi}$. For any $a \in A$, the operator ap ranges into $\overline{A\xi}$ so that $pap = ap$, and we also have $pa^*p = a^*p$ by the self-adjointness of A. It implies $ap = pa$, which deduces $p \in A'$. Thus $xp = px$ for $x \in A''$. On the other hand, observe that $a(1-p)\xi = (1-p)a\xi = 0$ for all $a \in A$. Then, $\langle (1-p)\xi, \eta\rangle = 0$ for any $\eta \in H = \overline{AH}$ by the non-degeneracy, so $p\xi = \xi$. Combining $xp = px$ and $p\xi = \xi$, we obtain $x\xi = xp\xi = px\xi$ so that $x\xi \in \overline{A\xi}$.

(c) It suffices to show A is σ-strongly dense in A'' because A is self-adjoint. Consider A as the non-degenerate $*$-subalgebra of $B(\ell^2(\mathbb{N}, H))$ via the diagonal map $B(H) \to B(\ell^2(\mathbb{N}, H))$, which is a injective normal unital $*$-homomorphism. We can check that A'' does not change if we replace $B(H)$ to $B(\ell^2(\mathbb{N}, H))$. By applying the part (b) for arbitrary $\xi \in \ell^2(\mathbb{N}, H)$, we deduce the desired result. □

12.6 (Kaplansky density theorem)**.** We say a continuous function $f : F \to \mathbb{C}$ on a closed set $F \subset \mathbb{C}$ is *strongly continuous* if the functional calculus $x \mapsto f(x)$ is If f is a

A $*$-isomorphism between von Neumann algebras is normal.

12.7 (Approximate identity)**.**

12.3 Borel functional calculus

12.8 (Sherman-Takeda theorem)**.** Let A be a C*-algebra. Define $M(\pi) := \pi(A)''$ for $\pi : A \to B(H)$ a representation. Let $\pi_u : A \to B(H_u)$ be the universal representation of A, the direct sum of all the GNS-representations of states of A. Consider the following three maps

$$\pi_u : A \to (M(\pi_u), \sigma w), \qquad \pi_u^* : M(\pi_u)_* \to A^*, \qquad \pi_u^{**} : A^{**} \to M(\pi_u),$$

constructed by adjoints.

(a) π_u^* is isometric.

(b) π_u^* is surjective. In particular, π_u^{**} is a $*$-isomorphsim.

(c) A^{**} enjoys a universal property in the sense that every $*$-homomorphism $\varphi : A \to M$ to a von Neumann algebra M has a unique normal extension $\widetilde{\varphi} : A^{**} \to M$ of φ.

Proof. (a) It holds for any representation of $\pi : A \to B(H)$. For each $l \in M(\pi)_*$ we have

$$\|\pi^*(l)\| = \sup_{\substack{\|a\|\le 1\\ a\in A}} |l(\pi(a))| = \sup_{\substack{\|x\|\le 1\\ x\in M(\pi)}} |l(x)| = \|l\|$$

by the Kaplansky density theorem and the σ-weak continuity of l.

(b) Let ω be a state of A. Since the universal representation π_u has the GNS representation of ω as a subrepresentation, ω is given by a vector state in π_u. By restriction of this vector state, we have a normal state of $M(\pi_u)$, which extends ω. Now the Jordan decomposition can be applied to verify that every bounded linear functional of A has a σ-weakly continuous extension on $M(\pi_u)$.

(c) We can define $\widetilde{\varphi}$ as the bitranspose of $\varphi : A \to (M, \sigma w)$, and it is a unique extension because A is σ-weakly dense in A^{**}. □

Remark 12.3.1. The bidual A^{**} is frequently viewed as a von Neumann algebra, and we call it the *enveloping von Neumann algebra* of a C*-algebra A. By the universal property, we have a normal $*$-homomorphism $M(\pi_u) \to M(\pi)$ that is in fact surjective for every representation π of A, and it fails to be injective even if π is faithful.

12.4 Predual

12.9 (Conditional expectations)**.** Let A be a closed subalgebra of a C*-algebra B. Let $\varphi : B \to A$ be a contractive idempotent surjective linear map. Such a map is called a *conditional expectation*.

(a) φ is an A-bimodule map.

(b) φ is completely positive.

Proof. Since each conclusion of (a) and (b) still holds for restriction, we may assume A and B are von Neumann algebras by thinking of the bitranspose $\varphi^{**} : B^{**} \to A^{**}$.

(a) Since the linear span of projections is σ-weakly dense in a von Neumann algebra, we are enough to show $p\varphi(b) = \varphi(pb)$ and $\varphi(bp) = \varphi(b)p$ for any projection $p \in A$.

Let $p \in A$ be a projection and let $b \in B$. Note that the surjectivity of φ implies that $p\varphi$ is also idempotent. Then, where $1 = 1_B$,

$$\begin{aligned}(1+t)^2\|p\varphi((1-p)b)\|^2 &= \|p\varphi((1-p)b) + tp\varphi(p\varphi((1-p)b))\|^2\\ &\le \|(1-p)b + tp\varphi((1-p)b)\|^2\\ &= \|(1-p)b\|^2 + t^2\|p\varphi((1-p)b)\|^2\end{aligned}$$

implies $p\varphi((1-p)b) = 0$ by letting $t \to \infty$. Putting $1_A - p$ and 1_A instead of p, we obtain

$$(1-p)\varphi((1-1_A+p)b) = 0, \qquad \varphi((1-1_A)b) = 0$$

respectively, which imply $(1-p)\varphi(pb) = 0$. Hence for any $b \in B$ we have

$$p\varphi(b) = p\varphi(pb) = \varphi(pb).$$

Similarly we can show $\varphi(b(1-p))p = 0$ and $\varphi(bp)(1-p) = 0$ for $b \in B$, we are done.

(b) Let $[b_{ij}] \in M_n(B)_+$. Let $\pi : A \to B(H)$ be a cyclic representation with a cyclic vector ψ. Then, $[\xi_i] \in H^n$ can be replaced to $[\pi(a_i)\psi]$, so we can check the positivity of inflations φ_n as

$$\sum_{i,j} \langle \pi(\varphi(b_{ij}))\pi(a_j)\psi, \pi(a_i)\psi\rangle = \langle \pi(\varphi(\sum_{i,j} a_i^* b_{ij} a_j))\psi, \psi\rangle \geq 0,$$

because it follows $\sum_{i,j} a_i^* b_{ij} a_j \geq 0$ by the positivity of b_{ij} from

$$\langle \pi_B(\sum_{i,j} a_i^* b_{ij} a_j)\xi, \xi\rangle = \sum_{i,j} \langle \pi_B(b_{ij})\pi_B(a_j)\xi, \pi_B(a_i)\xi\rangle \geq 0,$$

where π_B is any representation of B. □

12.10 (Sakai theorem)**.** Let A be a W^*-*algebra* with a predual F, which means that A is a C*-algebra and F is a norm closed subspace of A^* such that the restriction map $A^{**} \to F^* : x \mapsto x|_F$ is restricted to an isometric isomorphism $A \to F^*$. Consider the canonical embedding $A \subset A^{**}$ and the embedding $A^{**} \subset B(H)$ by the universal representation in which every element of A^* is a vector functional and every vector functional acts on A^{**} as an element of A^*, by the Sherman-Takeda theorem.

(a) There is an injective $*$-homomorphism $\pi : A \to A^{**}$ with weakly* closed image.

(b) π is a topological embedding with respect to $\sigma(A, F)$ and $\sigma(A^{**}, A^*)$.

(c) The predual F is unique in A^*.

Proof. (a) By the definition of predual, we have a linear map $\varepsilon : A^{**} \to A$ defined by the restriction on F, and it is a contractive idempotent surjective map, and hence is a A-bimodule map. Since A is dense in $\sigma(A^{**}, A^*)$ by the Goldstine theorem, and since ε is continuous between $\sigma(A^{**}, A^*)$ and $\sigma(A, F)$, we can see that ε is in fact a A^{**}-bimodule map, which means the kernel is a σ-weakly closed ideal of A^{**}. Thus, we have a central projection $z \in A^{**}$ such that $\ker\varepsilon = (1-z)A^{**}$. Define $\pi : A \to A^{**}$ such that $\pi(a) := za$. It is a $*$-homomorphism because z is central. The injectivity follows from $a = \varepsilon(a) = \varepsilon(za) = \varepsilon(\pi(a))$ for $a \in A$, and $x - \varepsilon(x) \in \ker\varepsilon$ implies $zx = z\varepsilon(x) \in zA$ for $x \in A^{**}$ so that the image $\pi(A) = zA = zA^{**}$ is σ-weakly closed in $B(H)$.

(b) Note that $\pi : A \to A^{**}$ is continuous with respect to the norm topology and $\sigma(A^{**}, A^*)$ so that its adjoint can have the form $\pi^* : A^* \to A^*$. For π to be an embedding, it suffices to prove the equality $\pi^*(A^*) = F$. First, suppose $l \in A^*$ satisfies $\pi^*(l) \in A^* \setminus F$. Because F is norm closed in A^*, by the Hahn-Banach extension, there is $x \in A^{**}$ such that $\langle x, \pi^*(l)\rangle \neq 0$ and $\langle x, f\rangle = 0$ for all $f \in F$. Since $\langle \varepsilon(x), f\rangle = \langle x, f\rangle = 0$ for every $f \in F$ from the definition of ε and F separates points A, we have $\varepsilon(x) = 0$ and $x \in \ker\varepsilon$ implies $zx = 0$. Take a net $a_\alpha \in A$ such that $a_\alpha \to x$ in $\sigma(A^{**}, A^*)$. Then, if we take $\xi, \eta \in H$ such that $\langle a, l\rangle = \langle a\xi, \eta\rangle$, then we have

$$\langle x, \pi^*(l)\rangle = \lim_\alpha \langle a_\alpha, \pi^*(l)\rangle = \lim_\alpha \langle za_\alpha, l\rangle = \lim_\alpha \langle za_\alpha\xi, \eta\rangle = \lim_\alpha \langle a_\alpha\xi, z\eta\rangle = \langle x\xi, z\eta\rangle = \langle zx\xi, \eta\rangle = 0,$$

which is a contradiction, so we have $\pi^*(A^*) \subset F$. Conversely, if $f \in F$, then we have $\langle a, \pi^*(f)\rangle = \langle za, f\rangle = \langle a, f\rangle$ because $(1-z)a \in \ker\varepsilon$ acts on F trivially by definition of ε, so $f = \pi^*(f) \in \pi^*(A^*)$.

(c) Suppose F_1 and F_2 are preduals of A. The identity $(A, \sigma(A, F_1)) \to (A, \sigma(A, F_2))$ is a $*$-isomorphism between von Neumann algebras, which automatically has σ-weak continuity, so it induces the equality $\sigma(A, F_1) = \sigma(A, F_2)$ of topologies. By taking duals for the two weak* topologies, we get $F_1 = F_2$. □

Exercises

12.11 (Extremally disconnected space)**.** $\sigma(B^\infty(\Omega))$ is extremally disconnected.

resolution of identity normal operator theories: multiplicity, invariant subspaces L^∞ representation

σ-weakly closed left ideal has the form Mp. II.3.12

Let $\mathfrak{m}$ be an algebraic ideal of a von Neumann algebra M, and $\overline{\mathfrak{m}}$ be its σ-weak closure. If $x \in (\overline{\mathfrak{m}})_+$, then there is an increasing net $(x_i) \subset \mathfrak{m}$ converges to x strongly. II.3.13

binary expansion and hereditary subalgebras