Introduction to Operator Algebras

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Contents

The set of all linear bounded operators $\mathscr{L}(H) = \mathscr{B}(H)$ on a given Banach space H ist a (Banach) algebra with $S \cdot T = S \circ T$. $M \subseteq \mathscr{L}$ ist a Subalgebra such that $M^* \subseteq M$ where T^* is the adjoint of T. This is also a closed subspace with respect to the strong topology. This is equivalent to $M = M''$ (when $X \subseteq \mathscr{B}(H), X' = \{T \in \mathscr{B}(H) \mid TS = ST \ \forall_{S \in X}\}$)

Some topological basics

Definition 0.1

- *Topology, Open*
- *Hausdorff, locally Hausdorff*
- *compact*

Definition 0.2 *A topological space X is **locally Hausdorff** if every $x \in X$ admits a compact neighborhood basis, that is for every $x \in X$ and every open set $U \ni x$ there exists an open set $V \ni x$ with $\overline{V}$ is compact.*

Corollary 0.3 *If a set V is compact in any subset $U \subseteq X$, it is also compact in X.*

Example 0.4 (Snake with two heads) Consider $I = [0, 1]$ with the standard topology and extend the set with an element 1^+ such that $I \cup 1^+ \setminus 1$ is isomorphic to I. Then $I \cup 1^+$ is locally Hausdorff and compact, but not Hausdorff.

Some results about locally compact Hausdorff spaces

Lemma 0.5 (Uryson's Lemma) *Let X be locally compact and Hausdorff. For all $F \subseteq X$ closed and $K \subseteq X$ compact with $F \cap K = \emptyset$, there exists an $f : X \to [0, 1]$ continuous such that $f|_K \equiv 1$ and $f|_F \equiv 0$.*

Theorem 0.6 (Tietze's extension theorem) *Let X be locally compact, $K \subseteq X$ compact and $f : K \to \mathbb{C}$ continuous. Then there exists a continuous $\tilde{f} : X \to \mathbb{C}$ such that $\tilde{f}|_K = f$.*

Theorem 0.7 (Alexandroff's conpactification) *If X is locally compact and Hausdorff, then $\tilde{X} \sqcup \{\infty\}$ is a compact Hausdorff space $\mathscr{O}(\tilde{X}) = \mathscr{O}(X) \cup \{K^{\complement} \cup \{\infty\} \mid K \text{ compact}\}$.*

Example 0.8 Compacting the real line $\mathbb{R}$ yields the space $\tilde{\mathbb{R}}$, which is isomorphic to the unit circle $\Pi = \mathbb{S}^1$.

Theorem 0.9 *Conversely, if Y is a compact Hausdorff space, then for all $y_0 \in Y$, $X \coloneqq Y \setminus \{y_0\}$ is locally compact (in respect to the subspace topology).*

More generally, if Y is locally compact and Hausdorff, and $Z \subseteq Y$ is a difference of open and closed subsets, of Y (i.e. $Z = U \setminus F$, where U is open in Y and F is closed in Y), then Z is locally compact.

1 Algebras

Definition 1.1 *An **algebra** is a (complex) vector space $\mathscr{A}$ endowed with a bilinear and associative multiplication: $\mathscr{A} \times \mathscr{A} \to \mathscr{A}, (a, b) \mapsto a \cdot b$. So*

(i) $(a + \alpha b) \cdot (c + \beta d) = ac + \alpha bc + \beta ad + \alpha\beta bd$.

(ii) $(a \cdot b) \cdot c = a \cdot (b \cdot c)$.

for all $a, b, c \in \mathscr{A}$ and $\alpha, \beta \in \mathbb{C}$. We say that $\mathscr{A}$ is

(i) ***commutative****, if $ab = ba$ for all $a, b \in \mathscr{A}$.*

(ii) ***unital****, if there exists $1 = 1_{\mathscr{A}} \in \mathscr{A}$ such that $1 \cdot a = a \cdot 1 = a$ for all $a \in \mathscr{A}$.*

Example 1.2

(i) $\mathbb{C}$, or more generally $\mathbb{C}^n = \mathbb{C} \oplus \cdots \oplus \mathbb{C}$, is an algebra.

(ii) Say X is any set; let $\mathbb{C}^X = \{f : X \to \mathbb{C}\}$ with pointwise multiplication $(f \cdot g)(x) = f(x) \cdot g(x)$. These are commutative unital algebras (with $1(x) = 1 \in \mathbb{C}$).

(iii) Consider the polynomials $\mathbb{C}[X] = \{\sum_{i=0}^n \lambda_i x^i \mid \lambda_i \in \mathbb{C}, n \in \mathbb{N}\}$ with the usuals operations. This is a commutative unital algebra.

(iv) Let X be a topological space and $C(X) = \{f : X \to \mathbb{C} \mid f \text{ is continouus}\} \subseteq \mathbb{C}^X$ the set of continuous functions on X. This is a commutative unital (sub)algebra (of $\mathbb{C}^X$).

(v) Take any vector space A define a (trivial) multiplication $a \cdot b \coloneqq 0$. This is a commutative Algebra (that is not unital unless $A = 0$).

(vi) $M_n(\mathbb{C})$ (the complex $n \times n$ matrices) with the usual multiplication are a non-commutative (unless $n = 1$) unital algebra.

(vii) Let V be any (complex) vector space. The set of all linear operators $L(V) := \{T : V \to VT \text{ linear operator}\}$ is a unital (non-commutative for $\dim V > 1$). We observe $\mathscr{L}(\mathbb{C}^n) \simeq M_n(\mathbb{C})$.

(viii) Let S be a semigroup (i.e. a set with an associative operation $S \times S \to S$, e.g. $(\mathbb{N}, +)$). Then $\mathbb{C}[S] = \{\sum_{s \in S} \lambda_s s \mid \lambda_s \in \mathbb{C}, |\{s : \lambda_s \neq 0\}| < \infty\}$ (the finite formal sums of elements of S) with the following product

$$\left(\sum_{s \in S'} \lambda_s s\right) \cdot \left(\sum_{t \in S} \lambda'_t t\right) := \sum_{s,t \in S} (\lambda_s \cdot \lambda'_t)(s \cdot t) \in S$$

Observe: As a vector space: $\mathbb{C}[S] \subseteq \mathbb{C}^S$. In general, this is neither commutative nor unital.

2 Normed algebras

Definition 2.1 *An algebra $\mathscr{A}$ is* ***normed****, if it is endowed with a (vector space) norm $\|\cdot\| : \mathscr{A} \to [0, \infty)$ satisfying $\|a \cdot b\| \leq \|a\| \cdot \|b\|$. If $\mathscr{A}$ is unital with unit $1_{\mathscr{A}}$, we usually assume $\|1_{\mathscr{A}}\| = 1$ except for $\mathscr{A} = 0$.*

Definition 2.2 *A* ***Banach algebra*** *is a normed algebra that is also complete (as a metric space with respect to the distance $d(a, b) := \|a - b\|$), i.e. every Cauchy sequence converges.*

Example 2.3 (i) If X is a compact space then $C(X)$ is a commutative unital Banach algebra with respect to the norm $\|f\|_\infty := \sup_{x \in X} |f(x)| < \infty$ (since X is compact).

(ii) If V is a normed (respectively Banach) vector space, e.g. $\mathbb{C}^n$ or $\ell^p(\mathbb{N})$, then $\mathscr{L}(V) = \{T \in L(V) \mid T \text{ is bounded/continouus}\}$ with $\|T\| := \sup_{\|v\|\leq 1} \|T(v)\| < \infty$ is a normed Banach algebra.

(iii) If X is a topological space, then $C_b(X) = \{f \in C(X) \mid \|f\|_\infty < \infty\}$ (bounded continuous functions) is a Banach space.

(iv) Let X again be a topological space. Then the set of all functions **vanishing at** ∞,

$$\begin{aligned} C_0(X) &= \{f \in C(X) \mid \forall_{\varepsilon>0} \exists_{K\subseteq X, K \text{ compact}} \forall_{x\notin K} |f(x)| < \varepsilon\} \\ &= \{f \in C(X) \mid \forall_{\varepsilon>0} \{x \in X \mid |f(x)| \geq \varepsilon\} \text{ is compact}\} \subseteq C_b(X), \end{aligned}$$

is also a Banach algebra.

Exercise 2.1 Assume X is locally compact and Hausdorff. Prove the following are equivalent:

(1) X is compact.

(2) $C(X) = C_0(X)$

(3) $C_0(X)$ is unital.

(4) The unit function $1 \in C_b(X)$ belongs to $C_0(X)$.

PROOF:

- (1) $\Rightarrow$ (2): Recall the definition of $C_0(X)$. If X is compact, every closed subset (especially every $\{x : |f(x)| \geq \varepsilon\}$) is compact, so the condition of $C_0(X)$ is trivial.
- (2) $\Rightarrow$ (3): Since $C(X)$ is unital, $C_0(X)$ is as well.
- (3) $\Rightarrow$ (4): Suppose C_0 is unital, and let $f \in C_0(X)$ be the unit. Then $f \cdot g = g$ for all $g \in C_0(X)$, i.e. $f(x)g(x) = g(x)\forall_{x\in X}\forall_{g\in C_0(X)}$. By Uryson's lemma, given any $x_0 \in X$, there exists $g \in C_0(X)$ with $g(x_0) = 1$ (by looking at $K = \{x_0\}$ and taking F as the complement of any relatively compact environment of x_0.). Then $f(x_0) = f(x_0)g(x_0) = g(x_0) = 1$. Doing this for every $x_0 \in X$ yields $f \equiv 1$.
- (4) $\Rightarrow$ (1): Since $1 \in C_0(X)$, for every $\varepsilon > 0$ the set $\{x \mid |f(x)| \geq \varepsilon\}$ is compact. Choose $\varepsilon = \frac{1}{2}$. Then, $\{x \mid |f(x)| = |1| \geq \frac{1}{2}\} = X$ is compact. $\square$

Exercise 2.2 Let X be a locally compact Hausdorff space. Prove that $C_0(X) \cong \{f \in C(X) \mid f(\infty) = 0\}$

3 Algebras

Definition 3.1 *A* ****-algebra*** *is a complex algebra* $\mathscr{A}$ *with an* ***involution*** $^* : \mathscr{A} \to \mathscr{A}$ *satisfying*

(i) $(a + \lambda b)^* = a^* + \overline{\lambda} b^*$

(ii) $(a^*)^* = a$

(iii) $(ab)^* = b^* a^*$

for all $a, b \in \mathscr{A}$ *and all* $\lambda \in \mathbb{C}$.

Definition 3.2 *A* ***normed*** ****-algebra*** *is a normed algebra* $\mathscr{A}$ *with an involution (such that* $\mathscr{A}$ *is a* **-algebra) also satisfying* $\|a^*\| = \|a\|$ *for all* $a \in \mathscr{A}$*.*

A ***Banach-*******-algebra*** *is a complete normed* **-algebra.*

Definition 3.3 *A* C^**-algebra is a Banach-***-algebra satisfying* $\|a^* \cdot a\| = \|a\|^2$*.*

Observation: Recall that $\|a \cdot b\| \leq \|a\| \cdot \|b\|$ in all normed algebras. Applying this to a C^*-algebra we get $\|a \cdot a^*\| \leq \|a^*\| \cdot \|a\|$. If $\mathscr{A}$ is a C^*-algebra, then $\|a\|^2 = \|a \cdot a^*\| \leq \|a^*\| \cdot \|a\|$, so $\|a\| = \|a^*\|$.

Example 3.4

(i) If X is a set, then $\mathbb{C}^X$ is a *-algebra with $f^* = \overline{f}$ and $\mathscr{C}^\infty(X)$ is a C^*-algebra.

(ii) If X is a topological space, then $C(X) \subseteq \mathbb{C}^X$ is also a *-subalgebra and for $\{f \in C(X) \mid \operatorname{supp}(f) = \overline{\{x \in X \mid |f(x)| \neq 0\}} \text{ compact}\}$ we have

$$C_c(X) =\subseteq C_0(X) \subseteq C_b(X) \subseteq C(X) \subseteq C^\infty(X)$$

and C^∞ is a C^*-algebra. C_c is a *-algebra, but not Banach in general.

If X is compact, it follows $C_c(X) = C_0(X) = C_b(X)$.

Observation: If X is locally compact and Hausdorff, then $\overline{C_c(X)} = C_0(X)$.

(iii) Let X be a measured space (X is endowed with a σ-algebra). Then $B_\infty(X) = \{f \in C^\infty \mid f \text{ is measurable}\}$ is a C^*-algebra. If μ is a measure on X (e.g. $X = \mathbb{R}^n$ and μ the Lebesgue measure) then $L^\infty(X, \mu)$ are the essentially bounded functions and

$$L^\infty(X) = \{f : X \to \mathbb{C} \mid \|f\| \coloneqq \inf\{c \geq 0 \mid \mu(\{x \mid |f(x)| > c\}) = 0\}\}$$

is also a C^*-algebra.

Observation: $L^2(X, \mu) =$ "μ-separable function", $L^\infty(X, \mu) \xrightarrow{\mu} B(L^2(X, \mu)), f \mapsto \mu_f = \{g \mapsto f \cdot g\}$

(iv) A non-example: Let $\mathbb{D}$ be the unit disk and $\mathscr{A}(\mathrm{d}) = \{f \in \mathbb{C}(\mathbb{D}) \mid \text{ analytic in } \mathbb{D}^\circ\}$

Morera's Theorem from complex analysis states that $f \in C(\mathbb{D})$ is analytic if and only if $\int_\gamma f(z)dz = 0$ for all closed and piecewise smooth paths in $\mathbb{D}^\circ$. From this, it follows that $\mathscr{A}(\mathbb{D})$ is closed in $C(\mathbb{D})$, therefore a Banach algebra. It is also a Banach-*-algebra with, but $f^* = \overline{f}$ (pointwise) is not possible, as $z \mapsto \overline{z}$ is not analytic. Thus, we have to choose $f^*(z) = f(\overline{z})$. But $\mathscr{A}(\mathbb{D})$ is not a C^*-algebra, as $\|f^* f\|_\infty \neq \|f\|_\infty^2$ for some $f \in \mathscr{A}(\mathbb{D})$.

(v) A non-commutative example: Let H be a Hilbert space and $B(H) = \mathscr{L}(H) = \{T : H \to H \mid T \text{bounded, continouus, linear}\}$ and $\|H\| \coloneqq \sup_{\|z\|<1} \|T(z)\| < \infty$. This is a C^*-algebra where T^* is the adjoint of T, that is $\langle T^* z, w\rangle = \langle z, Tw\rangle$ for all $z, w \in H$.

C^*-axiom: $\|T^* \cdot T\| \leq \|T\|^2$ since $\mathscr{L}(H)$ is a Banach algebra, and we also have

$$\begin{aligned}
\|T\|^2 &= \sup_{\|z\|<1} \|T(z)\|^2 = \sup_{\|z\|<1} \langle Tz, Tz\rangle = \sup_{\|z\|<1} \langle z, T^*Tz\rangle \\
&\leq \sup_{\|z\|<1} \|z\|\|T^*Tz\| \leq \sup_{\|z\|<1} \|z\|\|T^*T\| \leq \|T^*T\|
\end{aligned}$$

In particular, $M_n(\mathbb{C}) \simeq \mathscr{L}(\mathbb{C}^n)$ is a unital C^*-algebra.

(vi) To produce more examples, take any subset $S \subseteq \mathscr{L}(H)$ and take $C^*(S) \subseteq \mathscr{L}(H) = \overline{\operatorname{span}\{S_i \mid S_i \in S \cup S^*, i \leq n \in \mathbb{N}\}}$.

Example 3.5 Let $s \in \mathscr{L}(\ell^2(\mathbb{N}))$. The shift s, defined by $s(e_i) = e_{i+1}$ for all $i \in \mathbb{N}$ (where $\{e_i\}$ is the canonical basis of the sequence space), is an isometry, that is $s^* \cdot s = \mathrm{id}$. Since $s \cdot s^* \neq \mathrm{id}$, it is not surjective and not a proper isometry. We define

$$T = C^*(s) = \overline{\operatorname{span}\{s^n (s^*)^m \mid m, n \in \mathbb{N}_0\}} \subseteq \mathscr{L}(\ell^2(\mathbb{N}))$$

as the **Toeplitz algebra**.

Example 3.6 Let H be a Hilbert space and S the set of all finite rank operators on H.

Example 3.7

(i) **Commutative**: $C_0(X)$ for a locally Hausdorff space X.

(ii) **Non-commutative**: $\mathcal{L}(\mathfrak{H}) = \mathcal{B}(\mathfrak{H})$ for any Hilbert space $\mathfrak{H}$ (with dimension greater 1).

(iii) **More generally**: Take any subset $S \subseteq \mathcal{L}(\mathfrak{H})$ and construct $C^*(S) \subseteq \mathcal{L}(H)$ as

$$\overline{\operatorname{span}}\{S_1, \ldots, S_n \mid S_i \in S \cap S^*\}$$

Example 3.8 (Cuntz algebras) Take again $\mathfrak{H} = \ell^2\mathbb{N} = \{(\lambda_n)_{n \in \mathbb{N}_0} \mid \sum_{n=0}^{\infty} |\lambda_n|^2 < \infty\}$ where $\langle \lambda, \lambda' \rangle = \sum_{i \in \mathbb{N}_0} \overline{\lambda_i} \lambda'_i$ and which has the orthonormal base $(e_n)_{n \in \mathbb{N}}$ where $(e_n) = (\delta_{in})_{i \in \mathbb{N}_0}$.

On this algebra, define

- $S_1(e_n) = e_{2n}$.
- $S_2(e_n) = e_{2n+1}$.

We have partitioned the natural numbers into evens and odds. This defines two (proper) isometries $S_1, S_2 \in \mathscr{L}(\mathfrak{H})$, that is $S_i^* S_i = \mathrm{id}_{\mathfrak{H}}$, to subspaces of $\mathfrak{H}$. Notice: $S_i^* S_j = 0$ for $i \neq j$ as well as $S_1 S_1^* + S_2 S_2^* = \mathrm{id}_{\mathfrak{H}}$. Define $\mathcal{O}_2 = C^*(S_1, S_2) = \overline{\operatorname{span}}\{S_\alpha S_\beta^* \mid \alpha, \beta \text{ finite words in } \{1, 2\}\}$. For example, for $\alpha = 121211$ we have $S_\alpha = S_1 S_2 S_1 S_2 S_1^2$. $\mathcal{O}_2$ is called the **Cuntz algebra**. More generally, one can define $\mathcal{O}_3, \mathcal{O}_4$, ... Cuntz algebras. Joachim Cuntz proved that these are simple C^*-algebras with additional interesting properties we will see later.

Example 3.9 (Rotation algebras) Let $\mathfrak{H} = \ell^2(\mathbb{Z})$ (bi-infinite sequences) with basis $(e_n)_{n \in \mathbb{Z}}$ Define:

- $U(e_n) := e_{n+1}$ (bilateral shift)
- $V(e_n) := \lambda^n e_n$ where $\lambda \in \mathbb{C}$ is some fixed number $|\lambda| = 1$.

This defines two *unitary* operators: $UU^* = 1 = U^*U$ and $V^*V = 1 = V^*V$. If $\exp(2\pi i\theta), \theta \in \mathbb{R}$ define $A_\theta := C^*(U, V) \subseteq \mathscr{L}(\ell^2\mathbb{N})$.

There is a special relation between U and V where $UV = \lambda VU = \exp(2\pi i\theta)VU$. From this relation, we can describe $A_\theta = \overline{\operatorname{span}}\{\sum_{n,m \in \mathbb{Z}}^{\text{finite}} a_{n,m} U^n V^m \mid a_{n,m} \in \mathbb{C}\}$.

Furthermore, if $\theta \in \mathbb{R} \setminus \mathbb{Q}$, A_θ is simple.

Example 3.10 (**C^*-algebras of groups**) Let G be a (discrete) group. Look at $\mathfrak{H} = \ell^2(G) = \{(a_g)_{g\in G} \mid \sum_{g\in G} |a_g|^2 < \infty\}$ (Note: This limit will only converge if there are countably (or finitely) many non-zero parts) with ONB $(\delta_g)_{g\in G}$ where $\delta_g(h) = \delta_{gh}$. Define for each $g \in G$ an operator $\lambda_g \in \mathscr{L}(\ell^2 G)$ by $\lambda_g(\delta_h) = \delta_{gh}$. Notice that $h \mapsto gh$ is a bijection, and thus λ_g is a unitary operator with $\lambda_g^* = \lambda_{g^{-1}}$. We can now define the **reduced C^*-algebra** of the group:

$$C_R^*(G) := C_\lambda^*(G) \subseteq \mathscr{L}(\ell^2 G) = C^*(\lambda_g \mid g \in G)$$

Here, we have the relation $\lambda_g \cdot \lambda_h = \lambda_{gh}$ and thus $C_R^*(G) = \{\sum a_g \lambda_g \mid a_g \in \mathbb{C}\}$.

In general, take $U : G \to \mathscr{L}(H), g \mapsto U_g$ a **unitary representation of** G with $U_g U_h = U_{gh}$ and $U_1 = \mathrm{id}$ as well as $U_g^{-1} = U_{g^{-1}}$. Then $C_U^*(G) := \{\sum_{g\in G} a_g U_g \mid a_g \in \mathbb{C}\} \subseteq \mathscr{L}(H)$. There exists a **universal unitary representation** $C_{\max}^*(G)$, a full C^*-algebra of G.

Remark 3.11

(i) If G is abelian, then $C_U^*(G)$ is also abelian (commutative). In particular, C_λ^* is abelian. Later, we will prove $C_\lambda^*(G) \simeq C(\hat{G})$ where $\hat{G}$ is the dual of G, i.e. $\{X : G \to \mathbb{C} \text{ characters}\}$.

(ii) For many groups, like $G = \mathbb{F}_n$ (the free groups) the reduced C^*-algebra $C_\lambda^*(G)$ is simple.

4 Homomorphisms of algebras

Definition 4.1 *If $\mathscr{A}, \mathscr{B}$ are algebras, a **homomorphism** from $\mathscr{A}$ to $\mathscr{B}$ is a linear map $\varphi : \mathscr{A} \to \mathscr{B}$ such that $\varphi(ab) = \varphi(a)\varphi(b)$ for any $a, b \in \mathscr{A}$.*

*If $\mathscr{A}$ and $\mathscr{B}$ are *-algebras, a ***-homomorphism** is a homomorphism $\varphi : \mathscr{A} \to \mathscr{B}$ such that $\varphi(a^*) = \varphi(a)^*$ for all $a \in \mathscr{A}$.*

*If $\mathscr{A}, \mathscr{B}$ are Banach algebras, then usually we want to have **continuous** homomorphisms. Even more, we usually ask for **contractive** homomorphisms $\varphi : \mathscr{A} \to \mathscr{B}$, (that is $\|\varphi\| \leq 1$).*

We will be especially interested in **characters**:

Definition 4.2 *A **character** of an algebra $\mathscr{A}$ is a non-zero homomorphism $\chi : \mathscr{A} \to \mathbb{C}$.*

Example 4.3 Take any subalgebra $\mathscr{A} \subseteq \mathbb{C}^X$. Take $x_0 \in X$ and set $\chi_{x_0} := \mathrm{ev}_{x_0} : \mathscr{A} \to \mathbb{C}, f \mapsto f(x_0)$. This is not necessarily a character, but it is for example, if $\mathscr{A} = C(X)$ or $C_b(X)$ or $C_0(X)$ (if X is "nice", like Hausdorff).

Definition 4.4 *A (*)-isomorphism between two (*)-algebras $\mathscr{A}$ and $\mathscr{B}$ is a bijective (*)- homomorphism $\varphi : \mathscr{A} \xrightarrow{\sim} \mathscr{B}$.*

Definition 4.5 *A (*)**-ideal** of a *-algebra $\mathscr{A}$ is a subspace $I \subset A$ such that $I \cdot A \subseteq I$, $A \cdot I \subseteq I$ (if only one condition applies, we call this a **left ideal** or **right ideal**). For *-ideals, we also want $I^* = I$. We notate this as $I \trianglelefteq \mathscr{A}$.*

Example 4.6 If $\varphi : \mathscr{A} \to \mathscr{B}$ is a (*)-homomorphism, then $\ker\varphi \trianglelefteq \mathscr{A}$.

Example 4.7 If $I \trianglelefteq \mathscr{A}$ for $\mathscr{A}$ a (*)-algebra

$$\mathscr{A}/I = \{a + I \mid a \in \mathscr{A}\}$$

with $(a + I) \cdot (b + I) := ab + I$ and $(a + I)^* = a^* + I$ is a (*)-algebra.

Theorem 4.8 *If $\mathscr{A}$ is a Banach-*-algebra, then $I \trianglelefteq \mathscr{A}$ is a closed ideal, then the quotient $I/\mathscr{A}$ is also a Banach-*-algebra.*

Proof: Later. □

5 Spectral theory

Notation 5.1 If $\mathscr{A}$ is a unital algebra, we write

$$\mathrm{inv}(\mathscr{A}) = \{a \in \mathscr{A} \mid a \text{ is invertible in } \mathscr{A}\} = \{a \in \mathscr{A} \mid \exists_{a^{-1} \in \mathscr{A}} aa^{-1} = 1 = a^{-1}a\}$$

This is a group. Sometimes we also write $GL(\mathscr{A})$.

Definition 5.2 *Given a unital algebra $\mathscr{A}$ and $a \in \mathscr{A}$, we define its **spectrum** (in $\mathscr{A}$) as*

$$\sigma_{\mathscr{A}}(a) = \sigma(a) = \{\lambda \in \mathbb{C} \mid \lambda \cdot 1 - a \notin \mathrm{inv}(\mathscr{A})\}$$

and the resolvent of a (in $\mathscr{A}$) as

$$\rho_{\mathscr{A}}(a) = \rho(a) = \mathscr{A} \setminus \sigma_{\mathscr{A}}(a) = \{\lambda \in \mathbb{C} \mid \lambda - a \in \mathrm{inv}(\mathscr{A})\}$$

Example 5.3 (Linear Algebra) Let $\mathscr{A} = M_m(\mathbb{C})$ and $a \in \mathscr{A}$. Then we have

$$\sigma(a) = \{\lambda \in \mathbb{C} \mid \lambda - a \notin \mathrm{inv}(\mathscr{A})\} = \{\lambda \in \mathbb{C} \mid \det(\lambda - a) = 0\}$$

and these are the roots of the characteristic polynomial $\det(\lambda - a)$. This is exactly the usual spectrum from linear algebra.

Example 5.4 (Functional Analysis) Let $\mathscr{A} = \mathscr{L}(\mathfrak{H})$ – where $\mathfrak{H}$ is any Hilbert- or Banach space – and $T \in \mathscr{A}$. Then $\sigma_{\mathscr{A}}(T)$ is exactly the spectrum as defined in functional analysis.
If S is the shift in $\mathscr{L}(\ell^2\mathbb{N})$, then we have $\sigma(S) = \mathbb{D}$.

Example 5.5 Let $\mathscr{A} = \mathbb{C}[X]$. Here we have $\mathrm{inv}(\mathscr{A}) = \{a_0 X^0 \mid a_0 \in \mathbb{C} \setminus \{0\}\}$ the constant non-zero polynomials. If $a = \sum_{k=0}^{N} a_k x^k \in \mathscr{A}$, then we have two cases:

$$\sigma(a) = \begin{cases} \{a_0\} & a = a_0 \text{ (const.)} \\ \mathbb{C} & \text{otherwise} \end{cases}$$

Example 5.6 Let $\mathscr{A} = \mathbb{C}(X) = \{p, q \mid p, q \in \mathbb{C}[X], q \neq 0\}$. Now we have $\mathrm{inv}(\mathscr{A}) = \mathscr{A} \setminus \{0\}$. If $a \in \mathscr{A}$, then

$$\sigma(a) = \begin{cases} \{a_0\} & a = a_0 \text{ (const.)} \\ \emptyset & \text{otherwise} \end{cases}$$

Example 5.7 Let $\mathscr{A} = C(X)$ for any topological space X. Then

$$\mathrm{inv}(\mathscr{A}) = \{f \in C(X) \mid \forall_{x \in X} f(x) \neq 0\}$$

and

$$\sigma(f) = \{\lambda \in \mathbb{C} \mid \lambda - f \notin \mathrm{inv}(\mathscr{A})\} = \{\lambda \in \mathbb{C} \mid \exists_{x \in X} f(x) = \lambda\} = \mathrm{im}(f) = f(X).$$

Example 5.8 Let X be any topological space and consider $\mathscr{A} = C_b(X)$. Then

$$\mathrm{inv}(C_b(X)) = \{f \in C_b(X) \mid \exists_{\varepsilon > 0} \forall_{x \in X} |f(x)| \geq \varepsilon\}$$

and

$$\sigma(f) = \{\lambda \in \mathbb{C} \mid \lambda - f \in \mathrm{inv}(\mathscr{A})\} = \{\lambda \in \mathbb{C} \mid \exists_{(x_n)} f(x_n) \to \lambda\} = \overline{\mathrm{im}(f)} = \overline{f(X)}.$$

This is a compact subset of $\mathbb{C}$.

Theorem 5.9 (Algebraic spectral mapping theorem) *Let $\mathscr{A}$ be an algebra, $a \in \mathscr{A}$ and $p \in \mathbb{C}[X], p(X) = \sum_{k=0}^{n} \lambda_k X^k$ and define $p(a) = \sum_{k=0}^{n} \lambda_k a^k$. Recall that the mapping $\mathbb{C}[X] \to \mathscr{A}, p \mapsto p(a)$ is a unital homomorphism.*

Then $\sigma(p(a)) = p(\sigma(a))$ assuming $\sigma(a) \neq \emptyset$.

PROOF: If $p(X) = \lambda_0$ constant, this is clear (the spectrum is exactly λ_0 on both sides). Assume $p(x)$ is not constant. Fix $\mu \in \mathbb{C}$ and write

$$\mu - p(x) = \lambda_0(x - \lambda_1) \cdots (x - \lambda_n)$$

as per the fundamental theorem of algebra (note that these are not the same λ as before) with $\lambda_0 \neq 0$. Then $\mu - p(a) = \lambda_0(a - \lambda_1) \cdots (a - \lambda_n)$. Since these expressions commute, this product is invertible if and only if $(a - \lambda_i)$ is invertible for every i. So $\mu \in \sigma(p(a)) \Leftrightarrow \mu - p(a)$ is not invertible if and only if there exists an i for which $\lambda_i - a$ is not invertible, so $\lambda_i \in \sigma(a)$. But the λ_i are exactly the numbers satisfying $p(\lambda) = \mu$. Thus, μ is in $\sigma(p(a))$ if it is in the image of $\sigma(a)$ under p. Therefore, we conclude $\sigma(p(a)) = p(\sigma(a))$. $\square$

We now focus on invertible elements in **Banach algebras**.

Theorem 5.10 *If $\mathscr{A}$ is a unital Banach algebra and $a \in \mathscr{A}$ with $\|a\| < 1$ then $1 - a$ is invertible and $(1-a)^{-1} = \sum_{n=0}^{\infty} a^n$.*

PROOF: Observe that, since $\|a\| < 1$, we have $\sum_{n=0}^{\infty} \|a\|^n = \frac{1}{1-\|a\|} < \infty$. This implies the (absolute) convergence of $\sum_{n=0}^{\infty}$ by the characteristic property of Banach spaces. Hence $b := \lim_{N\to\infty} \sum_{n=0}^{N} a^n \in \mathscr{A}$. No, if $N \in \mathbb{N}$, then

$$(1-a)\left(\sum_{n=0}^{N} a^n\right) = \left(\sum_{n=0}^{N} a^n\right) - \left(\sum_{n=1}^{N+1} a^n\right) = 1 - a^{N+1} \to 1$$

because of $\|a\| < 1$. This yields $(1-a)b = 1$. $\square$

Theorem 5.11 *Let $\mathscr{A}$ be a non-empty, non-zero unital Banach algebra. Then* $\mathrm{inv}(\mathscr{A})$ *is an open subset of $\mathscr{A}$ and the function $f : \mathrm{inv}(\mathscr{A}) \to \mathscr{A}, a \mapsto a^{-1}$ is Frechet-differentiable and in particular continuous as well as $f'(a)b = -a^{-1}ba^{-1}$.*

Recall from calculus that $\frac{d}{dx}\frac{1}{x} = -\frac{1}{x^2}$. Also recall that $f : U \overset{\text{open}}{\subseteq} X \to Y$ with X, Y Banach spaces is **differentiable** at $x_0 \in U$ there exists an operator $D_{x_0} = f'(x_0) \in \mathscr{L}(X, Y)$ such that

$$\lim_{h\to 0} \frac{f\|(x_0 + h) - f(x_0) - D_{x_0}(h)\|}{\|h\|} = 0$$

PROOF: Take $a \in \mathrm{inv}(\mathscr{A})$. If $b \in \mathscr{A}$ such that $\|a - b\| < \|a^{-1}\|^{-1}$. From this, we have $\|ba^{-1} - 1\| = \|ba^{-1} - aa^{-1}\| = \|(b-a)a^{-1}\| \leq \|b - a\| \cdot \|a^{-1}\| < 1$. Per the previous theorem, $ba^{-1} \in \mathrm{inv}(\mathscr{A})$. This implies that b is also invertible. This shows that $\mathrm{inv}(\mathscr{A})$ is open.

Furthermore, if $\|b\| < 1$, then also $(\| - b\| < 1)$. Thus, $1 + b \in \mathrm{inv}(\mathscr{A})$ and $(1+b)^{-1} = \sum_{n=0}^{\infty}(-1)^n b^n$. Thus

$$\|(1+b)^{-1} - 1 + b\| = \left\|\sum_{n=0}^{\infty}(-1)^n b^n - 1 + b\right\| \leq \left\|\sum_{n=2}^{\infty}(-1)^n b^n\right\| \leq \sum_{n=2}^{\infty} \|b^n\| \leq \sum_{n=2}^{\infty} \|b\|^n = \frac{\|b\|^2}{1 - \|b\|}$$

Now let $a \in \inf(\mathscr{A})$ and $c \in \mathscr{A}$ such that $\|c\| < \frac{1}{2}\|a^{-1}\|^{-1}$. Then $\|a^{-}1c\| \leq \|a^{-1}\|\|c\| \leq \frac{1}{2}$. So if $b = a^{-1}$, then

$$\|(1 + a^{-1}c)^{-1} - 1 + a^{-1}c\| =\leq \frac{\|a^{-1}c\|^2}{1 = \|a^{-1}c\|} < 2\|a^{-1}c\|^2$$

Now, define $U : \mathscr{A} \to \mathscr{A}, b \mapsto -a^{-1}ba^{-1}$. Then this is a linear odd operation with $\|U\| \leq \|a^{-1}\|^2$ and we have

$$\begin{aligned}
\|(a + c)^{-1} - a^{-1} - U(c)\| &= \|(a + c)^{-1} - a^{-1} + a^{-1}ca^{-1}\| \\
&= \|(1 + a^{-1}c)^{-1}a^{-1} - a^{-1} + a^{-1}ca^{-1}\| \\
&\leq \|(1 + a^{-1}c)^{-1} - 1 + a^{-1}c\| \cdot \|a^{-1}\| \\
&\leq 2\|a^{-1}c\|^2\|a^{-1}\| \leq 2\|a^{-1}\|^3\|c\|^2
\end{aligned}$$

and thus

$$\lim_{c \to 0} \frac{\|(a + c)^{-1} - a^{-1} - U(c)\|}{\|c\|} = 0$$

□

Example 5.12 If we choose $\mathscr{A} = \mathbb{C}[X]$ and the norm $\|p\| = \sup_{\lambda \in [0,1]} |p(x)|$. Then $(\mathscr{A}, \|\cdot\|)$ is a normed (but not Banach) algebra. For example, we see that $\lim_{m \to 0} 1 + X/m = 1 \in \text{inv}(\mathscr{A})$, but $1 + X/m \notin \text{inv}(\mathscr{A})$ and thus $\text{inv}(\mathscr{A})$ is not open (because the complement is not closed).