

Introduction to Operator Algebras

Alcides Buss

Notes by: Linus Mußmächer

2336440

Summer 2023

Contents

1	Algebras	4
2	Normed algebras	5
3	Algebras	6
4	Homomorphisms of algebras	8
5	Spectral theory	9

The set of all linear bounded operators $\mathcal{L}(H) = \mathcal{B}(H)$ on a given Banach space H is a (Banach) algebra with $S \cdot T = S \circ T$. $M \subseteq \mathcal{L}$ is 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 $X \subseteq \mathcal{B}(H)$, $X' = \{T \in \mathcal{B}(H) \mid TS = ST \ \forall S \in X\}$)

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 \bar{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 $f : X \rightarrow [0, 1]$ 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 $f : K \rightarrow \mathbb{C}$ continuous. Then there exists a continuous $\tilde{f} : X \rightarrow \mathbb{C}$ such that $\tilde{f}|_K = f$.

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

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 $y_0 \in Y$, $X := Y \setminus \{y_0\}$ 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 \mathcal{A} endowed with a bilinear and associative multiplication: $\mathcal{A} \times \mathcal{A} \rightarrow \mathcal{A}, (a, b) \mapsto a \cdot b$. 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 $a, b, c \in \mathcal{A}$ and $\alpha, \beta \in \mathbb{C}$. We say that \mathcal{A} is

- (i) **commutative**, if $ab = ba$ for all $a, b \in \mathcal{A}$ and
- (ii) **unital**, if there exists $1 = 1_{\mathcal{A}} \in \mathcal{A}$ such that $1 \cdot a = a \cdot 1 = a$ for all $a \in \mathcal{A}$.

Example 1.2

- (i) \mathbb{C} , or more generally $\mathbb{C}^n = \mathbb{C} \oplus \dots \oplus \mathbb{C}$, is an algebra.
- (ii) Say X is any set; let $\mathbb{C}^X = \{f : X \rightarrow \mathbb{C}\}$ with point wise 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 usual operations. This is a commutative unital algebra.
- (iv) Let X be a topological space and $C(X) = \{f : X \rightarrow \mathbb{C} \mid f \text{ is continuous}\} \subseteq \mathbb{C}^X$ 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 $a \cdot b := 0$. 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 $L(V) := \{T : V \rightarrow V \mid T \text{ linear operator}\}$ is a unital (non-commutative for $\dim V > 1$). We observe $\mathcal{L}(\mathbb{C}^n) \simeq M_n(\mathbb{C})$.
- (viii) Let S be a semigroup (i.e. a set with an associative operation $S \times S \rightarrow S$, 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 \mathcal{A} is **normed**, if it is endowed with a (vector space) norm $\|\cdot\|: \mathcal{A} \rightarrow [0, \infty)$ satisfying $\|a \cdot b\| \leq \|a\| \cdot \|b\|$. If \mathcal{A} is unital with unit $1_{\mathcal{A}}$, we usually assume $\|1_{\mathcal{A}}\| = 1$ except for $\mathcal{A} = 0$.

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 $\mathcal{L}(V) = \{T \in L(V) \mid T \text{ is bounded/continuous}\}$ 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 $\{x \mid |f(x)| \geq \varepsilon\}$) 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 \mathcal{A} with an *involution* $*$: $\mathcal{A} \rightarrow \mathcal{A}$ satisfying

- (i) $(a + \lambda b)^* = a^* + \bar{\lambda}b^*$
- (ii) $(a^*)^* = a$
- (iii) $(ab)^* = b^*a^*$

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

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

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

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

is also a C*-algebra.

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

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

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 piece wise smooth paths in \mathbb{D}° . From this, it follows that $\mathcal{A}(\mathbb{D})$ is closed in $C(\mathbb{D})$, therefore a Banach algebra. It is also a Banach-*-algebra with, but $f^* = \bar{f}$ (point wise) is not possible, as $z \mapsto \bar{z}$ is not analytic. Thus, we have to choose $f^*(z) = f(\bar{z})$. But $\mathcal{A}(\mathbb{D})$ is not a C*-algebra, as $\|f^*f\|_\infty \neq \|f\|_\infty^2$ for some $f \in \mathcal{A}(\mathbb{D})$.

- (v) A non-commutative example: Let H be a Hilbert space and $B(H) = \mathcal{L}(H) = \{T : H \rightarrow H \mid T \text{ bounded, continuous, linear}\}$ and $\|H\| := \sup_{\|z\| < 1} \|T(z)\| < \infty$. 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 $\mathcal{L}(H)$ 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, $M_n(\mathbb{C}) \simeq \mathcal{L}(\mathbb{C}^n)$ is a unital C^* -algebra.

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

Example 3.5 Let $s \in \mathcal{L}(\ell^2(\mathbb{N}))$. 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 $s^* \cdot s = \text{id}$. Since $s \cdot s^* \neq \text{id}$, it is not surjective and not a proper isometry. We define

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

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

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

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 $S_1, S_2 \in \mathcal{L}(\mathfrak{H})$, that is $S_i^* S_i = \text{id}_{\mathfrak{H}}$, to subspaces of \mathfrak{H} . Notice: $S_i^* S_j = 0$ for $i \neq j$ as well as $S_1 S_1^* + S_2 S_2^* = \text{id}_{\mathfrak{H}}$. Define $\mathcal{O}_2 = C^*(S_1, S_2) = \overline{\text{span}\{S_\alpha S_\beta^* \mid \alpha, \beta \text{ finite words in } \{1, 2\}\}}$. 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 $\mathcal{O}_3, \mathcal{O}_4, \dots$ 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 $A_\theta := C^*(U, V) \subseteq \mathcal{L}(\ell^2\mathbb{N})$.

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 $A_\theta = \overline{\text{span}}\{\sum_{n,m \in \mathbb{Z}}^{\text{finite}} a_{n,m} U^n V^m \mid a_{n,m} \in \mathbb{C}\}$.

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 $\lambda_g \in \mathcal{L}(\ell^2 G)$ 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:

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

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 $U : G \rightarrow \mathcal{L}(H), g \mapsto U_g$ a **unitary representation of G** with $U_g U_h = U_{gh}$ and $U_1 = \text{id}$ as well as $U_g^{-1} = U_{g^{-1}}$. Then $C_U^*(G) := \{\sum_{g \in G} a_g U_g \mid a_g \in \mathbb{C}\} \subseteq \mathcal{L}(H)$. 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. $\{X : G \rightarrow \mathbb{C} \text{ characters}\}$.
- (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 \mathcal{A}, \mathcal{B} are algebras, a **homomorphism** from \mathcal{A} to \mathcal{B} is a linear map $\varphi : \mathcal{A} \rightarrow \mathcal{B}$ such that $\varphi(ab) = \varphi(a)\varphi(b)$ for any $a, b \in \mathcal{A}$.

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

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

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

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

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

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

Definition 4.5 A $(*)$ -ideal of a $*$ -algebra \mathcal{A} is a subspace $I \subset \mathcal{A}$ such that $I \cdot \mathcal{A} \subseteq I, \mathcal{A} \cdot I \subseteq I$ (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 $I \trianglelefteq \mathcal{A}$.

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

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

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

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

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

PROOF: Later. □

5 Spectral theory

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

$$\text{inv}(\mathcal{A}) = \{a \in \mathcal{A} \mid a \text{ is invertible in } \mathcal{A}\} = \{a \in \mathcal{A} \mid \exists a^{-1} \in \mathcal{A} aa^{-1} = 1 = a^{-1}a\}$$

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

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

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

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

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

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

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

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 $\mathcal{A} = \mathcal{L}(\mathfrak{H})$ – where \mathfrak{H} is any Hilbert- or Banach space – and $T \in \mathcal{A}$. Then $\sigma_{\mathcal{A}}(T)$ is exactly the spectrum as defined in functional analysis.

If S is the shift in $\mathcal{L}(\ell^2\mathbb{N})$, then we have $\sigma(S) = \mathbb{D}$.

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

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

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

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

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

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

and

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

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

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

and

$$\sigma(f) = \{\lambda \in \mathbb{C} \mid \lambda - f \in \text{inv}(\mathcal{A})\} = \{\lambda \in \mathbb{C} \mid \exists_{(x_n)} f(x_n) \rightarrow \lambda\} = \overline{\text{im}(f)} = \overline{f(X)}.$$

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

Theorem 5.9 (Algebraic spectral mapping theorem) *Let \mathcal{A} be an algebra, $a \in \mathcal{A}$ 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 $\mathbb{C}[X] \rightarrow \mathcal{A}$, $p \mapsto p(a)$ 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 \mathcal{A} is a unital Banach algebra and $a \in \mathcal{A}$ 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 $\sum_{n=0}^{\infty} a^n$ by the characteristic property of Banach spaces. Hence, $b := \lim_{N \rightarrow \infty} \sum_{n=0}^N a^n \in \mathcal{A}$. No, if $N \in \mathbb{N}$, then

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

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

Theorem 5.11 *Let \mathcal{A} be a non-empty, non-zero unital Banach algebra. Then $\text{inv}(\mathcal{A})$ is an open subset of \mathcal{A} and the function $f : \text{inv}(\mathcal{A}) \rightarrow \mathcal{A}$, $a \mapsto a^{-1}$ 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 $f : U \xrightarrow{\text{open}} X \rightarrow Y$ with X, Y Banach spaces is **differentiable** at $x_0 \in U$ there exists an operator $D_{x_0} = f'(x_0) \in \mathcal{L}(X, Y)$ such that

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

PROOF: Take $a \in \text{inv}(\mathcal{A})$. If $b \in \mathcal{A}$ 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, $ba^{-1} \in \text{inv}(\mathcal{A})$. This implies that b is also invertible. This shows that $\text{inv}(\mathcal{A})$ is open.

Furthermore, if $\|b\| < 1$, then also $\| -b \| < 1$. Thus, $1 + b \in \text{inv}(\mathcal{A})$ 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 $a \in \text{inv}(\mathcal{A})$ and $c \in \mathcal{A}$ such that $\|c\| < \frac{1}{2} \|a^{-1}\|^{-1}$. Then $\|a^{-1}c\| \leq \|a^{-1}\| \|c\| \leq \frac{1}{2}$. So if $b = a^{-1}c$, 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 $U : \mathcal{A} \rightarrow \mathcal{A}, b \mapsto -a^{-1}ba^{-1}$. 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

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

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

Theorem 5.13 *If \mathcal{A} is a Banach algebra with unit 1, then for all $a \in \mathcal{A}$ the spectrum $\sigma(a) \subseteq \mathbb{C}$ is closed and $\sigma(a) \subseteq \overline{B(0, \|a\|)} = D(0, \|a\|) := \{\lambda \in \mathbb{C} \mid |\lambda| \leq \|a\|\}$. Therefore, $\sigma(a)$ is compact by the Heine-Borell theorem.*

PROOF: By definition

$$\sigma(a) = \{\lambda \in \mathbb{C} \mid \lambda - a \notin \text{inv}(\mathcal{A})\}$$

is the inverse image of the closed subset $\mathcal{A} \setminus \text{inv}(\mathcal{A}) \subseteq \mathcal{A}$ by the continuous function $\lambda \mapsto \lambda - a$. Therefore, $\sigma(a)$ is closed.

Now if $|\lambda| \leq \|a\|$ then $\|\lambda^{-1}a\| < 1$. Then $1 - \lambda^{-1}a \in \text{inv}(\mathcal{A})$. Multiplying by λ yields $\lambda - a \in \text{inv}(\mathcal{A})$. Thus, $\{\lambda \in \mathbb{C} \mid |\lambda| > \|a\|\} \subseteq \rho(a)$ and thus $\sigma(a) \subseteq D(0, \|a\|)$. \square

Lemma 5.14 *Let \mathcal{A} be a unital Banach algebra and $a \in \mathcal{A}$. Then, the map $R_a : \rho(a) \subseteq \mathbb{C} \rightarrow \mathcal{A}, \lambda \mapsto (a - \lambda)^{-1}$ is Frechet-differentiable.*

PROOF: This follows from the following general result:

If $g : U \xrightarrow{\text{open}} X \rightarrow Y$ and $f : V \xrightarrow{\text{open}} Y \rightarrow Z$ for Banach spaces X, Y, Z with $g(U) \subseteq V$ are differentiable at $x_0 \in U$ or respectively $y_0 = g(x_0) \in V$, then $f \circ g$ is differentiable and $(f \circ g)'(x_0) = f'(g(x_0))g'(x_0)$. \square

Observation: For $R_a(\lambda) = (a - \lambda)^{-1}$ we get $R'_a(\lambda) = (a - \lambda)^{-2}$. We have $\mathcal{L}(\mathbb{C}, \mathcal{A}) \simeq \mathcal{A}$ by $T \mapsto T(1)$. Recall that if $f(a) = a^{-1}$ yields $f'(a)b = -a^{-1}ba^{-1}$.

Theorem 5.15 (Gelfand) *If $\mathcal{A} \neq 0$ is a unital Banach algebra and $a \in \mathcal{A}$ then $\sigma(a) \neq \emptyset$.*

PROOF: Suppose $\sigma(a) = \emptyset$. Idea: Show that $R_a : \rho(a) \subseteq \mathbb{C} \rightarrow \mathcal{A}, \lambda \mapsto (a - \lambda)^{-1} = \frac{1}{a - \lambda}$ is bounded and differentiable and achieve a contradiction by Liouville's theorem.

Claim: $\|(a - \lambda)^{-1}\| < \|a\|^{-1}$ if $|\lambda| > 2\|a\|$. Indeed, if $|\lambda| > 2\|a\|$ then $\|\lambda^{-1}a\| < \frac{1}{2}$, and in particular $1 - \lambda^{-1}a \in \text{inv}(\mathcal{A})$ and

$$\|(1 - \lambda^{-1}a)^{-1} - 1\| = \left\| \sum_{n=1}^{\infty} (\lambda^{-1}a)^{-1} \right\| \leq \sum_{n=1}^{\infty} \|\lambda^{-1}a\|^n = \frac{\|\lambda^{-1}a\|}{1 - \|\lambda^{-1}a\|} \leq 2\|\lambda^{-1}a\| < 1.$$

From here we deduce that $\|(1 - \lambda^{-1}a)^{-1}\| < 2$ and thus

$$\|(a - \lambda)^{-1}\| < \|\lambda^{-1}(\lambda^{-1}a - 1)^{-1}\| = \frac{\|(1 - \lambda^{-1}a)^{-1}\|}{|\lambda|} < \frac{2}{\lambda} < \frac{1}{\|\lambda\|}.$$

So $R_a : \mathbb{C} \rightarrow \mathcal{A}$ is bounded outside $\overline{B(0, 2\|a\|)}$. Since R_a is continuous, it is bounded on $\mathbb{C} \rightarrow \mathcal{A}$. Let $\varphi \in \mathcal{A}^*$ be a bounded linear functional in $\mathcal{L}(\mathcal{A}, \mathbb{C})$. Thus, φ is differentiable with $\varphi'(a) = \varphi$ for all $a \in \mathcal{A}$. Then $\varphi \circ R_a$ is differentiable and bounded, so it is an “integer” function. By Liouville's theorem, $\varphi \circ R_a$ is constant. Therefore, $\varphi \circ R_a(x) = \varphi \circ R_a(y)$ for all $x, y \in \mathcal{A}$. Especially, we have $\varphi((a - \lambda)^{-1}) = \varphi(a^{-1})$ for all φ . Hahn-Banach shows $(a - \lambda)^{-1} = a^{-1}$ for all λ , proving $a - \lambda = a$ for all a, λ . This is a contradiction. \square

Theorem 5.16 (Gelfand-Mazur) *If \mathcal{A} is a unital Banach algebra and every $a \neq 0$ admits an inverse (\mathcal{A} is a field), then $\mathcal{A} = \mathbb{C} \cdot 1$.*

PROOF: By the assumption, $\text{inv}(\mathcal{A}) = \mathcal{A} \setminus \{0\}$. By the previous theorem, if $a \in \mathcal{A}$ there exists some $\lambda \in \sigma(a)$, so $a - \lambda \notin \text{inv}(\mathcal{A})$, so $a - \lambda = 0$ and thus $a = \lambda \cdot 1$. \square

Corollary 5.17 *Let $\mathbb{C}(X) = \left\{ \frac{p(x)}{q(x)} \mid p(x), q(x) \in \mathbb{Q}[X] \right\}$ is a field, but it cannot be turned into a Banach algebra.*

Theorem 5.18 (Adjoining units - unitization of algebras) *Let \mathcal{A} be any algebra. Consider $\tilde{\mathcal{A}} = \mathcal{A} \oplus \mathbb{C}$ as a vector space. We write elements of $\tilde{\mathcal{A}}$ as $a + \lambda \cdot 1 := (a, \lambda)$. Think of $a = (a, 0)$ and $\lambda = (0, \lambda)$. Define*

$$(a + \lambda 1)(b + \lambda' 1) = (ab + \lambda' a + \lambda ab + b) + \lambda \cdot \lambda'.$$

Ten (exercise $\tilde{\mathcal{A}}$) becomes a unital algebra with $1_{\tilde{\mathcal{A}}} = 1 = (0, 1)$.

Notice that \mathcal{A} is an ideal in $\tilde{\mathcal{A}}$.

Moreover, we get a short exact sequence

$$0 \rightarrow \mathcal{A} \hookrightarrow \tilde{\mathcal{A}} \rightarrow \mathbb{C} \rightarrow 0$$

so $1 + \lambda \mapsto \lambda$.

If \mathcal{A} is a normed algebra, then $\tilde{\mathcal{A}}$ is normed by $\|a + \lambda \cdot 1\| := \|a\| + |\lambda|$

If \mathcal{A} is Banach and closed, then so is $\tilde{\mathcal{A}}$.

If \mathcal{A} is a $*$ -algebra, then so is $\tilde{\mathcal{A}}$ with $(a + \lambda 1)^*$.

If \mathcal{A} is a (Banach) normed $*$ -algebra, then so is $\tilde{\mathcal{A}}$.

If \mathcal{A} is a C^* -algebra, in general the norm given above is not a Norm on \mathcal{A} , but $\|a + \lambda \cdot 1\| := \sup_{b \in \mathcal{A}, b \in \mathcal{B}, b \leq 1} \|ab + \lambda b\|$ is.

Exercise 5.1 If \mathcal{A} is already unital, then $\tilde{\mathcal{A}} \simeq \mathcal{A} \oplus \mathbb{C}$ as algebras by $a + \lambda \cdot 1 \mapsto (a + \lambda 1_{\mathcal{A}}, -\lambda)$.

Definition 5.19 If \mathcal{A} is any algebra, then $\sigma(a) := \sigma_{\tilde{\mathcal{A}}}(a) = \sigma_{\tilde{\mathcal{A}}}(a, 0)$. Thus, we can identify $\mathcal{A} \hookrightarrow \tilde{\mathcal{A}}$.

Corollary 5.20

- (i) If \mathcal{A} is any algebra, then we always have $0 \in \sigma_{\mathcal{A}}(a)$ because if $a \in \mathcal{A}$ then $a \notin \text{inv}(\tilde{\mathcal{A}})$ as $\mathcal{A} \not\subseteq \tilde{\mathcal{A}}$.
- (ii) If \mathcal{A} is already unital, then $a \in \mathcal{A}$, then $\sigma_{\mathcal{A}}(a) = \sigma_{\tilde{\mathcal{A}}}(a)$. From 5.1 we know that $a - \lambda \cdot 1 \in \text{inv}(\tilde{\mathcal{A}})$ if and only if $a - \lambda 1_{\mathcal{A}} \in \text{inv}(\mathcal{A})$ and $\lambda(1 - 1_{\mathcal{A}}) \in \text{inv}(\mathbb{C})$. Then $\rho_{\mathcal{A}} = \{\lambda \in \rho_{\tilde{\mathcal{A}}} \mid \lambda \neq 0\}$. Therefore, $\sigma_{\mathcal{A}}(a) = \{0\} \cup \sigma_{\tilde{\mathcal{A}}}(a)$.