

Spectral Theorem For Unbounded Operators

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Geboren am 2. August 1992 in Engelskirchen

May 25, 2015

Bachelorarbeit Mathematik

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Zweitgutachter: ???

MATHEMATISCHES INSTITUT

MATHEMATISCH-NATURWISSENSCHAFTLICHE FAKULTÄT DER
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1 Preliminaries

In this section, I want to state a few theorems and definitions, which will be used later on. If no proof is given, a reference will be stated nevertheless. For an algebra \mathfrak{A} , we denote the invertible elements by $\mathbf{GL}(\mathfrak{A})$.

Definition 1.1 (Spectrum). Let \mathfrak{A} be a unital commutative Banach algebra. For A an element of \mathfrak{A} , the *spectrum* of A in \mathfrak{A} , is defined as

$$\mathrm{Sp}_{\mathfrak{A}}(A) := \{z \in \mathbb{C} \mid A - zI \notin \mathbf{GL}(\mathfrak{A})\}.$$

The *spectrum* of \mathfrak{A} is defined as

$$\mathrm{Sp}(\mathfrak{A}) := \{\chi : \mathfrak{A} \rightarrow \mathbb{C} \mid \chi \in \mathrm{Hom}_{\mathbb{C}\text{-Alg}}(\mathfrak{A}, \mathbb{C}), \chi \neq 0\}.$$

Proposition 1.2. *Using the notation above,*

$$\mathrm{Sp}_{\mathfrak{A}}(A) = \{\chi(A) \mid \chi \in \mathrm{Sp} \mathfrak{A}\}.$$

In other words, the spectrum of an element is the image of that element, under the spectrum of the algebra.

The proof can be found in [4, Ch. 4.2]. By \mathfrak{A}' we denote the dual space $\mathrm{Hom}_{\mathbb{C}}(\mathfrak{A}, \mathbb{C})$, endowed with the weak-* topology.

Theorem 1.3 (Gelfand–Naimark). *Let \mathfrak{A} be a commutative C^* -algebra. If $\mathrm{Sp}(\mathfrak{A})$ is equipped with the subspace topology of \mathfrak{A}' , it becomes a compact space, with a canonical isometric, involutive, surjective algebra homomorphism*

$$\mathcal{G} : \mathfrak{A} \rightarrow C(\mathrm{Sp}(\mathfrak{A})), \quad A \mapsto (\hat{A} := \mathcal{G}(A) : \mathrm{Sp}(\mathfrak{A}) \rightarrow \mathbb{C}, \quad \gamma \mapsto \gamma(A)).$$

The proof can be found in [4, Ch. 4.3]. The map in the theorem is the so called Gelfandtransform.

The reader not familiar with closed operators is advised to revisit the basic definitions found in [1, Ch. 10]. All operators are assumed to be linear. Let T be a operator on some Hilbert space \mathcal{H} . We will adopt the notation from [1, Ch. 10], that is T is not even assumed to be defined for any non zero element. Later on, we will only concern ourselves with densely defined, closed operators. By $\mathfrak{D}(T)$ and $\mathfrak{R}(T)$ we denote the domain and the range of the operator, respectively. The set of bounded linear operators will be called $\mathcal{B}(\mathcal{H})$ in, contrast to $\mathcal{L}(\mathcal{H})$, which is the set of all linear operators. The set of closed operators is denoted by $\mathcal{C}(\mathcal{H})$.

Definition 1.4. If T and S are operators on \mathcal{H} , we say T *extends* S , if $\mathfrak{D}(S) \subset \mathfrak{D}(T)$ and $Tx = Sx$ for all x in $\mathfrak{D}(S)$. We write $S \subset T$.

Let S and T be operators on \mathcal{H} . By $S + T$, we denote the operator with domain $\mathfrak{D}(S) \cap \mathfrak{D}(T)$ and rule $(S + T)x = Sx + Tx$. Note that this does not give $\mathcal{L}(\mathcal{H})$ the structure of a vector space, for $(S + T) - T \neq S$ since $\mathfrak{D}(T) \cap \mathfrak{D}(S) \neq \mathfrak{D}(S)$. TS is defined to be the operator with domain $S^{-1}\mathfrak{D}(T)$. The reader should be aware, that with the just defined operations, $\mathcal{L}(\mathcal{H})$ does not admit the structure of an algebra, and as previously remarked, not even that of a vector space. This is one of the reasons, why one has to be careful while working with unbounded operators.

Since closed operators are not defined on all of \mathcal{H} , there is no obvious definition of an inverse to such an operator. Hence, we have the following

Definition 1.5. Let T denote a closed operator on \mathcal{H} . We say that T is *boundedly invertible* if $T : \mathfrak{D}(T) \rightarrow \mathfrak{R}(T) = \mathcal{H}$ is a bijection, and $T^{-1} : \mathcal{H} \rightarrow \mathfrak{D}(T)$ is continuous.

Remark 1.6. If T is boundedly invertible, then the inverse is unique.

Lemma 1.7. *If $T \in \mathcal{C}(\mathcal{H})$, $S \in \mathcal{B}(\mathcal{H})$ and $TS = \text{id}$ then S is the bounded inverse of T .*

Proof. It remains to show that T is a bijection. Surjectivity is obvious. Note that $\ker(S) = 0$, which implies that $\ker(T) = 0$ as well. \square

2 Spectral Theorem For Bounded Operators

In this chapter, we use the Gelfandtransform to prove a continuous spectraltheorem for bounded normal operators, and some auxiliary results about the spectrum of C^* -algebras.

Proposition 2.1. *Let \mathfrak{A} be C^* -subalgebra of the C^* -algebra \mathfrak{B} . Let A be an element of \mathfrak{A} , which is invertible in \mathfrak{B} . Then A is already invertible in \mathfrak{A} . In other words*

$$\mathrm{Sp}_{\mathfrak{A}}(A) = \mathrm{Sp}_{\mathfrak{B}}(A) \text{ for all } A \text{ in } \mathfrak{A}.$$

Proof. First assume $A = A^*$. We have $\mathrm{Sp}_{\mathfrak{A}}(A) \subset \mathbb{R}$, implying that $(A + i\lambda I)$ is invertible in \mathfrak{A} , for all A in \mathfrak{A} . As

$$\lim_{\lambda \rightarrow 0} (A + i\lambda I) = A,$$

by continuity of the inverse map, and the assumption that A is invertible, we get

$$\lim_{\lambda \rightarrow 0} (A + i\lambda I)^{-1} = A^{-1}.$$

Because $(A + i\lambda I)^{-1}$ is an element of \mathfrak{A} for all $\lambda \neq 0$, the statement holds for self adjoint A , as \mathfrak{A} is a closed subalgebra.

For more general A , we consider the self adjoint element A^*A , with inverse $(A^*A)^{-1} = A^{-1}(A^{-1})^*$. Since \mathfrak{A} is an involutive algebra, A^*A is an element of \mathfrak{A} , which implies that A is left-invertible in \mathfrak{A} , with inverse $(A^*A)^{-1}A^*$. Using the same argument with the normal element AA^* , one gets the right-invertibility of A . Thus A is invertible, and the inverses coincide. \square

Corollary 2.2. *Let \mathfrak{A} be a C^* -subalgebra of $\mathcal{L}(\mathcal{H})$, $T \in \mathfrak{A}$. Then*

$$\mathrm{Sp}_{\mathfrak{A}}(T) = \mathrm{Sp}_{\mathcal{L}(\mathcal{H})}(T) = \mathrm{Sp}(T).$$

Proposition 2.3 (Functional calculus for normal elements). *Let \mathfrak{B} be a C^* -algebra with unit, and A a normal element. Then the algebra $\mathfrak{A} = \langle A, I \rangle$ generated by A and the identity I , is a normal involutive subalgebra, which is isomorphic to $C(\mathrm{Sp} A)$, where $\mathrm{Sp}(A)$ is identified with $\mathrm{Sp}(\mathfrak{A})$ via the Gelfandtransform.*

Proof. First, we show that $\mathcal{G}_A : \mathrm{Sp}(\mathfrak{A}) \rightarrow \mathbb{C}$ is injective. Let χ_1, χ_2 be elements of $\mathrm{Sp}(\mathfrak{A})$. If $\mathcal{G}_A(\chi_1) = \mathcal{G}_A(\chi_2) = \chi_2(A) = \chi_1(A)$, then also $\chi_1(A^*) = \chi_2(A^*)$. Since $\chi_1(I) = \chi_2(I) = 1$, we see that $\chi_1 = \chi_2$ on all polynomials in A and A^* . Because χ_1, χ_2 are continous, they have to coincide on \mathfrak{A} .

By Proposition 1.2, \mathcal{G}_A is surjective, and hence, \mathcal{G}_A is a continous bijection from $\mathrm{Sp}(\mathfrak{A})$ to $\mathrm{Sp}(A)$. As $\mathrm{Sp}(\mathfrak{A})$ is compact, \mathcal{G}_A is a homeomorphism. By the theorem of Gelfand–Neimark

$$\mathcal{G} : \mathfrak{A} \rightarrow C(\mathrm{Sp} \mathfrak{A})$$

is an isomorphism. We get the following commutative diagram, which yields the result

$$\begin{array}{ccc} \mathfrak{A} & \xrightarrow{B \mapsto \mathcal{G}_B} & C(\mathrm{Sp} \mathfrak{A}) \\ & \searrow^{B \mapsto \mathcal{G}_B \circ \mathcal{G}_A^{-1}} & \downarrow^{\mathcal{G}_B \mapsto \mathcal{G}_B \circ \mathcal{G}_A^{-1}} \\ & & C(\mathrm{Sp} A) \end{array}$$

□

Remark 2.4. Let $\Phi : C(\text{Sp } A) \rightarrow \mathfrak{A}$ be the inverse of the isomorphism from the previous theorem defined by $B \mapsto \mathcal{G}_B \circ \mathcal{G}_A^{-1}$.

For $f \in C(\text{Sp } A)$, we get

$$\Phi(f) = \mathcal{G}^{-1}(f \circ \mathcal{G}_A).$$

Thus, one retrieves the generators of \mathfrak{A} via

$$\begin{aligned} \Phi(1_{\text{Sp}(A)}) &= \mathcal{G}^{-1}(1_{\text{Sp}(A)} \circ \mathcal{G}_A) \\ &= \mathcal{G}^{-1}(1_{\text{Sp}(\mathfrak{A})}) \\ \Phi(\text{id}_{\text{Sp}(A)}) &= \mathcal{G}^{-1}(\text{id}_{\text{Sp}(A)} \circ \mathcal{G}_A) \\ &= \mathcal{G}^{-1}(\mathcal{G}_A) = A \\ \Phi(\overline{\text{id}}_{\text{Sp}(A)}) &= A^*. \end{aligned}$$

Φ gives us the possibility to identify functions on the closure of polynomials in z, \bar{z} on $\text{Sp}(A)$ with elements in A . By Stone-Weierstrass functions on the closure of polynomials in z, \bar{z} on $\text{Sp}(A)$ are all continuous functions on $\text{Sp}(A)$. Furthermore Φ is completely determined by its values on $1_{\text{Sp } A}$ and $\text{id}_{\text{Sp } A}$.

Example 2.5. Let $\mathfrak{B} = \mathcal{B}(\mathcal{H})$ be the space of bounded linear operators on some Hilbert space \mathcal{H} , $T \in \mathfrak{B}$ a normal element and \mathfrak{A} the C^* -algebra generated by T . $\text{Sp}(T) \subset \mathbb{C}$ is a compact subset, since T is bounded. Any entire function $f : \mathbb{C} \rightarrow \mathbb{C}$ is continuous on $\text{Sp}(A)$, and hence gives us an element $f(A) \in \mathfrak{A}$.

In general, a complex square root does not give a holomorphic function on $\text{Sp}(A)$. However for self adjoint A , we can still define a continuous square root on $\text{Sp}(A)$, as $\text{Sp } A \subset \mathbb{R}$:

$$\sqrt{\cdot} : \text{Sp}(A) \rightarrow \mathbb{C}, \quad z \mapsto \begin{cases} \sqrt{z} & \text{if } z > 0, \\ i\sqrt{-z} & \text{if } z < 0, \\ 0 & \text{if } z = 0. \end{cases}$$

Another interesting example is the absolute value. Fairly easy on the complex numbers, we now have the tools, to define it, for any normal bounded operator, using the just developed.

Proposition 2.6. *Let \mathfrak{B} be an involutive, unital Banach algebra, \mathfrak{A} a unital C^* -algebra, and let*

$$\Phi : \mathfrak{B} \rightarrow \mathfrak{A}$$

be an involutive algebra homomorphism. Then Φ is continuous and norm decreasing.

Proof. Let $B \in \mathfrak{B}$. We have

$$\text{Sp}_{\mathfrak{A}}(\Phi(B)) \subset \text{Sp}_{\mathfrak{B}}(B).$$

For the spectral radius one has

$$\rho(\Phi(B)) \leq \rho(B) \leq \|B\|.$$

And consequently

$$\begin{aligned}\|\Phi(B)\|^2 &= \|(\Phi(B))^*\Phi(B)\| \\ &= \|\Phi(B^*B)\| \\ &= \rho(\Phi(B^*B)) \leq \|B^*B\| \leq \|B\|^2.\end{aligned}$$

This gives

$$\|\Phi\| \leq 1.$$

□

Corollary 2.7. *Using the same notation as before, the isomorphism*

$$\Phi : C(\mathrm{Sp} \mathfrak{A}) \rightarrow \mathfrak{A}, f \mapsto \mathcal{G}^{-1}(f \circ \mathcal{G}_A)$$

is the only C^ -algebra homomorphism, with the property that*

$$\Phi(1_{\mathrm{Sp} A}) = I \text{ and } \Phi(\mathrm{id}_{\mathrm{Sp} A}) = A.$$

Proof. If $\Psi : C(\mathrm{Sp} A) \rightarrow \mathfrak{A}$ is another algebra homomorphism with the properties above, then $\Psi = \Phi$ on all polynomials in z and \bar{z} on $\mathrm{Sp}(A)$. We already know that both homomorphisms are continuous. Thus they must coincide on $C(\mathrm{Sp} A)$ by Stone-Weierstrass. □

3 Unbounded Operators

Since we have a functional calculus for normal bounded operators, one might hope that we can extend our results to unbounded operators. But the previous result relied on the Gelfandtransform, which in turn relied on the existence of certain structures, such as the operator being an element in an algebra. But as previously remarked, closed operators are not that nice.

One might try to associate some bounded operator B to T , apply the bounded functional calculus to B and then invert the process which gave the B . This is what we want to do now.

From now on, let $T \in \mathcal{L}(\mathcal{H})$ be a closed normal operator. We endow $\mathfrak{D}(T)$ with the graph scalar product

$$\langle x, y \rangle_T := \langle \iota x, \iota y \rangle_{\mathcal{H}} + \langle T \iota x, T \iota y \rangle_{\mathcal{H}},$$

making it a Hilbert space in itself. If there is no room for misinterpretation, we will omit the \mathcal{H} in the scalar product. The adjoint of T as a closed operator from \mathcal{H} to itself, will be called T^* . Let $\iota : \mathfrak{D}(T) \rightarrow \mathcal{H}$ be the inclusion. We have two ways to interpret this map;

1. as an operator on \mathcal{H} , namely the identity with domain $\mathfrak{D}(T)$, or
2. as a bounded linear operator $\iota : (\mathfrak{D}(T), \langle \cdot, \cdot \rangle_T) \rightarrow (\mathcal{H}, \langle \cdot, \cdot \rangle_{\mathcal{H}})$.

Using the second interpretation, we note that by $\Re(\iota^*) = \ker(\iota)^\perp$ and $\ker(\iota^*) = \Re(\iota)^\perp$, ι^* is a bijection, as $\mathfrak{D}(T)$ is dense in \mathcal{H} .

Lemma 3.1. $\mathfrak{D}(T^*T)$ is dense in $(\mathfrak{D}(T), \langle \cdot, \cdot \rangle_T)$.

Proof. We show that $\mathfrak{D}(T^*T)^{\perp_T} = 0$. Let $x \in \mathfrak{D}(T^*T)$, $y \in \mathfrak{D}(T^*T)^{\perp_T}$. Then

$$\begin{aligned} 0 &= \langle x, y \rangle_T = \langle \iota x, \iota y \rangle_{\mathcal{H}} + \langle T \iota x, T \iota y \rangle_{\mathcal{H}} \\ &= \langle \iota x, \iota y \rangle_{\mathcal{H}} + \langle T^* T \iota x, \iota y \rangle_{\mathcal{H}} = \langle (1 + T^* T) \iota x, \iota y \rangle_{\mathcal{H}}. \end{aligned}$$

Therefore, if we prove $\Re(1 + T^*T)$ is dense in \mathcal{H} , the claim is proven as well. Since $\Re(1 + T^*T)^{\perp_{\mathcal{H}}} = \ker(1 + T^*T)$, we prove injectivity of $(1 + T^*T) \in \mathcal{L}(\mathcal{H})$,

$$\begin{aligned} \|(1 + T^*T)x\|^2 &= \|x\|^2 + \|T^*Tx\|^2 + \langle x, T^*Tx \rangle + \langle T^*Tx, x \rangle \\ &= \|x\|^2 + \|T^*Tx\|^2 + 2\langle Tx, Tx \rangle \\ &= \|x\|^2 + \|T^*Tx\|^2 + 2\|Tx\|^2 \geq \|x\|^2. \end{aligned}$$

□

Proposition 3.2. $(I + T^*T)$ is boundedly invertible, with inverse ι^* .

Proof. For $x \in \mathfrak{D}(T)$, $y \in \mathcal{H}$ such that $\iota^*y \in \mathfrak{D}(T^*T)$. By definition

$$\begin{aligned} \langle \iota x, y \rangle_{\mathcal{H}} &= \langle x, \iota^*y \rangle_T = \langle \iota x, \iota^*y \rangle_{\mathcal{H}} + \langle T \iota x, T \iota^*y \rangle_{\mathcal{H}} \\ &= \langle \iota x, \iota^*y \rangle_{\mathcal{H}} + \langle \iota x, T^*T \iota^*y \rangle_{\mathcal{H}} = \langle \iota x, \iota^*y + T^*T \iota^*y \rangle_{\mathcal{H}}. \end{aligned}$$

Subtracting the left hand side, we get

$$0 = \langle \iota x, \iota^*y + T^*T \iota^*y - y \rangle.$$

Note that since ι^* is a continuous bijection and $\mathfrak{D}(T^*T) \subset \mathfrak{D}(T)$ is a dense subset of both $\mathfrak{D}(T)$ and \mathcal{H} , $(\iota^*)^{-1}(\mathfrak{D}(T^*T))$ is dense in \mathcal{H} . Since this equality holds for all $x \in \mathfrak{D}(T)$, we get

$$y = \iota^*y + T^*T\iota^*y = (1 + T^*T)\iota^*y,$$

which implies that $\iota^* = (I + T^*T)^{-1}$, as ι^* is bounded. \square

Define $A := \iota^*$ and $B := TA$. If we think of A corresponding $\frac{1}{1+|x|^2}$, then we would expect B to be bounded as well. As it turns out, this is true proven by the following

Lemma 3.3. $B = TA = T(I + T^*T)^{-1}$ is a bounded operator, and we have $AT \subset TA$.

Proof. Let $y \in \mathfrak{D}(I + T^*T)$ such that $(I + T^*T)y = x \in \mathfrak{D}(T)$. One has

$$\begin{aligned} \|x + T^*Tx\|^2 &= \langle x + T^*Tx, x + T^*Tx \rangle \\ &= \|x\|^2 + \langle x, T^*Tx \rangle + \langle T^*Tx, x \rangle + \|T^*Tx\|^2 \\ &= \|x\|^2 + 2\|Tx\|^2 + \|T^*Tx\|^2 \geq \|Tx\|^2. \end{aligned}$$

From that, $\|TAx\|^2 = \|Ty\|^2 \leq \|(I + T^*T)y\|^2 = \|x\|^2$, which proves that B is bounded.

To show that $AT \subset TA$, take $y \in \mathfrak{D}(AT) = \mathfrak{D}(T)$, $x \in \mathfrak{D}(T^*T)$ such that $y = (I + T^*T)x$. $T^*Tx \in \mathfrak{D}(T)$ which implies $Tx \in \mathfrak{D}(TT^*) = \mathfrak{D}(T^*T)$. Then

$$ATy = A(Tx + TT^*Tx) = A((I + T^*T)Tx) = A(I + T^*T)Tx = Tx,$$

and

$$TAy = T(I + T^*T)^{-1}(I + T^*T)x = Tx,$$

concluding that $AT = TA$ on $\mathfrak{D}(T)$. \square

The operator AT is bounded but not defined on all of \mathcal{H} . So we extend it in the following

Lemma 3.4. AT admits a bounded linear extension \overline{AT} to all of \mathcal{H} . We then have $\overline{AT} = TA$.

Proof. For $x \in \mathcal{H}$ we can choose a sequence $x_n \in \mathfrak{D}(T)$, with $x_n \rightarrow x$. Define $\overline{AT}(x) := TA(x)$. This is linear, because $AT = TA$ on $\mathfrak{D}(T)$ and TA is linear bounded, so the limit does not depend on the chosen sequence. \square

Remark 3.5. The previous two lemmata and proofs, still hold if we replace T by T^* , giving us

$$AT^* = T^*A \text{ and hence } B^* = T^*A.$$

One also has the identity

$$\begin{aligned} A^2 + B^*B &= (I + T^*T)^{-2} + T^*(I + T^*T)^{-1}T(I + T^*T)^{-1} \\ &= (I + T^*T)^{-2} + T^*T(I + T^*T)^{-1}(I + T^*T)^{-1} \\ &= (I + T^*T)(I + T^*T)^{-2} \\ &= (I + T^*T)^{-1} \\ &= A \end{aligned}$$

From now on, we identify $B = \overline{AT}$ and $B^* = \overline{AT^*}$ with their bounded extensions. Let $\mathfrak{A}(T) = \mathfrak{A} := \langle I, A, B, B^* \rangle$. Let $\chi \in \text{Sp}(\mathfrak{A}), \chi(A) = 0$. By our previous identity, we get

$$\chi(A)^2 + |\chi(B)|^2 = \chi(A),$$

which implies that $\chi(B) = 0$ as well. But for all $\chi \in \text{Sp}(\mathfrak{A}), \chi(I) = 1$. If such a χ exists, it is therefore unique. We call this character χ_∞ .

We define $\theta : \text{Sp}(\mathfrak{A}) \rightarrow \overline{\mathbb{C}}$ by

$$\chi \mapsto \begin{cases} \frac{\chi(B)}{\chi(A)} & , \text{ if } \chi \neq \chi_\infty \\ \infty & , \text{ if } \chi = \chi_\infty. \end{cases}$$

Since χ is a star-algebrahomomorphism, $A^2 + B^*B = A$ implies for $\chi \neq \chi_\infty$

$$\begin{aligned} \chi(A) &= \chi(A)\overline{\chi(A)} + \chi(B)\overline{\chi(B)} \\ \Leftrightarrow \frac{1}{\chi(A)} &= 1 + \frac{\chi(B)}{\chi(A)} \overline{\left(\frac{\chi(B)}{\chi(A)}\right)} = 1 + |\theta(\chi)|^2. \end{aligned}$$

Inverting the last equality gives

$$\chi(A) = \frac{1}{1 + |\theta(\chi)|^2}. \quad (*)$$

The definition of θ (and not $B = TA \Leftrightarrow T = \frac{B}{A}$), gives

$$\chi(B) = \chi(A) \frac{\chi(B)}{\chi(A)} = \chi(A) \theta(\chi). \quad (**)$$

Recalling the definition of the Gelfandtransformation, we see that our map

$$\theta : \text{Sp}(\mathfrak{A}) \setminus \{\chi_\infty\} \rightarrow \mathbb{C}$$

equals a fraction of two single Gelfandtransformations

$$\theta(\chi) = \frac{\chi(B)}{\chi(A)} = \frac{\mathcal{G}_B(\chi)}{\mathcal{G}_A(\chi)} = \frac{\mathcal{G}_B}{\mathcal{G}_A}(\chi).$$

But $\mathcal{G}_A \neq 0$ on $\text{Sp}(\mathfrak{A}) \setminus \{\chi_\infty\}$, which implies that θ is continuous on $\text{Sp}(\mathfrak{A}) \setminus \{\chi_\infty\}$. If χ_∞ exists, let $(\chi_\lambda)_{\lambda \in \Lambda}$ be a net converging to χ_∞ and $\chi_\lambda \neq \chi_\infty$ for all $\lambda \in \Lambda$. By continuity of \mathcal{G}_A we have

$$\mathcal{G}_A(\chi_\lambda) = \chi_\lambda(A) \rightarrow \chi_\infty(A) = 0.$$

Equation (*) implies

$$|\theta(\chi_\lambda)|^2 + 1 = \frac{1}{\chi_\lambda(A)} \rightarrow \infty,$$

which is equivalent to

$$|\theta(\chi_\lambda)| \rightarrow \infty.$$

We get the following

Lemma 3.6. θ extends to a continuous map

$$\theta : \text{Sp}(\mathfrak{A}) \rightarrow \overline{\mathbb{C}},$$

by $\theta(\chi_\infty) := \infty$. Furthermore $\theta : \text{Sp}(\mathfrak{A}) \rightarrow \overline{\mathbb{C}}$ is a homeomorphism onto its image.

Proof. The first claim is already proven. For the second claim we check θ is injective: Let $\chi_1, \chi_2 \neq \chi_\infty$. Equations (*) and (**) imply that if $\theta(\chi_1) = \theta(\chi_2)$, χ_1 coincides with χ_2 . Furthermore, χ_∞ is unique, which implies that θ is injective. Since $\text{Sp}(\mathfrak{A})$ is compact and $\overline{\mathbb{C}}$ is Hausdorff, this proves the second claim. \square

We have the Gelfandisomorphism $\mathcal{G} : \mathfrak{A} \rightarrow C(\text{Sp} \mathfrak{A})$. Combining with *theta*, one has

$$\begin{aligned} \mathfrak{A} &\longrightarrow C(\text{Sp} \mathfrak{A}) \longrightarrow C(\theta(\text{Sp} \mathfrak{A})) \\ x &\mapsto \mathcal{G}_x ; f \mapsto f \circ \theta^{-1} \\ \mathcal{G}^{-1} f &\longleftarrow f ; g \circ \theta \longleftarrow g. \end{aligned}$$

Define

$$\Phi : C(\theta(\text{Sp} \mathfrak{A})) \rightarrow \mathfrak{A}, \quad g \mapsto \mathcal{G}^{-1}(g \circ \theta).$$

Φ is an involutive algebrhomomorphism since \mathcal{G} is.

Proposition 3.7. Let T be a normal operator on \mathcal{H} , $\mathfrak{A} = \langle I, A, B \rangle$ the C^* -algebra associated to T . Then Φ is the only involutive algebrhomomorphism from $C(\theta(\text{Sp} \mathfrak{A}))$ onto \mathfrak{A} , such that

$$\Phi \left(\frac{1}{1 + |z|^2} \right) = A, \quad \Phi \left(\frac{z}{1 + |z|^2} \right) = B.$$

Proof.

$$\begin{aligned} \Phi^{-1}(A)(z) &= \mathcal{G}_A \circ \theta^{-1}(z) \\ &= \mathcal{G}_A(\theta^{-1}(z)) \\ &= \frac{1}{1 + |z|^2} \end{aligned}$$

using $\mathcal{G}_A(\chi) = \chi(A) = \frac{1}{1 + |\theta(\chi)|^2}$. Moreover

$$\begin{aligned} \Phi^{-1}(B)(z) &= \mathcal{G}_B \circ \theta^{-1}(z) \\ &= \mathcal{G}_B(\theta^{-1}(z)) \\ &= \frac{z}{1 + |z|^2}. \end{aligned}$$

To proof uniqueness, let $\Psi : C(\theta(\text{Sp} \mathfrak{A})) \rightarrow \mathfrak{A}$ be another involutive algebrhomomorphism such that

$$\Psi \left(\frac{1}{1 + |z|^2} \right) = A, \quad \Psi \left(\frac{z}{1 + |z|^2} \right) = B.$$

Then Φ coincides with Ψ on all polynomials in A, B, \overline{B} . The polynomials form an involutive algebra, which separates points. By Stone-Weierstrass it is dense, and therefore Φ equals Ψ since they are continuous. \square

Our goal is to construct a functional calculus for T . With respect to Φ , T corresponds to $I_{\theta(\text{Sp } \mathfrak{A})}$. But if $\chi_\infty \in \text{Sp}(\mathfrak{A})$, then $I_{\theta(\text{Sp } \mathfrak{A})} \notin C(\text{Sp } \mathfrak{A})$ since $\infty \notin \mathbb{C}$.

4 Extension Of Continuous Spectral Measures

In this section we follow We now want to extend a given spectral measure for continuous functions, like the one we obtained by the Gelfand-Neimark theorem, to measurable ones. To do so, we need to check whether the operators we attain are bounded, or densely defined.

Definition 4.1 (Spectral measure). Let X be a compact space and let

$$\Phi : C(X) \rightarrow \mathcal{L}(\mathcal{H})$$

be a map. Φ is called a *spectral measure*, if its image $\mathfrak{A} := \Phi(C(X))$ is a commutative star-subalgebra of $\mathcal{L}(\mathcal{H})$ and Φ induces an isomorphism onto its image.

Remark 4.2. By isomorphism we mean that

1. Φ is an involutive algebrhomomorphism,
2. Φ is a bijection onto \mathfrak{A} ,
3. Φ is an isometry: $\|\Phi f\| = \|f\|_\infty$.

Example 4.3. Let \mathfrak{m} be a positive Radon measure on our compact space X , meaning a continuous linear functional on $C(X)$, such that $\mathfrak{m}(f) = 0$ implies that $f = 0$. Set $\mathcal{H} := L^2(\mathfrak{m})$. We define

$$\begin{aligned} \Phi : C(X) &\rightarrow \mathcal{L}(L^2(\mathfrak{m})) \\ f &\mapsto (g \mapsto f \cdot g). \end{aligned}$$

Φ is a spectral measure. This claim is not obvious, and the proof that Φ is an isometry requires a bit of work, but is omitted here. It can be found in [3]. For all $g, h \in \mathcal{H}$ define

$$\mathfrak{m}_{g,h}(f) := \langle g, \Phi_f h \rangle.$$

We then have that the map

$$f \mapsto \mathfrak{m}_{g,h}(f)$$

is a linear form on $C(X)$ for every pair $(g, h) \in \mathcal{H} \times \mathcal{H}$.

Departing from this explicit example, we note that the previous construction of a positive Radon measure, can be extended to any spectral measure. Let \mathcal{H} be any Hilbert space, and Φ be a spectral measure. Then the mapping

$$\begin{aligned} \mathfrak{m}_{g,h} : C(X) &\rightarrow \mathbb{C} \\ f &\mapsto \langle g, \Phi_f(h) \rangle \end{aligned}$$

is a linear form on \mathcal{H} .

Theorem 4.4. For all $g, h, k \in \mathcal{H}$, $\alpha, \beta \in \mathbb{C}$ and $f, \phi, \psi \in C(X)$, it holds that $\mathfrak{m}_{g,h}$ is a Radon measure on X with the following properties:

- (i) $\|\mathfrak{m}_{g,h}\| \leq \|g\| \|h\|$
- (ii) $\mathfrak{m}_{\alpha g + h, \beta k} = \bar{\alpha} \beta \mathfrak{m}_{g,k} + \beta \mathfrak{m}_{h,k}$

$$(iii) \quad \overline{\mathbf{m}}_{g,h} = \mathbf{m}_{h,g}, \quad \overline{\mathbf{m}}_{g,h} : f \mapsto \overline{\mathbf{m}}_{g,h}(f) = \overline{\mathbf{m}_{g,h}(f)}$$

$$(iv) \quad \mathbf{m}_{g,g} \geq 0$$

$$(v) \quad \mathbf{m}_{\Phi_\phi g, \Phi_\psi h} = \overline{\phi\psi} \mathbf{m}_{g,h}.$$

Proof. (i)

$$\begin{aligned} \|\mathbf{m}_{g,h}\| &= \sup_{\|f\|_\infty \leq 1} |\mathbf{m}_{g,h}(f)| \\ &= \sup_{\|f\|_\infty \leq 1} |\langle g, \Phi_f h \rangle| \\ &\leq \sup_{\|f\|_\infty \leq 1} \|g\| \|\Phi_f\| \|h\| \\ &= \|g\| \|h\| \end{aligned}$$

since $\|\Phi_f\| = \|f\|_\infty$.

(ii) follows immediately from the linearity of $\langle \cdot, \cdot \rangle$

$$(iii) \quad \overline{\mathbf{m}}_{g,h}(f) = \overline{\langle g, \overline{fh} \rangle} = \langle \overline{fh}, g \rangle = f \langle h, g \rangle = \langle h, fg \rangle = \mathbf{m}_{h,g}(f).$$

(iv) Let $\phi \geq 0$. Because Φ is algebrahomomorphism we have

$$\Phi_\phi = \Phi_{\sqrt{\phi}} \Phi_{\sqrt{\phi}} = \Phi_{\sqrt{\phi}} \Phi_{\sqrt{\phi}} = \Phi_{\sqrt{\phi}}^* \Phi_{\sqrt{\phi}}.$$

$$\text{Therefore } \mathbf{m}_{g,g}(\phi) = \langle g, \Phi_\phi g \rangle = \langle \Phi_{\sqrt{\phi}} g, \Phi_{\sqrt{\phi}} g \rangle \geq 0.$$

$$(v) \quad \mathbf{m}_{\Phi_\phi g, \Phi_\psi h}(f) = \langle \Phi_\phi g, \Phi_f \Phi_\psi h \rangle = \langle g, \Phi_{\overline{\phi\psi} f} h \rangle = \overline{\phi\psi} \mathbf{m}_{g,h}(f)$$

□

We now extend $\mathbf{m}_{g,h}$ to measurable functions in the sense of [4] Chapter 4.5.

Definition 4.5. $N \subset X$ is called a Φ -set of measure zero, or Φ -null set, if N is a null set of $|\mathbf{m}_{g,h}|$ for all $g, h \in \mathcal{H}$, that is

$$|\mathbf{m}_{g,h}|(N) = 0.$$

Note that $|\mathbf{m}_{g,h}|$ is a real valued Radon measure. Hence we can talk about measurability of sets in the sense of Pedersen, found in [4].

A function $f : X \rightarrow \mathbb{C}$ is called Φ -measurable, if f is $|\mathbf{m}_{g,h}|$ -measurable for all $g, h \in \mathcal{H}$. Denote the set of all measurable functions $L^0(\Phi)$.

For technical reasons, we restrict the previous definition to functions that do not take the value ∞ on a nonzero set. As it turns out, the operators one gets from those functions are not even densely defined, and hence of no interest to us.

$$L^1(\Phi) := \{f \in L^0(\Phi) \mid f \in L^1(\mathbf{m}_{g,h}) \text{ for all } g, h \in \mathcal{H}\}$$

$$L^\infty(\Phi) := \{f \in L^0(\Phi) \mid \|f\|_\infty < \infty\}$$

where,

$$\|f\|_\infty := \inf \{\lambda > 0 \mid |f| \leq \lambda, \Phi\text{-a.e.}\}.$$

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By $\mathcal{E}(X)$ we denote the measurable subsets of X :

$$\mathcal{E}(X) := \{A \subset X \mid 1_A \in L^0(\Phi)\}.$$

Let $f \in L^0(\Phi)$.

$$\begin{aligned} \mathfrak{D}(f) &:= \{h \in \mathcal{H} \mid f \in L^1(\mathfrak{m}_{g,h}) \text{ for all } g \in \mathcal{H} \\ &\quad \text{and } g \mapsto \int f \, d\mathfrak{m}_{g,h} \text{ is continuous}\} \\ &= \{h \in \mathcal{H} \mid f \in L^1(\mathfrak{m}_{g,h}) \text{ for all } g \in \mathcal{H} \\ &\quad \text{and } \exists k \in \mathcal{H} \text{ such that } \int f \, d\mathfrak{m}_{g,h} = \langle g, k \rangle\} \end{aligned}$$

where the second equality is due to the Riesz representation theorem. The reader familiar with unbounded operators, will recognize the similarity with the definition of the adjoint operator. Using the second equality, we define

$$\Phi_f h := k(h, f) = k \text{ for } h \in \mathfrak{D}(f) =: \mathfrak{D}(\Phi_f).$$

In other words we have

$$\int f \, d\mathfrak{m}_{g,h} = \langle g, \Phi_f h \rangle = \langle g, k \rangle.$$

By sesquilinearity of $\langle \cdot, \cdot \rangle$, Φ_f is linear as well.

Remark 4.6. If we want to proof claims about $L^0(\Phi)$ it is enough to show them for $C(X)$, by since the expansion of measure is unique.

Lemma 4.7. For all $f \in L^0(\Phi)$ and $h \in \mathfrak{D}(f)$, $g \in \mathcal{H}$ it holds that

$$\mathfrak{m}_{g, \Phi_f h} = f \mathfrak{m}_{g,h}$$

Proof. By the remark, let $\phi \in C(X)$.

$$\begin{aligned} \mathfrak{m}_{g, \Phi_f h}(\phi) &= \langle g, \Phi_\phi(\Phi_f h) \rangle = \langle \Phi_{\bar{\phi}}, \Phi_f h \rangle = \int f \, d\mathfrak{m}_{\Phi_{\bar{\phi}}g,h} \\ &= \int f \phi \, d\mathfrak{m}_{g,h} = (f \mathfrak{m}_{g,h})(\phi) \end{aligned}$$

□

We now want to know, whether the operator we obtain from our expanded measure is bounded, and if not, is it densely defined. This will be done in the next lemmata, which are going to be summarized in a theorem at the end of the chapter.

Lemma 4.8. If $f \in L^\infty(\Phi)$, then $\mathfrak{D}(f) = \mathcal{H}$, $\Phi_f \in \mathcal{L}(\mathcal{H})$ and

$$\|\Phi_f\| = \|f\|_\infty = \inf \{ \alpha > 0 \mid \alpha \geq |f|, \Phi\text{-a.e.} \}.$$

Proof. Let $f \in L^\infty(\Phi)$. We have to show that $\mathfrak{D}(f) = \mathcal{H}$. Let $h \in \mathcal{H}$. For $g \in \mathcal{H}$ one gets:

$$\begin{aligned} \left| \int f \, d\mathfrak{m}_{g,h} \right| &\leq \int |f| \, d|\mathfrak{m}_{g,h}| \\ &\leq \|f\|_\infty \int d|\mathfrak{m}_{g,h}| \\ &= \|f\|_\infty \|\mathfrak{m}_{g,h}\| \\ &\leq \|f\|_\infty \|h\| \|g\| \end{aligned}$$

which implies

$$g \mapsto \int f \, d\mathfrak{m}_{g,h}$$

is continuous and f an element of $\mathcal{L}^1(\mathfrak{m}_{g,h})$. The third equality follows from

$$\|\mathfrak{m}_{g,h}\| = \sup_{\|\phi\|_\infty \leq 1} |\mathfrak{m}_{g,h}| = \sup_{\substack{|\phi| \leq 1 \\ \phi \in \mathcal{C}(X)}} |\mathfrak{m}_{g,h}| = \int d|\mathfrak{m}_{g,h}| = |\mathfrak{m}_{g,h}|(1).$$

This shows that the assignment $g \mapsto \int f \, d\mathfrak{m}_{g,h}$ defines a continuous map.

$$\begin{aligned} \|\Phi_f\| &= \sup_{\|g\|, \|h\| \leq 1} |\langle g, \Phi_f h \rangle| \\ &= \sup_{\|g\|, \|h\| \leq 1} \left| \int f \, d\mathfrak{m}_{g,h} \right| \\ &\leq \|f\|_\infty \end{aligned}$$

Other inequality, will be proved in Lemma 4.14. \square

Remark 4.9. If $f_n \rightarrow f$ in $L^\infty(\Phi)$, then

$$\Phi_f = \lim \Phi_{f_n} \text{ in } \mathcal{L}(\mathcal{H}).$$

We can therefore define our spectral measure for all bounded measurable functions.

Lemma 4.10. Let $f \in L^0(\Phi)$, (f_n) a net in $L^\infty(\Phi)$, and $\alpha, \beta \geq 0$ such that

$$\begin{aligned} |f_n| &\leq \alpha|f| + \beta \text{ for all } n \\ f_n &\rightarrow f \text{ } \Phi\text{-a.e.} \end{aligned}$$

Then the following statements about $h \in \mathcal{H}$ are equivalent:

- (i) $h \in \mathfrak{D}(f)$
- (ii) $\int^* |f|^2 \, d\mathfrak{m}_{h,h} < \infty$
- (iii) $(\Phi_{f_n} h)$ converges in \mathcal{H}

One then has

$$\begin{aligned} \|\Phi_f h\|^2 &= \int |f|^2 \, d\mathfrak{m}_{h,h} \text{ and} \\ \Phi_f h &= \lim \Phi_{f_n} h. \end{aligned}$$

For example, one can take the net $f_n = 1_{\mathcal{A}_n}$, where $\mathcal{A}_n = \{x \in X \mid |f(x)| \leq n\}$.

Proof. (i) \Rightarrow (ii):
Let $h \in \mathfrak{D}(f)$.

$$\begin{aligned} \infty > \|\Phi_f h\|^2 &= \langle \Phi_f, \Phi_f h \rangle \\ &= \int f \, d\mathbf{m}_{\Phi_f h, h} \\ &= \int f \bar{f} \, d\mathbf{m}_{h, h} \\ &= \int |f|^2 \, d\mathbf{m}_{h, h}. \end{aligned}$$

(ii) \Rightarrow (iii):

Let $h \in \mathcal{L}^2(\mathbf{m}_{h, h})$. Then for $g \in \mathcal{H}$

$$\begin{aligned} \langle g, (\Phi_{f_m} - \Phi_{f_n})h \rangle &= \langle g, \Phi_{f_m} \rangle - \langle g, \Phi_{f_n} \rangle \\ &= \int f_m \, d\mathbf{m}_{g, h} - \int f_n \, d\mathbf{m}_{g, h} \\ &= \int (f_m - f_n) \, d\mathbf{m}_{g, h} \\ &= \langle g, \Phi_{(f_m - f_n)} h \rangle \end{aligned}$$

Since g was arbitrary, we get $(\Phi_{f_m} - \Phi_{f_n})h = \Phi_{(f_m - f_n)}h$

$$\begin{aligned} \|(\Phi_{f_m} - \Phi_{f_n})h\|^2 &= \|\Phi_{(f_m - f_n)}h\|^2 \\ &= \int |f_m - f_n|^2 \, d\mathbf{m}_{h, h}. \end{aligned}$$

where the last equality holds, because $h \in \mathfrak{D}(f_m - f_n)$ and thus $f \in L^2(\Phi)$. By our assumption, we have $f_m - f_n \rightarrow 0$ Φ -a.e. Thus

$$|f_m - f_n|^2 \leq (2(\alpha|f| + \beta))^2 \in \mathcal{L}^1(\mathbf{m}_{h, h}),$$

because $\mathcal{L}^2(\mathbf{m}_{h, h}) \subset \mathcal{L}^1(\mathbf{m}_{h, h})$ by compactness of X , and $C(X) \in \mathcal{L}^1(\mathbf{m}_{h, h})$ by definition. Therefore Lebesgue's theorem about dominated convergence yields the claim.

(iii) \Rightarrow (ii):

Using Fatou's lemma, and again as above $\|\Phi_{f_n} h\|^2 = \int |f_n|^2 \, d\mathbf{m}_{h, h}$, we get

$$\begin{aligned} \infty > \|\lim_{n \rightarrow \infty} \Phi_{f_n} h\|^2 &= \lim_{n \rightarrow \infty} \|\Phi_{f_n} h\|^2 = \lim_{n \rightarrow \infty} \int |f_n|^2 \, d\mathbf{m}_{h, h} \\ &\geq \int^* \liminf_{n \rightarrow \infty} |f_n|^2 \, d\mathbf{m}_{h, h} = \int^* |f|^2 \, d\mathbf{m}_{h, h} \end{aligned}$$

(ii) \Rightarrow (i):

By Radon-Nikodym, there exists a Borel-measurable function $\phi : X \rightarrow \mathbb{C}$, $|\phi| = 1$, such that

$$|\mathbf{m}_{g, h}| = \phi \mathbf{m}_{g, h}.$$

Now define $\tilde{f} := \phi|f|$, $\tilde{f}_n := \phi|f_n|$. Thus

$$\int^* |\tilde{f}|^2 \, d\mathbf{m}_{h, h} = \int^* |f|^2 \, d\mathbf{m}_{h, h} < \infty.$$

By (ii) \Rightarrow (iii), $\lim \Phi_{\tilde{f}_n}$ exists. Hence, for $g \in \mathcal{H}$

$$\begin{aligned} \infty &> \|g\|^2 \lim_{n \rightarrow \infty} \|\Phi_{\tilde{f}_n} h\|^2 \geq \left| \left\langle g, \lim_{n \rightarrow \infty} \Phi_{\tilde{f}_n} h \right\rangle \right| = \left| \lim_{n \rightarrow \infty} \int \tilde{f}_n \, d\mathbf{m}_{g,h} \right| \\ &\geq \lim_{n \rightarrow \infty} \int |f_n| \, d|\mathbf{m}_{g,h}| \geq \int^* \liminf_{n \rightarrow \infty} |f_n| \, d|\mathbf{m}_{g,h}| = \int^* |f| \, d|\mathbf{m}_{g,h}|, \end{aligned}$$

which implies that $f \in \mathcal{L}^1(\mathbf{m}_{g,h})$. So once more by Lebegues theorem

$$\left\langle g, \lim_{n \rightarrow \infty} \Phi_{f_n} h \right\rangle = \lim_{n \rightarrow \infty} \int f_n \, d\mathbf{m}_{g,h} = \int f \, d\mathbf{m}_{g,h} = \langle g, \Phi_f h \rangle,$$

which means, $h \in \mathfrak{D}(f)$. □

Lemma 4.11. *For each $f \in L^0(\Phi)$, Φ_f is a normal Operator, and we have*

$$\Phi_f^* = \Phi_{\bar{f}}.$$

If f is real valued, then Φ_f is self-adjoint, and $\Phi_{1_A} =: E_A$ for $A \in \mathcal{E}(X)$ is an orthogonal projection.

Proof. First we show that Φ_f is densely defined.

We claim $E_{\mathcal{A}_n}(\mathcal{H}) \subset \mathfrak{D}(f)$, where $\mathcal{A}_n = \{x \in X \mid |f(x)| \leq n\}$. Let $h \in \mathcal{H}$. By Lemma 4.10 the claim is equivalent to

$$\int^* |f|^2 \, d\mathbf{m}_{E_{\mathcal{A}_n} h, E_{\mathcal{A}_n} h} < \infty.$$

We have

$$\int^* |f|^2 \, d\mathbf{m}_{E_{\mathcal{A}_n} h, E_{\mathcal{A}_n} h} = \int^* \bar{1}_{\mathcal{A}_n} 1_{\mathcal{A}_n} \, d\mathbf{m}_{h,h} \leq n^2 \int^* d\mathbf{m}_{h,h} \leq n^2 \|h\|^2 < \infty.$$

For $h \in \mathcal{H}$ we have $h = \lim_{n \rightarrow \infty} E_{\mathcal{A}_n} h$. Then $|1_{\mathcal{A}_n}| \leq 1$, and we have $1_{\mathcal{A}_n} \rightarrow 1$ pointwise Φ -a.e. Let $h \in \mathcal{H} = \mathfrak{D}(1)$. By Lemma 4.10 we have

$$h = \Phi_1 h = \lim_{n \rightarrow \infty} \Phi_{1_{\mathcal{A}_n}} = \lim_{n \rightarrow \infty} E_{\mathcal{A}_n} h,$$

which gives $\mathfrak{D}(f) \subset \mathcal{H}$ is dense, as $E_{\mathcal{A}_n} h \in \mathfrak{D}(f)$ by the claim.

Now we claim $\Phi_{\bar{f}} \subset \Phi_f^*$.

Let $g, h \in \mathfrak{D}(f) = \mathfrak{D}(\bar{f})$. Using Theorem 4.4 (iii), one has

$$\langle g, \Phi_f h \rangle = \int f \, d\mathbf{m}_{g,h} = \overline{\int \bar{f} \, d\bar{\mathbf{m}}_{g,h}} = \overline{\langle h, \Phi_{\bar{f}} g \rangle} = \langle \Phi_{\bar{f}} g, h \rangle$$

So, $g \in \mathfrak{D}(\Phi_f^*)$ and $\Phi_f^* g = \Phi_{\bar{f}} g$.

On the other hand, to show that $\Phi_{\bar{f}} \supset \Phi_f^*$ let $g \in \mathfrak{D}(\Phi_f^*)$. By Lemma 4.10, we only have to show $\Phi_{\bar{f}_n} g$ converges in \mathcal{H} , for some net satisfyig the conditions of Lemma 4.10. As a net, we take $f_n = 1_{\mathcal{A}_n}$, where $\mathcal{A}_n = \{x \in X \mid |f(x)| \leq n\}$. Let $h \in \mathcal{H}$.

$$\begin{aligned}
\langle \Phi_{\bar{f}_n} g, h \rangle &= \int \mathrm{d}\mathbf{m}_{\Phi_{\bar{f}_n} g, h} = \int f_n \mathrm{d}\mathbf{m}_{g, h} = \int f \mathrm{d}\mathbf{m}_{g, \Phi_{1_{\mathcal{A}_n}} h} = \int \mathrm{d}\mathbf{m}_{g, \Phi_f E_{\mathcal{A}_n} h} \\
&= \langle g, \Phi_1 \Phi_f E_{\mathcal{A}_n} h \rangle = \langle g, \Phi_f E_{\mathcal{A}_n} h \rangle = \langle \Phi_f^* g, E_{\mathcal{A}_n} h \rangle = \int 1_{\mathcal{A}_n} \mathrm{d}\mathbf{m}_{\Phi_f^* g, h} \\
&= \int \mathrm{d}\mathbf{m}_{E_{\mathcal{A}_n} \Phi_f^* g, h} = \langle E_{\mathcal{A}_n} \Phi_f^* g, h \rangle
\end{aligned}$$

$$\Phi_{\bar{f}_n} g = E_{\mathcal{A}_n} \Phi_f^* g \xrightarrow{n \rightarrow \infty} \Phi_f^* g, \text{ so } \Phi_{\bar{f}} = \Phi_f^*.$$

Now we claim Φ_f is a normal element. To show

$$\mathfrak{D}(\bar{f}) = \mathfrak{D}(\Phi_f^*) = \mathfrak{D}(\Phi_{\bar{f}}) = \mathfrak{D}(f),$$

which is already proven. Also already proven is now

$$\|\Phi_f^* h\| = \|\Phi_f h\|,$$

for example, by the norm formula of Lemma 4.10. Thus $\mathfrak{D}(\Phi_f^*) = \mathfrak{D}(\Phi_{\bar{f}})$ and $\|\Phi_f^* h\| = \|\Phi_f h\|$, which proves that Φ_f is normal. To show that this implies the usual definition of a normal operator, is left as an easy exercise using the polarization identity.

If now f is real valued, we have that $f = \bar{f}$, which gives the selfadjointness of Φ_f . Furthermore $E_{\mathcal{A}}^* = E_{\mathcal{A}}$. □

Lemma 4.12.

1. $f \in L^\infty(\Phi)$, $f \geq 0$ Φ -a.e. $\Rightarrow \Phi_f \geq 0$
2. $\mathcal{A} \in \mathcal{E}(X)$, $E_{\mathcal{A}} = 0 \Leftrightarrow \mathcal{A}$ Φ -null set
3. $U \in \mathcal{E}(X)$ open, $U \neq \emptyset \Rightarrow E_U \neq 0$

Proof. Left as an exercise. □

Lemma 4.13. For each $\varphi, \psi \in L^0(\Phi)$, $\alpha \in \mathbb{C}$, we have

- (i) $\Phi_{\alpha\varphi} = \alpha\Phi_\varphi$
- (ii) $\mathfrak{D}(\Phi_\varphi\Phi_\psi) = \mathfrak{D}(\varphi\psi) \cap \mathfrak{D}(\psi)$, and $\overline{\Phi_\varphi\Phi_\psi} = \Phi_{\varphi\psi}$
- (iii) $\overline{\Phi_\varphi + \Phi_\psi} = \Phi_{\varphi+\psi}$
- (iv) $\psi \in L^\infty(\Phi) \Rightarrow \Phi_\varphi + \Phi_\psi = \Phi_{\varphi+\psi}$, and $\Phi_\varphi\Phi_\psi = \Phi_{\varphi\psi}$.

Proof. (i)

$$\mathfrak{D}(\alpha\varphi) = \left\{ h \in \mathcal{H} \mid \int^* |\alpha\varphi|^2 d\mathbf{m}_{h,h} < \infty \right\} = \mathfrak{D}(\varphi)$$

and,

$$\langle g, \Phi_{\alpha\varphi} h \rangle = \int \alpha\varphi d\mathbf{m}_{g,h} = \alpha \int \varphi d\mathbf{m}_{g,h} = \langle \psi, \alpha\Phi_{\varphi} h \rangle$$

for all $g \in \mathcal{H}$.

(ii)

$$h \in \mathfrak{D}(\Phi_{\varphi}\Phi_{\psi}) \Leftrightarrow h \in \mathfrak{D}(\psi) \text{ and } \Phi_{\psi}h \in \mathfrak{D}(\varphi).$$

By Lemma 4.7, for $h \in \mathfrak{D}(\psi)$, $\mathbf{m}_{g,\Phi_{\psi}h} = \psi\mathbf{m}_{g,h}$

$$\int^* |\varphi| d|\mathbf{m}_{g,\Phi_{\psi}h}| = \int^* |\varphi\psi| d|\mathbf{m}_{g,h}|,$$

so

$$\int^* |\varphi| d|\mathbf{m}_{g,\Phi_{\psi}h}| < \infty \Leftrightarrow \int^* |\varphi\psi| d|\mathbf{m}_{g,h}| < \infty$$

and

$$g \mapsto \int^* \varphi d\mathbf{m}_{g,\Phi_{\psi}h} \text{ is continuous } \Leftrightarrow g \mapsto \int^* \varphi\psi d\mathbf{m}_{g,h} \text{ is continuous.}$$

But the last statement, reformulates to

$$h \in \mathfrak{D}(\psi) \text{ and } \Phi_{\psi}h \in \mathfrak{D}(\varphi) \Leftrightarrow h \in \mathfrak{D}(\psi) \text{ and } h \in \mathfrak{D}(\varphi\psi).$$

$$\langle g, \Phi_{\varphi}\Phi_{\psi}h \rangle = \int \varphi d\mathbf{m}_{g,\Phi_{\psi}h} = \int \varphi\psi d\mathbf{m}_{g,h} = \langle g, \Phi_{\varphi\psi}h \rangle$$

Thus $\Phi_{\varphi}\Phi_{\psi} \subset \Phi_{\varphi\psi}$. The prove of $\overline{\Phi_{\varphi}\Phi_{\psi}} = \Phi_{\varphi\psi}$ is analogous to the prove of $\overline{\Phi_{\varphi} + \Phi_{\psi}} = \Phi_{\varphi+\psi}$ and will be omitted.

(iii) To show

$$\mathfrak{D}(\varphi) \cap \mathfrak{D}(\psi) \subset \mathfrak{D}(\varphi + \psi).$$

Let $h \in \mathfrak{D}(\varphi) \cap \mathfrak{D}(\psi)$. By Lemma 4.10,

$$\int^* |\varphi|^2 d\mathbf{m}_{h,h}, \int^* |\psi|^2 d\mathbf{m}_{h,h} < \infty,$$

and by Minkowskys inequality

$$\left(\int^* |\varphi + \psi|^2 d\mathbf{m}_{h,h} \right)^{\frac{1}{2}} \leq \left(\int^* |\varphi|^2 d\mathbf{m}_{h,h} \right)^{\frac{1}{2}} + \left(\int^* |\psi|^2 d\mathbf{m}_{h,h} \right)^{\frac{1}{2}}.$$

Thus $h \in \mathfrak{D}(\varphi + \psi)$. Furthermore, for $g \in \mathcal{H}$

$$\langle g, (\Phi_{\varphi} + \Phi_{\psi})h \rangle = \int \varphi d\mathbf{m}_{g,h} + \int \psi d\mathbf{m}_{g,h} = \int (\varphi + \psi) d\mathbf{m}_{g,h} = \langle g, \Phi_{\varphi+\psi}h \rangle,$$

and thus $\Phi_{\varphi} + \Phi_{\psi} \subset \Phi_{\varphi+\psi}$. The rest of the proof will follow after part (iv).

(iv) $\psi \in L^\infty(\Phi)$ implies that $\mathfrak{D}(\psi)$ is already the whole space. Thus

$$\mathfrak{D}(\Phi_\varphi \Phi_\psi) = \mathfrak{D}(\varphi\psi) \cap \mathcal{H} = \mathfrak{D}(\varphi\psi),$$

and

$$\mathfrak{D}(\Phi_\varphi + \Phi_\psi) = \mathfrak{D}(\varphi) \cap \mathcal{H} = \mathfrak{D}(\varphi).$$

Therefore, we have proven

$$\Phi_\varphi \Phi_\psi = \Phi_{\varphi\psi} \text{ and } \Phi_\varphi \Phi_\psi = \Phi_{\varphi+\psi}.$$

In particular,

$$\mathcal{A} \in \mathcal{E}(\Phi) \Rightarrow E_{\mathcal{A}} \text{ is a projection.}$$

Rest of (ii)

For $\overline{\Phi_\varphi + \Phi_\psi} = \Phi_{\varphi+\psi}$, we need to show that for $h \in \mathfrak{D}(\varphi + \psi)$, there exists a net $(h_n) \in \mathfrak{D}(\varphi) \cap \mathfrak{D}(\psi)$, such that $\lim h_n = h$, and $\lim(\Phi_\varphi h_n + \Phi_\psi h_n) = \Phi_{\varphi+\psi} h$. Set $\mathcal{A}_n = \{x \in X \mid |\varphi(x)| + |\psi(x)| \leq n\}$. By Lemma 4.10, we have

$$E_{\mathcal{A}_n}(\mathcal{H}) \subset \mathfrak{D}(\varphi) \cap \mathfrak{D}(\psi)$$

and

$$\cup \mathcal{A}_n = X, \mathcal{A}_n \subset \mathcal{A}_{n+1}.$$

And thus

$$\lim E_{\mathcal{A}_n} = \text{id}$$

For all $h \in \mathfrak{D}(\varphi + \psi)$, one has

$$h = \lim E_{\mathcal{A}_n} h =: \lim h_n,$$

and using (iv) combined with the fact that $E_{\mathcal{A}_n}$ is bounded, we get

$$\begin{aligned} \Phi_{\varphi+\psi} h &= \lim E_{\mathcal{A}_n}(\Phi_{\varphi+\psi})h \\ &= \lim \Phi_{1_{\mathcal{A}_n}(\varphi+\psi)} h \\ &= \lim \Phi_{(\varphi+\psi)1_{\mathcal{A}_n}} h \\ &= \lim \Phi_{\varphi+\psi} E_{\mathcal{A}_n} h \\ &= \lim \Phi_{\varphi+\psi} h_n = \lim(\Phi_\varphi h_n + \Phi_\psi h_n) \end{aligned}$$

□

Lemma 4.14. For $f \in L^0(\Phi)$, one has

$$\Phi_f \in \mathcal{L}(\mathcal{H}) \Leftrightarrow f \in L^\infty(\Phi).$$

Proof. " \Leftarrow " already proven in Lemma 4.8.

For the other direction we proof $\|\Phi_f\| \geq \|f\|_\infty$. Let $\lambda < \|f\|_\infty$. Then $\mathcal{A}_\lambda := \{|f| \geq \lambda\}$ is not a Φ -null set. By the polarization identity, there exists a $h \in \mathcal{H}$, such that \mathcal{A}_λ is not a $\mathfrak{m}_{h,h}$ -null set. We have

$$\mathcal{A}_\lambda = \bigcup_{\substack{\mu \in \mathbb{Q} \\ \mu > \lambda}} \{\lambda \leq |f| \leq \mu\}$$

which gives

$$0 \neq \mathfrak{m}_{h,h}(\mathcal{A}_\lambda) = \sup_{\substack{\mu \in \mathbb{Q} \\ \mu > \lambda}} \mathfrak{m}_{h,h}(\{\lambda \leq |f| \leq \mu\}).$$

Therefore, there exists a $\mu > \lambda$, such that

$$\mathfrak{m}_{h,h}(\{\lambda \leq |f| \leq \mu\}) =: \mathfrak{m}_{h,h}(B) > 0.$$

We then have that $E_B h \in \mathfrak{D}(f)$, since f is bounded on B . Note that this is a priori not true for \mathcal{A}_λ .

$$\begin{aligned} \|\Phi_f E_B h\|^2 &= \int |f|^2 d\mathfrak{m}_{E_B h, E_B h} \\ &= \int_B |f|^2 d\mathfrak{m}_{h,h} \\ &\geq \lambda^2 \mathfrak{m}_{h,h}(B) \\ &= \lambda^2 \int \bar{1}_B 1_B d\mathfrak{m}_{h,h} \\ &= \lambda^2 \int d\mathfrak{m}_{E_B h, E_B h} = \lambda^2 \|E_B h\|^2 \end{aligned}$$

For $\tilde{h} := \frac{E_B h}{\|E_B h\|} \in \mathfrak{D}(f)$, we have $\|\Phi_f \tilde{h}\| \geq \lambda$. Since $\|\tilde{h}\| = 1$, $\|\Phi_f\| \geq \lambda$. \square

Lemma 4.15. For $f \in L^0(\Phi)$

Φ_f is invertible if and only if $\{f = 0\}$ is a Φ -null set and $\frac{1}{f} \in L^\infty(\Phi)$

One then has

$$\Phi_f^{-1} = \Phi_{\frac{1}{f}}$$

Proof. \Leftarrow : By the previous Lemma $\Phi_{\frac{1}{f}} \in \mathcal{L}(\mathcal{H})$, and by Lemma 4.13

$$\Phi_{\frac{1}{f}} \Phi_f \subset \Phi_{\frac{1}{f} f} = \Phi_1 = \text{id} = \Phi_{f \frac{1}{f}} = \Phi_f \Phi_{\frac{1}{f}}.$$

Hence, Φ_f is invertible.

\Rightarrow : Let $h \in E_{\{f=0\}}(\mathcal{H})$. Since $E_{\{f=0\}}$ is a projection, $E_{\{f=0\}} h = h$. Thus

$$\Phi_f h = \Phi_f E_{\{f=0\}} h = \Phi_{f \cdot 1_{\{f=0\}}} h = \Phi_0 h = 0.$$

Since Φ_f is invertible, $h = 0$ and $E_{\{f=0\}} = 0$ are immediate consequences. Therefore $\{f = 0\}$ is a Φ -null set.

It remains to show that $\frac{1}{f} \in L^\infty(\Phi)$. We have

$$\Phi_f \cdot \Phi_{\frac{1}{f}} \subset \Phi_1 = I.$$

On $\mathfrak{D}(\Phi_f \cdot \Phi_{\frac{1}{f}})$, it holds that $\Phi_{\frac{1}{f}} = \Phi_f^{-1}$. Since Φ_f is invertible, it is surjective. We claim $\mathcal{H} = \Phi_f(\mathfrak{D}(f)) \subset \mathfrak{D}(\Phi_{\frac{1}{f}})$

Umformattieren.

$$\begin{aligned} \int \left| \frac{1}{f} \right| d|\mathbf{m}_{g, \Phi_f h}| &= \sup_{|\phi| \leq \left| \frac{1}{f} \right|} \left| \int \phi d\mathbf{m}_{g, \Phi_f h} \right| \\ &= \sup_{|\phi| \leq \left| \frac{1}{f} \right|} \left| \int \phi f d\mathbf{m}_{g, h} \right| \leq \int d|\mathbf{m}_{g, h}| \leq \|h\| \|g\|. \end{aligned}$$

Thus $\mathfrak{D}(\Phi_{\frac{1}{f}}) = \mathcal{H}$, which implies $\frac{1}{f} \in L^\infty(\Phi)$, by Lemma 4.14. \square

Lemma 4.16. *Let $f \in L^0(\Phi)$. Then*

$$\text{Sp } \Phi_f = \bigcap_{E_{\mathcal{A}}=I} \overline{f(\mathcal{A})}$$

Proof. " \subset " Fix $\lambda \in \text{Sp } \Phi_f$, $\mathcal{A} \subset X$ such that $E_{\mathcal{A}} = I$. We claim that $\lambda \in \overline{f(\mathcal{A})}$. By Lemmata 4.13 and 4.15, $\Phi_f - \lambda I = \Phi_{f-\lambda}$ is not invertible implies that either

- a) $\{f - \lambda = 0\}$ is not a Φ -null set.
- b) $\{f - \lambda = 0\}$ is a Φ -null set, but $\frac{1}{f - \lambda} \notin L^\infty(\Phi)$.

Suppose a) holds. Since \mathcal{A}^c is a Φ -null set,

$$\mathcal{A} \cap \{f = \lambda\} \neq \emptyset.$$

This means there exists a $x \in \mathcal{A}$ such that $f(x) = \lambda$, that is

$$\lambda \in f(\mathcal{A}).$$

Suppose now that b) holds. By Lemma 4.15 $\frac{1}{f-\lambda} \notin L^\infty(\Phi)$ implies that $\frac{1}{f-\lambda}$ is unbounded on $\mathcal{A} \setminus \{f = \lambda\}$. Thus, there exists a sequence $(x_n) \in \mathcal{A} \setminus \{f = \lambda\}$, such that

$$\lim |f(x_n) - \lambda| = 0,$$

which implies that

$$\lambda = \lim f(x_n) \in \overline{f(\mathcal{A})}.$$

" \supset " Fix $\lambda \notin \text{Sp}(\Phi_f)$. We have to show that there exists a set \mathcal{A}_0 , $E_{\mathcal{A}_0} = I$ and $\lambda \notin \overline{f(\mathcal{A}_0)}$. By Lemma 4.15, $\Phi_f - \lambda I = \Phi_{f-\lambda}$ is invertible implies that $\{f = \lambda\}$ is a Φ -null set, and $\frac{1}{f-\lambda} \in L^\infty(\Phi)$. Thus with $M := \left\| \frac{1}{f-\lambda} \right\|_\infty$, $\{|f - \lambda| < \frac{1}{M}\}$ is a Φ -null set. Therefore, we can set $\mathcal{A}_0 := \{|f - \lambda| \geq \frac{1}{M}\}$. Then $E_{\mathcal{A}_0} = I$ and $d(\lambda, \overline{f(\mathcal{A}_0)}) \geq \frac{1}{M}$, that is

$$\lambda \notin \overline{f(\mathcal{A}_0)}.$$

\square

Summing up the previous lemmata, we get our

Theorem 4.17 (Main theorem).

1. If $f \in L^\infty(\Phi)$, then $\mathfrak{D}(f) = \mathcal{H}$, $\Phi_f \in \mathcal{L}(\mathcal{H})$ and

$$\|\Phi_f\| = \|f\|_\infty = \inf \{ \alpha > 0 \mid \alpha \geq |f|, \Phi\text{-a.e.} \}.$$

2. Let $f \in L^0(\Phi)$, (f_n) a net in $L^\infty(\Phi)$, and $\alpha, \beta \geq 0$ such that

$$\begin{aligned} |f_n| &\leq \alpha|f| + \beta \text{ for all } n \\ f_n &\rightarrow f \text{ } \Phi\text{-a.e.} \end{aligned}$$

Then the following statements about $h \in \mathcal{H}$ are equivalent:

- (i) $h \in \mathfrak{D}(f)$
- (ii) $\int^* |f|^2 d\mathbf{m}_{h,h} < \infty$
- (iii) $(\Phi_{f_n} h)$ converges in \mathcal{H}

One then has

$$\begin{aligned} \|\Phi_f h\|^2 &= \int |f|^2 d\mathbf{m}_{h,h} \text{ and} \\ \Phi_f h &= \lim \Phi_{f_n} h. \end{aligned}$$

3. For each $f \in L^0(\Phi)$, Φ_f is a normal Operator, and we have

$$\Phi_f^* = \Phi_f.$$

If f is real valued, then Φ_f is self-adjoint, and $E_A := \Phi_{1_A}$ for $A \in \mathcal{E}(X)$ is an orthogonal projection.

4. (i) $f \in L^\infty(\Phi)$,

$$f \geq 0 \text{ } \Phi\text{-a.e.} \Rightarrow \Phi_f \geq 0$$

(ii) $\mathcal{A} \in \mathcal{E}(X)$,

$$E_{\mathcal{A}} = 0 \Leftrightarrow \mathcal{A} \text{ } \Phi\text{-null set}$$

(iii) $U \in \mathcal{E}(X)$ open,

$$U \neq \emptyset \Rightarrow E_U \neq 0$$

5. For each $f, g \in L^0(\Phi)$, $\alpha \in \mathbb{C}$, we have

- (i) $\Phi_{\alpha f} = \alpha \Phi_f$
- (ii) $\overline{\Phi_f + \Phi_g} = \Phi_{f+g}$
- (iii) $\mathfrak{D}(\Phi_f \Phi_g) = \mathfrak{D}(fg) \cap \mathfrak{D}(g)$, and $\overline{\Phi_f \Phi_g} = \Phi_{fg}$
- (iv) if $g \in L^\infty(\Phi)$ then $\Phi_f + \Phi_g = \Phi_{f+g}$, and $\Phi_f \Phi_g = \Phi_{fg}$.

6. For $f \in L^0(\Phi)$, one has

$$\Phi_f \in \mathcal{L}(\mathcal{H}) \text{ if, and only if, } f \in L^\infty(\Phi).$$

7. For $f \in L^0(\Phi)$, we have

$$\text{Sp } \Phi_f = \bigcap_{A \in \mathcal{E}(X)} \overline{f(A)};$$

where, A runs over all $A \in \mathcal{E}(X)$ such that $E_A = I$ and $A \subset \mathfrak{D}(f)$.

5 Spectral Theorem for Unbounded Operators

Using the results from Chapter 4, we construct a spectral measure, for unbounded normal operators, completing the process started in chapter 3.

Theorem 5.1. *Let T be a normal operator on \mathcal{H} .*

$$\overline{\text{Sp}T}^{\mathbb{C}} = \text{Sp}T \cup \{\infty\} \Leftrightarrow T \text{ is unbounded.}$$

There exists a uniquely determined spectral measure

$$\Phi : \mathbb{C} \left(\overline{\text{Sp}T}^{\mathbb{C}} \right) \rightarrow \mathcal{L}(\mathcal{H})$$

such that

(i) $\{\infty\}$ is a Φ -zeroset

(ii) $\Phi_{\text{id}} = T$, where $\text{id}(\infty) := 0$, which is arbitrary.

Proof. In Proposition 3.7, we defined the inverse Gelfandisomorphism

$$\Phi : \mathbb{C}(\theta(\text{Sp}\mathfrak{A})) \rightarrow \mathfrak{A} \subset \mathcal{L}(\mathcal{H}), \quad g \mapsto \mathcal{G}^{-1}(g \circ \theta),$$

where $\mathfrak{A}(T) := \langle I, A, B, B^* \rangle$, $A := (1 + T^*T)^{-1}$, $B := TA$.

It followed that Φ is a spectral measure such that

$$A = \Phi_a, \quad a : \lambda \mapsto \frac{1}{1 + |\lambda|^2}$$

$$B = \Phi_b, \quad b : \lambda \mapsto \frac{\lambda}{1 + |\lambda|^2}.$$

We need to show that $\{\infty\}$ is a Φ -zeroset. To do that, it suffices to show that $E_{\{\infty\}} = 0$. We have

$$AE_{\{\infty\}} = \Phi_a \Phi_{1_{\{\infty\}}} = \Phi_a 1_{\{\infty\}} = \Phi_0 = 0.$$

Because A is the inverse of $1 + T^*T$, we get

$$E_{\{\infty\}} = (1 + T^*T)AE_{\{\infty\}} = 0.$$

Define $\text{id} : \theta(\text{Sp}\mathfrak{A}) \rightarrow \mathbb{C}$, via $\text{id}(\infty) = 0$. Thus,

$$\text{id} \in L^0(\Phi), \text{ and } (1 + |\text{id}|^2)a = 1 \quad \Phi\text{-a.e.}$$

Using the fact that a is bounded and Lemma 4.14, we get

$$I = \Phi_1 = \Phi_{(1+|\text{id}|^2)a} = \Phi_{(1+|\text{id}|^2)}\Phi_a.$$

Furthermore

$$\begin{aligned} I + TT^* &= \Phi_{(1+|\text{id}|^2)}\Phi_a(I + TT^*) \\ &= \Phi_{(1+|\text{id}|^2)}A(I + TT^*) \\ &\subset \Phi_{(1+|\text{id}|^2)}, \end{aligned}$$

and

$$T = (I + T^*T)AT \subset \Phi_{(1+|\text{id}|^2)}TA = \Phi_{(1+|\text{id}|^2)}B.$$

Since T is normal and hence closed, and $\Phi_{(1+|\text{id}|^2).b} = \Phi_{\text{id}}$, we get that

$$T = \Phi_{\text{id}}.$$

It still remains to show that

$$\theta(\text{Sp } \mathfrak{A}) = \overline{\text{Sp } T}^{\mathbb{C}}.$$

By Lemma 4.16, we have

$$\text{Sp } T = \text{Sp}(\Phi_{\text{id}}) = \bigcap_{E_U=I} \overline{\text{id}(U)}^{\mathbb{C}}.$$

Let $U \subset \theta \text{Sp}(\mathfrak{A}) \subset \overline{\mathbb{C}}$, such that U^c is a Φ -zeroset. Then

$$\begin{aligned} \text{id}(U) &= U && \text{if } \infty \notin U \\ &= (U \cup \{0\}) \setminus \{\infty\} && \text{if } \infty \in U, \end{aligned}$$

giving us

$$\begin{aligned} \overline{\text{id}(U)}^{\mathbb{C}} &= \overline{U}^{\mathbb{C}} && \text{if } \infty \notin U \\ &= (\overline{U}^{\mathbb{C}} \cup \{0\}) \setminus \{\infty\} && \text{if } \infty \in U. \end{aligned}$$

By Lemma 4.13, U^c does not contain any open sets. Thus

$$\overline{U}^{\mathbb{C}} = \theta(\text{Sp } \mathfrak{A}) \setminus \{\infty\},$$

and for each U , such that $E_U = I$

$$\theta(\text{Sp } \mathfrak{A}) \setminus \{\infty\} \subset \overline{\text{id}(U)}^{\mathbb{C}} \subset (\theta(\text{Sp } \mathfrak{A}) \cup \{0\}) \setminus \{\infty\}.$$

For $U_0 := \theta(\text{Sp } \mathfrak{A}) \setminus \{\infty\}$, it holds that $E_{U_0} = I$ and $\text{id}(U_0) = U_0$, and therefore It follows that

$$\text{Sp } T = \theta(\text{Sp } \mathfrak{A}) \setminus \{\infty\}.$$

If T is bounded, $\text{Sp } T$ is bounded as well, and hence compact, which gives

$$\overline{\text{Sp } T} = \text{Sp } T.$$

Since T is bounded, $I + T^*T = A^{-1}$ is bounded as well, and since $I + T^*T$ is invertible in $\mathcal{L}(\mathcal{H})$ it is invertible in \mathfrak{A} by Proposition 2.1. Thus $I + T^*T$ lies in \mathfrak{A} . $I = (I + T^*T)A$ now implies

$$1 = \chi_{\infty}(I) = \chi_{\infty}(I + T^*T)\chi_{\infty}(A) = \chi_{\infty}(I + T^*T) \cdot 0 = 0,$$

a contradiction. Thus $\text{Sp } T = \theta(\text{Sp } \mathfrak{A})$, if T is bounded.

If on the other hand, $\text{Sp } T$ is compact in \mathbb{C} , then

$$\text{id} \in L^{\infty}(\Phi), \text{ and so } T = \Phi_{\text{id}} \in \mathcal{B}(\mathcal{H}).$$

Thus, we have proven

$$T \text{ is bounded} \Leftrightarrow \text{Sp } T \text{ compact in } \mathbb{C}.$$

If now T is unbounded, then $\text{Sp } T$ is not compact in \mathbb{C} , and hence

$$\overline{\text{Sp } T}^{\mathbb{C}} = \text{Sp } T \cup \{\infty\}.$$

Since $\theta(\text{Sp } \mathfrak{A}) \subset \overline{\mathbb{C}}$ is compact, we get

$$\overline{\text{Sp } T}^{\mathbb{C}} = \theta(\text{Sp } \mathfrak{A}).$$

Thus there exists a spectral measure

$$\Phi : C(\overline{\text{Sp } T}^{\mathbb{C}}) \rightarrow \mathcal{L}(\mathcal{H}).$$

To check uniqueness, let Φ' be another spectral measure, such that ∞ is a Φ' -zerosect, and $\Phi'(\text{id}) = T$. To prove $\Phi = \Phi'$, by Stone-Weierstraß we only need to show

$$\Phi'_a = \Phi_a = A, \quad \Phi'_b = \Phi_b = B.$$

We know

$$T^*T = (\Phi'_{\text{id}})^* \Phi'_{\text{id}} \subset \Phi_{|\text{id}|^2}.$$

Since T^*T is normal and hence closed, we have equality.

$$\begin{aligned} \Phi'_a(I + T^*T) &= \Phi'_a \Phi'_{1+|\text{id}|^2} \subset \Phi'_{a(1+|\text{id}|^2)} = I \\ &= \Phi'_{a(1+|\text{id}|^2)} = \Phi'_a \Phi'_{(1+|\text{id}|^2)} = (I - T^*T) \Phi'_a, \end{aligned}$$

that is

$$\begin{aligned} \Phi'_a &= (I + T^*T)^{-1} = A \\ \Phi'_b &= \Phi'_{\text{id} \cdot a} = \Phi'_{\text{id}} A = T A = B. \end{aligned}$$

□

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