FREDHOLM OPERATORS BETWEEN HILBERT C*-MODULES

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The content here presented was produced during the last academic year of my bachelor’s degree in Mathematics at the Institute of Mathematics and Statistics of the University of São Paulo (IME-USP). This material represents a very important end of cycle for me, and therefore, I need to thank those responsible for not letting me give up on everything.

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- Francisco Felipe Chagas Rangel;
- Zeus Santos Nazaro da Silva;

[1] Do not forget that these are the one who tastes better!

- Isabella Matias Silva;
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Introduction

Contextualization

The present document builds upon Ruy Exel's paper "A Fredholm Operator approach to Morita Equivalence" [10], in a closer look to details. In it, the theory of generalized Fredholm operators between Hilbert C^*-modules is developed, and a generalization of the Brown, Green and Rieffel theorem concerning induced K-groups on equivalent Morita-Rieffel C^*-algebras is demonstrated. Here, I make sure to include all definitions and theorems necessary to understand the machinery developed by Exel in that article. In addition, I will include all the comments that I deemed relevant during my understanding of these topics.

The original theorem (henceforth, BGR) does not concern any K-theoretic relations, but the connection between a version of Morita equivalence for separable C^*-algebras A and B (claiming the existence of a certain (A, B)-bimodule) and what they call *stably isomorphic* relation between A and B, i.e. if $\mathscr{K}$ is the algebra of compact operators on a infinite dimensional separable Hilbert space, then $A \otimes \mathscr{K} \simeq B \otimes \mathscr{K}$. The theorem quoted above can be stated as:

> **Theorem** (BGR - [6, Theorem 1.2]) Let A and B be C^*-algebras. If A and B are "stably isomorphic", then they are strongly Morita equivalent. Conversely, if A and B are strongly Morita equivalent and if they both possess strictly positive elements, then they are stably isomorphic.

From now on, we follow Exel's terminology and we rename Rieffel's strong Morita equivalence to Morita-Rieffel equivalence.

A corollary of BGR is that σ-unital Morita-Rieffel equivalent C^*-algebras induce the same K-groups. In the original concept, the separability condition of the algebras is crucial for this result, given that the authors themselves found cases in which the theorem does not hold for non-separable ones. However, the same question about the induced K-groups was open when one abstains from this separability requirement. Besides that, the original proof guarantees that $A \otimes \mathscr{K}$ and $B \otimes \mathscr{K}$ are isomorphic, but without any clue on what this isomorphism should be. Hence, there is not any explicit expression to the induced K-theoretic isomorphism.

In his work, Exel exhibited explicit isomorphisms $K_0(A) \longrightarrow K_0(B)$ and $K_1(A) \longrightarrow K_1(B)$ for two C^*-algebras A and B Morita-Rieffel equivalents, dribbling the separability hypothesis. He achieves this goal by treating the mentioned Fredholm operators as in MINGO's approach [17] and obtaining the abelian group $F(A)$ of equivalence classes of (all) A-Fredholm operators with the same index.

This is the work of an undergraduate student who wanted to facilitate further studies in those topics with a more unified reference containing all the necessary ingredients. We developed all the necessary theory of Hilbert C^*-Modules and A-Fredholm operators. I encourage any reader to treat this document as a journey through many faces of mathematics, and to obviously check the source, which is available in Exel's website.

Itinerary

Here, we focus on detailing the construction of those Fredholm operators and the necessary predecessor steps. Therefore our road map can be described as follows:

(*i*) *K-theory for Banach Algebras*: Since the main result is a K-theoretic one and the index of our A-Fredholm operators will be elements of K_0, Chapter 1 is devoted to contain a minimalist toolkit bag, which consists of the definitions of the abelian groups $K_0(A)$ and $K_1(A)$ for a Banach algebra A, and the index map induced in a short exact sequence. Some famous properties about the K-theory of operator algebras will be mentioned, but only as snacks at boring adult parties.

(*ii*) *Hilbert and Finite-rank C^*-Modules*: In order to define the so-called *Fredholm operators* between Hilbert C^*-modules, naturally, one needs to understand what those modules are, where they live and what they feed on. The initial sections in Chapter 2 tackle abstract versions of these questions in a mathematical sense. In particular, one needs to understand a new notion of compactness and the so-called *finite-rank* modules described in Section 2.3. Those will replace our notion of finite-dimensionality.

One of the greatest technical theorems used in EXEL's arguments is the Kasparov Stabilization Theorem 2.4.6 presented in Section 2.4, being crucial to discarding the separability assumption in the target theorem and the definition of Fredholm operators, which will require the classification Theorem 2.6.3 about the *Quasi-Stably-Isomorphic Finite-Rank Hilbert C^*-modules*, to which the last Sections of Chapter 2 are dedicated. The purpose of this Chapter is to be a more detailed Section 2 of EXEL's paper [10].

(*iii*) *Generalised Fredholm operators*: As you may anticipate by the spoiling title, Chapter 3 is the place where the big star of the show is treated. Since our Fredholm operators don't need to have closed range, typical arguments involving projections can't be used. This will lead us to define in Section 3.1 a "smaller" class, called the *regular* operators, whose index can be defined. Later, it'll be shown that every general Fredholm operator can be regularized. Finally, we finish the Chapter by constructing a Fredholm portrait of $K_0(A)$, giving birth to an abelian group $F(A)$ and a isomorphism $\mathit{ind} : F(A) \longrightarrow K_0(A)$.

(iv) *A sketch of Exel's application to Morita Equivalence*: Up to this point, there is already too much to digest. Therefore, we discuss briefly what Morita-Rieffel equivalence is, and present only the skeleton of the arguments used by Exel, quoting without proving his main results.

All sections are filled with some examples and some historical context which I believe give a useful perspective. All C^*-algebras that appear in this text are complex, i.e. complex Banach algebras A endowed with an *involution*[2] $*$ which obeys the C^*-identity: $\|a^*a\| = \|a\|^2$ for all $a \in A$. If it is needed for some reader, I would recommend the absolute masterpiece produced by N. Wegge-Olsen [29], which contains not only results about C^*-algebras, but also K-theory, Hilbert C^*-modules and even some comments about Mingo's generalized Fredholm operators and their index.

[2] An operation $a \longmapsto a^*$ which is conjugate-linear, anti-commutative and has order 2

Contents

Chapter 1

K-theory of Banach Algebras

1.1 General portrait of homological theories

A homological theory for a category $\mathcal{C}$ consist in a sequence of covariant functors $H_n : \mathcal{C} \longrightarrow \mathbf{GrpAb}$ for each $n \in \mathbb{N}$ which satisfies some set of axioms, which depends on what theory one is interested. For example, if $\mathcal{C}$ contains a nice homotopical concept, it is rather common to ask for homotopical invariance. Some other axioms are required to obtain long exact sequences in order to deal with short exact sequences. The usual notation is:

$$\begin{aligned} H_n \colon\ \mathcal{C} &\longrightarrow \mathbf{GrpAb} \end{aligned}$$

$$\begin{tikzcd} A \arrow[r, mapsto] \arrow[d, "\phi"'] & H_n(A) \arrow[d, "\phi_n"'] \\ B \arrow[r, mapsto] & H_n(B) \end{tikzcd}$$

We also need a way to translate short exact sequences of the form

$$0 \longrightarrow A \longrightarrow B \longrightarrow C \longrightarrow 0$$

from the original category to higher counterparts obtained by H_n, hence, every homology theory seeks to define a connecting morphism $\delta_n : H_n(C) \longrightarrow H_{n+1}(A)$ into a long exact sequence:

$$\begin{tikzcd} H_0(A) \arrow[r] & H_0(B) \arrow[r] & H_0(C) \arrow[dll, rounded corners, "\delta_0"] \\ H_1(A) \arrow[r] & H_1(C) \arrow[r] & H_1(B) \arrow[dll, rounded corners, "\delta_1"] \\ H_2(A) \arrow[r] & H_2(B) \arrow[r] & \cdots \end{tikzcd}$$

On the other hand, as everything containing the prefix "co", cohomology theories are consisted of contra-variant functors $(H^n)_n$ with the same pay-off. The position of the index on the notation usually indicates what sort of theory one is dealing with.

Here we are concerned with a homology theory for complex Banach Algebras $\mathscr{B}$-**Alg** or, more popularly, for C^*-algebras $\boldsymbol{C^*}$- **Alg**, a.k.a., K-theory for Operator Algebras. It is the mirror image of Topological K-theory (developed by M. F. Atiyah and F. Hirzebruch [4]), in light of *Gelfand Duality* connecting the category of Locally Compact Hausdorff spaces and complex abelian C^*-algebras, but not restricted to commutative spaces, which is often referred to as the "Non-Commutative Topology".

We shall construct functors $K_n : \mathscr{B}\text{-}\mathbf{Alg} \longrightarrow \mathbf{GrpAb}$ and the connecting maps will be call *index map*, denoted by ∂. A remarkable aspect of operator K-theory is the *Bott periodicity*: $K_n \simeq K_{n+2}$, which then describes for any short exact sequence $0 \longrightarrow I \longrightarrow A \longrightarrow A/I \longrightarrow 0$, where $I \triangleleft A$, a six-term exact sequence:

$$\begin{tikzcd}
K_0(I) \arrow[r] & K_0(A) \arrow[r] & K_0(A/I) \arrow[d, "\partial"] \\
K_1(A/I) \arrow[u, "\partial"] & K_1(A) \arrow[l] & K_1(I) \arrow[l]
\end{tikzcd}$$

The details about functorial properties will be spared since it is outside of our scope. We will only include the definition of the groups K_0 and K_1 for complex Banach algebras, and the index map mentioned. The connecting map will be used in the classification of finite rank modules (Theorem 2.6.3), and later on, the index of our Fredholm operators. Hence it is important to define it in a helpful way.

1.2 The K_0-group

Our object is to deal with Hilbert C^*-modules, which are complete right A-modules with a generalized A-valued inner product for a given C^*-algebra A (plus some other details listed in 2.1.1), generalizing the concept of Hilbert space. Unfortunately, as we will see later on, there is no *Riesz representation lemma* and, there exists bounded linear operators that are not adjointable between Hilbert modules 2.2.5.

K-theory will be important since the index of our Fredholm operators will take values in the K_0 group of the scalar coefficients algebra A. Therefore, it is reasonable to understand some K-theory for C^*-algebras. But, it will be convenient to consider non necessarily self-adjoint idempotents (e.g. in the proof of 2.6.3), so that we can use K-theory for Banach algebras as our machinery. This is no big deal at all, since the induced constructions are equivalent when the Banach algebra in question happens to be a C^*-algebra.

For a given Banach Algebra A, the following definitions and constructions are inspired in the topological framework, by replacing vector bundles by finitely generated projective A-modules.

Definition 1.2.1. In any given Banach algebra A, for two idempotent elements x and y, define the following notions of equivalence:

(i) **Murray-von-Neuman equivalence**: There are elements $p, q \in A$ such that $x = pq$ and $y = qp$.

(ii) **Similarity**: Assuming that A is unital, there exists an invertible element $u \in \mathrm{GL}(A)$ such that $x = u^{-1}yu$.

(iii) **Homotopic**: There is a continuous path $\gamma \in C([0,1], A)$ of idempotents between x and y, i.e.,

$$\gamma(0) = x, \gamma(1) = y \quad \text{and} \quad \forall\ t \in [0,1], \gamma(t)^2 = \gamma(t).$$

If A is assured to be a C^*-algebra, those definitions are concerned with self-adjoint idempotent elements, a.k.a., projections. Two projections x, y are equivalent if there exists a *partial isometry* u such that $x = u^*u$ and $y = uu^*$.

For the canonical embedding $x \longmapsto \mathrm{diag}(x, 0)$ over matrices, consider the inductive limit $\mathbb{M}_\infty(A) := \varinjlim_{n \in \mathbb{N}} \mathbb{M}_n(A)$, which can be seen as the set of infinite matrices over A but only finitely many of the entries are non-zero.

***Remark* 1.2.2.** Note that $\mathbb{M}_\infty(A)$ contains no unity, but that doesn't stop us to declaring two elements x, y to be similar when they are similar in some square matrix space $\mathbb{M}_n(A)$. Therefore, all equivalence relations listed in the definition 1.2.1 coincide in $\mathbb{M}_\infty(A)$.

Simply shouting "Let A be a C^*-algebra" in the crowd is a powerfull classification tool, whenever is a mathematicians crowd[1].

(i) If you hear in response "unital or not?", you know that there is some C^*-algebraic fellow around you.

(ii) If the crowd contains mathematicians and no-one asks if A contains a unity or not, no C^*-algebraist is contained in the crowd. They are instantly assuming the unity is there.

This is because dealing without unital rings outside C^*-theories are usually simple. Just unitise and go on. However, the presence of unity in C^*-algebras is crucial to determine their underlying hidden topology, as explicitly is made in *Gelfand's duality* theorem.

The next definition is in charge to define the functor K_0 for both cases, but some intermediate steps are required from one to another.

Definition 1.2.3. Let A be a Banach algebra. The set of equivalence classes on $P_\infty(A) := \{x \in \mathbb{M}_\infty(A) \mid x^2 = x\}$ considering any relation $\sim$ contained in 1.2.1 is an abelian semi-group with $[x] + [y] := [\mathrm{diag}(x, y)]$. Before defining K_0, in order to include the non necessarily unital algebras, it is needed to be considered an auxiliar functor K_{00} much closer to the topological counterpart K^0 for compact spaces. This is necessary in order to obtain the Bott periodicity result for Banach algebras, and other good functorial properties.

[1]Otherwise, you are just playing creepy at dinner table again.

(i) $\boldsymbol{K_{00}}$: It is the Grothendieck group construction associated with the semi-group $V(A) \coloneqq P_\infty(A)/\!\sim$ where addition is given by $[x]+[y] \coloneqq [\mathrm{diag}(x,y)]$, generalising the construction of $\mathbb{Z}$ from $\mathbb{N}$ considering formal differences. In lighter sheets, for pairs (a,b) and (c,d) of elements in $V(A)$, let $(a,b) \equiv (c,d)$ whenever there exists[2] $z \in V(A)$ such that $a+d+z = c+b+z$. This is an equivalence relation over the pairs, and $[\,\cdot\,]_{00}$ will denote the related equivalence class.

We are mimicking the formal differences construction, so it is natural to define the addition operation coordinate-wise and let $[x]_{00} - [y]_{00} \coloneqq [(x,y)]_{00}$. Therefore, it is well defined the following covariant functor:

$$K_{00}\colon \quad \mathscr{B}\textbf{-Alg} \longrightarrow \textbf{GrpAb}$$

$$\begin{array}{ccccc} A & \longmapsto & V(A)\times V(A)/\!\equiv & & [x]_{00}-[y]_{00} \\ {\scriptstyle\phi}\downarrow & & {\scriptstyle\phi_{00}}\downarrow & & \downarrow \\ B & \longmapsto & V(B)\times V(B)/\!\equiv & & [\phi(x)]_{00}-[\phi(y)]_{00} \end{array}$$

Since every element in $V(A)$ is the class of some idempotent matrix p, we can state that every element in $K_{00}(A)$ is on the form $[p]_{00} - [q]_{00}$.

(ii) $\boldsymbol{K_0}$: In our next step, it's crucial to know exactly who $K_{00}(\mathbb{C})$ is. Hence, remember that two idempotents in $\mathbb{M}_n(\mathbb{C})$ are similar if, and only if, their images has the same dimension. Therefore $V(\mathbb{C}) \simeq \mathbb{N}$, and by historical nightmares with Analysis I exercise constructing the integer numbers, it is easy to infer that $K_{00}(\mathbb{C}) = \mathbb{Z}$.

For non necessarily unital A, consider $\widetilde{A} \coloneqq A \oplus \mathbb{C}$ the *unitisation* of A and the complex projection $\varepsilon : \widetilde{A} \twoheadrightarrow \mathbb{C}$, which induces the short exact sequence:

$$0 \longrightarrow A \hookrightarrow \widetilde{A} \xrightarrow{\ \varepsilon\ } \mathbb{C} \longrightarrow 0$$

The urge to obtain Bott periodicity theorem for Banach algebras, which is a relation between K_0 and K_1 in the presence of short exact sequences, will obligate the exactness of the following:

$$0 \longrightarrow K_0(A) \hookrightarrow K_0(\widetilde{A}) \xrightarrow{\ \varepsilon_0\ } K_0(\mathbb{C}) \longrightarrow 0$$

Since it is a morphism between unital Banach algebras, the induced map $\varepsilon_{00} : K_{00}(\widetilde{A}) \longrightarrow \mathbb{Z}$ is a well defined morphism, hence, it is possible to define the following:

$$K_0\colon \quad \mathscr{B}\textbf{-Alg} \longrightarrow \textbf{GrpAb}$$

$$\begin{array}{ccccc} A & \longmapsto & \ker(K_{00}(\widetilde{A}) \to \mathbb{Z}) & & a+z \\ {\scriptstyle\phi}\downarrow & & {\scriptstyle\phi_0}\downarrow & & \downarrow \\ B & \longmapsto & \ker(K_{00}(\widetilde{B}) \to \mathbb{Z}) & & \phi(a)+z \end{array}$$

[2] Since it is only a semi-group, the cancelation property do not hold necessarily over $V(A)$. One might check that this is the case if, and only if, the canonical map of $V(A)$ to the Grothendieck's associated group is injective.

Notice that $K_0(A)$ is precisely the set of elements $[p]_0 - [q]_0 \in K_{00}(\widetilde{A})$ such that $\varepsilon(p) \sim \varepsilon(q)$. If A is already unital, it is possible to show that $K_0(A) \simeq K_{00}(A)$.

***Remark* 1.2.4.** The argument to show that $V(\mathbb{C}) \simeq \mathbb{N}$ is equivalent for compact operators in an infinite-dimensional Hilbert space H, i.e. $V(\mathscr{K}(H)) \simeq \mathbb{N}$, which means that $K_0\mathscr{K}(H) = \mathbb{Z}$. On the other hand, any two infinite rank projections in $\mathscr{B}(H)$ are equivalent, hence $V\mathscr{B}(H) \simeq \mathbb{N}\cup\{\infty\}$, which is a semi-group without the cancellation property. Since everyone is equivalent to ∞, it is obtained that $K_{00}\mathscr{B}(H) \simeq 0$. The semi-group $V(A)$ has the cancellation property if, and only if, the inclusion $V(A) \hookrightarrow K_{00}(A)$ is injective.

Proposition 1.2.5 (Standard portrait of K_0)**.** Every element of $K_0(A)$ can be written as $[x + p_n]_0 - [p_n]_0$ where $x \in \mathbb{M}_{2n}(A)$ and $p_n \coloneqq \mathrm{diag}(I_n, 0)$.

Proof. Let $p, q \in \mathbb{M}_\infty(\widetilde{A})$ be some idempotent square matrices with order not larger than n, such that $\varepsilon_0([p]_0 - [q]_0) = 0$, i.e. $[p]_0 - [q]_0 \in K_0(A)$. Matrices $p \in \mathbb{M}_n(\widetilde{A})$ can be written as $(p_A, p_\mathbb{C}) \in \mathbb{M}_n(A) \oplus \mathbb{M}_n(\mathbb{C})$, i.e. an algebraic part p_A and a scalar part $p_\mathbb{C}$. Stating that $\varepsilon_0([p]_0 - [q]_0) = 0$ means that the scalar parts of p and q coincide.

The identity $I_n \in \mathbb{M}_\infty(\widetilde{A})$ can be seen as the projection operator of the first n-th coordinates, by filling it with 0's, but to avoid confusions, let it be denoted by p_n. With $y \leqslant x$ be given by $xy = yx = y$, one may see that $p \leqslant p_n$ and $q \leqslant p_n$. Notice that $\mathrm{diag}(0, p) \in \mathbb{M}_{2n}(\widetilde{A})$ is similar to p and orthogonal to I_n, i.e.

$$\begin{pmatrix} 0 & 0 \\ 0 & p \end{pmatrix}\begin{pmatrix} I_n & 0 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} I_n & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 & 0 \\ 0 & p \end{pmatrix} = 0.$$

Hence, the element $x \coloneqq \mathrm{diag}(-q, p)$ makes $x + p_n$ an idempotent and:

$$\begin{aligned} [x + p_n]_0 - [p_n]_0 &= [\mathrm{diag}(0,p)]_0 + [p_n - q]_0 - ([p_n - q]_0 + [q]_0) \\ &= [p]_0 - [q]_0 . \end{aligned}$$

□

1.3 The K_1-group

While K_0 is build upon equivalence classes of idempotent elements, K_1 uses invertible elements, and this makes the construction simpler. Let $\mathrm{GL}_\infty(A) \coloneqq \varinjlim_{n\in\mathbb{N}} \mathrm{GL}_n(A)$ considering the embedding $x \longmapsto \mathrm{diag}(x, 1)$. Calculus is back, and we shall consider exponentials inside a unital algebra A:

$$\exp(a) \coloneqq \sum_{n=0}^{\infty} \frac{a^n}{n!} \quad \text{and} \quad \log(1 + a) \coloneqq \sum_{n=1}^{\infty} -\frac{a^n}{n} \qquad (a \in A)$$

where the log is defined whenever $\|a\| < 1$. This is the case since elements of the form $z - a$ for complex z are invertible if $\|a\| < |z|$. If a and b does not commute, $\exp(a)\exp(b) \neq \exp(a + b)$. Moreover, it can be shown that the set of exponentials are not closed by multiplications.

Lemma 1.3.1. For a unital Banach algebra A, the connected component of the unity is the group generated by $\{\exp(a) \mid a \in A\} \subset \mathrm{GL}(A)$, denoted by $\exp(A)$.

Proof. Let $\mathrm{GL}^{(0)}(A)$ be the refered set, the connected component of 1. Notice that $t \longmapsto \exp(tb)$ for $t \in [0,1]$ is a continuous path of invertible elements between 1 and $\exp(b)$ for any b, hence $\exp(A) \subset \mathrm{GL}^{(0)}(A)$. It remais only to show the converse inclusion.

For some a with $\|1-a\| < 1$, let $b := \log(1+(a-1)) = \log(a)$, i.e. $a = \exp(b)$. Therefore, if $u \in \mathrm{GL}(A)$ and $\|v-u\| < \|u^{-1}\|^{-1}$, this means that $v = \exp(b)u$ for some b. But notice that for every $t \in [0,1]$, the following inequalities hold:

$$\|(1+t(u^{-1}v-1))-1\| = t\|u^{-1}v-1\| \leqslant t\|u^{-1}\|\|v-u\| < 1.$$

Hence $1+t(u^{-1}v-1)$ and $u+t(v-u)$ are invertible elements for all $t \in [0,1]$. From this treatment, if follows that $\exp(A)$ is an open and closed topological subspace of $\mathrm{GL}^{(0)}(A)$ which contains the unity, i.e. $\mathrm{GL}^{(0)}(A)$ coincides with $\exp(A)$. □

***Remark* 1.3.2.** Let $M \in \mathrm{GL}_n(\mathbb{C})$. Since 0 cannot be an eigenvalue of M (which is a finite set), it's possible to find $\alpha > 0$ such that $[0,\alpha]$ does not contains any of the eigenvalues of M or 1. Therefore, $1-\alpha t \neq 0$ for all $t \in [0,1]$ and $M_t := (1-\alpha t)^{-1}(M - t\alpha I_n)$ is a continuous path from M to the identity, i.e. $\mathrm{GL}_n(\mathbb{C})$ is connected.

In a not so distant future, the following result will be important in the presence of an ideal $I \lhd A$, when considering the usual projection $A \twoheadrightarrow A/I$.

Corollary 1.3.3. Any continuous surjection $A \longrightarrow B$ induces a lift from every element in $\mathrm{GL}_n^{(0)}(B)$ to one in $\mathrm{GL}_n^{(0)}(A)$.

Proof. Using 1.3.1, write $\prod_i \exp(b_i) \in \mathrm{GL}_n^{(0)}(B)$ for any desired element. Since there is a surjection, there exists lifts $a_i \in \mathrm{GL}_n(A)$ to each b_i such that $\prod_i \exp(a_i) \in \mathrm{GL}_n^{(0)}(A)$. □

Considering the homotopy equivalence relation, two elements in $\mathrm{GL}_\infty(A)$ are homotopical whenever they are in the same connected component in some $\mathrm{GL}_n(A)$. Denote the equivalence class by $[\,\cdot\,]_1$. Whence, the quotient $\mathrm{GL}_\infty(A)/\mathrm{GL}_\infty^{(0)}(A)$ is an abelian group with the multiplication $[x]_1[y]_1 = [xy]_1$. This operation is well defined since Homotopies are preserved by multiplication, hence $x \equiv x'$ and $y \equiv y'$ if, and only if $xy \equiv x'y'$. It's commutative once you note it is possible to find a connected path[3] between $\operatorname{diag}(y,1)$ and $\operatorname{diag}(1,y)$, hence

$$[x]_1[y]_1 = [xy]_1 = \left[\begin{pmatrix} xy & 0 \\ 0 & 1 \end{pmatrix}\right]_1 = \left[\begin{pmatrix} x & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} y & 0 \\ 0 & 1 \end{pmatrix}\right]_1 = \left[\begin{pmatrix} x & 0 \\ 0 & y \end{pmatrix}\right]_1$$

and similarly, one shows that $[xy]_1 = [\operatorname{diag}(y,x)]_1 = [y]_1[x]_1$. There we have, our $K_1(A)$ group. Since $\mathrm{GL}_n(\mathbb{C})$ is connected, it follows immediately that $K_1(\mathbb{C}) = 0$ and, therefore, we can deal with units the way it is intended: for non necessarily unital algebras A, let $K_1(A) := K_1(\widetilde{A})$.

[3] Let $z(\theta) = \left(\begin{smallmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{smallmatrix}\right)$ be the rotation matrix by some angle θ. Therefore, the continuous map $[0,\pi/2] \ni \theta \longrightarrow z(\theta)\operatorname{diag}(y,1)z(\theta)^{-1}$ is the desired path.

Definition 1.3.4. The functor K_1 can be seen as the following:

$$
\begin{array}{rccc}
K_1 : & \mathscr{B}\text{-}\mathbf{Alg} & \longrightarrow & \mathbf{GrpAb} \\
& A & \longmapsto & \mathrm{GL}_\infty(\widetilde{A})/\mathrm{GL}^{(0)}_\infty(\widetilde{A}) \qquad [x]_1 \\
& {\scriptstyle\phi}\downarrow & & {\scriptstyle\phi_1}\downarrow \qquad\qquad \downarrow \\
& B & \longmapsto & \mathrm{GL}_\infty(\widetilde{B})/\mathrm{GL}^{(0)}_\infty(\widetilde{B}) \quad [\phi(x)]_1
\end{array}
$$

Remark **1.3.5.** It should be stated that if one is dealing with a C^*-algebra, then K_1 can be obtained by the set of unitary matrices $U_n(A)$, i.e. $u^* = u^{-1}$; Since $U_n(A)/U_n^{(0)}(A) \cong \mathrm{GL}_n(A)/\,\mathrm{GL}_n^{(0)}(A)$, one can obtain a deformation retraction from $\mathrm{GL}_n(A)$ to $U_n(A)$ by the polar decomposition, hence, $K_1(A)$ is isomorphic to $U_\infty(A)/U_\infty^{(0)}(A)$.

1.4 The index map

Many important functorial properties like homotopy invariance, stability and half exactness are shared by K_0 and K_1, but in our needs, they will not be necessary. The reader may recall to [5] or [29] to a proper course.

We are now ready to define the so called index map. This name comes from the Fredholm operator theory since what we are about to construct is a generalization of the index of those operators. Consider $\mathscr{B}(H)$ the C^*-algebra of bounded operators between a Hilbert space H, and $\mathscr{K}(H)$ the ideal of compact operators. The *Atkinson* theorem states precisely that the *Calkin* algebra $\mathscr{Q}(H) \coloneqq \mathscr{B}(H)/\mathscr{K}(H)$ is a classifying one: T is a Fredholm operator if, and only if, $(T \bmod \mathscr{K}(H)) \in \mathrm{GL}\,\mathscr{Q}(H)$.

Since $K_0\mathscr{K}(H) = \mathbb{Z}$ and $K_1\mathscr{Q}(H)$ can be seen as the set of Fredholm operators up to homotopy[4], the index map $\mathit{ind} : K_1\mathscr{Q}(H) \longrightarrow K_0\mathscr{K}(H)$ is well defined. Our index map ∂ will generalize this map.

Construction 1.4.1. Let $I \lhd A$ and consider the following short exact sequence:

$$0 \longrightarrow I \hookrightarrow A \twoheadrightarrow {}^{A}\!/_{I} \longrightarrow 0$$

We are in position to construct $\partial : K_1(A/I) \longrightarrow K_0(I)$. For $[x]_1 \in K_1(A/I)$, let n be such that $x \in \mathrm{GL}_n(\widetilde{A/I})$. It's about time for the corollary 1.3.3 to shine: Since the projection $A \twoheadrightarrow A/I$ is a continuous surjection, so it is the unitisation induced morphism between the algebras, hence, one can lift the element $\mathrm{diag}(x, x^{-1}) \in \mathrm{GL}^{(0)}_{2n}(\widetilde{A/I})$ to some $w \in \mathrm{GL}^{(0)}_{2n}(\widetilde{A})$.

If $\pi : \mathrm{GL}_\infty(\widetilde{A}) \twoheadrightarrow \mathrm{GL}_\infty(\widetilde{A/I})$ is the quotient projection, notice that $\pi(wp_nw^{-1}) = p_n$, so that $wp_nw^{-1} \in \widetilde{I}$. Since wp_nw^{-1} is also an idempotent, notice that $[wp_nw^{-1}]_0 - [p_n]_0 \in K_0(I)$. And this is the image of the index map ∂ of some element $[x]_1$.

[4]Remind that two Fredholm operators in the same realm have the same index if, and only if they are homotopic.

An anxious mind would immediately panic. We have a TO-DO list before calling the day:

(*i*) Check that $[wp_nw^{-1}]_0 - [p_n]_0$ doesn't depend on the lift w chosen;

(*ii*) Check that $\partial([x]_1) = \partial([y]_1)$ for $x \equiv y$.

(*iii*) Check that ∂ is a group morphism.

Proof of TO-DO list items. If v is another lift of $\operatorname{diag}(x, x^{-1})$, notice that

$$vp_nv^{-1} = (vw^{-1})wp_nw^{-1}(vw^{-1})^{-1},$$

i.e. vp_nv^{-1} is similar to wp_nw^{-1}. This is enough to take care of (*i*).

In order to show that the index is well defined, suppose that $y \in \mathrm{GL}_n(\widetilde{A/I})$ is equivalent to x. Notice that

$$x^{-1}y \in \mathrm{GL}_n^{(0)}(\widetilde{A/I}) \quad \text{and} \quad \begin{pmatrix} x & 0 \\ 0 & I_n \end{pmatrix}\begin{pmatrix} I_n & 0 \\ 0 & y^{-1} \end{pmatrix} \in \mathrm{GL}_{2n}^{(0)}(\widetilde{A/I})$$

so by the corollary 1.3.3 again, let $a \in \mathrm{GL}_n^{(0)}(\widetilde{A})$ and $b \in \mathrm{GL}_{2n}^{(0)}(\widetilde{A})$ be the lifts respectively. But then $u := w\operatorname{diag}(a, b)$ is a lift of $\operatorname{diag}(y, y^{-1})$. From the fact that p_n commutes with $\operatorname{diag}(a, b)$, it is obtained that $up_nu^{-1} = wp_nw^{-1}$. Since we already showed that the choice of lift doesn't matter, (*ii*) is checked.

For $x, y \in \mathrm{GL}_n(\widetilde{A/I})$, suppose that w is a lift of $\operatorname{diag}(x, x^{-1})$ and v is a lift of $\operatorname{diag}(y, y^{-1})$. Notice that $\varpi := \operatorname{diag}(w, v)$ is a lift of $\operatorname{diag}(x, y, x^{-1}, y^{-1})$, hence

$$\begin{aligned}
\partial([x]_1[y]_1) &= [\varpi p_{2n}\varpi^{-1}]_0 - [p_{2n}]_0 \\
&= \left[\begin{pmatrix} w & 0 \\ 0 & v \end{pmatrix}\begin{pmatrix} p_n & 0 \\ 0 & p_n \end{pmatrix}\begin{pmatrix} w & 0 \\ 0 & v \end{pmatrix}^{-1}\right]_0 - \left[\begin{pmatrix} p_n & 0 \\ 0 & p_n \end{pmatrix}\right]_0 \\
&= \left[\begin{pmatrix} wp_nw^{-1} & 0 \\ 0 & vp_nv^{-1} \end{pmatrix}\right]_0 - \left[\begin{pmatrix} p_n & 0 \\ 0 & p_n \end{pmatrix}\right]_0 \\
&= [wp_nw^{-1}]_0 - [p_n]_0 + [vp_nv^{-1}]_0 - [p_n]_0 = \partial[x]_1 + \partial[y]_1
\end{aligned}$$

Therefore, it is a group morphism as our final item (*iii*) assures. □

Definition 1.4.2 (Index map in K-theory)**.** Using construction 1.4.1, the group morphism so called *index* map is given by

$$\begin{aligned}
\partial :\ K_1(A/I) &\longrightarrow K_0(I) \\
[x]_1 &\longmapsto [wp_nw^{-1}]_0 - [p_n]_0
\end{aligned}$$

whenever $x \in \mathrm{GL}_n(\widetilde{A/I})$ and $w \in \mathrm{GL}_{2n}^{(0)}(\widetilde{A})$ is a lift of $\operatorname{diag}(x, x^{-1})$.

Example 1.4.3. In a unital C^*-algebra A, if a unitary idempotent element u in $\mathrm{GL}_n(A/I)$ lifts to $v \in \mathbb{M}_n(A)$, the element

$$w := \begin{pmatrix} v & I_n - v^*v \\ I_n - vv^* & v^* \end{pmatrix}$$

is a lift for $\mathrm{diag}(u, u^{-1})$. Therefore:

$$\begin{aligned} \partial\,[u]_1 &= \left[wp_nw^{-1}\right]_0 - [p_n]_0 \\ &= \left[\begin{pmatrix} v & I_n - v^*v \\ I_n - vv^* & v^* \end{pmatrix}\begin{pmatrix} I_n & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} v^* & I_n - vv^* \\ I_n - v^*v & v \end{pmatrix}\right]_0 - \left[\begin{pmatrix} I_n & 0 \\ 0 & 0 \end{pmatrix}\right]_0 \\ &= \left[\begin{pmatrix} vv* & 0 \\ 0 & I_n - vv^* \end{pmatrix}\right]_0 - \left[\begin{pmatrix} I_n & 0 \\ 0 & 0 \end{pmatrix}\right]_0 \\ &= [I_n - v^*v]_0 - [I_n - vv^*]_0 \end{aligned}$$

Notice that when $A = \mathscr{B}(H)$ and $I = \mathscr{K}(H)$, we dealing again with Fredholm operators living in the Calkin algebra $\mathscr{Q}(H)$ and ∂ coincides with the Fredholm index, since $I_n - vv^*$ is a projection and

$$\partial\,[u]_1 = \boldsymbol{rank}\ (I_n - v^*v) - \boldsymbol{rank}\ (I_n - vv^*) = \dim\ker u - \dim\operatorname{coker} u.$$

Chapter 2

Hilbert C^*-modules

Hilbert modules first appeared in the work of I. Kaplansky [13] and W. Paschke [19] later. There are three main areas where Hilbert C^*-modules are heavily used to formulate mathematical concepts involving:

(i) **Induced representations of Morita equivalence** [6, 23, 22];

(ii) **Kasparov's KK-theory** [14];

(iii) **Cuntz-Pimsner algebras** [26, 24, 7];

(iv) **C^*-algebraic quantum groups** [30, 1];

(v) **Quantum Stochastic Differential Geometry** [3].

In what is tangible to this work, we address the Morita equivalence target by building a Fredholm operator approach between Hilbert modules, introduced by R. Exel [10]. Hence, this chapter is responsible for defining and studying those objects.

The material source contains for this chapter is contained the well written textbooks like [15, 12, 16].

2.1 The interest object

Definition 2.1.1 (Inner Product Module)**.** A right module E over a C^*-algebra (non-necessarily unital) blessed with a generalized inner product $\langle \cdot\,, \cdot \rangle : E \times E \longrightarrow A$ will be said to be a *inner product module* when $\langle \cdot\,, \cdot \rangle$ attends the following properties:

(i) **Twisted A-sesquilinear**: The first coordinate are involute-linear and the second one linear, i.e.,

$$\begin{cases} \langle x + ya, z \rangle = \langle x, z \rangle + a^* \langle y, z \rangle \\ \langle z, x + ya \rangle = \langle z, x \rangle + \langle z, y \rangle a \end{cases} \qquad \begin{pmatrix} x, y, z \in E \\ a \in A \end{pmatrix}$$

(ii) **A-Hermitian symmetry**: $\langle x, y \rangle = \langle y, x \rangle^*$ whenever $x, y \in E$.

(*iii*) **Positive definite**: For any $x \in E$, $\langle x, x\rangle = 0 \Leftrightarrow x = 0$. By (*ii*), we can say that $\langle x, x\rangle \geqslant 0$ since it is self-adjoint.

One could argue that we only need the inner product to be linear in the second coordinate and by the Hermitian symmetry conclude as a proposition that every inner product over Inner product modules is indeed twisted sesquilinear.

Proposition 2.1.2 (Cauchy-Schwartz inequality)**.** For any Inner product module E over A, the following inequality holds:

$$\|\langle x, y\rangle\|^2 \leqslant \|\langle x, x\rangle\| \cdot \|\langle y, y\rangle\|. \qquad (x, y \in E) \tag{2.1}$$

Proof. Given the fact that $0 \leqslant \langle a, a\rangle$ for $a \in A$, notice that with the accessory elements $a := \langle x, x\rangle$, $b := \langle y, y\rangle$ and $c := \langle x, y\rangle$,

$$\begin{aligned} 0 &\leqslant \langle x - ytc^*, x - ytc^*\rangle \\ &= \langle x, x - ytc^*\rangle - tc\langle y, x - ytc^*\rangle \\ &= \langle x, x\rangle - \langle x, y\rangle\, tc^* - tc\langle y, x\rangle + tc\langle y, y\rangle tc^* \\ &= a - 2tcc^* + t^2 cbc^* \end{aligned} \qquad (t \in \mathbb{R})$$

Since $2tcc^*$ is self-adjoint, we can add in both sides and maintain the inequality in the C^*-realm. Using the A-norm and assuming $t \geqslant 0$,

$$\begin{aligned} 2t\|cc^*\| &\leqslant \|a\| + t^2\|cbc^*\| \\ &\leqslant \|a\| + t^2\|c\|\|b\|\|c^*\| \\ \Rightarrow \quad 2t\|c\|^2 &\leqslant \|a\| + t^2\|b\|\|c\|^2 \end{aligned} \tag{2.2}$$

With a fairly nice quadratic polynomial in $\mathbb{R}[t]$ generated by (2.2) in our hands witch is always non negative, the discriminant must be non positive. Therefore:

$$\begin{aligned} (-2\|c\|^2)^2 - 4\|b\|\|c\|^2\|a\| &\leqslant 0 \\ \Rightarrow \quad \|\langle x, y\rangle\|^4 - \|\langle y, y\rangle\|\|\langle x, y\rangle\|^2\|\langle x, x\rangle\| &\leqslant 0 \end{aligned} \tag{2.3}$$

Assuming $\|\langle x, y\rangle\|^2 \neq 0$ means that (2.3) can be simplified into Cauchy-Schwartz inequality (2.1) by canceling $\|\langle x, y\rangle\|^2$. Otherwise[1], $\langle x, y\rangle = 0$ is a trivial case of the desired inequality. □

For any A-valued inner product as above, we define a norm $\|x\| := \sqrt{\|\langle x, x\rangle\|_A}$ on a Inner product C^*-module. Which means that for arbitrary $x, y \in E$ and $a \in A$, the following holds:

[1] Note that $\|\langle x, y\rangle\|^2 = 0$ if and only if $\langle x, y\rangle = 0$.

(*i*) $\|x\| = 0 \iff x = 0$.

(*ii*) $\|xa\| = \|a\|_A \|x\|$.

(*iii*) $\|x + y\| \leqslant \|x\| + \|y\|$.

Notice that the triangle inequality (*iii*) is a direct consequence of 2.1.2:

$$\begin{array}{rcl} \|x+y\|^2 & = & \|\langle x+y, x+y\rangle\|_A \\ & = & \|\langle x,x\rangle + \langle x,y\rangle + \langle y,x\rangle + \langle y,y\rangle\|_A \\ & \leqslant & \|x\|^2 + \|\langle x,y\rangle\|_A + \|\langle x,y\rangle^*\|_A + \|y\|^2 \\ & = & \|x\|^2 + 2\|\langle x,y\rangle\|_A + \|y\|^2 \\ & \overset{2.1.2}{\leqslant} & \|x\|^2 + 2\|x\|\|y\| + \|y\|^2 = (\|x\| + \|y\|)^2 \end{array}$$

as in the good old days. One identity that still remais is the polarization one: For every sesquilinear form $\varsigma : E \times E \longrightarrow A$

$$4\varsigma(y,x) = \sum_{n=0}^{3} i^n \varsigma(x + i^n y, x + i^n y). \qquad (x, y \in E) \tag{2.4}$$

Since it should be a normed space, hence a complex vector space, one may be concerned about the fact that A doesn't necessarily have a unit and therefore, zx for $z \in \mathbb{C}$ should be an worry.

Proposition 2.1.3. All inner product modules are naturally complex vector spaces, even the ones over non necessarily unital C^*-algebras.

Proof. Any Inner product module E is a $\mathbb{Z}$-module naturally because it is an abelian group with respect to the addition, and so is that $-\langle x,y\rangle = \langle x, -y\rangle$. Therefore, since the proof of Cauchy-Schwartz inequality 2.1.2 doesn't depend on the unity of A, no extra analysis is needed. For any approximate unit $(u_\lambda)_\lambda \subset A$, $(xu_\lambda)_\lambda \subset E$ converges to x, whence, for $z \in \mathbb{C}$, let $zx := \lim_\lambda x(zu_\lambda)$. Since A is a vector space, all properties are guaranteed and we are done. □

Definition 2.1.4. Inner product modules are called *Hilbert C^*-modules* when the induced norm is complete in the Cauchy sense.

Proposition 2.1.5. For a Hilbert C^*-module E over A, let EA denote the linear span of elements given by xa, for $x \in E$ and $a \in A$. Therefore $\overline{EA} = E$.

Proof. If $(u_\lambda)_\lambda \subset A$ is a approximate unit for A, then for all $x \in E$:

$$\begin{array}{rcl} \lim_\lambda \langle x - xu_\lambda, x - xu_\lambda\rangle & = & \lim_\lambda \left(\langle x,x\rangle - u_\lambda\langle x,x\rangle\right) \\ & & \quad - \lim_\lambda \left(\langle x,x\rangle u_\lambda - u_\lambda\langle x,x\rangle u_\lambda\right) = 0. \end{array}$$

Hence the elements of the form xu_λ are dense in E. □

***Remark* 2.1.6.** Let A and B be C^*-algebras. If E is a Hilbert B-module and the ideal I of the closure of the elements spanned by $\langle x, y\rangle$ is contained in A, then there is a way to make E into a Hilbert A-module without changing the inner product. Namely, let $(u_\lambda)_\lambda$ be an approximate unit for I. Then the identity

$$\begin{aligned}\langle xu_\eta a - xu_\lambda a, xu_\eta a - xu_\lambda a\rangle &= a^*u_\eta\langle x,x\rangle u_\eta a + a^*u_\lambda\langle x,x\rangle u_\lambda a \\ &\quad - a^*u_\eta\langle x,x\rangle u_\lambda a - a^*u_\lambda\langle x,x\rangle u_\eta a,\end{aligned}$$

holds for all $x \in E$ and $a \in A$, showing that $(xu_\lambda a)_\lambda$ converges in E. We can define $xa = \lim xu_\lambda a$, and it is straightforward to check that this makes E into a Hilbert A-module. This is particularly important when dealing with non unital C^*-algebras A, and we might have a look into the same module over $\widetilde{A}$.

Examples 2.1.7.

(*i*) Any traditional complex Hilbert space is a Hilbert $\mathbb{C}$-module.

(*ii*) Let $(E_i)_{i\in I}$ be a family of Hilbert C^*-modules over A. The direct sum will be:

$$\bigoplus_{i\in I} E_i := \Big\{x \in \prod_{i\in I} E_i \mid \sum_{i\in I}\langle x_i, x_i\rangle \in A\Big\}$$

It should be noticed that the convergence of $\sum_i\langle x_i, x_i\rangle$ is a weaker condition than requiring that the series of norms $\sum_i \|\langle x_i, x_i\rangle\|$ should converge. With the addition inner product $\langle x, y\rangle = \sum_i \langle x_i, y_i\rangle_{E_i}$, $\bigoplus_i E_i$ is a Hilbert C^*-module.

(*iii*) Subexamples of (*ii*) are: A it self endowed with $\langle a, b\rangle := a^*b$; $A^n = \bigoplus_{i=1}^n A$ for any natural number n.

(*iv*) **The standard Hilbert A-module $\mathscr{H}_A$**: Another subexample of (*ii*) can be given by $\mathscr{H}_A := \bigoplus_{n\in\mathbb{N}} A$, consisting of all sequences $(a_n)_n \subset A$ which $\sum_n a_n^*a_n$ converges.

(*v*) Given a Hilbert space H, the algebraic tensor product of H by A can be seen as an inner product C^*-module, with the bond:

$$\langle x \otimes a, y \otimes b\rangle := \langle x, y\rangle_H a^*b$$

$H \otimes A$ stands for its completion.

(*vi*) Let $X \in$ **CHaus** and $E \longrightarrow X$ a complex vector bundle. As we mention, $C(X)$ is a unital C^*-algebra. Whenever $d : E \times E \longrightarrow [0,\infty)$ is an Hermitian metric over E, the set $\Gamma(E)$ of continuous sections over E holds the title of Hilbert module over $C(X)$ when endowed with

$$\begin{aligned}\langle\,\cdot\,,\,\cdot\,\rangle :\ \ \Gamma(E)\times\Gamma(E) &\longrightarrow C(X)\\ (a,b) &\longmapsto d(a(\,\cdot\,), b(\,\cdot\,))\end{aligned}$$

as an inner product.

Lemma 2.1.8. Given two nets $(x_\lambda)_\lambda$ and $(y_\lambda)_\lambda$ and x, y in a Hilbert module E over a C^*-algebra A such that $x_\lambda \to x$ and $y_\lambda \to y$, $\lim_\lambda \langle x_\lambda, y_\lambda \rangle = \langle x, y\rangle$ holds.

Proof. From the Cauchy-Schartz inequality 2.1.2, is easy to obtain that

$$\|\langle x_\lambda - x, z\rangle\|_A \overset{(2.1)}{\leqslant} \|x_\lambda - x\|_E \|z\|_E \qquad (z \in E, \lambda \in \mathbb{A})$$

Analogously, $\|\langle z, y_\lambda - y\rangle\|_A \leqslant \|y_\lambda - y\|_E \|z\|_E$. For each and every index λ, it is possible to obtain the following inequality:

$$\begin{aligned} \|\langle x_\lambda, y_\lambda\rangle - \langle x, y\rangle\| &= \|\langle x_\lambda, y_\lambda\rangle - \langle x_\lambda, y\rangle + \langle x_\lambda, y\rangle - \langle x, y\rangle\| \\ &\leqslant \|\langle x_\lambda, y_\lambda - y\rangle\| + \|\langle x_\lambda - x, y\rangle\| \\ &\leqslant \|y_\lambda - y\|\|x_\lambda\| + \|y\|\|x_\lambda - x\| \end{aligned}$$

Let $\varepsilon > 0$. Notice that $x_\lambda \to x$, means that $\|x_\lambda\| \to \|x\|$. By $\|y_\lambda - y\| \to 0$, there exists λ_0 in which $\|y_\lambda - y\|\,\|x_\lambda\| < \varepsilon/2$. Similarly, there always exists λ_1 such that $\|x_\lambda - x\|_E < \varepsilon/2(\|y\| + 1)$ for $\lambda \succcurlyeq \lambda_1$. Since it exists λ_2 such that $\lambda_2 \succcurlyeq \lambda_0$ and $\lambda_2 \succcurlyeq \lambda_1$, we conclude that $\|\langle x_\lambda, y_\lambda\rangle - \langle x, y\rangle\| < \varepsilon$ for all scalars $\lambda \succcurlyeq \lambda_2$. □

2.2 Adjointable operators

Definition 2.2.1. Let E, F be Hilbert modules over a C^*-algebra A. A function $T : E \longrightarrow F$ is said to be *adjointable* if there exists a function $T^* : F \longrightarrow E$ which satisfies the following relation:

$$\langle Tx, y\rangle_F = \langle x, T^*y\rangle_E \qquad ((x, y) \in E \times F)$$

Besides talking about Hilbert modules, we had defined the adjoint concept for any function between Hilbert modules. That's because inner product relations naturally require these functions to be linear operators, and if they exist, the adjoint is unique. For an adjointable T, T^* is unique, adjointable and $T^{**} = T$. Moreover, $(ST)^* = T^*S^*$ for adjointable operators T and S.

Proposition 2.2.2. Every adjointable operator $T : E \longrightarrow F$, between Hilbert A-modules is bounded and continuous.

Proof. Since the set $\{\langle Tx, y\rangle_F = \langle x, T^*y\rangle_E \mid \|x\| \leqslant 1\} \subset A$ is bounded for all $y \in F$, Banach-Steinhaus theorem 2.2.3 implies that T is a bounded linear operators between normed spaces, i.e. it is continuous. □

> **Summoning 2.2.3** (Banach-Steinhaus "Uniform Boundness Principle" - [27]). Let $\mathcal{F}$ be a family of bounded linear operators from a Banach space X to a normed linear space Y. If $\mathcal{F}$ is pointwise bounded, then $\mathcal{F}$ is norm-bounded, i.e.

$$\forall\, x \in X, \sup_{T\in\mathcal{F}} \|Tx\| < \infty \quad \Rightarrow \quad \sup_{T\in\mathcal{F}} \|T\| < \infty.$$

Example 2.2.4. Given $x, y \in E$, the maps $y\langle x, \cdot\,\rangle$ and $x\langle y, \cdot\,\rangle$ are adjoints of each other. The linear span of those operator are what we will call the *finite rank* operators.

In traditional Hilbert spaces, every bounded operator is adjointable, thanks to the Riesz Lemma ([21, Theorem II.4]). But when talking about Hilbert modules, that might not be the case anymore:

Counterexample 2.2.5 (*Non-adjointable bounded operator*)**.** This one can be founded in W. Paschke's work [19, Remark 2.5]. Suppose that J is a closed right ideal of a unital C^*-algebra A such that no element of J^* acts as a left multiplicative identity on J[2]. Consider the right module $J \times A$ with inner product defined by

$$\langle (a_1, b_1), (a_2, b_2)\rangle = a_2^* a_1 + b_2^* b_1$$

for $a_1, a_2 \in J$ and $b_1, b_2 \in A$. In this new space we have $\|(a,b)\|^2_{J\times A} = \|a^*a + b^*b\| \leqslant \|a\|^2 + \|b\|^2$, hence $\|\cdot\|_{J\times A}$ is complete, i.e. $J \times A$ is a Hilbert module.

The operator $T(a, b) \coloneqq (0, a)$ for each $(a, b) \in J \times A$ is obviously a bounded one, but if we suppose that there exists T^* and let $(x, y) \coloneqq T^*(0, 1)$, notice that

$$a = \langle T(a, b), (0, 1)\rangle = \langle (a, b), T^*(0, 1)\rangle = x^*a + y^*b$$

for all (a, b). Necessarily, it is the case that $y = 0$ and $x^*a = a$ for all $a \in J$, hence x^* acts as a left multiplicative identity on J. But $x^* \in J^*$, and this contradicts our assumption of J.

Counterexample 2.2.6. Let X be a compact Hausdorff space and $Y \subset X$ a closed non-empty subset with dense complement. Let $E \coloneqq \{f \in C(X) \mid f(Y) = \{0\}\}$ and $\iota : E \hookrightarrow C(X)$ the bounded inclusion map. If ι were adjointable, $E \ni \iota^*(I_{C(X)}) = I_{C(X)} \notin E$, i.e. the inclusion is a non-adjointable bounded operator.

Proposition 2.2.7. With the operator norm $\|T\| \coloneqq \sup_{\|x\|=1} \|Tx\|$, the adjointable operators $\mathscr{L}(E, F)$ is C^*-algebra.

Proof. It is straight foward checking that $\mathscr{L}(E, F)$ is a Banach algebra with an involution. To check the C^*-norm property, for each adjointable T,

$$\begin{aligned} \|Tx\|^2 &= \|\langle Tx, Tx\rangle\| = \|\langle T^*Tx, x\rangle\| \overset{2.1.2}{\leqslant} \|T^*Tx\|\|x\| \\ &\leqslant \|T^*T\|\|x\|^2 \leqslant \|T^*\|\|T\|\|x\|^2 \end{aligned} \tag{2.5}$$

for all $x \in E$. A direct calculation using (2.5), shows that

$$\|T\|^2 = \sup_{\|x\|=1} \|Tx\|^2 \leqslant \sup_{\|x\|=1} \|T^*\|\|T\|\|x\|^2 = \|T^*\|\|T\|,$$

which means: $\|T\| \leqslant \|T^*\|$ and by extension, $\|T\| = \|T^*\|$. This automatically guarantee the C^*-norm property. □

[2]For instance, the algebra of complex valued continuous functions on the unit interval $C[0, 1]$, and the ideal $C_0[0, 1]$ of functions which vanish at 0.

Proposition 2.2.8 (Equivalence of positivity)**.** Let $T \in \mathscr{L}(E)$. For T to be positive in the C^*-algebra $\mathscr{L}(E)$ is equivalent to being positive in the scalars coefficients algebra: $\langle Tx, x\rangle \geqslant 0$ for all $x \in E$.

Proof. Assume that T is a positive element in the C^*-algebra of operators. In a C^*-algebra, we know that $a \geqslant 0 \quad \Leftrightarrow \quad a = b^*b$ for some b. With this in hands, let S be such that $T = S^*S$. Therefore:

$$\langle Tx, x\rangle = \langle S^*Sx, x\rangle = \langle Sx, Sx\rangle \overset{2.1.1(iii)}{\geqslant} 0. \qquad (x \in E) \tag{2.6}$$

Conversely, positive elements are self-adjoint, i.e. $\langle Tx, x\rangle = \langle x, Tx\rangle$. From the polarization identity 2.4, one can see that $\langle Tx, y\rangle = \langle x, Ty\rangle$ for all $x, y \in E$, showing that T is self-adjoint. By the Hahn decomposition[3], there exists two positive elements T_+ and T_- such that $T = T_+ - T_-$ and $T_+T_- = T_-T_+ = 0$. Then $\langle T_-y, y\rangle \leqslant \langle T_+y, y\rangle$ for any $y \in E$. In particular,

$$\langle T_-^3x, x\rangle = \langle T_-^2x, T_-x\rangle \leqslant \langle T_+T_-x, T_-x\rangle = 0.$$

On the other hand, $T_- \geqslant 0$ and $T_-^3 \geqslant 0$, hence $\langle T_-^3x, x\rangle \geqslant 0$ (because the statement in this direction is already proved). So the only possibility left is $\langle T_-^3x, x\rangle = 0$ for any x. By the polarization equality 2.4, this implies $\langle T_-^3x, y\rangle = 0$ for all $x, y \in \mathcal{M}$, hence $T_-^3 = 0$, $T_- = 0$. Thus, $T = T_+ \geqslant 0$. $\square$

Proposition 2.2.9. If $T \in \mathscr{L}(E, F)$ and $x \in E$, then $\langle Tx, Tx\rangle \leqslant \|T\|^2\langle x, x\rangle$.

Proof. Let ρ be a state of A. By repeated application of the Cauchy-Schwartz inequality to $\rho(\langle \cdot\,, \cdot\rangle)$:

$$\begin{aligned}
\rho(\langle T^*Tx, x\rangle) &\leqslant \rho\big(\langle T^*Tx, T^*Tx\rangle\big)^{\frac{1}{2}}\rho\big(\langle x, x\rangle\big)^{\frac{1}{2}} \\
&= \rho\big(\langle (T^*T)^2x, x\rangle\big)^{\frac{1}{2}}\rho\big(\langle x, x\rangle\big)^{\frac{1}{2}} \\
&\leqslant \rho\big(\langle (T^*T)^4x, x\rangle\big)^{\frac{1}{4}}\rho\big(\langle x, x\rangle\big)^{\frac{1}{2}+\frac{1}{4}} \\
&\vdots \\
&\leqslant \rho\big(\langle (T^*T)^{2^n}x, x\rangle\big)^{\frac{1}{2^n}}\rho\big(\langle x, x\rangle\big)^{\frac{1}{2}+\frac{1}{4}+\cdots+\frac{1}{2^n}} \\
&\leqslant \|x\|^{2^{1-n}}\|T^*T\|\rho\big(\langle x, x\rangle\big)^{1-\frac{1}{2^n}}
\end{aligned}$$

As $n \to \infty$, one deduces that $\rho(\langle Tx, Tx\rangle) \leqslant \|T\|^2\rho(\langle x, x\rangle)$. Since this is true for all states ρ, the desired inequality holds. $\square$

[3]Every element $a \in A$ in a C^*-algebra can be written as $a = a_+ - a_-$ with $a_+, a_- \geqslant 0$, $a_+a_- = a_-a_+ = 0$. This is called the Hahn decomposition.

2.3 Compact and Finite rank operators

We are heading towards the definition of generalized Fredholm operators between Hilbert modules, and for that, we need a replacement for the finite dimensional condition. Henceforth, we shall explore the example 2.2.4.

Let E be a Hilbert A-module. Consider the following operator:

$$\begin{aligned} \Omega: \quad E^n &\longrightarrow \mathscr{L}(A^n, E) \\ (x_i)_i &\longmapsto \Big((a_i)_i \overset{\Omega_x}{\longmapsto} \sum_{i=1}^n x_i a_i \Big) \end{aligned} \tag{2.7}$$

In order to obtain the adjoint operator, as far as algebraic manipulation goes, $\Omega_x^* : E \longrightarrow A^n$ has no other option else besides being the coordinate inner decomposition $(\langle x_i, \cdot \rangle)_i$: For $a \in A^n$ and $\xi \in E$,

$$\begin{aligned} \langle \Omega_x a, \xi \rangle_E &= \Big\langle \sum_{i=1}^n x_i a_i, \xi \Big\rangle_M \\ &= \sum_{i=1}^n a_i^* \langle x_i, \xi \rangle_E \\ &= \begin{bmatrix} a_1^* & \cdots & a_n^* \end{bmatrix} \begin{bmatrix} \langle x_1, \xi \rangle_E \\ \vdots \\ \langle x_n, \xi \rangle_E \end{bmatrix} \\ &= \Big\langle a, (\langle x_1, \xi \rangle_E, \dots, \langle x_n, \xi \rangle_E) \Big\rangle_{A^n} = \langle a, \Omega_x^* \xi \rangle_{A^n} \end{aligned}$$

If F is another Hilbert A-module and $n \in \mathbb{N}$, one should note that for $x \in E^n$ and $y \in F^n$, $\Omega_y \Omega_x^*$ rises a fair notion of *finite rank*, since their range elements are given by

$$\Omega_y \Omega_x^* \xi = \Omega_y^n \left(\langle x_1, \xi \rangle_E, \dots, \langle x_n, \xi \rangle_E \right) = \sum_{i=1}^n y_i \langle x_i, \xi \rangle_E. \tag{2.8}$$

Definition 2.3.1 (Compact and finite-rank operators)**.** Every operator of the form $\Omega_y \Omega_x^* : E \longrightarrow F$, where $(x, y) \in E^n \times F^n$ will be said to be an *A-finite rank operator*. The set of finite-rank operators will be denoted by $\mathrm{FR}_A(E, F)$. The set of *A-compact operators* between E and F are defined as the topological closure of the subspace $\mathrm{FR}_A(E, F) \subset \mathscr{L}(E, F)$ and it is denoted as $\mathscr{K}_A(E, F)$.

Unfortunately, A-compact operators need not to be compact in the sense of Banach spaces:

Counterexample 2.3.2. In a unital C^*-algebra A, the identity can be viewed as $\Omega_1 \Omega_1^* = I_A$ on the Hilbert module A. Hence $I_A \in \mathscr{K}(A)$, but it is a compact operator on the Banach space A if and only if A is finite-dimensional, since it is an invertible compact[4].

Proposition 2.3.3. In the standard Hilbert module $\mathscr{H}_A$ over a unital C^*-algebra A, the classical compact notion of compact operator is well rescued: If $E_n \subset \mathscr{H}_A$ denotes the free submodule generated by the first n canonical elements $e_0, e_1, \ldots, e_{n-1}$, the following are equivalent:

(*i*) $K \in \mathscr{K}_A(\mathscr{H}_A)$.

(*ii*) The norms of restrictions of K onto the orthogonal complements $E_n^\perp$ of the submodules E_n vanish as $n \longrightarrow \infty$.

Proof.

(*i*) $\Rightarrow$ (*ii*) Let $n \in \mathbb{N}$ and $p_n : \mathscr{H}_A \twoheadrightarrow E_n^\perp$ be the orthogonal projection and consider some finite rank operator $\Omega_y \Omega_x^*$ for $x, y \in \mathscr{H}_A^n$. Then, for any $z \perp E_n$, one has

$$\begin{aligned} \|\Omega_y \Omega_x^* z\|^2 &= \|\langle \Omega_y \Omega_x^* z, \Omega_y \Omega_x^* z\rangle\| \\ &= \|\langle y\langle x, z\rangle, y\langle x, z\rangle\rangle\| \\ &= \|\langle x, z\rangle^* \langle y, y\rangle \langle x, z\rangle\| \\ &\leqslant \|y\|^2 \|\langle x, z\rangle\|^2 \\ &= \|y\|^2\, \|\langle p_n x, z\rangle\|^2 \\ &\leqslant \|y\|^2\, \|p_n x\|^2\, \|z\|^2. \end{aligned}$$

Since $\|p_n x\|$ tends to zero, the same is true for the norm of the restriction of the operator $\Omega_y \Omega_x^*$ to the submodule $E_n^\perp$, hence, for the norm of any compact operator K.

(*i*) $\Leftarrow$ (*ii*) For a operator $K \in \mathscr{L}(\mathscr{H}_A)$, suppose that $\|K\restriction_{E_n^\perp}\|$ vanishes when $n \to \infty$. If z is an orthogonal element with respect to E_n, i.e. $\langle e_i, z\rangle = 0$ for any $i \leqslant n$, notice that if $e^n := (e_1, \ldots, e_n)$, then $\Omega_{Ke^n} \Omega_{e^n}^*(z) = 0$. Therefore:

$$\begin{aligned} &\lim_{n\to\infty} \sup_{\substack{z \in E_n^\perp \\ \|z\| \leqslant 1}} \left\| Kz - \sum_{i=1}^n K e_i \langle e_i, z\rangle \right\| \\ = &\lim_{n\to\infty} \sup_{\substack{z \in E_n^\perp \\ \|z\| \leqslant 1}} \|Kz\| = \lim_{n\to\infty} \|K\restriction_{E_n^\perp}\| = 0. \end{aligned}$$

If $z \in E_n$, one can see that $Kz = \Omega_{Ke^n} \Omega_{e^n}^*(z)$, so that the supreme can be taken in the hole $\mathscr{H}_A$. Therefore:

$$K = \lim_{n\to\infty} \sum_{i=1}^n \Omega_{Ke_i} \Omega_{e_i}^* \in \mathscr{K}_A(\mathscr{H}_A). \qquad \square$$

[4]If $T : X \longrightarrow Y$ is an invertible compact operator between Banach spaces in the classical sense, the boundness of T^{-1} rises a constant C such that $\|T^{-1}y\| \leqslant C\|y\|$, and by invertibility, $\|x\| \leqslant C\|Tx\|$. Thus, the image by T of the unit ball in X contains an open ball in Y. Since T is compact, Y is finite-dimensional, and so do X.

Examples 2.3.4.

(*i*) Let A be your favorite C^*-algebra. We shall see that $\mathscr{K}(A) \simeq A$. Notice that the map

$$\begin{aligned} L: \quad A &\longrightarrow \mathscr{L}(A) \\ a &\longmapsto (b \overset{L_a}{\longmapsto} ab) \end{aligned}$$

is well defined since L_{a^*} is the adjoint of L_a. It is no mistery that $\|L_a\| \leqslant \|a\|$, but notice that $\|L_a(a^*)\| = \|a\|\,\|a^*\|$, hence L is an isomorphism of A onto a closed $*$-subalgebra of $\mathscr{L}(A)$.

Since $a\langle b, \cdot\rangle = L_{ab^*}$, it follows that $\mathscr{K}(A)$ is the closure of (the image under L of) the linear span of products in A. But, since every C^*-algebra contains an approximate identity, the products above are dense, thus L is an isomorphism between A and $\mathscr{K}(A)$.

(*ii*) If A is a unital algebra, $\mathscr{K}(A) = \mathscr{L}(A)$ since any adjointable operator T consists of left multiplication by $T(1)$.

(*iii*) Reviewing 2.1.7(*v*), one can obtain that $\mathscr{K}(H \otimes A) \simeq \mathscr{K}(H) \otimes A$.

(*iv*) $\mathscr{K}(E^m, F^n) \simeq \mathbb{M}_{m\times n}(\mathscr{K}(E,F))$ and $\mathscr{L}(E^m, F^n) \simeq \mathbb{M}_{m\times n}(\mathscr{L}(E,F))$.

Proposition 2.3.5. For each $x \in E^n$, Ω_x is an A-compact operator.

Proof. Let $(u_\lambda)_\lambda \subset A$ be an approximate unit. Considering A it self as a Hilbert C^*-module, $\Omega_{u_\lambda}^* : A^1 \longrightarrow A$ is the standard multiplication by u_λ. Therefore, for each $a \in A$, we obtain the desired relation for $n = 1$:

$$\begin{aligned} \Omega_x a &= xa = x \lim_\lambda u_\lambda a \\ &\overset{u_\lambda = u_\lambda^*}{=} \lim_\lambda x\langle u_\lambda, a\rangle_A \overset{(2.8)}{=} \lim_\lambda \Omega_x \Omega_{u_\lambda}^* a \end{aligned} \tag{2.9}$$

For a general n, we arrive at a sum of finite 1-rank operators. Given $x \in E^n$ and $a \in A^n$, for each λ, we wish to obtain $y \in E^n$ and $b \in (A^n)^n$ such that,

$$\sum_{i=1}^{n} \Omega_{x_i} \Omega_{u_\lambda}^* a_i \overset{(*)}{=} \Omega_y \Omega_b^* a$$

in order to write a general Ω_x as a compact operator. To address $(*)$, let $y := x$ and $b := \mathrm{Diag}(u_\lambda) \in \mathbb{M}_{n\times n}(A) \simeq (A^n)^n$ the diagonal matrix whose non zero entries are u_λ.

Notice that

$$\begin{aligned}
\Omega_y \Omega_b^* a &= \Omega_x \Omega_{\mathrm{Diag}(u_\lambda)}^* a \\
&= \sum_{i=1}^n x_i \underbrace{\langle b_i, a \rangle_{A^n}}_{\sum_{j=1}^n \langle b_{ij}, a_j \rangle_A} \\
&= \sum_{i=1}^n x_i \langle b_{ii}, a_i \rangle_A \\
&\overset{u_\lambda = b_{ii}}{=} \sum_{i=1}^n \Omega_{x_i} \Omega_{u_\lambda}^* a_i
\end{aligned} \qquad (a \in A^n) \tag{2.10}$$

Therefore, for any $a \in A^n$, the following holds and the claim is proved.

$$\Omega_x a = \sum_{i=1}^n x_i a_i \overset{(2.9)}{=} \lim_\lambda \sum_{i=1}^n \Omega_{x_i} \Omega_{u_\lambda}^* a_i \overset{(2.10)}{=} \lim_\lambda \Omega_x \Omega_{\mathrm{Diag}(u_\lambda)}^* a. \qquad \square$$

Definition 2.3.6 (Finite-rank Hilbert Module)**.** A Hilbert Module M over an C^*-algebra A whose identity operator I_M is A-finite rank will be said to be an *A-finite rank* module.

Proposition 2.3.7. If E is an Hilbert A-module, the family of finite rank automorphisms $\mathrm{FR}(E)$ is a two-sided ideal of $\mathscr{L}(E)$.

Proof. Extending coordinate-wise, let $Ty := (Ty_1, \ldots, Ty_n)$ and notice that, for $T, S \in \mathscr{L}(E)$,

$$\begin{aligned}
T\Omega_y \Omega_x^* + \Omega_w \Omega_z^* S &= \sum_{i=1}^n Ty_i \langle x_i, \cdot \rangle + \sum_{j=1}^m w_j \langle S^* z_j, \cdot \rangle \\
&= \Omega_{(Ty,w)} \Omega_{(x,S^*z)}^*.
\end{aligned}$$

Therefore, any $\mathscr{L}(E)$-linear combination of finite rank operators is itself a finite rank one, as showed above, i.e. $\mathrm{FR}(E) \triangleleft \mathscr{L}(E)$. $\square$

Proposition 2.3.8. If the identity I_E in a Hilbert module E is a compact operator, then E has finite rank, i.e. $I_E \in \mathscr{K}(E) \Rightarrow I_E \in \mathrm{FR}(E)$.

Proof. Suppose that I_E is a compact operator in a given Hilbert C^*-module E. By construction, $\mathrm{FR}(E)$ is a dense subset of compact operators, so every open non-empty set $U \subset \mathscr{K}(E)$ obeys

$$U \cap \mathrm{FR}(E) \neq \varnothing \qquad (U \subset \mathscr{K}(E))$$

Since $\mathscr{K}(E)$ is a unital C^*-algebra, the invertible operators $\mathrm{GL}(\mathscr{K}(E))$ constitute a non-empty open set, hence there is a finite-rank invertible operator $F \in \mathrm{GL}(\mathscr{K}(E)) \cap \mathrm{FR}(E)$. Since $\mathrm{FR}(E)$ contains an invertible and is an ideal, it follows that $I_E = FF^{-1} \in \mathrm{FR}(E)$, i.e. the identity has finite rank. $\square$

In order to fully characterize finite rank Hilbert Modules over a given C^*-algebra, the same K-theoretic bias is seen right here through the representation by idempotents.

Theorem 2.3.9. A Hilbert C^*-module M has finite rank if, and only if, there exists an idempotent matrix $p \in \mathbb{M}_{n\times n}(A)$ such that M is isomorphic, as Hilbert A-modules, to pA^n.

Proof. Assume that M has finite rank, i.e. $I = \Omega_y\Omega_x^*$ for some $x, y \in M^n$. As presented in (2.11), $\Omega_x^*\Omega_y \in \mathscr{L}(A^n)$ is an idempotent operator, which corresponds to left multiplication by the idempotent matrix $p := (\langle x_i, y_j\rangle)_{i,j} \in \mathbb{M}_{n\times n}(A)$.

$$I = \Omega_y\Omega_x^* \quad\Rightarrow\quad \Omega_x^* = (\Omega_x^*\Omega_y)\Omega_x^* \quad\Rightarrow\quad \Omega_x^*\Omega_y = (\Omega_x^*\Omega_y)^2 \tag{2.11}$$

$\Omega_x^* : M \longrightarrow pA^n$ is invertible: The middle term of (2.11) tells us that $\Omega_x^* = p\Omega_x^*$. Therefore, consider the following:

$$\begin{aligned} T:\ pA^n &\longrightarrow M \\ pa &\longmapsto \Omega_y a \end{aligned}$$

That operator show us that Ω_x^* is an invertible operator: Given $a \in A^n$, $\xi \in M$, one obtains that $\Omega_x^*T(pa) = \Omega_x^*\Omega_y a = pa$ and $T\Omega_x^*\xi = T(p\Omega_x^*\xi) = \Omega_y\Omega_x^*\xi = \xi$, i.e. $T = \Omega_x^{*-1}$.

Since it is an adjointable, functional continuous calculus allow us to extract the square root $|\Omega_x^*| := (\Omega_x\Omega_x^*)^{1/2}$, which is self-adjoint. Besides being a linear bijection, Ω_x^* doesn't preserves inner products. But notice that $U := \Omega_x^*|\Omega_x^*|^{-1}$ does: For $\xi, \zeta \in M$,

$$\begin{aligned} \langle U\xi, U\zeta\rangle_{A^n} &= \langle \Omega_x^*|\Omega_x^*|^{-1}\xi, \Omega_x^*|\Omega_x^*|^{-1}\zeta\rangle_{A^n} \\ &= \langle \xi, |\Omega_x^*|^{-1}\Omega_x\Omega_x^*|\Omega_x^*|^{-1}\zeta\rangle_M \\ &= \langle \xi, |\Omega_x^*|^{-1}|\Omega_x^*|^2|\Omega_x^*|^{-1}\zeta\rangle_M = \langle \xi, \zeta\rangle_M. \end{aligned}$$

Hence U is a Hilbert isomorphism between M and pA^n. ☐

2.4 Kasparov Stabilization Theorem

The Kasparov Stabilization theorem ensures that the standard Hilbert C^*-module $\mathscr{H}_A$ is in a way, the largest countably generated Hilbert C^*-module, i.e. every countably generated Hilbert C^*-module is a direct summand in the canonical space $\mathscr{H}_A$. Technically, we need the main theorem of this section in order to classify the finite rank Hilbert C^*-modules in rank terms (Theorem 2.6.3), requiring some countability condition.

This may worry some readers, given that we already mentioned that Exel's approach to Fredholm operators is just the K-theoretical version of the BGR theorem without the separability assumption of the C^*-algebras. But do not panic since this enumerability shall be dribbled in Lemma 2.6.2.

Although it has been presented in [14, Theorem 2] by G. G. Kasparov, we follow [18] in the following road map: Defining strictly positive elements in a C^*-algebra and characterizing operators in $\mathscr{K}(E)$ whose range is dense. With this characterization, we prove Kasparov's theorem.

Definition 2.4.1. If a is a positive element in a C^*-algebra A and $\phi(a) \neq 0$ for all *states*[5] ϕ on A, then a is said to be *strictly positive*.

Proposition 2.4.2. A positive element $a \geqslant 0$ in a unital C^*-algebra A is strictly positive if and only if it is a invertible element.

Proof due to [11]. Suppose $a \in A$ is strictly positive. Since A is unital, the state space of A is weak*-compact, and it follows that the element $\varepsilon := \inf\{\phi(a) \mid \phi \text{ is a state on } A\}$ is strictly positive, i.e. $\varepsilon > 0$. Therefore $a - \varepsilon$ is a positive element, so that the spectrum of a is contained in $[\varepsilon, \infty)$, i.e. a is invertible since 0 is not in the spectrum of a.

Conversely, suppose that a is positive and invertible. Whence, its spectrum is a compact subset of $(0, \infty)$, and thus $a - \varepsilon$ is positive for some $\varepsilon > 0$. If ϕ is a non-zero positive linear functional on A, we have

$$\phi(a) = \varepsilon\phi(1) + \phi(a - \varepsilon) \geqslant \varepsilon\|\phi\| + 0 > 0. \qquad \square$$

Lemma 2.4.3. Let $a \in A$ be a positive element. Hence a is strictly positive if, and only if, aA is dense in A.

Proof. Conjure the following statement:

> **Summoning 2.4.4** ([8] - Lemma 2.9.4)**.** Let A be a C^*-algebra and L, L' two closed left ideals of A such that $L \subseteq L'$. Suppose every positive form on A that vanishes on L also vanishes on L'. Then $L = L'$.

Suppose that $L := aA$ is not a dense subset of $L' := A$, i.e. $\overline{L} \neq L'$. By the summoning, there is a state of A vanishing on aA. Such a state must vanish on a, so a is not strictly positive. Conversely, if ϕ is a state which $\phi(a) = 0$. Then, by Cauchy-Schwarz inequality for states:

$$|\phi(ab)|^2 \leqslant \phi(b^*b)\phi(a^*a) = 0 \qquad (b \in A)$$

i.e. ϕ vanishes on aA, hence it is not dense. $\square$

Proposition 2.4.5. Let E be a Hilbert A-module and T a positive element in the C^*-algebra $\mathscr{K}(E)$. Then T is strictly positive if and only if T has dense range.

Proof. If T is strictly positive, by 2.4.3 then $\overline{T\mathscr{K}(E)} = \mathscr{K}(E)$. Since $\overline{\mathscr{K}(E)E} = E$, we have that $\overline{\operatorname{Im} T} = \overline{T\mathscr{K}(E)E} = \overline{\mathscr{K}(E)E} = E$, i.e. T has dense image. Conversely, suppose that T has dense range. Therefore, for any $x, y \in E$, choose a sequence $(z_n)_n \subset E$ with $Tz_n \longrightarrow x$. Therefore,

$$\Omega_x\Omega_y^* = \lim_{n\to\infty} T\Omega_{z_n}\Omega_y^* \in \overline{T\mathscr{K}(E)}.$$

[5] Norm 1 positive linear functional $\phi : A \longrightarrow \mathbb{C}$.

So $T\mathscr{K}(E)$ is dense and T is strictly positive. $\square$

A Hilbert A-module M is countably generated if there is a sequence $(x_n)_n \subset M$ such that every x is the limit A-linear combinations of $(x_n)_n$.

Theorem 2.4.6 (Kasparov Stabilization Theorem)**.** If M is a countably generated Hilbert A-module, then $\mathscr{H}_A \simeq M \oplus \mathscr{H}_A$.

Proof. Assume that A is a unital C^*-algebra and let $(\eta_n)_n$ be a bounded sequence of generators for M, with each generator repeated infinitely often. Let $(e_n)_n$ be the canonical orthonormal basis for $\mathscr{H}_A$, i.e. only the n-th coordinate of e_n is 1 and 0 elsewhere. Define $T : \mathscr{H}_A \longrightarrow M \oplus \mathscr{H}_A$ linearly extending by $Te_n \coloneqq 2^{-n}\eta_n + 4^{-n}e_n$. Notice that, for the elements $\zeta_n \coloneqq \eta_n + 2^{-n}e_n$, T can be written as

$$T = \sum_{n=1}^{\infty} 2^{-n}\Omega_{\zeta_n}\Omega^*_{e_n} = \sum_{n=1}^{\infty} 2^{-n}(\eta_n + 2^{-n}e_n)\langle e_n, \cdot\rangle.$$

Therefore, T is a compact bijection. Since each η_n is repeated infinitely often, it is true that $\eta_n + 2^{-m}e_m = T(2^m e_m) \in \operatorname{Im} T$ for infinitely many m which $\eta_n = \eta_m$. Going through the limit when $m \longrightarrow \infty$, we see that

$$\eta_n + 0 = \lim_{m\to\infty} \eta_n + 2^{-m}e_m = \lim_{m\to\infty} T(2^m e_m) \in \overline{\operatorname{Im} T}$$

and $0 + e_n = 4^n(Te_n - 2^{-n}(\eta_n + 0))$. Therefore, both $\eta_n + 0$ and $0 + e_n$ are in the closure $\overline{\operatorname{Im} T}$.

Since $\{\eta_n + 0,\, 0 + e_n\}_n$ generates a dense submodule of $M \oplus \mathscr{H}_A$, T has dense range. Define new operators S and R given by $Se_n \coloneqq 0 + 4^{-n}e_n$ and $Re_n \coloneqq 2^{-n}\eta_n + 0$, in order that

$$\begin{aligned} T^*T &= S^*S + R^*R \\ &= \begin{pmatrix} 4^{-4} & 0 & 0 & \cdots \\ 0 & 4^{-8} & 0 & \cdots \\ 0 & 0 & 4^{-12} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} + \begin{pmatrix} 4^{-2}\langle\eta_1,\eta_1\rangle & 4^{-3}\langle\eta_1,\eta_2\rangle & 4^{-4}\langle\eta_1,\eta_4\rangle & \cdots \\ 4^{-3}\langle\eta_2,\eta_1\rangle & 4^{-4}\langle\eta_2,\eta_2\rangle & 4^{-5}\langle\eta_2,\eta_3\rangle & \cdots \\ 4^{-4}\langle\eta_3,\eta_1\rangle & 4^{-5}\langle\eta_3,\eta_2\rangle & 4^{-6}\langle\eta_3,\eta_1\rangle & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \end{aligned}$$

Hence $T^*T \geqslant S^*S$. Notice that S^*S has dense range, and by 2.4.5, it is strictly positive and so do T^*T. Therefore, $T|T|^{-1}$ is the desired isomorphism between those Hilbert modules. $\square$

Corollary 2.4.7. All finite rank Hilbert A-modules M can be regarded as submodules of $\mathscr{H}_A$.

Proposition 2.4.8. A Hilbert A-module E is countably generated if, and only if $\mathscr{K}(E)$ contains a strictly positive element, i.e. is σ-unital.

Proof. If A is unital and $(e_n)_n \subset \mathscr{H}_A$ is the canonical orthonormal basis, the operator $h \coloneqq \sum_n 2^{-n}e_n\langle e_n, \cdot\rangle$ is a strictly positive element in $\mathscr{K}(\mathscr{H}_A)$ since it has dense range. If $P \in \mathscr{L}(\mathscr{H}_A)$ is an idempotent self-adjoint operator, then PhP is strictly positive in $\mathscr{K}(P\mathscr{H}_A)$. Finally, notice that A is countably generated if, and only if $\widetilde{A}$ is countably generated. Therefore $\mathscr{K}_A(E) = \mathscr{K}_{\widetilde{A}}(E)$ is σ-unital if, and only if E is countably generated. $\square$

2.5 Rank definition of Finite Rank Modules

In order to define the actual *rank* of a finite rank module M, we wish to deal with the K_0-group as the K-algebraic theoreticals like, so we shall visualize our A-modules over $\widetilde{A}$, regardless if it already possesses a unity or not. This process naturally enrich our module, as showed in 2.5.2.

Definition 2.5.1 (Projective module)**.** Let M be an A-module. M is *projective* whenever there exists a map h such that it is commutative the following diagram:

$$\begin{tikzcd} & M \arrow[d] \arrow[dl, dashed, "h"'] \\ E \arrow[r, two heads] & F \end{tikzcd} \qquad (E, F \in \boldsymbol{A}\textbf{-Mod})$$

That is to say, for every epimorphism[6] $g : E \twoheadrightarrow F$ and $f : M \longrightarrow F$, there will always exist a map h such that $g \circ h = f$.

Proposition 2.5.2. Let A be a C^*-algebra. Every finite rank Hilbert A-module is a finitely generated projective Hilbert $\widetilde{A}$-module.

Proof. Let M be a finite rank Hilbert A-module. If $(a, \lambda) \in \widetilde{A}$, letting $(a, \lambda) \cdot \xi := a\xi + \lambda\xi$ turns M into an Hilbert $\widetilde{A}$-module. If $p \in \mathscr{L}(\widetilde{A}^n)$ is the idempotent such that $M \simeq p\widetilde{A}^n$ given by 2.3.9, notice that:

- (i) $\boldsymbol{\widetilde{A}^n \simeq M \oplus \ker p}$: We shall see that it is a direct sum:

  $$\widetilde{A}^n = p\widetilde{A}^n \oplus (I_{\widetilde{A}^n} - p)\widetilde{A}^n \tag{2.12}$$

  Indeed, if $x \in p\widetilde{A}^n \cap (I_{\widetilde{A}^n} - p)\widetilde{A}^n$, than $x = pa = (I_{\widetilde{A}^n} - p)b$ for some tuples a, b. Therefore
  $$x = pa = p(pa) = p(I_{\widetilde{A}^n} - p)b = (p - p^2)b = 0,$$
  and the sum in (2.12) is fact direct. Since $\ker p = (I_{\widetilde{A}^n} - p)\widetilde{A}^n$, the desired isomorphism holds since $p\widetilde{A}^n \simeq M$.

- (ii) **If there exists $\boldsymbol{Q}$ such that $\boldsymbol{M \oplus Q}$ is free, then $\boldsymbol{M}$ is projective**: Let E, F be $\widetilde{A}$-modules, $g : E \twoheadrightarrow F$ a surjective map and $f : M \longrightarrow F$. Let $(b_i)_i$ be a basis of $M \oplus Q$. By surjectivity, for all i, there is always $x_i \in M$ such that $g(x_i) = f(b_i)$.

  Define $\widetilde{h} : M \oplus Q \longrightarrow E$ extending linearly $\widetilde{h}(b_i) := x_i$, in order that $g \circ \widetilde{h} = f$. Therefore, $h := \widetilde{h}\restriction_M$ is the one necessary so that M is projective.

- (iii) **If $\boldsymbol{M}$ is a direct summand of a free rank module, then it is finitely generated**: Let $M \oplus Q \simeq \widetilde{A}^n$ for some $\widetilde{A}$-module Q. That way, Q can be both projected and embedded in $\widetilde{A}^n$ by morphisms. Let $\psi : \widetilde{A}^n \longrightarrow \widetilde{A}^n$ be the compositions of those. Then
  $$\operatorname{Im} \psi = \{(0, q) \in M \oplus Q \mid q \in Q\}$$

[6]For our purpose and needs, subjective morphism

is the kernel of the canonical projection $\Pi_M : \widetilde{A}^n \twoheadrightarrow M$. Therefore, the composition $\Pi_M \circ \psi : \widetilde{A}^n \twoheadrightarrow M$ is a surjection, telling the world that M must be finitely generated.

Since $\widetilde{A}^n$ is free module, setting $Q := \ker p$, one can see that M is projective by (ii) and finitely generated by (iii). $\square$

Lemma 2.5.3. Let p, q be idempotent square matrices with entries living in A. The following are equivalent:

(i) As Hilbert modules, $pA^m \simeq qA^n$.

(ii) p and q are Murray von-Neumann equivalent.

Proof.

$(i) \Rightarrow (ii)$ Let $T : pA^m \longrightarrow qA^n$ be a isomorphism. There exists unique matrices $r \in \mathbb{M}_{n\times m}(A)$ and $s \in \mathbb{M}_{m\times n}(A)$ which corresponds $spa = T(pa)$ and $rqb = T^{-1}(qb)$ for every $a \in A^m$ and $b \in A^n$. Notice that

$$\begin{cases} rs(pa) = T^{-1}T(pa) = pa = p^2a. \\ sr(qb) = TT^{-1}(qb) = qb = q^2b. \end{cases}$$

Therefore $p = rs$ and $q = sr$.

$(i) \Leftarrow (ii)$ The left multiplications maps $s : pA^m \longrightarrow qA^n$ and $r : qA^n \longrightarrow pA^m$ are mutual inverses of each otter:

$$\begin{cases} s(r(qb)) = (sr)^2b = q^2b = qb, & (b \in A^n). \\ r(s(pa)) = (rs)^2a = p^2a = pa, & (a \in A^m). \end{cases}$$

Therefore $pA^m \simeq qA^n$. $\square$

For a A-finite rank module M, M can be viewed as an finitely gerated projective $\widetilde{A}$-module, hence let p be as in 2.3.9 embedded in $\mathbb{M}_\infty(\widetilde{A})$. As an element of $V(\widetilde{A})$, the equivalence class of idempotents which represents M, is the set:

$$[M] := \{q \in \mathbb{M}_\infty(\widetilde{A}) \mid q^2 = q \in \mathbb{M}_n(\widetilde{A}), M \simeq qA^n\} = [p] \in V(\widetilde{A})$$

which by 2.5.3 is well defined.

Letting $[\,\cdot\,]_0 : V(\widetilde{A}) \hookrightarrow K_0(\widetilde{A})$ be the natural inclusion, $[q]_0 := [q] - [s(q)]$, one may see $[M]_0 \in K_0(\widetilde{A})$ as an element of $K_0(A)$. In fact, if $\varepsilon : \widetilde{A} \twoheadrightarrow \mathbb{C}$ is the projection of the complex component, $\varepsilon(p) = 0$ since M is originally a Hilbert A-module. Therefore,

$$\varepsilon_0([M]_0) = \varepsilon_0([p] - [s(p)]) = [\varepsilon(p)] - [\varepsilon(s(p))] = 0$$

$$\Rightarrow \quad [M]_0 \in \ker \varepsilon_0 = K_0(A).$$

Proposition 2.5.4. Let $P \in \mathscr{K}(E)$ be a compact self-adjoint idempotent operator over a Hilbert A-module E. Therefore, $\operatorname{Im} P$ is an A-finite rank Hilbert C^*-module.

Proof. Notice that $I_{\operatorname{Im} P} = P$. Since it is compact in E, there are nets $(y_\lambda)_\lambda, (x_\lambda)_\lambda \subset E^\infty$ such that $P = \lim_\lambda \Omega_{y_\lambda} \Omega^*_{x_\lambda}$. Therefore:

$$\begin{aligned} I_{\operatorname{Im} P} &= P = P^3 = P\Big(\lim_\lambda \Omega_{y_\lambda} \Omega^*_{x_\lambda}\Big)P \\ &= \lim_\lambda P\Omega_{y_\lambda}\Omega^*_{x_\lambda} P = \lim_\lambda \Omega_{Py_\lambda}\Omega^*_{P^* x_\lambda} \overset{P^*=P}{=} \lim_\lambda \Omega_{Py_\lambda}\Omega^*_{Px_\lambda}. \end{aligned}$$

In light of the 2.3.8, $\operatorname{Im} P$ is indeed a finite-rank module. □

***Remark* 2.5.5.** The range of an idempotent operator coincide with the range of some projection, i.e. self-adjoint idempotent operator. To see this, suppose that $a \in A$ is an idempotent in a unital C^*-algebra A. Let

$$h \coloneqq 1 + (a - a^*)(a^* - a) = 1 + aa^* - a^* - a + a^*a$$

With h in hands, one can draw the following conclusions:

(*i*) $h^* = h$.

(*ii*) Notice that $(a - a^*)(a^* - a) \geqslant 0$, hence $\operatorname{Spec}((a - a^*)(a^* - a)) \subset [0, \infty)$. Conjure one of the classical theorems in spectral theory:

> **Summoning 2.5.6** (Spectral mapping theorem - [25] - Theorem 10.28.(b)). Given an unital Banach algebra A and $a \in A$, the following holds:
>
> $$\operatorname{Spec}(p(a)) = \{p(\lambda) \mid \lambda \in \operatorname{Spec}(a)\} = p(\operatorname{Spec}(a))$$
>
> for each and every complex polynomial $p \in \mathbb{C}[x]$.

By the theorem 2.5.6,

$$\operatorname{Spec}(h) = 1 + \operatorname{Spec}((a - a^*)(a^* - a)) \subset [1, \infty).$$

Since $0 \notin \operatorname{Spec}(h)$, h is invertible.

(*iii*) $ah = aa^*a = ha$ and $a^*h = a^*aa^* = ha^*$.

(*iv*) $p \coloneqq aa^*h^{-1} = h^{-1}aa^*$. Indeed:

$$hp = haa^*h^{-1} = aa^*hh^{-1} = aa^*.$$

(*v*) p is self-adjoint:

$$p^* = (h^{-1})^*aa^* = (h^*)^{-1}aa^* = h^{-1}aa^* = p$$

(vi) p is idempotent:

$$p^2 = h^{-1}\underbrace{(aa^*a)}_{ha}a^*h^{-1} = h^{-1}h(aa^*h^{-1}) = p.$$

(vii) $pa = a$ and $ap = p$.

In particular, if $a := Q \in \mathscr{L}(E)$ is an idempotent operator, $\operatorname{Im} Q$ coincides with the range of p by (vii), which is a self-adjoint idempotent operator. In particular $E = \operatorname{Im} Q \oplus \operatorname{Im} Q^{\perp}$.

Definition 2.5.7. The *rank* of a finite rank Hilbert A-module will be defined as the class $\texttt{rank}\,(M) := [p]_0 \in K_0(A)$. The properties given in 2.5.4 and 2.5.5, we are able to define the *rank* of a given compact idempotent operator P as the rank of $\operatorname{Im} P$.

Let E be a Hilbert A-module and $P, Q \in \mathscr{K}(E)$ be two compact idempotent operators. Since their ranges are finite-rank modules (2.5.5 and 2.5.4), there are $x, y \in (\operatorname{Im} P)^n$ and $z, w \in (\operatorname{Im} Q)^m$ such that

$$P = I_{\operatorname{Im} P} = \Omega_y \Omega_x^* \quad \text{and} \quad Q = I_{\operatorname{Im} Q} = \Omega_w \Omega_z^*.$$

Let p and q be the matrices given by $p = \left(\langle x_i, y_j\rangle\right)_{i,j}$ and $q = \left(\langle z_i, w_j\rangle\right)_{i,j}$, used in the argument used in 2.3.9. As seen before, we get the following isomorphic Hilbert C^*-modules: $\operatorname{Im} P \simeq pA^n$ and $\operatorname{Im} Q \simeq qA^m$.

Lemma 2.5.8. Let P and Q be as in the above conditions. If P and Q are similar, i.e. there exists $u \in \operatorname{GL} \mathscr{L}(E)$ such that $P = uQu^{-1}$, the matrices p and q are Murray-von Neumann equivalent.

Proof. We have that $P = uQu^{-1}$, $\operatorname{Im} P \simeq pA^n$ and $\operatorname{Im} Q \simeq qA^m$. Therefore:

$$\Omega_y \Omega_x^* = P = uQu^{-1} = u\Omega_w \Omega_z^* u^{-1} = \Omega_{u(w)} \Omega_{(u^{-1})^*(z)}^*,$$

which means that

$$\sum_{i=1}^{n} y_i \langle x_i, \cdot\,\rangle = \sum_{i=1}^{m} u(w_i)\langle (u^{-1})^*(z_i), \cdot\,\rangle.$$

Notice that the matrix $\widehat{q} := \left(\langle (u^{-1})^*(z_i), u(w_j)\rangle\right)_{i,j}$ obeys $\operatorname{Im} uQu^{-1} \simeq \widehat{q}A^m$ by the construction of 2.3.9. But since $\langle (u^{-1})^*(z_i), u(w_j)\rangle = \langle z_i, w_j\rangle$, one concludes that $\widehat{q} = q$, hence, we obtain two isomorphisms such that the following diagram commutes.

$$\begin{tikzcd}
\operatorname{Im} P \arrow[r, equal] \arrow[d] & \operatorname{Im} uQu^{-1} \arrow[r, dashed] \arrow[d] & \operatorname{Im} Q \arrow[d] \\
pA^n \arrow[r, dashed] & qA^m \arrow[r, equal] & qA^m
\end{tikzcd}$$

Since $pA^n \simeq qA^m$ if, and only if p and q are Murray-von Neumann equivalent by 2.5.3, the result follows. $\square$

Corollary 2.5.9. Let P and Q be compact idempotent operators in $\mathscr{L}(E)$. If $[P]_0 = [Q]_0$, then $\texttt{rank}\,(P) = \texttt{rank}\,(Q)$.

2.6 Quasi-stably-isomorphic Hilbert modules

If X, Y, Z and W are Hilbert A-modules and T is in $\mathscr{L}(X \oplus Y, Z \oplus W)$, then T can be represented by a matrix

$$T = \begin{pmatrix} T_{ZX} & T_{ZY} \\ T_{WX} & T_{WY} \end{pmatrix}$$

where T_{ZX} is in $\mathscr{L}(X, Z)$ and similarly for the other matrix entries. Matrix notation is used to define our next important concept.

We are in touch with pretty algebraic properties of Hilbert modules, and in our case of finite rank ones. Since those modules can be seen as projective finitely generated, an algebraist might convince you that two generators $[M]_0, [N]_0 \in K_0(A)$ are equal if, and only if they are *stably-isomorphic*, i.e. there exists n such that $M \oplus A^n \simeq N \oplus A^n$. We will present a generalization of this concept in terms of the ***rank*** , darkly hidden:

Definition 2.6.1 (Quasi-stably-isomorphic finite rank)**.** Two Hilbert modules E and F are said to be *quasi-stably-isomorphic* if there exists a Hilbert module X and an invertible operator $T \in \mathrm{GL}\,\mathscr{L}(E \oplus X, F \oplus X)$ such that $I_X - T_{XX}$ is compact.

Notice that this is an equivalence relation. Before lighting that relationship, first we enrich the definition on the special case of finite-rank modules.

Lemma 2.6.2. Assume M and N are A-finite rank modules. If M and N are quasi-stably-isomorphic then the module X referred to in 2.6.1 can be taken to be countably generated.

Proof. Let X and T as in 2.6.1. Using matrix notation, we have:

$$\begin{aligned} T:\quad M \oplus X &\longrightarrow N \oplus X \\ (\xi, \eta) &\longmapsto \begin{pmatrix} T_{NM} & T_{NX} \\ T_{XM} & T_{XX} \end{pmatrix} \begin{pmatrix} \xi \\ \eta \end{pmatrix} \end{aligned}$$

Since it is an invertible operator, consider the inverse given in matrix notation as well:

$$T^{-1} = \begin{pmatrix} S_{MN} & S_{MX} \\ S_{XN} & S_{XX} \end{pmatrix}$$

We shall construct inductively a enumerable collection $\mathscr{C} \subset X$ in order to generate a specific submodule. Such a construction will be given by a collection $(\mathscr{C}_n)_{n \in \mathbb{N}} \subset \wp(X)$, in order that each $\mathscr{C}_n \subset X$ satisfies:

- (i) The images of the operators T_{XM}, S_{XN}, T^*_{NX} and S^*_{XM} are contained in the submodule of X generated by $\mathscr{C}_n$.
- (ii) $I_X - T_{XX}$ can be approximated by finite rank operators of the form $\Omega_y \Omega_x^*$, where the components of x and y belong to $\mathscr{C}_n$.

For a given $i \leqslant n$, let Π_i be the projection in the i-th coordinate of a tuple. In order to choose wisely, we write a technical issue:

(*iii*) **Choice of generators**: Let $r \in \mathscr{L}(P, X)$ where P is a finite rank Hilbert module. By assumption, there exists a natural number $n \in \mathbb{N}$ and tuples $x, y \in P^n$ such that $I_P = \Omega_y \Omega_x^*$. Notice that their existence depends on the domain of r. Therefore,

$$r = r\Omega_y \Omega_x^* = \sum_{i=1}^{n} r\Pi_i y \langle \Pi_i x, \cdot \rangle$$

We are using the i-th coordinate projection Π_i since new indexes are about to come. Hence, $\operatorname{Im} r$ is contained in the submodule generated by $\left(r\Pi_i y\right)_{i \leqslant n}$.

In order to obey (*i*), our initial collection $\mathscr{C}_0$ must contain all elements of the form $r\pi_i(y(r))$ for r varying over the desired operators. Since $I_X - T_{XX}$ is a compact set, there exists tuple sequences $(\boldsymbol{\xi}_n)_{n\in\mathbb{N}}, (\boldsymbol{\zeta}_n)_{n\in\mathbb{N}}$ such that

$$I_X - T_{XX} = \lim_{n\to\infty} \Omega_{\boldsymbol{\zeta}_n} \Omega_{\boldsymbol{\xi}_n}^*.$$

To facilitate the notation, write $\mathscr{O} := \{T_{XM}, S_{XN}, T_{NX}^*, S_{XM}^*\}$. Let $\mathscr{C}_0$ be given by:

$$\mathscr{C}_0 := \left\{r\Pi_i y \mid r \in \mathscr{O}, I_{\operatorname{dom}(r)} = \Omega_y \Omega_x^*\right\}_{i\in\mathbb{N}} \cup \bigcup_{n\in\mathbb{N}} \{\Pi_i \boldsymbol{\xi_n}, \Pi_i \boldsymbol{\zeta_n}\}_{i\in\mathbb{N}}$$

By construction, those properties are obeyed. Inductively, we set new collections in order to obey to above properties in terms of the operator T_{XX} and S_{XX}:

$$\mathscr{C}_{n+1} = \mathscr{C}_n \cup \bigcup_{r\in\mathscr{O}} r\left(\mathscr{C}_n\right) \qquad (n \in \mathbb{N})$$

in order that each $\mathscr{C}_n$ satisfies (*i*) and (*ii*). Therefore, the union $\mathscr{C} := \bigcup_n \mathscr{C}_n$ is then obviously countable, and also obeys those same properties above. In addition, the following one belongs to package:

(*iv*) **$\mathscr{C}$ is invariant under $\boldsymbol{T_{XX}, T_{XX}^{-1}, T_{XX}^*}$ and $\boldsymbol{(T_{XX}^{-1})^*}$.** Let $r \in \mathscr{L}(X)$ be one of the operators. If it was the case that $\mathscr{C}$ wasn't invariant over r, necessarily it would exists $w \in r(\mathscr{C})\backslash\mathscr{C}$, hence, $r^{-1}(w) \in \mathscr{C}_n$ for some n. However,

$$w = r(r^{-1}(w)) \in \mathscr{C}_n \cup r(\mathscr{C}_n) \subset \mathscr{C}_{n+1} \subset \mathscr{C}$$

i.e. it cannot be the case.

Let X' be the Hilbert submodule of X generated by $\mathscr{C}$. Because of (*i*) and (*iv*) we see that

$$T\left(M \oplus X'\right) \subseteq N \oplus X' \quad \text{and} \quad T^*\left(N \oplus X'\right) \subseteq M \oplus X'.$$

The restriction of T then gives an operator T' in $\mathscr{L}\left(M \oplus X', N \oplus X'\right)$. The same reasoning applies to T^{-1} providing $(T^{-1})'$ in $\mathscr{L}\left(N \oplus X', M \oplus X'\right)$ which is obviously the inverse of T'. In virtue of (*ii*) it is clear that T' satisfies the conditions of definition 2.6.1. □

In terms of the Morita-Rieffel equivalence, this is a big deal since we are not restricting ourselves into C^*-algebras with countably approximate identities. After studying Fredholm operators between Hilbert C^*-modules, one shall construct group morphisms $K_*(A) \longrightarrow K_*(B)$ for generic C^*-algebras A and B. Those maps turn out to be isomorphisms when A and B are Morita-Rieffel equivalent.

Theorem 2.6.3. Let M and N be quasi-stably-isomorphic finite rank Hilbert modules over a C^*-algebra A. Therefore, $\boldsymbol{rank}\ (M) = \boldsymbol{rank}\ (N)$.

Proof. Let $T \in \mathrm{GL}(\mathscr{L}(M \oplus X, N \oplus X))$ with X being a countably generated Hilbert module (2.6.2) and $I_X - T_{XX} \in \mathscr{K}(X)$. By the countability condition, we can apply Kasparov's Stabilization Theorem 2.4.6 in order to obtain that $X \oplus \mathscr{H}_A \simeq \mathscr{H}_A$. Without loss of generality, we can assume that $X = \mathscr{H}_A$.

Since M is finitely generated as an A-module, by Kasparov's theorem again, there exists a isomorphism $\varphi : \mathscr{H}_A \longrightarrow M \oplus \mathscr{H}_A$. Now, we construct operators F and G given by the compositions:

$$F : \mathscr{H}_A \xrightarrow{\varphi} M \oplus \mathscr{H}_A \xrightarrow{T} N \oplus \mathscr{H}_A \twoheadrightarrow \mathscr{H}_A \hookrightarrow M \oplus \mathscr{H}_A \xrightarrow{\varphi^{-1}} \mathscr{H}_A$$

$$G : \mathscr{H}_A \xrightarrow{\varphi} M \oplus \mathscr{H}_A \twoheadrightarrow \mathscr{H}_A \hookrightarrow N \oplus \mathscr{H}_A \xrightarrow{T^{-1}} M \oplus \mathscr{H}_A \xrightarrow{\varphi^{-1}} \mathscr{H}_A$$

Those are the first moments we are dealing with some generalized Fredholm operators, which will be introduced in Chapter 3. But this is not important for this particular proof. We state that

(*i*) **Both $\boldsymbol{I - FG}$ and $\boldsymbol{I - GF}$ are compact**: Let $\Pi_M = I_M \oplus 0$ and $\Pi_{\mathscr{H}_A} = 0 \oplus I$ be the coordinate projections. When composing, one can simplify:

$$FG : \mathscr{H}_A \xrightarrow{\varphi} M \oplus \mathscr{H}_A \xrightarrow{\Pi_{\mathscr{H}_A}} M \oplus \mathscr{H}_A \xrightarrow{\varphi^{-1}} \mathscr{H}_A$$

$$GF : \mathscr{H}_A \xrightarrow{\varphi} M \oplus \mathscr{H}_A \xrightarrow{T} N \oplus \mathscr{H}_A \xrightarrow{\Pi_{\mathscr{H}_A}} N \oplus \mathscr{H}_A \xrightarrow{T^{-1}} M \oplus \mathscr{H}_A \xrightarrow{\varphi^{-1}} \mathscr{H}_A$$

Meaning that

$$\begin{array}{rcl} I - FG & = & I - \varphi^{-1}\Pi_{\mathscr{H}_A}\varphi \\ & = & \varphi^{-1}\Pi_M\varphi \end{array} \quad \text{and} \quad \begin{array}{rcl} I - GF & = & I - \varphi^{-1}T^{-1}\Pi_{\mathscr{H}_A}T\varphi \\ & = & (T\varphi)^{-1}\Pi_N(T\varphi) \end{array}$$

Therefore, $I - FG$ and $I - GF$ are unitarily equivalent to Π_M and Π_N, which are compact operators.

(*ii*) $\boldsymbol{I - FG}$ **and** $\boldsymbol{I - GF}$ **are idempotents**: Notice that $F = \varphi^{-1}(0_M \oplus \Pi_{\mathscr{H}_A}T\varphi(\,\cdot\,))$. Therefore:

$$\begin{array}{rcl} FGF & = & \varphi^{-1}(0_M \oplus \Pi_{\mathscr{H}_A}T\varphi GF(\,\cdot\,)) \\ & = & \varphi^{-1}(0_M \oplus \Pi_{\mathscr{H}_A}T\varphi\varphi^{-1}T^{-1}\Pi_{\mathscr{H}_A}T\varphi(\,\cdot\,)) \\ & = & \varphi^{-1}(0_M \oplus \Pi_{\mathscr{H}_A}T\varphi(\,\cdot\,)) = F. \end{array}$$

Similarly, one can check that $GFG = G$. Hence, $I - FG$ and $I - GF$ are idempotents.

(iii) ***F* and *G* are compact perturbations of the identity**: The operators which ignores φ and φ^{-1} in the constructions of F and G, are represented by

$$F' := \begin{pmatrix} 0 & 0 \\ T_{\mathscr{H}_A M} & T_{\mathscr{H}_A\mathscr{H}_A} \end{pmatrix} \quad \text{and} \quad G' := \begin{pmatrix} 0 & S_{M\mathscr{H}_A} \\ 0 & S_{\mathscr{H}_A\mathscr{H}_A} \end{pmatrix}$$

where $S := T^{-1}$. Since $T_{\mathscr{H}_A\mathscr{H}_A}$ is a compact perturbation of the identity and both M and N are finite rank modules (and so any operator having either M or N as domain or codomain must be compact), one concludes that F' and G', hence, F and G are indeed, compact perturbations of the identity.

For sake of notation, let $\mathscr{Q}(E) := \mathscr{L}(E)/\mathscr{K}(E)$ for a Hilbert A-module E. Since the compact set is an ideal of the adjointable maps, one can consider the following exact sequence of C^*-algebras:

$$0 \longrightarrow \mathscr{K}(\mathscr{H}_A) \hookrightarrow \mathscr{L}(\mathscr{H}_A) \xrightarrow{\pi} \mathscr{Q}(\mathscr{H}_A) \longrightarrow 0 \tag{2.13}$$

Notice that we can consider the index map ∂ induced by (2.13). As stated in item (iii), one concludes that $\pi(F) = 1_{\mathscr{Q}(\mathscr{H}_A)}$. Since I_2 is a lift of $\mathrm{diag}(1_{\mathscr{Q}(\mathscr{H}_A)}, {1_{\mathscr{Q}(\mathscr{H}_A)}}^{-1})$, one can obtain that

$$\partial([1_{\mathscr{Q}(\mathscr{H}_A)}]_1) = [I_2 p_2 I_2^{-1}]_0 - [p_2]_0 = 0.$$

We can extract more information by writing down who is the index in terms of F and G. By (i), is easy to see that $\pi(F)$ and $\pi(G)$ are each others inverse in $\mathscr{Q}(\mathscr{H}_A)$. In order to compute the index, the element

$$w := \begin{pmatrix} F & I-FG \\ I-GF & G \end{pmatrix} \in \mathrm{GL}_2^{(0)}(\mathscr{Q}(\mathscr{H}_A))$$

is a lift of $\mathrm{diag}(\pi(F), \pi(F)^{-1})$, and its inverse just swaps F and G places. Therefore:

$$\begin{aligned} 0 &= \partial\left([\pi(F)]_1\right) \\ &= \left[wp_2w^{-1}\right]_0 - [p_2]_0 \\ &= \left[\begin{pmatrix} F & I-FG \\ I-GF & G \end{pmatrix}\begin{pmatrix} I & 0 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} G & I-GF \\ I-FG & F \end{pmatrix}\right]_0 - \left[\begin{pmatrix} I & 0 \\ 0 & 0 \end{pmatrix}\right]_0 \\ &= \left[\begin{pmatrix} FG & 0 \\ 0 & I-GF \end{pmatrix}\right]_0 - \left[\begin{pmatrix} I & 0 \\ 0 & 0 \end{pmatrix}\right]_0 \\ &= [I-GF]_0 - [I-FG]_0 \end{aligned}$$

Hence $[I-FG]_0 = [I-GF]_0$ and by the corollary 2.5.9, one obtains that $\mathit{rank}\ (I-FG) = \mathit{rank}\ (I-GF)$. We had seen that $I-FG = \varphi^{-1}\Pi_M\varphi$, i.e. $\mathrm{Im}(I-FG) \simeq M$. Therefore:

$$\mathit{rank}\ (M) = [M]_0 = [\mathrm{Im}(I-FG)]_0 = \mathit{rank}\ (I-FG).$$

Similarly, one obtains that $\mathit{rank}\ (N) = \mathit{rank}\ (I-GF)$ and consequentially, $\mathit{rank}\ (M) = \mathit{rank}\ (N)$ as we were looking. $\square$

Chapter 3

Fredholm Operators

In regular Fredholm theory, one would define Fredholm operators as those with both kernel and cokernel were finite dimensional. Here, our concepts involving "finiteness" depends on a fixed C^*-algebra A, so, talking about dimension is kinda tricky. But classical Atikinson's theorem characterizes Fredholm operators in terms only of compactness, which we fully characterize in Theorem 2.6.3. That points towards a generalization.

Definition 3.0.1 (A-Fredholm)**.** A given $T \in \mathscr{L}(E, F)$ is said to be A-Fredholm if it is invertible modulo $\mathrm{FR}(E, F)$, i.e. exists $S \in \mathscr{L}(F, E)$ such that both $I_E - ST$ and $I_F - TS$ are A-finite rank operators.

If adjointable operators S, S' and T are such that both TS and $S'T$ are Fredholm, one can obtain operators R and R' such that $I - T(SR)$ and $I - (R'S')T$ are finite-rank ones. Hence T is Fredholm.

Proposition 3.0.2. If T is invertible modulo $\mathscr{K}(E, F)$, then it is A-Fredholm. Hence, definition 3.0.1 really fits the sentence "Atikinson's trivialization".

Proof. Let us digress a little bit:

> ***Remark* 3.0.3.** Let $J \lhd A$ be a non-closed ideal of a unital C^*-algebra, and suppose that $a \in A$ is invertible modulo $\overline{J}$ (the topological closure), i.e. there exists $b \in A$ such that $(1 - ab) \in \overline{J}$. Therefore, there exists a sequence $(j_n)_n \subset J$ such that $j_n \to (1 - ab)$, which means that at least one of then, say j, obeys $\|1 - ab - j\| < 1$. Since $ab + j = 1 - (1 - ab - j)$, $ab + j$ is invertible[1]. Therefore, some algebraic manipulation shows that
>
> $$a \underbrace{b(ab + j)^{-1}}_{x_1} - 1 = -j(ab + j)^{-1} \in J$$
>
> i.e. a is right invertible modulo J. But since b also ensure that $(1 - ba) \in \overline{J}$, hence it exist x_2 such that $(x_2 a - 1) \in J$. Notice that
>
> $$x_2(ax_1 - 1) = \big((x_2 a)x_1 - x_2\big) = (x_1 - x_2) \in J,$$

[1] Notice that $(\lambda - a) \in \mathrm{GL}(A)$ whenever $\|a\| < |\lambda|$.

i.e. $[x_1] = [x_2]$ in the quotient algebra A/J. Therefore, there is a representative of the class of x_1 and x_2, say x, such that both $1 - ax$ and $1 - xa$ belong to J, i.e. a is invertible modulo J. ☕

With this digression in mind, notice that if $(I_E - TS) \in \mathscr{K}(E, F)$, there exist an element R such that both $I_E - TR$ and $I_F - RT$ are finite-rank operators, i.e. T is Fredholm. □

***Remark* 3.0.4.** Let H and W be complex Hilbert spaces. The set of classical Fredholm operators coincide with the $\mathbb{C}$-Fredholm ones. ☕

Example 3.0.5 ([28])**.** Let $X \in$ **CHaus** and $\mathscr{F}(\ell^2(\mathbb{N}))$ the set of $\mathbb{C}$-Fredholm classical operators over the separable Hilbert space $\ell^2(\mathbb{N})$. We avoid writing $\ell^2(\mathbb{N})$ everywhere, so $\mathscr{B}$, $\mathscr{K}$ and $\mathscr{F}$ will respectively denote the bounded, compact and Fredholm operators over $\ell^2(\mathbb{N})$.

For any continuous family of operators[2] $T : X \longrightarrow \mathscr{B}$, it is possible to see T as a $C(X)$-endomorphism over the standard Hilbert $C(X)$-module $\mathscr{H}_{C(X)}$:

$$\begin{aligned} \widehat{T}: \quad \mathscr{H}_{C(X)} &\longrightarrow \mathscr{H}_{C(X)} \\ \xi &\longmapsto (x \mapsto T_x \xi(x)) \end{aligned}$$

Each $T_x \coloneqq T(x)$ is a classical operator in a Hilbert space, so $T^* \in C(X, \mathscr{B})$. Hence $\widehat{T}$ is adjointable. In order to show that continuous families of Fredholm operators extent to $C(X)$-Fredholm ones, we need the following claim:

(*i*) $\boldsymbol{\widehat{T}}$ **is $\boldsymbol{C(X)}$-compact whenever Im $\boldsymbol{T} \subset \mathscr{K}$:** Let $\varepsilon > 0$ and $T \in C(X, \mathscr{K})$. For each $x \in X$, pick a finite rank operator R_x so that $\|R_x - T_x\| \leqslant \varepsilon/3$, and pick a neighborhood U_x such that $\|T_x - T_y\| \leqslant \varepsilon/3$ for $y \in U_x$. Since X is compact, extract a finite subcover $U_1, \ldots, U_n$ of $(U_x)_{x \in X}$, and a partition of unity $\lambda_1, \ldots, \lambda_n$. Then
$$\|T_x - \sum_{i=1}^{n} \lambda_j(x) R_{x_j}\| \leqslant \varepsilon\,.$$
Therefore, is a finite rank the operator $\sum_i \lambda_i(\,\cdot\,) R_{x_i}$ and, $\widehat{T}$ is compact.

Suppose that the range of T is constituted only by Fredholm operators, which we will denote by $\mathscr{F}$. In order to see the extension of T to the standard Hilbert $C(X)$-module, $\widehat{T} \in \mathscr{L}(\mathscr{H}_{C(X)})$ is a $C(X)$-Fredholm operator, we must conjure the following:

> **Summoning 3.0.6** (Classical Bartle-Graves theorem - Corollary 17.67 [2])**.** Every surjective continuous linear operator between Banach spaces[a] admits continuous right inverse, but not necessarily a linear one. ☕
>
> [a]More generally, completely metrizable locally convex spaces, i.e. Fréchet spaces.

[2]For example, $T : [0, 1] \longrightarrow \mathscr{F}$, $T_x(\xi) \coloneqq (x\xi_n)_n$.

Bartle-Graves theorem has significant improvements and different versions (e.g., [9]), but for our needs, we are fine with the above.

Consider the Calkin algebra given by the quotient of compact operators: $\mathscr{Q} \coloneqq \mathscr{B}/\mathscr{K}$ and π be the quotient map. Bartle-Graves theorem offers a continuous section $\sigma : \mathscr{Q} \longrightarrow \mathscr{B}$ such that $\pi\sigma A = A$. Let S be given by the composition:

$$\begin{tikzcd} X \arrow[rr, dashed, "S"] \arrow[d, "T"'] & & \mathscr{F} \\ \mathscr{F} \arrow[r, two heads, "\pi"'] & \mathrm{GL}\,\mathscr{Q} \arrow[r, "(\,\cdot\,)^{-1}"'] & \mathrm{GL}\,\mathscr{Q} \arrow[u, "\sigma"'] \end{tikzcd}$$

Since $T_x \in \mathscr{F}$ if and only if $\pi(T_x)$ is invertible in $\mathscr{Q}$ (by Atikinson's theorem), S is well defined and continuous (each arrow above is), hence defines a endomorphism $\widehat{S}$ in $\mathscr{H}_{C(X)}$. We are left to show that both $I - \widehat{S}\widehat{T}$ and $I - \widehat{T}\widehat{S}$ are $C(X)$-compact operators in $\mathscr{H}_{C(X)}$.

Since $1_{C(X)} - T \cdot S$ and $1_{C(X)} - S \cdot T$ are continuous families with compact range, $\widehat{T}$ is indeed $C(X)$-Fredholm by *(i)*.

In the classical Fredhom theory between Hilbert spaces, one only requires that $\ker T$ and $\operatorname{coker} T$ are finite dimensional. Those assumptions are sufficient to guarantee that every classical Fredholm operator has closed range, hence orthogonal decompositions are abundant in the proofs. Unfortunately, our definition allow non topologically closed ranges.

Example 3.0.7 (Non closed range A-Fredholm operator)**.** $C[0,1]$ is a unital C^*-algebra, that we shall consider as a Hilbert C^*-module. Choose T to be

$$\begin{aligned} T : \quad C[0,1] &\longrightarrow C[0,1] \\ f &\longmapsto (x \mapsto xf(x)) \end{aligned}$$

Since the algebra is unital, any adjointable operator is $C[0,1]$-compact: $\mathscr{L}(C[0,1]) \simeq \mathscr{K}(C[0,1])$ (for instance, see Example 2.3.4*(ii)*), hence must be $C[0,1]$-Fredholm as well. Unfortunately, the square root $\sqrt{\cdot}$ doesn't belong to the range of T, but it can be approximated by the Bernstein polynomials $B_n(x) \coloneqq \sum_{k \leqslant n} \binom{n}{k} \sqrt{k/n}\, x^k (1-x)^{n-k}$.

Therefore, in order to develop the theory of Fredholm operator between Hilbert modules and, in some extent, try to obtain a correspondence with the classical theory, we shall dodge the closure condition. Hence, we will focus on a smaller class of operators: those which admit pseudo-inverse, henceforth, the *regular* ones. Later, we shall extent our results to general Fredholm operators, showing that each and everyone is, in some extent, regularizable.

3.1 Regular Fredholm operators

Definition 3.1.1 (Regular operators)**.** It is said to be *regular* any operator $T \in \mathscr{L}(E, F)$ that admits a *pseudo-inverse*, i.e. there exists $S \in \mathscr{L}(F, E)$ such that $TST = T$ and $STS = S$.

Example 3.1.2. The operators F and G constructed in the proof of Theorem 2.6.3 are regular Fredholm operators which are pseudo-inverses of each other: $FGF = F$ and $GFG = G$.

For a regular Fredholm operator T, such a pseudo-inverse S fits the Fredholm criteria of T: If S' is such that $I_E - S'T$ and $I_F - TS'$ are finite-rank operators,

$$\begin{aligned}(I_E - S'T)(I_E - ST) &= (I_E - S'T) - (I_E - S'T)ST \\ &= I_E - S'T - ST + \underbrace{S'TST}_{S'T} = I_E - ST\end{aligned}$$

Since $\mathrm{FR}(E, F)$ is an ideal, the above manipulation shows that $I_E - ST$ is indeed a finite-rank operator (and similarly for $I_F - TS$).

***Remark* 3.1.3.** When S is such that TS and ST are idempotents, it is called a *Moore-Penrose* inverse. To motivate the study of regular Fredholm operators as some way to deal with a weaker version of "the range is closed", we exhibit the following theorem:

> **Theorem**. For a Hilbert space H, a bounded operator $T \in \mathscr{B}(H)$ admits a Moore-Penrose pseudo-inverse S if, and only if, $\operatorname{Im} T$ is closed.

One way is pretty simple to prove: If there exists a Moore-Penrose pseudo-inverse S, $\operatorname{Im} T = \operatorname{Im} TS$. Since TS is a orthogonal projection by hypothesis, $\operatorname{Im} T$ is closed.

Conversely, consider the following decompositions

$$H = \ker T \oplus \operatorname{Im} T^* = \ker T^* \oplus \operatorname{Im} T.$$

Therefore, $T\restriction_{\operatorname{Im} T^*}$ is an injective bounded operator, with a bounded inverse S. Similarly, $T^*\restriction_{\operatorname{Im} T}$ admits a bounded inverse R. Those inverses can be extended to all the space, by setting it to zero outside their original domains (which is fine, since the kernels are all there is left in each case). One can verify that $R = S^*$ and that S induces a Moore-Penrose inverse.

Proposition 3.1.4. Let $T \in \mathscr{L}(E, F)$ be a A-Fredholm operator. If T admits a pseudo-inverse S, then:

(i) $I_E - ST$ and TS are idempotents with ranges $\ker T$ and $\operatorname{Im} T$.

(ii) $\ker T$ and $\ker T^*$ are finite rank modules.

Proof. Notice that $(ST)^2 = S(TST) = ST$ and similarly for TS, i.e. they are idempotents. It is easy to see that $I_E - ST$ also has the idempotent badge, $\operatorname{Im}(I_E - ST) = \ker T$ and $\operatorname{Im} TS = \operatorname{Im} T$.

Is easy to see that $I_{\ker T} = (I_E - ST)\restriction_{\ker T}$. When supposing that T is A-Fredholm, let $x, y \in E^n$ be such that $I_E - ST = \Omega_y \Omega_x^*$. Idempotent operators share their range with some projection by the remark 2.5.5. Since $I_E - ST$ is an idempotent, there exists a self-adjoint idempotent operator P such that $\operatorname{Im}(I_E - ST) = \operatorname{Im} P = \ker T$. Therefore, with $a = \Omega_y \Omega_x^*$ and $p = P$, 2.5.5.(vii) guarantee that

$$\Omega_y \Omega_x^* \restriction_{\ker T} = P \Omega_y \Omega_x^* P \overset{P^* = P}{=} \Omega_{Py} \Omega_{Px}^*.$$

Since $Py, Px \in (\ker T)^n$, it follows that $I_{\ker T} = \Omega_{Py}\Omega^*_{Px}$ is a finite-rank operator over $\ker T$, i.e. $\ker T$ is a finite-rank module. Very much the same is sufficient to obtain that $\ker T^*$ also is a finite-rank module. □

The rank of a finite rank module is well defined as seen before. Hence, the above proposition enable us to define the Index of regular Fredholm operators.

Definition 3.1.5. If T is a regular A-Fredholm operator, set their *index* to be the $K_0(A)$ element given by

$$\boldsymbol{ind}\, T \coloneqq \boldsymbol{rank}\,(\ker T) - \boldsymbol{rank}\,(\ker T^*).$$

Proposition 3.1.6. If $T \in \mathscr{L}(E, F)$ is a regular Fredholm operator, then:

(i) $\boldsymbol{ind}\, T^* = -\boldsymbol{ind}\, T$.

(ii) For any pseudo-inverse S, $\boldsymbol{rank}\,(\ker T^*) = \boldsymbol{rank}\,(\ker S)$ and $\boldsymbol{ind}\, S = -\boldsymbol{ind}\, T$.

(iii) If there are invertible operators U and V between Hilbert modules such that the following diagram commutes, then VTU is Fredholm and $\boldsymbol{ind}\,(VTU) = \boldsymbol{ind}\, T$.

$$\begin{tikzcd} X \arrow[r, "\simeq", "U"'] \arrow[rrr, bend left, "VTU"] & E \arrow[r, "T"'] & F \arrow[r, "\simeq", "V"'] & Y \end{tikzcd}$$

(iv) If $T_i \in \mathscr{L}(E_i, F_i)$ is a regular Fredholm operator for $i \in \{1, 2\}$, the direct sum $T_1 \oplus T_2$ is also regular Fredholm and $\boldsymbol{ind}\,(T_1 \oplus T_2) = \boldsymbol{ind}\, T_1 + \boldsymbol{ind}\, T_2$.

Proof.

(i) Clear.

(ii) Since S and T^* are Fredholm operators, $\ker T^*$ and $\ker S$ are finite rank modules (3.1.4). In what comes next, keep in mind that $(\operatorname{Im} T)^\perp = \ker T^*$. Visiting again the remark 2.5.5, one can conclude that for any idempotent $Q : F \longrightarrow E$, $F = \operatorname{Im} Q \oplus (\operatorname{Im} Q)^\perp$. Since TS is an idempotent, we obtain the following diagram of equality:

$$\begin{tikzcd} \operatorname{Im}(I_F - TS) \oplus \operatorname{Im} TS \arrow[r, equal] \arrow[d, equal] & F \arrow[r, equal, "2.5.5"] & (\operatorname{Im} TS)^\perp \oplus \operatorname{Im} TS \arrow[d, equal, "(\operatorname{Im} TS)^\perp = (\operatorname{Im} T)^\perp = \ker T^*"] \\ \ker S \oplus \operatorname{Im} TS & & \ker T^* \oplus \operatorname{Im} TS \end{tikzcd}$$

Therefore, $\ker S$ and $\ker T^*$ are quasi-stably-isomorphic. Therefore, 2.6.3 guarantee that $\boldsymbol{rank}\,(\ker S) = \boldsymbol{rank}\,(\ker T^*)$. Consequentially, $\boldsymbol{ind}\, S = -\boldsymbol{ind}\, T$.

(iii) Notice that $\ker VT = \ker T$ since V is invertible, hence $\boldsymbol{rank}\,(\ker VT) = \boldsymbol{rank}\,(\ker T)$. Analysing $U\restriction_{\ker TU}$, one obtains that $\ker TU \simeq \ker T$, thus $\boldsymbol{rank}\,(\ker TU) = \boldsymbol{rank}\,(\ker T)$. The exact same roll goes for the adjoints. Therefore, the indexes coincide.

(*iv*) It is the case that $\Omega_{\xi_1 \oplus \xi_2} = \Omega_{\xi_1} \oplus \Omega_{\xi_2}$ for any $\xi_1 \oplus \xi_2 \in E_1 \oplus E_2$, which is sufficient to infer that $T_1 \oplus T_2$ is a Fredholm operator.

Since $\ker(T_1 \oplus T_2) = \ker T_1 \oplus \ker T_2$, $\ker(T_1 \oplus T_2)$ is a finite rank module. If $\boldsymbol{rank}\ T_i = [p_i]_0$, it is clear that

$$\begin{aligned}\boldsymbol{rank}\ (\ker(T_1 \oplus T_2)) &= [\operatorname{diag}(p_1, p_2)]_0 \\ &= [p_1]_0 + [p_2]_0 \\ &= \boldsymbol{rank}\ (\ker T_1) + \boldsymbol{rank}\ (\ker T_2).\end{aligned}$$

Therefore, the desired index relation follows. □

Since our compact operators aren't necessarily the same as in Hilbert space case, the index invariance under compact perturbations needs to be handed carefully.

Proposition 3.1.7. If $T \in \mathscr{L}(E)$ is a regular Fredholm operator such that $(I - T) \in \mathscr{K}(E)$, then $\boldsymbol{ind}\ T = 0$.

Proof. Let S be a pseudo-inverse of T. Since $I - T$ is a compact operator and the compact operators is an ideal, notice that S is a compact perturbation of the identity:

$$S = I + S(I - T) - (I - ST)$$

Considering the isomorphism map $U : \ker T \oplus \operatorname{Im} S \longrightarrow \ker S \oplus \operatorname{Im} S$ given by

$$U := \begin{pmatrix} I - TS & I - TS \\ S & S \end{pmatrix} \qquad U^{-1} = \begin{pmatrix} I - ST & (I - ST)T \\ ST & STT \end{pmatrix}$$

with the fact that $I - S = I_{\operatorname{Im} S} - U_{\operatorname{Im} S \operatorname{Im} S}$ is compact, the modules $\ker T$ and $\ker S$ are quasi-stably-isomorphic. By 2.6.3, $\boldsymbol{rank}\ (\ker T) = \boldsymbol{rank}\ (\ker S)$, hence

$$\begin{aligned}\boldsymbol{ind}\ T &= \boldsymbol{rank}\ (\ker T) - \boldsymbol{rank}\ (\ker T^*) \\ &\overset{3.1.6(ii)}{=} \boldsymbol{rank}\ (\ker T) - \boldsymbol{rank}\ (\ker S) = 0. \quad \square\end{aligned}$$

Theorem 3.1.8. If $T_1, T_2 \in \mathscr{L}(E, F)$ are regular Fredholm operators such that $T_1 - T_2$ is compact, then $\boldsymbol{ind}\ T_1 = \boldsymbol{ind}\ T_2$.

Proof. The action plan for the proof will be as follows: Build accessory operators U and R in function of the given maps, such that U is invertible and $\boldsymbol{ind}\ R = \boldsymbol{ind}\ T_2 - \boldsymbol{ind}\ T_1$. Hence, we show that $\boldsymbol{ind}\ (UR)$ is a compact perturbation of the identity, so we can use the previous theorem and obtain that $\boldsymbol{ind}\ R = \boldsymbol{ind}\ (UR) = 0$.

Let S_1 and S_2 be pseudo inverses for T_1 and T_2. Define operators U and R in $\mathscr{L}(E \oplus F)$ by

$$U := \begin{pmatrix} I_E - S_1 T_1 & S_1 \\ T_1 & I_F - T_1 S_1 \end{pmatrix} \text{ and } R := \begin{pmatrix} 0 & S_1 \\ T_2 & 0 \end{pmatrix}.$$

(*i*) $\boldsymbol{ind}\ \boldsymbol{R} = \boldsymbol{ind}\ \boldsymbol{T_2} - \boldsymbol{ind}\ \boldsymbol{T_1}$: Using the coordinate switch operator (which has index zero since it is a invertible one), one obtains that:

$$\begin{tikzcd} E \oplus F \arrow[rr, "R"] \arrow[dr, "(x,y)\mapsto(y,x)"'] & & E \oplus F \\ & F \oplus E \arrow[ur, "S_1 \oplus T_2"'] & \end{tikzcd} \qquad \begin{aligned} \boldsymbol{ind}\ R &\overset{3.1.6(iii)}{=} \boldsymbol{ind}\ (S_1 \oplus T_2) \\ &\overset{3.1.6(iv)}{=} \boldsymbol{ind}\ S_1 + \boldsymbol{ind}\ T_2 \\ &\overset{3.1.6(ii)}{=} -\boldsymbol{ind}\ T_1 + \boldsymbol{ind}\ T_2. \end{aligned}$$

(*ii*) $\boldsymbol{U}$ **is invertible**: Since $I_E - S_1T_1$ and $I_F - T_1S_1$ are idempotents,

$$\begin{aligned} U^2 &= \begin{pmatrix} I_E - S_1T_1 & S_1 \\ T_1 & I_F - T_1S_1 \end{pmatrix}^2 \\ &= \begin{pmatrix} (I_E - S_1T_1)^2 + S_1T_1 & (I_E - S_1T_1)S_1 + S_1(I_F - T_1S_1) \\ T_1(I_E - S_1T_1) + (I_F - T_1S_1)T_1 & T_1S_1 + (I_F - T_1S_1)^2 \end{pmatrix} \\ &= \begin{pmatrix} I_E & 0 \\ 0 & I_F \end{pmatrix} = I_{E\oplus F}. \end{aligned}$$

Therefore U is invertible.

(*iii*) $\boldsymbol{UR}$ **is a compact perturbation of identity**: First, we obtain UR:

$$UR = \begin{pmatrix} I_E - S_1T_1 & S_1 \\ T_1 & I_F - T_1S_1 \end{pmatrix} \begin{pmatrix} 0 & S_1 \\ T_2 & 0 \end{pmatrix} = \begin{pmatrix} S_1T_2 & 0 \\ (I_F - T_1S_1)T_2 & T_1S_1 \end{pmatrix}$$

Bravely evaluating the difference, we must determine if is compact the following operator:

$$I_{E\oplus F} - UR = \begin{pmatrix} I_E - S_1T_2 & 0 \\ (T_1S_1 - I_F)T_2 & I_F - T_1S_1 \end{pmatrix}$$

Notice that all operators in the second row are compact since T_1 is Fredholm. From the hypothesis, $T_1 - T_2$ is compact, hence:

$$\begin{aligned} I_E - S_1T_2 &= I_E - S_1T_1 + S_1T_1 - S_1T_2 \\ &= (I_E - S_1T_1) + S_1(T_1 - T_2) \in \mathscr{K}(E). \end{aligned}$$

Since each entry of $I_{E\oplus F} - UR$ is a compact operator, the claim is proved.

Using 3.1.6(*iii*) again, we have that $\boldsymbol{ind}\ (UR) = \boldsymbol{ind}\ R$. Since UR is a compact perturbation of the identity, it follows that $\boldsymbol{ind}\ (UR) = 0$ by Proposition 3.1.7. □

3.2 Regularization of Fredholm operators

Time to extend our concepts to general Fredholm operators. A change in algebras will be necessary, so we write our next lemma with new a C^*-algebra notation.

Lemma 3.2.1. Let B be a unital C^*-algebra and $T \in \mathscr{L}_B(E, F)$ a B-Fredholm but not necessarily regular. There exists a natural n and some $x \in E^n$ such that

$$\begin{pmatrix} T & 0 \\ \Omega_x^* & 0 \end{pmatrix} : E \oplus B^n \longrightarrow F \oplus B^n$$

is a regular B-Fredholm operator.

Proof. Let S be a pseudo-inverse of T such that both $I_E - ST$ and $I_F - TS$ are finite rank operators, and $I_E - ST = \Omega_y \Omega_x^*$ for some $y \in F^n$, $x \in E^n$. We will construct operators $\widetilde{T}$ and $\widetilde{S}$ that are regular Fredholm. Define the following operators:

$$\widetilde{T} := \begin{pmatrix} T & 0 \\ \Omega_x^* & 0 \end{pmatrix} \quad \text{and} \quad \widetilde{S} := \begin{pmatrix} S & \Omega_y \\ 0 & 0 \end{pmatrix}.$$

(*i*) **$\widetilde{T}$ and $\widetilde{S}$ are pseudo-inverses of each other, hence regular**: In what follows, we need the expressions:

(*a*) $T\Omega_y\Omega_x^* = T(I_E - ST) = T - TST = 0$.

(*b*) $\Omega_x^*(ST + \Omega_y\Omega_x^*) = \Omega_x^*(ST + I_E - ST) = \Omega_x^*$.

Notice that

$$\begin{aligned} \widetilde{T}\widetilde{S}\widetilde{T} &= \begin{pmatrix} T & 0 \\ \Omega_x^* & 0 \end{pmatrix} \begin{pmatrix} S & \Omega_y \\ 0 & 0 \end{pmatrix} \begin{pmatrix} T & 0 \\ \Omega_x^* & 0 \end{pmatrix} \\ &= \begin{pmatrix} TS & T\Omega_y \\ \Omega_x^* S & \Omega_x^*\Omega_y \end{pmatrix} \begin{pmatrix} T & 0 \\ \Omega_x^* & 0 \end{pmatrix} \\ &= \begin{pmatrix} TST + T\Omega_y\Omega_x^* & 0 \\ \Omega_x^*(ST + \Omega_y\Omega_x^*) & 0 \end{pmatrix} \overset{(a)+(b)}{=} \begin{pmatrix} T & 0 \\ \Omega_x^* & 0 \end{pmatrix} = \widetilde{T} \end{aligned}$$

Similarly, one can obtain that $\widetilde{S}\widetilde{T}\widetilde{S} = \widetilde{S}$, hence $\widetilde{T}$ and $\widetilde{S}$ are regular due to the fact that they are each others pseudo-inverses.

(*ii*) **$\widetilde{T}$ and $\widetilde{S}$ are Fredholm operators**: Notice that:

$$I_{E\oplus B^n} - \widetilde{S}\widetilde{T} = \begin{pmatrix} I_E & 0 \\ 0 & I_{B^n} \end{pmatrix} - \begin{pmatrix} ST+\Omega_y\Omega_x^* & 0 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & I_{B^n} \end{pmatrix}$$

$$I_{F\oplus B^n} - \widetilde{T}\widetilde{S} = \begin{pmatrix} I_F & 0 \\ 0 & I_{B^n} \end{pmatrix} - \begin{pmatrix} TS & T\Omega_y \\ \Omega_x^* S & \Omega_x^*\Omega_y \end{pmatrix} = \begin{pmatrix} I_F - TS & -T\Omega_y \\ -\Omega_x^* S & I_{B^n} - \Omega_x^*\Omega_y \end{pmatrix} \tag{3.1}$$

Lets check that every entry in those matrices are compact:

(*a*) **I_E is finite rank**: Since B is unital, $I_{B^n} = \Omega_{(1_E,\ldots,1_E)}\Omega^*_{(1_E,\ldots,1_E)}$.

(*b*) **$I_F - TS$ is finite rank**: By assumption.

(*c*) **$-\Omega_x^* S, -T\Omega_y$ and $I_{B^n} - \Omega_x^*\Omega_y$ are compact**: This is due to the fact that Ω_y and Ω_x^* are compact (proposition 2.3.5) and the set of compact operators is an ideal.

Therefore, $I_{E\oplus B^n} - \widetilde{S}\widetilde{T}$ and $I_{F\oplus B^n} - \widetilde{T}\widetilde{S}$ are compact operators. Finally, proposition 3.0.2 guarantee that both $\widetilde{T}$ and $\widetilde{S}$ are regular Fredholm operators. □

Definition 3.2.2 (Regularization of a Fredholm operator)**.** Given an A-Fredholm $T \in \mathscr{L}_A(E, F)$, the *regularization of* T is the $\widetilde{A}$-Fredholm $\widetilde{T} \in \mathscr{L}_{\widetilde{A}}(E\oplus\widetilde{A}^n, F\oplus\widetilde{A}^n)$ constructed in lemma 3.2.1 for $B = \widetilde{A}$.

Proposition 3.2.3. For any A-Fredholm operator T, despite the fact that the regularization $\widetilde{T}$ is an $\widetilde{A}$-Fredholm operator, the index of $\widetilde{T}$ lies in $K_0(A)$.

Proof. Let $\varepsilon : \widetilde{A} \twoheadrightarrow \mathbb{C}$ the complex projection. Since $K_0(A)$ is the kernel of ε_0, we seek to obtain that $\varepsilon_0(\textbf{\textit{ind}}\,\widetilde{T}) = 0$. We borrow notations and results from the proof of 3.2.1, i.e. $I_E - ST = \Omega_y\Omega_x^*$ and

$$\widetilde{T} \coloneqq \begin{pmatrix} T & 0 \\ \Omega_x^* & 0 \end{pmatrix} \quad \text{and} \quad \widetilde{S} \coloneqq \begin{pmatrix} S & \Omega_y \\ 0 & 0 \end{pmatrix}$$

are regular $\widetilde{A}$-Fredholm operators and pseudo-inverses of each otter. To compute the index of $\widetilde{T}$, first we obtain that $\textbf{\textit{rank}}\,(\ker \widetilde{T}) = n{\cdot}1_{K_0(A)}$; in order to obtain $\textbf{\textit{rank}}\,(\ker \widetilde{T}^*) = \textbf{\textit{rank}}\,(\ker \widetilde{S})$, we will introduce two new operators P and Q, such that the rank of $\ker \widetilde{S}$ will coincide with the embedding of trace of $\varepsilon(Q)$, which will be equal to n.

Now, we look to verify those claims:

(*i*) $\boldsymbol{\textit{rank}\,(\ker \widetilde{T}) = n \cdot 1_{K_0(A)}}$: In the proof of Lemma 3.2.1 (3.1), we saw that $I_{E\oplus\widetilde{A}^n} - \widetilde{S}\widetilde{T} = 0 \oplus I_{\widetilde{A}^n}$. Since $\ker \widetilde{T} = \operatorname{Im}(I_{E\oplus\widetilde{A}^n} - \widetilde{S}\widetilde{T})$, it follows that

$$\textbf{\textit{rank}}\,(\ker \widetilde{T}) = [0 \oplus I_{\widetilde{A}^n}]_0 = n \cdot [1_{\widetilde{A}}]_0 = n \cdot 1_{K_0(A)}.$$

For notation sake, let:

$$P \coloneqq I_{F\oplus\widetilde{A}^n} - \widetilde{T}\widetilde{S} \overset{(3.1)}{=} \begin{pmatrix} I_F - TS & -T\Omega_y \\ -\Omega_x^* S & I_{B^n} - \Omega_x^*\Omega_y \end{pmatrix} \tag{3.2}$$

(*ii*) $\boldsymbol{\ker \widetilde{S} = \operatorname{Im} P}$. Lets check that the two sets coincide: In one direction, $\widetilde{S} - \widetilde{S}\widetilde{T}\widetilde{S} = 0$ since $\widetilde{S}$ and $\widetilde{T}$ are pseudo-inverses of each other. Hence $\ker \widetilde{S} \supset \operatorname{Im} P$. Conversely, the elements of the range of P can be written as:

$$\begin{aligned} P(\zeta + a) &= \begin{pmatrix} I_F - TS & -T\Omega_y \\ -\Omega_x^* S & I_{B^n} - \Omega_x^*\Omega_y \end{pmatrix} \begin{pmatrix} \zeta \\ a \end{pmatrix} \\ &= \begin{pmatrix} \zeta - T(S\zeta + \Omega_y a) \\ a - \Omega_x^*(\Omega_y a + S\zeta) \end{pmatrix} \end{aligned}$$

whenever $\zeta \in F$ and $a \in \widetilde{A}^n$. If $(\zeta + a) \in \ker \widetilde{S}$, then $P(\zeta + a) = \zeta + a$, hence $\zeta \oplus a$ is in the range of P, i.e. $\ker \widetilde{S} \subset \operatorname{Im} P$.

Hence, we shall compute $\textbf{\textit{rank}}\,(\operatorname{Im} P)$. Since $\widetilde{S}$ is a regular Fredholm operator, $\operatorname{Im} P = \ker \widetilde{S}$ is a finite-rank module (3.1.4), i.e. $I_{\operatorname{Im} P}$ can be written as $\Omega_\phi\Omega_\psi^*$ for some $m \in \mathbb{N}$ and a pair of tuples $\phi, \psi \in (F \oplus B^n)^m$, hence

$$I_{\operatorname{Im} P} = \Omega_\phi\Omega_\psi^* \quad \Rightarrow \quad P = \Omega_\phi\Omega_\psi^* P$$

Replacing if necessary each coordinate ϕ_i with $P\phi_i$ if necessary, we can assume that $P\Omega_\phi = \Omega_\phi$. This will lead us to the next claim:

(*iii*) $\boldsymbol{Q := \Omega_\psi^* \Omega_\phi \in \mathscr{L}(\widetilde{A}^n)}$ **is an idempotent operator**: Indeed:

$$Q^2 \overset{P\Omega_\phi = \Omega_\phi}{=} (\Omega_\psi^* P \Omega_\phi)^2 = \Omega_\psi^* P \underbrace{(\Omega_\phi \Omega_\psi^*)}_{P} P \Omega_\phi = \Omega_\psi^* \Omega_\phi = Q.$$

Therefore, Q is an idempotent operator in $\mathscr{L}(\widetilde{A}^n)$ which corresponds to left multiplication by the matrix $(\langle \phi_i, \psi_j \rangle)_{i,j}$, and $\operatorname{Im} Q \simeq \operatorname{Im} P$ as $\widetilde{A}$-modules.

(*iv*) $\boldsymbol{\mathit{Tr}\,\varepsilon(Q) = n}$: Let $(e_r)_r$ be the canonical basis of $\widetilde{A}^n$. We shall write the coordinates of ϕ and ψ as:

$$\phi_i = \zeta_i + a_i \quad \text{and} \quad \psi_i = \xi_i + b_i$$

for $\zeta_i, \xi_i \in F$ and $a_i, b_i \in \widetilde{A}^n$. Hence $\varepsilon(\langle \psi_i, \phi_i \rangle) = \varepsilon(\langle b_i, a_i \rangle)$ which enables us to expand in the following way:

$$\begin{aligned} \mathit{Tr}\,\varepsilon(Q) &= \sum_{i=1}^m \varepsilon\left(\langle \psi_i, \phi_i \rangle\right) \\ &= \sum_{i=1}^m \varepsilon\left(\langle b_i, a_i \rangle\right) \\ &= \varepsilon\left(\sum_{i=1}^m \sum_{r=1}^n \langle b_i, e_r \rangle \langle e_r, a_i \rangle\right) \\ &= \varepsilon\left(\sum_{i=1}^m \sum_{r=1}^n \langle e_r, a_i \langle b_i, e_r \rangle \rangle\right) \\ &= \varepsilon\left(\sum_{r=1}^n \langle (0, e_r), P(0, e_r) \rangle\right) \end{aligned}$$

Using the definition of P in (3.2), the term $\sum_{r=1}^n \langle (0, e_r), P(0, e_r) \rangle$ can be expressed as

$$\sum_{r=1}^n \langle e_r, (I_{B^n} - \Omega_x^* \Omega_y) e_r \rangle = n \cdot 1_A - \sum_{r=1}^n \langle x_r, y_r \rangle$$

hence $\mathit{Tr}\,\varepsilon(Q) = n$.

With all these steps, we conclude that

$$\mathit{rank}\,(\ker \widetilde{S}) = \mathit{rank}\,(\operatorname{Im} P) = \mathit{rank}\,(\operatorname{Im} Q) = \mathit{Tr}\,\varepsilon(Q) \cdot 1_{K_0(A)} = n \cdot 1_{K_0(A)}$$

and finally that $\varepsilon_0(\mathit{ind}\,\widetilde{T}) = 0$. □

The statement of 3.2.3 is meant to refer to the specific construction of $\widetilde{T}$ obtained in 3.2.2. But note that any regular Fredholm operator in $\mathscr{L}_{A^u}(E \oplus \widetilde{A}^n, F \oplus \widetilde{A}^n)$, which has T in the upper left corner, will differ from the $\widetilde{T}$ above, by an $\widetilde{A}$-compact operator. Therefore its index will coincide with that of $\widetilde{T}$ by 3.2.1, and so will be in $K_0(A)$ as well.

Definition 3.2.4. If T is a Fredholm operator in $\mathscr{L}(E, F)$, then the Fredholm index of T, denoted $\mathit{ind}\,T$, is defined to be the index of the regular Fredholm operator $\widetilde{T}$ constructed in proposition 3.2.3.

It is clear that all properties listed in 3.1.6 are naturally extended to general Fredholm operators;

As consequence of the Atikinson's theorem in the classical theory, one can obtain that the original index is locally constant. Since it is now our definition, we can extract the same proof.

Proposition 3.2.5. Let $\mathscr{Q}(E,F)$ be the Calkin algebra and $\pi : \mathscr{L}(E,F) \longrightarrow \mathscr{Q}(E,F)$ be the quotient projection. The set of Fredholm operators $\mathscr{F}(E,F) := \pi^{-1}\,\mathrm{GL}\,\mathscr{Q}(E,F) \subset \mathscr{L}(E,F)$ is an open subset and $\boldsymbol{ind} : \mathscr{F}(E,F) \longrightarrow K_0(A)$ is locally constant.

Proof. The fact that $\mathscr{F}(E,F)$ is an open set follows from the continuity of π on the the invertible elements of a unital C^*-algebra. To check the continuity of the index, let T be a Fredholm operator and S be one of its pseudo-inverses. If R is a Fredholm operator in the open ball around T of radius $\|S\|^{-1}$,

$$\|TS - RS\| \leqslant \|T - R\|\|S\| \leqslant 1.$$

Hence $I - (TS - RS)$ is a invertible Fredholm operator, which means that it has index 0. Notice that $(I - (TS - RS))T = RST$. Therefore:

$$\begin{aligned} \boldsymbol{ind}\, T &= \boldsymbol{ind}\, ((I - (TS - RS))T) \\ &= \boldsymbol{ind}\, (RST) = \boldsymbol{ind}\, R + \boldsymbol{ind}\, S + \boldsymbol{ind}\, T \end{aligned}$$

hence $\boldsymbol{ind}\, R = -\boldsymbol{ind}\, S$. Since R was an arbitrary element of the open ball, it follows necessarily that $\boldsymbol{ind} \restriction_{B(T,\|S\|^{-1})}(R) = -\boldsymbol{ind}\, S$, i.e. the index is locally constant. $\square$

Proposition 3.2.6. Choose A-Fredholm operators T_1 and T_2 between the following Hilbert A-modules.

$$\begin{tikzcd} E \arrow[r, "T_1"'] \arrow[rr, bend left, "T_2T_1"] & F \arrow[r, "T_2"'] & G \end{tikzcd}$$

Therefore, T_2T_1 is a Fredholm operator and $\boldsymbol{ind}\,(T_2T_1) = \boldsymbol{ind}\, T_1 + \boldsymbol{ind}\, T2$.

Proof. Assume beforehand that $E = F = \mathscr{H}_A$ and consider $H_t : \mathscr{H}_A \oplus \mathscr{H}_A \longrightarrow \mathscr{H}_A \oplus \mathscr{H}_A$ be a continuous path of Fredholm operators given by

$$H_t := \begin{pmatrix} T_1 & 0 \\ 0 & I \end{pmatrix} \begin{pmatrix} \cos(t) & -\sin(t) \\ \sin(t) & \cos(t) \end{pmatrix} \begin{pmatrix} I & 0 \\ 0 & T_2 \end{pmatrix} \begin{pmatrix} \cos(t) & \sin(t) \\ -\sin(t) & \cos(t) \end{pmatrix}$$

for $t \in [0, \pi/2]$, which connects $T_1 \oplus T_2$ to $T_2T_1 \oplus I$. Therefore

$$\begin{aligned} \boldsymbol{ind}\,(T_2T_1) &= \boldsymbol{ind}\,(H_{\pi/2}) = \boldsymbol{ind}\,(H_0) \\ &= \boldsymbol{ind}\,(T_1 \oplus T_2) = \boldsymbol{ind}\, T_2 + \boldsymbol{ind}\, T_1. \end{aligned}$$

The general case follows by using the Kasparov stabilization theorem 2.4.6. $\square$

Proposition 3.2.7. For any $\alpha \in K_0(A)$, there exists a Fredholm operator T with $\boldsymbol{ind}\,(T) = \alpha$.

Proof. Write $\alpha = [p]_0 - [q]_0$ with $\varepsilon_0([p]_0 - [q]_0) = 0$, for self-adjoint idempotent matrices. Hence $\varepsilon(p)$ and $\varepsilon(q)$ are similar matrix. After performing a conjugation of, say q, by a complex unitary matrix, we may assume that $\varepsilon(p)$ and $\varepsilon(q)$ are in fact equal, hence $(p-q) \in \mathbb{M}_n(A)$. With bricks in hands, choose

$$\begin{aligned} T: \quad pA^n &\longrightarrow qA^n \\ x &\longmapsto qx \end{aligned}$$

which is our desired Fredholm operator we were looking for, as showed in the following claims.

(*i*) ***T* is a Fredholm operator**: Let $S : qA^n \longrightarrow pA^n$ be the similar operator given by $Sy = py$. Let $(u_\lambda)_\lambda$ be an approximate identity for A. Therefore, consider the tuples ξ and η^λ, where their coordinates are given by:

$$\xi_i = p(p-q)p_i \quad \text{and} \quad \eta_i^\lambda = p_i u_\lambda \qquad (1 \leqslant i \leqslant n)$$

With the tuples defined, remember that $\langle a, b\rangle_A = a^*b$, hence:

$$\begin{aligned} \Omega_\xi \Omega^*_{\eta^\lambda} x &= \sum_{i=1}^n \xi_i \langle \eta_i^\lambda, x\rangle_A \\ &= \sum_{i=1}^n \xi_i \big((p_i u_\lambda)^* x\big) \\ &= \sum_{i=1}^n p(p-q)p_i u_\lambda p_i^* x \end{aligned}$$

for each $x \in pA^n$. Therefore, the following converges uniformly:

$$\begin{aligned} \lim_\lambda \Omega_\xi \Omega^*_{\eta^\lambda} x &= \sum_{i=1}^n p(p-q)p_i p_i^* x \\ &= p(p-q)px & (\|x\| \leqslant 1) \\ &= x - pqx = (I - ST)x \end{aligned}$$

The above shows that $I_{pA^n} - ST$ is compact, and the same conclusions can be drawn for $I_{qA^n} - TS$ also. By applying 3.0.2, the claim is proved.

(*ii*) $\texttt{ind}\, \boldsymbol{T = \alpha}$: In order to compute the index of T, consider the operators

$$T' = \begin{pmatrix} qp & q(I-p) \\ (I-q)p & (I-q)(I-p) \end{pmatrix} \quad \text{and} \quad S' = \begin{pmatrix} pq & p(I-q) \\ (I-p)q & (I-p)(I-q) \end{pmatrix}$$

Direct computation shows that

$$S'T' = \begin{pmatrix} I_{pA^n} & 0 \\ 0 & I_{\widetilde{A}^n} - p \end{pmatrix} \quad \text{and} \quad T'S' = \begin{pmatrix} I_{qA^n} & 0 \\ 0 & I_{\widetilde{A}^n} - q \end{pmatrix},$$

from which it follows that S' is a pseudo-inverse for T' and hence that T' is a regular $\widetilde{A}$-Fredholm operator.

By construction, $I - S'T'$ and $I - T'S'$ are compact self-adjoint idempotents, hence their ranges are finite rank modules (2.5.4). Moreover, we already know that

$$\mathrm{Im}(I - S'T') = \ker T' \quad \text{and} \quad \mathrm{Im}(I - T'S') = \ker S'$$

which turns possible the index calculation:

$$\begin{aligned} \mathit{ind}\, T &= \mathit{ind}\, T' \\ &= \mathit{rank}\ (\ker T') - \mathit{rank}\ (\ker S') \\ &= \mathit{rank}\ \mathrm{Im}(I - S'T') - \mathit{rank}\ \mathrm{Im}(I - T'S') \\ &= [p]_0 - [q]_0 = \alpha \end{aligned}$$

as desired. □

3.3 Fredholm Picture of $K_0(A)$

We already saw that every element of $K_0(A)$ is the index of some Fredholm operator.

In order to avoid any set-theoretical problems, choose ω to be one of your favorite cardinal numbers, as long as it is greater than the cardinality of each and every A^n for every integer n. Denote by $F_0(A)$ the family of all A-Fredholm operators whose domain and codomain are Hilbert modules with cardinality no larger than ω. With the addition given by the direct sum, this is a unital, abelian semi-group. We will introduce a equivalence relation in $F_0(A)$, by characterizing whenever two operators T_1 and T_2 contains the same index.

Notice that whenever $T \oplus I_{A^n}$ is a compact perturbation of an invertible operator, one can conclude by 3.1.8 that $\mathit{ind}\, T = 0$. This is a good indicator for an equivalence relation:

Proposition 3.3.1. Let $T \in \mathscr{L}(E, F)$ be Fredholm operator with $\mathit{ind}\, T = 0$. Therefore, there exists some integer n such that $T \oplus I_{A^n}$ is a compact perturbation of an invertible operator.

Proof. Let $\widetilde{T}$ be the regularization of T and, as always, there is an integer n and a operator S such that $I - \widetilde{S}\widetilde{T} = 0 \oplus I_{\widetilde{A}^n}$ described in the proof of Lemma 3.2.1 (3.1).

(*i*) **There exists n such that $\mathrm{Im}(I - \widetilde{T}\widetilde{S}) \cong \widetilde{A}^n$:** The hypothesis of null index is equivalent to $\mathit{rank}\ \mathrm{Im}(I - \widetilde{S}\widetilde{T}) = \mathit{rank}\ \mathrm{Im}(I - \widetilde{T}\widetilde{S})$, hence

$$\mathit{rank}\ \mathrm{Im}(I - \widetilde{T}\widetilde{S}) = \mathit{rank}\ \mathrm{Im}(0 \oplus I_{\widetilde{A}^n}) = n \cdot 1_{K_0(A)}$$

i.e. $\mathrm{Im}(I - \widetilde{T}\widetilde{S})$ is stably isomorphic to $\widetilde{A}^n$ as $\widetilde{A}$-modules, meaning that for some integer r, $\mathrm{Im}(I - \widetilde{T}\widetilde{S}) \oplus \widetilde{A}^r \simeq \widetilde{A}^{n+r}$. Remember that $\Omega_x^* = (\langle x_i, \cdot \rangle)_{i \leqslant n}$, hence, for $0 \in E^m$, $\Omega^*_{(x,0)}(\,\cdot\,) = (\Omega^*_x(\,\cdot\,), 0)$ and the regularization $\widetilde{T}$ can be updated to

$$\widetilde{T} = \begin{pmatrix} (T, 0) & 0 \\ \Omega^*_{(x,0)} & 0 \end{pmatrix}$$

As seen, n can be increased without essentially changing $\widetilde{T}$. Therefore, there is no danger in assuming that $\mathrm{Im}(I - \widetilde{T}\widetilde{S}) \simeq \widetilde{A}^n$.

(*ii*) **There is a orthonormal generating set $((\zeta_i + a_i))_{i\leqslant n} \subset \mathrm{Im}(I - \widetilde{T}\widetilde{S})$ such that $\varepsilon((a_1, \ldots, a_n)) = I_{\mathbb{M}_n(\widetilde{A})}$:** Let $(p_i)_{i\leqslant n} \subset \mathrm{Im}(I - \widetilde{T}\widetilde{S})$ with $p_i = (\zeta_i + a_i) \in F \oplus \widetilde{A}^n$. The elements p_i can be choosen so that they generate the module and $\langle p_i, p_j\rangle = \delta_{i,j}$, i.e. they are orthonormal. Since each $a_i \in \widetilde{A}^n$, one can write $a_i = (a_{i,r})_{r\leqslant n}$. Hence, orthonormality can be written as:

$$\begin{aligned}\delta_{i,j} &= \langle p_i, p_j\rangle_{F\oplus\widetilde{A}^n}\\ &= \langle \zeta_i, \zeta_j\rangle_F + \langle a_i, a_j\rangle_{\widetilde{A}^n}\\ &= \langle \zeta_i, \zeta_j\rangle_F + \sum_{r=1}^{n} \langle a_{i,r}, a_{j,r}\rangle_{\widetilde{A}}\\ &= \langle \zeta_i, \zeta_j\rangle_F + \sum_{r=1}^{n} a_{i,r}^* a_{j,r}\end{aligned}$$

The projected matrix $u := \varepsilon((a_{i,r})_{i,r})$ is unitary, i.e. $uu^* = u^*u = I_{\mathbb{M}_n(\widetilde{A})}$. Whence, setting $q_i := \sum_j u_{ij}^* p_j$, we obtain $q_i = \xi_i + b_i$ in which $\varepsilon(b_{i,j}) = \delta_{i,j}$, i.e. $\varepsilon((b_1, \ldots, b_n)) = I_{\mathbb{M}_n(\widetilde{A})}$. At the end of the day, one can suppose that $(p_i)_{i\leqslant n}$ attends the required condition, otherwise, replace p by q.

With this simplifications, we have in hands the following isomorphism:

$$\begin{aligned}U:\ E \oplus \widetilde{A}^n &\longrightarrow F \oplus \widetilde{A}^n\\ \xi + b &\longmapsto \begin{pmatrix} T & \Omega_\zeta\\ \Omega_x^* & \Omega_a\end{pmatrix}\begin{pmatrix}\xi\\ b\end{pmatrix}\end{aligned}$$

since $\Omega_\zeta \oplus \Omega_a$ is an explicit isomophism between $\mathrm{Im}(I - \widetilde{T}\widetilde{S})$ and $\widetilde{A}^n$. Notice that $(E \oplus \widetilde{A}^n) \cdot A = A^n$ for any Hilbert A-module E. Thus, U can be restricted to an element in $\mathrm{GL}\,\mathscr{L}(E \oplus A^n, F \oplus A^n)$. With this in mind, notice that the difference operator

$$U - T \oplus I_{A^n} = \begin{pmatrix} 0 & \Omega_\zeta\\ \Omega_x^* & ((a_{ij} - \delta_{ij}))_{i,j}\end{pmatrix}$$

is compact, since the right lower entry $((a_{ij} - \delta_{ij}))_{i,j}$ is compact. But this matrix was seen to be in $\mathbb{M}_n(A)$, since its projection by ε is zero. □

As consequence, proposition 3.3.1 immediately characterizes whenever two Fredholm operators between different Hilbert modules have the same index.

Corollary 3.3.2. Whenever two Fredholm operators $T_i \in \mathscr{L}(E_i, F_i)$ $(i \in \{1, 2\})$ share the same index $\mathit{ind}\, T_1 = \mathit{ind}\, T_2$, there exists a integer n such that

$$T_1 \oplus T_2^* \oplus I_{A^n} : E_1 \oplus F_2 \oplus A^n \longrightarrow E_2 \oplus F_1 \oplus A^n$$

is a A-compact perturbation of an invertible operator.

Declare two operators in $T_1, T_2 \in F_0(A)$ to be equivalent whenever $T_1 \oplus T_2^* \oplus I_{A^n}$ is a compact perturbation of an invertible operator, i.e. $\mathit{ind}\, T_1 = \mathit{ind}\, T_2$. Denote $F(A)$ to be the induced set of equivalence classes, which is an abelian group when equipped with the direct sum operation $\oplus$, where $(\,\cdot\,)^{-1} : T \longmapsto T^*$.

It is about time to consider the index map between $F(A)$ and $K_0(A)$, since 3.2.7 already shows that it is a surjective map, and the equivalence relation ensures the injectivity. More over, since $[\mathrm{diag}(x, y)]_0 = [x]_0 + [y]_0$ in $K_0(A)$, we had produced the following Atiyah-Jänich analogue:

Corollary 3.3.3. The index map

$$\mathit{ind} \ : F(A) \longrightarrow K_0(A)$$

is a group isomorphism.

Chapter 4

An Application to Morita-Rieffel Equivalence

Morita equivalence is a concept from ring theory, where two rinds are said to be Morita equivalent if their categories of modules are naturally equivalent. Although no corresponding theorems can be reused in the C^*-algebraic, M. Rieffel presents a notion of such an equivalence between C^*-algebras related to the existence of particular Hilbert (A, B)-bimodules, the so called Rieffel's imprimitivity bimodule [22, 23, 6]. The treatment of Morita equivalence between C^*-algebras is often called strongly Morita, but we will reference to it as Morita-Rieffel equivalence in order to give credit where credit's due.

4.1 Preliminars on Hilbert C^*-bimodules

Let A and B be two C^*-algebras. A Hilbert (A, B)-bimodule X is a space with two inner products:

$$(\cdot \mid \cdot) : X \times X \longrightarrow A \quad \text{and} \quad \langle \cdot , \cdot \rangle : X \times X \longrightarrow B$$

where $(X, (\cdot \mid \cdot))$ is a *left* Hilbert A-module and $(X, \langle \cdot , \cdot \rangle)$ a *right* Hilbert B-module, which satisfies the following transition relation:

$$(x \mid y)z = z\langle y, z\rangle$$

In order to make sense, it is required that $(\cdot \mid \cdot)$ to be usual sesquilinear in a left Hilbert module: linear in the first entry, and involuted-linear in the second.

Definition 4.1.1. A Hilbert (A, B)-bimodule X is said to be *left-full* (resp. right-full) if $(X \mid X)$ coincides with A (resp. if $\langle X, X\rangle$ coincides with B).

Let X be a (A, B)-bimodule and let E be a right Hilbert A-module. The algebraic tensor product module $E \otimes_A^{\mathrm{alg}} X$ has a natural B-valued inner-product given by

$$\langle \xi \otimes x, \zeta \otimes y\rangle \coloneqq \langle x, \langle \xi, \zeta\rangle y\rangle$$

for $\xi, \zeta \in E$ and $x, y \in X$. Since it may not be complete and contain norm zero elements, those conditions need to be forced, in order to see $E \otimes_A X$ as a Hilbert B-module.

If $T \in \mathscr{L}_A(E, F)$, there is an induced linear transformation in the tensor product:

$$\begin{aligned} T \otimes I_X : \quad E \otimes_A X &\longrightarrow F \otimes_A X \\ \xi \otimes x &\longmapsto T\xi \otimes x \end{aligned}$$

It is the case that $T \otimes I_X \in \mathscr{L}_B(E \otimes_A X, F \otimes_A X)$ and $\|T \otimes I_X\| \leqslant \|T\|$.

A full treatment of Hilbert bimodules should consider the representations of bimodules, in order to tackle all necessities for dealing with abstract tensor products. Since we're only exposing R. Exel's result, mind not our avoiding of such topic, my dear reader.

Definition 4.1.2 (Morita-Rieffel)**.** Let A and B be C^*-algebras. A bimodule X is said to be an (A, B)-*imprimitivity bimodule* if X is a left-full Hilbert A-module and a right-full Hilbert B-module. The algebras in context are said to be *Morita-Rieffel* equivalent if there exist such an imprimitivity bimodule.

Examples 4.1.3.

(*i*) Every C^*-algebra A is an (A, A)-imprimitivity bimodule with $(a \mid b) = ab^*$ and $\langle a, b\rangle = a^*b$.

(*ii*) Isomorphic C^*-algebras are necessarily Morita-Rieffel equivalent. Indeed, if $\phi : A \longrightarrow B$ is an isomorphism, the operation $ax := \phi(a)x$, as well as the inner-products $\langle x, y\rangle := x^*y$ and $(x \mid y) := \phi^{-1}(xy^*)$ make B an (A, B)-imprimitivity bimodule.

(*iii*) If $p \in \mathscr{L}(A)$ is a projection, i.e. $p^2 = p^* = p$, then Ap is a $(pAp, \overline{ApA})$-imprimitivity bimodule regarded with the inner-products: $\langle ap, bp\rangle := pa^*bp$ and $(ap \mid bp) := apb^*$.

(*iv*) Let H be a Hilbert space, which is a right Hilbert $\mathbb{C}$-module, with some inner product $\langle \cdot\,, \cdot\rangle$. If $\mathscr{K} := \mathscr{K}(H)$ is the usual C^*-algebra of compact operators, consider the $\mathscr{K}$-valued inner product

$$\begin{aligned} (\,\cdot \mid \cdot\,) : \quad H \times H &\longrightarrow \mathscr{K} \\ (x, y) &\longmapsto \left(z \overset{x \otimes \overline{y}}{\longmapsto} \langle z, y\rangle x \right) \end{aligned}$$

One can check that $(x \otimes \overline{y})^* = y \otimes \overline{x}$, $(x \otimes \overline{y})(z \otimes \overline{w}) = \langle z, y\rangle (x \otimes \overline{w})$ and the operator norm of $x \otimes \overline{x}$ is $\|x\|^2$, which will lead to $(H, (\,\cdot \mid \cdot\,))$ being a Hilbert $\mathscr{K}$-module.

Notice that $(H \mid H) = \overline{\operatorname{Span}\{\langle \cdot\,, y\rangle x\}} = \mathscr{K}$ since each $(x \mid y)$ is a finite-rank 1 operator. Since $\langle H, H\rangle = \mathbb{C}$, one concludes that H is a $(\mathscr{K}, \mathbb{C})$-imprimitivity bimodule.

A full treatment about Morita-Rieffel equivalence, including the construction of the tensor product, the verification that it is, indeed, an equivalence relation and many otter properties, the reader may check [20].

4.2 K-theory and Hilbert C^*-bimodules

Throughout this section, suppose that A and B are two C^*-algebras Morita-Rieffel equivalent, and let X denote the (A, B)-imprimitivity bimodule associated with.

> **Summoning 4.2.1** ([10], Corollary 4.3)**.** If $T \in \mathscr{L}_A(E, F)$ is an A-Fredholm operator, the induced operator $(T \otimes I_X) \in \mathscr{L}_B(E \otimes_A X, F \otimes_A X)$ is B-Fredholm. ☕

Definition 4.2.2. Let X be a left-full Hilbert (A, B)-bimodule. For $\alpha \in K_0(A)$, choose T to be a Fredholm operator in which $\textit{ind}\ (T) = \alpha$ using the isomorphism given by the corollary 3.3.3. This induces a morphism X_* which commutes the following diagram:

$$\begin{tikzcd} F(A) \arrow[r, "\cdot \otimes I_X"] \arrow[d, "ind"'] & F(B) \arrow[d, "ind"] \\ K_0(A) \arrow[r, dashed, "X_*"'] & K_0(B) \end{tikzcd}$$

This application is well defined since

$$\textit{ind}\ (T_1) = \textit{ind}\ (T_2) \quad \Rightarrow \quad \textit{ind}\ (T_1 \otimes I_X) = \textit{ind}\ (T_2 \otimes I_X)$$

as stated in [10], Proposition 4.4. Since tensor products are associative, one concludes that $Y_* \circ X_* = (X \otimes_B Y)_*$.

Consider X^* to be the conjugated module by $*$, which is (B, A)-imprimitivity bimodule. Considering the composition law and the summoning 4.2.3, we can consider the inverse of X_* given by $(X^*)_* : K_0(B) \longrightarrow K_0(A)$.

> **Summoning 4.2.3** ([10], Proposition 4.13)**.** For any left-full Hilbert (A, B)-bimodule X, the tensor product $X \otimes_B X^*$ is a Hilbert (A, A)-bimodule isomorphic to $(A \mid A)$. ☕

Therefore, X_* is an isomorphism. If $SA := C_0(\mathbb{R}) \otimes A$ denotes the suspension C^*-algebra of A, one can induce a suspension of X, given by $SX := C_0(\mathbb{R}) \otimes X$. Since $K_1(A) \simeq K_0(SA)$ and SA and SB are Morita-Rieffel equivalent, one can induce an isomorphism $(SX)_* : K_1(A) \longrightarrow K_1(B)$. Summarizing, its obtained the Brown-Green-Rieffel theorem without considering the separability of the C^*-algebras:

Theorem 4.2.4 (Exel)**.** For A and B Morita-Rieffel equivalent C^*-algebras, the (A, B)-imprimitivity bimodule X induces two isomorphisms: $X_* : K_0(A) \longrightarrow K_0(B)$ and $(SX)_* : K_1(A) \longrightarrow K_1(B)$.

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