

Advanced Analysis

September 25, 2025

Suppose we have some function of the form $-\Delta + q \in \mathbb{L}(H)$ satisfying $R_A(\lambda)(A - \lambda I)^{-1}$ bounded on $\text{Im}(\lambda) > 0$ and not surjective for $\text{Im}(\lambda) = 0$.

IMAGE 1

Waves: solutions to $\partial_{tt}u + Au = 0$ on \mathbb{R}^n .

Mathematical Tools

- Spectral theory of unbounded operators
- Complex analysis
- Functional analysis
- Microlocal analysis
- Semiclassical analysis

Classical Resonances in ODEs

IMAGE 2

A harmonic oscillator assuming no friction.

We have an acceleration force, $m\ddot{x}(t) = -kx(t)$ which gives $\ddot{x} + \omega_0^2 x = 0$ with $\omega_0 = \sqrt{\frac{k}{m}}$ and has solution $x(t) = A \cos(\omega_0 t) + B \sin(\omega_0 t)$.

With forcing, i.e. $m\ddot{x}(t) = -kx(t) + A \sin(\omega t)$, we have $\ddot{x} + \omega_0^2 x = A' \sin(\omega t)$.

If $|\omega| \neq |\omega_0|$, then $x(t) \sim \text{trig}\left(\left(\frac{\omega - \omega_0}{2}\right)t\right) \left(\left(\frac{\omega + \omega_0}{2}\right)t\right)$ the low and high frequencies respectively.

IMAGE 3

Beats (non-amplified)

If instead $|\omega| = |\omega_0|$, then $x(t) \propto \text{trig}(\omega t)t$.

IMAGE 4

In general, $\dot{x} + Ax = 0$ for $x \in \mathbb{R}^n$, $x(t) = \exp(-tA)x(0)$.

In the case where A is skew-adjoint, i.e. $\text{sp}(A) \subseteq i\mathbb{R}$, $(x, Ax) = 0 \forall x \in \mathbb{R}^n$, then

$$\frac{d}{dt}(x, x) = (\dot{x}, x) + (x, \dot{x}) = (-Ax, x) - (x, Ax) = 0$$

Which implies that $\|x(t)\|$ is constant and the dynamics are norm preserving.

To generate resonant solutions, if $(i\omega, v)$ is an eigenpair of A ($\omega \in \mathbb{R}$), consider $\dot{x} + Ax = e^{-i\omega t}v$. As an ansatz, we look for a solution of the form $x(t) = a(t)v$ and the equation becomes $(\dot{a}(t) + i\omega a)v = e^{-i\omega t}v$. Then

$$\begin{aligned} e^{-i\omega t} \frac{d}{dt}(e^{i\omega t} a) &= e^{-i\omega t} \\ \frac{d}{dt}(e^{i\omega t} a) &= 1 \\ a(t) &= te^{-i\omega t}. \end{aligned}$$

Resonances in PDEs

Consider one-dimensional waves on $[0, L]$, $L > 0$.

$$\begin{cases} \partial_{tt}u + \partial_{xx}u = 0 \\ u|_{t=0} = f & x \in [0, L] \\ \partial_t u|_{t=0} = g & x \in [0, L] \\ u(0, t) = u(L, t) = 0 & \forall t \geq 0 \end{cases}$$

We want to think about this as $\partial_{tt}u = Au = 0$ where A is the Dirichlet Laplacian $Au = -\partial_{xx}u$ with Dirichlet boundary conditions. We then want to find the spectral decomposition of A , $Au - \lambda u = 0 = -\partial_x^2 u - \lambda u$.

$$\begin{aligned} \lambda = 0. \quad u(x) = A + Bx &\implies A = B = 0 \\ \lambda = -p^2. \quad u(x) = Ae^{px} + be^{-px} &\implies A = B = 0 \\ \lambda = p^2. \quad u(x) = A\cos(px) + B\sin(px) &\implies 0 = u(0) = A \quad 0 = u(L) = B\sin(pl) \implies p = k\pi, k \in \mathbb{N} \end{aligned}$$

Therefore there are infinitely many eigenpairs $\lambda_n = \left(\frac{n\pi}{L}\right)^2$, $\phi_n(x) = \sin\left(\frac{k\pi x}{L}\right)$.

IMAGE 5

The family $\{\phi_n, n \in \mathbb{N}\}$ is dense in $L^2([0, L])$ where the unbounded operator $(-\partial_x^2)$ with Dirichlet boundary conditions is self-adjoint.

Other Prototypes

(of unbounded self-adjoint operators with discrete spectrum)

- Laplace-Beltrami operators on compact manifolds without boundary.

IMAGE 6

- On compact domains with boundary there is the Laplacian with Dirichlet boundary conditions.

The (Quantum) Harmonic Oscillator

$H = -\frac{d^2}{dx^2} + x^2$ on \mathbb{R} , on $L^2(\mathbb{R})$ with $(f, g) = \int_{\mathbb{R}} f(x) \overline{g(x)} dx$.

H acts on the Schwarz space $\mathcal{S}(\mathbb{R}) := \left\{ f \in C^\infty(\mathbb{R}), \forall k, \ell \geq 0, \sup_{x \in \mathbb{R}} \left| x^k \left(\frac{d}{dx} \right)^\ell f(x) \right| < \infty \right\}$.

- The action of $H : \mathcal{S}(\mathbb{R})$ is continuous.
- H is L^2 -symmetric: $\int_{\mathbb{R}} -f'' \bar{g} + x^2 f \bar{g} dx = (Hf, g) = (f, Hg) = \int_{\mathbb{R}} -\bar{g}'' f + x^2 f \bar{g} dx$ (integrating by parts).

We seek eigenvalues $Hu = \lambda u$. If (u, λ) and (v, μ) are eigenpairs, then

$$0 = (Hu, v) - (u, Hv) = (\lambda u, v) - (u, \mu v) = (\lambda - \bar{\mu})(u, v)$$

Where if the difference is nonzero then $(u, v) = 0$.

We can write $H = L^+ L^- + I$ where $L^+ = -\frac{d}{dx} + x$ and $L^- = \frac{d}{dx} + x$ and also $[H, L^+] = 2L^+$ and $[H, L^-] = -2L^-$.

Note that H is a non-negative operators

$$(Hf, f) = \int_{\mathbb{R}} ((f')^2 + x^2 f^2) dx > 0$$

for $f \neq 0$ and $f \in \mathcal{S}(\mathbb{R})$. Thus $\text{sp}(H) \subseteq (0, \infty)$. If $Hv = \lambda v$, then $H(L^+ v) = [H, L^+]v + L^+(Hv) = (\lambda + 2)L^+ v$. Similarly $H(L^- v) = (\lambda - 2)L^- v$.

Now we want to solve $L^- \phi_0 = 0$. $\frac{d}{dx} \phi_0 + x \phi_0 = 0$ tells us that $\phi_0(x) = \frac{1}{\sqrt{\pi}} e^{-x^2/2}$ (L^2 -normalized). Therefore $H\phi_0 = \phi_0$ and the we have an eigenvalues of one. So we may construct $\phi_n = \frac{(L^+)^n \phi_0}{|| (L^+)^n \phi_0 ||}$ which gives an eigenvector of H with eigenvalues $2n + 1$. Note that $|| (L^+)^n \phi_0 || = \sqrt{2^n n!}$.

Fact: $\phi_n = p_n(x) e^{-x^2/2}$ where p_n is the Hermite polynomial of degree n .

$$\delta_{nq} = (\phi_n, \phi_q) = \int_{\mathbb{R}} p_n(x) p_q(x) e^{-x^2} dx$$

Theorem

$\{\phi_n\}_{n \geq 0}$ is dense in $L^2(\mathbb{R})$ (if $\int_{\mathbb{R}} g \phi_n dx = 0$ for all n , then $g = 0$).

Proof (Sketch)

For $g \in L^2$, $\xi \in \mathbb{R}$, $F_g(\xi) = \int_{\mathbb{R}} e^{ix\xi} g(x) \phi_0(x) dx = \widehat{g\phi_0}(\xi)$. We observe that

- F_g is real-analytic in ξ .
- $F_g^{(k)}(0) = \int_{\mathbb{R}} (-ix)^k g(x) \phi_0(x) dx = 0$ by assumption.

So we have a real-analytic function where all derivatives vanish at a point. So $F_g \equiv 0$, $g\phi_0 = 0$, and $g = 0$.

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One of the overarching goals is to obtain large time asymptotics of the solution $v(x, t)$ ($x \in \mathbb{R}$, $t > 0$) to

$$\begin{cases} -\partial_{tt} v - P_V v = F(x, t) & \text{on } \mathbb{R}_x \times (0, \infty)_t \\ v(x, 0) = \partial_t v(x, 0) = 0, & F \in C_C^\infty(\mathbb{R}_x \times (0, \infty)_t) \end{cases}$$

where $P_V = D_x^2 + V(x) = -\left(\frac{\partial}{\partial}\right)^2 + V(x)$ and $D_x = \frac{1}{i} \frac{\partial}{\partial x}$. The operator D_x is symmetric and self-adjoint on appropriately chosen domains. For $f(x)$ and $\hat{f}(\xi) = \int_{\mathbb{R}} e^{-ix\xi} f(x) dx$, $\widehat{D_x f} = \xi \hat{f}(\xi)$. $V \in L_{\text{comp}}^\infty(\mathbb{R})$ (i.e. compactly supported L^∞) is the potential. If $f, g \in \mathcal{S}(\mathbb{R})$, then $(P_V f, g)_{L^2(\mathbb{R})} = (f, P_V g)_{L^2(\mathbb{R})}$.

IMAGE 1

Another way to look at this assuming v exists, we can consider $u(x, \lambda) := \int_0^\infty e^{it\lambda} v(x, t) dt$ (the Fourier-Laplace transform of v) with $\lambda \in \mathbb{C}$, $\text{Im}(\lambda) > 0$. Write $\lambda = \xi + ic$, $c > 0$, such that $u(x, \xi + ic) = \int_0^\infty e^{it\xi} e^{-ct} v(x, t) dt = \mathcal{F}_{t \mapsto \xi}(t \mapsto$

$e^{-ct} v(x, t))(x, -\xi)$. Then $u(x, \lambda)$ solves

$$\begin{aligned} \int_0^\infty e^{it\lambda} (-\partial_{tt} v - P_V v) dt &= \int_0^\infty e^{it\lambda} F(x, t) dt = \hat{F}(x, \lambda) \\ (\lambda^2 - P_V) \underbrace{\int_0^\infty e^{it\lambda} v(x, t) dt}_{u(x, \lambda)} &= \hat{F}(x, \lambda) \end{aligned}$$

which is an entire function in λ .

To Do:

- Study solvability of $(\lambda^2 - P_V)u = \hat{F}(x, \lambda)$.
- Return to v .

For frozen c , we can get $v(x, t)$ back by Fourier inversion.

$$\begin{aligned} e^{-ct} v(x, t) &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{-it\xi} u(x, \xi + ic) d\xi \\ v(x, t) &= \frac{1}{2\pi} \int_{\mathbb{R}} e^{-it(\xi + ic)} u(x, \xi + ic) d\xi \\ v(x, t) &= \frac{1}{2\pi} \int_{\text{Im}(\lambda)=c} e^{-it\lambda} u(x, \lambda) d\lambda \end{aligned}$$

IMAGE 2

where the spectral problem is invertible.

1D Waves in the Time Domain

Suppose $R > 0$ is such that $\text{supp } V \subset [-R, R]$ and $\text{supp } F \subset [-R, R] \times (0, \infty)$. If $|x| > R$, the PDE looks like $\partial_{tt} v - \partial_{xx} v = 0 = (\partial_t + \partial_x)(\partial_t - \partial_x)v$. Setting $\xi = x + t$ and $\mu = x - t$, then it follows that

$$\partial_\xi \partial_\mu v = 0 \implies v = F(\xi) + G(\mu) = F(x + t) + G(x - t)$$

IMAGE 3

On $x > R$, we can expect $v(x, t) = F_+(x + t) + G_+(x - t)$; on $x < -R$, we expect $v(x, t) = F_-(x + t) + G_-(x - t)$. The terms G_+ and F_- are outgoing whereas the terms F_+ and G_- are incoming and, given that we assumed a source, we expect to be zero.

What does incoming/outgoing look like on the spectral side? $(\lambda^2 - P_V)u = \hat{F}(x, \lambda)$ supported in $|x| \leq R$. For $|x| > R$, $(\lambda^2 + \partial_x^2)u = 0$ leads to $u = Ae^{ix\lambda} + Be^{-ix\lambda}$. For $x > R$, $u(x) = a_+ e^{i\lambda|x|} + b_+ e^{-i\lambda|x|}$ for $x < -R$, $u(x) = a_- e^{i\lambda|x|} + b_- e^{-i\lambda|x|}$. u is outgoing if and only if $b_\pm = 0$ and incoming if and only if $a_\pm = 0$.

P_V is an unbounded, symmetric operator on a Hilbert space. For $z \in \mathbb{C}$, $\text{sp}(P_V)$ is the set on the complement of which $(P_V - Z)$ is boundedly invertible. That is, $\forall f, \exists ! u$ such that $(P_V - z)u = f$ and $\|u\| \lesssim \|f\|$.

Waves in the Time Domain [Evans, §2.4]

Goal: if v solves

$$\begin{aligned}\partial_{tt}v - \partial_{xx}v &= f(x, t) \quad x \in \mathbb{R}, \quad t > 0, \quad f \in C_C^\infty(\mathbb{R} \times (0, \infty)) \\ v(x, 0) &= \partial_t v(x, 0) = 0 \quad x \in \mathbb{R}\end{aligned}$$

then $v(x, t) = \frac{1}{2} \int_0^t \int_{x-s}^{x+s} f(y, t-s) dy ds$. We look at

$$\begin{cases} \partial_{tt}v - \partial_{xx}v = 0 \rightsquigarrow v(x, t) = F(x+t) + G(x-t) \\ v(x, 0) = g(x), \quad \partial_t v(x, 0) = h(x) \end{cases}$$

Initial conditions gives us

$$\begin{cases} F(x) + G(x) = g(x) \\ F'(x) - G'(x) = h(x) \end{cases} \quad \begin{cases} G'(x) = \frac{1}{2}(g'(x) - h(x)) \\ F'(x) = \frac{1}{2}(g'(x) + h(x)) \end{cases}$$

So

$$\begin{aligned}F(x) &= \frac{1}{2} \left(g(x) + \int_0^x h(s) ds \right) + C_1 \\ G(x) &= \frac{1}{2} \left(g(x) - \int_0^x h(s) ds \right) + C_2 \\ v(x, t) &= \frac{1}{2} (g(x+t) + g(x-t)) + \frac{1}{2} \int_{x-t}^{x+t} h(s) ds + C\end{aligned}$$

IMAGE 4

This has a finite speed of propagation in the sense that if we suppose $\text{supp}(g, h) \subset [-R, R]$ then $v(x, t) = 0$ whenever $x > R+t$ or $x < -R-t$.

Now we want to go from the homogeneous problem to the inhomogeneous problem. The idea is to think about $v(x, t) = \int_0^t v(x, t; s) ds$ where $v(x, t; s)$ solves the homogeneous problem

$$\begin{cases} \partial_{tt}v(\cdot, \cdot; s) - \partial_{xx}v(\cdot, \cdot; s) = 0 \\ v(\cdot, s; s) = 0, \quad \partial_t v(\cdot, s; s) = f(x, s) \end{cases}$$

Then

$$\partial_{tt}v - \partial_{xx}v = 0 \iff \partial_t \begin{pmatrix} v \\ \partial_t v \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ \partial_{xx} & 0 \end{pmatrix} \begin{pmatrix} v \\ \partial_t v \end{pmatrix} \quad \text{and} \quad \begin{bmatrix} v \\ \partial_t v \end{bmatrix}_{t=s} = \begin{bmatrix} * \\ * \end{bmatrix}$$

So $v(x, t; s) = \frac{1}{2} \int_{x-(t-s)}^{x+(t-s)} f(y, s) dy$ and $v(x, t) = \frac{1}{2} \int_0^t \int_{x-s}^{x+s} f(y, t-s) dy ds$ follows.

Going back to the original PDE, $(-\partial_{tt} - P_V)v = F$ is equivalent to $(\partial_{tt} - \partial_{xx})v = -(Vv + F)$ which leads to the conclusion that $v(x, t) = -\frac{1}{2} \int_0^t \int_{x-s}^{x+s} (Vv + F)(y, t-s) dy ds$. For $|x| > R$, v is outgoing.

IMAGE 5

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Take some complex vector space and consider the Hilbert space $(\mathcal{H}, (\cdot, \cdot))$ with (\cdot, \cdot) satisfying

$$\begin{cases} (\lambda f, g) = \lambda(f, g) \\ (f, \lambda g) = \overline{\lambda}(f, g) \\ (f, g) = \overline{(g, f)} \\ f \mapsto (f, g) =: \|f\|^2 \text{ a norm} \\ (\mathcal{H}, \|\cdot\|) \text{ complete with respect to the norm} \end{cases}$$

• Examples

- $(\mathbb{C}^n, (a, b) = \sum_{j=1}^n a_j \overline{b_j})$, $a = (a_1, \dots, a_n)$, $b = (b_1, \dots, b_n)$
- $L^2(x, \mu)$ (e.g. $[0, 1]$ and the Lebesgue measure), $(f, g) = \int_X f \overline{g} d\mu$.

Bounded Operators: $T : \mathcal{H} \rightarrow \mathcal{H}$ bounded if and only if $\overbrace{\sup_{\|x\|=1} \|Tx\|}^{\|T\|} < \infty$ satisfying

$$\begin{cases} \mathcal{B}(\mathcal{H}) \text{ the space of bounded operators on } \mathcal{H} \text{ (a complex vector space)} \\ \|\cdot\| \text{ is a norm on } \mathcal{B}(\mathcal{H}), \text{ making it complete} \\ \text{There is a multiplication, } \mathcal{B}(\mathcal{H}) \ni A, B \mapsto AB \text{ and } \|AB\| \leq \|A\| \|B\| \end{cases}$$

Adjoint: if $A \in \mathcal{B}(\mathcal{H})$, $\exists! A^* \in \mathcal{B}(\mathcal{H})$ such that $\forall f, g \in \mathcal{H}$, $(Af, g) = (f, A^*g)$ where A is symmetric/self-adjoint if $A = A^*$. These notions are different in the world of unbounded operators.

• Example

- $\mathcal{H} = \mathbb{C}^n$: $T \in M_n(\mathbb{C})$ symmetric if and only if T is Hermitian. $t_{ij} = \overline{t_{ji}}$.
- $\mathcal{H} = L^2([0, 1])$, $Tf(t) = tf(t)$. $(Tf, g) = \int_0^1 tf(t) \overline{g(t)} dt = \int_0^1 f(t) \overline{tg(t)} dt = (f, Tg)$.
- $\mathcal{H} = L^2(\mathbb{R})$ with the Fourier transform. $\|f(x)\|^2 = c \|\hat{f}(\xi)\|^2$ (Parseval's Equality).

Finite Dimensional Spectral Theorem

If $A \in M_n(\mathbb{C})$ is Hermitian, there exists an orthonormal basis (ϕ_1, \dots, ϕ_n) of \mathbb{C}^n and real eigenvalues $\lambda_1, \dots, \lambda_n$ such that $A\phi_j = \lambda_j\phi_j$.

Important observation: if A is Hermitian, then λ_j is real for each j , and $\overline{(A\phi_j, \phi_j)} = (\phi_j, A\phi_j) = (A\phi_j, \phi_j) = \lambda_j \|\phi_j\|^2$.

So $\lambda_j = \frac{(A\phi_j, \phi_j)}{\|\phi_j\|^2}$ is real. If $\lambda_j \neq \lambda_k$, then $(\phi_j, \phi_k) = 0$ since $(A\phi_j, \phi_k) - (\phi_j, A\phi_k) = (\lambda_j - \overline{\lambda_k})(\phi_j, \phi_k)$.

Notation: Let $u, v \in \mathbb{C}^n$, denote $u \otimes \overline{v}$ the operator $(u \otimes \overline{v})w = (w, v)u$.

With A as in the theorem, we can write $A = \sum_{j=1}^n \lambda_j \phi_j \otimes \overline{\phi_j}$ ($I = \sum_{j=1}^n \phi_j \otimes \overline{\phi_j}$). A second way of writing this is

IMAGE 1

Where $U^* = U^{-1}$ and $A = U\Lambda U^*$. This allows us to construct a functional calculus for A where

$$\begin{cases} A^2 = U\Lambda U^* U\Lambda U^* = U\Lambda^2 U^* \\ A^n = U\Lambda^n U^* \\ p(A) = U \cdot p(\Lambda) \cdot U^*, \text{ } p \text{ a polynomial} \end{cases}$$

Defining $f(A) := U \cdot f(\Lambda) \cdot U^*$, we obtain a Banach algebra homomorphism. Then $f \in C([-||A||, ||A||])$ is also a Banach algebra with sup norm and pointwise multiplication.

IMAGE 2

Then we can map $C([-||A||, ||A||]) \ni f \mapsto f(A) \in \mathcal{B}(\mathcal{H})$. This is useful for solving ODEs.

• Prototypes

- Heat equation: $\partial_t u + Au = 0$, $u|_{t=0} = u_0$, $u(t) = e^{-tA} u_0$.
- Schrödinger equation: $i\partial_t u + Au = 0$, $u|_{t=0} = u_0$, $u(t) = e^{-itA} u_0$.
- Wave equation: $\partial_{tt} u + Au = 0$, $u|_{t=0} = u_0$, $\partial_t u|_{t=0} = u_1$.

Write $u(t) := \sum_{j=1}^n u_j(t) \phi_j$ with the PDE $\sum_{j=1}^n (u_j'' + \lambda_j u_j) \phi_j = 0$. Then $u_j'' + \lambda_j u_j = 0$, $u_j(0) = u_{j,0}$, and $u_j'(0) = u_{j,1}$. Suppose $\lambda_j > 0$ for all j . Then $u_j(t) = u_{j,0} \cos(\sqrt{\lambda_j} t) + \frac{u_{j,1}}{\sqrt{\lambda_j}} \sin(\sqrt{\lambda_j} t)$. So

$$u(t) = \sum_{j=1}^n \cos(\sqrt{\lambda_j} t) u_{j,0} \phi_j + \frac{1}{\sqrt{\lambda_j}} \sin(\sqrt{\lambda_j} t) u_{j,1} \phi_j$$

Therefore $u = \cos(t\sqrt{A}) u_0 + A^{-1/2} \sin(t\sqrt{A}) u_1$.

Spectrum of a Bounded Operator

Take $T \in \mathcal{B}(\mathcal{H})$. We say that T is invertible (within $\mathcal{B}(\mathcal{H})$) if and only if $\exists S \in \mathcal{B}(\mathcal{H})$ such that $TS = ST = I$.

Counterexample: take $\mathcal{H} = \ell^2(\mathbb{N}_0) = \{u = (u_n)_{n \geq 0} : \sum |u_n|^2 < \infty\}$ and $Au = \left(\frac{1}{n} u_n\right)_{n \geq 0}$. Then the proxy for $A^{-1}u = (nu_n)_{n \geq 0}$ is not bounded.

Given $T \in \mathcal{B}(\mathcal{H})$, the resolvent set of T is $\rho(T) = \{\lambda \in \mathbb{C} : (T - \lambda I) \text{ is invertible}\}$. Invertibility is equivalent to $\forall y \in \mathcal{H}$, $\exists! x$ such that $Tx - \lambda x = y$ with an estimate $||x|| \leq ||y||$.

For $\lambda \in \rho(T)$, denote $R(\lambda)$ or $R_T(\lambda) = (T - \lambda I)^{-1} \in \mathcal{B}(\mathcal{H})$ the resolvent of T . Properties of the resolvent set:

1. $\rho(T) \neq \emptyset$ (in fact, if $||\lambda| > ||T||$ then $\lambda \in \rho(T)$).
2. $\rho(T)$ is open.
3. the map $\rho(T) \ni \lambda \mapsto R_T(\lambda) \in \mathcal{B}(\mathcal{H})$ is holomorphic in the sense that $\forall \lambda_0 \in \rho(T)$, $\exists R_T'(\lambda_0) \in \mathcal{B}(\mathcal{H})$ such that $\lim_{\lambda \rightarrow \lambda_0} \left\| \frac{R_T(\lambda) - R_T(\lambda_0)}{\lambda - \lambda_0} - R_T'(\lambda_0) \right\| = 0$.

For a., if $||\lambda| > ||T||$, $Tx - \lambda x = y \iff \left(I - \frac{T}{\lambda}\right)x = -\frac{y}{\lambda} \iff x = \sum_{k=0}^{\infty} \frac{T^k}{\lambda^{k+1}} y$. Then $R_T(\lambda) = \frac{1}{\lambda} \sum_{k=0}^{\infty} \left(\frac{T}{\lambda}\right)^k$ and

$$||R_T(\lambda)|| \leq \frac{1}{||\lambda||} \frac{1}{1 - ||T/\lambda||} \leq \frac{1}{||\lambda| - ||T||}$$

For b., pick $\lambda_0 \in \rho(T)$ and find $r > 0$ such that $||\lambda - \lambda_0| < r \implies \lambda \in \rho(T)$. Then $Tx - \lambda x = y \iff (T - \lambda_0)x - (\lambda - \lambda_0)x = y \iff x - (\lambda - \lambda_0)R_T(\lambda_0)x = R_T(\lambda_0)y$ where if $||(\lambda - \lambda_0)R_T(\lambda_0)|| < 1$ it is boundedly solvable by Neumann series.

For c.,

$$\begin{aligned}
R_T(\lambda) - R_T(\lambda_0) &= (T - \lambda I)^{-1} - (T - \lambda_0 I)^{-1} \\
(T - \lambda I)(R_T(\lambda) - R_T(\lambda_0)) &= I - (T - \lambda_0 I + (\lambda_0 - \lambda)I)(T - \lambda_0 I)^{-1} \\
(T - \lambda I)(R_T(\lambda) - R_T(\lambda_0)) &= I - I + (\lambda - \lambda_0)R_T(\lambda_0) \\
R_T(\lambda) - R_T(\lambda_0) &= (\lambda - \lambda_0)R_T(\lambda)R_T(\lambda_0)
\end{aligned}$$

So $\frac{R_T(\lambda) - R_T(\lambda_0)}{\lambda - \lambda_0} - R_T(\lambda_0)^2 = o(\lambda - \lambda_0)$.

Then we define the spectrum $\sigma(T) := \mathbb{C} \setminus \rho(T)$ which is closed since $\rho(T)$ is open.

Lemma

If $T \in \mathcal{B}(\mathcal{H})$ is self-adjoint, then $\sigma(T) \subseteq [-||T||, ||T||]$.

• Proof

First we know $\sigma(T) \subseteq \{|\lambda| \leq ||T||\}$. We want to show that it is real, and that if $\lambda = a + ib$ and $b \neq 0$ then $T - (a + ib)I$ is invertible.

$T - (a + bi)I$ is injective.

$$\begin{aligned}
||(T - (a + ib))x||^2 &= (Tx - (a + ib)x, Tx - (a + ib)x) \\
&= ||Tx||^2 + (a^2 + b^2)||x||^2 - (Tx, (a + ib)x) - ((a + ib)x, Tx) \\
&= ||Tx||^2 + (a^2 + b^2)||x||^2 - (a - ib)(Tx, x) - (a + ib)(x, Tx) \\
&= ||Tx||^2 + a^2||x||^2 - 2a(x, Tx) + b^2||x||^2 \geq b^2||x||^2
\end{aligned}$$

since $||Tx||^2 + a^2||x||^2 - 2a(x, Tx) \geq 0$ by Cauchy-Schwarz. Therefore $T - (a + ib)$ is injective and, by the open mapping theorem, $(T - (a + ib))^* = T - (a - ib)$ is surjective. Similarly for $T - (a - ib)$, and the norm estimate is $||(T - (a + ib))^{-1}|| \leq \frac{1}{b}$. Note that $\frac{1}{b} = \frac{1}{\text{dist}(a + ib, \mathbb{R})}$.

Note that the spectrum of T may no longer be made of eigenvalues in the non-finite case. There may exist λ such that $T - \lambda I$ is not injective, $\exists v \neq 0$ $Tv = \lambda v$. Recall the example $Tf(t) = tf(t)$ with $f \in L^2((\cdot, \cdot), dt)$. T is self-adjoint, $||T|| \leq 1$, and $(Tf, f) = \int_0^1 t|f(t)|^2 dt \geq 0$. So $\sigma(T) \subseteq [0, 1]$. For $\lambda \in [0, 1]$ is $T - \lambda I$ injective? $Tf = \lambda f \iff tf(t) = \lambda f(t) \iff (t - \lambda)f(t) = 0$ which implies $f \equiv 0$ in $L^2([0, 1])$. Is $T - \lambda I$ surjective? $(t - \lambda)f(t) = g(t) \iff f(t) = \frac{g(t)}{t - \lambda}$, so $g(t) \equiv 1 \in L^2([0, 1])$ which implies $f(t) = \frac{1}{t - \lambda}$ is not $L^2([0, 1])$ and $\sigma(T) = [0, 1]$.

October 9, 2025

Spectral Resolution

Take \mathcal{H} a Hilbert space, and say that $P \in \mathcal{B}(\mathcal{H})$ is an orthogonal projection if $P^2 = P$ and $P^* = P$. Then let $\mathcal{P}(\mathcal{H}) = \{P \in \mathcal{B}(\mathcal{H}), P \text{ is an orthogonal projection}\}$.

• Examples

$$- \phi \in \mathcal{H}, ||\phi|| = 1, P := \phi \otimes \bar{\phi}. \text{ Then } P\psi = (\psi, \phi)\phi \text{ and } P^2\psi = P(\psi, \phi)\phi = (\psi, \phi)(\phi, \phi)\phi = P\psi.$$

- ϕ_1, \dots, ϕ_n an orthonormal family with $P = \sum_{k=1}^n \phi_k \otimes \bar{\phi}_k$.
- $\mathcal{H} = \ell^2(\mathbb{N})$, $e_j = (0, 0, \dots, 0, 1, 0, \dots)$ and $I = \sum_{j=1}^{\infty} e_j \otimes \bar{e}_j$.
- $\mathcal{H} = L^2(\mathbb{R})$. Fix I an interval with χ_I the characteristic function for I . Then take $Pf := \chi_I f$.
 - * $PPf = \chi_I \chi_I f = \chi_I f = Pf$.
 - * $\int_{\mathbb{R}} \chi_I f \bar{g} dx = \int_{\mathbb{R}} f \overline{\chi_I g} dx$.
 - * If I has a nonempty interior, then $\text{Range}(P) = \{f \in L^2(\mathbb{R}), \text{supp } f \subset I\} \simeq L^2(I)$.

Definition: Spectral Resolution

A spectral resolution is a map $\mathbb{R} \ni \lambda \mapsto E(\lambda) \in \mathcal{P}(\mathcal{H})$ satisfying

1. $\forall f \in \mathcal{H}$, $\|E(\lambda)f\|$ is increasing.
2. $\exists [a, b]$ such that $E(\lambda) = 0$ if $\lambda < a$ and $E(\lambda) = \text{Id}$ if $\lambda \geq b$.
3. $E(\lambda)$ is right continuous. That is, $\forall f \in \mathcal{H}$, $\lambda \in \mathbb{R}$,

$$\lim_{\substack{\mu \rightarrow \lambda \\ \mu > \lambda}} \|E(\mu)f - E(\lambda)f\| = 0$$

Alternatively, we can require $E(\lambda)E(\mu) = E(\min\{\mu, \lambda\})$.

Long story short: the collection of self-adjoint bounded operators is in one-to-one correspondence with the collection of spectral resolutions.

• Examples

- $A \in M_n(\mathbb{C})$, $A^* = A$, with eigencouples $(\lambda_1, \phi_1), \dots, (\lambda_n, \phi_n)$ and simple spectrum $\lambda_1 < \lambda_2 < \dots < \lambda_n$. Define $E(\lambda) := \sum_{j: \lambda_j \leq \lambda} \phi_j \otimes \bar{\phi}_j$.
 - * $A = I$ gives $E(\lambda) = 0$ for $\lambda < 1$ and $E(\lambda) = \text{Id}$ for $\lambda \geq 1$.
 - * $A = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}$ gives $E(\lambda) = \text{Id}_{\lambda \geq 1} e_1 \otimes e_1 + \text{Id}_{\lambda \geq 2} e_2 \otimes e_2$.
 - If $f = f_1 e_1 + f_2 e_2$, then $\|E(\lambda)f\|^2 = \text{Id}_{\lambda \geq 1}(\lambda) \|f_1\|^2 + \text{Id}_{\lambda \geq 2}(\lambda) \|f_2\|^2$.

Spectral Measures

A spectral resolution gives rise to spectral measures

$$f, g \in \mathcal{H} \quad \lambda \mapsto (E(\lambda)f, g) = F(\lambda) \in \mathbb{C}$$

This defines a Lebesgue-Stieljes measure

$$\mu_F : \mu_F((a, b]) = F(b) - F(a), \quad \forall a, b \in \mathbb{R}$$

We can construct this as follows:

- When $f = g$, $\lambda \mapsto (E(\lambda)f, f) = (E(\lambda)^2 f, f) = \|E(\lambda)f\|^2$ (increasing).
- When $f \neq g$,

$$(E(\lambda)f, g) = (E(\lambda)f, E(\lambda)g) = \frac{1}{4} \left(\|E(\lambda)(f+g)\|^2 - \|E(\lambda)(f-g)\|^2 - i\|E(\lambda)(f+ig)\|^2 + i\|E(\lambda)(f-ig)\|^2 \right)$$

$\{E(\lambda)\}_{\lambda \in \mathbb{R}}$ defines a projection-valued measure E_Ω , $\Omega \subset \mathbb{R}$ a Borel set. Start with $E_{(a,b]} = E(b) - E(a)$. We would like for E_Ω to satisfy $E_{\Omega_1} E_{\Omega_2} = E_{\Omega_1 \cap \Omega_2}$, $E_\emptyset = 0$, $E_\mathbb{R} = \text{Id}$.

Theorem: Spectral Theorem

For $A \in \mathcal{B}(\mathcal{H})$ self-adjoint, there exist $a, b \in \mathbb{R}$ and an A -dependent spectral resolution $\{E(\lambda)\}_{\lambda \in \mathbb{R}}$ such that

$$A = \int_{a-}^b \lambda dE(\lambda)$$

in the sense that $(Af, g) = \int_{a-}^b \lambda d(E(\lambda)f, g)$ for all $f, g \in \mathcal{H}$. This is amenable to creating a functional calculus

$C([-||A||, ||A||]) \rightarrow$ bounded self-adjoint operators that commute with A

$$h \mapsto h(A) := \int_{a-}^b h(\lambda) dE(\lambda)$$

The idea is that $E(\lambda) = \chi_{(-\infty, \lambda]}(A)$. Once E is constructed, this leads to E_Ω for Ω Borel. We say that a measure μ is supported in G (Borel) if for every Ω Borel, $\mu(\Omega) = \mu(\Omega \cap G)$. Then $\text{supp } E \subset \sigma(A)$.

Functional Calculus

We want to make sense of $h(A)$ for h in a large enough class. If p is a polynomial, we can make sense of $p(A) = \sum_{k=0}^n a_k A^k$ which is self-adjoint and bounded.

For $h \in C([-||A||, ||A||])$, h is uniformly approximated by polynomials. We want to show that p_n is uniformly Cauchy which implies that $p_n(A)$ converges to some $h(A)$.

For $h = \chi_{(-\infty, \lambda]}$, we proceed by approximation by tent functions.

IMAGE 1

Definition: Positive Operator

If S is a self-adjoint, bounded operator on \mathcal{H} , we say that S is positive ($S \geq 0$) if $(Sf, f) \geq 0$, $\forall f \in \mathcal{H}$. For S_1, S_2 self-adjoint and bounded, we say that $S_1 \geq S_2$ if and only if $S_1 - S_2 \geq 0$.

For $T \in \mathcal{B}(\mathcal{H})$, self-adjoint, set $a := \inf_{||f||=1} (Tf, f)$ and $b := \sup_{||f||=1} (Tf, f)$. Then $a\text{Id} \leq T \leq b\text{Id}$.

$$((T - a\text{Id})f, f) = (Tf, f) - a(f, f) = (f, f) \left(\left(T \frac{f}{||f||}, \frac{f}{||f||} \right) - a \right) \geq 0$$

We want to show that if p is a polynomial on $[-||A||, ||A||]$, then $(\inf_{[-||A||, ||A||]} p) \text{Id} \leq p(A) \leq (\sup_{[-||A||, ||A||]} p) \text{Id}$.

Lemma

If T_1 and T_2 are positive and commute, then $T_1 T_2 \geq 0$.

Square Root Lemma

If $A \geq 0$ (i.e. bounded, self-adjoint, and positive), then $\exists! B \geq 0$ such that $B^2 = A$ and B commutes with any operator that commutes with A .

- **Proof**

Use the power series of $z \mapsto \sqrt{1-z}$ at $z = 0$.

$$1 + \sum_{k=1}^{\infty} c_k z^k$$

We can find that $c_k < 0$ for all $k \geq 1$ and that the series converges uniformly on $\{|z| \leq 1\}$.

Now let $A \geq 0$ which implies that $0 \text{Id} \leq I - A \leq 1 \text{Id}$. Without loss of generality, suppose $\text{supp } \|A\| \leq 1$. The idea is to write

$$B = \sqrt{A} = \sqrt{I - (I - A)} = I + \sum_{k=1}^{\infty} c_k (I - A)^k$$

which converges strongly because the series converges uniformly. Then $B^2 = A$. We see that $B \geq 0$ using the fact that $\text{sign}(c_k) < 0$ which implies $\sum_{k \geq 1} c_k \geq -1$. The proof of uniqueness can be found in the text.

Proof of Lemma

Assuming the square root lemma, write $T_2 = B^2$. Then since $[T_1, T_2] = 0$, $[B, T_1] = 0$. Then

$$(T_1 T_2 f, f) = (T_1 B^2 f, f) = (B T_1 B f, f) = (T_1 (B f), B f) \geq 0$$

Weaker Version

Instead of $(\inf_{[-\|A\|, \|A\|]} p) \text{Id} \leq p(A) \leq (\sup_{[-\|A\|, \|A\|]} p) \text{Id}$, we have that if $\min_{[-\|A\|, \|A\|]} p \geq 0$, then $p(A) \geq 0$.

Proof

If $p \geq 0$ on $[-\|A\|, \|A\|]$, we can factor it as a product of positive pieces

$$p(x) = \prod_{\substack{r_j < -\|A\| \\ s_j \geq \|A\|}} \underbrace{(x - r_j)}_{\geq 0} \underbrace{(s_j - x)}_{\geq 0} ((x - a_j)^2 + b_j^2)$$

$$p(A) = \prod_{\substack{r_j < -\|A\| \\ s_j \geq \|A\|}} \underbrace{(A - r_j)}_{\geq 0} \underbrace{(s_j - A)}_{\geq 0} \underbrace{((A - a_j)^2 + b_j^2)}_{\geq 0}$$

Using the previous lemma, we have that $P(A) \geq 0$.

Proof

Finally, to show that $(\inf_{[-\|A\|, \|A\|]} p) \text{Id} \leq p(A) \leq (\sup_{[-\|A\|, \|A\|]} p) \text{Id}$, we see that $p - \inf p$ and $\text{supp } f - p$ are positive polynomials and apply the weaker version to them.

Definition

We can define $h(A)$ for $h \in C(-||A||, ||A||)$ by Weierstrass approximation. There exist p_n polynomials such that $\sup_{[-||A||, ||A||]} |p_n - h| \xrightarrow{n \rightarrow \infty} 0$. Then p_n is uniformly Cauchy, so

$$\inf(p_n - p_m) \text{Id} \leq p_n(A) - p_m(A) \leq \sup(p_n - p_m) \text{Id}$$

which implies that

$$||p_n(A) - p_{n-1}(A)|| \leq \max(\sup(p_n - p_m), -\inf(p_n - p_m)) \xrightarrow{n, m \rightarrow \infty} 0.$$

So $p_n(A)$ is Cauchy in $(\mathcal{B}(\mathcal{H}), || \cdot ||)$ which means it converges. We call $h(A) = \lim_{n \rightarrow \infty} p_n(A)$. We still want to show that $h(A)$ is bounded and self-adjoint.

October 14, 2025

Spectral Theorem for Bounded Self-Adjoint Operators

If $A \in \mathcal{B}(\mathcal{H})$ is self-adjoint such that $a||f||^2 \leq (Af, f) \leq b||f||^2 \quad \forall f \in \mathcal{H}$, then there exists a spectral resolution $\{E(\lambda)_{\lambda \in \mathbb{R}}\}$ such that $A = \int_a^b \lambda dE(\lambda)$.

Proof (Continued)

We would like that $E(\lambda) = \phi^\lambda(A)$ where $\phi^\lambda := \chi_{(-\infty, \lambda]}$, however ϕ^λ is not continuous so instead we can approximate it as

$$\phi_n^\lambda := \begin{cases} 1, & x \leq \lambda \\ \text{linear on } \left[\lambda, \lambda + \frac{1}{n} \right] \\ 0, & x \geq \lambda + \frac{1}{n} \end{cases}$$

IMAGE 1

To demonstrate this, we need the following proposition.

Proposition

If T_n is a sequence of positive operators and $T_n \geq T_{n+1} \geq 0$, then there exists some $T \geq 0$ such that $T_n f \rightarrow T f, \quad \forall f \in \mathcal{H}$.

Proof

Fix $f \in \mathcal{H}$, and consider $(T_n f, f)$ which is decreasing, bounded from below, and therefore converges and is Cauchy. Now as an estimate, we can say that if $S \in \mathcal{B}(\mathcal{H})$ is self-adjoint where $0 \leq S \leq MI$, then $\forall f \in \mathcal{H}$ we know that

$$||Sf||^2 \leq (Sf, f)^{1/2} M^{3/2} ||f||.$$

To see this, we look at $t \mapsto (S(S + tI)f, (S + tI)f) \geq 0$ since $S \geq 0$. Then

$$(S(S + tI)f, (S + tI)f) = (S^2 f, S f) + 2t ||Sf||^2 + t^2 (Sf, f)$$

So $\Delta < 0$ if and only if

$$\begin{aligned} ||Sf||^4 - (S^2f, Sf)(Sf, f) &< 0 \\ ||Sf||^4 &\leq (Sf, f)(S^2f, Sf) \\ &\leq (Sf, f) \underbrace{||S^2f||}_{M^3||f||^2} ||Sf|| \end{aligned}$$

We apply this to $T_n - T_m = S$ where $T_n - T_m \leq T_0$ for all $n \leq m$. Then

$$||(T_n - T_m)f||^2 \leq ((T_n - T_m)f, f)^{1/2} ||f|| ||T_0||^{3/2}$$

Since (T_nf, f) is Cauchy, T_nf is Cauchy and therefore converges. It remains to check that T is linear, positive, satisfies, $T \leq T_0$, etc.

Spectral Theorem Proof Continued

For each n , $\phi_n^\lambda(A)$ makes sense and is positive since $\phi_n^\lambda(t) \geq 0$. Since $\phi_n^\lambda \geq \phi_{n+1}^\lambda$, $\phi_n^\lambda(A) \geq \phi_{n+1}^\lambda(A)$. Thus, by the preceding proposition, $\phi^\lambda(A) := \lim_{n \rightarrow \infty} \phi_n^\lambda(A)$ exists as a bounded, self-adjoint, positive operator. It remains to check the spectral resolution properties.

The final property to check is that $\forall f \in \mathcal{H}$, $(Af, f) = \int_a^b \lambda d(E(\lambda)f, f)$. The idea is to approximate multiplication by t with piecewise constant functions. We fix a partition $a = \lambda_0 \leq \dots \leq \lambda_k = b$ such that $\sup(\lambda_{j+1} - \lambda_j) < \delta$. Then

$$t\phi^{\lambda_k}(t) = t = \phi^{\lambda_0}(t) + \sum_{j=1}^k t(\phi^{\lambda_j}(t) - \phi^{\lambda_{j-1}}(t))$$

for all $a \leq t \leq b$.

IMAGE 2

Then

$$\begin{aligned} \lambda^{j-1} &\leq t \leq \lambda^j \\ \lambda^{j-1}(\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) &\leq t(\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) \leq \lambda^j(\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) \\ \sum_{j=1}^k \lambda^{j-1}(\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) &\leq t \sum_{j=1}^k (\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) \leq \sum_{j=1}^k \lambda^j(\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) \\ &\leq \sum_{j=1}^k (\lambda^j - \delta)(\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) \end{aligned}$$

Adding $\lambda_0 \phi^{\lambda_0}$, we see that

$$t \leq \lambda_0 \phi^{\lambda_0} + \sum_{j=1}^k \lambda^j(\phi^{\lambda_j} - \phi^{\lambda_{j-1}}) \leq t + \delta$$

IMAGE 3

When we apply this to A ,

$$A \leq \lambda_0 E(\lambda_0) + \sum_{j=1}^k \lambda^j (E(\lambda_j) - E(\lambda_{j-1})) \leq A + \delta I$$

Finally, we see that

As one refines the partition, $\delta \rightarrow 0$ and $(A, f, f) = \int_a^b \lambda d(E(\lambda)f, f)$.

Then if $\phi \in C([-||A||, ||A||])$, $\phi(A) = \int_a^b \phi(\lambda) dE(\lambda)$.

$$\left| (Af, f) - \lambda_0(E(\lambda_0)f, f) - \sum_{j=1}^k \lambda^j (E(\lambda_j)f, f) - (E(\lambda_{j-1}f, f)) \right| \leq \delta ||I||^2$$

Functional Calculus

We observe that for $g \in C_C^\infty(\mathbb{C})$, $g(w) = \frac{1}{\pi} \int_{\mathbb{C}} \frac{1}{w-z} \partial_{\bar{z}} g(z) d^2 z$. Then $f(A) := \frac{i}{\pi} \int_{\mathbb{C}} (A-z)^{-1} \partial_{\bar{z}} \tilde{f}(z) d^2 z$ where $\partial_{\bar{z}} \tilde{f} = O((\text{Im}(z))^n)$ for $n \geq 3$ as $\text{Im}(z) \rightarrow 0$.

Proposition

For every $f \in \mathcal{H}$, the Lebesgue-Stieltjesmeasure corresponding to $F(\lambda) = (E(\lambda)f, f)$ is supported on $\sigma(A)$.

Since $\sigma(A) \subseteq [a, b]$ is closed, $[a, b] \setminus \sigma(A)$ is open (i.e. $\bigcup_{k \in \mathbb{N}} J_k$ for open intervals J_k). We want to show that $F(\lambda)$ is constant on each J_k (equivalently: $\int_{J_k} dF(\lambda) = 0$).

IMAGE 4

Fix $J_k \ni x_0$. Then $R_A(x_0) = (A - x_0 I)^{-1}$ exists, and we can pick $\varepsilon > 0$ such that $\forall z \in \overline{B_\varepsilon(x_0)}$, $||R_A(z)|| \leq M$. Then for $z \in B_\varepsilon(x_0) + \text{Im}(z) \neq 0$,

$$R_A(z) = (A - zI)^{-1} = \phi_z(A)$$

and $\phi_z(t) = \frac{1}{t-z} \in C([a, b])$. Consider

$$R_A(z)R_A(\bar{z}) = \psi_z(A) = \int \frac{1}{|\lambda - z|^2} dE(\lambda)$$

with $\psi_z(t) = \frac{1}{|t-z|^2}$. It follows that for all $z \in \overline{B_\varepsilon(x_0)} \setminus \mathbb{R}$,

$$\int_{x_0-\varepsilon}^{x_0+\varepsilon} \frac{1}{|\lambda - z|^2} dF(\lambda) \leq \int \frac{1}{|\lambda - z|^2} dF(\lambda) = (R_A(z)R_A(\bar{z})f, f) \leq M^2 ||f||^2$$

which stays true for all $z \in \overline{B_\varepsilon(x_0)}$. In particular for $x \in (x_0 - \varepsilon, x_0 + \varepsilon)$,

$$\int_{x_0-\varepsilon}^{x_0+\varepsilon} dx \int_{x_0-\varepsilon}^{x_0+\varepsilon} \frac{1}{|\lambda - z|^2} dF(\lambda) \leq 2\varepsilon M^2 ||f||^2$$

Since Fubini holds, we observe that $\int_{x_0-\varepsilon}^{x_0+\varepsilon} \frac{1}{|\lambda - x|^2} dx = \infty$, so it must be the case that $\int_{x_0-\varepsilon}^{x_0+\varepsilon} dF(\lambda) = 0$.

Discrete Spectrum vs Essential Spectrum

Recall the spectral measure of A , $E_\Omega(A)$ for $\Omega \subset \mathbb{R}$ Borel where $E_{(a,b]} = E(b) - E(a)$. We say that $\lambda \in \sigma_d(A)$ (the discrete spectrum of A) if there exists $\varepsilon > 0$ such that $\dim(\text{range}(E_{(\lambda-\varepsilon, \lambda+\varepsilon)})) < \infty$. Likewise, $\lambda \in \sigma_{\text{ess}}(A)$ (the essential spectrum) if $\forall \varepsilon > 0$, $\dim(\text{range}(E_{(\lambda-\varepsilon, \lambda+\varepsilon)})) = \infty$.

As an example, take $\mathcal{H} = \ell^2(\mathbb{N})$ with $(Au)_n = \frac{u_n}{n}$ and $A = \sum_{j=1}^{\infty} \frac{1}{j} e_j \otimes e_j$.

IMAGE 5

Discrete spectra include eigenvalues of finite multiplicity.

Essential spectra include accumulation points of eigenvalues, eigenvalues of infinite multiplicity, absolutely continuous spectrum, s.c. spectrum.

Another example if $Af(t) = tf(t)$ on $L^2([0, 1])$. Then $E(\lambda)f(t) = \chi_{(-\infty, \lambda]}f(t)$, and $E_{(a, b]}f(t) = \chi_{(a, b]}f(t)$. $\forall x_0 \in [0, 1]$, we have that $\text{range}(E_{(x_0 - \varepsilon, x_0 + \varepsilon)}) = L^2((x_0 - \varepsilon, x_0 + \varepsilon))$.

IMAGE 6

October 16, 2025

Compact Operators and Analytic Fredholm Theorem

Definition: Spectral Radius

For $A \in \mathcal{B}(\mathcal{H})$, we say that the spectral radius of A is $r(A) = \sup_{\lambda \in \sigma(A)} |\lambda| < \infty$

Theorem

1. if $A \in \mathcal{B}(\mathcal{H})$, then $r(A) = \limsup_{n \rightarrow \infty} \|A^n\|^{1/n}$.
2. If A is, in addition, self-adjoint, then $r(A) = \|A\|$.

As a non-example, consider $A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$. Then $\sigma(A) = \{0\}$, but $r(A) = 0 \neq \|A\|$.

Proof

Recall Hadamard's Formula: $\sum_{k=0}^{\infty} a_k z^k$ has radius of convergence R computed by $\frac{1}{R} = \limsup_{n \rightarrow \infty} |a_n|^{1/n}$. This holds even when a_k are members of a Banach algebra (e.g. $\mathcal{B}(\mathcal{H})$).

Set $z = \frac{1}{\lambda}$, such that $0 < |z| < \frac{1}{r(A)}$ and implies the existence of

$$R_A\left(\frac{1}{z}\right) = \left(A - \frac{1}{z}I\right)^{-1} = -(I - zA)^{-1} = -z \sum_{k=0}^{\infty} A^k z^k.$$

So we have that $r(A) = \frac{1}{R} = \limsup_{k \rightarrow \infty} \|A^k\|^{1/k}$.

Now if A is self-adjoint, $\|A^2\| = \|A\|^2$ since $\|A^2\| \leq \|A\|^2$ by submultiplicativity and $\|A^2\| \geq \sup_{\|x\|=1} (x, A^2 x) = \sup_{\|x\|=1} \|Ax\|^2 = \|A\|^2$ using Cauchy-Schwarz.

By induction, $\|A^{2^k}\|^{1/2^k} = \|A\|$ which implies that $r(A) = \|A\|$.

Another Spectral Decomposition

For $T : \mathcal{H} \rightarrow \mathcal{H}$ bounded, we say that λ is in the point spectrum of T if $T - \lambda I$ is not-injective. We say that λ is in the residual spectrum of T if $T - \lambda I$ is injective but does not have dense range.

IMAGE 1

Self-adjoint operators have no residual spectrum (RS, Thm VI.8).

Definition: Compact Operators

$K \in \mathcal{B}(\mathcal{H})$ is compact if K maps bounded sequences to sequences with a limit point. Equivalently, if $B_{\mathcal{H}} = \{x \in \mathcal{H} : \|x\| \leq 1\}$ then K is compact if $K(B_{\mathcal{H}})$ has compact closure (i.e. is precompact).

$\mathcal{K}(\mathcal{H})$, the collection of compact operators on \mathcal{H} , is a closed linear subspace of $\mathcal{B}(\mathcal{H})$ since if $T, S \in \mathcal{K}(\mathcal{H})$, then $T + S \in \mathcal{K}(\mathcal{H})$. We have also that $\mathcal{K}(\mathcal{H})$ is a 2-sided ideal of $\mathcal{B}(\mathcal{H})$ since when T is compact and S is bounded, ST and TS are compact.

Examples

- For a finite-rank operator $A : \mathcal{H} \rightarrow \mathcal{H}$, $\text{range}(A) < \infty$. The general form of A is $A = \sum_{j=1}^n \phi_j \otimes \bar{\psi}_j$ for $\phi_j, \psi_j \in \mathcal{H}$.
- Strong limits of finite-rank operators.
- $(Au)_n = \frac{1}{n}u_n$ on $\ell^2(\mathbb{N})$. Note that $A_n = \sum_{j=1}^n \frac{1}{j}e_j \otimes e_j$ shows that $\|A - A_n\| \leq \frac{1}{n+1}$.
- The inclusion $h^1 \hookrightarrow \ell^2$ where $h^1 = \{u \in \mathbb{C}^{\mathbb{N}} : \sum_{j=1}^{\infty} j^2 |u_j|^2 < \infty\}$.

Proposition

If \mathcal{H} is separable, all compact operators arise as limits of finite-rank operators.

Proof

We want to show that for $A \in \mathcal{K}(\mathcal{H})$, $\forall \varepsilon > 0$, $\exists A_\varepsilon$ finite-rank such that $\|A - A_\varepsilon\| < \varepsilon$.

Let $\varepsilon > 0$ be given. Since $A(B_{\mathcal{H}})$ is precompact, it is totally bounded. That is $\exists y_1, \dots, y_n \in A(B_{\mathcal{H}})$ such that $\forall x \in A(B_{\mathcal{H}})$, $\min_{1 \leq j \leq n} \|x - y_j\| < \varepsilon$.

Let P_ε be the orthogonal projection onto $\text{span}\{y_1, \dots, y_n\}$, and set $A_\varepsilon = P_\varepsilon A$. Then for $f \in B_{\mathcal{H}}$ and $x = Af \in A(B_{\mathcal{H}})$,

$$\|Af - A_\varepsilon f\| = \|x - P_\varepsilon x\| \leq \min_{1 \leq j \leq n} \|x - y_j\| < \varepsilon$$

So $\|A - A_\varepsilon\| < \varepsilon$.

Exercise: confirm whether this argument needs separability.

Theorem: Analytic Fredholm Theorem

Let $D \subset \mathbb{C}$ be open and connected. Let $f : D \rightarrow \mathcal{B}(\mathcal{H})$ be an analytic, operator-valued function such that $f(z) \in \mathcal{K}(\mathcal{H})$ for all $z \in D$. Then

1. either $(I - f(z))^{-1}$ exists for no $z \in D$
2. or $(I - f(z))^{-1}$ exists for all $z \in D \setminus S$, where S is a discrete set (finite-rank, no accumulation points) in D .

Then $(I - f(z))^{-1}$ is meromorphic in D , analytic in $D \setminus S$, residues at poles are finite-rank, and if $z \in S$, $f(z)\psi = \psi$ has a nonzero solution for $\psi \in \mathcal{H}$.

Application

If K is compact, consider $f(z) = zK$. At $z = 0$, $I - f(z) = I$ so this is invertible which implies that the theorem holds for $\frac{1}{z} \in \mathbb{C}$ (taking $D = \mathbb{C} \setminus \{0\}$). We have $R_K(\lambda) = -\frac{1}{\lambda} \left(I - f\left(\frac{1}{\lambda}\right) \right)^{-1}$. Note that K is not necessarily self-adjoint. Note that K is not necessarily self-adjoint.

Proof

We want to prove that either (a) or (b) hold locally for any $z_0 \in D$.

Fix $z_0 \in D$, $r > 0$ such that $\|f(z) - f(z_0)\| < \frac{1}{2}$ for $z \in D_r(z_0)$. Choose $F = \sum_{j=1}^n \phi_j \otimes \bar{\psi}_j$ a finite-rank operator such that $\|f(z_0) - F\| < \frac{1}{2}$. Then $\forall z \in D_r(z_0)$,

$$\|f(z) - F\| \leq \|f(z) - f(z_0)\| + \|f(z_0) - F\| < 1$$

which implies that $(I - (f(z) - F))^{-1}$ exists and is holomorphic on $D_r(z_0)$.

Define $g(z) = F(I - f(z) + F)^{-1}$, and observe that $(I - f(z)) = (I - g(z))(I - f(z) + F) = I - f(z) + F - \overbrace{g(z)(I - f(z) + F)}^F$.
Write

$$g(z) = \sum_{j=1}^n \phi_j \otimes \bar{\psi}_j \cdot (I - f(z) + F)^{-1} = \sum_{j=1}^n \phi_j \otimes \bar{\psi}_j(z)$$

where $\psi_j(z) = ((I - f(z) + F)^{-1})^* \psi_j$ is holomorphic in z . Then $I - f(z)$ is invertible if and only if $I - g(z)$ is invertible. We claim that this holds if and only if $d(z) \neq 0$ for some holomorphic function d .

When is $I - g(z)$ invertible?

Injectivity: if $g(z)\phi = \phi$, we expect $\phi = \sum_{j=1}^n \beta_j \phi_j$. So $g(z)\phi = \phi$ if and only if

$$\sum_{j=1}^n \phi_j \left(\sum_{k=1}^n \beta_k \phi_k, \psi_j \right) = \sum_{j=1}^n \beta_j \phi_j$$

where $\beta_j = \sum_{k=1}^n \beta_k (\phi_k, \psi_j(z))$. If $A_{jk}(z) := (\phi_k, \psi_j(z))$, then this has a solution if and only if $\det(I - A(z)) = 0$. Call $d := \det(I - A(z))$. Moreover, if $d(z) \neq 0$ then $I - g(z)$ is invertible. We can solve $(I - g(z))\phi = \psi$ for ϕ given $\psi \in \mathcal{H}$. So $\phi = \psi + g(z)\phi$ which motivates an ansatz $\phi = \psi + \sum_{j=1}^n \beta_j \phi_j$. Then

$$(I - g(z))\phi = (I - g(z))\psi + \sum_{j=1}^n (\beta_j - A_{jk}\beta_k)\phi_j = \psi$$

If and only if

$$\sum_{j=1}^n (\beta_j - A_{jk}\beta_k)\phi_j = \sum_{j=1}^n (\psi, \psi_j(z))\phi_j$$

which is boundedly invertible as long as $d(z) \neq 0$.

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Definition: Unbounded Operator

Let $(\mathcal{H}, (\cdot, \cdot))$ a Hilbert space. An unbounded operator is a linear map $A : \mathcal{D}(A) \rightarrow \mathcal{H}$, $\mathcal{D}(A) \subsetneq \mathcal{H}$ ($\mathcal{D}(A)$ the domain of A).

Hypothesis: $\overline{\mathcal{D}(A)} = \mathcal{H}$.

Why "unbounded?" BEcause, generally, $\sup_{f \in \mathcal{D}(A) \setminus \{0\}} \frac{\|Af\|}{\|f\|} = \infty$.

Examples

1. $\mathcal{H} = L^2(\mathbb{R})$, $Af(t) = tf(t)$. Then $A\left(\frac{1}{|t|}\right) \notin L^2(\mathbb{R})$, and $\mathcal{D}(A) = C_C(\mathbb{R})$. Consider $f_n(t)$ like

IMAGE 1

1. $\mathcal{H} = L^2(\mathbb{R})$, $Af(x) = D_x f(x) = \frac{1}{i} \frac{\partial}{\partial x} f(x)$. Then $\mathcal{D}(A) = \mathcal{S}(\mathbb{R})$, and we can see unboundedness from $f(x) = e^{-\frac{x^2}{\sigma}}$ for $\sigma > 0$.

$$\begin{aligned} \int f^2(x) dx &= \int e^{-\frac{x^2}{\sigma}} dx \stackrel{y=\frac{x}{\sqrt{(\sigma)}}}{=} \sqrt{\sigma} \int e^{-2y^2} dy \\ \int (f')^2(x) dx &= \int \frac{4x^2}{\sigma^2} e^{-\frac{x^2}{\sigma}} dx \stackrel{y=\frac{x}{\sqrt{(\sigma)}}}{=} \frac{1}{\sqrt{\sigma}} \int 4y^2 e^{-2y^2} dy \end{aligned}$$

So $\frac{\|Af\|^2}{\|f\|^2} = \frac{C}{\sigma} \xrightarrow{\sigma \rightarrow 0} \infty$.

Definition: Extension of an Unbounded Operator

We say that B extends A (and write $A \subseteq B$) if $\mathcal{D}(A) \subset \mathcal{D}(B)$ and $B|_{\mathcal{D}(A)} = A$. We have that $A = B$ when $A \subset B$ and $B \subseteq A$.

Definition: Closed Operator

To recover a notion of continuity, we look at closed operators.

We say that $(A, \mathcal{D}(A))$ is closed if and only if $\forall u_n \in \mathcal{D}(A)$ such that $u_n \rightarrow u \in \mathcal{H}$ and $Au_n \rightarrow v \in \mathcal{H}$, $u \in \mathcal{D}(A)$ and $v = Au$.

Equivalently, A is closed if the graph of A , $\Gamma(A) = \{(u, Au) : u \in \mathcal{D}(A)\}$, is closed in $\mathcal{H} \times \mathcal{H}$.

We say that A is closable if there exists some B such that $A \subseteq B$.

Example

- $(P, \mathcal{D}(P), \mathcal{H}) = (D_x, C_C^\infty(\mathbb{R}), L^2(\mathbb{R}))$.
 - P is not closed, because there exists $u_n \in C_C^\infty(\mathbb{R})$ such that $u_n \rightarrow u \in \mathcal{H}$, $D_x u_n \rightarrow v \in \mathcal{H}$, yet $u \notin C_C^\infty(\mathbb{R})$.
 - Take $u \in H^1 \setminus C_C^\infty(\mathbb{R})$, $u_n \in C_C^\infty(\mathbb{R})$ converging to u in H^1 .
- Recall that
 - $H^1(\mathbb{R}) = \{f \in L^2(\mathbb{R}) : f'(x) \in L^2(\mathbb{R})\}$, $\|f\|_{H^1}^2 = \|f\|_{L^2(\mathbb{R})}^2 + \|f'\|_{L^2(\mathbb{R})}^2$.
 - $C_C^\infty(\mathbb{R})$ is dense in $H^1(\mathbb{R})$.
 - $H^1(\mathbb{R})$ is complete.

Exercise: prove that if $\mathcal{D}(B) := H^1(\mathbb{R})$ and $Bf = D_x f$, then B is closed and $B|_{C_C^\infty(\mathbb{R})} = P$.

Adjoints of Unbounded Operators

In the bounded case, we have $A \in \mathcal{B}(\mathcal{H})$, $u \in \mathcal{H}$ and define $\ell_u(v) = (u, Av) \in \mathcal{H}'$ (\mathcal{H}' the dual space). By Riesz Representation Theorem, $\exists! w := A^* u$ such that $\forall v \in \mathcal{H}$, $(A^* u, v) = (u, A v)$.

In the unbounded case, we need to define A^* and $\mathcal{D}(A^*)$.

For $u \in \mathcal{H}$, set $\ell_u = (u, Av)$, $v \in \mathcal{D}(A)$. If ℓ_u extends to an element of \mathcal{H}' (i.e. if we can prove an estimate $|\ell_u(v)| \leq$

$c||v||_{\mathcal{H}}$, then by Riesz Representation Theorem $\exists! w \in \mathcal{H}$, called A^*u , such that $\forall v \in \mathcal{D}(A)$, $(A^*u, v) = (u, A^*v)$. Then

$$\mathcal{D}(A^*) = \{u \in \mathcal{H} : \begin{matrix} \mathcal{D}(A) \rightarrow \mathbb{C} \\ v \mapsto (u, Av) \end{matrix} \text{ extends to an element of } H^1\}.$$

Example

- $(P, \mathcal{D}(P), \mathcal{H}) = (D_x, C_C^\infty(\mathbb{R}), L^2(\mathbb{R}))$.

- Observe that $\forall f, g \in C_C^\infty(\mathbb{R})$, $(D_x f, g) = (f, D_x g)$.

- Take $f \in \mathcal{H}$ and $g \in C_C^\infty(\mathbb{R})$. Then if $f \in C_C^\infty$ or $f \in H^1(\mathbb{R})$, $g \mapsto (f, D_x g) = (D_x f, g)$ and

$$|(D_x f, g)| \leq \|D_x f\|_{L^2(\mathbb{R})} \|g\|_{L^2(\mathbb{R})} \leq \|f\|_{H^1(\mathbb{R})} \|g\|_{L^2(\mathbb{R})}$$

- Then $B(f, g) = D_x f, g) - (f, D_x g)$.

- So $\mathcal{D}(P^*) \supseteq C_C^\infty(\mathbb{R})$ and, in fact, $\mathcal{D}(P^*) = H^1(\mathbb{R})$.

- P^* is closed (this is always true of any adjoint).

- $P \subset P^*$, we say that P is symmetric.

Generally, if $(A, \mathcal{D}(A))$ is an unbounded operator, then $\Gamma(A^*) = J((\Gamma(A))^\perp)$ where $J : \mathcal{H} \times \mathcal{H} \rightarrow \mathcal{H} \times \mathcal{H}$ by $J(u, v) = (-v, u)$. Recall that $(\Gamma(A))^\perp$ is always closed, so A^* is always closed.

Definitions:

We say that P is symmetric if $P \subseteq P^*$.

We say that P is self-adjoint if $P = P^*$.

We say that P is essentially self-adjoint if $P^* = \overline{P}$.

Important Questions

1. Given a symmetric operator $(P \subseteq P^*)$, to find a self-adjoint operator A such that $P \subseteq A = A^* \subseteq P^*$. We call A self-adjoint extension of P . If $P^* = \overline{P}$ (essentially self-adjoint), then it must be the unique extension.
2. How to find or parameterize all self-adjoint extensions? (This problem is hard.)

Example

- $P = (D_x, H_0^1([0, 1]), L^2(0, 1))$ (where elements of $H_0^1([0, 1])$ vanish on the boundary).

- $P^* = (D_x, H^1([0, 1])) \supsetneq P$.

- There exists a “circle” of self-adjoint extensions, parameterized by any point on the unit circle.

General Principle

If $\Omega \subset \mathbb{R}^n$ is open, bounded and with smooth boundary $\partial\Omega$ ($\mathcal{H} = L^2(\Omega)$), and P is some differential operator (e.g. $P = \Delta$) such that $\forall f, g \in C_C^\infty(\Omega)$. $(Pf, g) = (f, Pg)$. By Green's Identity,,

$$\begin{aligned} \int_{\Omega} (\Delta f g - f \Delta g) dx &= \int_{\Omega} \nabla((\nabla f)g - f(\nabla g)) dx \\ &= \int_{\partial\Omega} (g \nabla f - f \nabla g) \cdot \nu ds \\ &= \int_{\partial\Omega} \left(g \frac{\partial f}{\partial \nu} - f \frac{\partial g}{\partial \nu} \right) ds \end{aligned}$$

Examples

- $P = (P = \Delta, C_C^\infty(\Omega), L^2(\Omega))$.
 - P symmetric.
 - $\mathcal{D}(P^*) = \{u \in L^2(\Omega) : \Delta u \in L^2\}$.
 - Let $P_{\min} = \overline{(P, C_C^\infty(\Omega))}$ and define $P_{\max} = P_{\min}^*$. Then $\mathcal{D}(P_{\max}) = \{u \in L^2(\Omega) : Pu \in L^2(\Omega)\}$.
 - The self-adjoint extensions lie inbetween.
- $(D_x, H_0^1([0, 1])) = \{u \in H^1([0, 1]) : u(0) = u(1) = 0\}, L^2([0, 1])$.
 - Observe that the evaluation map $C^\infty([0, 1]) \ni f \mapsto f(0)$ extends boundedly to $\tau : H^1([0, 1]) \rightarrow \mathbb{C}$.
 - For $f, g \in C^\infty([0, 1])$,

$$(D_x f, g) - (f, D_x g) = \int_0^1 \frac{1}{i} f' \bar{g} - f \left(\frac{1}{i} \bar{g}' \right) = \frac{1}{i} \int_0^1 (f \bar{g})' = \frac{1}{i} (f(1) \bar{g}(1) - f(0) \bar{g}(0))$$

- Then if $g \in \mathcal{D}(P_{\min})$,

$$\begin{aligned} |(f, D_x g)| &= |(D_x f, g) + \frac{1}{i} (\overbrace{f(1) \bar{g}(1)}^{=0} - \overbrace{f(0) \bar{g}(0)}^{=0})| \\ &\leq \|f\|_{H^1} \|g\|_{L^2} \end{aligned}$$

- Therefore $\mathcal{D}(P_{\min}^*) = \mathcal{D}(P_{\max}) = H^1([0, 1])$, and we note that $P_{\max}^* = P_{\min}$.

Now suppose that T is a self-adjoint extension of P ($P_{\min} \subseteq T \subseteq P_{\max}$). If T is self-adjoint, then $\forall f, g \in \mathcal{D}(T) \subseteq H^1([0, 1])$, $f(0) \bar{g}(0) - f(1) \bar{g}(1) = 0$.

For $f = g$, $|f(0)|^2 = |f(1)|^2$ for some fixed f , then $\exists \alpha \in S^1$ such that $f(1) = \alpha f(0)$. Then for any other g ,

$$0 = f(0)(\bar{g}(0) - \alpha \bar{g}(1)) = \alpha f(0)(\overline{\alpha g(0) - g(1)})$$

Therefore $g(1) = \alpha g(0)$ for the same fixed α .