

Operator theory

Lecturer: Roman Bessonov

PART I

Compact and Fredholm operators

Preliminaries

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Def.: (X, ρ) - metric space if X -set, and ρ is a metric:

- i) $\rho(x, y) \geq 0 \quad \forall x, y \in X. \quad \rho(x, y) = 0 \Leftrightarrow x = y$
- ii) $\rho(x, y) = \rho(y, x) \quad \forall x, y \in X$
- iii) $\rho(x, z) \leq \rho(x, y) + \rho(y, z) \quad \forall x, y, z \in X$

Def.: $U \subseteq X$ is open if $\forall x \in U. \exists \delta > 0$.

s.t. $B(x, \delta) \subset U \quad (B(x, \delta) = \{y \in X \mid \rho(x, y) < \delta\})$

Def.: $K \subset X$ is compact if every open cover $\{U_\alpha\}_{\alpha \in I}$ of K has a finite subcover.

cover: $\{U_\alpha\}_\alpha$ is a cover of K if $\bigcup_{\alpha \in I} U_\alpha \supset K$

Def.: A precompact set $A \subset X$ is a set $A \subset X$

s.t. \bar{A} is compact.

closure
of A
in X

Def: $\{x_j\}_{j \geq 1}$ is Cauchy sequence in X if

$\forall \varepsilon > 0. \exists N = N(\varepsilon). \rho(x_j, x_k) < \varepsilon \quad \forall j, k \geq N(\varepsilon).$

Def: X is complete if \forall Cauchy $\{x_j\}_{j \geq 1} \subset X$.

$\exists x \in X. \rho(x_j, x) \rightarrow 0$ as $j \rightarrow \infty$

(Every Cauchy sequence converges.)

Ex. $(\mathbb{R}^n, \rho_{\mathbb{R}^n}(\{x_i\}, \{y_i\}) := \sqrt{\sum |x_i - y_i|^2})$ - complete metric space

Ex. $(\mathbb{Q}, \rho_{\mathbb{R}})$ - metric space but non-complete

Ex. $[0, 1]$ is a compact-subset of $(\mathbb{R}, \rho_{\mathbb{R}})$

Ih: $K \subseteq \mathbb{R}^n$ is compact \Leftrightarrow closed and bounded

Def: $A \subset (X, \rho)$ is bounded if $\exists x \in X. \exists R > 0. A \subset B(x, R)$

Ex. $(X, \rho) = \ell^2(\mathbb{Z}) = \left(\left\{ \overset{\uparrow}{\{x_j\}}_{j \in \mathbb{Z}} \mid \sum_{j \in \mathbb{Z}} |x_j|^2 < \infty, \right. \right. \rho(\{x_j\}, \{y_j\}) = \sqrt{\sum_{j \in \mathbb{Z}} |x_j - y_j|^2}$

$B[0, 1] = \{y \in \ell^2(\mathbb{Z}) : \rho(0, y) \leq 1\}$

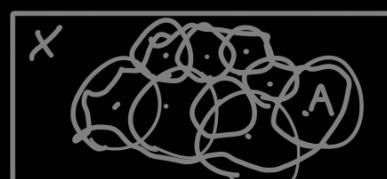
- bounded, closed but not compact HW

Theorem: Let (X, ρ) be a complete metric space,

$A \subset X$. The following assertions are equivalent:

i) A is precompact

ii) $\forall \varepsilon > 0. \exists_n$ a finite ε -net $\{x_j\}_{j=1}^{N_\varepsilon}$ in A ,
that is, $\bigcup_{j=1}^{N_\varepsilon} B(x_j, \varepsilon) \supset A$.



(iii) $\forall \{x_j\}_{j \geq 1} \subset A$ there is a converging subsequence to some element $x \in X$.

Proof: i) \Rightarrow ii) $\{U_x\}_{x \in A} = \{B(x, \varepsilon)\}_{x \in A}$ - open cover of A .

- is an open cover of \bar{A} :

$$(\forall y \in \bar{A}. \exists x \in A. d(x, y) < \varepsilon_2 \Rightarrow y \in B(x, \varepsilon))$$

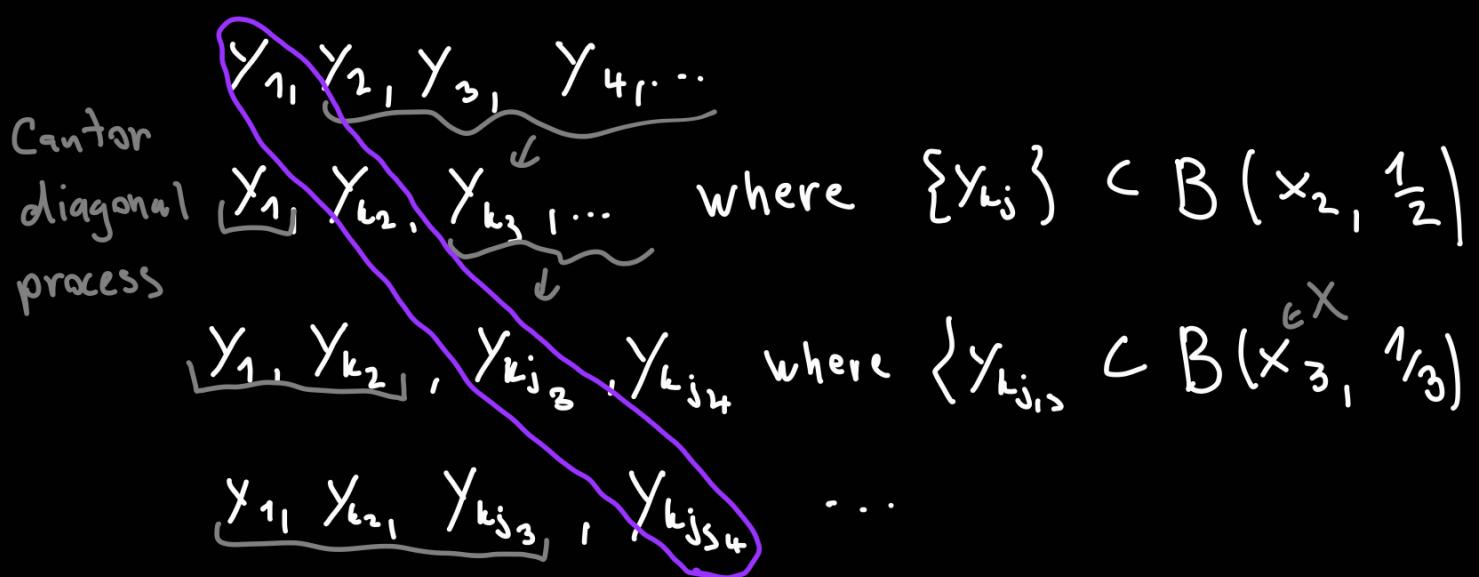
definition of closure

$\Rightarrow \exists \{U_{x_j}\}_{j=1}^N$ - finite subcover of \bar{A}

$\Rightarrow \{U_{x_i}\}_i^N$ is a ε -net in A

ii) \Rightarrow iii) Observe that $\forall \varepsilon > 0$. any sequence $\{y_i\} \subset A$ has an infinite subsequence that is contained in some $B(x, \varepsilon)$. (we have a finite ε -net)

Assume that $\{y_k\}$ is arbitrary in A .



Consider $z_1 = y_1$

$$z_2 = y_{k_2}$$

$$z_3 = y_{k_{j_3}}$$

$$z_4 = y_{k_{j_4}}$$

⋮

Claim: $\{z_j\}$ is a Cauchy sequence.

Indeed $\underset{k < j}{\rho(z_j, z_k)} < \frac{1}{k}$

because $z_j, z_k \in B(x_k, \frac{1}{k})$ $\rho(z_j, z_k) < \frac{2}{k} \xrightarrow[k \rightarrow \infty]{} 0$

X is complete $\Rightarrow \{z_j\}$ converges

iii) \Rightarrow i):

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Plan: a) A contains a dense countable subset

a) b) c) b) If $\{U_d\}_{d \in I}$ is an open cover of \bar{A}

under assumption $\Rightarrow \exists \{U_{d,j}\}_{j \in J}$ - an open countable subcover of \bar{A}

3) c) $\Rightarrow \{U_{d,j}\}_{j=1}^\infty$ is a cover of \bar{A}

a) Observe that $\forall \varepsilon > 0$ there exists at most $N(\varepsilon)$ points

$\Delta \{Y_j(\varepsilon)\}_{1 \leq j \leq N(\varepsilon)}$ s.t. $\rho(Y_k(\varepsilon), Y_j(\varepsilon)) > \varepsilon \quad \forall k \neq j$.

(If this is not true, then $\exists \{Y_j(\varepsilon)\}_{j=1}^\infty$ such that

$\rho(Y_j(\varepsilon), Y_k(\varepsilon)) > \varepsilon$ and it cannot contain a convergent subsequence by Cauchy criterion.)

Now $E = \left\{ Y_k \left\{ \frac{1}{n} \right\} \mid 1 \leq k \leq N \left(\frac{1}{n} \right), n \geq 1 \right\}$ is a dense countable subset.

(E is dense since $\forall n. \forall x \in A. \min_{1 \leq k \leq N(\frac{1}{n})} \{\rho(x, Y_k(\frac{1}{n}))\} \leq \frac{1}{n}$ by construction)

b) Assume that $\{U_d\}_{d \in I}$ is some open cover of \bar{A} .

For every $x \in \bar{A}$ define

$$\varepsilon(x) := \sup \left\{ \varepsilon > 0 \mid B(x, \varepsilon) \subset U_d \text{ for some } d \right\} > 0$$

Claim: if $\{Y_j\}_{j=1}^\infty$ is a countable dense subset in A , then

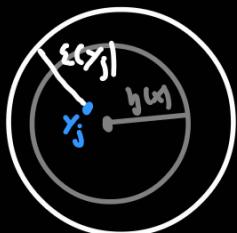
$\{B(y_j, \varepsilon(y_j))\}_{j=1}^{\infty}$ is an open cover for \bar{A} .

Take $x \in \bar{A}$. $\exists d_x$. $x \in U_{d_x}$, and let $h(x) > 0$

such that $B(x, h(x)) \subset U_{d_x}$ (U_{d_x} is open $\Rightarrow h(\varepsilon) \exists$)

Find y_j such that $d(x, y_j) < \frac{h(x)}{10}$.

Then, since $h(x) \leq 2\varepsilon(x)$, $x \in B(y_j, \varepsilon(y_j)) \Leftrightarrow d(x, y_j) < \varepsilon(y_j)$



$\varepsilon(y_j) \geq \frac{h(x)}{10}$ - Because $B(y_j, \frac{h(x)}{5}) \subset U_{d_x}$ by triangle inequality and $\varepsilon(y_j)$ satisfies $\textcircled{4}$.

Since $\{B(y_j, \varepsilon(y_j))\}_{j=1}^{\infty}$ is an open cover for \bar{A} , then $\{U_{d_{y_j}}\}_{j=1}^{\infty}$ is an open cover for \bar{A} , where $U_{d_{y_j}}$ is the set U_d from the definition of $\varepsilon(y_j)$ (that is, $U_d \supset B(y_j, \varepsilon(y_j))$).

Since we have $\textcircled{4*}$, $\bigcup_{j=1}^{\infty} U_{d_{y_j}} \supset \bar{A}$.

c) Claim: $\exists N$. $\{U_{d_{y_j}}\}_{j=1}^N$ is a cover of \bar{A} .

Suppose this is not the case $\Rightarrow \forall j \geq 1$. $\exists x_j \in A_j \setminus \bigcup_{k=1}^j U_{d_{y_k}}$.

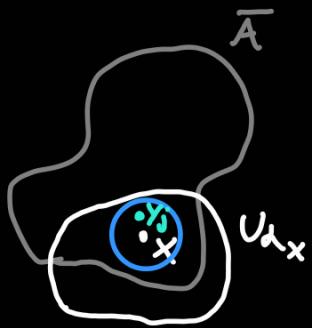
Consider $\{x_j\}_{j=1}^{\infty}$, and assume that the sequence $\{x_{j_k}\}$ converges to some $x \in X$. Note that $x \in \bar{A}$ ($x_j \in \bar{A}$).

$\Rightarrow \exists j_*. x \in U_{d_{y_{j_*}}} \Rightarrow \exists \delta > 0$. s.t. $B(x, \delta) \subset U_{d_{y_{j_*}}}$, but $x_{j_k} \notin U_{d_{y_{j_*}}}$ for large k by construction.

(in particular, $x_{j_k} \notin B(x, \delta)$, hence $d(x, x_{j_k}) > \delta$, but this contradicts the fact that $x_{j_k} \rightarrow x$).

We have shown that $\{x_j\} \subset \bar{A}$ cannot have a convergent subsequence.

Then if $\tilde{x}_j \in A$. $d(\tilde{x}_j, x_j) < \frac{1}{j}$, then $\{\tilde{x}_j\}$ also has no convergent subsequence. So, we assumed there is no



finite subcover $\{U_{\alpha_j}\}$ and found a sequence $\{\tilde{x}_j\}_{j \in \mathbb{N}}$ that has no converging subsequence, a contradiction with 3). Therefore $3) \Rightarrow 1)$. □

Examples of compact sets and their properties:

1) $K \subset (X, \delta)$ is compact $\Rightarrow K$ is bounded

Indeed, if K is not bounded, then $\{B(x, n)\}_{n \geq 1}$ is an open cover without a finite subcover.

2) $K \subset (X, \delta)$ is compact, then it is closed
 $(\Leftrightarrow \{x_j\} \subset K \text{ such that } x_j \rightarrow x \text{ in } (X, \delta) \text{ we also have } x \in K)$

Let's check that $X \setminus K$ is open. Take $y \in X \setminus K$, take $x \in K$, let $\delta(x) > 0$. $B(x, \delta(x)) \cap B(y, \delta(x)) \neq \emptyset$
 $\{B(x, \delta(x))\}_{x \in K}$ is an open cover, let $\{B(x_j, \delta(x_j))\}_{j=1}^N$ be a finite subcover, then $\delta := \min_{1 \leq j \leq N} \delta(x_j)$, $B(y, \delta) \cap K = \emptyset$
 $\Rightarrow X \setminus K$ is open.

Another proof: Suppose $\{y_j\} \subset K$ s.t. $y_j \rightarrow y$, $y \notin K$.

$$U_j = \{x \in X \mid \delta(x, y) > \frac{1}{j}\}$$

$\{U_j\}_{j=1}^\infty$ open cover, $\{U_{j_k}\}_{k=1}^N$ finite subcover

$$\varepsilon := \min_{1 \leq k \leq N} \left(\frac{1}{j_k} \right), \quad \delta(x, y) > \varepsilon \quad \forall x \in K \quad \text{contradiction} \quad \blacksquare$$

linear space = vector space

3) Let X be a finite-dimensional complete linear normed space. Then $E \subset X$ is compact $\Leftrightarrow E$ is closed and bounded.

\Leftrightarrow : Examples 1+2.

\Leftarrow : $X = \left\{ \sum_1^N c_k e_k \mid c_k \in \mathbb{C} \right\}$, $N = \dim X$, $\{e_k\}_1^N$ -basis

$$\varphi(\sum c_k e_k) = \max_{1 \leq k \leq N} |c_k| \text{ - norm on } X$$

Since all norms on finite dimensional vcc. spaces are equivalent.

$$\exists A, B > 0. \quad A \|x\| \leq \varphi(x) \leq B \|x\| \quad \forall x \in X.$$

$$\text{in particular the set } \left\{ \left\{ c_k(x) \right\}_1^N, \quad x \in E \right\} \\ x = \sum c_k(x) e_k$$

is bounded (=bdd) in \mathbb{C}^n for every bounded $E \subset X$.

$$\sup_{x \in E} \varphi(x) \leq B \cdot \sup_{x \in E} \|x\| < \infty$$

\Rightarrow for any sequence $\left\{ \left\{ c_k(x_j) \right\}_{k=1}^N \right\}_{j=1}^\infty$ one can extract a converging subsequence in \mathbb{C}^n , i.e.

$$c_k(x_{j_n}) \rightarrow c_k \quad n \rightarrow \infty.$$

But then $\sum c_k(x_{j_n}) e_k \rightarrow \sum c_k e_k$ in X

\Rightarrow bounded subsets are precompact in X

\Rightarrow bdd + closed sets are compact

4) $\ell^2(\mathbb{Z}) = \left\{ \{c_k\}_{k \in \mathbb{Z}} \mid \sum |c_k|^2 < \infty \right\}$

$$\|\{c_k\}\| = \sqrt{\sum_{k=1}^\infty |c_k|^2}$$

$$B[0,1] = \left\{ \{c_k\}_{k \in \mathbb{Z}} \in \ell^2(\mathbb{Z}) \mid \|\{c_k\}\| < 1 \right\}$$

Then this set is bounded, closed, but neither compact nor precompact.

Proof: there is no finite $\frac{1}{2}$ -net in $B[0,1]$,
 bccu $s(e_i, e_j) > \frac{1}{2}$ for $e_k = (0, \dots, 0, \overset{\uparrow}{1}, 0, \dots, 0)$.

Definition: X is a Banach space if it is a linear normed space such that X is complete with respect to this norm.

Example: Let (K, ρ) be a metric compact space.

$$C(K) := \{f : K \rightarrow \mathbb{C} \mid \text{cont. in the metric } \rho\}$$

$$(\Leftrightarrow f(x_j) \rightarrow f(x) \quad \forall x_j \rightarrow x \text{ in } (K, \rho))$$

$$\|f\|_{C(K)} = \|f\| := \max_{x \in K} |f(x)| \quad - \text{norm in } C(K)$$

Theorem: [Arzela-Ascoli]: Assume that K is a complete compact metric space. $E \subset C(K)$ is precompact \Leftrightarrow

$$\Leftrightarrow \begin{cases} 1 | E \text{ is bounded in } C \\ 2 | \text{functions in } E \text{ are equicontinuous, that is,} \\ \quad \forall \varepsilon > 0, \exists \delta_\varepsilon > 0. |f(x) - f(y)| < \varepsilon \quad \forall x, y \in K. \rho(x, y) < \delta_\varepsilon \\ \quad \forall f \in E \end{cases}$$

We will need 1+2 \Rightarrow precompactness.

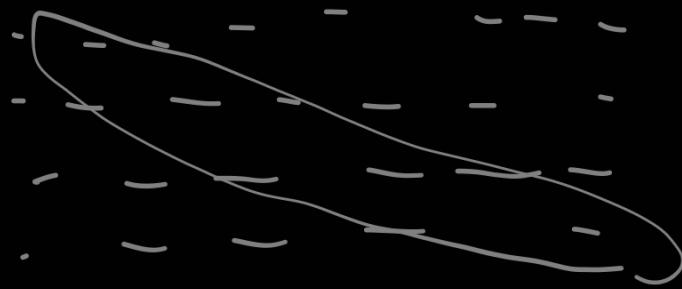
Proof: Find a dense sequence $\{x_j\}$ in K .
 (such sequence exists because K is compact)

Then take $\{f_n\}$ arbitrary sequence in E .

We want to find a converging subsequence of $\{f_n\}$
 (then E - precompact)

For this find a subsequence $\{f_{n_k}\}$ such that
 $f_{n_k}(x_j) \rightarrow F(x_j)$ for every j

(Cantor diagonalization process + uniform boundedness)



look at the proof
from the 1st
lecture

Claim: f_{n_k} is Cauchy sequence in $C(K)$.

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Aim: $\|f_{n_s} - f_{n_m}\|_{C(K)} \rightarrow 0$ as $s, m \rightarrow \infty$

For simplicity let $g_s = f_{n_s}$ $s \geq 1$.

Idea:

$$|g_s(x) - g_m(x)| \leq |g_s(x) - g_s(x_j)| + \underbrace{|g_s(x_j) - g_m(x_j)|}_{\substack{\leq \frac{\epsilon}{3} \\ \text{for all } s \text{ if } x_j \\ \text{is close to } x}} + \underbrace{|g_m(x_j) - g_m(x)|}_{\substack{\text{take } s, m \text{ large} \\ \text{enough:} \\ \leq \frac{\epsilon}{3}}} + \underbrace{|g_m(x_j) - g_m(x)|}_{\substack{\leq \frac{\epsilon}{3} \\ \text{for all } s \text{ if } x_j \\ \text{is close to } x \\ (\text{uniform continuity})}}$$

To make the idea work we need to check that in this construction we can deal only with finite number of points x_j , $j=1, \dots, N(\epsilon)$.

For this it suffices to find $N(\delta_\epsilon)$ such that

$\exists (x, x_j) \in \delta_\epsilon$ for every $x \in K$ and x_j , $j=1 \dots N_\epsilon$.
($\{x_j\}_{j=1}^{N(\delta_\epsilon)}$ is δ_ϵ -net).

So, it remains to show that if $\{x_j\}_{j=1}^\infty$ is dense then $\forall \delta_\epsilon > 0. \exists N(\delta_\epsilon). \{x_j\}_{j=1}^{N(\delta_\epsilon)}$ is a δ_ϵ -net.

To this end, let $\{y_k\}_1^N$ is a $\delta_{\epsilon/2}$ -net in K (K is compact). Let $\{x_j\}_{j=1}^{N(\delta_\epsilon)}$ be the part of $\{x_j\}$ such that

$$\text{dist}(\{x_j\}_{j=1}^{N(\delta_\epsilon)}, y_k) \leq \frac{\delta_\epsilon}{2} \quad \forall 1 \leq k \leq N.$$

\Rightarrow then $\{x_j\}_{j=1}^{N(\delta_\epsilon)}$ is a δ_ϵ -net by triangle inequality. \blacksquare
($\|g_s - g_m\|_{C(K)} \leq \frac{\epsilon}{3} + \frac{\epsilon}{3} + \frac{\epsilon}{3}$ for s, m large enough)

Example: $K = [0, 1]$, $E_A = \left\{ f \in C[0, 1] \mid f(0) = 0, f \text{ is Lipschitz}, \text{ with constant at most } A \right\}$

E_A is compact

i) E_A is bounded in $C[0, 1]$:

$$|f(x)| \leq |f(x) - f(0)| \leq A|x| \leq A$$

$$E_A \subset B(0, A)$$

ii) $|f(x) - f(y)| \leq A|x - y| \leq A\delta = \varepsilon$ if $\varepsilon > 0$, $\delta := \frac{\varepsilon}{A}$,
 $x, y \in [0, 1]: |x - y| \leq \delta$

i + ii + AA theorem $\Rightarrow E_A$ is precompact

iii) E_A is closed

If $f_n \rightarrow f$ in $C(K)$ then $f_n(0) \rightarrow f(0) \Rightarrow f(0) = 0$

$$|f_n(x) - f_n(y)| \leq A|x - y|$$

\downarrow

$$|f(x) - f(y)| \Rightarrow f \text{ is Lip}(A)$$

Example: Let $E = \left\{ \sum_{k \in \mathbb{Z}} c_k e^{2\pi i kx}, \text{ where } c_k \in \mathbb{C}: |c_k| \leq \frac{1}{k^2+1} \right\}$

Then E is compact as well in $C[0, 1]$.

i) bbs: $f \in E$. $\|f\| \leq \sum_{k \in \mathbb{Z}} \frac{1}{k^2+1}$

Details: exercise

ii) equicontinuity $f = \sum_{|k| \leq N} + \sum_{|k| > N}$ small if N large
 Lipschitz with some constant
 $A_N \sim \text{does not depend on } F$

Compact operators: basic properties

Definition: Let X, Y be Banach spaces, $T: X \rightarrow Y$ a linear map. T is called **bounded** if $T(B(0,1))$ is a bounded in Y set in Y . T is called **compact** if $T(B(0,1))$ is a precompact set in Y . ($B(0,1) = \{ \|x\|_X < 1\}$) bounded linear operator

Some observations:

- 1) If $S \subset X$ is bdd then $T(S)$ is ^{bdd}_{precompact} for any ^{bdd}_{compact} operator
- 2) T is compact $\Rightarrow T$ is bounded
(precompact sets are bounded)
- 3) with the norm $\|T\| = \sup_{x \in B(0,1)} \|Tx\|_Y$, the set of bdd linear operators becomes a linear normed space, to be denoted by $B(X,Y)$ or $B(X)$ if $X=Y$.
- 4) A linear map between Banach spaces X, Y is continuous if and only if it is bounded.
Hint: $\|Tx - Ty\| \leq \|T\| \cdot \|x - y\|$, so bounded operators are Lipschitz.

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Definition: **Banach algebra** is an associative algebra which is a linear space with a norm $\|\cdot\|$ such that it's a Banach space with respect to this norm (it is complete with respect to this norm) and $\|T_1 T_2\| \leq \|T_1\| \|T_2\|$ for any elements in this algebra.

Proposition: Let X be a Banach space, then $B(X,X)$ is a Banach algebra.

Proof: $\lambda_1 T_1 + \lambda_2 T_2 \in \mathcal{B}(X, X)$ $\forall T_1, T_2 \in \mathcal{B}(X, X)$ (proved)
 $T_1 \cdot T_2 \in \mathcal{B}(X, X)$, since $\forall x \in X$. $\|T_1 T_2 x\| \leq \|T_1\| \cdot \|T_2 x\|$
 $\Rightarrow \|T_1\| \cdot \|T_2\| \leq \|T_1\| \cdot \|T_2\|$ since $T_1 \in \mathcal{B}(X, X)$ we have
 $\sup_{\substack{y \in X \\ \|y\| \leq 1}} \|T_1 T_2 y\| \leq \|T_1\| \|T_2\| \forall y \in X$

We see that $T_1 T_2 \in \mathcal{B}(X, X)$ and $\|T_1 T_2\| \leq \|T_1\| \|T_2\|$.

Now let us prove that $\mathcal{B}(X, X)$ is Banach.

Let us show that $\sum_{n=1}^{\infty} B_k$ converges if $\sum_{k \in \mathcal{B}(X, X)} \|B_k\| < \infty$.

$$T_n = \sum_{k=1}^n B_k, \quad x \in X, \quad \|T_N x - T_M x\| = \left\| \sum_{M+1}^N B_k x \right\| \leq \sum_{M+1}^N \|B_k\| \|x\| \xrightarrow[M, N \rightarrow \infty]{} 0,$$

because of (*).

$\Rightarrow \{T_N x\}_N$ Cauchy in X , but X -banach $\Rightarrow \exists T x = \lim_{N \rightarrow \infty} T_N x$

Moreover, $\|Tx\| = \lim_{N \rightarrow \infty} \|T_N x\| \leq \lim_{N \rightarrow \infty} \sum_{k=1}^N \|B_k\| \|x\| \leq (\sum_{k=1}^{\infty} \|B_k\|) \|x\|$.

$\Rightarrow T \in \mathcal{B}(X, X)$, $\|T\| \leq \sum_{k=1}^{\infty} \|B_k\|$

$$\sup_{\substack{x \in X \\ \|x\| \leq 1}} \|Tx - T_N x\| = \lim_{N \rightarrow \infty} \|T_N x - T_N x\| \leq \sup_{\|x\| \leq 1} \lim_{N \rightarrow \infty} \sum_{k=1}^N \|B_k\| \|x\| = \sum_{k=1}^{\infty} \|B_k\| \xrightarrow[N \rightarrow \infty]{(*)} 0 \quad \square$$

$S_{\infty}(X, X)$ (index ∞ will be explained later)

Proposition: The set $S_{\infty}(X)$ of all compact operators on X is a two-sided ideal in $\mathcal{B}(X) = \mathcal{B}(X, X)$: $\forall T_1 \in S_{\infty}(X), \forall T_2 \in \mathcal{B}(X)$. $T_1 T_2 \in S_{\infty}(X)$ and $T_2 T_1 \in S_{\infty}(X)$.

Proof: Take $\{x_n\}_{n=1}^{\infty}$ s.t. $\|x_n\| \leq 1$, and let us check that there is a subsequence $\{x_{n_k}\}$: $T_1 T_2 x_{n_k}$ converges.

Note that $\{T_2 x_{n_k}\} \subset B_X(0, \|T_2\|)$. T_1 takes $B_X(0, \|T_2\|)$ into a precompact subset of $X \Rightarrow \exists \{T_1 T_2 x_{n_k}\}$ -convergent subsequence

Now let's consider $\{T_2 T_1 x_n\}$. Note that $\{T_1 x_n\}$ -convergent subsequence ($T_1 \in S_{\infty}(X)$). Then $\{T_2 T_1 x_n\}$ converges, since T_2 is continuous.

Proposition: $S_\infty(X, Y)$ is a closed subset in $\mathcal{B}(X, Y)$, i.e.

$T_n \in S_\infty(X, Y)$, $T_n \rightarrow T$ in $\mathcal{B}(X, Y) \Rightarrow T \in S_\infty(X, Y)$?

Proof: Let's find a finite ε -net in $T(B_X[0, 1])$.

Take finite $\varepsilon/3$ -net for $T_n B_X(0, 1)$ for n : $\|T - T_n\| \leq \varepsilon/2$; denote it by $\{y_k\}_{k=1}^N$, then

$$\begin{aligned} \|Tx - Tx_k\| &\leq \underbrace{\|Tx - T_nx\|}_{A} + \underbrace{\|T_nx - T_nx_k\|}_{B} + \underbrace{\|T_nx_k - Tx_k\|}_{C} \\ &\leq \varepsilon/3 + \varepsilon/3 + \varepsilon/3 \leq \varepsilon. \end{aligned}$$

for any $1 \leq k \leq N$
so choose k : $B \leq \varepsilon/2$
and note $A \leq \|T - T_n\| \leq \varepsilon/2$
for every $x \in B_X(0, 1)$
 $C \leq \varepsilon/3$

Corollary: If T is a limit of finite-rank operators in $\mathcal{B}(X, Y)$, then $T \in S_\infty(X, Y)$.

Proof: Since finite-rank operators are in $S_\infty(X, Y)$, we have $T \in S_\infty(X, Y)$ by the previous proposition. \square

Remark: At a general Banach space $\exists T \in S_\infty(X, Y)$ such that $\nexists \{T_n\}_n$: $\text{rank } T_n < \infty$ and $\|T - T_n\| \rightarrow 0$.

Definition: Let X be a Banach space. $\{e_k\}_{k=1}^\infty$ is a **Schauder basis** if $\forall x \in X \exists \{c_k(x)\}_{k=1}^\infty$ such that $x = \sum_{k=1}^\infty c_k(x)e_k$, where the series converges in X .

Theorem: Let X be a Banach space with Schauder basis, then $T \in S_\infty(X) \Leftrightarrow \exists T_n. \text{rank } T_n \leq n$ and $\|T - T_n\| \rightarrow 0$. (here $\text{rank } S = \dim S(X) \quad \forall S \in \mathcal{B}(X)$)

Proof: (\Leftarrow): we already know

(\Leftrightarrow) : Let $T \in S_\infty(X)$, and let $P_n : X \mapsto \sum_{k=1}^{\infty} c_k(x) e_k$.

P is linear: $\forall \alpha, \beta \in \mathbb{C}, \forall x, y \in X. P_n(\alpha x + \beta y) = \alpha P_n(x) + \beta P_n(y)$?

$$\left. \begin{array}{l} \text{If } x = \sum c_k(x) e_k \\ y = \sum c_k(y) e_k \end{array} \right\} \Rightarrow \alpha x + \beta y = \sum_{k=1}^{\infty} (\alpha c_k(x) + \beta c_k(y)) e_k$$

$$\alpha x + \beta y = \sum_{k=1}^{\infty} c_k(\alpha x + \beta y) e_k$$

by uniqueness by def. of Schauder basis

$$c_k(\alpha x + \beta y) = \alpha c_k(x) + \beta c_k(y) \quad \forall k$$

$$\begin{aligned} \text{Then } P_n(\alpha x + \beta y) &= \sum_{n=1}^{\infty} c_k(\alpha x + \beta y) e_k = \sum_{n=1}^{\infty} \alpha c_n(x) e_n + \sum_{n=1}^{\infty} \beta c_n(y) e_n \\ &= \alpha P_n(x) + \beta P_n(y) \quad \Rightarrow P_n \text{ linear} \end{aligned}$$

Note that $T_n := P_n T$ are such that $\text{rank}(T_n) \leq n$ because $\dim P_n T(x) \leq \dim P_n(x) \leq n$.

It remains to show that $T_n \rightarrow T$ in $\mathcal{B}(X)$. Since T is compact, $\forall \varepsilon > 0. \exists \{x_k\}_{k=1}^N$ such that $\|x_k\| \leq 1 \forall k$ and $\{Tx_k\}_{k=1}^N$ is a ε -net in $T(B_X(0,1))$. Now take $x \in B_X(0,1)$ and write $\|Tx - T_n x\| \leq \|Tx - Tx_n\| + \|Tx_n - T_n x\| + \|T_n x - T_n x\|$

$$\begin{aligned} &\leq \underbrace{\|Tx - Tx_n\|}_{\leq \varepsilon \text{ for some } k} + \underbrace{\|Tx_n - P_n Tx_n\|}_{\leq \varepsilon \text{ if } n \text{ large enough for any fixed } k} + \underbrace{\|P_n Tx_n - P_n Tx\|}_{\leq \|P_n\| \cdot \|Tx_n - Tx\|} \\ &\leq \varepsilon + \varepsilon + \underbrace{\sup_{n \in \mathbb{N}} \|P_n\|}_{< \infty} \varepsilon \end{aligned}$$

$\sup \|P_n\| < \infty$ by Banach-Schauder theorem on uniform point-wise convergence.

$$\|T - T_n\| \leq \varepsilon (2 + \sup \|P_n\|) \text{ for } n \text{ large enough} \quad \square$$

Theorem [Banach-Schteinhaus]: Assume that $\{T_n\}_{n=1}^{\infty} \subset \mathcal{B}(X)$ where X is a Banach space, such that

$$\sup_n \|T_n x\| \leq C(x) < \infty \quad \begin{matrix} \text{local information} \\ \sim \text{uniform estimate} \end{matrix}$$

For every $x \in X$. Then $\sup_n \|T_n\| < \infty$. In particular, one can take C in place of $C(x)$.

Remark: In our situation, $\sup_{1 \leq n < \infty} \|P_n\| \leq C(x) < \infty$ because $P_n x \rightarrow x$ in X .

Banach adjoint operators

October 15, 2025

Definition: Let X be a Banach space, then $X^* = \mathcal{B}(X, \mathbb{C})$ is called the dual space to X . The elements of X^* are called functionals.

Examples: (can ignore, if one does not know measure theory)

i) $L^p(\mu) = \left\{ f : S \rightarrow \mathbb{C} \mid \begin{array}{l} f \text{ is measurable with respect to } \sigma\text{-algebra} \\ \text{of } \mu \end{array}, \int_S |f|^p d\mu < \infty \right\}$

$f=g$
if $f(x)=g(x)$
for μ -a.e.xes

$$\|f\|_{L^p(\mu)} = \left(\int_S |f|^p d\mu \right)^{1/p}$$

$$(L^p(\mu))^* = L^q(\mu) \text{ where } \frac{1}{p} + \frac{1}{q} = 1$$

ii) $\ell^p(\mathbb{Z}) = \left(\left\{ \{x_k\}_{k \in \mathbb{Z}} \mid \sum_{k \in \mathbb{Z}} |x_k|^p < \infty \right\}, \|\{x_k\}\|_{\ell^p(\mathbb{Z})} = \left(\sum_k |x_k|^p \right)^{1/p} \right)$

$$\ell^p(\mathbb{Z})^* = \ell^q(\mathbb{Z}), \text{ where } \frac{1}{p} + \frac{1}{q} = 1$$

In these examples, the following identification is assumed:

i) $g \in L^q(\mu) \leftrightarrow \phi_g : f \mapsto \int_S f g d\mu, \quad \phi_g : L^p(\mu) \rightarrow \mathbb{C}$

ii) $\{y_k\}_{k=1}^\infty$ in $\ell^q(\mathbb{Z}) \leftrightarrow \phi_{\{y_k\}} : \{x_k\} \mapsto \sum_{k \in \mathbb{Z}} x_k y_k$

$\phi_{\{y_k\}} : \ell^p(\mathbb{Z}) \rightarrow \mathbb{C}$

Remark: i) is non-trivial measure theory

More examples:

iii) $C_0(\mathbb{Z}) = \left\{ \{x_k\}_{k \in \mathbb{Z}} \mid x_k \rightarrow 0 \text{ as } |k| \rightarrow \infty \right\}$

$C_0^*(\mathbb{Z}) = \ell^1(\mathbb{Z})$ same identification

(Hausdorff is actually sufficient \Leftrightarrow hard)

iv) Let K be a compact metric space, and $X = C(K)$.
Then $X^* = M(K)$.

{ the set of Borel measures on K (complex valued) } $\|\mu\|(K) = \sup_{\substack{K = \cup E_n \\ E_n \cap E_j = \emptyset \\ n \neq j}} \sum_{n \in \mathbb{Z}} |\mu(E_n)| < \infty \}$

set of
cont. maps
 $(K, \mathcal{S}) \rightarrow \mathbb{C}$

Riesz - Markov representation theorem

Here $\mu \in M \xrightarrow{\text{(bi)}} \phi_\mu : f \mapsto \int_K f d\mu$

We can also define ℓ^p, L^p for $p = \infty$:

- $\ell^\infty(\mathbb{Z}) := \left\{ \{x_k\} \subset \mathbb{C} : \sup_{k \in \mathbb{Z}} |x_k| < \infty \right\}$

- $L^\infty(\mu) := \left\{ f : \mathbb{R} \rightarrow \mathbb{C} : \text{ess sup } |f| < \infty \right\}$

Remark: If $1 \leq p < \infty$ then $(L^p)^* = L^q, (L^q)^* = L^p$

Bvt for $p=1$ $(L^1)^* = L^\infty$, $(L^\infty)^* \neq L^1$
 $L^1(\mathbb{Z})^* = l^\infty(\mathbb{Z})$, bvt $(l^\infty(\mathbb{Z}))^* \neq l^1(\mathbb{Z})$

Definition: Let X, Y be Banach spaces, $T \in \mathcal{B}(X, Y)$. Then $T^* \in \mathcal{B}(Y^*, X^*)$ is defined by

$$T^* : \Psi_{Y^*} \longmapsto \left(\left(T^* \Psi \right) : x \mapsto \langle Tx, T^* \psi \rangle \right),$$

where $\langle x, \phi \rangle = \phi(x)$ for $x \in X, \phi \in X^*$. $\Psi(Tx)$

Remark: $\langle Tx, \psi \rangle = \langle x, T^* \psi \rangle \rightarrow$ this formula is equivalent to the definition of T^*

Remark: Operation that sends x, ϕ into $\phi(x) = \langle x, \phi \rangle$ for $x \in X, \phi \in X^*$ is called a pairing of Banach spaces X, X^* .

Example: For $f \in C[0,1]$, μ on $[0,1]$ then the pairing is $\langle \phi, \mu \rangle = \int_0^1 f d\mu$, see (*).

Theorem: Let X, Y be Banach spaces, $T \in \mathcal{B}(X, Y)$. Then the map $T^* : Y^* \rightarrow X^*$ defined by $\langle x, T^* \psi \rangle := \langle Tx, \psi \rangle$, $x \in X$, is an element of $\mathcal{B}(Y^*, X^*)$.
 $(\Leftrightarrow (T^* \psi)(x) = \psi(Tx))$

Lemma 1 [Hahn-Banach theorem]: Let X be a Banach space, $E \subset X$ - subspace in X , $\phi_0 : E \rightarrow \mathbb{C}$ is linear and bdd ($\Leftrightarrow \phi_0 \in E^*$). Then $\exists \phi \in X^*$ such that $\phi|_E = \phi_0$ and $\|\phi\| = \|\phi_0\|$.

Lemma 2 ["Sufficient amount of functionals"] :

Let $x \in X$, then $\|x\| = \sup_{\|\phi\| \leq 1} |\phi(x)|$.

Proof: $|\phi(x)| \leq \|\phi\| \cdot \|x\| \leq \|x\|$, so $\|x\| \geq \sup_{\|\phi\| \leq 1} |\phi(x)|$

To prove " \leq ", define $E = \text{span}\{x\} = \{\lambda x, \lambda \in \mathbb{C}\}$,
 $\Phi_0: Y \rightarrow \mathbb{C}$, if $y = c_y x \in E$.

Assume that $\|x\| = 1$, then $\|\Phi_0\|_{E^*} = \sup_{\|y\| \leq 1} |\Phi_0(y)| = (\text{from } (**),$
 $|c_y| = \|y\| \text{ if } \|x\| = 1) = \sup_{\|y\| \leq 1} \|y\| = 1$.

Hahn-Banach theorem $\Rightarrow \exists \tilde{\Phi}_0 \in X^*: \|\tilde{\Phi}_0\| = 1, \Phi_0|_E = \tilde{\Phi}_0$.

In particular $\sup_{\|\Phi\| \leq 1} |\Phi(x)| \geq |\tilde{\Phi}| = |\Phi_0(x)| = 1 = \|x\|$.

We have proved " \leq " in the case where $\|x\| = 1$.

The general case follows from consideration of $\frac{x}{\|x\|}$ in
place of X .

October 21, 2025

We are proving that $T \in \mathcal{B}(X, Y) \Rightarrow T^* \in \mathcal{B}(Y^*, X^*)$ and $\|T\| = \|T^*\|$.

Let $T \in \mathcal{B}(X, Y)$, consider

$$\begin{aligned} \|T^*\| &= \sup_{\substack{\psi \in Y^* \\ \|\psi\| \leq 1}} \|T^* \psi\|_{X^*} = \sup_{\substack{\psi \in Y^* \\ \|\psi\| \leq 1}} \sup_{\substack{x \in X \\ \|x\| \leq 1}} |(T^* \psi)(x)| \\ &= \sup_{\substack{\psi \in Y^* \\ \|\psi\| \leq 1}} \sup_{\substack{x \in X \\ \|x\| \leq 1}} |\langle x, T^* \psi \rangle| \\ &= \sup_{\substack{\psi \in Y^* \\ \|\psi\| \leq 1}} \sup_{\substack{x \in X \\ \|x\| \leq 1}} |\langle T_x, \psi \rangle| \\ &= \sup_{\substack{\psi \in Y^* \\ \|\psi\| \leq 1}} \sup_{\substack{x \in X \\ \|x\| \leq 1}} |\psi(Tx)| \\ &= \sup_{\substack{x \in X \\ \|x\| \leq 1}} \sup_{\substack{\psi \in Y^* \\ \|\psi\| \leq 1}} |\psi(Tx)| \end{aligned}$$

= $\|Tx\|$ Lemma "Sufficient amount of functionals"

$$= \sup_{\|x\| \leq 1} \|Tx\| = \|T\| < \infty$$

The claim follows. □

Corollary: $T \in \mathcal{B}(X, Y)$ is invertible ($\exists T^{-1} \in \mathcal{B}(Y, X)$) iff $T^* \in \mathcal{B}(Y^*, X^*)$ is invertible ($\exists (T^*)^{-1} \in \mathcal{B}(X^*, Y^*)$).

We prove just \Rightarrow .

Proof: Assume that T is invertible $\Leftrightarrow T^{-1}T = I_X$
 $TT^{-1} = I_Y$,

Let's take adjoint operators and see:

$$\left. \begin{array}{l} (T^{-1}T)^* = (I_X)^* \\ (TT^{-1})^* = (I_Y)^* \end{array} \right\} \Leftrightarrow \left\{ \begin{array}{l} T^*(T^{-1})^* = I_X^* \\ (T^{-1})^*T^* = I_Y^* \end{array} \right.$$

Exercise: $(AB)^* = B^*A^*$

It remains to check that $I_X^* = I_{X^*}$, $I_Y^* = I_{Y^*}$. Then, by the previous theorem, $(T^{-1})^* \in \mathcal{B}(X^*, Y^*)$, hence T^* is invertible and its bounded inverse is $(T^*)^{-1} = (T^{-1})^*$.

Let's check that $I_X^* = I_{X^*}$. Take $\bar{x} \in X^*$, $x \in X$.

$$(I_X^*\bar{x})(x) = \langle x, I_X^*\bar{x} \rangle = \langle I_X^*x, \bar{x} \rangle = \langle x, \bar{x} \rangle = \bar{x}x$$

$$(I_X^*\bar{x})(x) \stackrel{\text{def}}{=} (\bar{x})x = \bar{x}(x).$$

Similarly, $I_Y^* = I_{Y^*}$. □

The „pairing notation” is often not used in literature, but it is very useful to not make mistakes.

Theorem [Schauder]: We have $T \in S_\infty(X, Y) \Leftrightarrow T^* \in S_\infty(Y^*, X^*)$.

Proof: We will prove just " \Rightarrow ".

Consider $K = \overline{TB_X(0,1)}$ - a compact set. Let $C(K)$ be the Banach space of continuous functions on K with

$$\|f\|_{C(K)} = \max_{s \in K} |f(s)|, \quad f: K \rightarrow \mathbb{C}$$

Let $E := \{\psi \in Y^* \mid \|\psi\|_{Y^*} \leq 1, \psi \text{ is considered as a function on } K\}$

$K \subset Y$, K metric space with respect to the metric $s(x_1, x_2) = \|x_2 - x_1\|_Y$

So, $E \subset C(K)$ and we claim that E is precompact.

1) Uniform boundedness:

$\psi \text{ cont.}$

$$\psi \in E \Rightarrow \|\psi\|_{C(K)} = \max_{s \in K} |\psi(s)| = \max_{s \in \overline{TB_X(0,1)}} |\psi(s)| = \sup_{x \in B_X(0,1)} |\psi(Tx)|$$

$$\leq \|\psi\| \sup_{\|x\| \leq 1} \|Tx\| \leq \|\psi\| \cdot \|T\| \leq \underbrace{\|T\|}_{\substack{\text{does not} \\ \text{depend on } \psi}} < \infty$$

2) Equicontinuity: take $s_1, s_2 \in K$, let's estimate

$$|\psi(s_1) - \psi(s_2)| = |\psi(s_1 - s_2)| \leq \|\psi\| \cdot \|s_1 - s_2\| \leq \|s_1 - s_2\|,$$

so maps from E are Lipschitz with constant 1, hence equicontinuous.

\Rightarrow By Arzela-Ascoli theorem, E is precompact.

We are now ready to prove $T^* \in S_\infty(Y^*, X^*)$. For this, we need to check that if $\{\psi_n\}$ is a sequence in $B_{Y^*}(0,1)$, then $\exists \{\psi_{n_k}\}$ such that $T^* \psi_{n_k}$ converges in X^* . So, take $\{\psi_n\} \subset B_{Y^*}(0,1)$ and consider it as elements $E \subset C(K)$.

Let $\{\psi_{n_k}\}$ be such that $\psi_{n_k} \xrightarrow{\text{w*}} \psi$ in $C(K)$. (E is precompact!)

Let's prove that $\{T^*\psi_{n_k}\}$ is Cauchy in X^* , then the theorem will follow.

Take $x \in X$, $\|x\| \leq 1$, and consider

$$\begin{aligned}
 \| (T^*\psi_{n_k})(x) - (T^*\psi_{n_j})(x) \| &= \| \langle x, T^*\psi_{n_k} \rangle - \langle x, T^*\psi_{n_j} \rangle \| \\
 &= \| \langle Tx, \psi_{n_k} \rangle - \langle Tx, \psi_{n_j} \rangle \| \\
 &= \| \psi_{n_k}(Tx) - \psi_{n_j}(Tx) \| \\
 &\leq \sup_{s \in K} \| \psi_{n_k}(s) - \psi_{n_j}(s) \| \\
 &= \underbrace{\|\psi_{n_k} - \psi_{n_j}\|}_{\varepsilon_{k,j} - \text{does not depend on } x} \Big|_{C(K)} \longrightarrow 0 \quad \text{by } (*).
 \end{aligned}$$

$$\Rightarrow \|T^*\psi_{n_k} - T^*\psi_{n_j}\| \leq \varepsilon_{k,j} \longrightarrow 0.$$

□

Fredholm alternative

Example: Consider the equation $f(t) - \int_0^1 e^{t-s} f(s) ds \stackrel{(*)}{=} g(t)$ in $L^2[0,1]$.

Question: For which $g \in L^2[0,1]$ do we have a solution $f \in L^2[0,1]$?

Observation: g has to satisfy $\int_0^1 e^{-t} g(t) dt = 0$

Indeed, $\int_0^1 e^{-t} g(t) dt = \int_0^1 e^{-t} f(t) dt - \int_0^1 e^{-t} \left(\int_0^1 e^{t-s} f(s) ds \right) dt = 0$

It is not clear so far if there are other restrictions.

Theorem [Fredholm alternative]: Let X be a Banach space, $T = I - K$ for $K \in S^\infty(X, X)$. Then

$$\text{Ran } T = \{x \in X \mid \langle x, \varrho \rangle = 0 \ \forall \varrho \in \ker T^*\}.$$

In other words, either:

- (1) $\ker T^* = \{0\}$ and the equation $Tf = g$ has solution $\forall g \in X$.
- or (2) $\ker T^* \neq \{0\}$ and the equation $Tf = g$ has solutions only for g s.t. $\langle g, \varrho \rangle = 0 \ \forall \varrho \in \ker T^*$.

Let's complete the consideration of the example:
 we need to check that $K: f \rightarrow \int_0^1 e^{t-s} f(s) ds$ is compact
 (exercise) and find $\text{Ker } T^*$.

$$\phi \in \text{Ker } T^* \Leftrightarrow T^* \phi = 0$$

Adjoint operator T^* is defined by

$$\begin{aligned} \langle Tf, g \rangle &= \langle f, T^*g \rangle \quad f, g \in L^2[0,1] \\ \Leftrightarrow \langle f - \int_0^1 e^{t-s} f(s) ds, g \rangle &= \int_0^1 f(t) g(t) dt - \int_0^1 \left(\int_0^1 e^{t-s} f(s) ds \right) g(t) dt \\ &= \int_0^1 f(t) g(t) dt - \int_0^1 f(s) \left(\int_0^1 e^{t-s} g(t) dt \right) ds \\ &= \langle f, g - \int_0^1 e^{t-s} g(t) dt \rangle_{L^2[0,1]} \end{aligned}$$

$$(T^*g): s \mapsto g(s) - \int_0^1 e^{t-s} g(t) dt, \quad s \in [0,1].$$

$$T^*g = 0 \Leftrightarrow g(s) = \int_0^1 e^{t-s} g(t) dt \quad \text{a.e. on } [0,1]$$

$$\Leftrightarrow e^s g(s) = \underbrace{\int_0^1 e^{t-s} g(t) dt}_{\text{constant}} \quad \text{for almost every } s \in [0,1]$$

$$\Rightarrow \text{So, } \text{Ker } T^* = \{c \cdot e^{-s}, c \in \mathbb{C}\}, \quad \dim(\text{Ker } T^*) = 1.$$

By Fredholm theorem, equation $(**)$ is solvable \Leftrightarrow
 $\forall c \in \mathbb{C}. \langle g, c \cdot e^{-s} \rangle = 0 \Leftrightarrow \int_0^1 g(s) e^{-s} ds = 0$, which is $(***)$.

Preliminaries

Lemma [almost orthogonality in Banach spaces]: Let X be a Banach space, $E \subseteq X$ - a linear closed subspace, $\varepsilon > 0$. Then $\exists x_0 \in X$ such that $\|x_0\| = 1$, $\text{dist}(x_0, E) \geq 1 - \varepsilon$.

Proof: Since $E \neq X$, then $\exists \tilde{x}_0 \in X \setminus E$. Since E is closed, we have $\text{dist}(\tilde{x}_0, E) = \delta > 0$ for some $\delta > 0$. Now consider $\tilde{y}_0 \in E$ such that $\delta \leq \|\tilde{x}_0 - \tilde{y}_0\| \leq (1+\eta)\delta$ for some $\eta \in (0, 1)$.

Now let $x_\eta := \frac{\tilde{x}_0 - \tilde{y}_0}{\|\tilde{x}_0 - \tilde{y}_0\|}$, $\|x_\eta\| = 1$.

$$\begin{aligned}\text{dist}(x_\eta, E) &= \frac{1}{\|\tilde{x}_0 - \tilde{y}_0\|} \text{dist}(\tilde{x}_0 - \tilde{y}_0, E) \\ &= \frac{1}{\|\tilde{x}_0 - \tilde{y}_0\|} \text{dist}(\tilde{x}_0, E) \\ &= \frac{\delta}{\|\tilde{x}_0 - \tilde{y}_0\|} \geq \frac{1}{1+\eta}\end{aligned}$$

Choosing η so that $\frac{1}{1+\eta} = 1 - \varepsilon$, we are done.

October 22, 2025

Lemma: Let X be a Banach space. Then $I: X \mapsto X$ is compact on $X \Leftrightarrow \dim X < \infty$.

Proof: $\dim X < \infty \Rightarrow I \in S_\infty(X)$ - we already know $I \in S_\infty(X) \Rightarrow \dim X < \infty$:

Suppose $\dim X = +\infty$, find a sequence $\{e_n\}: \|e_n\| = 1 \quad \forall n \in \mathbb{N}$

$e_1 \in X$ - arbitrary

$e_2: \text{dist}(e_2, \text{span}\{e_1\}) \geq \frac{1}{2}$

$e_3: \text{dist}(e_3, \text{span}\{e_1, e_2\}) \geq \frac{1}{2}$

$e_4: \text{etc}$

existence of $\{e_n\}$
follows from previous
lemma, because
 $\text{span}\{e_1, \dots, e_k\} \neq X$
 $\forall k \in \mathbb{N}$

Then $\{e_n\} \subset B_X[0, 1] = I(B_X[0, 1])$ but there is no convergent subsequence, because $\|e_k - e_j\| \geq \frac{1}{2} \quad \forall k, j$. \blacksquare

Lemma: Let X be a Banach space, $K \in \mathcal{S}_\infty(X)$, $T = I - K$.
 Then: 1) $\dim(\text{Ker } T) < \infty$.
 2) $\text{Ran } T$ is closed in X . [closed range Lemma]

Proof: 1): We have $I|_{\text{Ker } T} = \underbrace{(I-K)|_{\text{Ker } T}}_0 + \underbrace{K|_{\text{Ker } T}}_{\in \mathcal{S}_\infty(\text{Ker } T, S)}$

$$I|_{\text{Ker } T} \in \mathcal{S}_\infty(\text{Ker } T, X) \Rightarrow I \in \mathcal{S}^\infty(\text{Ker } T) \Rightarrow \dim(\text{Ker } T) < \infty$$

2): The statement is equivalent to the fact that if $\{x_n\} \subset X$ s.t. $TX_n \rightarrow y$ in X then $\exists x \in X. Tx = y$.

2.a) Let $\{x_n\} : \|x_n\| \leq c \quad \forall n$.

Then $(I-K)(x_n) \rightarrow y$, $(I-K)(x_{n_k}) \xrightarrow{(*)} y$
 For every subsequence x_{n_k}

Let's choose x_{n_k} : Kx_{n_k} converges to $z \in X$
 (use $K \in \mathcal{S}_\infty(X)$)

Then $x_{n_k} \rightarrow y+z$ by (*), take $x = y+z$:

$$T(y+z) = \lim_{k \rightarrow \infty} Tx_{n_k} = y, \text{ so } Tx = y. \quad \checkmark$$

2.b) $\text{dist}(x_n, \text{Ker } T) \leq c \quad \forall n \in \mathbb{Z}$

Take $\tilde{x}_n := x_n - w_n$, where $w_n \in \text{Ker } T : \|\tilde{x}_n\| \leq 2c$.

We have $\lim_{n \rightarrow \infty} T\tilde{x}_n = \lim_{n \rightarrow \infty} Tx_n$ by step 2a) $\exists \tilde{x} : T\tilde{x} = y \quad \checkmark$

2.c) $\text{dist}(x_n, \text{Ker } T) \rightarrow +\infty$. Let us show that this situation does not occur. Suppose the converse:

Consider $\tilde{x}_n = x_n - \underbrace{w_n}_{\text{Ker } T} : \text{dist}(x_n, \text{Ker } T) \leq \|\tilde{x}_n\| \leq 2\text{dist}(x_n, \text{Ker } T)$

For $z_n = \frac{\tilde{x}_n}{\|\tilde{x}_n\|}$ we have $Tz \rightarrow 0$.

$$Tz_n = T \frac{\tilde{x}_n}{\|\tilde{x}_n\|} = T \frac{x_n}{\|x_n\|} = \frac{Tx_n}{\|x_n\|} \rightarrow \begin{cases} y & \Rightarrow Tx_n \text{ is bdd in } X \\ +\infty & \end{cases}$$

$$\Rightarrow \|Tz_n\| \leq \frac{2\|y\|}{\|\tilde{x}_n\|} \rightarrow 0 \quad \text{for } n \text{ large enough}$$

At the same time, $Tz_n = z_n - Kz_n$

$\Rightarrow \exists \{z_{n_k}\}$ s.t. $\{Kz_{n_k}\}$ converges to some $z \in X$

$$\Rightarrow z_{n_k} = \underbrace{Tz_{n_k}}_{\rightarrow 0} + \underbrace{Kz_{n_k}}_{\rightarrow z} \rightarrow z$$

We have $Tz = 0$ ($= \lim Tz_{n_k} = \lim Tz_n = 0$)

$\Leftrightarrow z \in \text{Ker } T$, $0 = \text{dist}(z, \text{Ker } T) =$

$$= \lim_{k \rightarrow \infty} \text{dist}(z_{n_k}, \text{Ker } T)$$

$$= \lim_{k \rightarrow \infty} \text{dist}\left(\frac{\tilde{x}_{n_k}}{\|\tilde{x}_{n_k}\|}, \text{Ker } T\right)$$

$$= \lim \frac{\text{dist}(\tilde{x}_{n_k}, \text{Ker } T)}{\|\tilde{x}_{n_k}\|}$$

$$= \lim \frac{\text{dist}(x_{n_k}, \text{Ker } T)}{\|\tilde{x}_{n_k}\|}$$

$$\stackrel{(*)}{\geq} \frac{1}{2} \quad \leadsto \text{contradiction}$$



Lemma: Let X be a Banach space, $T \in \mathcal{B}(X)$:

$\text{Ker}(T) = \{0\}$ and $T^{k+1}X = T^kX$ for some $k \geq 0$.

Then $\text{Ran } T = X$.

Proof: We need to prove that $\forall a \in X. \exists \tilde{a} \in X. T\tilde{a} = a$.

We know that: $T^{k+1}a = T^k\tilde{a}$ for every a and some \tilde{a} depending on a . $\downarrow \text{Ker } T^k \neq \{0\} \Rightarrow \text{Ker } T \neq \{0\}$

$$\Rightarrow T^k(a - T\tilde{a}) = 0 \Rightarrow a - T\tilde{a} = 0 \Rightarrow a = T\tilde{a}$$



Theorem [Fredholm]: Let X be a Banach space.

$K \in S_\infty(X)$, $T = I - K$. Then TFAE:

1) T is invertible in $\mathcal{B}(X)$ 2) $\text{Ker } T = \{0\}$ 3) $\text{Ran } T = X$

1) T^* is invertible in $\mathcal{B}(X)$ 2) $\text{Ker } T^* = \{0\}$ 3) $\text{Ran } T^* = X^*$

Proof: We will prove $2 \Rightarrow 3 \Rightarrow 2' \Rightarrow 3' \Rightarrow 2$, $1 \Rightarrow 1' \Rightarrow 2'$, $2 \wedge 3 \Rightarrow 1$

(2) \Rightarrow (3): If $T^k X = T^{k+1} X$ for some k , we are done by the lemma.

Define $X_k := T^k X$, $k \geq 0$, and note that $X_0 \supset X_1 \supset X_2 \supset X_3 \dots$

Assume that all inclusions are strict, i.e. $X_k \supsetneq X_{k+1} \forall k$.

The subspaces X_k are closed by the closed range lemma (by induction). By the almost orthogonality lemma: $\exists \{y_k\}_{k=0}^\infty$ s.t.

i) $y_k \in X_k \forall k$ ii) $\|y_k\| = 1 \forall k$ iii) $\text{dist}(y_k, X_{k+1}) \geq \frac{1}{2}$

Since K is compact $\{Ky_k\}$ contains a convergent subsequence $\{Ky_{k_j}\}_{j=1}^\infty$. On the other hand, if $j < m$

$$\begin{aligned} Ky_{k_j} - Ky_{k_m} &= (Ky_{k_j} - y_{k_j}) - (Ky_{k_m} - y_{k_m}) + y_{k_j} - y_{k_m} \\ &= y_{k_j} - y_{k_m} - \underbrace{(Ty_{k_j} - Ty_{k_m})}_{\in X_{k_j+1}} \end{aligned}$$

Since $y_{k_m} \in X_{k_m}$, $j < m$, $k_j < k_m$, $k_j+1 \leq k_m$, $X_{k_m} \subset X_{k_j+1}$
 $\Rightarrow y_{k_m} \in X_{k_j+1}$; $Ty_{k_m} \subset T X_{k_j+1} \subset X_{k_j+1}$; $Ty_{k_j} \in T(X_{k_j}) = X_{k_j+1}$
 $\Rightarrow Ky_{k_j} - Ky_{k_m} = y_{k_j} + R$, $R \in X_{k_j+1}$. Since $\|y_{k_j} + R\| \geq \frac{1}{2}$ by (iii),
we get a contradiction ($\{Ky_{k_j}\}$ is not Cauchy).

(3) \Rightarrow (2): Take $\phi \in \text{Ker } T^*$. We have

$$\begin{aligned} T^* \phi = 0 &\Leftrightarrow \langle x, T^* \phi \rangle = 0 \quad \forall x \in X \Leftrightarrow \langle Tx, \phi \rangle = 0 \quad \forall x \in X \Leftrightarrow \\ &\Leftrightarrow \langle y, \phi \rangle = 0 \quad \forall y \in X \quad (\text{by 3}) \Leftrightarrow \phi = 0 \end{aligned}$$

(2') \Rightarrow (3'): (the same as $2 \Rightarrow 3$ using Schauder's theorem)

(3') \Rightarrow (2): Assume that $\text{Ran } T^* = X^*$ and take $x \in \text{Ker } T$. We have $Tx = 0 \Leftrightarrow \langle Tx, \phi \rangle = 0 \quad \forall \phi \in X^* \Leftrightarrow \langle x, T^*\phi \rangle \quad \forall \phi \in X^*$ $\Leftrightarrow \langle x, \Psi \rangle = 0 \quad \forall \Psi \in X^* \quad (\text{by 3'}) \Leftrightarrow x = 0$ Lemma on sufficient amount of functionals

Conclusion: $(2) \Leftrightarrow (3) \Leftrightarrow (2') \Leftrightarrow (3')$

(1) \Rightarrow (1'): We already know for arbitrary $T \in \mathcal{B}(X)$.

(1') \Rightarrow (2'): Invertible operators are injective.

$(2') \Leftrightarrow (1), (3)$

(2 & 3) \Rightarrow (1): This holds for every $T \in \mathcal{B}(X)$ by the following fundamental theorem from general F.A.:

Theorem [linear mapping theorem]: Let X, Y be Banach spaces, $T: X \rightarrow Y$ - linear bijection. Then $T \in \mathcal{B}(X, Y) \Leftrightarrow T^{-1} \in \mathcal{B}(Y, X)$.

Check injectivity: $Tx_1 = Tx_2 \Leftrightarrow T(x_1 - x_2) = 0 \Leftrightarrow x_1 - x_2 = 0 \quad (\text{by 1}) \Leftrightarrow x_1 = x_2$

Surjectivity: $\text{Ran } T = X \quad (\text{by 3})$



Remark: If $T = I - K$, $K \in \mathcal{S}_{\infty}(X)$, and $\text{Ker } T = \{0\}$ then the equation $Tx = y$ has a unique solution for every $y \in X$.

Remark: $\text{Ker } T = \{0\} \Leftrightarrow \text{Ker } T^* = \{0\}$, so we have proved half of Fredholm Alternative.

Theorem: Let X be a Banach space, $T \in \mathcal{B}(X)$. Then $\overline{\text{Tx}} = \{x \in X \mid \langle x, \phi \rangle = 0 \quad \forall \phi \in \text{Ker } T\}$.

Remark: This implies the other half of Fredholm alternative since $\overline{\text{Tx}} = \text{Tx}$ for $T = I - K$, $K \in \mathcal{S}_{\infty}(X)$.

Lemma [seperation lemma]: Let Y be a Banach space, $Y_0 \subsetneq Y$ - a closed subspace, then $\exists \phi \in Y^*: \phi|_{Y_0} = 0$, $\phi(y) \neq 0$ for some $y \in Y \setminus Y_0$.

Proof: Take $y \in Y \setminus Y_0$, define $\Phi_0: \text{span}\{y, Y_0\} \rightarrow \mathbb{C}$ by $\Phi_0(cy + y_0) \mapsto c$, for $c \in \mathbb{C}, y_0 \in Y_0$.

$$1) \{cy, y_0 \mid c \in \mathbb{C}, y_0 \in Y_0\} = \text{span}\{y, Y_0\} \quad \text{clear } \checkmark$$

$$2) \underbrace{cy + y_0}_c = \underbrace{\tilde{c}y + \tilde{y}_0}_{\tilde{c}} \Leftrightarrow (c - \tilde{c})y = y_0 - \tilde{y}_0 \in Y_0 \Leftrightarrow c = \tilde{c} \Rightarrow \Phi_0(c) = \Phi_0(\tilde{c})$$

\Rightarrow correctness OK

3) Φ_0 is linear - clear

$$4) \Phi_0|_{Y_0} = 0 \quad (c=0 \text{ on } Y)$$

$$5) |\Phi_0(cy + y_0)| \stackrel{?}{\leq} A \|cy + y_0\| \quad \forall c, y_0$$

$$|\Phi_0(cy + y_0)| = |c| = (\text{dist}(y, \underbrace{Y_0}_{\text{closed}}))^{-1} \cdot |c| \cdot \text{dist}(y, Y_0)$$

$$= \text{dist}(y, Y_0)^{-1} \cdot \text{dist}(|c|y, Y_0) = \text{dist}(y, Y_0)^{-1} \cdot \text{dist}(|c|y, Y_0)$$

\nearrow

$$|c|y = \alpha \cdot e \cdot y_0, |\alpha|=1$$

$$\text{dist}(|c|y, Y_0) = \text{dist}(\underbrace{|c|y_0}_{c}, \underbrace{Y_0}_y)$$

$$\leq \text{dist}(y, Y_0)^{-1} \|cy + y_0\|, \quad \text{so } A = \text{dist}(y, Y_0)^{-1} \text{ works}$$

$$6) \Phi_0(y) = 1 \neq 0$$

\Rightarrow Use the Hahn-Banach theorem and extend Φ_0 to the whole Y . □

We actually proved that the lemma holds $\forall y \in Y \setminus Y_0$.

We can now prove the theorem from above.

Theorem: Let X be a Banach space, $T \in \mathcal{B}(X)$. Then
 $\overline{Tx} = \{x \in X \mid \langle x, \phi \rangle = 0 \quad \forall \phi \in \text{Ker } T^*\}$.

Proof: We have $Tx \subset E$, $E = \{x \mid \langle x, \phi \rangle = 0 \quad \forall \phi \in \text{Ker } T^*\}$,
because $\langle Tx, \phi \rangle = \langle x, T^* \phi \rangle = 0 \quad \forall \phi \in \text{Ker } T^*$.
Then $\overline{Tx} \subset \overline{E} = E$ since E is closed.
 $(\begin{matrix} x_n \rightarrow x \text{ and } \langle x_n, \phi \rangle = 0 \text{ for some } \phi \in X^* \\ \text{then } \langle x, \phi \rangle = \lim \langle x_n, \phi \rangle = 0 \end{matrix})$

We now need to check $\overline{Tx} \supset X$. If not, the inclusion $\overline{Tx} \subset E$ is proper and by the separation lemma $\exists \phi : \phi|_{\overline{Tx}} = 0$ ^(*) but $\phi(e) \neq 0$ for some $e \in E$.

$$\begin{aligned} (\ast) \Rightarrow \phi|_{Tx} = 0 &\Leftrightarrow \langle Tx, \phi \rangle = 0 \quad \forall x \in X \Leftrightarrow \langle x, T^* \phi \rangle = 0 \quad \forall x \in X \\ \Leftrightarrow \phi \in \text{Ker } T^* &\Rightarrow \phi(e) = 0 \quad \forall e \in E \text{ by definition of } E, \text{ contradiction. } \square \end{aligned}$$

Classical form of Fredholm alternative for integral equations

Theorem: Let (S, μ) be a space with measure μ , and let $K(x, y) : S \times S \rightarrow \mathbb{C}$:

$$\iint_{S \times S} |K(x, y)|^2 d\mu(x) d\mu(y) < \infty.$$

Then either equation $f(y) + \int_S K(x, y) f(x) d\mu(x) = 0$ ^(***) has only the trivial solution $f=0$ and the equation

$$f(y) + \int_S K(x, y) f(x) d\mu(x) = g(y)$$

is solvable for every $g \in L^2(S, \mu)$ or the equation $(**)$ has a non-trivial solution in $L^2(S, \mu)$.

Remark: Uniqueness implies existence.

Proof: Let's define $T = I - K$, $(Kf)(y) = \int_S K(x, y) f(x) d\mu(x)$. Consider T as an operator on $L^2(S, \mu)$.

Then $(**)$ $\Leftrightarrow \text{Ker } T = \{0\} \Leftrightarrow TL^2(S, \mu) = L^2(S, \mu)$ by Fredholm alternative,
modulo the fact that $K \in \text{Soo}(L^2(S, \mu))$. □

↑ This we postpone until
Hilbert Spaces theory.

Remarks: Further reading:

- 1) $\dim \text{Ker } T = \dim \text{Ker } T^*$ if $T = I - K$, $K \in \text{Soo}$, it coincides with the dimension of the space of solutions
- 2) There is a version of Fredholm theory for general operators $T \in \mathcal{B}(X)$: $\dim(\text{Ker } T) < \infty$, $\dim(X/\text{Ran } T) < \infty$.

Spectrum of compact operators

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Definition: Let $T \in \mathcal{B}(X)$, X Banach space.

$\sigma(T) := \{\lambda \in \mathbb{C} \mid \lambda I - T \text{ is not invertible in } \mathcal{B}(X)\}$
is called the **spectrum** of T .

Definition: A number $\lambda \in \mathbb{C}$ is called an **eigenvalue** of T if $\exists e \in X \setminus \{0\}$. $Te = \lambda e$.

Definition: $\sigma_p(T) := \{\lambda \text{ eigenvalue of } T\}$... point spectrum of T .

Remark: We have $\sigma_p(T) \subset \sigma(T)$ for every $T \in \mathcal{B}(X)$.

Proof: $\lambda \in \sigma_p(T) \Rightarrow \lambda I - T$ is not injective because $\text{Ker}(\lambda I - T) \neq \{0\}$.

Remark: In general, we might have $\sigma_p(T) \neq \sigma(T)$ and even $\sigma_p(T) = \emptyset$.

Theorem: Let X be a Banach space, $\dim X = +\infty$, and let $K \in S_\infty(X)$. Then $0 \in \sigma(K)$, $\sigma(K) \setminus \{0\} \subset \sigma_p(T)$, moreover, each eigenvalue has a finite multiplicity, and $\#\{\lambda \in \sigma_p(K) \mid |\lambda| \geq r\} < \infty$ for every $r > 0$.

Proof: $0 \in \sigma(K)$ since $0 \notin \sigma(K)$, then $\exists K^{-1} \in \mathcal{B}(X)$:
 $I = K K^{-1} = K^{-1} K$, but then $I \in S_\infty(X) \Rightarrow \dim X < \infty$, contradiction.

Now let's prove that $\sigma(K) \setminus \{0\} \subset \sigma_p(K)$.

Take $\lambda \in \sigma(K)$ and assume that $\lambda \notin \sigma_p(K)$. Then

$$\text{Ker}(\lambda I - K) = \{0\} \Leftrightarrow \text{Ker}(I - \frac{1}{\lambda} K) = \{0\}$$

$\Rightarrow I - \frac{1}{\lambda} K$ is invertible by Fredholm theorem - contradiction.

Now let's prove that $\dim E_\lambda < \infty$.

$$E_\lambda := \{e \in X \mid Ke = \lambda e\} \quad \left(\begin{array}{l} \text{definition for :} \\ \lambda \text{ has finite multiplicity} \end{array} \right)$$

If this is not the case, there is a sequence $\{e_n\}_{n=1}^\infty$ such that $\text{dist}(e_n, \text{span}\{e_1, \dots, e_{n-1}\}) \geq \frac{1}{2}$, $\|e_n\| = 1$.

Consider $\{Ke_n\} = \{\lambda_n e_n\}$: we cannot choose a convergent subsequence from this sequence - contradiction with $K \in S_\infty(X)$.

To prove $\#\{\lambda \in \sigma_p(K) \mid |\lambda| \geq r\} < \infty$ for every $r > 0$, assume the converse and let $e_n \in X$: $Ke_n = \lambda_n e_n$, $\|e_n\| = 1$, $\lambda_n \in \sigma_p(K)$, $\lambda_n \neq \lambda_k$ for $k \neq n$.

Define $E_n := \text{span}\{e_1, \dots, e_n\} \quad \forall n$.

Observation: $E_{n+1} \supsetneq E_n \quad \forall n$.

Clearly $E_{n+1} \supset E_n$. If $E_{n+1} = E_n$ for some n , there exists the first such n . Then

$$\lambda_{n+1} e_{n+1} = \sum_{k=1}^n \lambda_{n+1} \alpha_k e_k$$

$$\lambda_{n+1}e_{n+1} = \sum_{k=1}^n d_k \lambda_k e_k$$

$$\Rightarrow 0 = \sum_{k=1}^n d_k (\lambda_{n+1} - \lambda_k) e_k \Rightarrow d_{n+1} - \lambda_n = 0 \\ \Rightarrow \lambda_{n+1} = \lambda_n \dots \text{contradiction}$$

\Rightarrow The observation is true.

Let's choose $y_{n+1} \in E_{n+1}$ such that $\|y_{n+1}\| = 1$, $\text{dist}(y_{n+1}, E_n) \geq \frac{r}{2}$
It remains to prove that $\{K_{y_n}\}$ does not have a convergent subsequence.

$$x_{n+1} = d_{n+1}e_{n+1} + R_n, \text{ where } R_n \in E_n$$

$$Ky_{n+1} - Ky_{m+1} = \lambda_{n+1}d_{n+1}e_{n+1} + \tilde{R}_n - \lambda_{m+1}d_{m+1}e_{m+1} - \tilde{R}_m$$

Assume that $n \geq m+1$, then

$$\begin{array}{c} \tilde{R}_n - \underbrace{\lambda_{m+1}d_{m+1}e_{m+1}}_{\substack{\in E_n \\ \in E_{m+1} \subset E_n}} + \tilde{R}_m \in E_n \\ \uparrow \quad \uparrow \quad \uparrow \\ E_n \quad E_{m+1} \subset E_n \quad E_m \subset E_n \end{array}$$

$$\begin{aligned} \Rightarrow \|Ky_{n+1} - Ky_{m+1}\| &\geq \text{dist}(\lambda_{n+1}d_{n+1}e_{n+1}, E_n) \\ &= |\lambda_{n+1}| \text{dist}(d_{n+1}e_{n+1}, E_n) \\ &= |\lambda_{n+1}| \text{dist}(y_{n+1}, E_n) \\ &\geq r \cdot \frac{1}{2} > 0 \end{aligned}$$

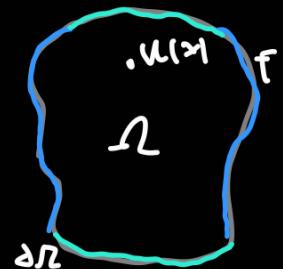
□

Scheme of the solution of Dirichlet problem in $\mathbb{R}^n, n \geq 3$, by means of Fredholm theory

Dirichlet problem: find $u \in C^2(\Omega) \cap C(\bar{\Omega})$ (Ω is a domain in \mathbb{R}^n)
 $\partial\Omega \in C^2$
such that

$$\begin{cases} \Delta u = 0 \\ u|_{\partial\Omega} \stackrel{(*)}{=} f \end{cases} \quad \text{where } f \in C(\partial\Omega)$$

Physics interpretation: heat



Scheme for solution: we search for a solution of the form

$$u(x) = \int_{\partial\Omega} K(x,y) \varphi(y) dy, \quad K(x,y) = c_n \frac{(x-y, n_y)}{\|x-y\|_{\mathbb{R}^n}^n}$$

n_y is the outward unit normal, $c_n \in \mathbb{R}$

$\Delta u = 0$ for every $\varphi \in C(\partial\Omega)$, we only need to find good φ (such that $(*)$ will hold)

$$u_\varphi(x) = -\varphi(x) + \int_{\partial\Omega} K(x,y) \varphi(y) dy \quad \text{if } x \in \partial\Omega$$

$$u_\varphi = (-I + K)\varphi, \quad K\varphi = \int K(x,y) \varphi(y) dy$$

To check that $\exists \varphi: u_\varphi = f$ on $\partial\Omega$ we just check that $K \in S_\infty(C(\partial\Omega))$ and $\text{Ker}(-I + K) = \{0\}$
 \Rightarrow we are done by Fredholm alternative.

This is hard to prove (course on PDEs)