15a. Operators on Hilbert spaces

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1. Boundedness, continuity, operator norms
2. Adjoints
3. Stable subspaces and complements
4. Spectrum, eigenvalues
5. Generalities on spectra
6. Positive examples
7. Cautionary examples
8. Weyl’s criterion for continuous spectrum

1. Boundedness, continuity, operator norms

A linear (not necessarily continuous) map \( T : X \to Y \) from one Hilbert space to another is bounded if, for all \( \varepsilon > 0 \), there is \( \delta > 0 \) such that \( |Tx|_Y < \varepsilon \) for all \( x \in X \) with \( |x|_X < \delta \).

[1.1] Proposition: For a linear, not necessarily continuous, map \( T : X \to Y \) of Hilbert spaces, the following three conditions are equivalent:
(i) \( T \) is continuous
(ii) \( T \) is continuous at 0
(iii) \( T \) is bounded

Proof: For \( T \) continuous as 0, given \( \varepsilon > 0 \) and \( x \in X \), there is small enough \( \delta > 0 \) such that \( |Tx' - 0|_Y < \varepsilon \) for \( |x' - 0|_X < \delta \). For \( |x'' - x|_X < \delta \), using the linearity,

\[
|Tx'' - Tx|_X = |T(x'' - x) - 0|_X < \delta
\]

That is, continuity at 0 implies continuity.

Since \( |x| = |x - 0| \), continuity at 0 is immediately equivalent to boundedness. ///

[1.2] Definition: The kernel \( \ker T \) of a linear (not necessarily continuous) linear map \( T : X \to Y \) from one Hilbert space to another is

\[
\ker T = \{x \in X : Tx = 0 \in Y\}
\]

[1.3] Proposition: The kernel of a continuous linear map \( T : X \to Y \) is closed.

Proof: For \( T \) continuous

\[
\ker T = T^{-1}\{0\} = X - T^{-1}(Y - \{0\}) = X - T^{-1}(\text{open}) = X - \text{open} = \text{closed}
\]

since the inverse images of open sets by a continuous map are open. ///

[1.4] Definition: The operator norm \( |T| \) of a linear map \( T : X \to Y \) is

\[
\text{operator norm } T = |T| = \sup_{x \in X : |x|_X \leq 1} |Tx|_Y
\]

[1.5] Corollary: A linear map \( T : X \to Y \) is continuous if and only if its operator norm is finite. ///
2. Adjoints

An adjoint $T^*$ of a continuous linear map $T : X \to Y$ from a pre-Hilbert space $X$ to a pre-Hilbert space $Y$ (if $T^*$ exists) is a continuous linear map $T^* : Y \to X$ such that

$$\langle Tx, y \rangle_Y = \langle x, T^*y \rangle_X$$

[2.1] Remark: When a pre-Hilbert space $X$ is not complete, that is, is not a Hilbert space, an operator $T : X \to Y$ may fail to have an adjoint.

[2.2] Theorem: A continuous linear map $T : X \to Y$ from a Hilbert space $X$ to a Hilbert space $Y$ has a unique adjoint $T^*$.

[2.3] Remark: In fact, the target space of $T$ need not be a Hilbert space, that is, need not be complete, but we will not use this.

Proof: For each $y \in Y$, the map

$$\lambda_y : X \to \mathbb{C}$$

given by

$$\lambda_y(x) = \langle Tx, y \rangle$$

is a continuous linear functional on $X$. By Riesz-Fréchet, there is a unique $x_y \in X$ so that

$$\langle Tx, y \rangle = \lambda_y(x) = \langle x, x_y \rangle$$

Try to define $T^*$ by $T^*y = x_y$. This is a well-defined map from $Y$ to $X$, and has the adjoint property

$$\langle Tx, y \rangle_Y = \langle x, T^*y \rangle_X.$$ 

To prove that $T^*$ is continuous, prove that it is bounded. From Cauchy-Schwarz-Bunyakowsky

$$|T^*y|^2 = |\langle T^*y, T^*y \rangle_X| = |\langle y, TT^*y \rangle_Y| \leq |y| \cdot |TT^*y| \leq |y| \cdot |T| \cdot |T^*y|$$

where $|T|$ is the operator norm. For $T^*y \neq 0$, divide by it to find

$$|T^*y| \leq |y| \cdot |T|$$

Thus, $|T^*| \leq |T|$. In particular, $T^*$ is bounded. Since $(T^*)^* = T$, by symmetry $|T| = |T^*|$. Linearity of $T^*$ is easy. ///

[2.4] Corollary: For a continuous linear map $T : X \to Y$ of Hilbert spaces, $T^{**} = T$. ///

An operator $T \in \text{End}(X)$ commuting with its adjoint is normal, that is,

$$TT^* = T^*T$$

This only applies to operators from a Hilbert space to itself. An operator $T$ is self-adjoint or hermitian if $T = T^*$. That is, $T$ is hermitian when

$$\langle Tx, y \rangle = \langle x, Ty \rangle \quad (\text{for all } x, y \in X)$$

An operator $T$ is unitary when

$$TT^* = \text{identity map on } Y \quad T^*T = \text{identity map on } X$$
There are simple examples in infinite-dimensional spaces where $TT^* = 1$ does not imply $T^*T = 1$, and vice-versa. Thus, it does not suffice to check something like $\langle Tx, Tx \rangle = \langle x, x \rangle$ to prove unitariness. Obviously hermitian operators are normal, as are unitary operators, using the more careful definition.

3. Stable subspaces and complements

Let $T : X \to X$ be a continuous linear operator on a Hilbert space $X$. A vector subspace $Y$ is $T$-stable or $T$-invariant if $Ty \in Y$ for all $y \in Y$. Often one is most interested in the case that the subspace be closed in addition to being invariant.

[3.1] Proposition: For $T : X \to X$ a continuous linear operator on a Hilbert space $X$, and $Y$ a $T$-stable subspace, $Y^\perp$ is $T^*$-stable.

Proof: For $z \in Y^\perp$ and $y \in Y$,

$$\langle T^* z, y \rangle = \langle z, T^{**} y \rangle = \langle z, Ty \rangle$$

since $T^{**} = T$, from above. Since $Y$ is $T$-stable, $Ty \in Y$, and this inner product is 0, and $T^* z \in Y^\perp$.

///

[3.2] Corollary: For continuous self-adjoint $T$ on a Hilbert space $X$, and $Y$ a $T$-stable subspace, both $Y$ and $Y^\perp$ are $T$-stable.

///

[3.3] Remark: Normality of $T : X \to X$ is insufficient to assure the conclusion of the corollary, in general. For example, with the two-sided $\ell^2$ space

$$X = \{ \{c_n : n \in \mathbb{Z}\} : \sum_{n \in \mathbb{Z}} |c_n|^2 < \infty \}$$

the right-shift operator

$$(Tc)_n = c_{n-1} \quad \text{(for n \in \mathbb{Z})}$$

has adjoint the left shift operator

$$(T^* c)_n = c_{n+1} \quad \text{(for n \in \mathbb{Z})}$$

and

$$T^* T = TT^* = 1_X$$

So this $T$ is not merely normal, but unitary. However, the $T$-stable subspace

$$Y = \{ \{c_n\} \in X : c_k = 0 \text{ for } k < 0 \}$$

is not $T^*$-stable, nor is its orthogonal complement $T$-stable.

On the other hand, adjoint-stable collections of operators have a good stability result:

[3.4] Proposition: Suppose for every $T$ in a set $A$ of bounded linear operators on a Hilbert space $V$ the adjoint $T^*$ is also in $A$. Then, for an $A$-stable subspace $W$ of $V$, the orthogonal complement $W^\perp$ is also $A$-stable.

Proof: For $y$ in $W^\perp$ and $T \in A$, for $x \in W$,

$$\langle x, Ty \rangle = \langle T^* x, y \rangle \in \langle W, y \rangle = \{0\}$$

since $T^* \in A$.  

///
4. Spectrum, eigenvalues

For a continuous linear operator $T \in \text{End}(X)$, the $\lambda$-eigenspace of $T$ is

$$X_\lambda = \{ x \in X :Tx = \lambda x \}$$

If this space is not simply $\{0\}$, then $\lambda$ is an eigenvalue.

[4.1] Proposition: An eigenspace $X_\lambda$ for a continuous linear operator $T$ on $X$ is a closed and $T$-stable subspace of $X$. For normal $T$ the adjoint $T^*$ acts by the scalar $\lambda$ on $X_\lambda$.

Proof: The $\lambda$-eigenspace is the kernel of the continuous linear map $T-\lambda$, so is closed. The stability is clear, since the operator restricted to the eigenspace is a scalar operator. For $v \in X_\lambda$, using normality,

$$\langle(T - \lambda)v, v\rangle = \langle T^*(T - \lambda)v, v\rangle = T^*v \cdot v = 0 = 0$$

Thus, $X_\lambda$ is $T^*$-stable. For $x, y \in X_\lambda$,

$$\langle(T^* - \lambda)x, y\rangle = \langle x, (T - \lambda)y\rangle = \langle x, 0 \rangle$$

Thus, $(T^* - \lambda)x = 0$. ///

[4.2] Proposition: For $T$ normal, for $\lambda \neq \mu$, and for $x \in X_\lambda, y \in X_\mu$, always $\langle x, y \rangle = 0$. For $T$ self-adjoint, if $X_\lambda \neq 0$ then $\lambda \in \mathbb{R}$. For $T$ unitary, if $X_\lambda \neq 0$ then $|\lambda| = 1$.

Proof: Let $x \in X_\lambda, y \in X_\mu$, with $\mu \neq \lambda$. Then

$$\lambda \langle x, y \rangle = \langle Tx, y \rangle = \langle x, T^*y \rangle = \langle x, \overline{\mu}y \rangle = \mu \langle x, y \rangle$$

invoking the previous result. Thus,

$$\langle \lambda - \mu \rangle \langle x, y \rangle = 0$$

giving the result. For $T$ self-adjoint and $x$ a non-zero $\lambda$-eigenvector,

$$\lambda \langle x, x \rangle = \langle x, T^*x \rangle = \langle x, Tx \rangle = \langle x, \lambda x \rangle = \lambda \langle x, x \rangle$$

Thus, $(\lambda - \overline{\lambda})\langle x, x \rangle = 0$. Since $x$ is non-zero, the result follows. For $T$ unitary and $x$ a non-zero $\lambda$-eigenvector,

$$\langle x, x \rangle = \langle T^*Tx, x \rangle = \langle Tx, Tx \rangle = |\lambda|^2 \cdot \langle x, x \rangle$$

///

In what follows, for a complex scalar $\lambda$ write simply $\lambda$ for scalar multiplication by $\lambda$ on a Hilbert space $X$.

[4.3] Definition: The spectrum $\sigma(T)$ of a continuous linear operator $T : X \rightarrow X$ on a Hilbert space $X$ is the collection of complex numbers $\lambda$ such that $T - \lambda$ does not have a continuous linear inverse.

[4.4] Definition: The discrete spectrum $\sigma_{\text{disc}}(T)$ is the collection of complex numbers $\lambda$ such that $T - \lambda$ fails to be injective. In other words, the discrete spectrum is the collection of eigenvalues.

[4.5] Definition: The continuous spectrum $\sigma_{\text{cont}}(T)$ is the collection of complex numbers $\lambda$ such that $T - \lambda \cdot 1_X$ is injective, does have dense image, but fails to be surjective.

[4.6] Definition: The residual spectrum $\sigma_{\text{res}}(T)$ is everything else: neither discrete nor continuous spectrum. That is, the residual spectrum of $T$ is the collection of complex numbers $\lambda$ such that $T - \lambda \cdot 1_X$ is injective, and fails to have dense image (so is certainly not surjective).
Remark: To see that there are no other possibilities, note that the Closed Graph Theorem implies that a bijective, continuous, linear map $T : X \to Y$ of Banach spaces has continuous inverse. Indeed, granting that the inverse exists as a linear map, its graph is
\[
\text{graph of } T^{-1} = \{(y, x) \in Y \times X : (x, y) \text{ in the graph of } T \subset X \times Y\}
\]
Since the graph of $T$ is closed, the graph of $T^{-1}$ is closed, and by the Closed Graph Theorem $T^{-1}$ is continuous.

The potential confusion of residual spectrum does not occur in many situations of interest

Proposition: A normal operator $T : X \to X$ has empty residual spectrum.

Proof: The adjoint of $T - \lambda$ is $T^* - \bar{\lambda}$, so consider $\lambda = 0$ to lighten the notation. Suppose that $T$ does not have dense image. Then there is non-zero $z$ such that
\[
0 = \langle z, Tx \rangle = \langle T^*z, x \rangle \quad \text{(for every } x \in X)\]
Therefore $T^*z = 0$, and the 0-eigenspace $Z$ of $T^*$ is non-zero. Since $T^*(Tz) = T(T^*z) = T(0) = 0$ for $z \in Z$, $T^*$ stabilizes $Z$. That is, $Z$ is both $T$ and $T^*$-stable. Therefore, $T = (T^*)^*$ acts on $Z$ by (the complex conjugate of) 0, and $T$ has non-trivial 0-eigenvectors, contradiction.

5. Generalities on spectra

It is convenient to know that spectra of continuous operators are non-empty, compact subsets of $\mathbb{C}$.

Knowing this, every non-empty compact subset of $\mathbb{C}$ is easily made to appear as the spectrum of a continuous operator, even normal ones, as below.

Proposition: The spectrum $\sigma(T)$ of a continuous linear operator $T : V \to V$ on a Hilbert space $V$ is bounded by the operator norm $|T|_{\text{op}}$.

Proof: For $|\lambda| > |T|_{\text{op}}$, an obvious heuristic suggests an expression for the resolvent $R_\lambda = (T - \lambda)^{-1}$:
\[
(T - \lambda)^{-1} = -\lambda^{-1} \cdot (1 - \frac{T}{\lambda})^{-1} = -\lambda^{-1} \cdot \left(1 + \frac{T}{\lambda} + \left(\frac{T}{\lambda}\right)^2 + \ldots\right)
\]
The infinite series converges in operator norm for $|T/\lambda|_{\text{op}} < 1$, that is, for $|\lambda| > |T|_{\text{op}}$. Then
\[
(T - \lambda) \cdot (-\lambda^{-1}) \cdot \left(1 + \frac{T}{\lambda} + \left(\frac{T}{\lambda}\right)^2 + \ldots\right) = 1
\]
giving a continuous inverse $(T - \lambda)^{-1}$, so $\lambda \notin \sigma(T)$.

Remark: The same argument applied to $T^n$ shows that $\sigma(T^n)$ is inside the closed ball of radius $|T^n|_{\text{op}}$.

By the elementary identity
\[
T^n - \lambda^n = (T - \lambda) \cdot (T^{n-1} + T^{n-2}\lambda + \ldots + T\lambda^{n-2} + \lambda^{n-2})
\]
$(T - \lambda)^{-1}$ exists for $|\lambda^n| > |T^n|_{\text{op}}$, that is, for $|\lambda| > |T^n|_{\text{op}}^{1/n}$. That is, $\sigma(T)$ is inside the closed ball of radius $\inf_{n \geq 1} |T^n|_{\text{op}}^{1/n}$. The latter expression is the spectral radius of $T$. This notion is relevant to non-normal operators, such as the Volterra operator, whose spectral radius is 0, while its operator norm is much larger.

Proposition: The spectrum $\sigma(T)$ of a continuous linear operator $T : V \to V$ on a Hilbert space $V$ is compact.

Proof: That \( \lambda \notin \sigma(T) \) is that there is a continuous linear operator \((T - \lambda)^{-1}\). We claim that for \( \mu \) sufficiently close to \( \lambda \), \((T - \mu)^{-1}\) exists. Indeed, a heuristic suggests an expression for \((T - \mu)^{-1}\) in terms of \((T - \lambda)^{-1}\). The algebra is helpfully simplified by replacing \( T \) by \( T + \lambda \), so that \( \lambda = 0 \). With \( \mu \) near 0 and granting existence of \( T^{-1} \), the heuristic is

\[
(T - \mu)^{-1} = (1 - \mu T^{-1})^{-1} = \left(1 + \mu T^{-1} + (\mu T^{-1})^2 + \ldots\right) \cdot T^{-1}
\]

The geometric series converges in operator norm for \(|\mu T^{-1}|_{op} < 1 \), that is, for \(|\mu| < |T^{-1}|_{op}^{-1} \). Having found the obvious candidate for an inverse,

\[
(1 - \mu T^{-1}) \cdot \left(1 + \mu T^{-1} + (\mu T^{-1})^2 + \ldots\right) = 1
\]

and

\[
(T - \mu) \cdot \left(1 + \mu T^{-1} + (\mu T^{-1})^2 + \ldots\right) \cdot T^{-1} = 1
\]

so there is a continuous linear operator \((T - \mu)^{-1}\), and \( \mu \notin \sigma(T) \). Having already proven that \( \sigma(T) \) is bounded, it is compact. ///

[5.4] Proposition: The spectrum \( \sigma(T) \) of a continuous linear operator on a Hilbert space \( V \neq \{0\} \) is non-empty.

Proof: The argument reduces the issue to Liouville’s theorem from complex analysis, that a bounded entire (holomorphic) function is constant. Further, an entire function that goes to 0 at \( \infty \) is identically 0.

Suppose the resolvent \( R_\lambda = (T - \lambda)^{-1} \) is a continuous linear operator for all \( \lambda \in \mathbb{C} \). The operator norm is readily estimated for large \( \lambda \):

\[
|R_\lambda|_{op} = |\lambda|^{-1} \cdot \left|1 + \frac{T}{\lambda} + \left(\frac{T}{\lambda}\right)^2 + \ldots\right|_{op}
\]

\[
\leq |\lambda|^{-1} \cdot \left(1 + \left|\frac{T}{\lambda}\right|_{op} + \left|\frac{T}{\lambda}\right|_{op}^2 + \ldots\right) = \frac{1}{|\lambda|} \cdot \frac{1}{1 - \frac{|T|_{op}}{|\lambda|}}
\]

This goes to 0 as \( |\lambda| \to \infty \). Hilbert’s identity asserts the complex differentiability as operator-valued function:

\[
\frac{R_\lambda - R_\mu}{\lambda - \mu} = R_\lambda \cdot \frac{(T - \mu) - (T - \lambda)}{\lambda - \mu} \cdot R_\mu = R_\lambda \cdot R_\mu \to R_\lambda^2 \quad \text{(as \( \mu \to \lambda \))}
\]

since \( \mu \to R_\mu \) is continuous for large \( \mu \), by the same identity:

\[
|R_\lambda - R_\mu|_{op} \leq |\lambda - \mu| \cdot |R_\mu| \cdot |R_\lambda|_{op}
\]

Thus, the scalar-valued functions \( \lambda \to \langle R_\lambda v, w \rangle \) for \( v, w \in V \) are complex-differentiable, and satisfy

\[
|\langle R_\lambda v, w \rangle| \leq |R_\lambda v| \cdot |w| \leq |R_\lambda|_{op} \cdot |v| \cdot |w| \leq \frac{1}{|\lambda|} \cdot \frac{1}{1 - \frac{|T|_{op}}{|\lambda|}} \cdot |v| \cdot |w|
\]

By Liouville, \( \langle R_\lambda v, w \rangle = 0 \) for all \( v, w \in V \), which is impossible. Thus, the spectrum is not empty. ///

[5.5] Proposition: The entire spectrum, both point-spectrum and continuous-spectrum, of a self-adjoint operator is a non-empty, compact subset of \( \mathbb{R} \). The entire spectrum of a unitary operator is a non-empty, compact subset of the unit circle.
Proof: For self-adjoint $T$, we claim that the imaginary part of $\langle (T - \mu)v, v \rangle$ is at least $\langle v, v \rangle$ times the imaginary part of $\mu$. Indeed, $\langle Tv, v \rangle$ is real, since

$$\langle Tv, v \rangle = \langle v, T^* v \rangle = \langle v, T v \rangle = \overline{\langle Tv, v \rangle}$$

so

$$\langle (T - \mu)v, v \rangle = \langle Tv, v \rangle - \mu \cdot \langle v, v \rangle$$

and

$$|\text{Im}(\langle (T - \mu)v, v \rangle)| = |\text{Im}\mu| \cdot |\langle v, v \rangle|$$

and by Cauchy-Schwarz-Bunyakowsky

$$|(T - \mu)v| \cdot |v| \geq |\langle (T - \mu)v, v \rangle| \geq |\text{Im}\mu| \cdot |\langle v, v \rangle| = |\text{Im}\mu| \cdot |v|^2$$

Dividing by $|v|$,

$$|(T - \mu)v| \geq |\text{Im}\mu| \cdot |v|$$

This inequality shows more than the injectivity of $T - \mu$. Namely, the inequality gives a bound on the operator norm of the inverse $(T - \mu)^{-1}$ defined on the image of $T - \mu$. The image is dense since $\mu$ is not an eigenvalue and there is no residual spectrum for normal operators $T$. Thus, the inverse extends by continuity to a continuous linear map defined on the whole Hilbert space. Thus, $T - \mu$ has a continuous linear inverse, and $\mu$ is not in the spectrum of $T$.

For $T$ unitary, $|Tv| = |v|$ for all $v$ implies $T|_{\text{op}} = 1$. Thus, $\sigma(T)$ is contained in the unit disk, by the general bound on spectra in terms of operator norms. From $(T - \lambda)^* = T^* - \overline{\lambda}$, the spectrum of $T^*$ is obtained by complex-conjugating the spectrum of $T$. Thus, for unitary $T$, the spectrum of $T^{-1} = T^*$ is also contained in the unit disk. At the same time, the natural

$$T - \lambda = -T \cdot (T^{-1} - \lambda^{-1}) \cdot \lambda$$

gives

$$(T - \lambda)^{-1} = -\lambda^{-1} \cdot (T^{-1} - \lambda^{-1})^{-1} \cdot T^{-1}$$

so $\lambda^{-1} \in \sigma(T^{-1})$ exactly when $\lambda \in \sigma(T)$. Thus, the spectra of both $T$ and $T^* = T^{-1}$ are inside the unit circle. \[///\]

[5.6] Remark:

6. Positive examples

Let $\ell^2$ be the usual space of square-summable sequences $(a_1, a_2, \ldots)$, with standard orthonormal basis

$$e_j = (0, \ldots, 0, 1, 0, \ldots)$$

1 at $j$th position

[6.1] Multiplication operators with specified eigenvalues Given a countable, bounded list of complex numbers $\lambda_j$, the operator $T : \ell^2 \to \ell^2$ by

$$T : (a_1, a_2, \ldots) \mapsto (\lambda_1 \cdot a_1, \lambda_2 \cdot a_2, \ldots)$$

has $\lambda_j$-eigenvector the standard basis element $e_j$. Clearly

$$T^* : (a_1, a_2, a_3, \ldots) \mapsto (\overline{\lambda}_1 \cdot a_1, \overline{\lambda}_2 \cdot a_2, \overline{\lambda}_3 \cdot a_3, \ldots)$$
so $T$ is normal, in the sense that $TT^* = T^*T$. To see that there are no other eigenvalues, suppose $Tv = \mu \cdot v$ with $\mu$ not among the $\lambda_j$. Then
\[
\mu \cdot \langle v, e_j \rangle = \langle Tv, e_j \rangle = \langle v, T^* e_j \rangle = \langle v, \overline{\lambda_j} e_j \rangle = \lambda_j \cdot \langle v, e_j \rangle
\]
Thus, $(\mu - \lambda_j) \cdot \langle v, e_j \rangle = 0$, and $\langle v, e_j \rangle = 0$ for all $j$. Since $e_j$ form an orthonormal basis, $v = 0$. ///

[6.2] Every compact subset of $\mathbb{C}$ is the spectrum of an operator
Grant for the moment a countable dense subset $\{\lambda_j\}$ of a non-empty compact subset $C$ of $\mathbb{C}$, and as above let
\[
T : (a_1, a_2, a_3, \ldots) \rightarrow (\lambda_1 \cdot a_1, \lambda_2 \cdot a_2, \lambda_3 \cdot a_3, \ldots)
\]
We saw that there are no further eigenvalues. Since spectra are closed, the closure $C$ of $\{\lambda_j\}$ is contained in $\sigma(T)$.

It remains to show that the continuous spectrum is no larger than the closure $C$ of the eigenvalues, in this example. That is, for $\mu \notin C$, exhibit a continuous linear $(T - \mu)^{-1}$.

For $\mu \notin C$, there is a uniform lower bound $0 < \delta \leq |\mu - \lambda_j|$. That is, $\sup_j |\mu - \lambda_j|^{-1} \leq \delta^{-1}$. Thus, the naturally suggested map
\[
(a_1, a_2, \ldots) \rightarrow ((\lambda_1 - \mu)^{-1} \cdot a_1, (\lambda_2 - \mu)^{-1} \cdot a_2, \ldots)
\]
is a bounded linear map, and gives $(T - \mu)^{-1}$.

[6.3] Two-sided shift has no eigenvalues
Let $V$ be the Hilbert space of two-sided sequences $(\ldots, a_{-1}, a_0, a_1, \ldots)$ with natural inner product
\[
\langle (\ldots, a_{-1}, a_0, a_1, \ldots), (\ldots, b_{-1}, b_0, b_1, \ldots) \rangle = \ldots + a_{-1}b_{-1} + a_0b_0 + a_1b_1 + \ldots
\]
The right and left two-sided shift operators are
\[
(R \cdot a)_n = a_{n-1} \quad \quad (L \cdot a)_n = a_{n+1}
\]
These operators are mutual adjoints, mutual inverses, so are unitary. Being unitary, their operator norms are 1, so their spectra are non-empty compact subsets of the unit circle.

They have no eigenvalues: indeed, for $Rv = \lambda \cdot v$, if there is any index $n$ with $v_n \neq 0$, then the relation $Rv = \lambda \cdot v$ gives $v_{n+k+1} = \lambda \cdot v_{n+k}$ for $k = 0, 1, 2, \ldots$. Since $|\lambda| = 1$, such a vector is not in $\ell^2$.

Nevertheless, we claim that $\lambda \in \sigma(L)$ for every $\lambda$ with $|\lambda| = 1$, and similarly for $R$. Indeed, for $\lambda$ not in the spectrum, there is a continuous linear operator $(L - \lambda)^{-1}$, so $|(L - \lambda)v| \geq \delta \cdot |v|$ for some $\delta > 0$. It is easy to make approximate eigenvectors for $L$ for any $|\lambda| = 1$: let
\[
v^{(\ell)} = (\ldots, 0, \ldots, 0, 1, \lambda, \lambda^2, \lambda^3, \ldots, \lambda^\ell, 0, 0, \ldots)
\]
Obviously it doesn’t matter where the non-zero entries begin. From
\[
(L - \lambda)v^{(\ell)} = (\ldots, 0, \ldots, 0, 1, 0, \ldots, 0, \lambda^{\ell+1}, 0, 0, \ldots)
\]
\[
|(L - \lambda)v^{(\ell)}| = \sqrt{1 + 1}, \text{ while } |v^{(\ell)}| = \sqrt{\ell + 1}. \text{ Thus, } |(L - \lambda)v^{(\ell)}|/|v^{(\ell)}| \rightarrow 0, \text{ and there can be no } (L - \lambda)^{-1}.
\]
Thus, every $\lambda$ on the unit circle is in $\sigma(R)$.

[3] To make a countable dense subset of $C$, for $n = 1, 2, \ldots$ cover $C$ by finitely-many disks of radius $1/n$, each meeting $C$, and in each choose a point of $C$. The union over $n = 1, 2, \ldots$ of these finite sets is countable and dense in $C$. 8
[6.4] Compact multiplication operators on $\ell^2$  For a sequence of complex numbers $\lambda_n \to 0$, we claim that the multiplication operator

$$T : (a_1, a_2, \ldots) \mapsto (\lambda_1 \cdot a_1, \lambda_2 \cdot a_2, \ldots)$$

is compact. We already showed that it has eigenvalues exactly $\lambda_1, \lambda_2, \ldots$, and spectrum the closure of $\{\lambda_j\}$. Thus, the spectrum includes 0, but 0 is an eigenvalue only when it appears among the $\lambda_j$, which may range from 0 times to infinitely-many times.

To prove that the operator is compact, we prove that the image of the unit ball is pre-compact, by showing that it is totally bounded. Given $\varepsilon > 0$, take $k$ such that $|\lambda_i| < \varepsilon$ for $i > k$. The ball in $\mathbb{C}^k$ of radius $\max\{|\lambda_j| : j \leq k\}$ is precompact, so has a finite cover by $\varepsilon$-balls, centered at points $v^1, \ldots, v^N$. For $v = (v_1, v_2, \ldots)$ with $|v| \leq 1$,

$$Tv = (\lambda_1 v_1, \lambda_2 v_2, \ldots, \lambda_k v_k, 0, 0, \ldots) + (0, \ldots, 0, \lambda_{k+1} v_{k+1}, \lambda_{k+2} v_{k+2}, \ldots)$$

With $v^j$ the closest of the $v^1, \ldots, v^N$ to $(\lambda_1 v_1, \lambda_2 v_2, \ldots, \lambda_k v_k, 0, 0, \ldots)$,

$$|Tv - v^j| < \varepsilon + |(0, \ldots, 0, \lambda_{k+1} v_{k+1}, \lambda_{k+2} v_{k+2}, \ldots)| < \varepsilon + \varepsilon \cdot |(0, \ldots, 0, v_{k+1}, v_{k+2}, \ldots)| \leq \varepsilon + \varepsilon |v| \leq 2\varepsilon$$

Thus, the image of the unit ball under $T$ is covered by finitely-many $2\varepsilon$-balls. ///

[6.5] Multiplication operators on $L^2[a, b]$  For $\varphi \in C^o[a, b]$, we claim that the multiplication operator

$$M_\varphi : L^2[a, b] \mapsto L^2[a, b]$$

by

$$M_\varphi f(x) = \varphi(x) \cdot f(x)$$

is normal, and has spectrum the image $\varphi[a, b]$ of $\varphi$. The eigenvalues are $\lambda$ such that $\varphi(x) = \lambda$ on a subset of $[a, b]$ of positive measure. The normality is clear, so, beyond eigenvalues, we need only examine continuous spectrum, not residual.

On one hand, if $\varphi(x) = \lambda$ on a set of positive measure, there is an infinite-dimensional sub-space of $L^2[0, 1]$ of functions supported there, and all these are eigenvectors. On the other hand, if $f \neq 0$ in $L^2[0, 1]$ and $\varphi(x) \cdot f(x) = \lambda \cdot f(x)$, even if $f$ is altered on a set of measure 0, it must be that $\varphi(x) = \lambda$ on a set of positive measure.

To understand the continuous spectrum, for $\varphi(x_o) = \lambda$ make approximate eigenvectors by taking $L^2$ functions $f$ supported on $[x_o - \delta, x_o + \delta]$, where $\delta > 0$ is small enough so that $|\varphi(x) - \varphi(x_o)| < \varepsilon$ for $|x - x_o| < \delta$. Then

$$|(M_\varphi - \lambda)f|_{L^2}^2 = \int |\varphi(x) - \lambda|^2 \cdot |f(x)|^2 \, dx \leq \varepsilon^2 \cdot |f|_{L^2}^2$$

Thus, $\inf_{f \neq 0} |(M_\varphi - \lambda)f|_{L^2} / |f|_{L^2} = 0$, so $M_\varphi - \lambda$ is not invertible. If $\lambda$ is not an eigenvalue, it is in the continuous spectrum. On the other hand, if $\varphi(x) \neq \lambda$, then there is some $\delta > 0$ such that $|\varphi(x) - \lambda| \geq \delta$ for all $x \in [0, 1]$, by the compactness of $[0, 1]$. Then

$$|(M_\varphi - \lambda)f|_{L^2}^2 = \int_0^1 |\varphi(x) - \lambda|^2 \cdot |f(x)|^2 \, dx \geq \int_0^1 \delta^2 \cdot |f(x)|^2 \, dx = \delta^2 \cdot |f|_{L^2}^2$$

Thus, there is a continuous inverse $(M_\varphi - \lambda)$, and $\lambda$ is not in the spectrum.
7. Cautionary examples: non-normal operators

[7.1] Shift operators on one-sided $\ell^2$ We claim the following: The right-shift

$$R : (a_1, a_2, \ldots) \rightarrow (0, a_1, a_2, \ldots)$$

and the left-shift

$$L : (a_1, a_2, a_3, \ldots) \rightarrow (a_2, \ldots)$$

are mutual adjoints. These operators are not normal, since $L \circ R = 1_{\ell^2}$ but $R \circ L : (a_1, a_2, \ldots) \rightarrow (0, a_2, \ldots)$

The eigenvalues of the left-shift $L$ are all complex numbers in the open unit disk in $\mathbb{C}$. In particular, there is a continuum of eigenvalues and eigenvectors, so they cannot be mutually orthogonal. The spectrum $\sigma(L)$ is the closed unit disk.

The right-shift $R$ has no eigenvalues, has continuous spectrum the unit circle, and residual spectrum the open unit disk with 0 removed.

Indeed, suppose

$$(0, a_1, a_2, \ldots) = R(a_1, a_2, \ldots) = \lambda \cdot (a_1, a_2, \ldots)$$

With $n$ the lowest index such that $a_n \neq 0$, the $n^{th}$ component in the eigenvector relation gives $0 = a_{n-1} = \lambda \cdot a_n$, so $\lambda = 0$. Then, the $(n+1)^{th}$ component gives $a_n = \lambda \cdot a_{n+1} = 0$, contradiction. This proves that $R$ has no eigenvalues.

Oppositely, for $|\lambda| < 1$,

$$L(1, \lambda, \lambda^2, \ldots) = (\lambda, \lambda^2, \ldots) = \lambda \cdot (1, \lambda, \lambda^2, \ldots)$$

so every such $\lambda$ is an eigenvector for $L$. On the other hand, for $|\lambda| = 1$, in an eigenvector relation

$$(a_2, \ldots) = L(a_1, a_2, \ldots) = \lambda \cdot (a_1, a_2, \ldots)$$

let $n$ be the smallest index $n$ with $a_n \neq 0$. Then $a_{n+1} = \lambda \cdot a_n$, $a_{n+2} = \lambda \cdot a_{n+1}$, $\ldots$, so

$$(a_1, a_2, \ldots) = (0, \ldots, 0, a_n, \lambda a_n, \lambda^2 a_n, \ldots)$$

But this is not in $\ell^2$ for $|\lambda| = 1$ and $a_n \neq 0$, so $\lambda$ on the unit circle is not an eigenvalue.

For $|\lambda| = 1$, we can make approximate $\lambda$-eigenvectors for $L$ by

$$v^{[N]} = (1, \lambda, \lambda^2, \ldots, \lambda^N, 0, 0, \ldots)$$

since

$$(L - \lambda) v^{[N]} = (\lambda, \lambda^2, \ldots, \lambda^N, 0, 0, 0, \ldots) - \lambda \cdot (1, \lambda, \lambda^2, \ldots, \lambda^N, 0, 0, \ldots) = (0, 0, \ldots, 0, 0, \lambda^{N+1}, 0, 0, \ldots)$$

Since

$$\frac{|(L - \lambda)v^{[N]}|}{|v^{[N]}|} = \frac{|\lambda|^{N+1}}{(1 + |\lambda|^2 + \ldots + |\lambda|^{2N})^{1/2}} = \frac{1}{\sqrt{N+1}} \rightarrow 0$$

there can be no continuous $(L - \lambda)^{-1}$. Thus, $\lambda$ on the unit circle is in the spectrum, but not in the point spectrum.
That the unit circle is in the spectrum also follows from the observation above that all \( \lambda \) with \( |\lambda| < 1 \) are eigenvalues, and the fact that the spectrum is closed.

The spectrum of \( L \) is bounded by the operator norm \( |L|_{op} \), and \( |L|_{op} \) is visibly 1, so is nothing else in the spectrum.

To see that the unit circle is the continuous spectrum of \( L \), as opposed to residual, we show that \( L - \lambda \) has dense image for \( |\lambda| = 1 \). Indeed, for \( w \) such that, for all \( v \in \ell^2 \),

\[
0 = \langle (L - \lambda)v, w \rangle = \langle v, (L^* - \overline{\lambda})w \rangle = \langle v, (R - \overline{\lambda})w \rangle
\]

we would have \((R - \overline{\lambda})w = 0\). However, we have seen that \( R \) has no eigenvalues. Thus, \( L - \lambda \) always has dense image, and the unit circle is continuous spectrum for \( L \).

Reversing that discussion, every \( \lambda \) with \( |\lambda| < 1 \) is in the residual spectrum of \( R \), because such \( \lambda \) is not an eigenvalue, and \( R - \lambda \) does not have dense image: for \( w \) a \( \overline{\lambda} \)-eigenvector for \( L \),

\[
\langle (R - \lambda)v, w \rangle = \langle v, (R^* - \overline{\lambda})w \rangle = \langle v, (L - \overline{\lambda})w \rangle = \langle v, 0 \rangle = 0
\]

That is, the image \((R - \lambda)^2\) is in the orthogonal complement to the eigenvector \( w \). The same computation shows that the unit circle is continuous spectrum for \( R \), because it is not eigenvalues for \( L \).

[7.2] **Volterra operator** We will show that the Volterra operator \( Vf(x) = \int_0^x f(t) dt \) on \( L^2[0,1] \) is not self-adjoint, that its spectrum is \{0\}, and that it has no eigenvalues.

As in the next chapter, since the Volterra operator is given by an \( L^2 \) integral kernel, it is Hilbert-Schmidt, hence compact.

A relation \( Tf = \lambda \cdot f \) for \( f \in L^2 \) and \( \lambda \neq 0 \) implies \( f \) is continuous:

\[
|\lambda| \cdot |f(x + h) - f(x)| = |Tf(x + h) - Tf(x)| \leq \int_x^{x+h} |f(t)| dt = \leq |h|^{\frac{1}{2}} \cdot |f|_{L^2}
\]

The fundamental theorem of calculus would imply \( f \) is continuously differentiable and \( \lambda \cdot f' = (Tf)' = f \). Thus, \( f \) would be a constant multiple of \( e^{x/\lambda} \), by the mean value theorem. However, by Cauchy-Schwarz-Bunyakowsky, for a \( \lambda \)-eigenfunction

\[
|\lambda| \cdot |f(x)| \leq |x|^{\frac{1}{2}} \cdot |f|_{L^2}
\]

No non-zero multiple of the exponential satisfies this. Thus, there are no eigenvectors for non-zero eigenvalues.

For \( f \in L^2[0,1] \) and \( Tf = 0 \in L^2[0,1] \), \( Tf \) is almost everywhere 0. Since \( x \to Tg(x) \) is unavoidably continuous, \( Tf(x) \) is 0 for all \( x \). Thus, for all \( x, y \) in the interval,

\[
0 = 0 - 0 = Tf(y) - Tf(x) = \int_x^y f(t) dt
\]

That is, \( x \to Tf(x) \) is orthogonal in \( L^2[0,1] \) to all characteristic functions of intervals. Finite linear combinations of these are dense in \( C^0[0,1] \) in the \( L^2 \) topology, and \( C^0[0,1] \) is dense in \( L^2[0,1] \). Thus \( f = 0 \), and there are no eigenvectors for the Volterra operator.

To see that the spectrum is at most \{0\}, show that the spectral radius is 0:

\[
T^n f(x) = \int_0^x \int_0^{x_{n-1}} \cdots \int_0^{x_2} \int_0^{x_1} f(t) dt dx_1 \cdots dx_{n-1} = \int_0^x f(t) \left( \int_t^x \int_t^{x_{n-1}} \cdots \int_t^{x_2} dx_1 \cdots dx_{n-1} \right) dt
\]

\[
= \int_0^x f(t) \cdot \frac{(x - t)^{n-1}}{(n-1)!} dt
\]
From this, \(|T^n|_{op} \leq \frac{1}{n^2}\), and
\[
\log \lim_{2n} \left( \frac{1}{(2n)!} \right)^{1/2n} = -\lim_{2n} \frac{1}{2n} \log(2n)! = -\lim_{2n} \frac{1}{2n} \sum_{1 \leq k \leq 2n} \log k
\]
\[
= -\lim_{2n} \frac{1}{2n} \sum_{1 \leq k \leq n} (\log k + \log(2n - k + 1)) \leq -\lim_{2n} \frac{1}{2n} \sum_{1 \leq k \leq n} (\log k + \log(2n - k + 1))
\]
\[
\leq -\lim_{2n} \frac{1}{2n} \sum_{1 \leq k \leq n} \log 2n = -\lim_{2n} \log(2n) = -\infty
\]
since \(k(2n - k) \geq 2n\) for \(1 \leq k \leq n\), noting the sign. That is, \(\lim_n |T^n|_{op}^{1/n} = 0\), so the spectral radius is 0. Since the spectrum is non-empty, it must be exactly \(\{0\}\).

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8. Weyl’s criterion for continuous spectrum

H. Weyl gave a criterion for continuous spectrum analogous to the definition of discrete spectrum. This criterion is decisive for normal operators.

For \(\lambda \in \mathbb{C}\), a sequence \(\{v_n\}\) of vectors (normalized so that all their lengths are 1 or at least bounded away from 0) in the Hilbert space \(V\) such that \((T - \lambda)v_n \to 0\) as \(n \to +\infty\) is an approximate eigenvector for \(\lambda\).

[8.1] **Theorem:** For \(\lambda\) not an eigenvalue for \(T\), and for \((T - \lambda)V\) not closed, \(\lambda\) is in the spectrum of \(T\) if and only if \(\lambda\) has an approximate eigenvector.

[8.2] **Remark:** This criterion is not uniformly reliable for detecting residual spectrum, which is why we must impose a further condition. [2] For example, we have seen that, for \(T : V \to V\) a norm linear operator, for \(\lambda\) in the spectrum but not an eigenvalue, \((T - \lambda)V\) is dense in \(V\) but is not all of \(V\). Thus, the hypothesis of the theorem is met for normal \(T\). We give an example of failure to detect residual spectrum after the proof.

**Proof:** Certainly if \(\lambda\) is an eigenvector, with non-zero eigenvalue \(v\), the constant sequence \(v, v, v, \ldots\) fits the requirement.

For general spectrum, let \(S = T - \lambda\). For \(v_1, v_2, \ldots\) with \(|v_n| = 1\) and \(Sv_n \to 0\), any alleged (continuous [3]) \(S^{-1}\) would give, interchanging \(S^{-1}\) and the limit by continuity,
\[
0 = S^{-1}(\lim_n Sv_n) = \lim_n S^{-1}Sv_n = \lim_n v_n
\]
contradiction. Thus, existence of an approximate eigenvector for \(T - \lambda\) implies that \(T - \lambda\) is not invertible.

Conversely, for \(S = T - \lambda\) not invertible, but \(\lambda\) not an eigenvector, then \(S\) is injective but not surjective. We further assume that the image of \(S\) is not closed. [4] In that case, \(S\) is injective, not surjective, and

[2] Recall that residual spectrum of \(T\) is \(\lambda\) such that \(T - \lambda\) is injective, but does not have dense image.

[3] Recall that when there is an everywhere-defined, linear inverse \(S^{-1}\) to \(S\), necessarily \(S\) is a continuous bijection, and by the open mapping theorem \(S\) is open. That is, there is \(\delta > 0\) such that \(|Sv| \geq \delta \cdot |v|\) for all \(v\). This exactly asserts the boundedness of \(S^{-1}\), so \(S^{-1}\) is continuous.

[4] The image is not closed, for example, when \(T\) (hence \(S\)) has no residual spectrum, which is the case when \(T\) (hence \(S\)) is normal, or self-adjoint.
by non-closedness of the image there is \( v_o \) (with \( |v_o| = 1 \)) not in the image of \( S \), and \( v_1, v_2, \ldots \) such that \( Sv_1, Sv_2, \ldots \to v_o \). If \( \{v_n\} \) were a Cauchy sequence, then it would have a limit, and by continuity of \( S \)

\[
v_o = \lim_n Sv_n = S(\lim_n v_n)
\]

and \( v_o \) would be in the image of \( S \), contradicting our assumption. Thus, \( \{v_n\} \) is not Cauchy. In particular, we can replace \( \{v_n\} \) by a subsequence such that there is \( \delta > 0 \) such that \( |v_m - v_n| \geq \delta \) for all \( m \neq n \). Then \( w_n = v_n - v_{n+1} \) forms an approximate 0-eigenvector, since their lengths are bounded away from 0, and

\[
Sw_n = S(v_n - v_{n+1}) = Sv_n - Sv_{n+1} \to v_o - v_o = 0
\]
as desired.

[8.3] **Remark:** As noted, the case that \( \lambda \) is not an eigenvector, \( T - \lambda \) is not surjective, and/but the image of \( S = T - \lambda \) is closed, can only occur for non-normal \( T \). For example, \( T : \ell^2 \to \ell^2 \) by

\[
T(c_1, c_2, \ldots) = (c_1, 0, c_2, 0, c_3, 0, \ldots)
\]
is injective, not surjective, and has closed image. It is not invertible, but there is no approximate eigenvector for 0, so the criterion fails in this (non-normal) example.