Spectraltheory

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Contents

Chapter I

Unbounded, adjoint and self-adjoint operators

Let H be a separable Hilbert space, i.e. a real or complex inner product space that is also a complete metric space with respect to the distance function induced by the inner product $\langle \cdot, \cdot \rangle$ on H.

Recall: A mapping $\langle \cdot, \cdot \rangle \colon H \times H \to \mathbb{C}$ is called an **inner product**, if for all $x, y \in H$, $\lambda \in \mathbb{C}$ holds:

(S1) $\langle x_1 + x_2, y \rangle = \langle x_1, y \rangle + \langle x_2, y \rangle$, $\langle x, y_1 + y_2 \rangle = \langle x, y_1 \rangle + \langle x, y_2 \rangle$

(S2) $\langle \lambda x, y \rangle = \lambda \langle x, y \rangle$, $\langle x, \lambda y \rangle = \overline{\lambda} \langle x, y \rangle$

(S3) $\langle x, y \rangle = \overline{\langle y, x \rangle}$

(S4) $\langle x, x \rangle \geq 0, \quad \langle x, x \rangle = 0 \iff x = 0$

A linear operator T in H is a linear map

$$u \mapsto Tu$$

defined on a subspace $\mathcal{D}(T)$ of H, and we call $\mathcal{D}(T)$ the **domain** of T. For $T \colon \mathcal{D}(T) \to H$ we denote the **range** of T with

$$\mathcal{R}(T) \coloneqq \mathrm{Image}(T).$$

We say that T is **bounded** if it is continuous from $\mathcal{D}(T)$ into H, with respect to the topology induced by H. We recall that if $\mathcal{D}(T) = H$ holds, boundedness of a linear operator is equivalent to continuity in 0, boundedness of $T(U_{(X,\|\cdot\|)})$ in Y and that there $\exists c < \infty$ such that $\|Tx\| \leq c\|x\|$, for proof see theorem 3.3 in the functional analysis course.

From now on, if $\mathcal{D}(T) \neq H$ we will assume that $\mathcal{D}(T)$ is **dense** in H, i.e. $\overline{\mathcal{D}(T)} = H$. If in this case T would be bounded then T has a unique continuous extension to all of H, for proof see proposition 5.10 in the functional analysis course. As this simplifies many considerations some of the following theorems would be trivial, and hence, we won't focus on bounded operators during this lecture.

Recall: An operator is called **closed** if the graph

$$G(T) := \left\{(x, y) \in H \times H \;\middle|\; x \in \mathcal{D}(T), y = Tx\right\}$$

is closed in $H \times H$.

Definition I.1: *Let $T \colon \mathcal{D}(T) \to H$ be a (linear) operator with $\mathcal{D}(T)$ dense in H. Then T is called **closed** if for all*

$$u_n \in \mathcal{D}(T),\; u_n \to u \in H \text{ and } Tu_n \to v \in H$$

follows that

$$u \in \mathcal{D}(T),\; v = Tu$$

holds.

Example:

a) Let $H = L^2(\mathbb{R}^n)$, then $\mathcal{D}(T_0) = C_c^\infty(\mathbb{R}^n)$ is dense in H. Define the operator

$$T_0 = -\Delta,$$

and take $u \in W^{2,2}(\mathbb{R}^n) \setminus C_c^\infty(\mathbb{R}^n)$, s.t $u \in L^2(\mathbb{R}^n)$. Due to the density:

$$\exists\; (u_n)_{n\in\mathbb{N}} \subseteq C_c^\infty(\mathbb{R}^n)\colon\; u_n \to u \text{ in } W^{2,2}(\mathbb{R}^n).$$

As a result, $(u_n, -\Delta u_n) \in G(T_0)$ converges in $L^2 \times L^2$ to $(u, -\Delta u) \notin G(T_0)$.

b) Let $H = L^2(\mathbb{R}^n)$, and set $\mathcal{D}(T_1) = W^{2,2}(\mathbb{R}^n) \subseteq H$. Define the operator

$$T_1 = -\Delta.$$

For $(u_n)_{n\in\mathbb{N}} \subseteq \mathcal{D}(T_1)$ with

$$u_n \to u \in H \text{ and } (-\Delta u_n) \to v \in L^2$$

follows that $-\Delta u = v \in L^2(\mathbb{R}^n)$ weakly, i.e. for all $\varphi \in C_c^\infty(\mathbb{R}^n)$:

$$\int_{\mathbb{R}^n} v\varphi \longleftarrow \int_{\mathbb{R}^n} (-\Delta u_n)\,\varphi = \int_{\mathbb{R}^n} u_n\,(-\Delta\varphi) \longrightarrow \int_{\mathbb{R}^n} u\,(-\Delta\varphi)\,.$$

$\overset{PDE}{\Longrightarrow} u \in W^{2,2}(\mathbb{R}^n) = \mathcal{D}(T_1) \Rightarrow T_1$ is closed.

Definition I.2: *An operator T is called **closable** $\iff$ $\overline{G(T)}$ is a graph.*

Remark: We call $\overline{T}$ the **closure** of T, and in such case we have

$$\mathcal{D}\left(\overline{T}\right) := \left\{x \in H \;\middle|\; \exists\, y\colon (x,y) \in \overline{G(R)}\right\}$$

For any $x \in \mathcal{D}\left(\overline{T}\right)$ the assumption that $\overline{G(T)}$ is a graph implies that y is unique and hence

$$\Rightarrow G(\overline{T}) = \overline{G(T)},\ \overline{T}x := y$$

Equivalently, $\mathcal{D}\left(\overline{T}\right)$ is the set of all $x \in H$ such that there exists a sequence $x_n \in \mathcal{D}(T)$ with $x_n \to x$ in H and Tx_n is a cauchy sequence. For such x we define

$$\overline{T}x := \lim_{n\to\infty} Tx_n$$

Example: Let $T_0 := -\Delta$, $\mathcal{D}(T_0) = C_c^\infty(\mathbb{R}^n)$ is closable with $\overline{T_0} = T_1$.

Proof: Let $u \in L^2(\mathbb{R}^n)$ such that there exists $(u_n)_{n\in\mathbb{N}} \subseteq C_c^\infty(\mathbb{R}^n)$ with $u_n \to u$ in L^2 and $-\Delta u_n \to u$ in L^2, as above:

$$-\Delta u = v \in L^2$$

For a given u the function v is unique, and hence, T_0 is closable. Let $\overline{T_0}$ be the closure with domain $\mathcal{D}\left(\overline{T_0}\right)$ and $u \in \mathcal{D}(T_0)$

$$\Rightarrow \Delta u \in L^2 \Rightarrow u \in W^{2,2}(\mathbb{R}^n) = \mathcal{D}(T_1) \Rightarrow \mathcal{D}\left(\overline{T_0}\right) \subseteq \mathcal{D}(T_1)$$

but $C_c^\infty(\mathbb{R}^n)$ is dense in $\mathcal{D}(T_1) = W_{2,2}(\mathbb{R}^n)$

$$\Rightarrow W^{2,2}(\mathbb{R}^n) \subseteq \mathcal{D}\left(\overline{T_0}\right) \Rightarrow \mathcal{D}\left(\overline{T_0}\right) = \mathcal{D}(T_1)$$

$\Rightarrow T_1 = \overline{T_0}$. $\square$

Remark: Assume for a second in the example above that $W^{2,2} \not\subseteq \mathcal{D}(T_0)$ holds:

$$\Rightarrow \exists u \in W^{2,2} \setminus D\left(\overline{T_0}\right),\ \exists (u_n)_{n\in\mathbb{N}} \in C_c^\infty(\mathbb{R}^n) : u_n \to u \text{ in } W^{2,2},$$

using the same arguments as in the example above $\Rightarrow \overline{T_0}$ not closed!

Recall: If $T\colon H \to H$ is bounded then T^* is defined through

$$\langle u, T^*v\rangle = \langle Tu, v\rangle,\ \forall u, v \in H$$

$u \mapsto \langle Tu, v\rangle$ defines a continuous linear map on H $(\in H')$. Riesz' representation theorem then ensures the existence of T^*.

Definition I.3: *If T is an unbounded operator on H with dense domain we define*

$$\mathcal{D}(T^*) \coloneqq \left\{v \in H\colon \mathcal{D}(T) \ni u \mapsto \langle Tu, v\rangle \text{ can be extended as a linear continuous form on } H\right\}$$

Using Riesz' representation theorem $\exists! f \in H$:

$$\langle u, f\rangle = \langle Tu, v\rangle,\ \forall u \in \mathcal{D}(T)$$

then define $T^*v = f$, where the uniqueness follows from the density of $\mathcal{D}(T)$ in H.

Remark: If $\mathcal{D}(T) = H$ and T is bounded then we recover the "old" adjoint.

Example: $T_0^* = T_1$,

$$\begin{aligned}\mathcal{D}(T_0^*) &= \left\{v \in L^2(\mathbb{R}^n)\colon C_c^\infty(\mathbb{R}^n) \ni u \mapsto \langle -\Delta u, v\rangle \text{ extendable as a lin. continuous form on } L^2(\mathbb{R}^n)\right\}\\ &= \left\{v \in L^2(\mathbb{R}^n)\colon -\Delta v \in L^2(\mathbb{R}^n)\right\} = W^{2,2}(\mathbb{R}^n) = \mathcal{D}(T_1)\end{aligned}$$

Damit ist

$$\langle T_1 u, v\rangle = \langle -\Delta u, v\rangle = \int v\,(-\Delta u) = \int (-\Delta v)\,u = \langle u, T_1 v\rangle$$

Theorem I.1: *T^* is a closed operator.*

Proof: $v_n \in \mathcal{D}(T^*)$ such that $v_n \to v$ in H and $T^* v_n \to w^*$ in H for $(v, w^*) \in H \times H$. For all $u \in \mathcal{D}(T)$ we have

$$\langle Tu, v\rangle = \lim_{n\to\infty} \langle Tu, v_n\rangle = \lim_{n\to\infty} \langle u, T^* v_n\rangle = \langle u, w^*\rangle$$

$(H \ni u \mapsto \langle u, w^*\rangle$ is continuous$) \Rightarrow v \in \mathcal{D}(T^*)$ and $w^* = T^* v$ by definition. □

Theorem I.2: *Let T be an operator in H with domain $\mathcal{D}(T)$. Then*

$$G(T^*) = \left(V\left(\overline{G(T)}\right)\right)^{\perp}$$

where $V\colon H \times H \to H \times H, V(x, y) = (y, -x)$ $(V^2 = -\mathbb{I})$.

Proof: Let $u \in \mathcal{D}(T), (v, w^*) \in H \times H$

$$\Rightarrow \langle V(u, Tu), (v, w^*)\rangle_{H\times H} = \langle Tu, v\rangle - \langle u, w^*\rangle$$

Considering the right-hand side it follows

$$\langle Tu, v\rangle - \langle u, w^*\rangle = 0\, \forall u \in \mathcal{D}(T) \iff v \in \mathcal{D}(T^*) \text{ and } w^* = T^* v \iff (v, w^*) \in G(T^*),$$

and considering the left-hand side:

$$\Rightarrow \langle V(u, Tu), (v, w^*)\rangle_{H\times H} = 0\ \forall u \in \mathcal{D}(T) \iff (v, w^*) \in V(G(T))^{\perp}$$

In general: $U^{\perp} = \overline{U}^{\perp}$, and hence

$$\Rightarrow V(G(T))^{\perp} = \left(\overline{V(G(T))}\right)^{\perp} = \left(V\left(\overline{G(T)}\right)\right)^{\perp}.$$

□

Theorem I.3: *Let T be a closable operator. Then:*

a) $\mathcal{D}(T^*)$ is dense in H

b) $T^{**} := (T^*)^* = \overline{T}$

Proof:

a) Proof through contradiction: $D(T^*)$ not dense in $H \to \exists w \neq 0 : \langle w, v\rangle = 0\ \forall v \in \overline{\mathcal{D}(T^*)}$

$$\begin{aligned}
&\Longrightarrow \langle (0,w), (T^*v, -v)\rangle_{H\times H} = 0\ \forall v \in \mathcal{D}(T^*)\\
&\Longrightarrow (0,w) \perp V(G(T^*))\\
&\xrightarrow[I.2]{Thm} V\left(\overline{G(T)}\right) = G(T^*)^{\perp}\\
&\Longrightarrow V\left(G(T^*)^{\perp}\right) = \overline{G(T)}
\end{aligned}$$

For any $M \subseteq H \times H$ we have $V\left(M^{\perp}\right) = V(M)^{\perp}$ since for $(u,v) \in V(M)^{\perp}$, $(x,y) \in M$

$$\langle V(u,v), (x,y)\rangle_{H\times H} = -\langle (u,v), V(x,y)\rangle_{H\times h} \Rightarrow V(u,v) \in M^{\perp} \Rightarrow (u,v) \in V\left(M^{\perp}\right)$$

$$\Longrightarrow V(G(T^*))^{\perp} = \overline{G(T)} = G\left(\overline{T}\right) \Longrightarrow (0,w) \in G\left(\overline{T}\right) \Longrightarrow w = 0$$

b) $G(T^{**}) \overset{Thm}{\underset{I.2}{=}} V\left(\overline{G(T^*)}\right)^{\perp} \overset{Thm}{\underset{I.1}{=}} V(G(T^*))^{\perp} \overset{(\perp)}{=} G\left(\overline{T}\right) \Longrightarrow \mathcal{D}(T^{**}) = \mathcal{D}\left(\overline{T}\right), T^{**} = \overline{T}$

□

Definition I.4: *We say $T\colon \mathcal{D}(T) \to H$ is **symmetric** if and only if*

$$\langle Tu, v\rangle = \langle u, Tv\rangle \quad \forall u, v \in \mathcal{D}(T)$$

Example: $T_0 = -\Delta$, $\mathcal{D}(T_0) = C_c^{\infty}(\mathbb{R}^n)$

$$\int_{\mathbb{R}^n} (-\Delta u)\, v = \int_{\mathbb{R}^n} u\,(-\Delta v)$$

Remark: If T is symmetric $\Rightarrow \mathcal{D}(T) \subseteq \mathcal{D}(T^*)$ and

$$Tu = T^*u \quad \forall u \in \mathcal{D}(T)$$

$\Rightarrow (T^*, \mathcal{D}(T^*))$ is an extension of $(T, \mathcal{D}(T))$.

Lemma I.1: *A symmetric operator T is closable.*

Proof: It suffice to show that for $u_n \in \mathcal{D}(T)$ with $u_n \to 0$ and $Tu_n \to x \in H$ we have $x = 0$

$$\langle x, v\rangle \leftarrow \langle Tu_n, v\rangle = \langle u_n, Tv\rangle \to \langle 0, Tu\rangle = 0 \quad \forall v \in \mathcal{D}(T)$$

$\Rightarrow x = 0$. □

Remark: The proof actually shows that if $\mathcal{D}(T^*)$ is dense in H, then T is closable.

Definition I.5: *We call an operator T self-adjoint if*

$$T = T^* \text{ and } Tu = T^*u \quad \forall u \in \mathcal{D}(T),$$

note that the first property implies that $\mathcal{D}(T) = \mathcal{D}(T^*)$.

Theorem I.4: *Every self-adjoint operator is closable.*

Proof: Lemma I.1 □

Theorem I.5: *Let T be an invertible self-adjoint operator, then T^{-1} is also self-adjoint.*

Proof: For $T\colon \mathcal{D}(T) \to \mathcal{R}(T)$ consider

Step 1 $\mathcal{R}(T)$ is dense in H. We have to show that $\mathcal{R}(T)^{\perp} = \{0\}$.
Let $w \in H$ such that

$$\langle Tu, w\rangle = 0\ \forall u \in \mathcal{D}(T)$$

$\Longrightarrow w \in \mathcal{D}(T^*)$ and $T^*w = 0 \underset{s.a.}{\overset{inj.}{\Longrightarrow}} w = 0$.

Step 2 Let $w\colon H \times H \to H \times H$, $w(x,y) = (y,x)$

$$\Longrightarrow G\left(T^{-1}\right) = \left\{ \left(x, T^{-1}x\right) : x \in \mathcal{D}(T) \right\} = w(G(T)) = \left\{ (Ty, y) : y \in \mathcal{D}(T) \right\}$$

$$\begin{aligned} G\left(T^{-1}\right) &= G\left((T^*)^{-1}\right) \underset{Thm.I.2}{\overset{Proof}{=}} w\left(V\left(G(T)^{\perp}\right)\right) \\ &= V\left(w(G(T))^{\perp}\right) = V(w(G(T)))^{\perp} \\ &= V\left(G\left(T^{-1}\right)\right)^{\perp} \underset{I.2}{\overset{Thm.}{=}} G\left(\left(T^{-1}\right)^*\right) \end{aligned}$$

$\Rightarrow T^{-1} = (T^{-1})^*$

□

Chapter II

Representation Theorems

Theorem II.1 (Riesz)**:** *Let* $u \mapsto F(u)$ *be a linear continuous function on* H*. Then* $\exists! w \in H$*:*

$$F(u) = \langle u, w \rangle \quad \forall u \in H$$

Lax-Milgram: V Hilbertspace, sesquilinear form is defined on $V \times V$, $(u, v) \mapsto \alpha(u, v)$ continuous with

$$|\alpha(u, v)| \leq c\|u\|\|v\| \quad \forall u, v \in V$$

Riesz: $\exists$ linear map $A \colon V \to V$:

$$\alpha(u, v) = \langle Au, v \rangle$$

Definition II.1: *A bilinear form* $a \colon V \times V \to \mathbb{R}$ *is* V***-coercive*** *if there exists* $\lambda > 0$ *such that*

$$a\,(u, u) \geq \lambda \|u\|^2 \quad \forall u \in V$$

Theorem II.2: *Let* a *be a continuous sesquilinear and* V*-coercive on* $V \times V$ *then* A *is an isomorphism.*

Proof:

Step 1: A is injective:

$$\|Au\|\|u\| \overset{C.S.}{\geq} |\langle Au, u \rangle| = |a(u, u)| \geq \lambda \|u\|^2 \tag{+}$$

$\Rightarrow \|Au\| \geq \lambda \|u\|$ for all $u \in V$.

Step 2: $A(V)$ is dense in V. Let $u \in V$ such that

$$\langle Au, v \rangle = 0 \quad \forall v \in V$$

take $v = u \Rightarrow a(u, u) = 0 \Rightarrow u = 0$.

Step 3: $\mathbb{R}(A) = A(V)$ is closed. Let v_n be a sequence in $A(V)$ and let u_n be such that

$$Au_n = v_n$$

$\overset{(+)}{\Longrightarrow} u_n$ is a Cauchy sequence $\Rightarrow u_n \to u \in V$ und $Au_n \to Au \Rightarrow v_n \to Au \in A(V)$

Step 4: $u = A^{-1}v \overset{(+)}{\Longrightarrow} \|A^{-1}v\| \leq \lambda^{-1}\|v\| \ \forall v \in V$.

□

Next we consider two Hilbert spaces V, H with $V \subset H$ (the inclusion is continuous), i.e.

$$\exists c < \infty: \quad \|u\|_H \leq c\|u\|_V \quad \forall u \in V$$

and we assume that V is dense in H.

Example: $V = W^{1,2}(\mathbb{R}^n)$, $H = L^2(\mathbb{R}^n)$

$$\|u\|_L^2 \leq \|u\|_{W^{1,2}}$$

There exists a natural injection from H into V'. Let $h \in H$ then $V \ni u \mapsto \langle u, h\rangle_H$ is continuous on $V \xRightarrow[\text{Thm. II.1}]{} \exists l_h \in V'$:

$$l_h(u) = \langle u, h\rangle_H \quad \forall u \in V$$

injectivity follows from density of V in H. $V \subseteq H \subset V'$ cont. sesquilinear form a on $V \times V$ which is V-coercive $\to$ Associate an unbounded operator S with a

$$\mathcal{D}(S) := \Big\{u \in V : a(u,v) \text{ is cont. on } V \text{ with respect to the topology induced by } H\Big\}$$

Theorem II.3: *Let a be a continuous sesquilinear form on V which is V-coercive then S is bijective from $\mathcal{D}(S)$ into H and $S^{-1} \in L(H, \mathcal{D}(S))$. Moreover, $\mathcal{D}(S)$ is dense in H.*

Proof:

1) S injective: $\exists \alpha > 0$:

$$\alpha\|u\|_H^2 \leq C\alpha\|u\|_V^2 \leq C\,|a(u,u)| = c\,|\langle Su, u\rangle_H| \leq c\|Su\|_H\|u\|_H, \quad \forall u \in \mathcal{D}(S)$$

$\Rightarrow \alpha\|u\|_H \leq c\|Su\|_H,\ \forall u \in \mathcal{D}(S)$ $(+)$.

2) S surjective:
   Let $h \in H$. Choose $w \in V$ such that

$$\langle h, v \rangle_H = \overline{\langle v, h \rangle_H} = \overline{l_h(v)} = \langle w, v \rangle \quad \forall v \in V$$

   where we used Riesz' representation theorem in the last step.

$$\text{(Note: } l_h \in V' \Rightarrow \overline{l_h} \in \text{continuous lineare form on } V\text{).}$$

   Define $u \coloneqq A^{-1}w \in V \Rightarrow a(u, v) = \langle Au, v \rangle_V = \langle w, v \rangle_V = \langle h, v \rangle_H$

$$\Rightarrow u \in \mathcal{D}\left(S\right), \; Su = h$$

   (V dense in H). (+) implies that S^{-1} is continuous.

3) Density of $\mathcal{D}\left(S\right)$:
   Let $h \in H$ such that $\langle u, h \rangle_H = 0 \; \forall u \in \mathcal{D}\left(S\right)$. S surjective $\exists v \in DOS$: $Sv = h$

$$\Rightarrow \langle Sv, u \rangle = 0 \; \forall u \in \mathcal{D}\left(S\right)$$

$$\Rightarrow \langle Sv, v \rangle_H = 0 \Rightarrow a(v, v) = 0 \Rightarrow v = 0 \Rightarrow h = 0$$

   a hermitian iff

$$a(u, v) = \overline{a(v, u)} \quad \forall u, v \in V$$

□

Theorem II.4: *Under the assumptions of Theorem II.3 and a being hermitian it follows that*

a) S is closed

b) $S = S^*$

c) $\mathcal{D}\left(S\right)$ dense in V

Proof:

a) Theorem I.4

b) a hermitian

$$\Rightarrow \langle Su, v\rangle_H = a(u,v) = \overline{a(v,u)} = \overline{\langle Sv, u\rangle_H} = \langle u, Sv\rangle_H \quad \forall u, v \in \mathcal{D}(S)$$

$\Rightarrow S$ symmetric $\Rightarrow \mathcal{D}(S) \subset \mathcal{D}(S^*)$. Let $v \in \mathcal{D}(S^*)$, S surjective

$$\Rightarrow v_0 \in \mathcal{D}(S) : Sv_0 = S^*v.$$

For all $u \in \mathcal{D}(S)$ we get

$$\langle Su, v_0\rangle_H = \langle u, Sv_0\rangle_H = \langle u, S^*v\rangle_H = \langle Su, v\rangle_H$$

$\Rightarrow v = v_0 \Rightarrow \mathcal{D}(S) = \mathcal{D}(S^*)$, $Sv = S^*v \ \forall v \in \mathcal{D}(S)$.

c) follows from Theorem II.3

$\square$

Chapter III

Friedrichs extension

Definition III.1: *Let T_0 be a symmetric unbounded operator with domain $\mathcal{D}(T_0)$ we say that T_0 is semi bounded if $\exists c > 0$:*

$$\langle T_0 u, u\rangle_H \geq -c\|u\|_H^2 \quad \forall u \in \mathcal{D}(T_0)$$

Example:

a) Schrödinger Operator. $\mathbb{R}^m$, $H = L^2(\mathbb{R}^m)$, $\mathcal{D}(T_0) = C_c^\infty(\mathbb{R}^m)$

$$T_0 \coloneqq -\Delta + V,$$

$V \in C_0(\mathbb{R}^m)$ with $V(x) \geq -c \ \forall x \in \mathbb{R}^m$

Addendum

Theorem (Riesz' representation theorem, FA 17.2)**:** To all $x' \in X'$ there exists a unique $x \in X$ such that

$$x'(y) = \langle y, x \rangle,$$

for $y \in X$ and $\|x'\|_{X'} = \|x\|_X$.

Stichwortverzeichnis