Assignment 7

Due Monday 22 April 2024 (*revised!*)

This Assignment is based on sections 3.2, 3.3, 3.4, 4.1, and 4.2 of our textbook, Borthwick (2020) *Spectral Theory: Basic Concepts and Applications*, Springer.

PLEASE DO THE FOLLOWING EXERCISES.

P33. The adjoint of a linear map between complex Hilbert spaces $\mathcal{H}_1$ and $\mathcal{H}_2$ can be defined. Here we consider bounded operators only. For $T \in \mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)$ the *(Hilbert space) adjoint* T^* is the unique linear map $T^* \in \mathcal{L}(\mathcal{H}_2, \mathcal{H}_1)$ so that

$$\langle v, Tu \rangle_2 = \langle T^* v, u \rangle_1 \qquad \text{for all } u \in \mathcal{H}_1 \text{ and } v \in \mathcal{H}_2.$$

When $\mathcal{H}_1 = \mathcal{H}_2$ this is the same definition as in section 3.2.

(a) Show that $(T^*)^* = T$ and that $(ST)^* = T^* S^*$.

(b) Show that if T is invertible with $T^{-1} \in \mathcal{L}(\mathcal{H}_2, \mathcal{H}_1)$ then $(T^*)^{-1} = (T^{-1})^*$.

(c) Suppose that $Q \in \mathcal{L}(\mathcal{H}_1, \mathcal{H}_2)$ satisfies $Q^* Q = I_1$ and $QQ^* = I_2$ where I_i is the identity map on $\mathcal{H}_i$. Show that Q is unitary.

Hints. For part **(a)** assume that $S \in \mathcal{L}(\mathcal{H}_2, \mathcal{H}_3)$. For part **(b)** use $TT^{-1} = I_2$ and $T^{-1}T = I_1$, and then apply **(a)**. For part **(c)** use the definition on page 17 of the text: U is *unitary* if it is a bijective isometry.

P34. **(a)** Suppose $\{\phi_n\}$ is an orthonormal basis of a complex Hilbert space $\mathcal{H}$. Define the map $Q \in \mathcal{L}(\mathcal{H}, \ell^2)$, where $\ell^2 = \ell^2(\mathbb{N})$, by $(Qf)_n = \langle \phi_n, f \rangle_{\mathcal{H}}$ for $f \in \mathcal{H}$. Give a formula for Q^*. Show that Q is unitary.

(b) Let T be a closed (unbounded) linear operator on $\mathcal{H}$. Suppose $\phi_n \in \mathcal{D}(T)$ and $T\phi_n = \lambda_n \phi_n$, for $n \in \mathbb{N}$ and $\lambda_n \in \mathbb{C}$. If $\{\phi_n\}$ is an orthonormal basis of $\mathcal{H}$ then Q in part **(a)** unitarily diagonalizes T in the sense that

$$QTQ^* = M$$

defines an unbounded multiplication operator on ℓ^2.

Hints. For part **(a)** you may use **P33(c)**, though that is not the only way. For part **(b)**, make sure to define the domain of M and the action of M on elements of $\mathcal{D}(M)$.

P35. **(a)** Let $\mathcal{H} = L^2(\mathbb{R})$. Define $(M_{x^2}\, v)(x) = x^2 v(x)$, an unbounded multiplication operator with domain $\mathcal{D}(M_{x^2}) = \{v \in \mathcal{H} \,:\, x^2 v(x) \in \mathcal{H}\}$. Define $(Tv)(x) = v''(x)$, an unbounded second derivative operator with domain $\mathcal{D}(T) = C_0^\infty(\mathbb{R})$. Show that these operators have no eigenvalues.

(b) Let $\mathcal{H} = L^2(0, \pi)$. Define $(M_{x^2}\, v)\,(x) = x^2 v(x)$, a multiplication operator with domain $\mathcal{D}(M_{x^2}) = \{v \in \mathcal{H} \,:\, x^2 v(x) \in \mathcal{H}\}$. Show that M_{x^2} is actually bounded, but that it has no eigenvalues.

(c) Let $\mathcal{H} = L^2(0, \pi)$. Define $(Tv)(x) = v''(x)$, a second derivative operator with domain $\mathcal{D}(T) = \{v \in \mathcal{H} \,:\, v \in C^2[0, \pi] \text{ and } v(0) = v(\pi) = 0\}$. Show that T is unbounded, and that $\phi_k(x) = \sin(kx)$ is an eigenfunction for any $k \in \mathbb{N}$. Find the corresponding eigenvalues.

Hints. For part **(a)** you may use results in Example 3.3. For part **(b)** you may use the result in Example 2.8.

Comments. You do not need to prove self-adjointness or spectrum. However, textbook Examples 3.2, 3.5, and 3.22 show both M_{x^2} are self-adjoint. Example 3.26 shows that T in part **(a)** is essentially self-adjoint. Example 3.20 sketches why T in part **(c)** is essentially self-adjoint. See Theorems 4.5 for the spectrum of both M_{x^2}, thus by unitary-equivalence for the closure of T in part **(a)** also. Use **P34(b)** for the spectrum of the closure of T in part **(b)**.

P36. Let $\mathcal{H}$ be a complex Hilbert space. Recall that if A is a symmetric operator on $\mathcal{H}$ then $v \in \mathcal{D}(A)$ implies $\langle v, Av\rangle \in \mathbb{R}$. We will write $A - z$ for $A - zI$.

(a) Suppose A is a symmetric operator on $\mathcal{H}$. Show that if $z \in \mathbb{C}$ then

$$\mathrm{Im}\,\langle v, (A - z)v\rangle = -\mathrm{Im}(z)\|v\|^2.$$

(b) If furthermore $z \in \mathbb{C}$ is strictly complex, i.e. $\mathrm{Im} z \neq 0$, then

$$\|v\| \le \frac{\|(A - z)v\|}{|\mathrm{Im}(z)|}.$$

In this situation, show that $A - z$ is injective.

P37. Let $\mathcal{H}$ be a complex Hilbert space. Recall that $\mathcal{L}(\mathcal{H})$ is a normed vector space with norm $\|T\| = \sup_{\|v\|=1} \|Tv\|$, and also recall Theorem 2.10.

(a) Suppose that $T \in \mathcal{L}(\mathcal{H})$, $z \in \mathbb{C}$, and $|z| > \|T\|$. Show that

$$\sum_{k=0}^{\infty} z^{-k} T^k$$

converges to $S \in \mathcal{L}(\mathcal{H})$.

(b) Under the same assumptions, show that

$$S(T - zI) = (T - zI)S = -zI.$$

Explain why this shows $z \in \rho(T)$.