Maths Problem Set 3 - Spectral Theory

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Q 4.2[1] The eigenvalue of this linear differential operator $D[p](x) = p^{'}(x)$ is 0. Also, the eigenspace is $\sum_{\lambda}(D) = \{a + bx + cx^2 \in V | b = c = 0\}$
Algebraic and geometric multiplicities of D are the dimension of $\sum_{\lambda}(D)$, which is 1 and the algebraic multiplicity of $\lambda_i = 0$ is 1.

Ex 4.4 *Proof of (i)* Note that by the definition of eigenvalues, eigenvalues in a 2 x 2 matrix satisfy the following;

$$p(\lambda) = \lambda^2 - (a + d)\lambda + (ad - bc) = 0$$

where

$$A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

Using quadratic formula,

$$(a + d)^2 - 4(ad - bc) = (a - d)^2 + 4bc$$

Now A^H is Hermitian i.e $A^H = A$. This implies that a and d are real numbers, and the multiplication of $b = \bar{c}$ and $c = \bar{b}$ results in positive number. Thus, $(a-d)^2+4bc > 0$, implying that the solutions of characteristic equations are all real.
Proof of (ii)
If we find the quadratic formula of this 2nd order polynomial equation, then

$$D = (a - d)^2 + 4bc = -(a_1 - d_1)^2 - 4(abs(b)^2) < 0$$

Q. 4.6

[1] I have used the Latex file of Jay Hyung in this problem set

Proof. Let A be an upper triangular matrix. Consider $det(\lambda I - A) = 0$. This results in the following equation;

$$\prod_{i=1}^{n}(\lambda - a_i i)$$

, where a_{ii} is the ith diagonal entry. This expression equals to zero, iff $\lambda = a_{ii}$ for some i. Thus, the diagonal entries of the matrix are the eigenvalues.

Q. 4.8

Proof of (i). Set the following matrix;

$$\begin{bmatrix} sin(t_1) & cos(t_1) & sin(2t_1) & cos(2t_1) \\ sin(t_2) & cos(t_2) & sin(2t_2) & cos(2t_2) \\ sin(t_3) & cos(t_3) & sin(2t_3) & cos(2t_3) \\ sin(t_4) & cos(t_4) & sin(2t_4) & cos(2t_4) \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

with $t_1 = 0, t_2 = \pi/2, t_3 = \pi, t_4 = 3/2\pi$. This results in $c_1 = c_2 = c_3 = c_4 = 0$.
Proof of (ii). Let $D[p](x) := p^{'}(x)$. By calculation, the matrix that represents this differential operator is the following;

$$\begin{bmatrix} 0 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -2 \\ 0 & 0 & 2 & 0 \end{bmatrix}$$

Answer of (iii). Let $V_1 = span(\{sin(x), cos(x)\})$ and $V_1 = span(\{sin(2x), cos(2x)\})$.

Q 4.13

Answer.

$$D = \begin{bmatrix} 1 & 0 \\ 0 & 0.4 \end{bmatrix}$$

and

$$P = \begin{bmatrix} 0.7454 & 0.7454 \\ -0.4714 & 0.9428 \end{bmatrix}$$

Q 4.15

Proof. Due to the assumption that A is semi-simple, A is diagonalizable, i.e. $\exists P\ s.t. P^{-1}AP = D$, where D is diagonal matrix. Then, $A^k = PD^kP^{-1}$. Then,

$$\begin{aligned} f(A) =& a_0I + a_1A + ... + a_nA^n \\ =& a_0PIP^{-1} + a_1PDP^{-1} + ... + a_nPD^nP^{-1} \\ =& P(a_0 + I + a_1D + ... + a_nD^n)P^{-1} \end{aligned}$$

Thus, the eigenvalues of $f(A)$ are $(f(\lambda_i))_{i=1}^n$

Q 4.16

Proof of (i). The Markov Chain which this matrix A^T represents is irreducible and aperiodic. Thus, there exists a distribution π such that $A\pi = \pi$. If we solve this, then $\pi = (2/3, 1/3)$, which is exactly the same with the first and the second columns of $\lim_{n\to\infty} A^n$
Answer of (ii). Yes, $\|\lim A^n\|_\infty = 4/3$, and $\|\lim A^n\|_F = \sqrt{10}/3$
Answer of (iii). By the Theorem 4.3.12, $f(\lambda_1) = 3 + 5 * \lambda_1 + \lambda_1^3 = 9$, and $f(\lambda_2) = 3 + 5 * \lambda_2 + \lambda_2^3 = 5.0640$

Q 4.18

Proof. Note that

$$det(A^T - \lambda I) = det((A - \lambda I)^T) = det(A - \lambda I) = 0$$

Thus, $A^Tx = \lambda x$, and with transposition, $x^TA = \lambda x^T$

Q 4.20

Proof. Note that $A^H = A$. Using the notations in the Definition 4.4.1,

$$B^H = (U^HAU)^H = U^HA^HU = U^HAU = B$$

Q. 4.24

Proof. Due to the assumption that the matrix A is hermitian, all the eigenvalues of

A are real, because;

$$\begin{aligned}v^H Av =& \lambda v^H v \\ \lambda v^H v =& v^H Av = (v^H Av)^H = \bar{\lambda} v^H v\end{aligned}$$

Thus, $\lambda = \bar{\lambda}$, meaning that the eigenvalues are real. Also, due to this fact, the matrix A is positive semi-definite. Thus, by Proposition 4.5.6, the eigenvectors of A corresponding to distinct eigenvalues are orthogonal. Then, any vector x can be expressed in the following;

$$x = \sum_{j=1}^{n} c_j v_j = Vc$$

, where v_js are orthonormal eigenvectors.

This results in the following;

$$\begin{aligned}\rho(x) =& \frac{x^H Ax}{x^H x} \\ =& \frac{c^H V^H AVc}{c^H V^H Vc} \\ =& \frac{c^H \mathbf{A} c}{c^H c}\end{aligned}$$

where $A = V\mathbf{A}V^H$, and $\mathbf{A}$ is diagonal matrix. Thus,

$$\rho(x) = \frac{\lambda_1 |c_1|^2 + \cdots \lambda_n |c_n|^2}{|c_1|^2 + \cdots |c_n|^2 +}$$

Thus, $\rho(x)$ are real with hermitian matrix, A. We can do the same proof for Skewed matrix. **Q. 4.25**

Proof of (i). Note that the following holds due to the assumption that $[x_1, ..., x_n]$ are orthonormal vectors;

$$x_i^H x_j = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases}$$

Thus,

$$(x_1 x_1^H + \cdots + x_n x_n^H) x_j = x_j = I x_j$$

for all j. Thus, the statement holds.

Proof of (ii). Note that by the Thoerem 4.4.14, A is orthonormally diagonalizable, i,e.

$$A = UTU^H$$

with T being diagonal, and U being orhonormal. This results in;

$$A = \sum_{i=1}^{n} t_{ii} u_i u_i^H$$

Q. 4.27

Note that the positive-definite matrix A satisfies the following;

$$\forall x \neq 0, x^H A x > 0$$

If we feed the standard basis vector to x, then

$$e_i^H A e_i = a_{ii} > 0$$

Thus, all the diagonal entries are real and positive. Q.E.D

Q. 4.28

Proof. Note that by the same logic of Ex. 4.27, one can show that the diagonal entries of any semi-positive definite matrix are non-negative. For the first inequality, we need to show that AB is a semi-positive definite matrix.

Note that $\forall x \neq 0, x^T A x, x^T B x \geq 0$. Then,

$$(x^T A x)(x^T B x) = (x^T A)(x x^T)(B x) \geq 0$$

Note that $x x^T$ is positive scalar when $x \neq 0$. Thus, $x^T A B x \geq 0$, implying that AB is positive semi-definite. This leads to the result that

$$tr(AB) \geq 0$$

Lastly, by using Cauchy-Scwartz inequality, we have

$$tr(AB) \leq tr(A)tr(B)$$

Ex. 4.31

Proof of (i). Note that we want to show $\|\mathbf{A}\|_2 = \sqrt{\lambda_{\max}(\mathbf{A}^H\mathbf{A})}$
We can first simply prove when $\mathbf{P}$ is hermitian,

$$\lambda_{\max} = \max_{\|\mathbf{x}\|_2=1} \mathbf{x}^H\mathbf{P}\mathbf{x}$$

That's because when $\mathbf{P}$ is Hermitian, there exists one and only one unitary matrix $\mathbf{U}$ that can diagonalize $\mathbf{P}$ as $\mathbf{U^HPU} = \mathbf{D}$ (so $\mathbf{P} = \mathbf{UDU^H}$), where $\mathbf{D}$ is a diagonal matrix with eigenvalues of $\mathbf{P}$ on the diagonal, and the columns of $\mathbf{U}$ are the corresponding eigenvectors. Let $\mathbf{y} = \mathbf{U^H}\mathbf{x}$ and substitute $\mathbf{x} = \mathbf{U}\mathbf{y}$ to the optimization problem, we obtain

$$\max_{\|\mathbf{x}\|_2=1} \mathbf{x}^H\mathbf{P}\mathbf{x} = \max_{\|\mathbf{y}\|_2=1} \mathbf{y}^H\mathbf{D}\mathbf{y} = \max_{\|\mathbf{y}\|_2=1} \sum_{i=1}^{n} \lambda_i |y_i|^2 \leq \lambda_{\max} \max_{\|\mathbf{y}\|_2=1} \sum_{i=1}^{n} |y_i|^2 = \lambda_{\max}$$

Thus, just by choosing $\mathbf{x}$ as the corresponding eigenvector to the eigenvalue $\lambda_{\mathbf{max}}$, $\max_{\|\mathbf{x}\|_2=1} \mathbf{x}^H\mathbf{P}\mathbf{x} = \lambda_{\max}$. This proves $\|\mathbf{A}\|_2 = \sqrt{\lambda_{\max}(\mathbf{A}^H\mathbf{A})}$

Proof of (ii). Note that if the matrix A is invertible, then;

$$A^{-1} = (U\Sigma V^H)^{-1} = (V^H)^{-1}\Sigma^{-1}U^{-1} = \hat{U}\Sigma^{-1}\hat{V}^H$$

Note that $\hat{U}$ and $\hat{V}$ are all trivially orthornormal. Also, inverted diagonal matrix Σ^{-1} takes the inverse values of its diagonal entries on its diagonal line. Thus, $\|A^{-1}\|_2 = \sigma_n^{-1}$

Proof of (iii).

Note that according to the property of singular values(positive and real), the following holds;

$$\Sigma = \Sigma^T = \Sigma^H$$

Thus, by (i), $\|A\|_2 = \|A^H\|_2 = \|A^T\|_2$
Also,

$$A^HA = V\Sigma^HU^HU\Sigma V^H = V\Sigma^H\Sigma V^H = V\Sigma^2V^H$$

Thus, $\|A^HA\|_2 = \|A\|_2^2$

Proof of (iv).

Note that

$$UAV = UU_1\Sigma V_1^H V = \hat{U}\Sigma\hat{V}^H$$

Note that $\hat{U}$ and $\hat{V}$ are orthonormal. For example,

$$\hat{U}^H\hat{U} = (UU_1)^H UU_1 = U_1^H U^H UU_1 = U_1^H U_1 = I$$

The same argument can be used to prove that $\hat{V}$ is orthonormal. Thus, $\|UAV\|_2 = \|A\|_2$. **Q. 4.32**

We first prove (ii), and then use the result to prove (i).

Proof of (ii).

$$\begin{aligned}\|A\|_F^2 =& tr(AA^H) = tr(U\Sigma V^H V\Sigma^H U^H)\\ =& tr(U\Sigma\Sigma^H U^H)\\ =& tr(\Sigma\Sigma^H U^H U)\\ =& tr(\Sigma\Sigma^H)\\ =& \sigma_1^2 + ... + \sigma_n^2\end{aligned}$$

Proof of (i).

$$\begin{aligned}\|U_1AV_1\|_F^2 =& tr((U_1AV_1)(U_1AV_1)^H)\\ =& tr(U_1AV_1V_1^H A^H U_1^H)\\ =& tr(U_1AA^H U_1^H)\\ =& tr(AA^H U_1^H U_1)\\ =& tr(AA^H)\\ =& tr(\Sigma\Sigma^H)\\ =& \sigma_1^2 + ... + \sigma_n^2\end{aligned}$$

Thus, $\|A\|_F = \|U_1AV_1^H\|$ Q.E.D

Q. 4.33

Proof.

$$
\begin{aligned}
|y^H Ax| =& |y^H (U\Sigma V^H)x| \\
=& |y^H (\sum_{i=1}^{r} \sigma_i u_i v_i^H|)x \\
\leq& \sigma_{max} | \sum_{i=1}^{r} y^H u_i v_i^H x|
\end{aligned}
$$

Note that $\|y^H u_i v_i^H\|_2 \leq \|y^H\| \|u_i\| \|v_i^H\| \leq 1 \times 1 \times 1 = 1$. Thus,

$$
\sigma_{max} | \sum_{i=1}^{r} y^H u_i v_i^H x| \leq \sigma_{max} | \sum_{i=1}^{r} x_u| \leq \sigma_{max}
$$

We can attain equality when $\|y^H u_i v_i^H\|_2 = 1$, and $\sum_{i=1}^{r} (x_i)^2 = 1$, which is possibly chosen due to the assumption that x and y are free variable of supremum, and U and V, which are the matrices of SVD of A and orthonormal, are arbitrary. **Q. 4.36**

Answer. Try any non-symmetric matrix. For example,

$$
A = \begin{bmatrix} 2 & 1 \\ 3 & 4 \end{bmatrix}
$$

gives $\lambda_1 = 1, \lambda_2 = 5$ as eigenvalues, but it gives $\sigma_1 = 0.9262, \sigma_2 = 5.3983$ as singular values.

Q. 4.38

Proof of (i).

$$
\begin{aligned}
AA^+ A =& (U\Sigma V^H)(V\Sigma^{-1} U^H)(U\Sigma V^H) \\
=& U\Sigma\Sigma^{-1} U^H U\Sigma V^H \\
=& U\Sigma V^H \\
=& A
\end{aligned}
$$

Proof of (ii).

$$
\begin{aligned}
A^+AA^+ =&(V\Sigma^{-1}U^H)(U\Sigma V^H)(V\Sigma^{-1}U^H)\\
=&U\Sigma^{-1}V^H\\
=&A^+
\end{aligned}
$$

Proof of (iii).

$$
\begin{aligned}
(AA^+)^H =&(A^+)^H A^H\\
=&(V\Sigma^{-1}U^H)^H(U\Sigma V^H)^H\\
=&UU^H\\
=&AA^+
\end{aligned}
$$

Proof of (v).

We use the facts above and the fact that if $X = YZ$, then $\mathcal{R}(X) \subseteq \mathcal{R}(Y)$. We need only to show that the matrices AA^+ and A^+A are Hermitian, idempotent, and their ranges are equal to the subspaces on which they are supposed to project.

Both AA^+ and A^+A are obviously Hermitian; see (iii) and (iv). In addition, (i) and (ii) imply that they are idempotent. It remains to show that $\mathcal{R}(AA+) = R(A)$ and $\mathcal{R}(A^+A) = \mathcal{R}(A^H)$. Clearly, $\mathcal{R}(AA^+) \subseteq \mathcal{R}(A)$; $\mathcal{R}(A) \subseteq \mathcal{R}(AA^+)$ follows from (i). From (iv), we have $A^+A = A^H(A^+)^H$, so $\mathcal{R}(A^+A) \subseteq \mathcal{R}(A^H)$. From (i) and (iv), $A^H = A^+AA^H$, so $\mathcal{R}(A^H) \subseteq \mathcal{R}(A^+A)$.