

18.06 Problem Set 10 Solution

Total: 100 points

Section 6.6. Problem 12. These Jordan matrices have eigenvalues $0, 0, 0, 0$. They have two eigenvectors (one from each block). But the block sizes don't match and they are *not similar*:

$$J = \left(\begin{array}{cc|cc} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{array} \right) \quad \text{and} \quad K = \left(\begin{array}{ccc|c} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & 0 \end{array} \right)$$

For any matrix M , compare JM with MK . If they are equal show that M is not invertible. Then $M^{-1}JM = K$ is impossible; J is *not similar* to K .

Solution (4 points) Let $M = (m_{ij})$. Then

$$JM = \left(\begin{array}{cccc} m_{21} & m_{22} & m_{23} & m_{24} \\ 0 & 0 & 0 & 0 \\ m_{41} & m_{42} & m_{43} & m_{44} \\ 0 & 0 & 0 & 0 \end{array} \right) \quad \text{and} \quad MK = \left(\begin{array}{ccc|c} 0 & m_{11} & m_{12} & 0 \\ 0 & m_{21} & m_{22} & 0 \\ 0 & m_{31} & m_{32} & 0 \\ \hline 0 & m_{41} & m_{42} & 0 \end{array} \right).$$

If $JM = MK$ then

$$m_{21} = m_{22} = m_{24} = m_{41} = m_{42} = m_{44} = 0,$$

which in particular means that the second row is either a multiple of the fourth row, or the fourth row is all 0's. In either of these cases M is not invertible.

Suppose that J were similar to K . Then there would be some invertible matrix M such that $K = M^{-1}JM$, which would mean that $MK = JM$. But we just showed that in this case M is never invertible! Contradiction. Thus J is not similar to K .

Section 6.6. Problem 14. Prove that A^T is *always similar* to A (we know that the λ 's are the same):

1. For one Jordan block J_i : find M_i so that $M_i^{-1}J_iM_i = J_i^T$ (see example 3).
2. For any J with blocks J_i : build M_0 from blocks so that $M_0^{-1}JM_0 = J^T$.

3. For any $A = MJM^{-1}$: Show that A^T is similar to J^T and so to J and so to A .

Solution (4 points)

1. Suppose that we have one Jordan block J_i . Then

$$\begin{pmatrix} & & & & 1 \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ 1 & & & & \end{pmatrix} \begin{pmatrix} \lambda & 1 & 0 & \cdots & 0 \\ & \lambda & 1 & \cdots & 0 \\ & & \lambda & \cdots & 0 \\ & & & \ddots & \\ & & & & \lambda \end{pmatrix} \begin{pmatrix} & & & & 1 \\ & & & & \\ & & & & \\ & & & & \\ & & & & \\ 1 & & & & \end{pmatrix} = \begin{pmatrix} \lambda & & & & \\ 1 & \lambda & & & \\ 0 & 1 & \lambda & & \\ & & & \ddots & \\ 0 & 0 & 0 & \cdots & \lambda \end{pmatrix}$$

so J is similar to J^T .

2. Suppose that each J_i satisfies $J_i^T = M_i^{-1}J_iM_i$. Let M_0 be the block-diagonal matrix consisting of the M_i 's along the diagonal. Then

$$\begin{aligned} M_0^{-1}JM_0 &= \begin{pmatrix} M_1^{-1} & & & \\ & M_2^{-1} & & \\ & & \ddots & \\ & & & M_n^{-1} \end{pmatrix} \begin{pmatrix} J_1 & & & \\ & J_2 & & \\ & & \ddots & \\ & & & J_n \end{pmatrix} \begin{pmatrix} M_1 & & & \\ & M_2 & & \\ & & \ddots & \\ & & & M_n \end{pmatrix} \\ &= \begin{pmatrix} M_1^{-1}J_1M_1 & & & \\ & M_2^{-1}J_2M_2 & & \\ & & \ddots & \\ & & & M_n^{-1}J_nM_n \end{pmatrix} \\ &= \begin{pmatrix} J_1^T & & & \\ & J_2^T & & \\ & & \ddots & \\ & & & J_n^T \end{pmatrix} = J^T \end{aligned}$$

- 3.

$$A^T = (MJM^{-1})^T = (M^{-1})^T J^T M^T = (M^T)^{-1} J^T (M^T).$$

So A^T is similar to J^T , which is similar to J , which is similar to A . Thus any matrix is similar to its transpose.

Section 6.6. Problem 20. Why are these statements all true?

- (a) If A is similar to B then A^2 is similar to B^2 .
- (b) A^2 and B^2 can be similar when A and B are not similar.
- (c) $\begin{pmatrix} 3 & 0 \\ 0 & 4 \end{pmatrix}$ is similar to $\begin{pmatrix} 3 & 1 \\ 0 & 4 \end{pmatrix}$.
- (d) $\begin{pmatrix} 3 & 0 \\ 0 & 3 \end{pmatrix}$ is not similar to $\begin{pmatrix} 3 & 1 \\ 0 & 3 \end{pmatrix}$.
- (e) If we exchange rows 1 and 2 of A , and then exchange columns 1 and 2 the eigenvalues stay the same. In this case $M = ?$

Solution (4 points)

- (a) If A is similar to B then we can write $A = M^{-1}BM$ for some M . Then $A^2 = M^{-1}B^2M$, so A^2 is similar to B^2 .
- (b) Let

$$A = \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \quad B = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}.$$

Then $A^2 = B^2$ (so they are obviously similar) but A is not similar to B because nothing but the zero matrix is similar to the zero matrix.

- (c)

$$\begin{pmatrix} 3 & 0 \\ 0 & 4 \end{pmatrix} = \begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 3 & 1 \\ 0 & 4 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}.$$

- (d) These are not similar because the first matrix has a plane of eigenvectors for the eigenvalue 3, while the second only has a line.
- (e) In order to exchange two rows of A we multiply on the left by

$$M = \begin{pmatrix} 0 & 1 & & \\ 1 & 0 & & \\ & & 1 & \\ & & & 1 \end{pmatrix}.$$

In order to exchange two columns we multiply on the right by the same M . As $M = M^{-1}$ we see that the new matrix is similar to the old one, so the eigenvalues stay the same.

Section 6.6. Problem 22. If an $n \times n$ matrix A has all eigenvalues $\lambda = 0$ prove that A^n is the zero matrix.

Solution (12 points) Suppose that we have a Jordan block of size i with eigenvalue 0. Then notice that J^2 will have a diagonal of 1's two diagonals above the main diagonal and zeroes elsewhere. J^3 will have a diagonal of 1's three diagonals above the main diagonal, and zeroes elsewhere. Therefore $J^i = 0$, since there is no diagonal i diagonals above the main diagonal. If A has all eigenvalues $\lambda = 0$ then A is similar to some matrix with Jordan blocks J_1, \dots, J_k with each J_i of size n_i and $\sum_{i=1}^k n_i = n$. Each Jordan block will have eigenvalue 0, so we know that $J_i^{n_i} = 0$, and thus $J_i^n = 0$.

As A^n is similar to a block-diagonal matrix with blocks $J_1^n, J_2^n, \dots, J_k^n$ and each of these is 0 we know that $A^n = 0$.

Another way to see this is to note that if A has all eigenvalues 0 this means that the characteristic polynomial of A must be x^n , as this is the only polynomial of degree n all of whose roots are 0. Thus $A^n = 0$ by the Cayley-Hamilton theorem.

Section 6.6. Problem 23. For the shifted QR method in the Worked Example 6.6 B, show that A_2 is similar to A_1 . No change in eigenvalues, and the A 's quickly approach a diagonal matrix.

Solution (12 points) We are asked to show that $A_2 = R_1 Q_1 - cs^2 I$ is similar to $A_1 = Q_1 R_1 - cs^2 I$. Note that

$$Q_1 A_2 Q_1^{-1} = Q_1 (R_1 Q_1 - cs^2 I) Q_1^{-1} = Q_1 R_1 - Q_1 cs^2 I Q_1^{-1} = Q_1 R_1 - cs^2 I = A_1.$$

Thus A_2 is similar to A_1 , and thus their eigenvalues are the same.

Section 6.6. Problem 24. If A is similar to A^{-1} , must all the eigenvalues equal 1 or -1 ?

Solution (12 points)
No. Consider:

$$\begin{pmatrix} 2 & 0 \\ 0 & \frac{1}{2} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}^{-1} \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & 2 \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

Thus $\begin{pmatrix} 2 & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$ is similar to $\begin{pmatrix} 2 & 0 \\ 0 & \frac{1}{2} \end{pmatrix}^{-1}$.

Section 6.7. Problem 4. Find the eigenvalues and unit eigenvectors of $A^T A$ and AA^T . Keep each $Av = \sigma u$ for the Fibonacci matrix $A = \begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix}$. Construct the singular value decomposition and verify that A equals $U\Sigma V^T$.

Solution (4 points)

$$A^T A = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix} \quad AA^T = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}.$$

Note that these are the same. (This makes sense, as A is symmetric.) The eigenvalues of this are the roots of $x^2 - 3x + 1$, which are $(3 \pm \sqrt{5})/2$. The unit eigenvectors of this will be

$$\begin{pmatrix} \sqrt{\frac{2}{5-\sqrt{5}}} \\ \sqrt{\frac{3-\sqrt{5}}{5-\sqrt{5}}} \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} \sqrt{\frac{3-\sqrt{5}}{5-\sqrt{5}}} \\ -\sqrt{\frac{2}{5-\sqrt{5}}} \end{pmatrix}.$$

Then

$$U = \begin{pmatrix} \sqrt{\frac{2}{5-\sqrt{5}}} & -\sqrt{\frac{3-\sqrt{5}}{5-\sqrt{5}}} \\ \sqrt{\frac{3-\sqrt{5}}{5-\sqrt{5}}} & \sqrt{\frac{2}{5-\sqrt{5}}} \end{pmatrix} \quad V = \begin{pmatrix} \sqrt{\frac{2}{5-\sqrt{5}}} & \sqrt{\frac{3-\sqrt{5}}{5-\sqrt{5}}} \\ \sqrt{\frac{3-\sqrt{5}}{5-\sqrt{5}}} & -\sqrt{\frac{2}{5-\sqrt{5}}} \end{pmatrix}$$

and

$$\Sigma = \begin{pmatrix} \frac{1+\sqrt{5}}{2} & \\ & \frac{\sqrt{5}-1}{2} \end{pmatrix}.$$

Section 6.7. Problem 11. Suppose A has orthogonal columns w_1, \dots, w_n of lengths $\sigma_1, \dots, \sigma_n$. What are U, Σ and V in the SVD?

Solution (4 points) We will first solve this assuming all of the w_i are nonzero; at the end we will give a modification for the solution in the case that some are 0. As the columns of A are orthogonal we know that $A^T A$ will be a diagonal matrix with diagonal entries $\sigma_1^2, \dots, \sigma_n^2$. Thus $U = I$ and Σ is the diagonal matrix with entries $\sigma_1, \dots, \sigma_n$. Then if we define V to be the matrix whose i -th row is the vector w_i/σ_i we will have $A = U\Sigma V^T$, as desired.

Suppose that some of w_i are zero. Take all of the w 's that are nonzero and complete them to an orthogonal basis u_1, \dots, u_n satisfying the conditions that if $w_i \neq 0$ then $u_i = w_i$, and if $w_i = 0$ then $|u_i| = 1$. Then let U, Σ be as above, and V be the matrix whose i -th row is w_i/σ_i if $\sigma_i \neq 0$, and u_i if $\sigma_i = 0$. Then $A = U\Sigma V^T$, as desired.

Section 6.7. Problem 17. The $1, -1$ first difference matrix A has $A^T A$ the second difference matrix. The singular vectors of A are *sine vectors* V and *cosine vectors* u . Then $Av = \sigma u$ is the discrete form of $d/dx(\sin cx) = c(\cos cx)$. This is the best SVD I have seen.

$$A = \begin{pmatrix} 1 & 0 & 0 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & -1 \end{pmatrix} \quad A^T A = \begin{pmatrix} 2 & -1 & 0 \\ -1 & 2 & -1 \\ 0 & -1 & 2 \end{pmatrix}.$$

Then the orthogonal sine matrix is

$$V = \frac{1}{\sqrt{2}} \begin{pmatrix} \sin \pi/4 & \sin 2\pi/4 & \sin 3\pi/4 \\ \sin 2\pi/4 & \sin 4\pi/4 & \sin 6\pi/4 \\ \sin 3\pi/4 & \sin 6\pi/4 & \sin 9\pi/4 \end{pmatrix}.$$

- Put numbers in V : The unit eigenvectors of $A^T A$ are singular vectors of A . Show that the columns of V have $A^T A v = \lambda v$ with $\lambda = 2 - \sqrt{2}, 2, 2 + \sqrt{2}$.
- Multiply AV and verify that its columns are orthogonal. They are $\sigma_1 u_1$ and $\sigma_2 u_2$ and $\sigma_3 u_3$. The first columns of the cosine matrix U are u_1, u_2, u_3 .
- Since A is 4×3 we need a fourth orthogonal vector u_4 . It comes from the nullspace of A^T . What is u_4 ?

Solution (12 points)

- We are asked to show that the columns of V are eigenvectors of $A^T A$. The characteristic polynomial of $A^T A$ is $x^3 - 6x^2 + 10x - 4$, which can be factored as $(x - 2)(x^2 - 4x + 2)$. By the quadratic formula the roots of this are exactly the eigenvalues specified.

Note that

$$V = \begin{pmatrix} 1/2 & 1/\sqrt{2} & 1/2 \\ 1/\sqrt{2} & 0 & -1/\sqrt{2} \\ 1/2 & -1/\sqrt{2} & 1/2 \end{pmatrix}.$$

Then note that the three vectors $\begin{pmatrix} 1 \\ \sqrt{2} \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 1 \\ -\sqrt{2} \\ 1 \end{pmatrix}$ are scalar multiples of the columns of V , and it is easy to check that they are indeed eigenvectors of $A^T A$ with the right eigenvalues.

(b)

$$AV = \frac{1}{2} \begin{pmatrix} 1 & \sqrt{2} & 1 \\ \sqrt{2}-1 & -\sqrt{2} & -\sqrt{2}-1 \\ 1-\sqrt{2} & -\sqrt{2} & 1+\sqrt{2} \\ -1 & \sqrt{2} & -1 \end{pmatrix}.$$

It is easy to check that these columns are orthogonal.

(c) Note that $A^T = \begin{pmatrix} 1 & -1 & 0 & 0 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -1 \end{pmatrix}$. The nullspace of this is generated by

$$\begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix}.$$

Section 8.5. Problem 4. The first three *Legendre polynomials* are $1, x, x^2 - 1/3$. Choose c so that the fourth polynomial $x^3 - cx$ is orthogonal to the first three. All integrals go from -1 to 1 .

Solution (4 points) We compute

$$\int_{-1}^1 x^3 - cx \, dx = 0 \quad \int_{-1}^1 (x^3 - cx)x \, dx = \frac{2}{5} - \frac{2}{3}c \quad \int_{-1}^1 (x^3 - cx)(x^2 - \frac{1}{3}) \, dx = 0.$$

Thus in order for $x^3 - cx$ to be orthogonal to the other three we need $c = 3/5$.

Section 8.5. Problem 5. For the square wave $f(x)$ in Example 3 show that

$$\int_0^{2\pi} f(x) \cos x \, dx = 0 \quad \int_0^{2\pi} f(x) \sin x \, dx = 4 \quad \int_0^{2\pi} f(x) \sin 2x \, dx = 0.$$

Which three Fourier coefficients come from those integrals?

Solution (4 points) By definition, coefficients that come from these are a_1, b_1, b_2 , respectively. We compute

$$\begin{aligned} \int_0^{2\pi} f(x) \cos x \, dx &= \int_0^{\pi} \cos x \, dx - \int_{\pi}^{2\pi} \cos x \, dx = 0 \\ \int_0^{2\pi} f(x) \sin x \, dx &= \int_0^{\pi} \sin x \, dx - \int_{\pi}^{2\pi} \sin x \, dx = 4 \\ \int_0^{2\pi} f(x) \sin 2x \, dx &= \int_0^{\pi} \sin 2x \, dx - \int_{\pi}^{2\pi} \sin 2x \, dx = 0. \end{aligned}$$

Section 8.5. Problem 12. The functions $1, \cos x, \sin x, \cos 2x, \sin 2x, \dots$ are a basis for a Hilbert space. Write the derivatives of those first five functions as combinations of the same five functions. What is the 5×5 “differentiation matrix” for those functions?

Solution (12 points)

We know that $1' = 0$, and that

$$(\cos x)' = -\sin x \quad (\sin x)' = \cos x \quad (\cos 2x)' = -2 \sin 2x \quad (\sin 2x)' = 2 \cos 2x.$$

Thus the “differentiation matrix” is

$$\begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -2 \\ 0 & 0 & 0 & 2 & 0 \end{pmatrix}.$$

Section 8.5. Problem 13. Find the Fourier coefficients a_k and b_k of the square pulse $F(x)$ centered at $x = 0$: $f(x) = 1/h$ for $|x| \leq h/2$ and $F(x) = 0$ for $h/2 < |x| \leq \pi$. As $h \rightarrow 0$, this $F(x)$ approaches a delta function. Find the limits of a_k and b_k .

Solution (12 points) We compute

$$\begin{aligned} a_0 &= \frac{1}{\pi} \int_{-\pi}^{\pi} F(x) dx = \frac{1}{h\pi} \int_{-h/2}^{h/2} 1 dx = \frac{1}{\pi}. \\ a_k &= \frac{1}{\pi} \int_{-\pi}^{\pi} F(x) \cos kx dx = \frac{1}{\pi h} \int_{-h/2}^{h/2} \cos kx dx = \frac{1}{\pi h k} \sin kx \Big|_{-h/2}^{h/2} = \frac{2}{\pi h k} \sin \frac{kh}{2}. \\ b_k &= \frac{1}{\pi} \int_{-\pi}^{\pi} F(x) \sin kx dx = \frac{1}{\pi h} \int_{-h/2}^{h/2} \sin kx dx = \frac{1}{\pi k} \cos kx \Big|_{-h/2}^{h/2} = 0. \end{aligned}$$

Thus as $h \rightarrow 0$ we see that $a_0 \rightarrow 1/\pi$ and $b_k \rightarrow 0$. We also compute

$$\lim_{h \rightarrow 0} a_k = \lim_{h \rightarrow 0} \frac{1}{\pi} \frac{2}{hk} \sin \frac{hk}{2} = \frac{1}{\pi} \lim_{x \rightarrow 0} \frac{\sin x}{x} = \frac{1}{\pi}$$

where we set $x = hk/2$.

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18.06 Linear Algebra
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