Math 218D-1: Homework #11

due Wednesday, April 3, at 11:59pm

1. Compute the following complex numbers.

a) $(1+i)+(2-i)$ **b)** $(1+i)(2-i)$ **c)** $\overline{2-i}$ **d)** $\dfrac{1+i}{2-i}$

e) $|1+i|$ **f)** $2e^{2\pi i/3}$ **g)** $5e^{3\pi i}$

2. Express each complex number in polar coordinates $re^{i\theta}$.

a) $1+i$ **b)** $\dfrac{-1+i\sqrt{3}}{2}$ **c)** $-\sqrt{3}-3i$ **d)** $\dfrac{1}{1+i}$ **e)** $\left(1-i\sqrt{3}\right)^n$

3. For which numbers θ is $e^{i\theta}=1$? What about -1?

4. For each matrix A and each vector x, decide if x is an eigenvector of A, and if so, find the eigenvalue λ.

a) $\begin{pmatrix} 2 & 3 \\ -3 & 2 \end{pmatrix}, \begin{pmatrix} i \\ 1 \end{pmatrix}$ **b)** $\begin{pmatrix} -4 & 13 & 13 \\ 2 & -2 & -4 \\ -4 & 8 & 10 \end{pmatrix}, \begin{pmatrix} 1+5i \\ -2i \\ 4i \end{pmatrix}$

c) $\begin{pmatrix} 1 & 1 & 1 \\ -1 & -3 & -3 \\ -2 & 0 & -1 \end{pmatrix}, \begin{pmatrix} 2+i \\ 1 \\ -i \end{pmatrix}$

Careful! It is difficult to recognize by inspection if two complex vectors are (complex) scalar multiples of each other.

5. For each 2×2 matrix A, **i)** compute the characteristic polynomial, **ii)** find all (real and complex) eigenvalues, and **iii)** find a basis for each eigenspace, using HW9#14 when applicable. **iv)** Is the matrix diagonalizable (over the complex numbers)? If so, find an invertible matrix C and a diagonal matrix D such that $A=CDC^{-1}$.

a) $\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$ **b)** $\begin{pmatrix} 1 & 2 \\ -2 & 1 \end{pmatrix}$ **c)** $\begin{pmatrix} -3 & 5 \\ -10 & 7 \end{pmatrix}$

6. Diagonalize the following matrix over the complex numbers:[1]

$$A=\begin{pmatrix} 1 & 4 & -6 \\ -6 & 7 & -22 \\ -2 & 1 & -5 \end{pmatrix}.$$

[1] This problem is included to make you do Gaussian elimination by hand with complex numbers *one time*, so that you'll be grateful to have computers do it for you in the future.

7. A certain forest contains a population of rabbits and a population of foxes. If there are r_n rabbits and f_n foxes in year n, then

$$\begin{aligned} r_{n+1} &= 3r_n - \ f_n \\ f_{n+1} &= \ \ r_n + 2f_n: \end{aligned}$$

in other words, each rabbit produces three baby rabbits on average, but there is some loss due to predation by foxes; each fox produces two babies on average, but this is increased with ample prey.

a) Let $v_n = \binom{r_n}{f_n}$. Find a matrix A such that $v_{n+1} = Av_n$.

b) Find an eigenbasis of A. (The eigenvectors and eigenvalues will be complex.) [**Hint:** Part **d)** will be easier if you choose the eigenvectors with first coordinate equal to 1.]

c) Suppose that $r_0 = 2$ and $f_0 = 1$. Find closed formulas for r_n and f_n. Find a formula for r_n involving only real numbers. (This latter formula can involve an arctan.)

d) In this model, the populations do not stabilize. How many years will it take for the foxes to eat all of the rabbits?

In general, any 2×2 difference equation with a complex eigenvalue will exhibit oscillation centered at zero. This phenomenon can be described explicitly, but is beyond the scope of this course.

8. **a)** Let A be an $n \times n$ matrix. Prove that λ is an eigenvalue of A with geometric multiplicity n if and only if $A = \lambda I_n$.

b) Find a non-diagonal 2×2 matrix such that 1 is an eigenvalue with algebraic multiplicity 2.

9. Find examples of real 2×2 matrices A with the following properties.

a) A is invertible and diagonalizable over the real numbers.

b) A is invertible but not diagonalizable over the complex numbers.

c) A is diagonalizable over the real numbers but not invertible.

d) A is neither invertible nor diagonalizable over the complex numbers.

This shows that *invertibility and diagonalizability have nothing to do with each other*.

10. Let A be an $n \times n$ matrix.

a) Show that the product of the (real and complex) eigenvalues, counted with algebraic multiplicity, is equal to $\det(A)$.

b) [**Optional**] Show that the sum of the (real and complex) eigenvalues, counted with algebraic multiplicity, is equal to $\mathrm{Tr}(A)$.

(Both of these are identities involving the characteristic polynomial of A.)

11. Let V be a plane in $\mathbf{R}^3$, let $L = V^\perp$ be the orthogonal line, let P_L be the matrix for orthogonal projection onto L, and let $R_V = I_3 - 2P_L$ be the reflection over V, as in HW9#6.

a) Prove that there exists an invertible 3×3 matrix C such that

$$P_L = C \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} C^{-1}.$$

Use this to show that the characteristic polynomial of P_L is $-\lambda^2(\lambda - 1)$.

b) Prove that

$$R_V = C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{pmatrix} C^{-1}$$

for the same matrix C of part **a)**. Use this to show that the characteristic polynomial of R_V is $-(\lambda - 1)^2(\lambda + 1)$ and that $\det(R_V) = -1$.

(Compare HW9#6, HW10#3, and HW10#11.)

12. For each matrix in HW10#2(a)–(c), compute the algebraic and geometric multiplicity of each eigenvalue. What does your answer say about diagonalizability?

Optional: do (d)–(g) as well.

13. Give an example of each of the following, or explain why no such example exists. All matrices should have real entries.

a) A 3×3 matrix with eigenvalues $0, 1, 2$, and corresponding eigenvectors

$$\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \quad \begin{pmatrix} 1 \\ -1 \\ 1 \end{pmatrix}, \quad \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}.$$

b) A 4×4 matrix having eigenvalue 2 with algebraic multiplicity 2 and geometric multiplicity 3.

c) A 3×3 matrix with one complex (non-real) eigenvalue and two real eigenvalues.

d) A 2×2 matrix A such that A^2 is diagonalizable over the real numbers but A is not diagonalizable, even over the complex numbers.

[**Hint:** try a nonzero matrix A such that $A^2 = 0$.]

14. Decide if each statement is true or false, and explain why.

a) If A and B are diagonalizable $n\times n$ matrices, then so is AB.

b) An $n\times n$ matrix with n (different) eigenvalues is diagonalizable.

c) An $n\times n$ matrix is diagonalizable if it has n eigenvalues, counted with algebraic multiplicity.

d) Any 2×2 real matrix with a complex (non-real) eigenvalue is diagonalizable over the complex numbers.

e) Any 3×3 real matrix with a complex (non-real) eigenvalue is diagonalizable over the complex numbers.

f) Any 4×4 real matrix with a complex (non-real) eigenvalue is diagonalizable over the complex numbers.

g) Any 2×2 real matrix has a real eigenvalue.

h) Any 3×3 real matrix has a real eigenvalue.

i) Any $n\times n$ matrix has a (real or complex) eigenvalue.

j) If the characteristic polynomial of A is $-(\lambda^3-1)=-(\lambda^2+\lambda+1)(\lambda-1)$, then the 1-eigenspace of A is a line.

15. For each matrix, decide if it is stochastic, positive stochastic, or not stochastic.

$$\textbf{a)}\ \begin{pmatrix} .3 & .1 & .2 \\ .4 & .4 & .4 \\ .3 & .5 & .4 \end{pmatrix} \qquad \textbf{b)}\ \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad \textbf{c)}\ \begin{pmatrix} .3 & .4 \\ .4 & .3 \\ .3 & .3 \end{pmatrix}$$

$$\textbf{d)}\ \frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \qquad \textbf{e)}\ \begin{pmatrix} .3 & -.1 & .2 \\ .4 & .6 & .4 \\ .3 & .5 & .4 \end{pmatrix} \qquad \textbf{f)}\ \begin{pmatrix} .3 & 0 & .2 \\ .4 & 0 & .4 \\ .3 & 0 & .4 \end{pmatrix}$$

16. For each positive stochastic matrix A and each vector v_0, **a)** find the steady state vector w of A, and **b)** compute $\lim_{k\to\infty} A^k v_0$.

$$\textbf{a)}\ A=\begin{pmatrix} .64 & .54 \\ .36 & .46 \end{pmatrix},\ v_0=\begin{pmatrix} 3 \\ 4 \end{pmatrix} \qquad \textbf{b)}\ A=\frac{1}{40}\begin{pmatrix} 13 & 11 & 8 \\ 5 & 19 & 8 \\ 22 & 10 & 24 \end{pmatrix},\ v_0=\begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}$$

$$\textbf{c)}\ A=\frac{1}{150}\begin{pmatrix} 38 & 6 & 9 & 34 \\ 54 & 78 & 57 & 42 \\ 23 & 21 & 54 & 4 \\ 35 & 45 & 30 & 70 \end{pmatrix},\ v_0=\begin{pmatrix} 3 \\ -1 \\ -1 \\ -2 \end{pmatrix}$$

17. Pretend that there are four car rental agencies in Durham. Suppose that a customer renting a car from agency i will return the car the next day to agency j, with the following probabilities:

		Renting from agency			
		1	2	3	4
Returning to agency	1	22.8%	9.2%	2.4%	0.4%
	2	19.6%	44.4%	16.8%	22.8%
	3	8.4%	7.6%	27.2%	11.2%
	4	49.2%	38.8%	53.6%	65.6%

For instance, a customer renting from agency 3 has a 53.6% probability of returning it to agency 4.

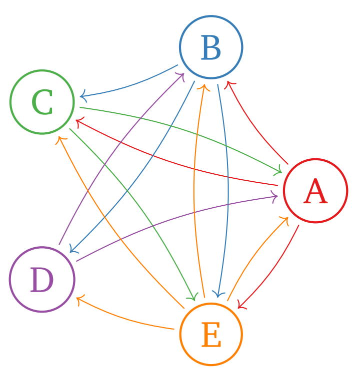
If there are 100 cars available for rental, how many cars will be at each agency after a long time?

18. Evaluate

$$\lim_{k\to\infty}\begin{pmatrix} .3 & .1 & .2 \\ .4 & .4 & .4 \\ .3 & .5 & .4 \end{pmatrix}^k \begin{pmatrix} -1 \\ 2 \\ -1 \end{pmatrix} =$$

without doing any computations.

19. Consider the following Internet with five pages:



a) Compute the importance matrix A.

b) Compute the Google matrix G with damping factor $p = 0.15$.

c) Find the PageRank vector (with the help of a computer). Which page is the most important?

20. Decide if each statement is true or false, and explain why.

a) A positive stochastic matrix has a 1-eigenvector whose coordinates are all *negative*.

b) The 1-eigenspace of a positive stochastic matrix can be a plane.

c) If $\lambda \neq 1$ is an eigenvalue of a positive stochastic matrix, then $|\lambda| < 1$.

d) If $\lambda \neq 1$ is an eigenvalue of a positive stochastic matrix and v is a λ-eigenvector, then the coordinates of v sum to zero.

e) A positive stochastic matrix is diagonalizable.