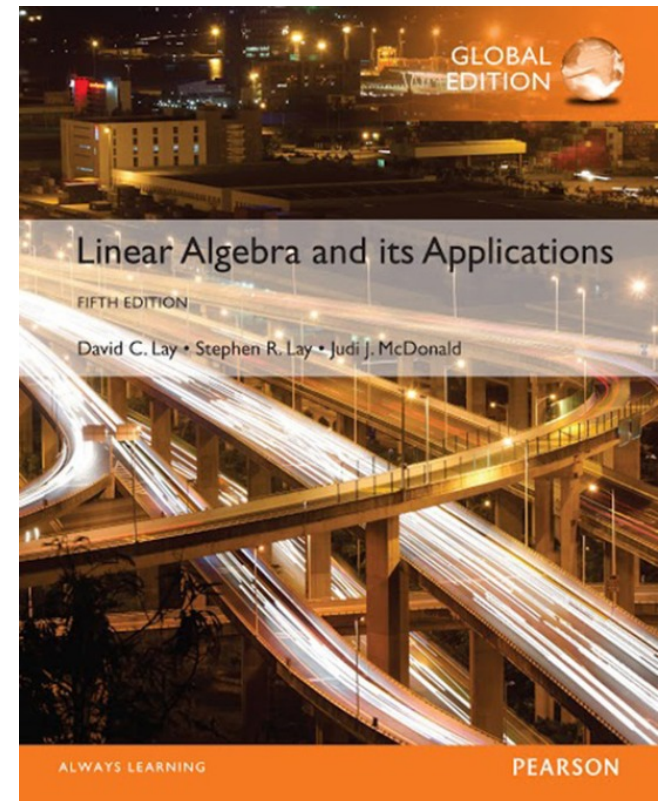


5

Eigenvalues and Eigenvectors

5.1

EIGENVECTORS AND EIGENVALUES



EIGENVECTORS AND EIGENVALUES

- **Definition:** An eigenvector of an $n \times n$ matrix A is a nonzero vector \mathbf{x} such that $A\mathbf{x} = \lambda\mathbf{x}$ for some scalar λ . A scalar λ is called an eigenvalue of A if there is a nontrivial solution \mathbf{x} of $A\mathbf{x} = \lambda\mathbf{x}$; such an \mathbf{x} is called an eigenvector corresponding to λ .
- λ is an eigenvalue of an $n \times n$ matrix A if and only if the equation

$$(A - \lambda I)\mathbf{x} = 0 \quad (3)$$

has a nontrivial solution.

- The set of all solutions of (3) is just the null space of the matrix $A - \lambda I$.

EIGENVECTORS AND EIGENVALUES

- So this set is a *subspace* of \mathbb{R}^n and is called the **eigenspace** of A corresponding to λ .
- The eigenspace consists of the zero vector and all the eigenvectors corresponding to λ .
- **Example 3:** Show that 7 is an eigenvalue of matrix

$$A = \begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix} \text{ and find the corresponding eigenvectors.}$$

EIGENVECTORS AND EIGENVALUES

- **Solution:** The scalar 7 is an eigenvalue of A if and only if the equation

$$A\mathbf{x} = 7\mathbf{x} \quad (1)$$

has a nontrivial solution.

- But (1) is equivalent to $A\mathbf{x} - 7\mathbf{x} = \mathbf{0}$, or

$$(A - 7I)\mathbf{x} = \mathbf{0} \quad (2)$$

- To solve this homogeneous equation, form the matrix

$$A - 7I = \begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix} - \begin{bmatrix} 7 & 0 \\ 0 & 7 \end{bmatrix} = \begin{bmatrix} -6 & 6 \\ 5 & -5 \end{bmatrix}$$

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- The columns of $A - 7I$ are obviously linearly dependent, so (2) has nontrivial solutions.
- To find the corresponding eigenvectors, use row operations:

$$\begin{bmatrix} -6 & 6 & 0 \\ 5 & -5 & 0 \end{bmatrix} \sim \begin{bmatrix} 1 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\begin{aligned} x_1 - x_2 &= 0 \\ \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} &= x_2 \begin{bmatrix} 1 \\ 1 \end{bmatrix} \end{aligned}$$

- The general solution has the form $x_2 \begin{bmatrix} 1 \\ 1 \end{bmatrix}$.
- Each vector of this form with $x_2 \neq 0$ is an eigenvector corresponding to $\lambda = 7$.

EIGENVECTORS AND EIGENVALUES

- **Example 4:** Let $A = \begin{bmatrix} 4 & -1 & 6 \\ 2 & 1 & 6 \\ 2 & -1 & 8 \end{bmatrix}$. An eigenvalue of A is 2. Find a basis for the corresponding eigenspace.

- **Solution:** Form

$$A - 2I = \begin{bmatrix} 4 & -1 & 6 \\ 2 & 1 & 6 \\ 2 & -1 & 8 \end{bmatrix} - \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 2 \end{bmatrix} = \begin{bmatrix} 2 & -1 & 6 \\ 2 & -1 & 6 \\ 2 & -1 & 6 \end{bmatrix}$$

and row reduce the augmented matrix for $(A - 2I)\mathbf{x} = \mathbf{0}$.

EIGENVECTORS AND EIGENVALUES

$$\begin{bmatrix} 2 & -1 & 6 & 0 \\ 2 & -1 & 6 & 0 \\ 2 & -1 & 6 & 0 \end{bmatrix} \sim \begin{bmatrix} 2 & -1 & 6 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$2x_1 = x_2 - 6x_3$$

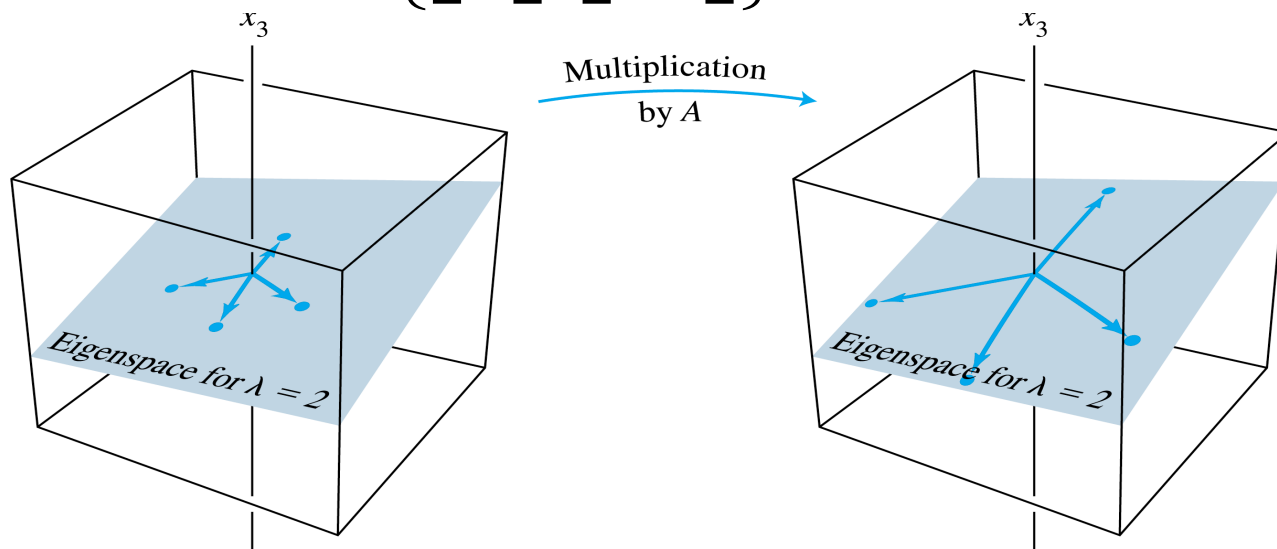
- At this point, it is clear that 2 is indeed an eigenvalue of A because the equation $(A - 2I)x = 0$ has free variables.
- The general solution is

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = x_2 \begin{bmatrix} 1/2 \\ 1 \\ 0 \end{bmatrix} + x_3 \begin{bmatrix} -3 \\ 0 \\ 1 \end{bmatrix}, \text{ } x_2 \text{ and } x_3 \text{ free.}$$

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- The eigenspace, shown in the following figure, is a two-dimensional subspace of \mathbb{R}^3 . A basis is

$$\left\{ \begin{bmatrix} 1 \\ 2 \\ 0 \end{bmatrix}, \begin{bmatrix} -3 \\ 0 \\ 1 \end{bmatrix} \right\}$$



A acts as a dilation on the eigenspace.

EIGENVECTORS AND EIGENVALUES

- **Theorem 1:** The eigenvalues of a triangular matrix are the entries on its main diagonal.
- **Proof:** For simplicity, consider the 3×3 case.
- If A is upper triangular, the $A - \lambda I$ has the form

$$\begin{aligned} A - \lambda I &= \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ 0 & a_{22} & a_{23} \\ 0 & 0 & a_{33} \end{bmatrix} - \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda & 0 \\ 0 & 0 & \lambda \end{bmatrix} \\ &= \begin{bmatrix} a_{11} - \lambda & a_{12} & a_{13} \\ 0 & a_{22} - \lambda & a_{23} \\ 0 & 0 & a_{33} - \lambda \end{bmatrix} \end{aligned}$$

EIGENVECTORS AND EIGENVALUES

- The scalar λ is an eigenvalue of A if and only if the equation $(A - \lambda I)\mathbf{x} = \mathbf{0}$ has a nontrivial solution, that is, if and only if the equation has a free variable.
- Because of the zero entries in $A - \lambda I$, it is easy to see that $(A - \lambda I)\mathbf{x} = \mathbf{0}$ has a free variable if and only if at least one of the entries on the diagonal of $A - \lambda I$ is zero.
- This happens if and only if λ equals one of the entries a_{11} , a_{22} , a_{33} in A .

EIGENVECTORS AND EIGENVALUES

- **Theorem 2:** If $\mathbf{v}_1, \dots, \mathbf{v}_r$ are eigenvectors that correspond to distinct eigenvalues $\lambda_1, \dots, \lambda_r$ of an $n \times n$ matrix A , then the set $\{\mathbf{v}_1, \dots, \mathbf{v}_r\}$ is linearly independent. **Proof by Contradiction**
- **Proof:** Suppose $\{\mathbf{v}_1, \dots, \mathbf{v}_r\}$ is linearly dependent.
- Since \mathbf{v}_1 is nonzero, Theorem 7 in Section 1.7 says that one of the vectors in the set is a linear combination of the preceding vectors.
- Let p be the least index such that \mathbf{v}_{p+1} is a linear combination of the preceding (linearly independent) vectors.

EIGENVECTORS AND EIGENVALUES

- Then there exist scalars c_1, \dots, c_p such that

$$(5) \quad c_1 \mathbf{v}_1 + \cdots + c_p \mathbf{v}_p = \mathbf{v}_{p+1}$$

- Multiplying both sides of (5) by A and using the fact that $A\mathbf{v}_k = \lambda_k \mathbf{v}_k$ for each k , we obtain

$$c_1 A\mathbf{v}_1 + \cdots + c_p A\mathbf{v}_p = A\mathbf{v}_{p+1}$$

$$c_1 \lambda_1 \mathbf{v}_1 + \cdots + c_p \lambda_p \mathbf{v}_p = \lambda_{p+1} \mathbf{v}_{p+1} \quad (6)$$

- Multiplying both sides of (5) by λ_{p+1} and subtracting the result from (6), we have

$$c_1 (\lambda_1 - \lambda_{p+1}) \mathbf{v}_1 + \cdots + c_p (\lambda_p - \lambda_{p+1}) \mathbf{v}_p = 0 \quad (7)$$

EIGENVECTORS AND EIGENVALUES

- Since $\{\mathbf{v}_1, \dots, \mathbf{v}_p\}$ is linearly independent, the weights in (7) are all zero.
- But none of the factors $\lambda_i - \lambda_{p+1}$ are zero, because the eigenvalues are distinct.
- Hence $c_i = 0$ for $i = 1, \dots, p$.
- But then (5) says that $\mathbf{v}_{p+1} = 0$, which is impossible.

an eigenvector is a non-zero vector.



EIGENVECTORS AND DIFFERENCE EQUATIONS

- Hence $\{\mathbf{v}_1, \dots, \mathbf{v}_r\}$ cannot be linearly dependent and therefore must be linearly independent.
- If A is an $n \times n$ matrix, then (8) is a *recursive* description of a sequence $\{x_k\}$ in \mathbb{R}^n .

$$\mathbf{x}_{k+1} = A\mathbf{x}_k \quad (k = 0, 1, 2, \dots) \quad (8)$$

- A **solution** of (8) is an explicit description of $\{x_k\}$ whose formula for each x_k does not depend directly on A or on the preceding terms in the sequence other than the initial term \mathbf{x}_0 .

EIGENVECTORS AND DIFFERENCE EQUATIONS

- The simplest way to build a solution of (8) is to take an eigenvector \mathbf{x}_0 and its corresponding eigenvalue λ and let

$$\mathbf{x}_k = \lambda^k \mathbf{x}_0 \quad (k = 1, 2, \dots) \quad (9)$$

- This sequence is a solution because

$$A\mathbf{x}_k = A(\lambda^k \mathbf{x}_0) = \lambda^k (A\mathbf{x}_0) = \lambda^k (\lambda \mathbf{x}_0) = \lambda^{k+1} \mathbf{x}_0 = \mathbf{x}_{k+1}$$