Announcements

October 24

- WeBWorK assignment 5.1 is due **Monday** at 6am.
- Midterm 2 will take place in recitation this Friday, 10/28.
  - This is the day before the withdrawal deadline.
  - It covers §§2.1–2.3, 2.8, 2.9, 3.1, and 3.2.
- A practice exam has been posted on the website.
  - I'll post the solutions in the next couple of days.
- There are study tips on Piazza.
- Post requests for Wednesday's review session on Piazza.
- **Triple office hours this week**: today 2–4pm, Wednesday 1–3pm, Thursday 2:30–4:30pm, and by appointment, in Skiles 221.
  - As always, TAs' office hours are posted on the website.
  - Math Lab is also a good place to visit.

Section 5.2

The Characteristic Equation

We have a couple of new ways of saying "A is invertible" now:

The Invertible Matrix Theorem

Let A be a square $n \times n$ matrix, and let $T\colon \mathbf{R}^n \to \mathbf{R}^n$ be the linear transformation $T(x) = Ax$. The following statements are equivalent.

1. A is invertible.
2. T is invertible.
3. A is row equivalent to I_n.
4. A has n pivots.
5. $Ax = 0$ has only the trivial solution.
6. The columns of A are linearly independent.
7. T is one-to-one.
8. $Ax = b$ is consistent for all b in $\mathbf{R}^n$.
9. The columns of A span $\mathbf{R}^n$.
10. T is onto.
11. A has a left inverse (there exists B such that $BA = I_n$).
12. A has a right inverse (there exists B such that $AB = I_n$).
13. A^T is invertible.
14. The columns of A form a basis for $\mathbf{R}^n$.
15. $\operatorname{Col} A = \mathbf{R}^n$.
16. $\dim \operatorname{Col} A = n$.
17. $\operatorname{rank} A = n$.
18. $\operatorname{Nul} A = \{0\}$.
19. $\dim \operatorname{Nul} A = 0$.

19. The determinant of A is *not* equal to zero.
20. The number 0 is *not* an eigenvalue of A.

The Characteristic Polynomial

Let A be a square matrix.

$$\begin{aligned} \lambda \text{ is an eigenvalue of } A &\iff Ax = \lambda x \text{ has a nontrivial solution} \\ &\iff (A - \lambda I)x = 0 \text{ has a nontrivial solution} \\ &\iff A - \lambda I \text{ is not invertible} \\ &\iff \det(A - \lambda I) = 0. \end{aligned}$$

This gives us a way to compute the eigenvalues of A.

Definition

Let A be a square matrix. The **characteristic polynomial** of A is

$$f(\lambda) = \det(A - \lambda I).$$

The **characteristic equation** of A is the equation

$$f(\lambda) = \det(A - \lambda I) = 0.$$

Important

The eigenvalues of A are the roots of the characteristic polynomial $f(\lambda) = \det(A - \lambda I)$.

The Characteristic Polynomial
Example

Question: what are the eigenvalues of

$$A = \begin{pmatrix} 5 & 2 \\ 2 & 1 \end{pmatrix}?$$

Answer: First we find the characteristic polynomial:

$$\begin{aligned} f(\lambda) &= \det(A - \lambda I) = \det\left[\begin{pmatrix} 5 & 2 \\ 2 & 1 \end{pmatrix} - \begin{pmatrix} \lambda & 0 \\ 0 & \lambda \end{pmatrix}\right] = \det\begin{pmatrix} 5-\lambda & 2 \\ 2 & 1-\lambda \end{pmatrix} \\ &= (5-\lambda)(1-\lambda) - 2\cdot 2 \\ &= \lambda^2 - 6\lambda + 1. \end{aligned}$$

The eigenvalues are the roots of the characteristic polynomial, which we can find using the quadratic formula:

$$\lambda = \frac{6 \pm \sqrt{36-4}}{2} = 3 \pm 2\sqrt{2}.$$

Question: what is the characteristic polynomial of

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

Answer:

$$\begin{aligned} f(\lambda) &= \det(A - \lambda I) = \det \begin{pmatrix} a - \lambda & b \\ c & d - \lambda \end{pmatrix} \\ &= (a - \lambda)(d - \lambda) - bc \\ &= \lambda^2 - (a + d)\lambda + (ad - bc) \end{aligned}$$

What do you notice about $f(\lambda)$? The constant term is $\det(A)$, which is zero if and only if $\lambda = 0$ is a root.

Question: what are the eigenvalues of the rabbit population matrix

$$A = \begin{pmatrix} 0 & 6 & 8 \\ \frac{1}{2} & 0 & 0 \\ 0 & \frac{1}{2} & 0 \end{pmatrix}?$$

Answer: First we find the characteristic polynomial:

$$\begin{aligned} f(\lambda) = \det(A - \lambda I) &= \det \begin{pmatrix} -\lambda & 6 & 8 \\ \frac{1}{2} & -\lambda & 0 \\ 0 & \frac{1}{2} & -\lambda \end{pmatrix} \\ &= 8\left(\frac{1}{4} - 0 \cdot -\lambda\right) - \lambda\left(\lambda^2 - 6 \cdot \frac{1}{2}\right) \\ &= -\lambda^3 + 3\lambda + 2. \end{aligned}$$

We know from before that one eigenvalue is $\lambda = 2$: indeed, $f(2) = -8 + 6 + 2 = 0$. Doing polynomial long division, we get:

$$\frac{-\lambda^3 + 3\lambda + 2}{\lambda - 2} = -\lambda^2 - 2\lambda - 1 = -(\lambda + 1)^2.$$

Hence $\lambda = -1$ is also an eigenvalue.

Algebraic Multiplicity

Definition

The **algebraic multiplicity** of an eigenvalue λ is its multiplicity as a root of the characteristic polynomial.

This is not a very interesting notion *yet*. It will become interesting when we also define *geometric* multiplicity later.

Example

In the rabbit population matrix, $f(\lambda) = -(\lambda - 2)(\lambda + 1)^2$, so the algebraic multiplicity of the eigenvalue 2 is 1, and the algebraic multiplicity of the eigenvalue -1 is 2.

Example

In the matrix $\begin{pmatrix} 5 & 2 \\ 2 & 1 \end{pmatrix}$, $f(\lambda) = (\lambda - (3 - 2\sqrt{2}))(\lambda - (3 + 2\sqrt{2}))$, so the algebraic multiplicity of $3 + 2\sqrt{2}$ is 1, and the algebraic multiplicity of $3 - 2\sqrt{2}$ is 1.

If A is an $n \times n$ matrix, the characteristic polynomial

$$f(\lambda) = \det(A - \lambda I)$$

turns out to be a polynomial of degree n, and its roots are the eigenvalues of A.

Poll

If you count the eigenvalues of A, with their algebraic multiplicities, you will get:

A. Always n.

B. Always at most n, but sometimes less.

C. Always at least n, but sometimes more.

D. None of the above.

The answer depends on whether you allow *complex* eigenvalues. If you only allow real eigenvalues, the answer is B. Otherwise it is A, because any degree-n polynomial has exactly n *complex* roots, counted with multiplicity. Stay tuned.

Similarity

Definition

Two $n \times n$ matrices A and B are **similar** if there is an invertible $n \times n$ matrix C such that

$$A = CBC^{-1}.$$

What does this mean? Say the columns of C are $v_1, v_2, \ldots, v_n$. These form a basis $\mathcal{B} = \{v_1, v_2, \ldots, v_n\}$ for $\mathbf{R}^n$ because C is invertible. If $x = c_1 v_1 + c_2 v_2 + \cdots + c_n v_n$ then

$$[x]_{\mathcal{B}} = \begin{pmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{pmatrix} \implies x = c_1 v_1 + c_2 v_2 + c_n v_n = C[x]_{\mathcal{B}}.$$

Since $x = C[x]_{\mathcal{B}}$ we have $[x]_{\mathcal{B}} = C^{-1}x$.

Suppose $B[x]_{\mathcal{B}} = [y]_{\mathcal{B}}$. Then

$$Ax = CBC^{-1}x = CB[x]_{\mathcal{B}} = C[y]_{\mathcal{B}} = y.$$

So A does what B does to the $\mathcal{B}$-cooordinates.

Similarity

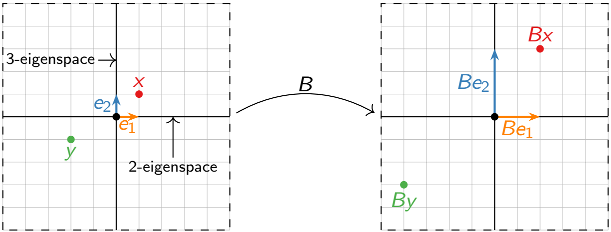
Example

$$A = \begin{pmatrix} 1 & 2 \\ -1 & 4 \end{pmatrix} \quad B = \begin{pmatrix} 2 & 0 \\ 0 & 3 \end{pmatrix} \quad C = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix} \quad \implies \quad A = CBC^{-1}.$$

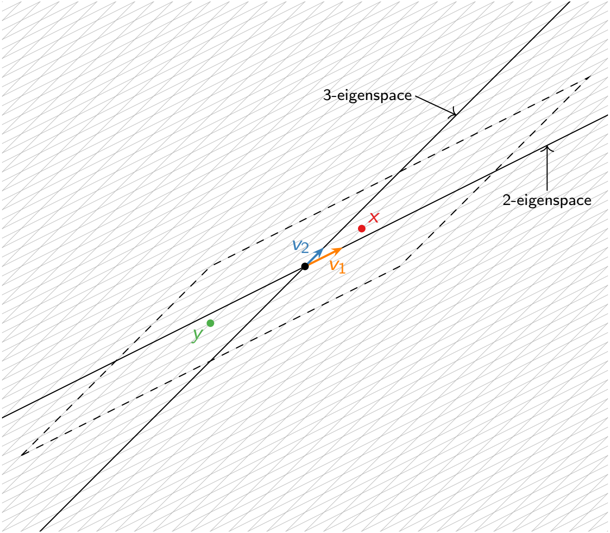
What does B do geometrically? It scales the x-direction by 2 and the y-direction by 3.

So A does what B does, with respect to the basis $\mathcal{B} = \left\{ \begin{pmatrix} 2 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \end{pmatrix} \right\}$.

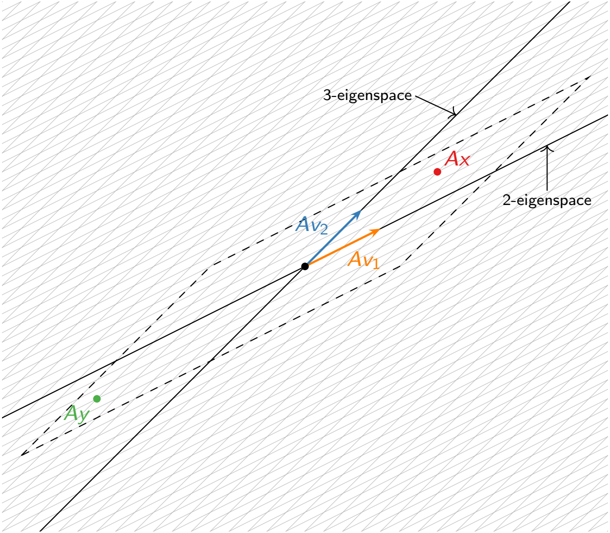
B acting on the usual coordinates



A does what B does to the $\mathcal{B}$-coordinates



A does what B does to the $\mathcal{B}$-coordinates



Similar Matrices Have the Same Characteristic Polynomial

Fact: If A and B are similar, then they have the same characteristic polynomial.

Why? Suppose $A = CBC^{-1}$.

$$\begin{aligned} A - \lambda I &= CBC^{-1} - \lambda I \\ &= CBC^{-1} - C(\lambda I)C^{-1} \\ &= C(B - \lambda I)C^{-1}. \end{aligned}$$

Therefore,

$$\begin{aligned} \det(A - \lambda I) &= \det\big(C(B - \lambda I)C^{-1}\big) \\ &= \det(C)\det(B - \lambda I)\det(C^{-1}) \\ &= \det(B - \lambda I), \end{aligned}$$

because $\det(C^{-1}) = \det(C)^{-1}$.

Conseqence: similar matrices have the same eigenvalues!
(But different eigenvectors in general.)

Warnings

1. Matrices with the same eigenvalues need not be similar. For instance,

$$\begin{pmatrix} 2 & 1 \\ 0 & 2 \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} 2 & 0 \\ 0 & 2 \end{pmatrix}$$

both only have the eigenvalue 2, but they are not similar.

2. Similarity has nothing to do with row equivalence. For instance,

$$\begin{pmatrix} 2 & 1 \\ 0 & 2 \end{pmatrix} \quad \text{and} \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

are row equivalent, but they have different eigenvalues.

Applications to Difference Equations

Let $B = \begin{pmatrix} 1 & 0 \\ 0 & 1/2 \end{pmatrix}$. Fix a vector v_0, and let $v_1 = Bv_0$, $v_2 = Bv_1$, etc., so $v_n = B^n v_0$.

Question: what happens to the v_i's for different choices of v_0?

Answer: note that e_1 and e_2 are eigenvectors of B, with eigenvalues 1 and $1/2$:

$$Be_1 = e_1 \qquad Be_2 = \frac{1}{2} e_2.$$

Therefore,

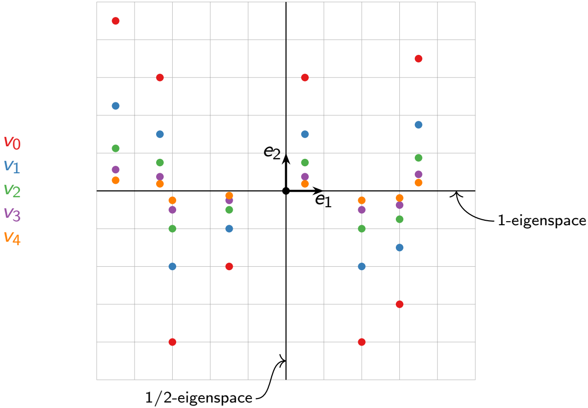
$$B^n e_1 = e_1 \qquad B^n e_2 = \frac{1}{2^n} e_2,$$

so

$$B^n \begin{pmatrix} a \\ b \end{pmatrix} = B^n(ae_1 + be_2) = ae_1 + \frac{b}{2^n} e_2 = \begin{pmatrix} a \\ b/2^n \end{pmatrix}.$$

So the x-coordinate of v_n equals the x-coordinate of v_0, and the y-coordinate gets halved every time.

$$B\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1/2 \end{pmatrix}\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} a \\ b/2 \end{pmatrix}$$



So all points get "sucked into the x-axis."

Let $A = \begin{pmatrix} 3/4 & 1/4 \\ 1/4 & 3/4 \end{pmatrix}$. Fix a vector v_0, and let $v_1 = Av_0$, $v_2 = Av_1$, etc., so $v_n = A^n v_0$.

Question: what happens to the v_i's for different choices of v_0?

The characteristic polynomial is

$$f(\lambda) = \det \begin{pmatrix} 3/4 - \lambda & 1/4 \\ 1/4 & 3/4 - \lambda \end{pmatrix} = \lambda^2 - \frac{3}{2}\lambda + \frac{1}{2} = (\lambda - 1)\Big(\lambda - \frac{1}{2}\Big).$$

Eigenvectors with eigenvalues 1 and 1/2 are, respectively,

$$w_1 = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \qquad w_2 = \begin{pmatrix} 1 \\ -1 \end{pmatrix}.$$

These are linearly independent because they have distinct eigenvalues; therefore they form a basis $\mathcal{B} = \{w_1, w_2\}$ for $\mathbf{R}^2$. As before,

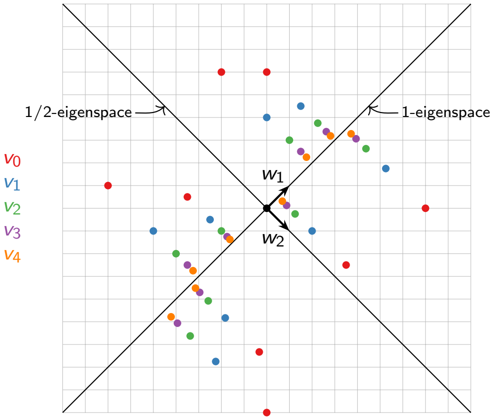
$$A^n(aw_1 + bw_2) = aw_1 + \frac{b}{2^n} w_2.$$

In fact, $A = CBC^{-1}$, with $C = \left[\begin{smallmatrix} 1 & 1 \\ 1 & -1 \end{smallmatrix}\right]$. (Why?)

Applications to Difference Equations

Picture of the more complicated example

$$w_1 = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad Aw_1 = w_1 \qquad w_2 = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad Aw_2 = \frac{1}{2} w_2$$



So all points get "sucked into the 1-eigenspace."

The matrix $A = \begin{pmatrix} 3/4 & 1/4 \\ 1/4 & 3/4 \end{pmatrix}$ is called a **stochastic matrix**.

The phenomenon that v_n tends towards an eigenvector as n gets large is very common.

It happened with the rabbit population matrix, for a similar reason.

Google's PageRank algorithm uses a stochastic matrix, with exactly the same property. But it has dimensions approximately (1 gazillion)$\times$(1 gazillion).