Announcements

Wednesday, November 7

- The third midterm is on **Friday, November 16**.
  - That is one week from this Friday.
  - The exam covers §§*4.5, 5.1, 5.2. 5.3, 6.1, 6.2, 6.4, 6.5* (through today's material).
- WeBWorK 6.1, 6.2 are due today at 11:59pm.
- The quiz on Friday covers §§6.1, 6.2.
- My office is Skiles 244 and Rabinoffice hours are: Mondays, 12–1pm; Wednesdays, 1–3pm.

Recall: an $n \times n$ matrix A is **diagonalizable** if it is similar to a diagonal matrix:

$$A = CDC^{-1} \quad \text{for} \quad D = \begin{pmatrix} \lambda_1 & 0 & \cdots & 0 \\ 0 & \lambda_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n \end{pmatrix}.$$

It is easy to take powers of diagonalizable matrices:

$$A^i = CD^iC^{-1} = C \begin{pmatrix} \lambda_1^i & 0 & \cdots & 0 \\ 0 & \lambda_2^i & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n^i \end{pmatrix} C^{-1}.$$

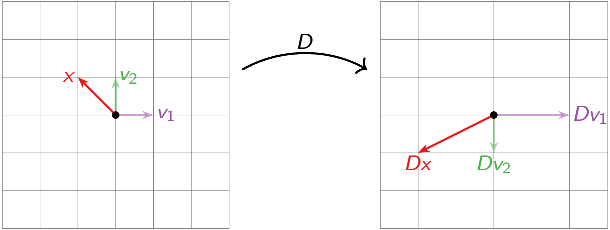
We begin today by discussing the *geometry* of diagonalizable matrices.

Geometry of Diagonal Matrices

A diagonal matrix $D = \begin{pmatrix} 2 & 0 \\ 0 & -1 \end{pmatrix}$ just scales the coordinate axes:

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

This is easy to visualize:



$$x = \begin{pmatrix} -1 \\ 1 \end{pmatrix} \implies Dx = \begin{pmatrix} -2 \\ -1 \end{pmatrix}.$$

Geometry of Diagonal*izable* Matrices

We had this example last time: $A = CDC^{-1}$ for

$$A = \begin{pmatrix} 1/2 & 3/2 \\ 3/2 & 1/2 \end{pmatrix} \qquad D = \begin{pmatrix} 2 & 0 \\ 0 & -1 \end{pmatrix} \qquad C = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

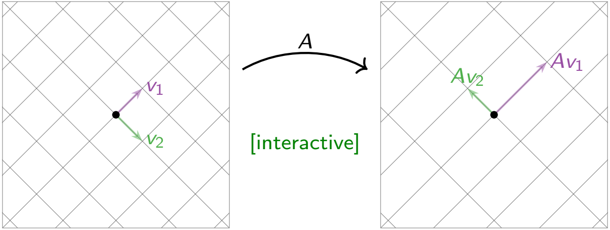
The eigenvectors of A are $v_1 = \binom{1}{1}$ and $v_2 = \binom{1}{-1}$ with eigenvalues 2 and -1.

The eigenvectors form a *basis* for $\mathbf{R}^2$ because they're linearly independent.

Any vector can be written as a linear combination of basis vectors:

$$x = a_1 v_1 + a_2 v_2 \implies Ax =$$

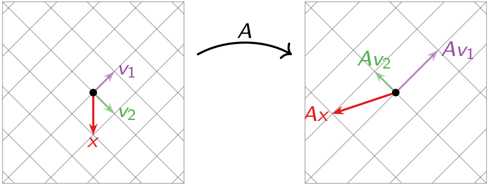
Conclusion: A scales the "v_1-direction" by 2 and the "v_2-direction" by -1.



Geometry of Diagonal*izable* Matrices
Continued

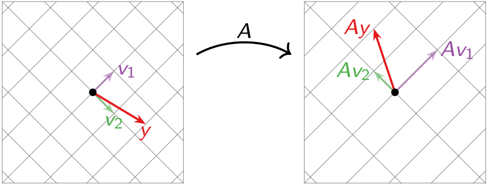
Example: $x = \begin{pmatrix} 0 \\ -2 \end{pmatrix} = -1v_1 + 1v_2$

$$Ax = -1Av_1 + 1Av_2 = -2v_1 + -1v_2$$



Example: $y = \frac{1}{2}\begin{pmatrix} 5 \\ -3 \end{pmatrix} = \frac{1}{2}v_1 + 2v_2$

$$Ay = \frac{1}{2}Av_1 + 2Av_2 = 1v_1 + -2v_2$$



Dynamics of Diagonalizable Matrices

We motivated diagonalization by taking powers:

$$A^i = CD^iC^{-1} = C \begin{pmatrix} \lambda_1^i & 0 & \cdots & 0 \\ 0 & \lambda_2^i & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \lambda_n^i \end{pmatrix} C^{-1}.$$

This lets us compute powers of matrices easily. How to visualize this?

$$A^n v = A(A(A \cdots (Av)) \cdots)$$

Multiplying a vector v by A^n means repeatedly multiplying by A.

$$A = \frac{1}{10}\begin{pmatrix} 11 & 6 \\ 9 & 14 \end{pmatrix} = CDC^{-1} \quad \text{for} \quad C = \begin{pmatrix} 2/3 & 1 \\ -1 & 1 \end{pmatrix} \qquad D = \begin{pmatrix} 2 & 0 \\ 0 & 1/2 \end{pmatrix}.$$

Eigenvectors of A are $v_1 = \binom{2/3}{-1}$ and $v_2 = \binom{1}{1}$ with eigenvalues 2 and 1/2.

$$\begin{aligned} A(a_1v_1 + a_2v_2) &= 2a_1v_1 + \frac{1}{2}a_2v_2 \\ A^2(a_1v_1 + a_2v_2) &= 4a_1v_1 + \frac{1}{4}a_2v_2 \\ A^3(a_1v_1 + a_2v_2) &= 8a_1v_1 + \frac{1}{8}a_2v_2 \\ &\vdots \\ A^n(a_1v_1 + a_2v_2) &= 2^na_1v_1 + \frac{1}{2^n}a_2v_2 \end{aligned}$$

What does repeated application of A do geometrically?

It makes the "v_1-coordinate" very big, and the "v_2-coordinate" very small.

[interactive]

$$A = \frac{1}{6}\begin{pmatrix} 5 & -1 \\ -2 & 4 \end{pmatrix} = CDC^{-1} \quad \text{for} \quad C = \begin{pmatrix} -1 & 1/2 \\ 1 & 1 \end{pmatrix} \qquad D = \begin{pmatrix} 1 & 0 \\ 0 & 1/2 \end{pmatrix}.$$

Eigenvectors of A are $v_1 = \binom{-1}{1}$ and $v_2 = \binom{1/2}{1}$ with eigenvalues 1 and 1/2.

$$\begin{aligned}
A(a_1v_1 + a_2v_2) &= a_1v_1 + \frac{1}{2}a_2v_2 \\
A^2(a_1v_1 + a_2v_2) &= a_1v_1 + \frac{1}{4}a_2v_2 \\
A^3(a_1v_1 + a_2v_2) &= a_1v_1 + \frac{1}{8}a_2v_2 \\
&\vdots \\
A^n(a_1v_1 + a_2v_2) &= a_1v_1 + \frac{1}{2^n}a_2v_2
\end{aligned}$$

What does repeated application of A do geometrically?

It "sucks everything into the 1-eigenspace."

[interactive]

Dynamics of Diagonalizable Matrices

Poll

$$A = \frac{1}{30}\begin{pmatrix} 12 & 2 \\ 3 & 13 \end{pmatrix} = CDC^{-1} \quad \text{for} \quad C = \begin{pmatrix} 2/3 & -1 \\ 1 & 1 \end{pmatrix} \qquad D = \begin{pmatrix} 1/2 & 0 \\ 0 & 1/3 \end{pmatrix}.$$

Section 6.5

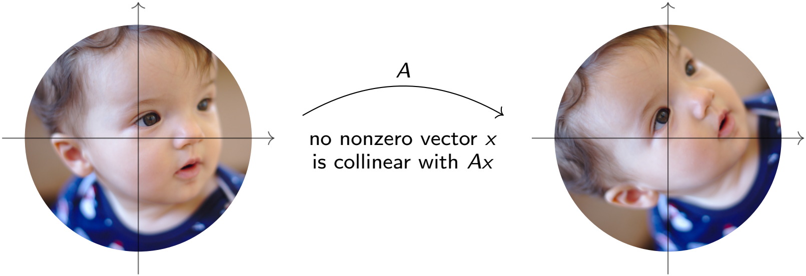
Complex Eigenvalues

A Matrix with No Eigenvectors

Consider the matrix for the linear transformation for rotation by $\pi/4$ in the plane. The matrix is:

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

This matrix has no eigenvectors, as you can see geometrically: [interactive]



or algebraically:

$$f(\lambda) = \lambda^2 - \operatorname{Tr}(A)\,\lambda + \det(A) = \lambda^2 - \sqrt{2}\,\lambda + 1 \implies \lambda = \frac{\sqrt{2} \pm \sqrt{-2}}{2}.$$

Complex Numbers

It makes us sad that -1 has no square root. If it did, then $\sqrt{-2} = \sqrt{2} \cdot \sqrt{-1}$.

Mathematician's solution: we're just not using enough numbers! We're going to declare by *fiat* that there exists a square root of -1.

Definition

The number i is defined such that $i^2 = -1$.

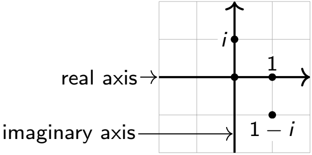
Once we have i, we have to allow numbers like $a + bi$ for real numbers a, b.

Definition

A *complex number* is a number of the form $a + bi$ for a, b in $\mathbf{R}$. The set of all complex numbers is denoted $\mathbf{C}$.

Note $\mathbf{R}$ is contained in $\mathbf{C}$: they're the numbers $a + 0i$.

We can identify $\mathbf{C}$ with $\mathbf{R}^2$ by $a + bi \longleftrightarrow \binom{a}{b}$. So when we draw a picture of $\mathbf{C}$, we draw the plane:



Operations on Complex Numbers

Addition:

Multiplication:

Complex conjugation: $\overline{a+bi} = a - bi$ is the **complex conjugate** of $a + bi$.
Check: $\overline{z+w} = \overline{z} + \overline{w}$ and $\overline{zw} = \overline{z} \cdot \overline{w}$.

Absolute value: $|a + bi| = \sqrt{a^2 + b^2}$. This is a *real* number.
Note: $(a+bi)(\overline{a+bi}) = (a+bi)(a-bi) = a^2 - (bi)^2 = a^2 + b^2$. So $|z| = \sqrt{z\overline{z}}$.
Check: $|zw| = |z| \cdot |w|$.

Division by a nonzero real number: $\dfrac{a+bi}{c} = \dfrac{a}{c} + \dfrac{b}{c}i$.

Division by a nonzero complex number: $\dfrac{z}{w} = \dfrac{z\overline{w}}{w\overline{w}} = \dfrac{z\overline{w}}{|w|^2}$.

Example:

$$\frac{1+i}{1-i} =$$

Real and imaginary part: $\text{Re}(a+bi) = a \qquad \text{Im}(a+bi) = b$.

The Fundamental Theorem of Algebra

The whole point of using complex numbers is to solve polynomial equations. It turns out that they are enough to find all solutions of all polynomial equations:

Fundamental Theorem of Algebra

Every polynomial of degree n has exactly n complex roots, counted with multiplicity.

Equivalently, if $f(x) = x^n + a_{n-1}x^{n-1} + \cdots + a_1 x + a_0$ is a polynomial of degree n, then

$$f(x) = (x - \lambda_1)(x - \lambda_2) \cdots (x - \lambda_n)$$

for (not necessarily distinct) complex numbers $\lambda_1, \lambda_2, \ldots, \lambda_n$.

Important

If f is a polynomial with *real* coefficients, and if λ is a complex root of f, then so is $\overline{\lambda}$:

$$\begin{aligned} 0 = \overline{f(\lambda)} &= \overline{\lambda^n + a_{n-1}\lambda^{n-1} + \cdots + a_1\lambda + a_0} \\ &= \overline{\lambda}^n + a_{n-1}\overline{\lambda}^{n-1} + \cdots + a_1\overline{\lambda} + a_0 = f\big(\overline{\lambda}\big). \end{aligned}$$

Therefore complex roots of real polynomials come in *conjugate pairs*.

Degree 2: The quadratic formula gives you the (real or complex) roots of any degree-2 polynomial:

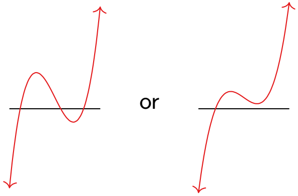
$$f(x) = x^2 + bx + c \implies x = \frac{-b \pm \sqrt{b^2 - 4c}}{2}.$$

For instance, if $f(\lambda) = \lambda^2 - \sqrt{2}\lambda + 1$ then

$$\lambda =$$

Note the roots are complex conjugates if b, c are real.

Degree 3: A real cubic polynomial has either three real roots, or one real root and a conjugate pair of complex roots. The graph looks like:



respectively.

A Matrix *with* an Eigenvector

Every matrix is guaranteed to have *complex* eigenvalues and eigenvectors.
Using rotation by $\pi/4$ from before:

$$A = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix} \quad \text{has eigenvalues} \quad \lambda = \frac{1 \pm i}{\sqrt{2}}.$$

Let's compute an eigenvector for $\lambda = (1+i)/\sqrt{2}$:

A similar computation shows that an eigenvector for $\lambda = (1-i)/\sqrt{2}$ is $\begin{pmatrix} -i \\ 1 \end{pmatrix}$.

So is $i\begin{pmatrix} -i \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ i \end{pmatrix}$ (you can scale by *complex* numbers).

Conjugate Eigenvectors

For $A = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & -1 \\ 1 & 1 \end{pmatrix}$,

$$\text{the eigenvalue } \frac{1+i}{\sqrt{2}} \text{ has eigenvector } \begin{pmatrix} i \\ 1 \end{pmatrix}.$$

$$\text{the eigenvalue } \frac{1-i}{\sqrt{2}} \text{ has eigenvector } \begin{pmatrix} -i \\ 1 \end{pmatrix}.$$

Do you notice a pattern?

Fact

Let A be a real square matrix. If λ is a complex eigenvalue with eigenvector v, then $\overline{\lambda}$ is an eigenvalue with eigenvector $\overline{v}$.

Why?

$$Av = \lambda \implies A\overline{v} = \overline{Av} = \overline{\lambda v} = \overline{\lambda}\,\overline{v}.$$

> Both eigenvalues and eigenvectors of real square matrices occur in conjugate pairs.

A 3×3 Example

Find the eigenvalues and eigenvectors of

$$A = \begin{pmatrix} \frac{4}{5} & -\frac{3}{5} & 0 \\ \frac{3}{5} & \frac{4}{5} & 0 \\ 0 & 0 & 2 \end{pmatrix}.$$

The characteristic polynomial is

We computed the roots of this polynomial (times 5) before:

$$\lambda = \quad 2, \quad \frac{4+3i}{5}, \quad \frac{4-3i}{5}.$$

We eyeball an eigenvector with eigenvalue 2 as $(0, 0, 1)$.

A 3 × 3 Example

Continued

$$A = \begin{pmatrix} \frac{4}{5} & -\frac{3}{5} & 0 \\ \frac{3}{5} & \frac{4}{5} & 0 \\ 0 & 0 & 2 \end{pmatrix}$$

To find the other eigenvectors, we row reduce:

Summary

- Diagonal matrices are easy to understand geometrically.
- Diagonalizable matrices behave like diagonal matrices, except with respect to a basis of eigenvectors.
- Repeatedly multiplying by a matrix leads to fun pictures.
- One can do arithmetic with complex numbers just like real numbers: add, subtract, multiply, divide.
- An $n \times n$ matrix always exactly has complex n eigenvalues, counted with (algebraic) multiplicity.
- The complex eigenvalues and eigenvectors of a *real* matrix come in complex conjugate pairs:

$$Av = \lambda v \quad \Longrightarrow \quad A\overline{v} = \overline{\lambda}\overline{v}.$$