The Characteristic Equation

Geometric Algorithms
Lecture 18

CAS CS 132

Introduction

Recap Problem

$$\begin{bmatrix} 5 & 2 & 3 & 0 \\ -1 & 2 & -3 & 1 \\ 2 & 4 & 10 & 0 \\ 1 & 2 & 3 & 5 \end{bmatrix}$$

Determine the dimension of the eigenspace of A for the eigenvalue 4. Hint: eigenspace is Nul$(A-4I)$

(try not to do any row reductions)

Hint: rank-nullity theorem

$$\begin{bmatrix} 5 & 2 & 3 & 0 \\ -1 & 2 & -3 & 1 \\ 2 & 4 & 10 & 0 \\ 1 & 2 & 3 & 5 \end{bmatrix}$$

Answer: 2

$$A - 4I = \begin{bmatrix} 1 & 2 & 3 & 0 \\ -1 & -2 & -3 & 1 \\ 2 & 4 & 6 & 0 \\ 1 & 2 & 3 & 1 \end{bmatrix}$$

$\vec{a}_1$, $\vec{a}_4$ form a basis for Col(A)

$$\text{rank}(A-4I) = \dim(\text{Col}(A-4I)) = 2$$

rank-nullity:

$$\text{rank}(B) + \dim(\text{Nul}(B)) = n$$

$$\dim(\text{Nul}(A-4I)) = 4 - 2 = \boxed{2}$$

Objectives

1. Briefly recap eigenvalues and eigenvectors.
2. Get a primer on determinants.
3. Determine how to find eigenvalues (not just verify them).

Keyword

eigenvectors

eigenvalues

eigenspaces

eigenbases

determinant

characteristic equation

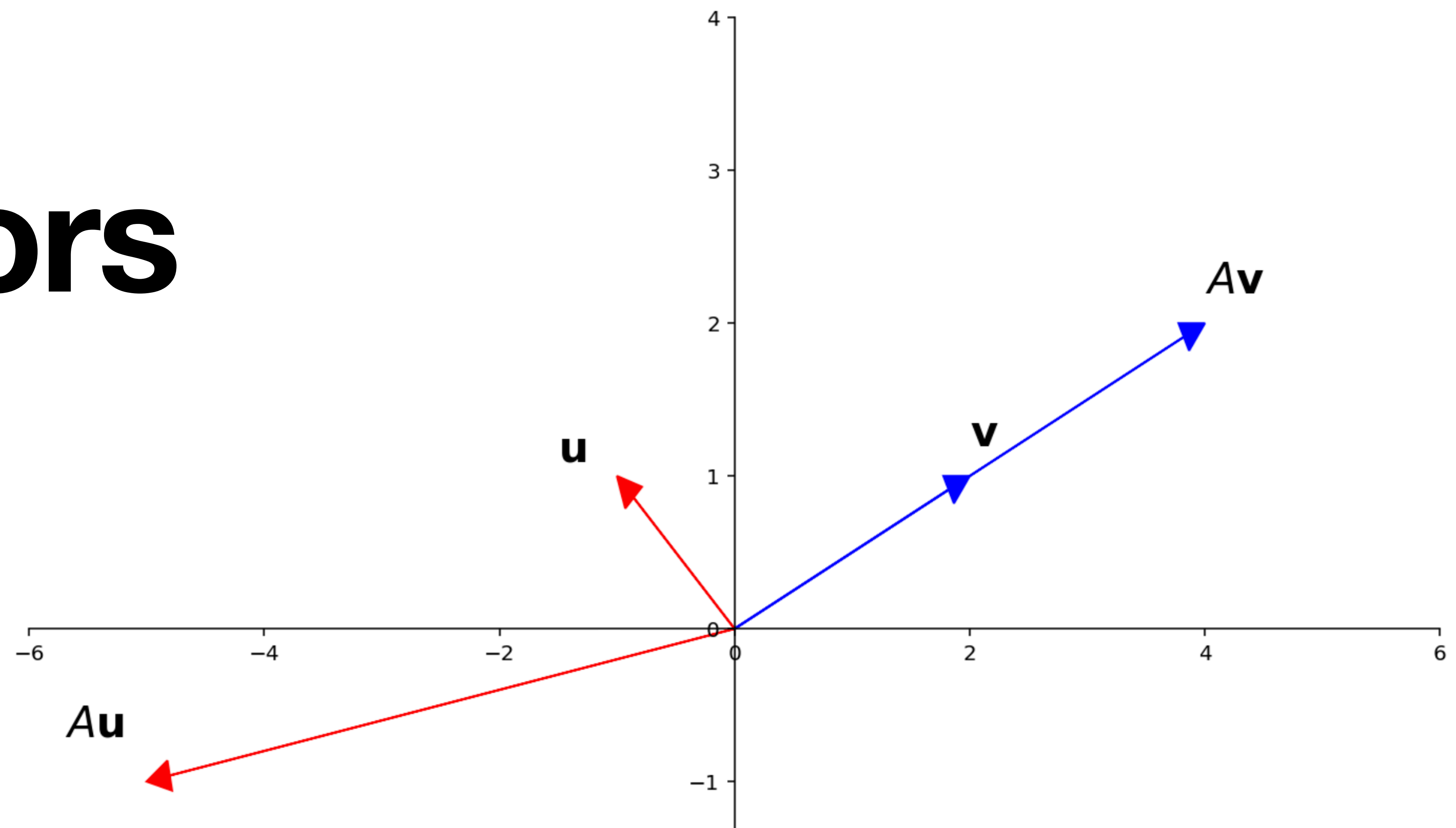
polynomial roots

triangular matrices

multiplicity

Recap

Recall: Eigenvalues/vectors



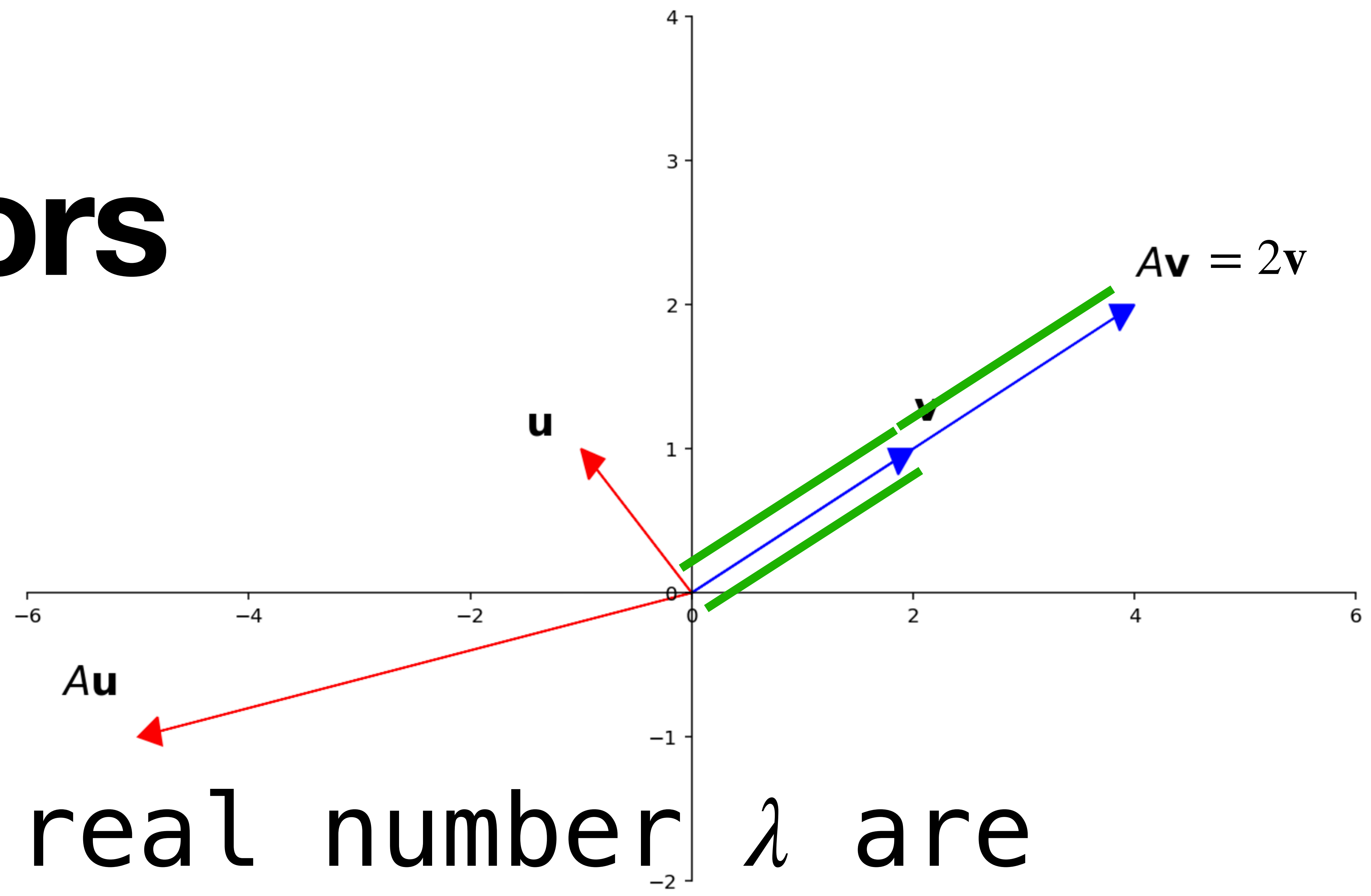
A *nonzero* vector $\mathbf{v}$ in $\mathbb{R}^n$ and real number λ are an **eigenvector and eigenvalue** for a $n \times n$ matrix A if

apply A to $\vec{v}$ scaling / stretching $\vec{v}$ by λ

$$A\mathbf{v} = \lambda\mathbf{v}$$

same as

Recall: Eigenvalues/vectors



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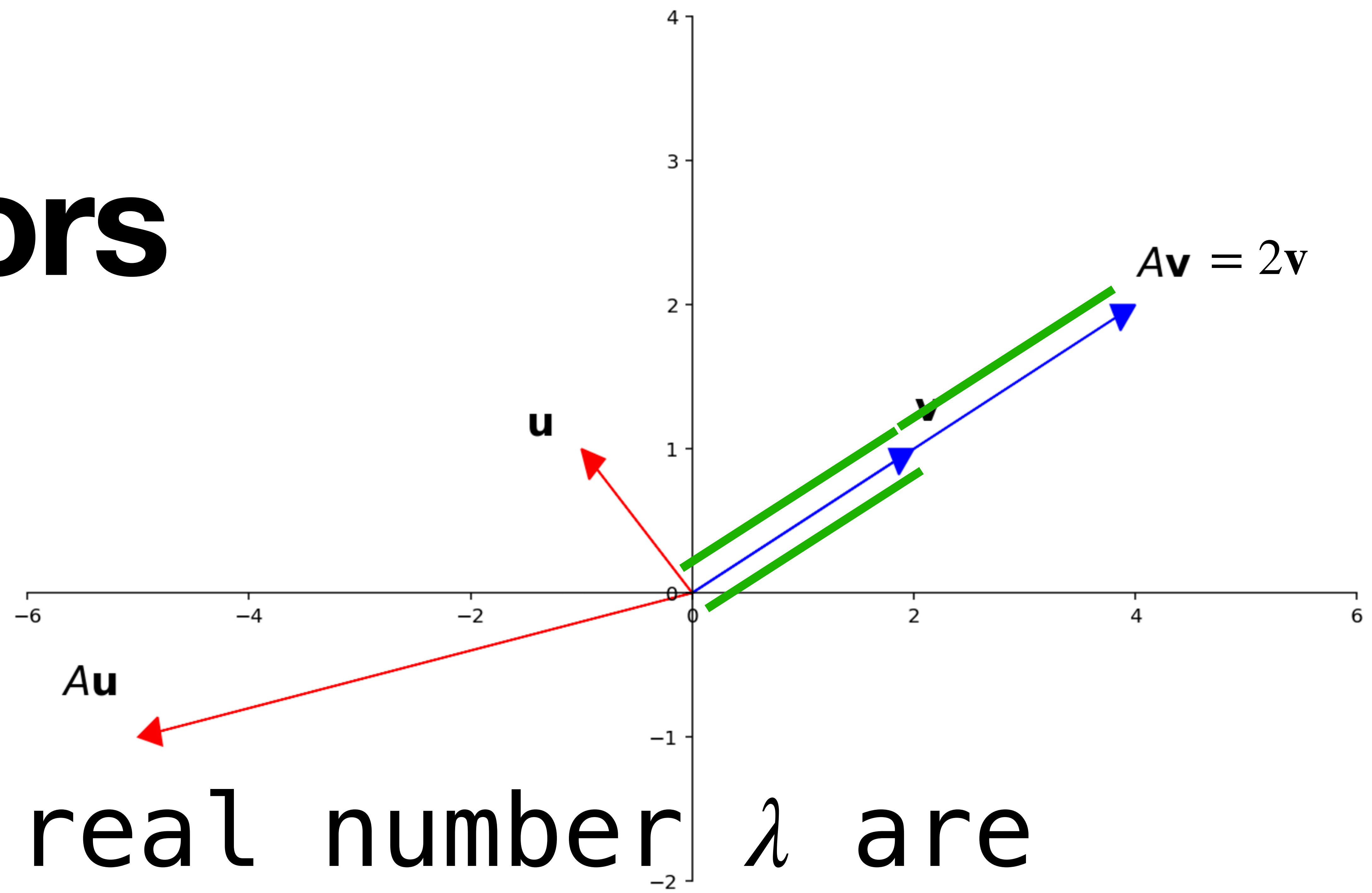
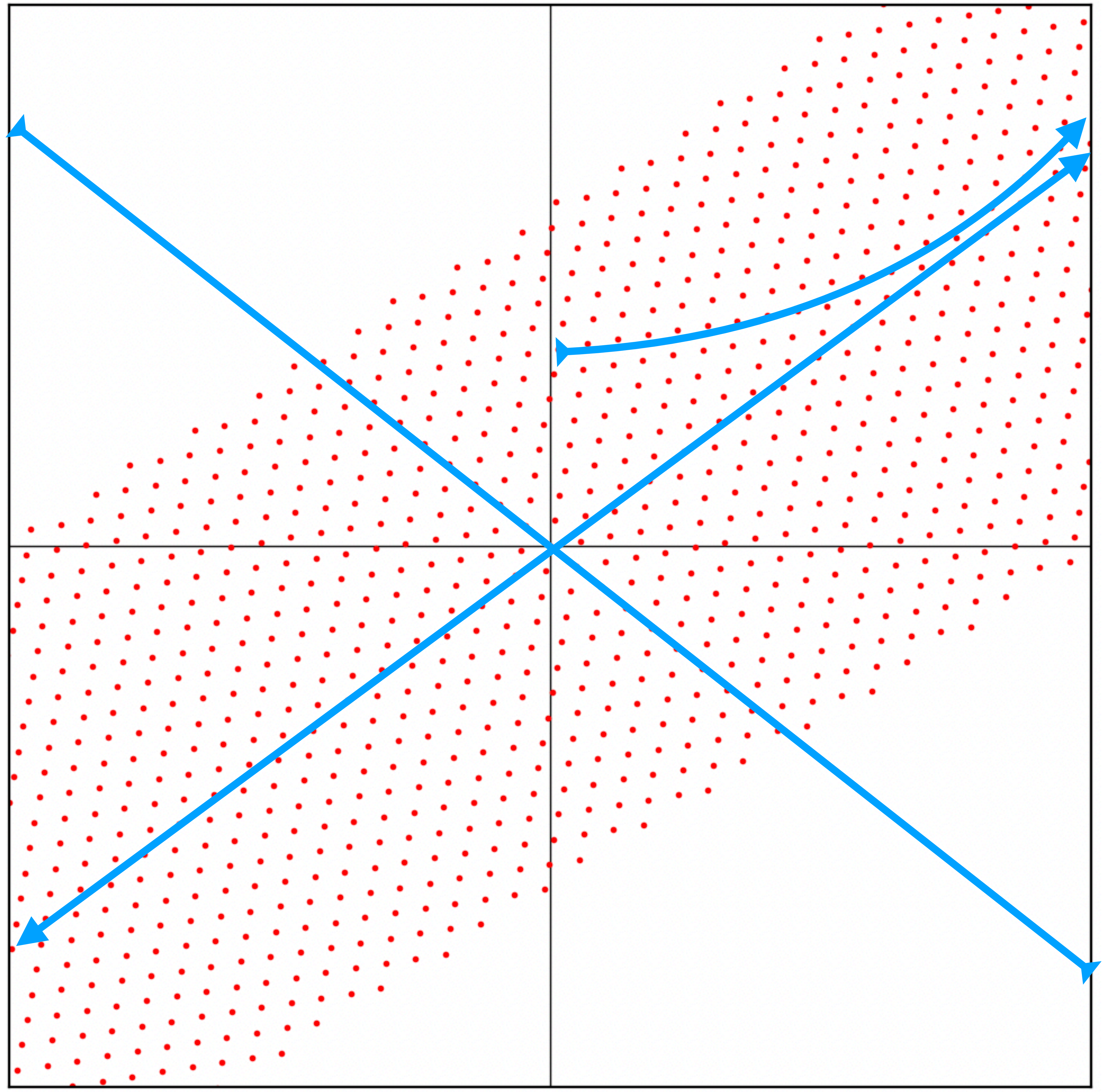


A *nonzero* vector $\mathbf{v}$ in $\mathbb{R}^n$ and real number λ are an **eigenvector and eigenvalue** for a $n \times n$ matrix A if

$$A\mathbf{v} = \lambda\mathbf{v}$$

$\mathbf{v}$ is "just scaled" by A, not rotated

Recall: The Picture



Recall: Verifying Eigenvectors

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Solution. Easy. Work out the matrix-vector multiplication.

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Example.

$$\begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix} \begin{bmatrix} 6 \\ -5 \end{bmatrix} = \begin{bmatrix} -24 \\ 20 \end{bmatrix} = -4 \begin{bmatrix} 6 \\ -5 \end{bmatrix} \checkmark$$

$$\begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 13 \\ 9 \end{bmatrix} \times$$

Recall: Verifying Eigenvalues

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

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*If we don't need the vector we can just show that $A - \lambda I$ is **not** invertible (by IMT).*

Recall: Finding Eigenspaces

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Question. Find a basis for the eigenspace of A corresponding to λ.

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Solution. Find a basis for $\text{Nul}(A - \lambda I)$.

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Solution. Find a basis for $\text{Nul}(A - \lambda I)$.

(we did this for our recap problem)

Finding Eigenvalues

Finding Eigenvalues

Question. Determine the eigenvalues of A, along with their associated eigenspaces.

Finding Eigenvalues

Question. Determine the eigenvalues of A, along with their associated eigenspaces.

Solution (Idea). Can we somehow "solve for λ" in the equation

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

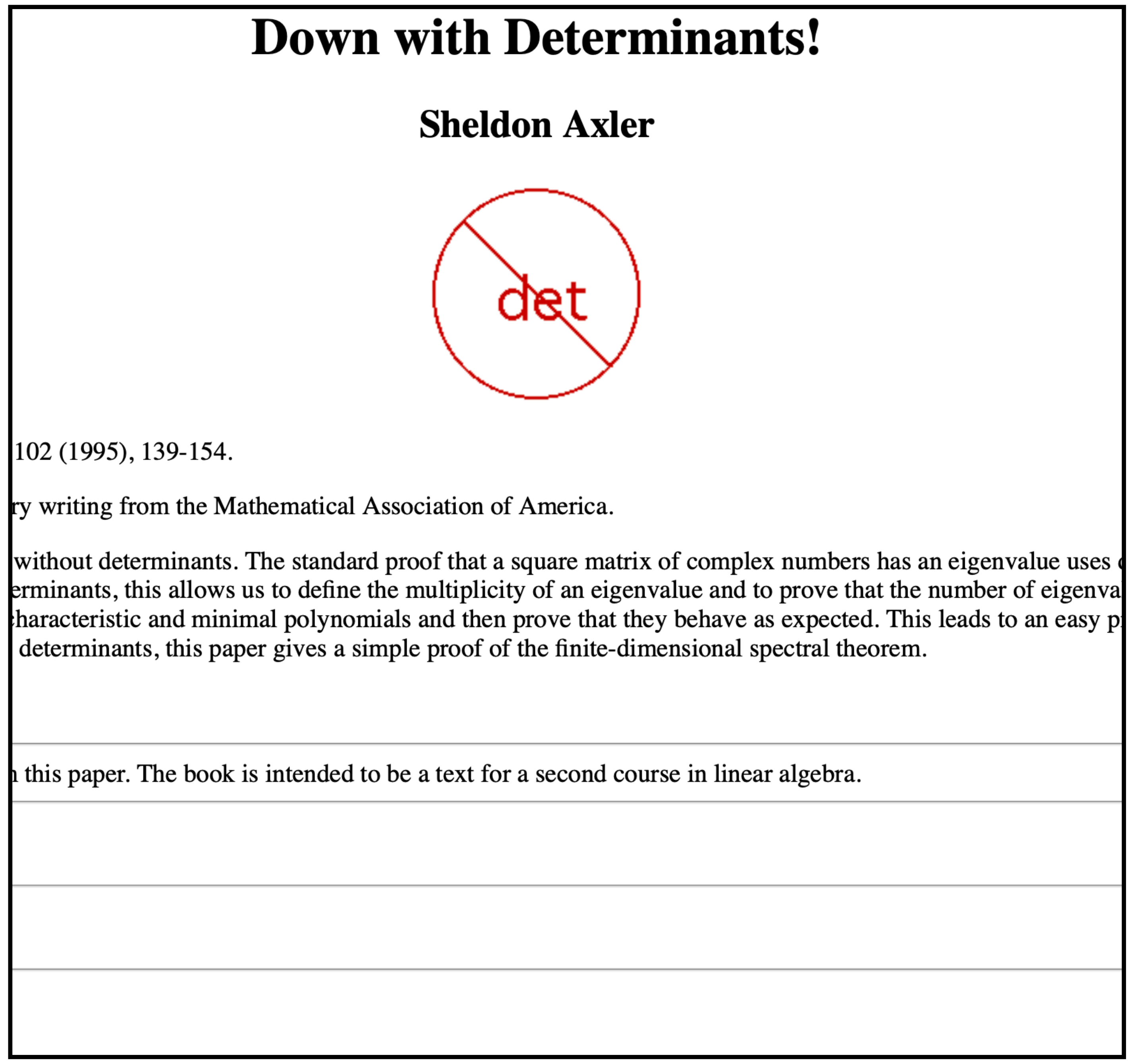
Determinants

An Aside: Determinants are Mysterious

Determinants are strangely polarizing

Some people love them, some people hate them

We'll only scratch the surface...



Down with Determinants!

Sheldon Axler

102 (1995), 139-154.

ry writing from the Mathematical Association of America.

without determinants. The standard proof that a square matrix of complex numbers has an eigenvalue uses
erminants, this allows us to define the multiplicity of an eigenvalue and to prove that the number of eigenva
haracteristic and minimal polynomials and then prove that they behave as expected. This leads to an easy p
determinants, this paper gives a simple proof of the finite-dimensional spectral theorem.

this paper. The book is intended to be a text for a second course in linear algebra.

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In broad strokes, it's a big sum of products of entries of A.

A Scary-Looking Definition (we won't use)

$$\det(A) = \sum_{\sigma \in S_n} (-1)^{\text{sgn}(\sigma)} A_{1\sigma(1)} A_{2\sigma(2)} \ldots A_{n\sigma(n)}$$

`We can think of this function as a procedure:`

A Scary-Looking Definition (we won't use)

$$\det(A) = \sum_{\sigma \in S_n} (-1)^{\mathrm{sgn}(\sigma)} A_{1\sigma(1)} A_{2\sigma(2)} \ldots A_{n\sigma(n)}$$

We can think of this function as a procedure:

```
FUNCTION det(A):
  total = 0
  FOR all matrix B we can get by swapping a bunch of rows of A:
    s = 1 IF (# of swaps necessary) is even ELSE -1
    total += s * (product of the diagonal entries of B)
  RETURN total
```

The Determinant of 2×2 Matrices

$$\det \begin{bmatrix} a & b \\ c & d \end{bmatrix} = ad - bc$$

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$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \rightarrow^{0} \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

$$(-1)^0 ad$$

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$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \to^1 \begin{bmatrix} c & d \\ a & b \end{bmatrix}$$

$$(-1)^1 cb$$

The Determinant of 3×3 matrices

$$\det \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} = aei + bfg + cdh - ceg - bdi - afh$$

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$$\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \to^2 \begin{bmatrix} g & h & i \\ a & b & c \\ d & e & f \end{bmatrix}$$

$$(-1)^2 gbf$$

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$$(-1)^{1} gec$$

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$$(-1)^1 ahf$$

Another Perspective

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

Let's row reduce an arbitrary 2×2 matrix:

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix} \sim \begin{bmatrix} a & b \\ ca - ca & da - cb \end{bmatrix} \sim \begin{bmatrix} a & b \\ 0 & \boxed{da - cb} \end{bmatrix}$$

$da - cb = 0$ then A is <u>not</u> invertible

Another Perspective

$$\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}$$

Let's row reduce an arbitrary 3×3 matrix:

$$\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix} \sim \begin{bmatrix} a & b & c \\ ad & ae & af \\ ag & ah & ai \end{bmatrix} \sim \begin{bmatrix} a & b & c \\ 0 & ae-bd & af-cd \\ 0 & ah-bg & ai-cg \end{bmatrix}$$

$$\det\left(\begin{bmatrix} ae-bd & af-cd \\ ah-bg & ai-cg \end{bmatrix} \right) = a\left(\ldots \right)$$

↑ formula from last slide.

Determinants and Invertibility

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Theorem. A matrix is invertible if and only if $\det(A) \neq 0$.

So we can yet again extend the IMT:

- A is invertible
- $\det(A) \neq 0$
- 0 is not an eigenvalue

These must be all true or all false.

Determinants (the definition we'll use)

$$\det(A) = \frac{(-1)^s}{c} U_{11} U_{22} \dots U_{nn}$$

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Defintion. The **determinant** of a matrix A is given by the above equation, where

- U is an echelon form of A
- s is the number of row swaps used to get U
- c is the product of all scalings used to get U

if there are no scalings then $c = 1$

Determinants (the definition we'll use)

product of diagonal entries

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non-invertible ⇒ non-pivot column ⇒ 0 on the diagonal

Determinants (the definition we'll use)

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product of diagonal entries

0 if A is not invertible

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Example

$$\begin{bmatrix} 1 & 5 & 0 \\ 2 & 4 & -1 \\ 0 & -2 & 0 \end{bmatrix}$$

Let's find the determinant of this matrix:

$s = \not{0}\ 1 \quad c = 1$

$$\begin{bmatrix} 1 & 5 & 0 \\ 2 & 4 & -1 \\ 0 & -2 & 0 \end{bmatrix} \xrightarrow{R_2 \leftarrow R_2 - 2R_1} \begin{bmatrix} 1 & 5 & 0 \\ 0 & -6 & -1 \\ 0 & -2 & 0 \end{bmatrix} \xrightarrow{swap(R_2, R_3)} \begin{bmatrix} 1 & 5 & 0 \\ 0 & -2 & 0 \\ 0 & -6 & -1 \end{bmatrix}$$

$$\xrightarrow{R_3 \leftarrow R_3 - 3R_2} \begin{bmatrix} 1 & 5 & 0 \\ 0 & -2 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

$$\det(A) = \frac{(-1)^s}{c}(1)(-2)(-1)$$

$$= \frac{(-1)^1}{1}(1)(-2)(-1) = \boxed{-2}$$

Example (Again)

$$\begin{bmatrix} 1 & 5 & 0 \\ 2 & 4 & -1 \\ 0 & -2 & 0 \end{bmatrix}$$

Let's find the determinant of this matrix again but with a different sequence of row operations:

$s = 0 \qquad c = 1 \cdot 2$

$$\begin{bmatrix} 1 & 5 & 0 \\ 2 & 4 & -1 \\ 0 & -2 & 0 \end{bmatrix} \xrightarrow{R_1 \leftarrow 2R_1} \begin{bmatrix} 2 & 10 & 0 \\ 2 & 4 & -1 \\ 0 & -2 & 0 \end{bmatrix} \xrightarrow{R_2 \leftarrow R_2 - R_1} \begin{bmatrix} 2 & 10 & 0 \\ 0 & -6 & -1 \\ 0 & -2 & 0 \end{bmatrix}$$

$$\xrightarrow{R_3 \leftarrow R_3 - \frac{1}{3}R_2} \begin{bmatrix} 2 & 10 & 0 \\ 0 & -6 & -1 \\ 0 & 0 & \frac{1}{3} \end{bmatrix}$$

$$\det(A) = \frac{(-1)^s}{c}(2)(-6)\left(\tfrac{1}{3}\right)$$

$$= \frac{(-1)^0}{2}(2)(-6)\left(\tfrac{1}{3}\right) = -2$$

The definition holds no matter which sequence of row operations you use.

How To: Determinants

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Question. Determine the determinant of a matrix A.

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How To: Determinants

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3. Determine the product of entries along the diagonal of U, call this P.

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$(-1)^s$

4. The determinant of A is $\frac{sP}{c}$.

The Shorter Version

Beyond small matrices, we'll often just use computers.

With NumPy:

```
numpy.linalg.det(A)
```

Properties of Determinants

Properties of Determinants (1)

$$\det(AB) = \det(A)\det(B)$$

It follows that AB is invertible if and only if A and B are invertible

(we won't verify this)

Question

Use the fact that $\det(AB) = \det(A)\det(B)$ *to give an expression for* $\det(A^{-1})$ *in terms of* $\det(A)$.

Hint. What is $\det(I)$? $= 1$

Answer: $1/\det(A)$

$$1 = \det(I) = \det(AA^{-1}) = \boxed{\det(A)} \cdot \det(A^{-1})$$

<u>so</u>

$$\det(A^{-1}) = \frac{1}{\det(A)}$$

Properties of Determinants (2)

$$\det(A^T) = \det(A)$$

It follows that A^T is invertible if and only if A is invertible.

(we also won't verify this)

Question

If $A^{-1} = A^T$*, then what are the possible values of* $\det(A)$*?*

$$\det(A^T)\det(A) = \det(A^T A) = 1$$

$$\det(A)^2 = 1$$

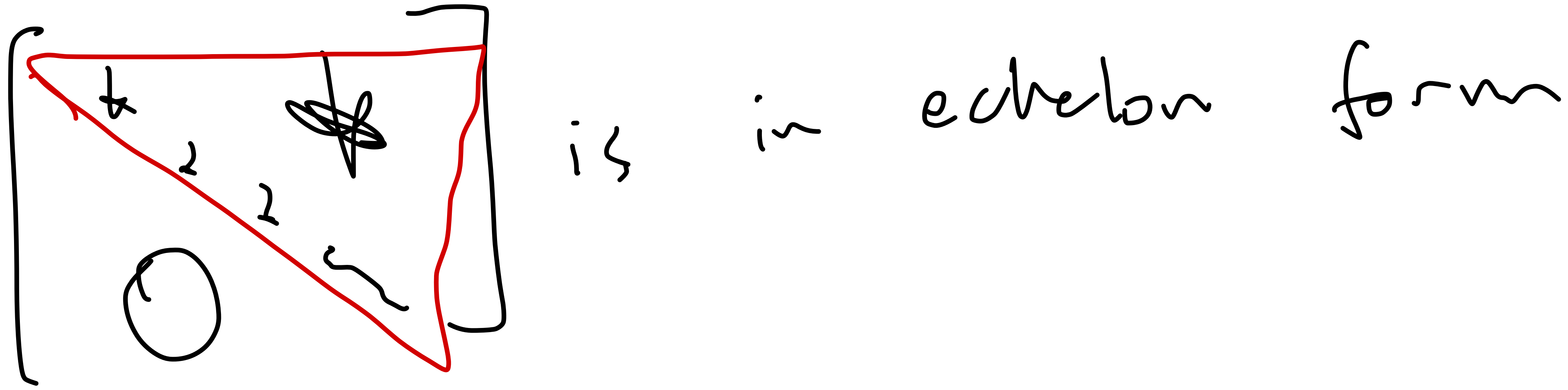
$$\det(A) = 1, -1$$

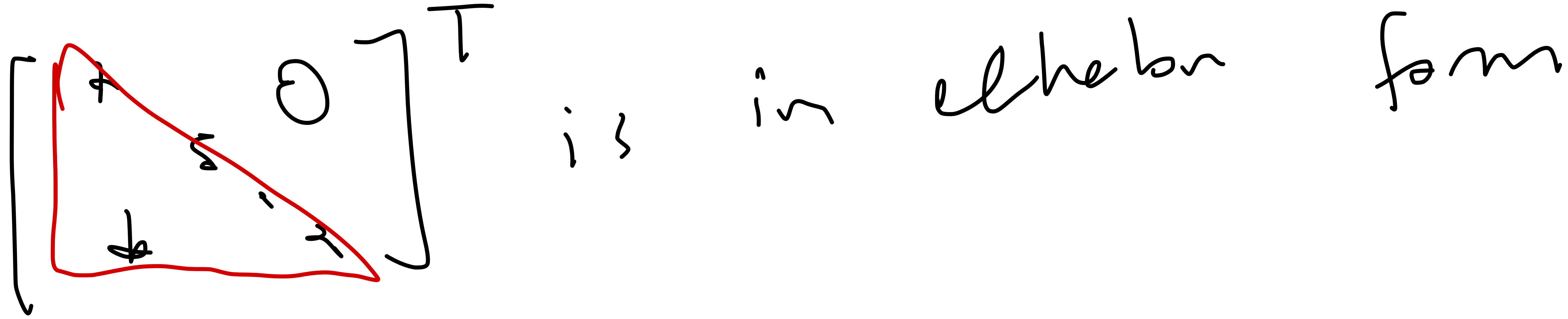
Answer: ± 1

Properties of Determinants (3)

Theorem. If A is triangular, then $\det(A)$ is the product of entries along the diagonal.

Verify:





Question

$$\begin{bmatrix} 1 & 5 & -4 \\ -1 & -5 & 5 \\ -2 & -8 & 7 \end{bmatrix}$$

Find the determinant of the above matrix.

$$\begin{bmatrix} 1 & 5 & -4 \\ -1 & -5 & 5 \\ -2 & -8 & 7 \end{bmatrix}$$

Answer

$s = \cancel{0}\ 1 \qquad r = 1$

$$\begin{bmatrix} 1 & 5 & -4 \\ -1 & -5 & 5 \\ -2 & -8 & 7 \end{bmatrix} \sim \begin{bmatrix} 1 & 5 & -4 \\ 0 & 0 & 1 \\ 0 & 2 & -1 \end{bmatrix} \sim \begin{bmatrix} 1 & 5 & -4 \\ 0 & 2 & -1 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\det(A) = \frac{(-1)^1}{1}(1)(2)(1) = \boxed{-2}$$

Characteristic Equation

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But a matrix may not have numbers as entries.

What kind of thing is the determinant, really?

$$\begin{bmatrix} 2-\lambda & 5 \\ 3 & 4-\lambda \end{bmatrix}$$

The determinant of a matrix A is an <u>arithmetic expression</u> written in terms of the entries of A.

But a matrix may not have numbers as entries.

We might think of the matrix $A - \lambda I$ has having *polynomials* as entries.

What kind of thing is the determinant, really?

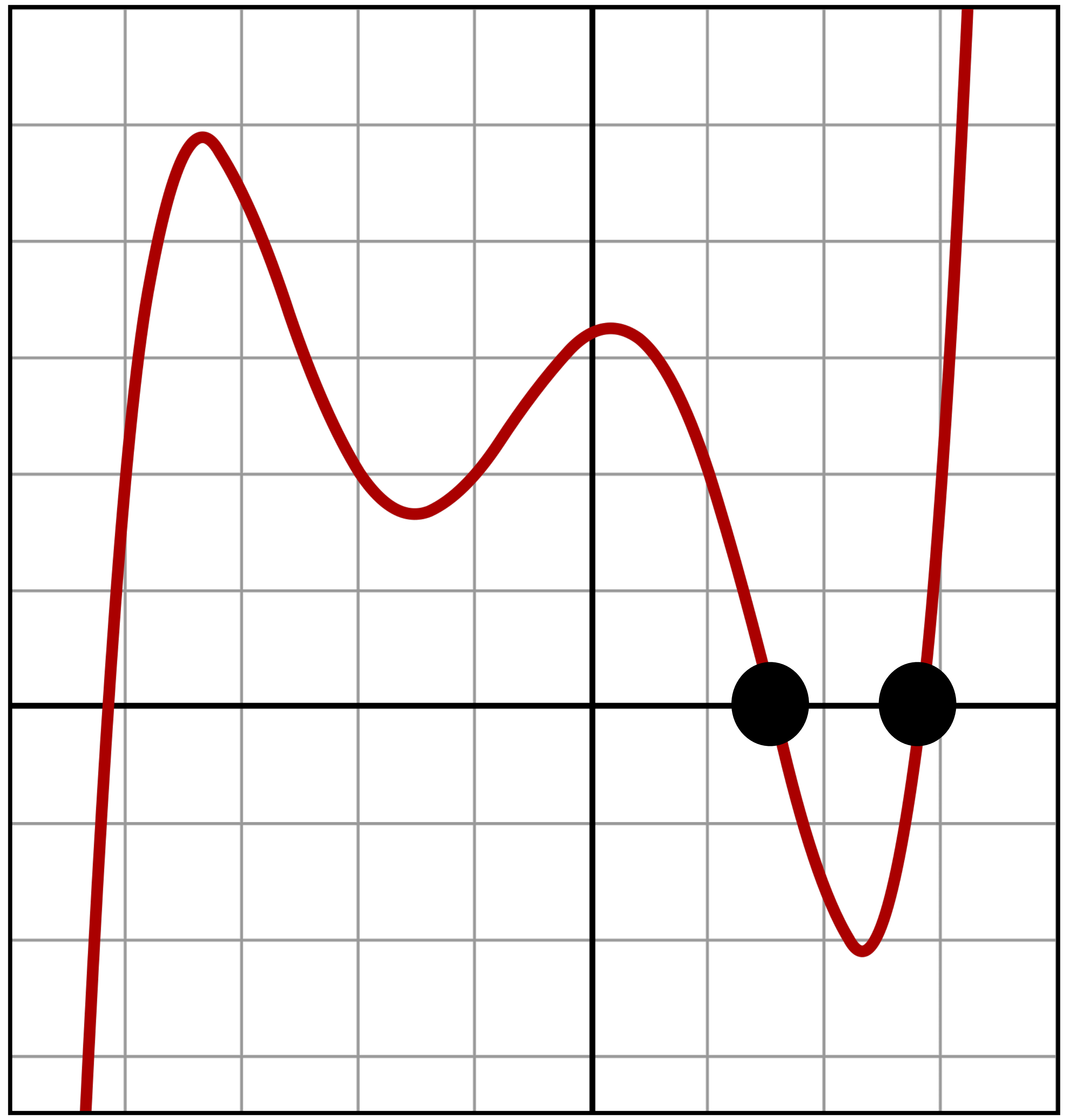
The determinant of a matrix A is an <u>arithmetic expression</u> written in terms of the entries of A.

But a matrix may not have numbers as entries.

We might think of the matrix $A - \lambda I$ has having *polynomials* as entries.

Then $\det(A - \lambda I)$ is a **polynomial.**

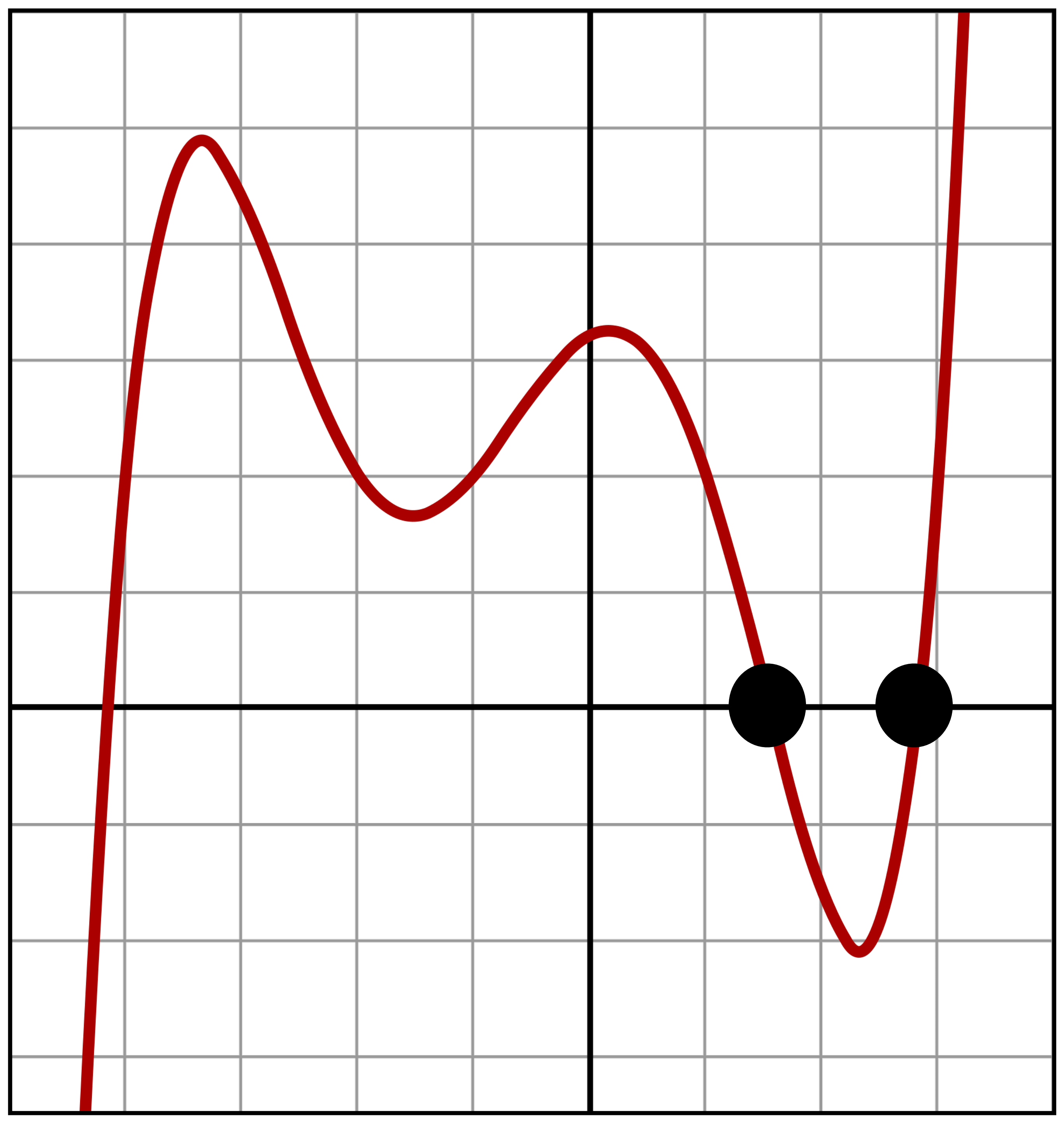
Reminder: Polynomial Roots



https://commons.wikimedia.org/wiki/File:Quintic_polynomial.svg

Reminder: Polynomial Roots

A **root** of a polynomial $p(x)$ is a value r such that $p(r) = 0$.



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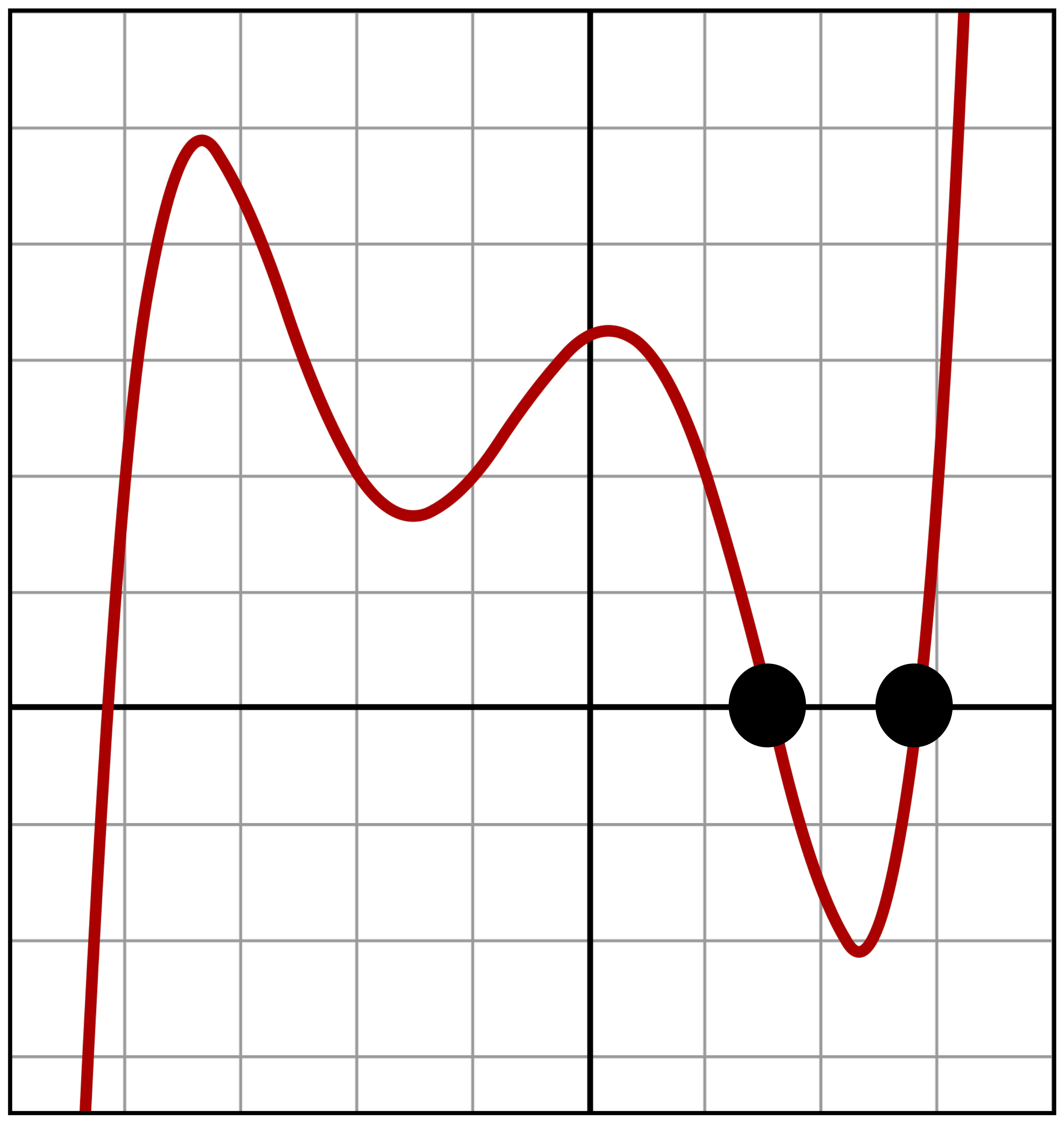

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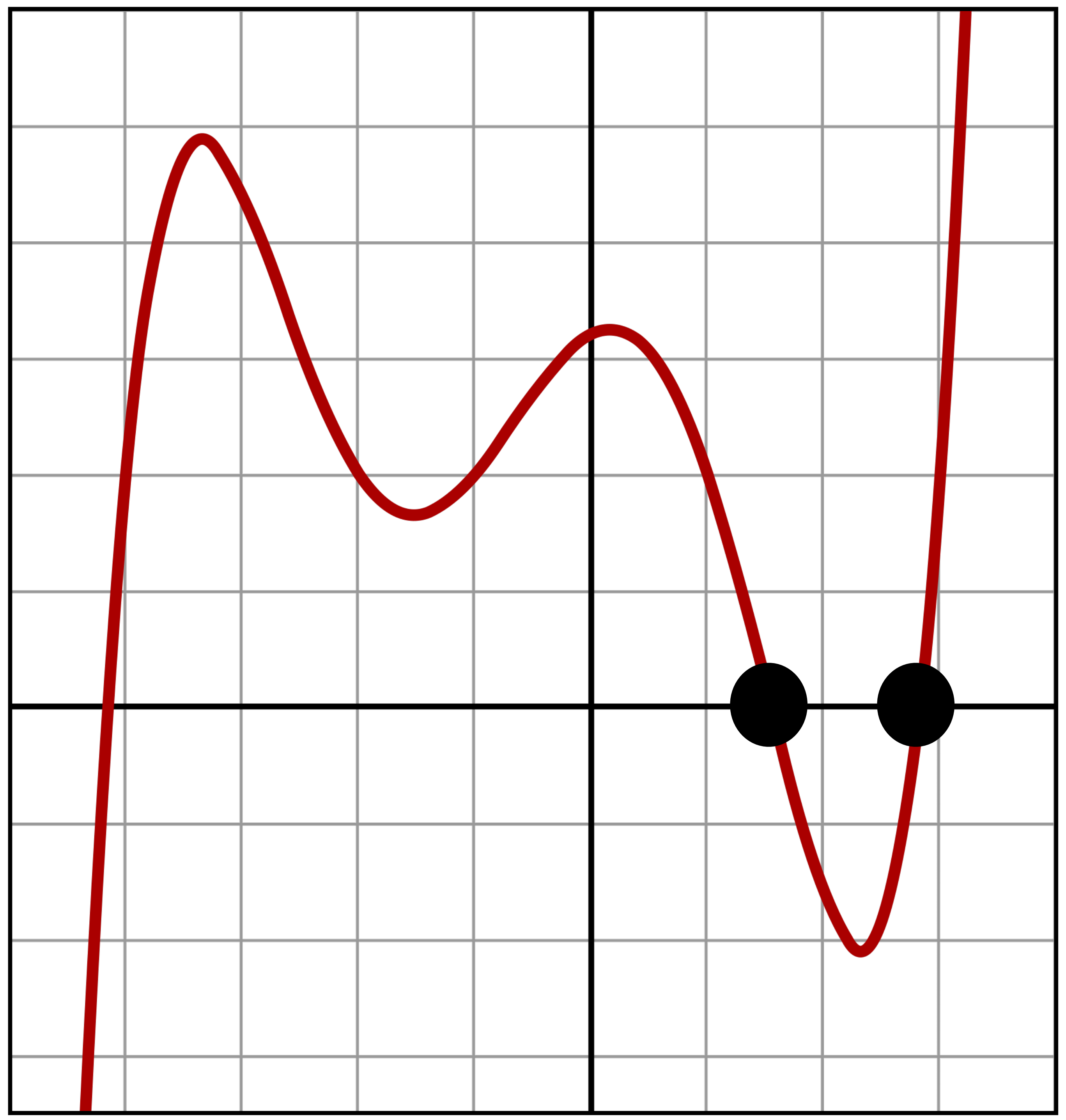
Reminder: Polynomial Roots

A **root** of a polynomial $p(x)$ is a value r such that $p(r) = 0$.

(A polynomial may have many roots)

If r is a root of $p(x)$, then it is possible to find a polynomial $q(x)$ such that

$$p(x) = (x - r)q(x)$$



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This is a polynomial with the eigenvalues of A as roots.

So we can "solve" for the eigenvalues in the equation

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

Example: 2×2 Matrix*

$A = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$

Let's find the characteristic polynomial of this matrix:

$\det \begin{bmatrix} 1-\lambda & 1 \\ 1 & -\lambda \end{bmatrix} = (1-\lambda)(-1) - 1 =$

$\lambda^2 - \lambda - 1$

$\frac{-b \pm \sqrt{b^2-4ac}}{2a}$ $\quad \frac{1 \pm \sqrt{(-1)^2 - 4(1)(-1)}}{2}$ $\quad \frac{1+\sqrt{5}}{2}, \frac{1-\sqrt{5}}{2}$

eigenvalues of A

*we won't deal explicitly with matrices beyond 2×2, though there may be conceptual questions about larger matrices

Example: 2×2 Matrix*

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$$

Let's find the characteristic polynomial of this matrix:

An Aside: What is this matrix?

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A Special Linear Dynamical System

$$\mathbf{v}_{k+1} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \mathbf{v}_k \qquad \mathbf{v}_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

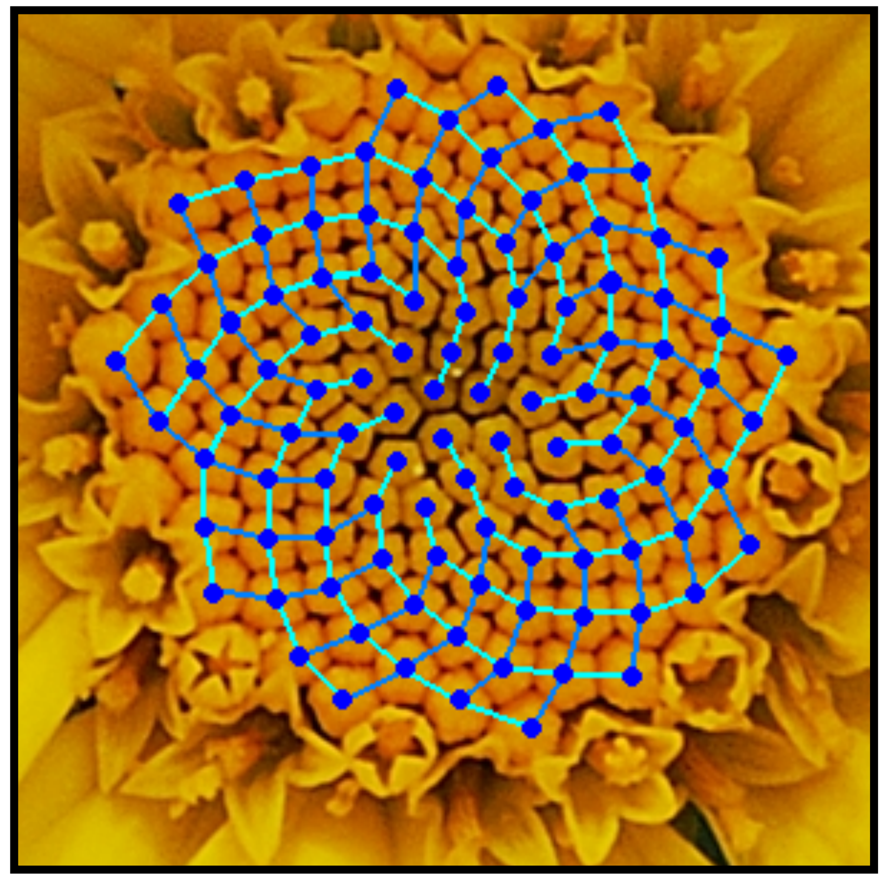
Consider the system given by the above matrix.

What does this system represent?:

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x+y \\ x \end{bmatrix}$$

$$\begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 1 \end{bmatrix}, \begin{bmatrix} 3 \\ 2 \end{bmatrix}, \begin{bmatrix} 5 \\ 3 \end{bmatrix}, \begin{bmatrix} 8 \\ 5 \end{bmatrix}, \begin{bmatrix} 13 \\ 8 \end{bmatrix}, \ldots$$

Fibonacci Numbers



$$F_0 = 0$$

$$F_1 = 1$$

$$F_k = F_{k-1} + F_{k-2}$$

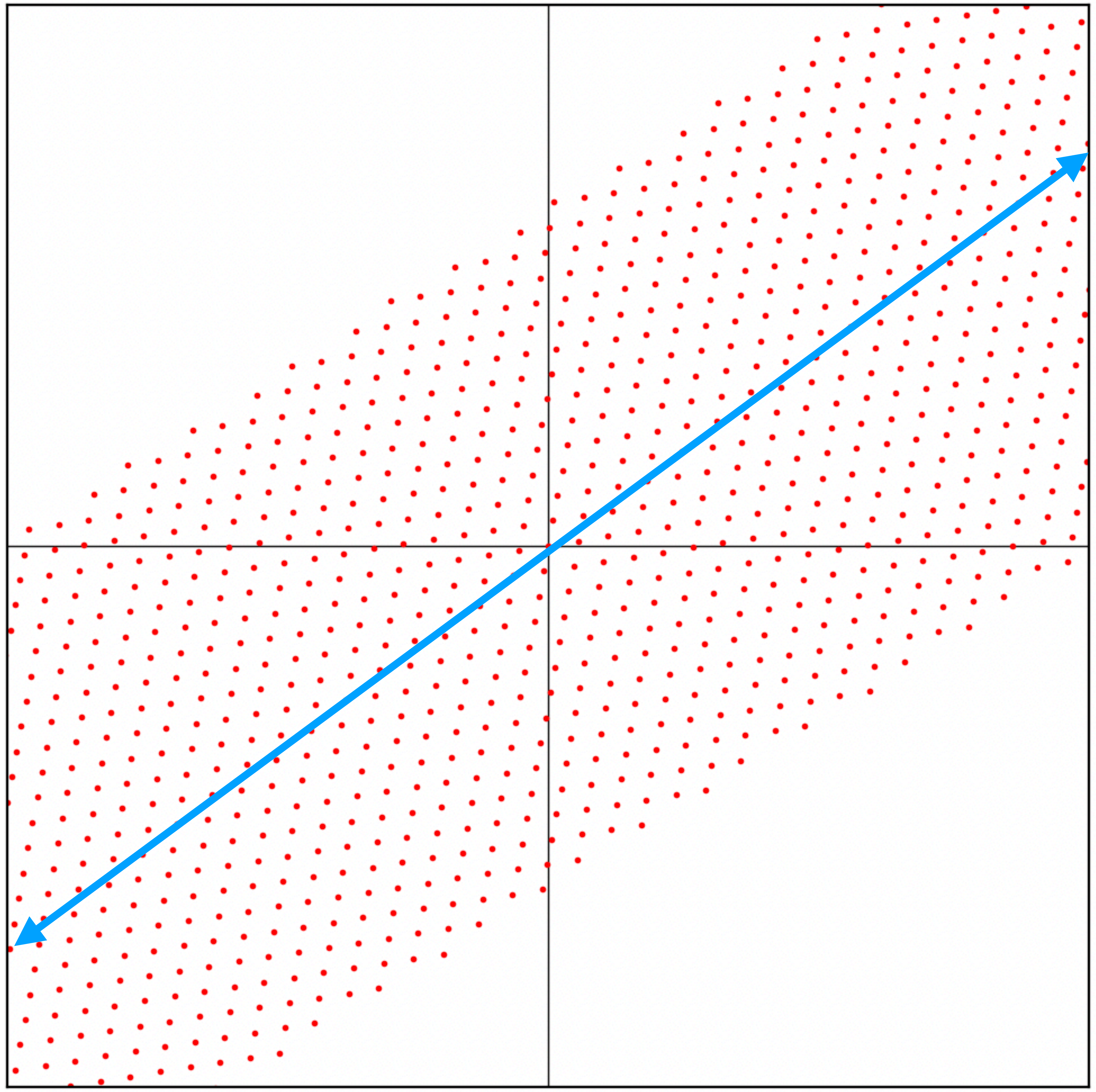
```
define fib(n):
  curr, next ← 0, 1
  repeat n times:
    curr, next ← next, curr + next
  return curr
```

The Fibonacci numbers are defined in terms of a recurrence relation.

They seem to crop-up in nature, engineering, etc.

https://commons.wikimedia.org/wiki/File:FibonacciChamomile.PNG

Recall: The Fibonacci Matrix



The largest eigenvalue is the <u>slope</u> of this line

The slope is the ratio of the entries

Golden Ratio

$$\varphi = \frac{1+\sqrt{5}}{2} \qquad \frac{F_{k+1}}{F_k} \to \varphi \text{ as } k \to \infty$$

This is the largest eigenvalue of $\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix}$.

To Come. The "long term behavior" is the Fibonacci sequence is defined by the golden ratio.

Example: Triangular matrix

$$\begin{bmatrix} 1 & -3 & 0 & 6 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 2 \\ 0 & 0 & 0 & 4 \end{bmatrix}$$

The characteristic polynomial of a triangular matrix comes <u>pre-factored</u>:

$$\det(A - \lambda I) = (1 - \lambda)(-\lambda)(1 - \lambda)(4 - \lambda)$$

How To: Finding Eigenvalues

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Question. Find all eigenvalues of the matrix A.

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Solution. Find the roots of the characteristic polynomial of A.

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In Reality. We'll mostly just use

numpy.linalg.eig(A)

An Observation: Multiplicity

$$\lambda^1(\lambda - 1)^2(\lambda - 4)^1$$

multiplicities

In the examples so far, we've seen a number appear as a root multiple times.

This is called the **multiplicity** of the root.

Is the multiplicity meaningful in this context?

Multiplicity and Dimension

Theorem. The dimension of the eigenspace of A for the eigenvalue λ is at most the multiplicity of λ in $\det(A - \lambda I)$.

The multiplicity is an upper bound on "how large" the eigenspace is.

Example

Let A be a 5×5 matrix with characteristic polynomial $(x-1)^3(x-3)(x+5)$.

» What is $\text{rank}(A)$?

» What is the minimum possible rank of $A - I$?

Application: Similar Matrices

Definition. Two square matrices A and B are **similar** if there is an invertible matrix P such that

$$A = P^{-1}BP$$

Application: Similar Matrices

Theorem. Similar matrices have the same eigenvalues.

Verify:

Summary

The determinant of a matrix is an arithmetic expression of its entries.

The characteristic polynomial is the determinant of $A - \lambda I$ viewed as a polynomial of λ, and it tells us what the eigenvalues of a matrix are.