Eigenvalues and Eigenvectors

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Chapter 5

- In chapter 4, we already know how to consider a function from different aspects (coordinate system)
- Learn how to find a “good” coordinate system for a function
- Scope: Chapter 5.1 – 5.4
    - Chapter 5.4 has *

Outline

- What is Eigenvalue and Eigenvector?
  - Eigen (German word): "unique to” or "belonging to"
- How to find eigenvectors (given eigenvalues)?
- Check whether a scalar is an eigenvalue
- How to find all eigenvalues?

- Reference: Textbook Chapter 5.1 and 5.2

Definition

Eigenvalues and Eigenvectors

- If $Av = \lambda v$ (v is a vector, λ is a scalar)
  - v is an eigenvector of A **excluding zero vector**
  - λ is an eigenvalue of A that corresponds to v

A must be square

$$\begin{bmatrix} 5 & 2 & 1 \\ -2 & 1 & -1 \\ 2 & 2 & 4 \end{bmatrix} \overset{v}{\boxed{\begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix}}} = \begin{bmatrix} 4 \\ -4 \\ 4 \end{bmatrix} = \overset{\lambda}{4} \overset{v}{\begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix}}$$

Eigen value

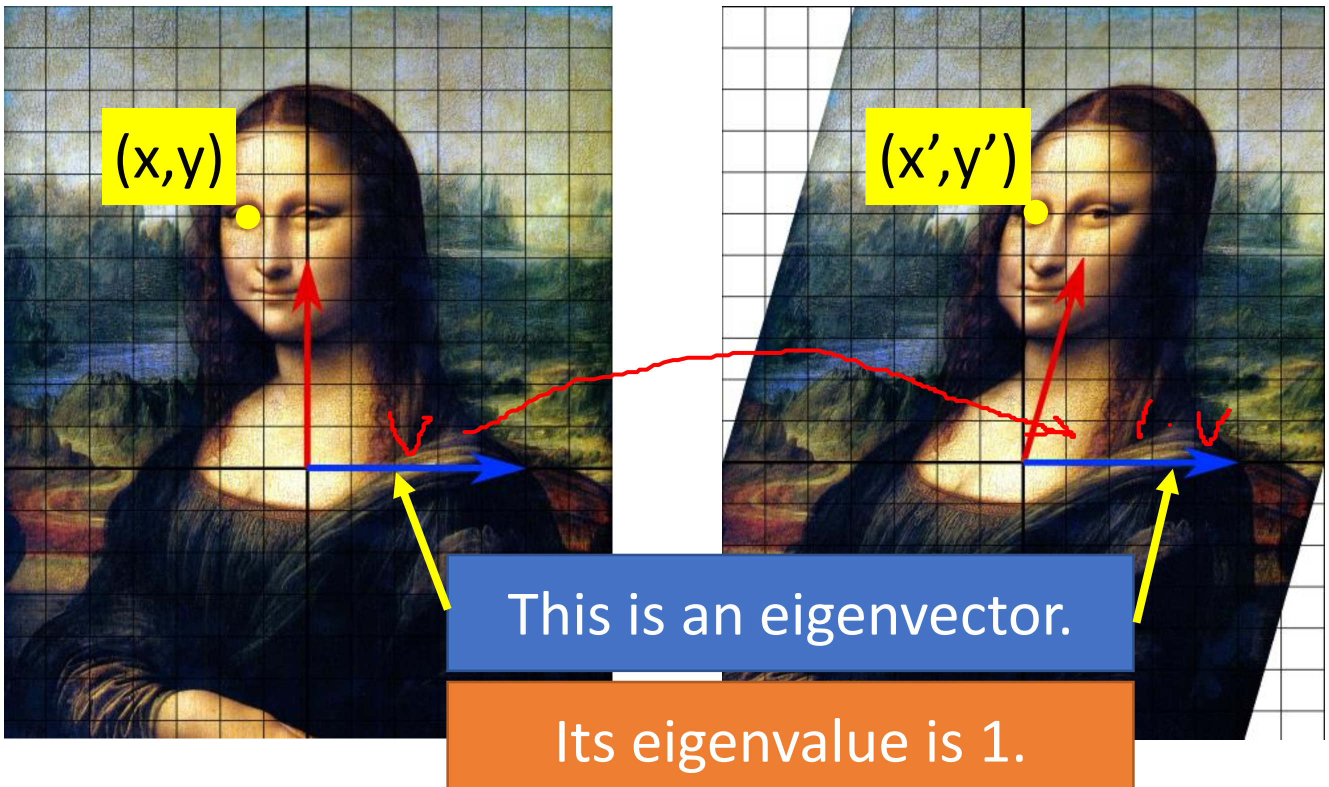
Eigen vector

Eigenvalues and Eigenvectors

- If $Av = \lambda v$ (v is a vector, λ is a scalar)
  - v is an eigenvector of A excluding zero vector
  - λ is an eigenvalue of A that corresponds to v
- T is a ***linear operator.*** If $\mathrm{T}(v) = \lambda v$ (v is a vector, λ is a scalar)
  - v is an eigenvector of T excluding zero vector
  - λ is an eigenvalue of T that corresponds to v

Eigenvalues and Eigenvectors

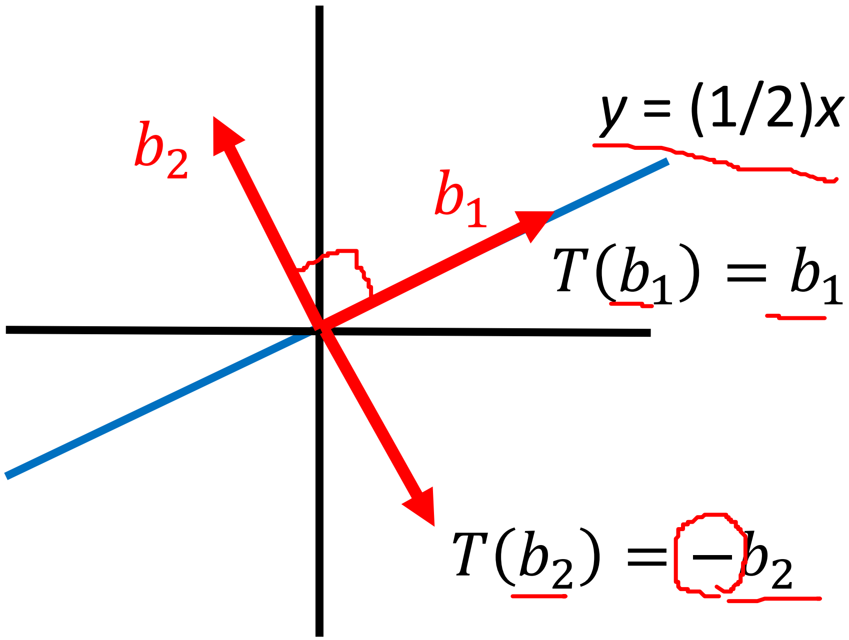
- Example: Shear Transform $\begin{bmatrix} x' \\ y' \end{bmatrix} = T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right)$



Eigenvalues and Eigenvectors

- Example: Reflection

reflection operator T about the line $y = (1/2)x$



$\mathbf{b}_1$ is an eigenvector of T

Its eigenvalue is 1.

$\mathbf{b}_2$ is an eigenvector of T

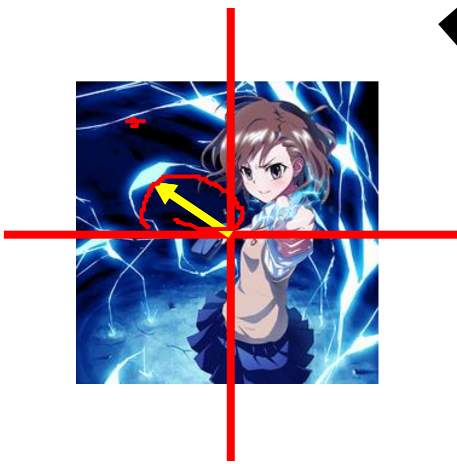
Its eigenvalue is -1.

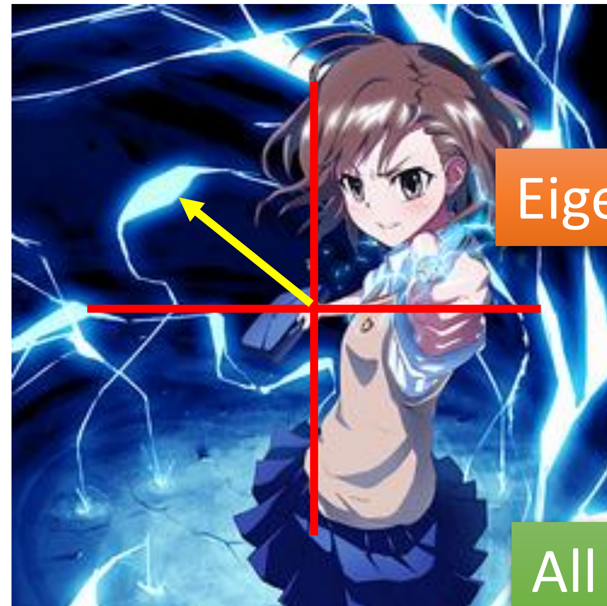
Eigenvalues and Eigenvectors

- Example:

Expansion and Compression

$$\lambda \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

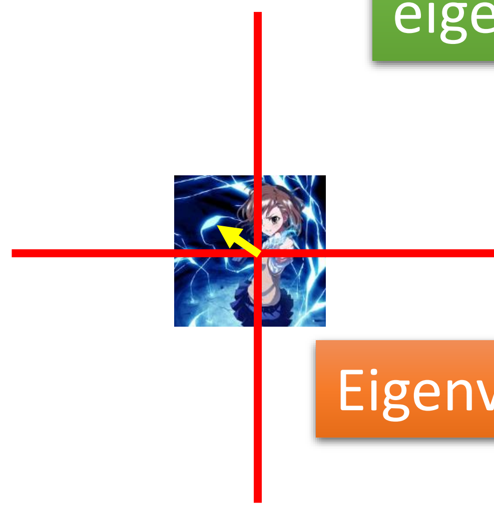




Eigenvalue is 2

All vectors are eigenvectors.

$$\begin{bmatrix} 0.5 & 0 \\ 0 & 0.5 \end{bmatrix}$$



Eigenvalue is 0.5

Eigenvalues and Eigenvectors

- Example: Rotation

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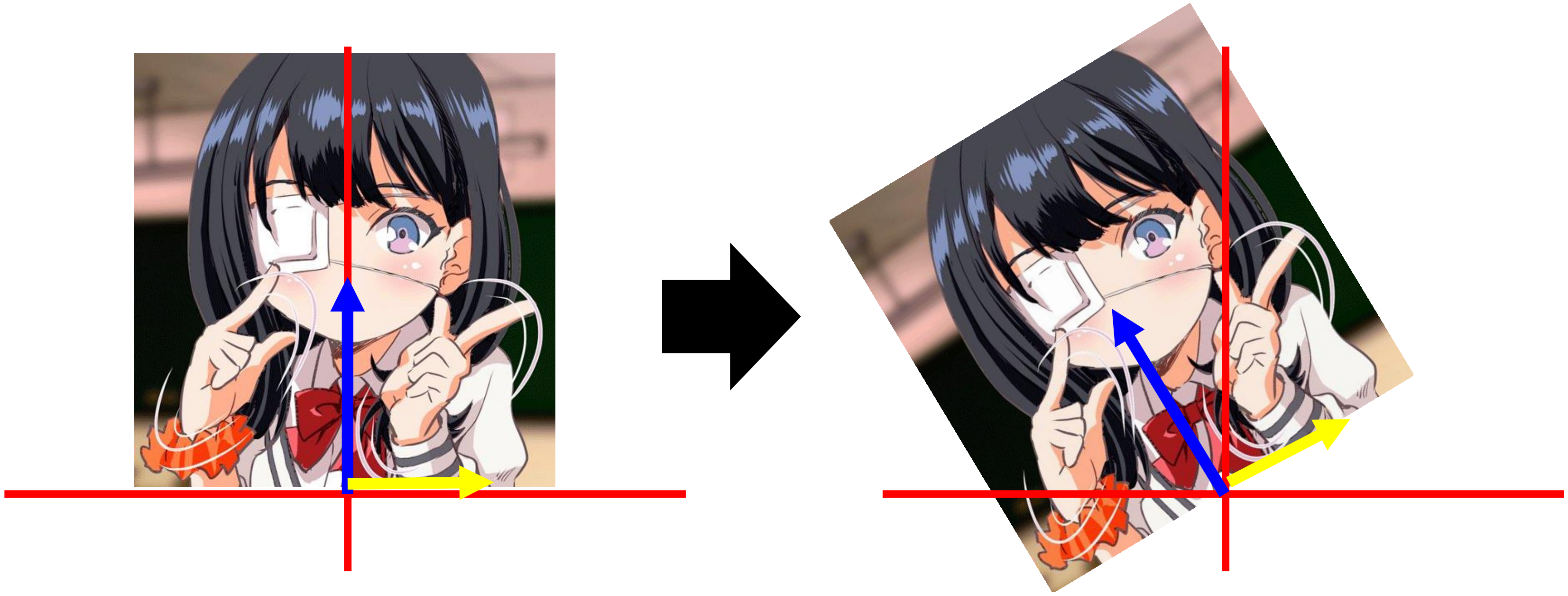


Do any n x n matrix or linear operator have eigenvalues?

How to find eigenvectors (given eigenvalues)

$Av = \lambda v \qquad A(cv) = cAv = c\lambda v = \lambda(cv)$

Eigenvalues and Eigenvectors

$Au = \lambda u \qquad A(v+u)$

- An eigenvector of A corresponds to a unique eigenvalue.
- An eigenvalue of A has infinitely many eigenvectors.

Example:

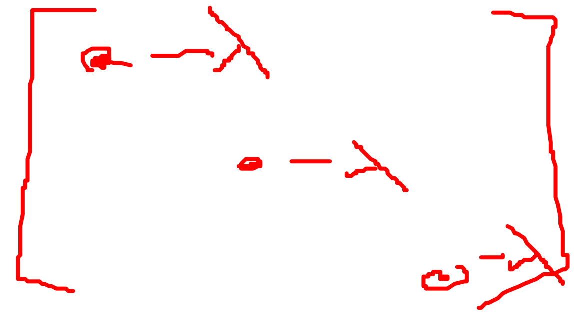
$$A = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 2 \\ 0 & 2 & 1 \end{bmatrix} \quad v = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad u = \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$$

$$\begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 2 \\ 0 & 2 & 1 \end{bmatrix} \begin{bmatrix} \cancel{1}\ 2 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix} \qquad \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 2 \\ 0 & 2 & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \\ 1 \end{bmatrix}$$

v ~~Eigenvalue~~= -1 v $\qquad$ u ~~Eigenvalue~~= -1 u

Do the eigenvectors correspond to the same eigenvalue form a subspace?

Eigenspace



- Assume we know λ is the eigenvalue of matrix A
- Eigenvectors corresponding to λ

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

$$A\mathbf{v} - \lambda\mathbf{v} = \mathbf{0}$$

$$A\mathbf{v} - \lambda I_n\mathbf{v} = \mathbf{0}$$

$$\underbrace{\boxed{(A - \lambda I_n)}}_{\text{matrix}}\mathbf{v} = \mathbf{0}$$

Eigenvectors corresponding to λ are nonzero solution of

$$(A - \lambda I_n)\mathbf{v} = \mathbf{0}$$

Eigenvectors corresponding to λ

$$= \underbrace{Null(A - \lambda I_n)}_{\text{eigenspace}} - \{\mathbf{0}\}$$

Eigenspace of λ:

Eigenvectors corresponding to λ + $\{\mathbf{0}\}$

Check whether a scalar is an eigenvalue

Check Eigenvalues

$Null(\boxed{A-\lambda I_n})$:
eigenspace of λ

- How to know whether a scalar λ is the eigenvalue of A?

Check the dimension of eigenspace of λ

If the dimension is 0

→ Eigenspace only contains {0}

→ No eigenvector

→ λ is not eigenvalue

Check Eigenvalues

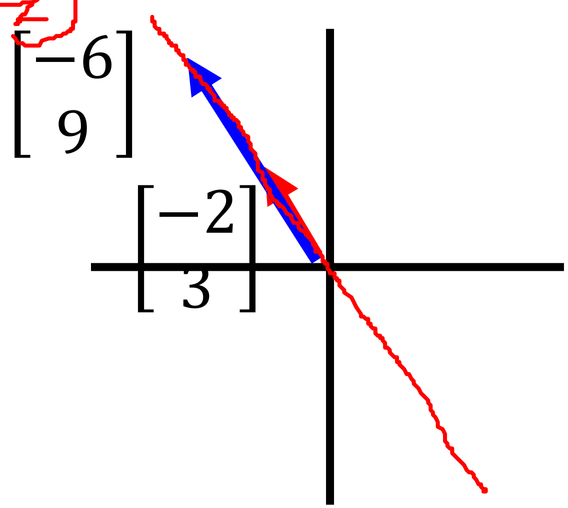
$Null(A - \lambda I_n)$:
eigenspace of λ

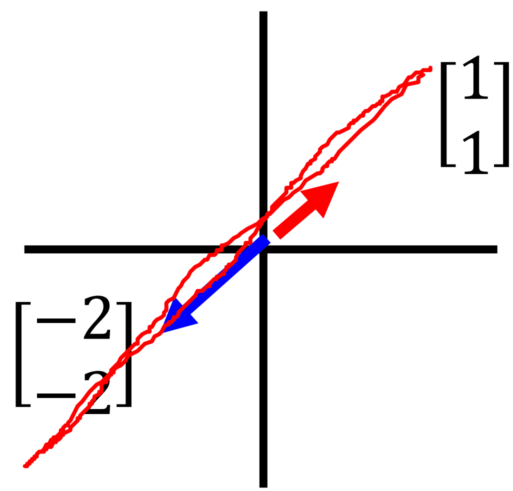
- Example: to check 3 and –2 are eigenvalues of the linear operator T

$$T\left(\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}\right) = \begin{bmatrix} -2x_2 \\ -3x_1 + x_2 \end{bmatrix} \qquad A = \begin{bmatrix} 0 & -2 \\ -3 & 1 \end{bmatrix}$$

$\begin{bmatrix} -3 & -2 \\ -3 & -2 \end{bmatrix}$ $Null(A - 3I_n)$=?

$Null(A + 2I_n)$=? $\begin{bmatrix} 2 & -2 \\ -3 & 3 \end{bmatrix}$





Check Eigenvalues

$Null(A - \lambda I_n)$:
eigenspace of λ

- Example: check that 3 is an eigenvalue of B and find a basis for the corresponding eigenspace

$$B = \begin{bmatrix} 3 & 0 & 0 \\ 0 & 1 & 2 \\ 0 & 2 & 1 \end{bmatrix}$$

find the solution set of $(B - 3I_3)\mathbf{x} = \mathbf{0}$

find the RREF of

$B - 3I_3$

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

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_3 \\ x_3 \end{bmatrix}$$

$$= x_1 \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + x_3 \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$$

Looking for Eigenvalues

Looking for Eigenvalues

$\boxed{\text{A scalar } t \text{ is an eigenvalue of A}}$

$\Leftrightarrow$ Existing $v \neq 0$ such that $Av = tv$

$\Leftrightarrow$ Existing $v \neq 0$ such that $Av - tv = 0$

$\Leftrightarrow$ Existing $v \neq 0$ such that $(A - tI_n)v = 0$

$\Leftrightarrow$ $(A - tI_n)v = 0$ has multiple solution

$\Leftrightarrow$ The columns of $(A - tI_n)$ are Dependent

$\Leftrightarrow$ $(A - tI_n)$ is not invertible

$\Leftrightarrow$ $\boxed{det(A - tI_n) = 0}$

Looking for Eigenvalues

- Example 1: Find the eigenvalues of $A = \begin{bmatrix} -4 & -3 \\ 3 & 6 \end{bmatrix}$

$\boxed{\text{A scalar } t \text{ is an eigenvalue of A} \Leftrightarrow det(A - tI_n) = 0}$

$$A - tI_2 = \begin{bmatrix} -4 - t & -3 \\ 3 & 6 - t \end{bmatrix}$$

$\det(A - tI_2)$ =0

det A = -15

trace A = 2

$\Rightarrow$ t = -3 or 5

The eigenvalues of *A* are -3 or 5.

Looking for Eigenvalues

- Example 1: Find the eigenvalues of $A = \begin{bmatrix} -4 & -3 \\ 3 & 6 \end{bmatrix}$

The eigenvalues of *A* are -3 or 5.

<u>Eigenspace of -3</u>

$$Ax = -3x \Rightarrow (A + 3I)x = 0$$

find the solution

<u>Eigenspace of 5</u>

$$Ax = 5x \Rightarrow (A - 5I)x = 0$$

find the solution

Looking for Eigenvalues

- Example 2: find the eigenvalues of linear operator

$$T\left(\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}\right) = \begin{bmatrix} -x_1 \\ 2x_1 - x_2 - x_3 \\ -x_3 \end{bmatrix} \xrightarrow[\text{standard matrix}]{} A = \begin{bmatrix} -1 & 0 & 0 \\ 2 & -1 & -1 \\ 0 & 0 & -1 \end{bmatrix}$$

$$\boxed{\text{A scalar } t \text{ is an eigenvalue of A} \Longleftrightarrow det(A - tI_n) = 0}$$

$$A - tI_n = \begin{bmatrix} -1-t & 0 & 0 \\ 2 & -1-t & -1 \\ 0 & 0 & -1-t \end{bmatrix}$$

$$\Rightarrow \quad det(A - tI_n) = (-1-t)^3$$

Looking for Eigenvalues

- Example 3: linear operator on $\mathcal{R}^2$ that rotates a vector by 90°

A scalar t is an eigenvalue of A $\Leftrightarrow$ $det(A - tI_n) = 0$

standard matrix of the 90°-rotation: $\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

$$\det\left(\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} - tI_2\right)$$

No eigenvalues, no eigenvectors

Characteristic Polynomial

A scalar t is an eigenvalue of A $\Leftrightarrow$ $det(A - tI_n) = 0$

A is the standard matrix of linear operator T

$det(A - tI_n)$: Characteristic polynomial of A

linear operator T

$det(A - tI_n) = 0$: Characteristic equation of A

linear operator T

Eigenvalues are the roots of characteristic polynomial or solutions of characteristic equation.

Characteristic Polynomial

- In general, a matrix A and RREF of A have different characteristic polynomials. $\Rightarrow$ Different Eigenvalues
- Similar matrices have the same characteristic polynomials $\Rightarrow$ The same Eigenvalues

$$\boxed{B = P^{-1}AP}$$

$$
\begin{aligned}
det(B - tI) &= det(P^{-1}AP - P^{-1}(tI)P) \\
&= det(P^{-1}(A - tI)AP) \\
&= det(P^{-1})det(A - tI)det(P) \\
&= \left(\frac{1}{det(P)}\right)det(A - tI)det(P) = det(A - tI)
\end{aligned}
$$

Characteristic Polynomial

- Question: What is the order of the characteristic polynomial of an $n \times n$ matrix A?
  - The characteristic polynomial of an $n \times n$ matrix is indeed a polynomial with degree n
  - Consider $\det(A - tI_n)$
- Question: What is the number of eigenvalues of an $n \times n$ matrix A?
  - Fact: An n x n matrix A have less than or equal to n eigenvalues
  - Consider complex roots and multiple roots

Characteristic Polynomial v.s. Eigenspace

- Characteristic polynomial of A is

$det(A - tI_n)$ Factorization

multiplicity

$$= (t-\lambda_1)^{m_1}(t-\lambda_2)^{m_2}\ldots(t-\lambda_k)^{m_k}\underline{(\ldots\ldots)}$$

Eigenvalue:	λ_1	λ_2	λ_k
Eigenspace: (dimension)	d_1 $\leq m_1$	d_2 $\leq m_2$	d_k $\leq m_k$

Characteristic Polynomial

- The eigenvalues of an upper triangular matrix are its diagonal entries.

Characteristic Polynomial:

$$\begin{bmatrix} a & * & * \\ 0 & b & * \\ 0 & 0 & c \end{bmatrix}$$

$$det \begin{bmatrix} a-t & * & * \\ 0 & b-t & * \\ 0 & 0 & c-t \end{bmatrix}$$

$$= (a-t)(b-t)(c-t)$$

The determinant of an upper triangular matrix is the product of its diagonal entries.

Summary

- If $Av = \lambda v$ (v is a vector, λ is a scalar)
  - v is an eigenvector of A excluding zero vector
  - λ is an eigenvalue of A that corresponds to v
- Eigenvectors corresponding to λ are nonzero solution of $(A - \lambda I_n)\mathbf{v} = \mathbf{0}$

Eigenvectors corresponding to λ

$$= \underbrace{Null(A - \lambda I_n)}_{\text{eigenspace}} - \{\mathbf{0}\}$$

Eigenspace of λ:

Eigenvectors corresponding to λ + $\{\mathbf{0}\}$

- A scalar t is an eigenvalue of A

$\Leftrightarrow$ $\boxed{det(A - tI_n) = 0}$