Eigenvectors & Eigenvalues:

Linear Algebra

Major sources:

Winter 2022 - Dan Calderone

Eigenvectors & Eigenvalues

Square matrix: $A \in \mathbb{R}^{n \times n}$

Eigenvalue/Eigenvector Problem

A transforms $\mathbb{R}^n$ ***…which directions stay unchanged?*** → **Eigenvectors**

…within those directions…

…how much do vectors get stretched → **Eigenvalues**

Eigenvector Equation

$$Ax = x\lambda$$

Eigenvector $x \in \mathbb{C}^n$ **Eigenvalue** $\lambda \in \mathbb{C}$

Spans of eigenvectors (& generalized eigenvectors) are called **A-invariant subspaces**

Eigenvalues:

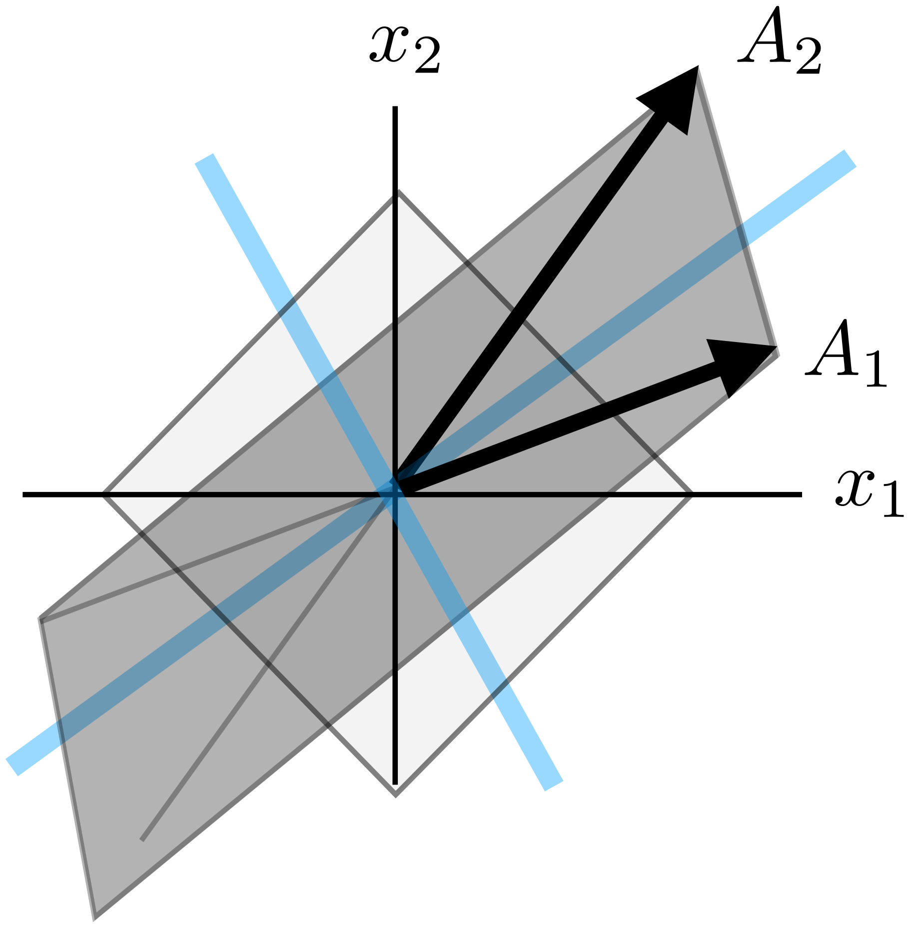
Fundamental property of matrices
Do **not** change with coordinate/similarity transformations

Eigenvectors:

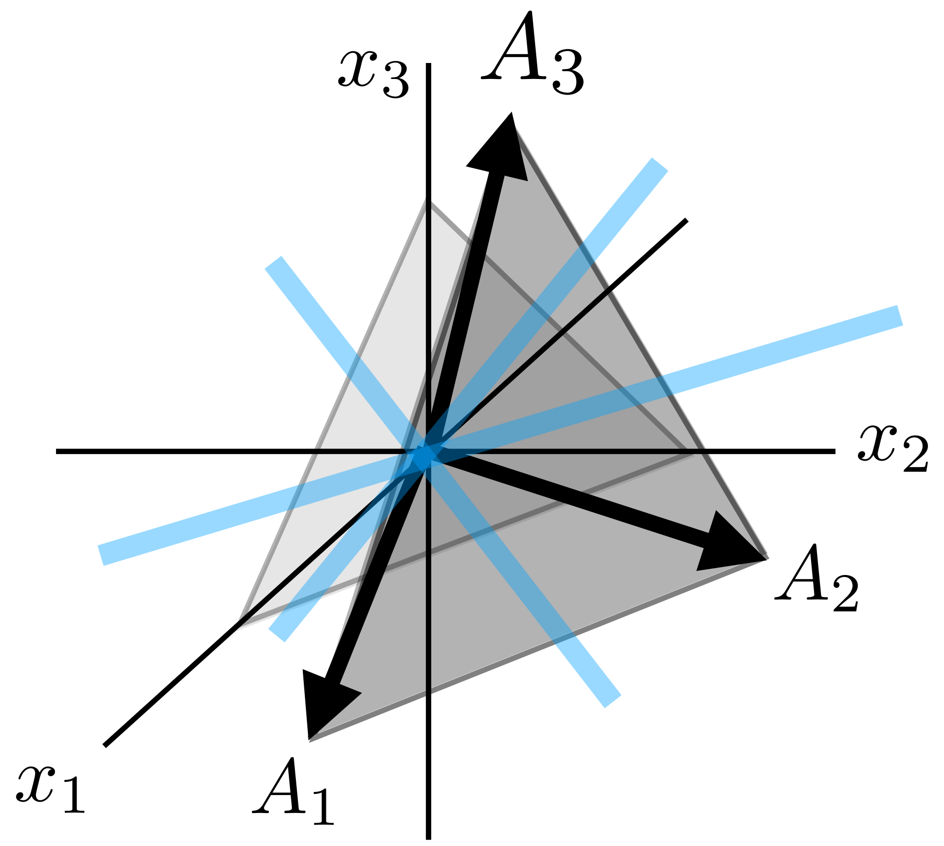
…coordinate dependent (do change with coordinate/similarity transformations)

Picture Examples:

$$A = \begin{bmatrix} | & | \\ A_1 & A_2 \\ | & | \end{bmatrix} \in \mathbb{R}^{2 \times 2}$$



$$A = \begin{bmatrix} | & | & | \\ A_1 & A_2 & A_3 \\ | & | & | \end{bmatrix} \in \mathbb{R}^{3 \times 3}$$



Eigenvector/Eigenvalue equation

Square matrix: $A \in \mathbb{R}^{n \times n}$

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0 \qquad v \in \mathcal{N}(A - \lambda I)$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0 \qquad w^* \in \mathcal{N}^L(A - \lambda I) = 0$$

For any eigenvalue, right and left eigenvectors come in pairs
since $A - \lambda I$ drops row and column rank at the same time

Eigenvectors exist only for values of s where $A - sI$ drops rank…

…how to characterize…. ➡ $sI - A$ drops rank only when $\det(sI - A) = 0$

Characteristic Polynomial

$\mathrm{char}_A(s) = \det(sI - A)$ **n-th order polynomial** ➡ **n roots**

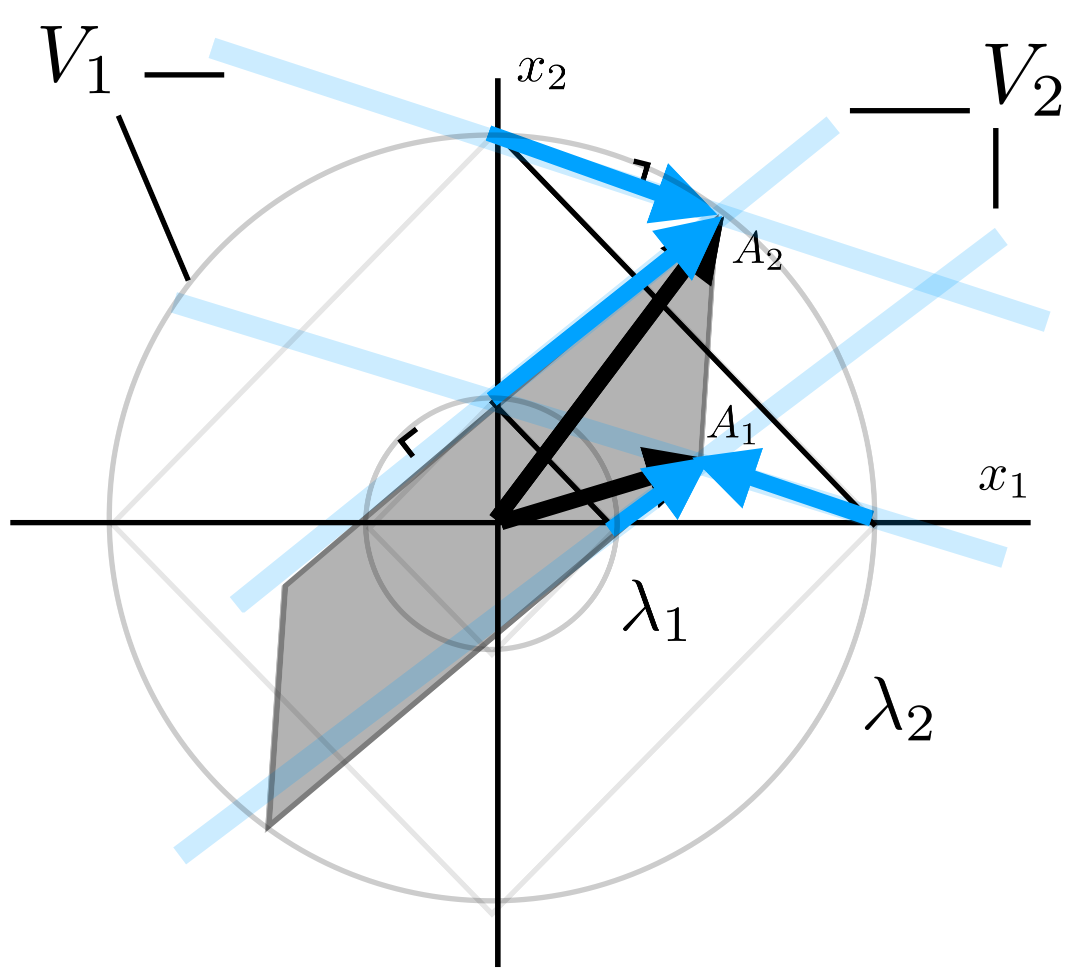
Roots are eigenvalues: λ solution to $\mathrm{char}_A(s) = 0$

Fundamental
Theorem of Algebra

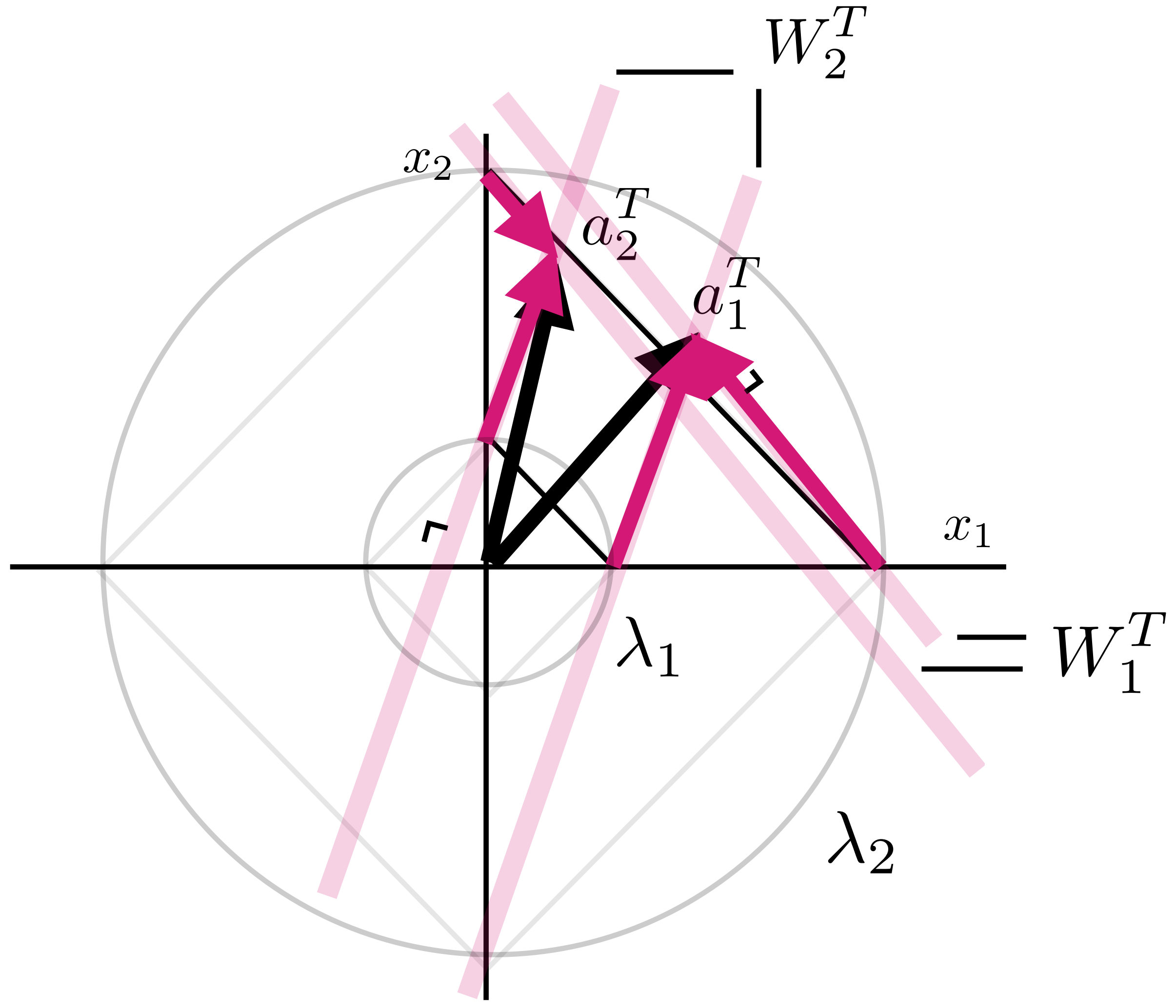
Picture Examples:

$\mathbb{R}^{2 \times 2}$

COLUMN GEOMETRY



ROW GEOMETRY



(see below)

Eigenvector/Eigenvalue equation

Square matrix: $A \in \mathbb{R}^{n \times n}$

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0 \qquad v \in \mathcal{N}(A - \lambda I)$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0 \qquad w^* \in \mathcal{N}^L(A - \lambda I) = 0$$

For any eigenvalue, right and left eigenvectors come in pairs since $A - \lambda I$ drops row and column rank at the same time

Eigenvectors exist only for values of s where $A - sI$ drops rank…

…how to characterize…. ➡ $sI - A$ drops rank only when $\det(sI - A) = 0$

Characteristic Polynomial

$\text{char}_A(s) = \det(sI - A)$ **n-th order polynomial** ➡ **n roots**

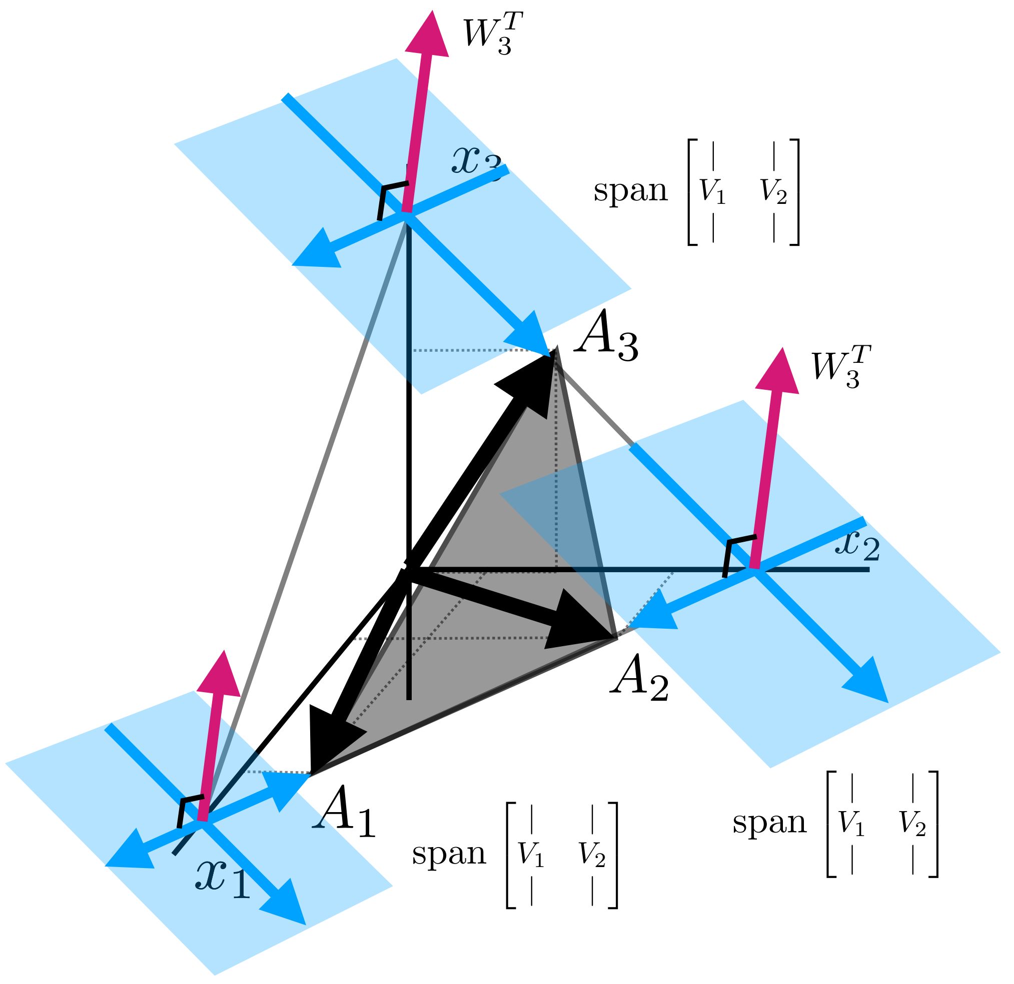
Roots are eigenvalues: λ solution to $\text{char}_A(s) = 0$

Fundamental Theorem of Algebra

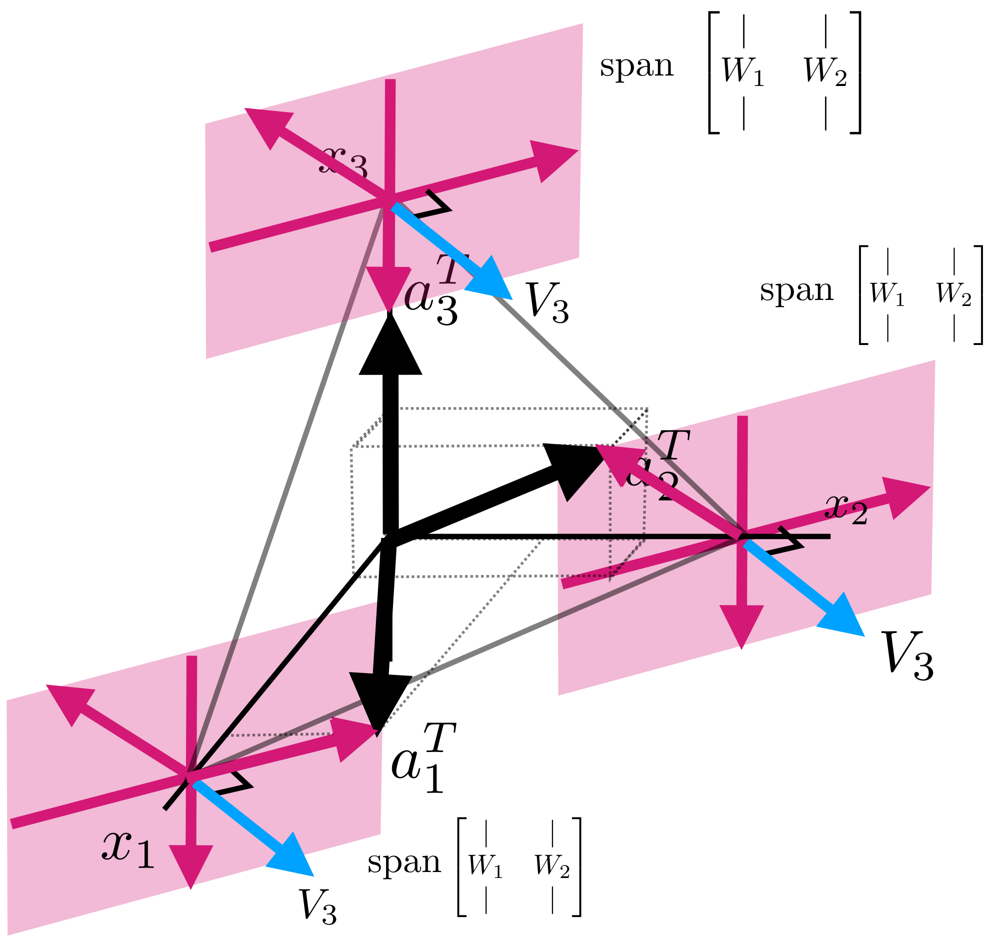
Picture Examples:

$\mathbb{R}^{3\times 3}$

COLUMN GEOMETRY



ROW GEOMETRY



(see below)

Eigenvector/Eigenvalue Picture

Eigenvectors exist only for values of *s* where $A - sI$ drops rank…

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Characteristic Polynomial

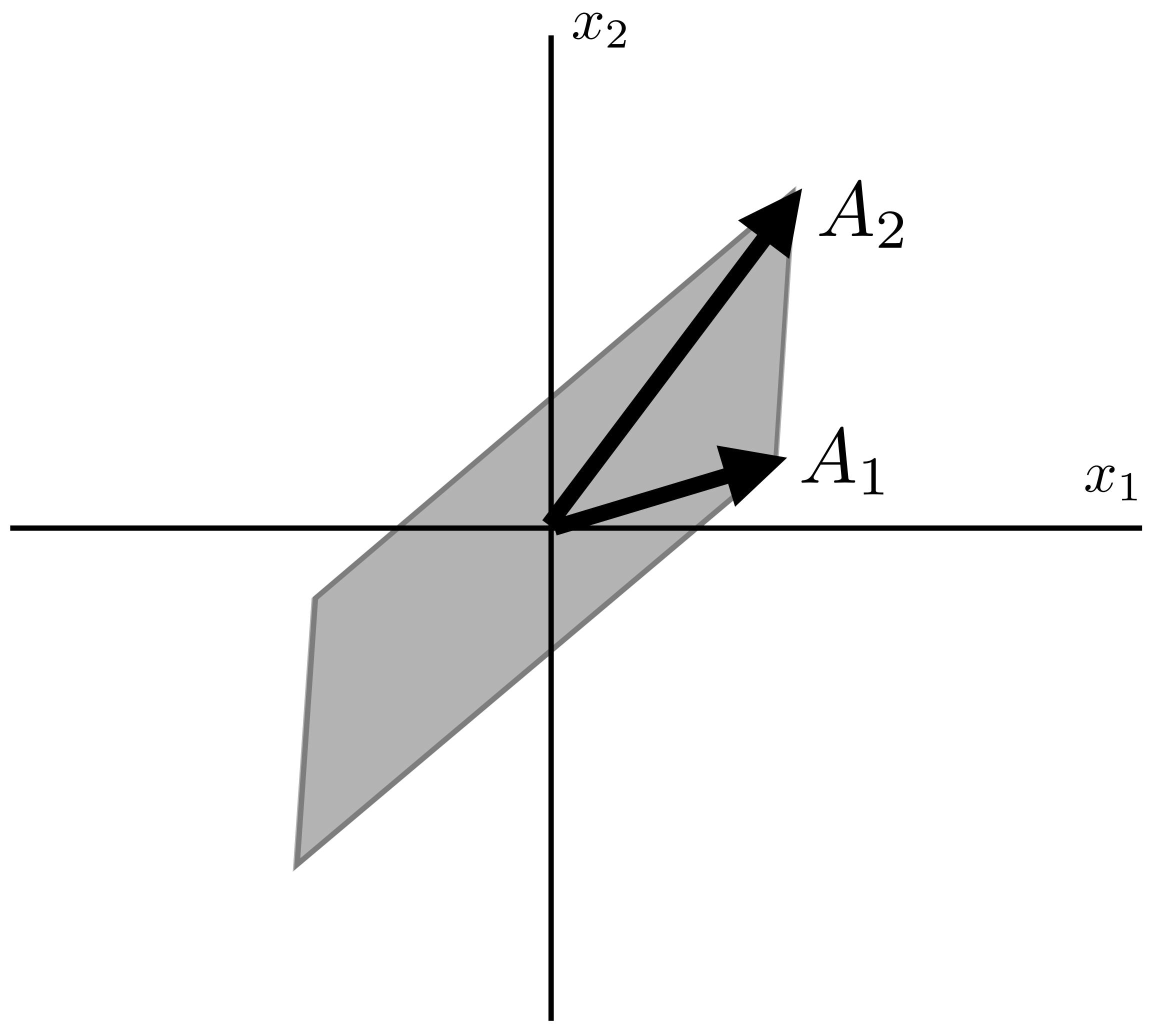
$sI - A$ drops rank only when

$$\text{char}_A(s) = \det(sI - A) = 0$$

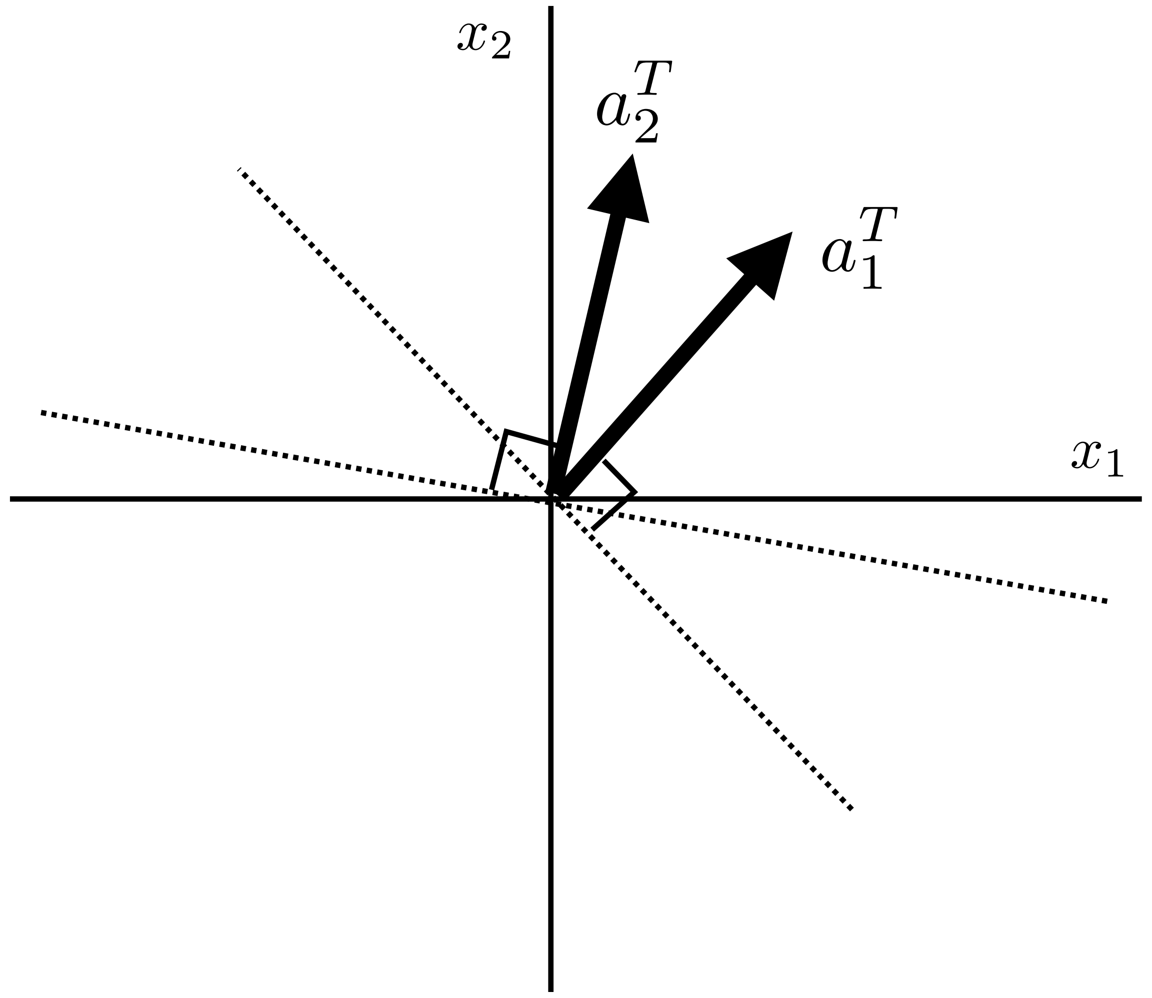
$$A \in \mathbb{R}^{2\times 2}$$

$$A = \begin{bmatrix} | & | \\ A_1 & A_2 \\ | & | \end{bmatrix} = \begin{bmatrix} -a_1^T- \\ -a_2^T- \end{bmatrix} = \begin{bmatrix} | & | \\ V_1 & V_2 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \end{bmatrix}$$

COLUMN GEOMETRY



ROW GEOMETRY



Eigenvector/Eigenvalue Picture

Eigenvectors exist only for values of s where $A - sI$ drops rank...

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \quad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \quad w^*(A - \lambda I) = 0$$

Characteristic Polynomial

$sI - A$ drops rank only when

$$\text{char}_A(s) = \det(sI - A) = 0$$

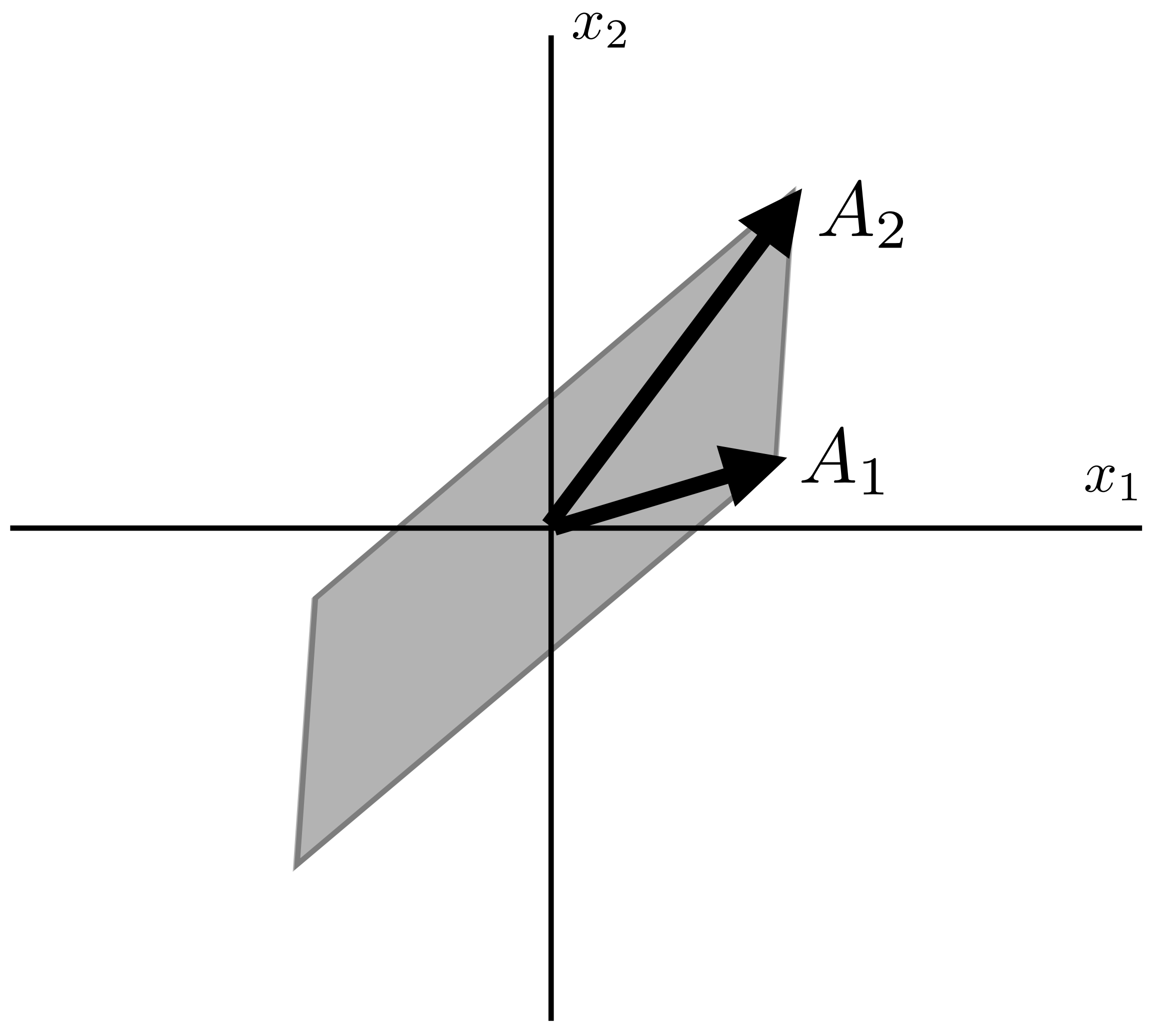
$$A \in \mathbb{R}^{2\times 2}$$

$$A = \begin{bmatrix} | & | \\ A_1 & A_2 \\ | & | \end{bmatrix} = \begin{bmatrix} -a_1^T- \\ -a_2^T- \end{bmatrix} = \begin{bmatrix} | & | \\ V_1 & V_2 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \end{bmatrix}$$

COLUMN GEOMETRY

$$\begin{bmatrix} A - \lambda I \end{bmatrix}$$

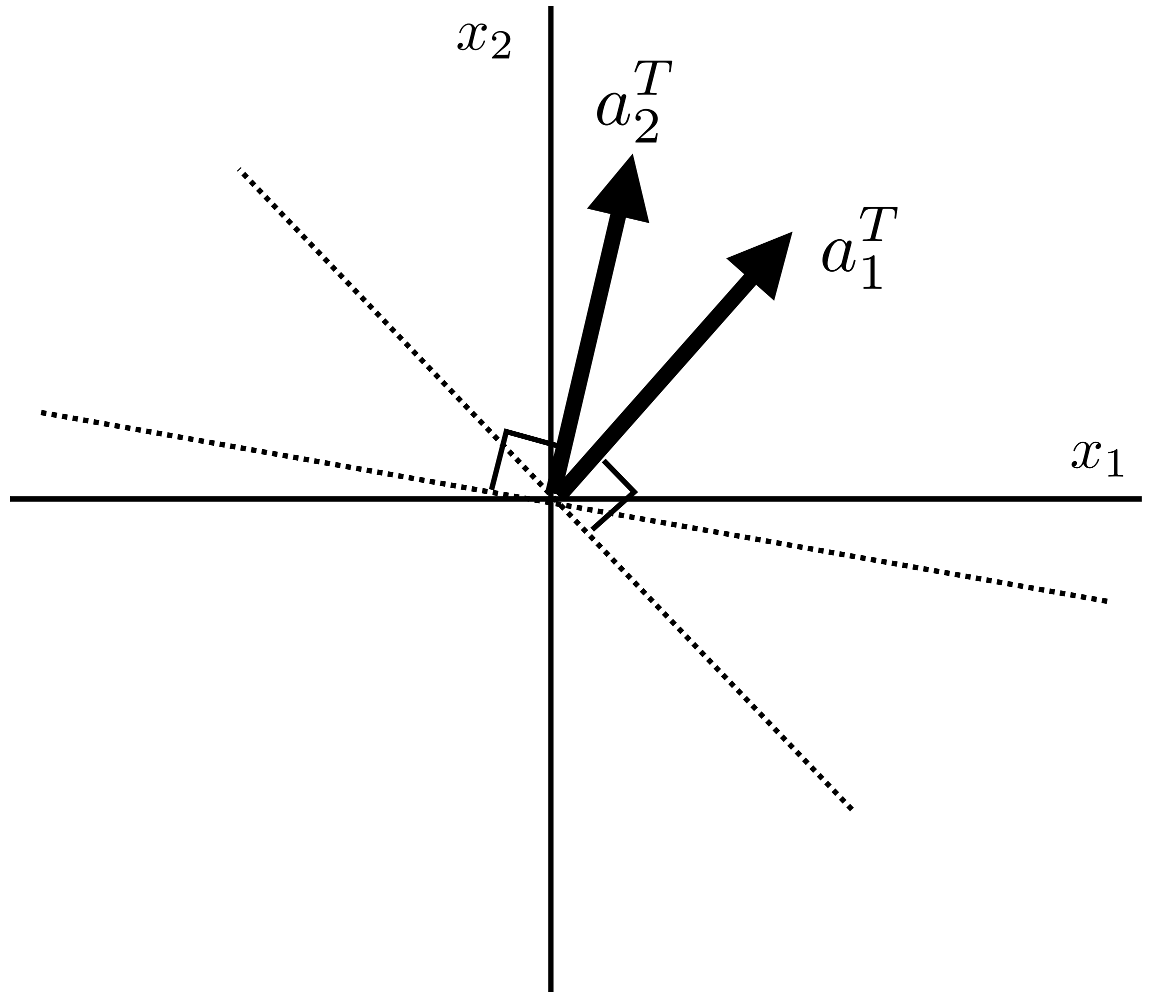
drops rank for eigenvalue



ROW GEOMETRY

$$\begin{bmatrix} A - \lambda I \end{bmatrix}$$

drops rank for eigenvalue



Eigenvector/Eigenvalue Picture

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Eigenvectors exist only for values of s where $A - sI$ drops rank...

Characteristic Polynomial

$sI - A$ drops rank only when

$$\text{char}_A(s) = \det(sI - A) = 0$$

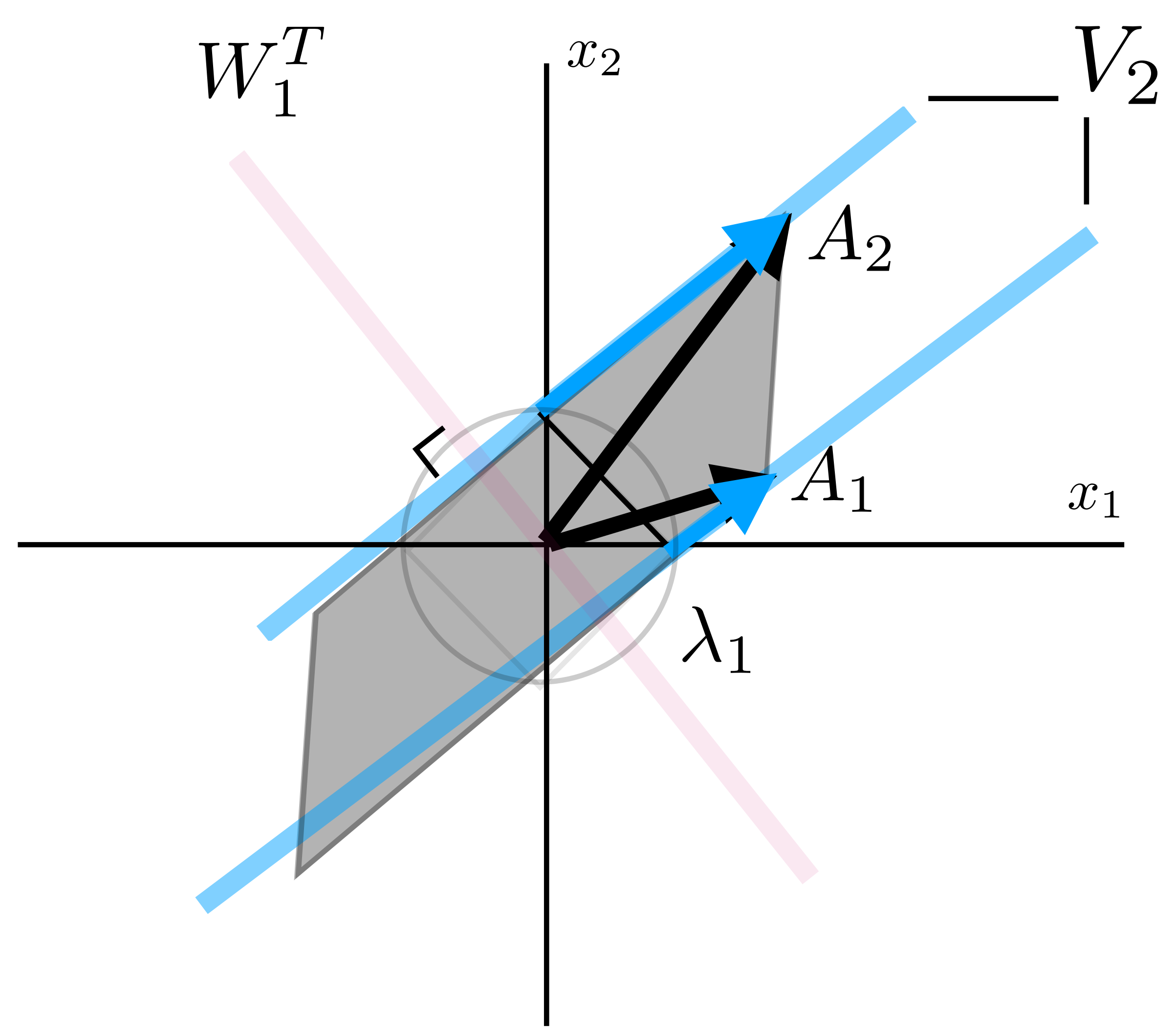
$$A \in \mathbb{R}^{2\times 2}$$

$$A = \begin{bmatrix} | & | \\ A_1 & A_2 \\ | & | \end{bmatrix} = \begin{bmatrix} -a_1^T- \\ -a_2^T- \end{bmatrix} = \begin{bmatrix} | & | \\ V_1 & V_2 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \end{bmatrix}$$

COLUMN GEOMETRY

$$\begin{bmatrix} A - \lambda_1 I \end{bmatrix}$$

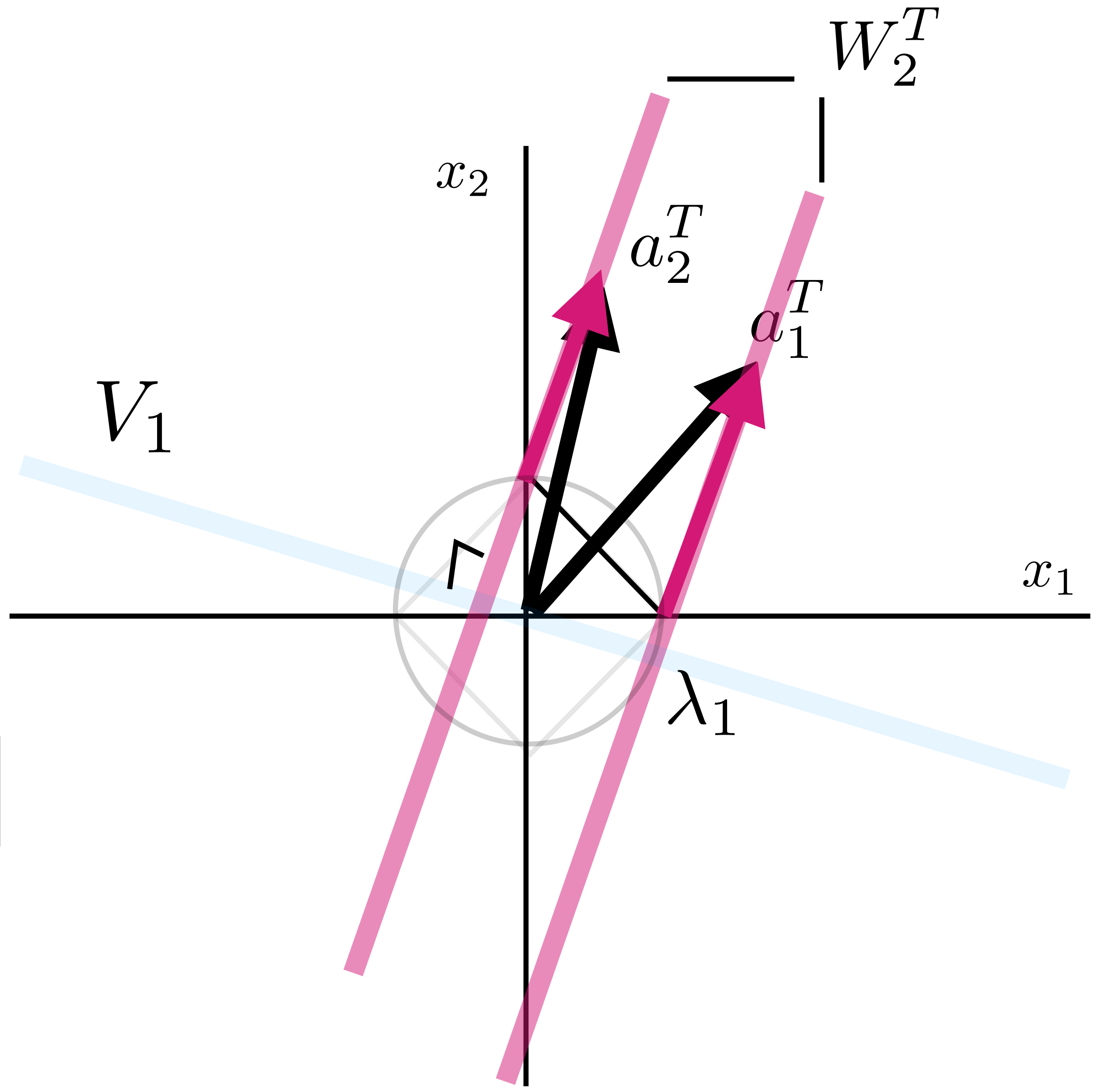
$$\begin{bmatrix} | \\ V_2 \\ | \end{bmatrix} \begin{bmatrix} \lambda_2 - \lambda_1 \end{bmatrix} \begin{bmatrix} - & W_2^T & - \end{bmatrix}$$



ROW GEOMETRY

$$\begin{bmatrix} A - \lambda_1 I \end{bmatrix}$$

$$\begin{bmatrix} | \\ V_2 \\ | \end{bmatrix} \begin{bmatrix} \lambda_2 - \lambda_1 \end{bmatrix} \begin{bmatrix} - & W_2^T & - \end{bmatrix}$$



Eigenvector/Eigenvalue Picture

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Eigenvectors exist only for values of s where $A - sI$ drops rank...

Characteristic Polynomial

$sI - A$ drops rank only when

$$\text{char}_A(s) = \det(sI - A) = 0$$

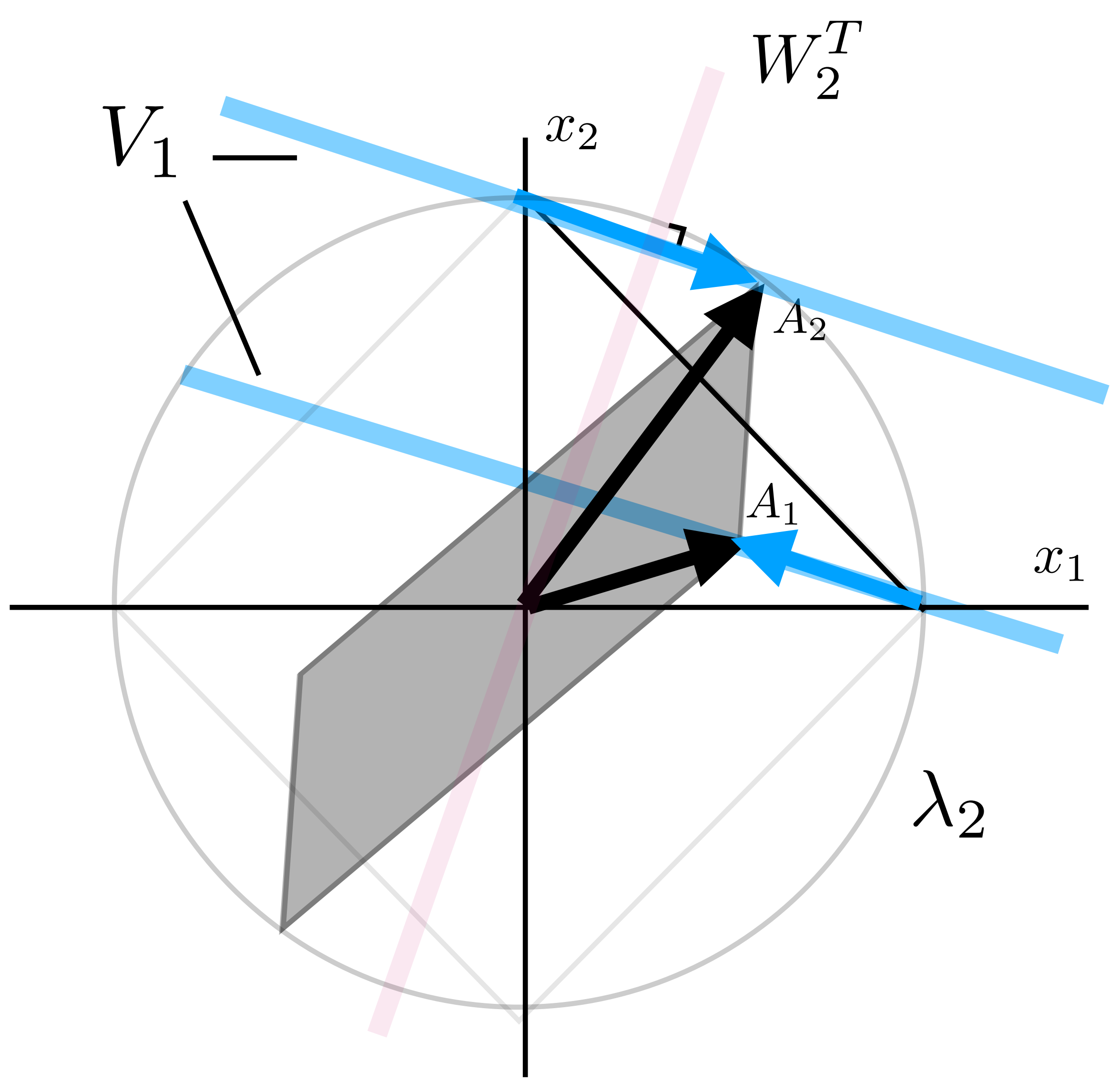
$$A \in \mathbb{R}^{2\times 2}$$

$$A = \begin{bmatrix} | & | \\ A_1 & A_2 \\ | & | \end{bmatrix} = \begin{bmatrix} -a_1^T- \\ -a_2^T- \end{bmatrix} = \begin{bmatrix} | & | \\ V_1 & V_2 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \end{bmatrix}$$

COLUMN GEOMETRY

$$\begin{bmatrix} A - \lambda_2 I \end{bmatrix}$$

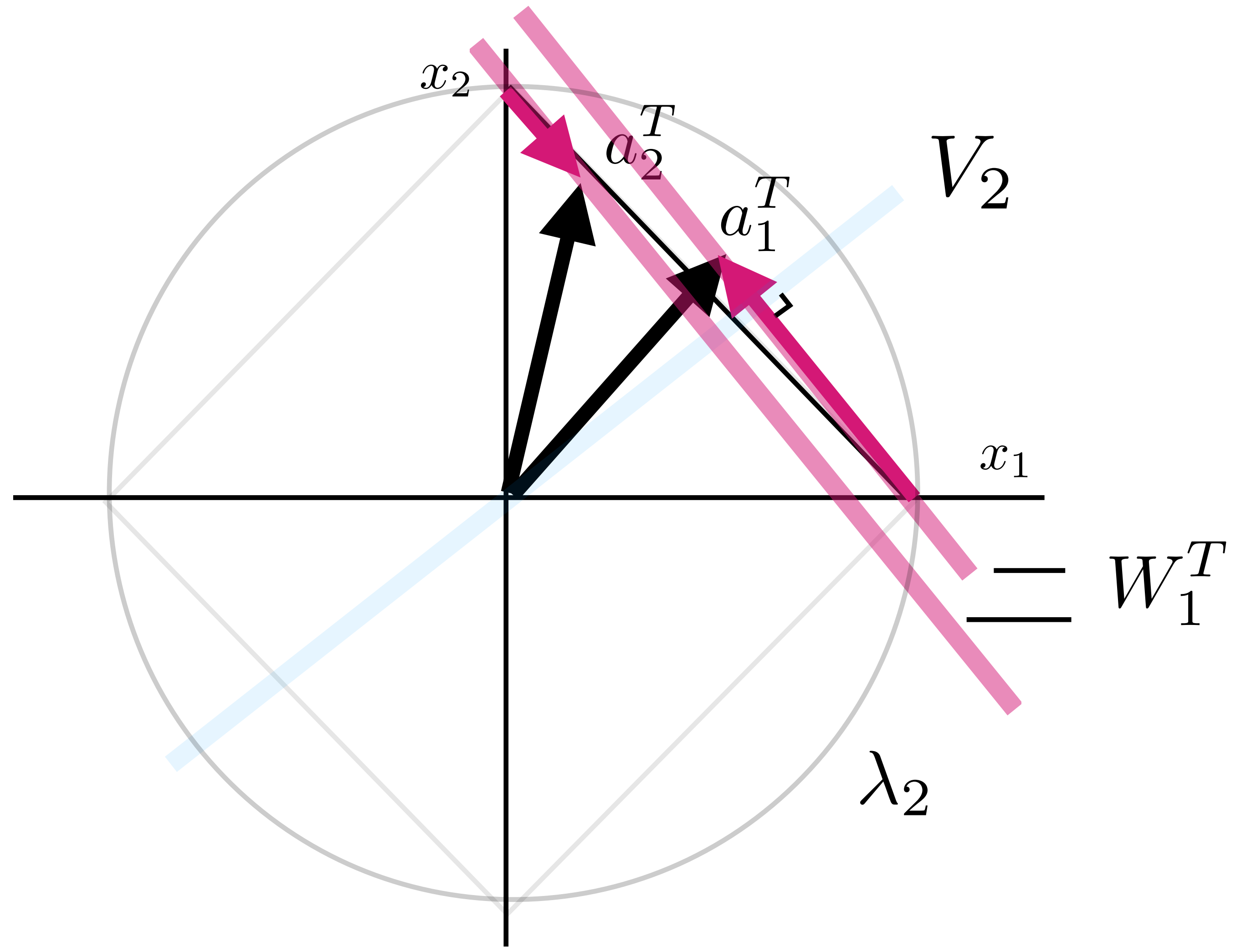
$$\begin{bmatrix} | \\ V_1 \\ | \end{bmatrix} \begin{bmatrix} \lambda_1 - \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \end{bmatrix}$$



ROW GEOMETRY

$$\begin{bmatrix} A - \lambda_2 I \end{bmatrix}$$

$$\begin{bmatrix} | \\ V_1 \\ | \end{bmatrix} \begin{bmatrix} \lambda_1 - \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \end{bmatrix}$$



Eigenvector/Eigenvalue Picture

Eigenvectors exist only for values of s where $A - sI$ drops rank…

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Characteristic Polynomial

$sI - A$ drops rank only when

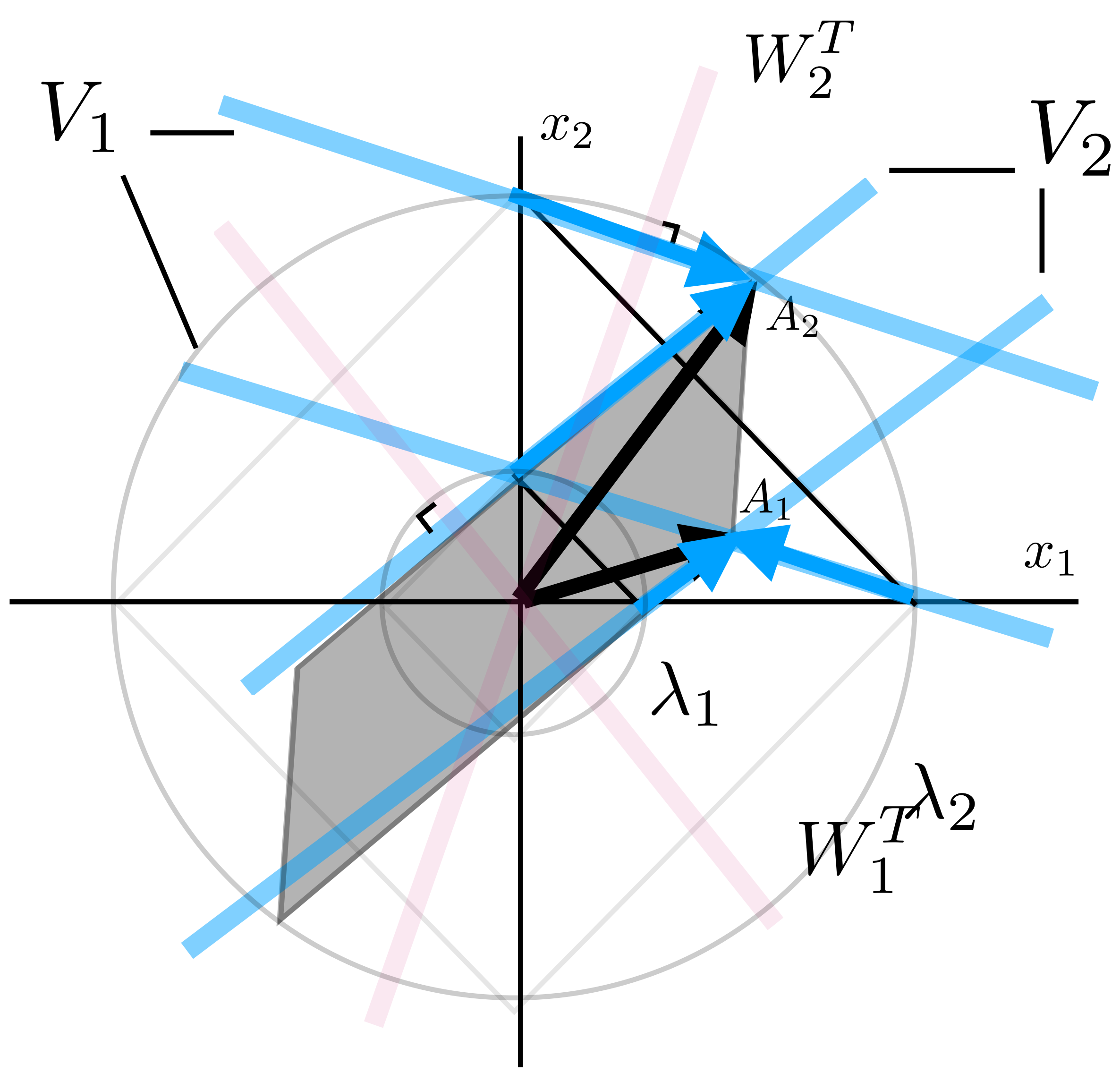
$$\text{char}_A(s) = \det(sI - A) = 0$$

$$A \in \mathbb{R}^{2\times 2}$$

$$A = \begin{bmatrix} | & | \\ A_1 & A_2 \\ | & | \end{bmatrix} = \begin{bmatrix} -a_1^T- \\ -a_2^T- \end{bmatrix} = \begin{bmatrix} | & | \\ V_1 & V_2 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \begin{bmatrix} - \ W_1^T \ - \\ - \ W_2^T \ - \end{bmatrix}$$

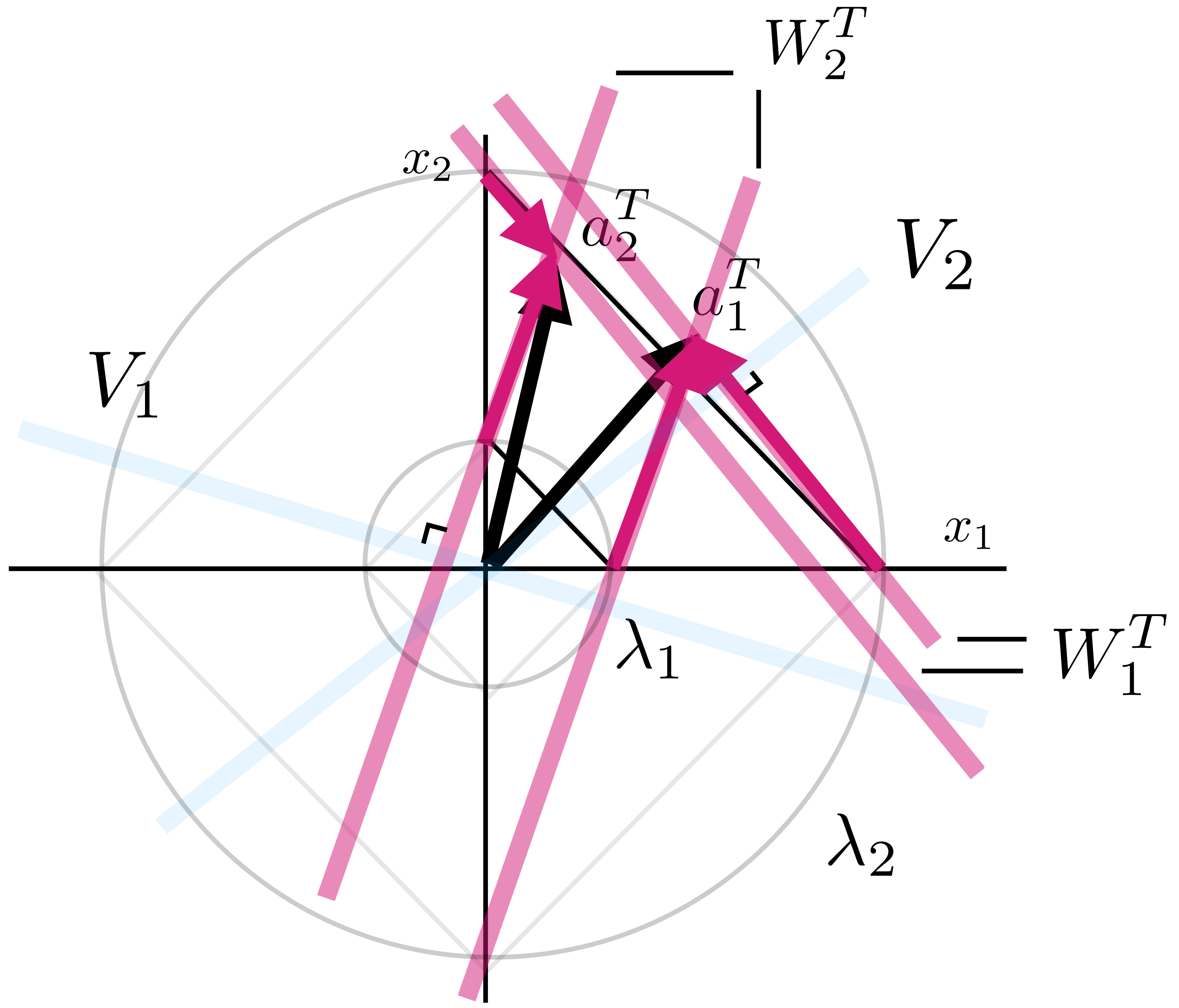
COLUMN GEOMETRY

$$\begin{bmatrix} A - \lambda I \end{bmatrix}$$



ROW GEOMETRY

$$\begin{bmatrix} A - \lambda I \end{bmatrix}$$



Eigenvector/Eigenvalue Picture

Eigenvectors exist only for values of s where $A - sI$ drops rank...

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Characteristic Polynomial

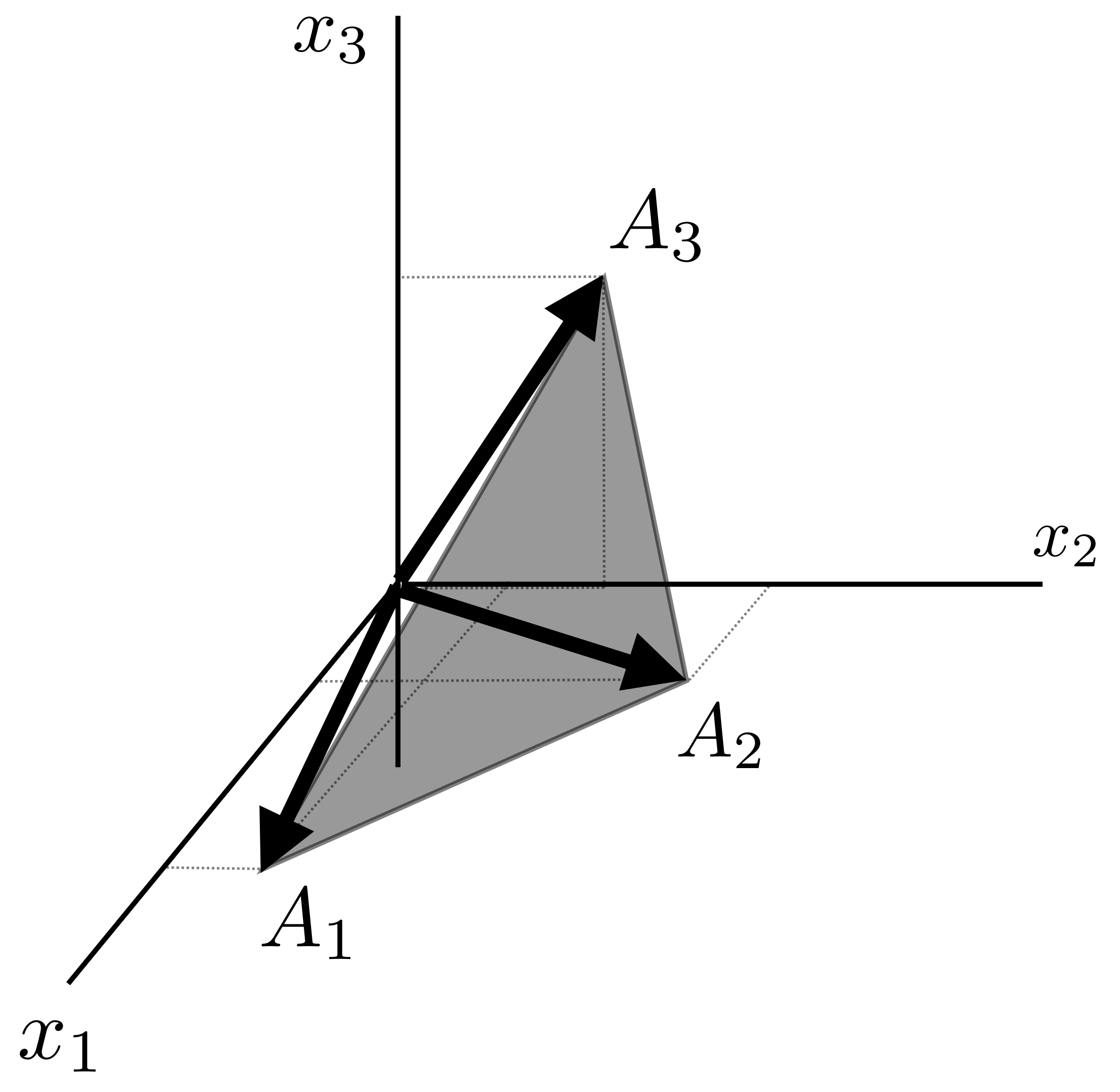
$sI - A$ drops rank only when

$$\text{char}_A(s) = \det(sI - A) = 0$$

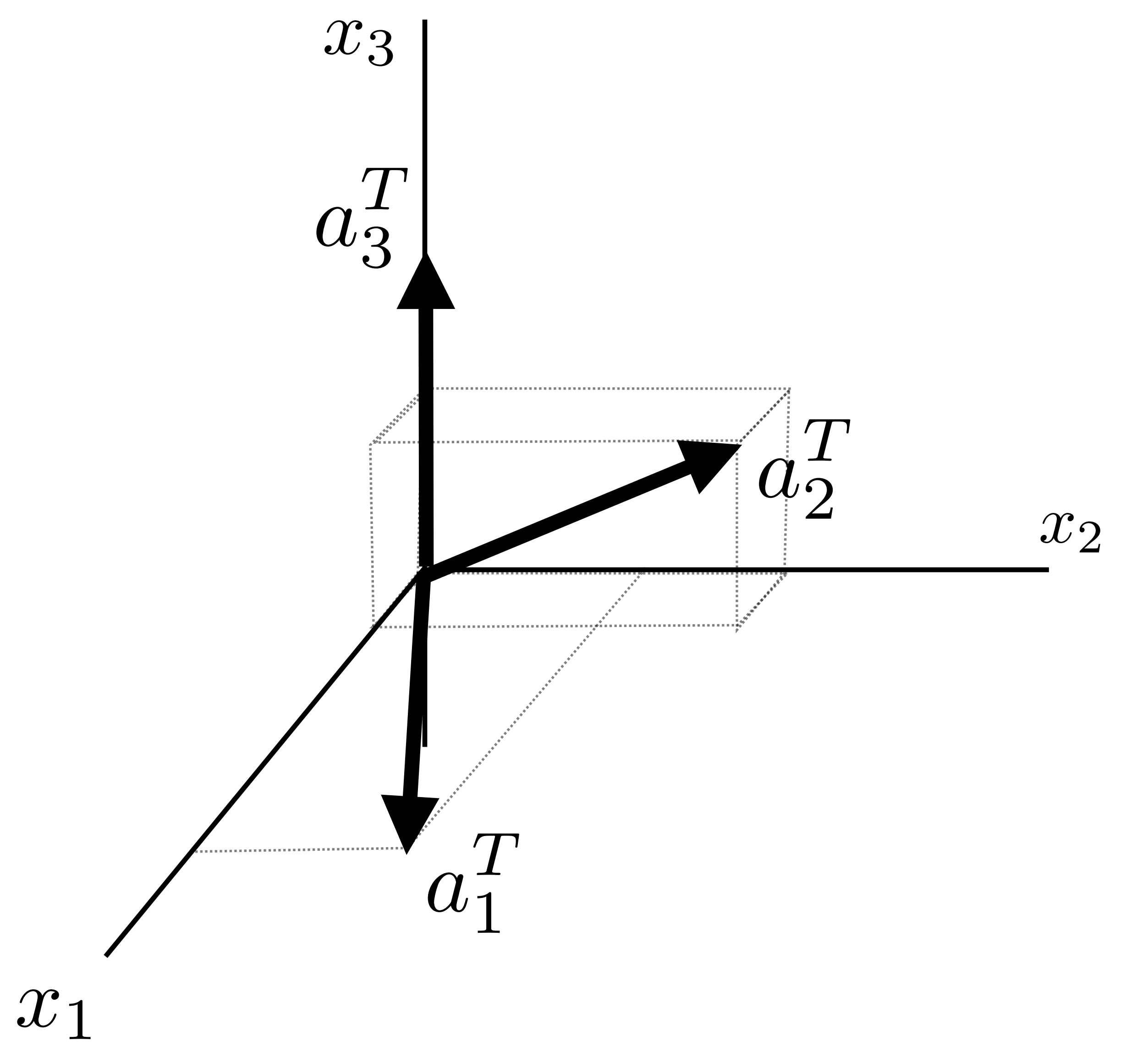
$$A \in \mathbb{R}^{3\times 3}$$

$$A = \begin{bmatrix} | & | & | \\ A_1 & A_2 & A_3 \\ | & | & | \end{bmatrix} = \begin{bmatrix} - & a_1^T & - \\ - & a_2^T & - \\ - & a_3^T & - \end{bmatrix} = \begin{bmatrix} | & | & | \\ V_1 & V_2 & V_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \\ - & W_3^T & - \end{bmatrix}$$

COLUMN GEOMETRY



ROW GEOMETRY



Eigenvector/Eigenvalue Picture

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Eigenvectors exist only for values of s where $A - sI$ drops rank...

Characteristic Polynomial

$sI - A$ drops rank only when

$$\mathrm{char}_A(s) = \det(sI - A) = 0$$

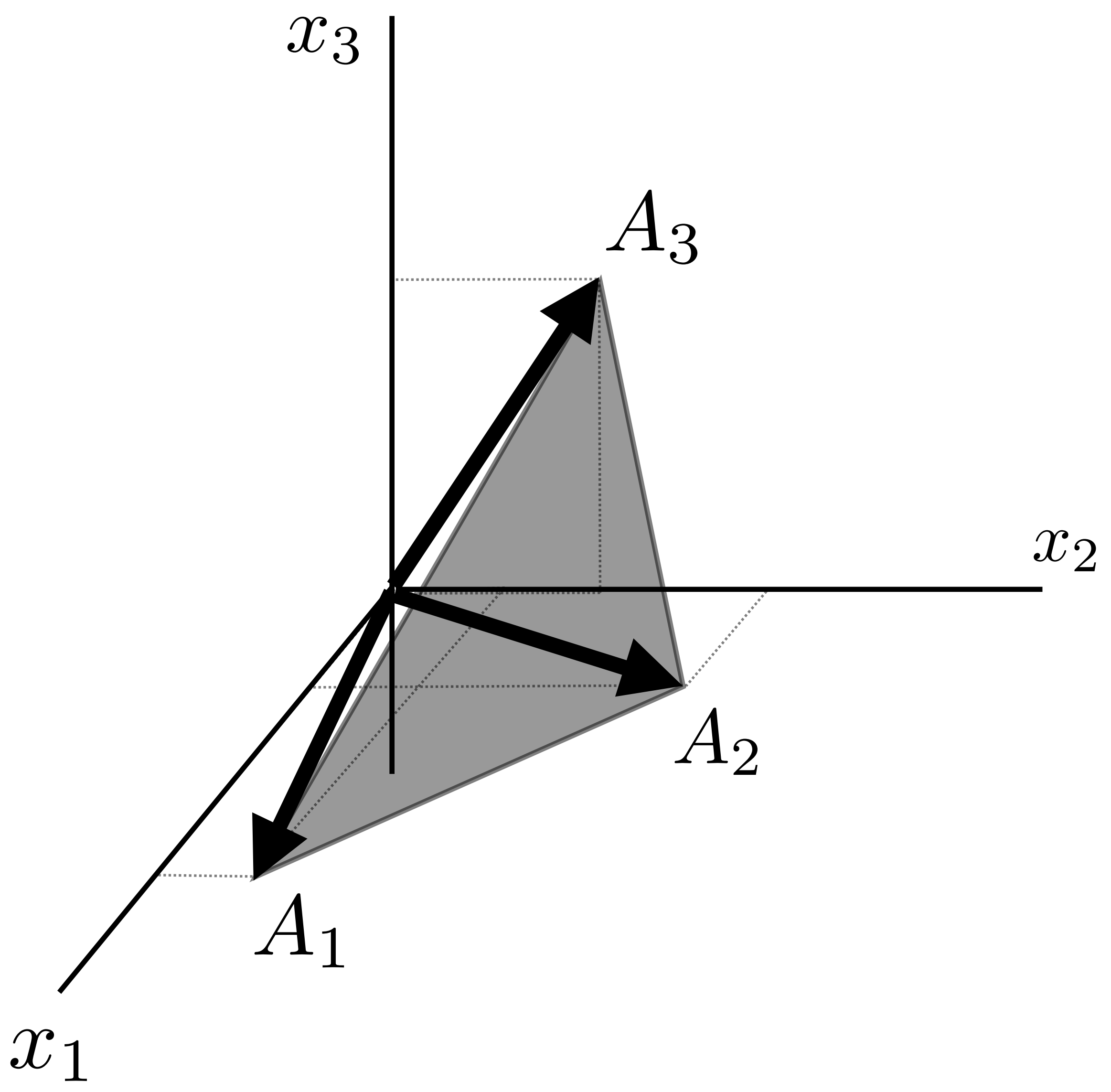
$$A \in \mathbb{R}^{3\times 3}$$

$$A = \begin{bmatrix} | & | & | \\ A_1 & A_2 & A_3 \\ | & | & | \end{bmatrix} = \begin{bmatrix} - & a_1^T & - \\ - & a_2^T & - \\ - & a_3^T & - \end{bmatrix} = \begin{bmatrix} | & | & | \\ V_1 & V_2 & V_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \\ - & W_3^T & - \end{bmatrix}$$

COLUMN GEOMETRY

$$\begin{bmatrix} A - \lambda I \end{bmatrix}$$

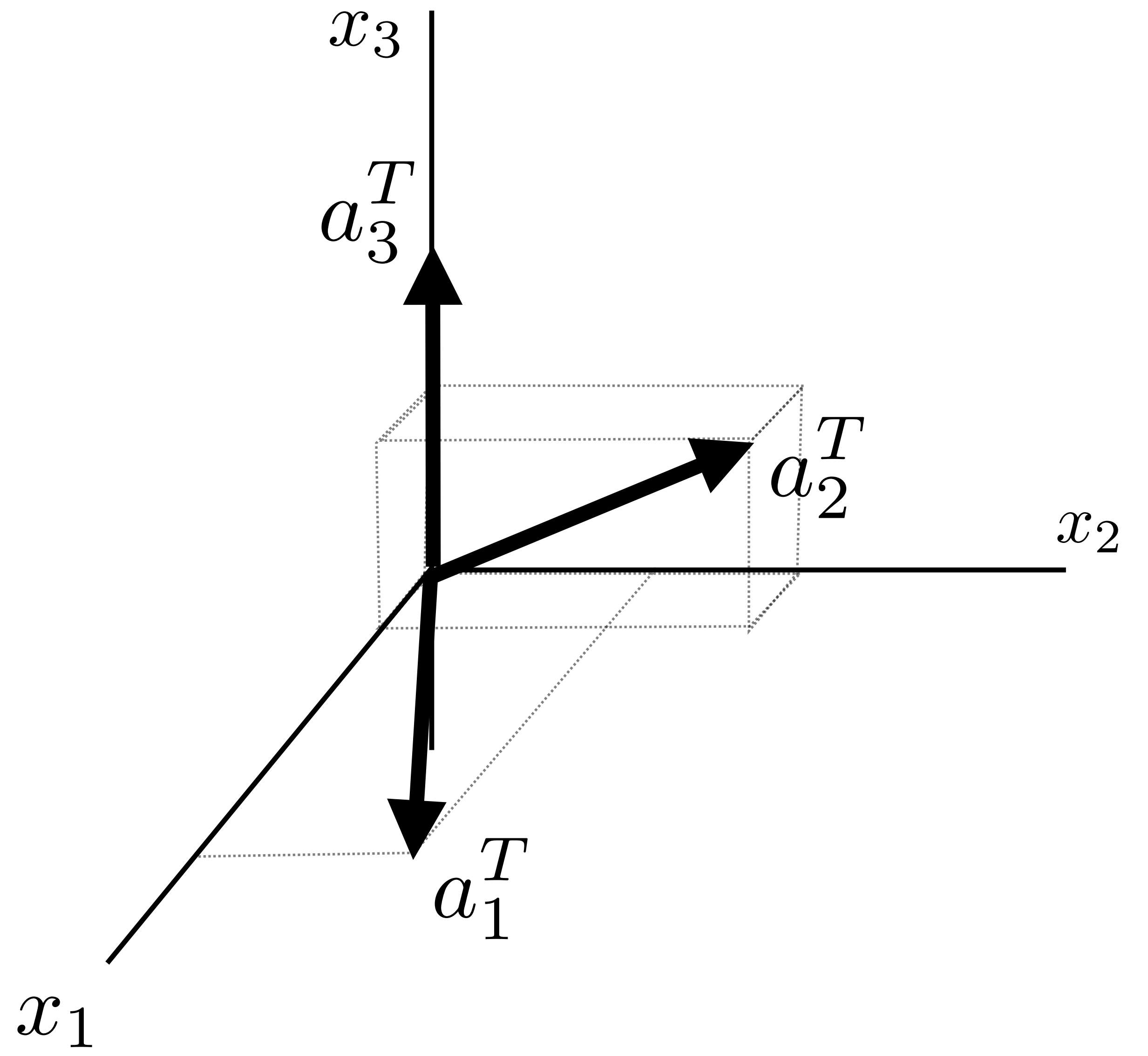
drops rank for eigenvalue



ROW GEOMETRY

$$\begin{bmatrix} A - \lambda I \end{bmatrix}$$

drops rank for eigenvalue



Eigenvector/Eigenvalue Picture

Eigenvectors exist only for values of s where $A - sI$ drops rank...

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Characteristic Polynomial

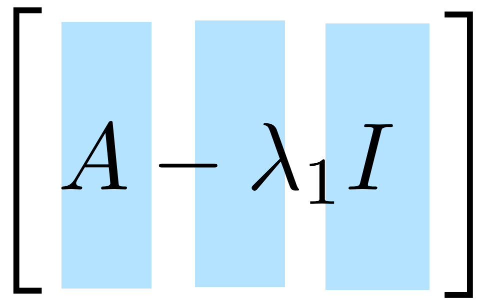
$sI - A$ drops rank only when

$$\text{char}_A(s) = \det(sI - A) = 0$$

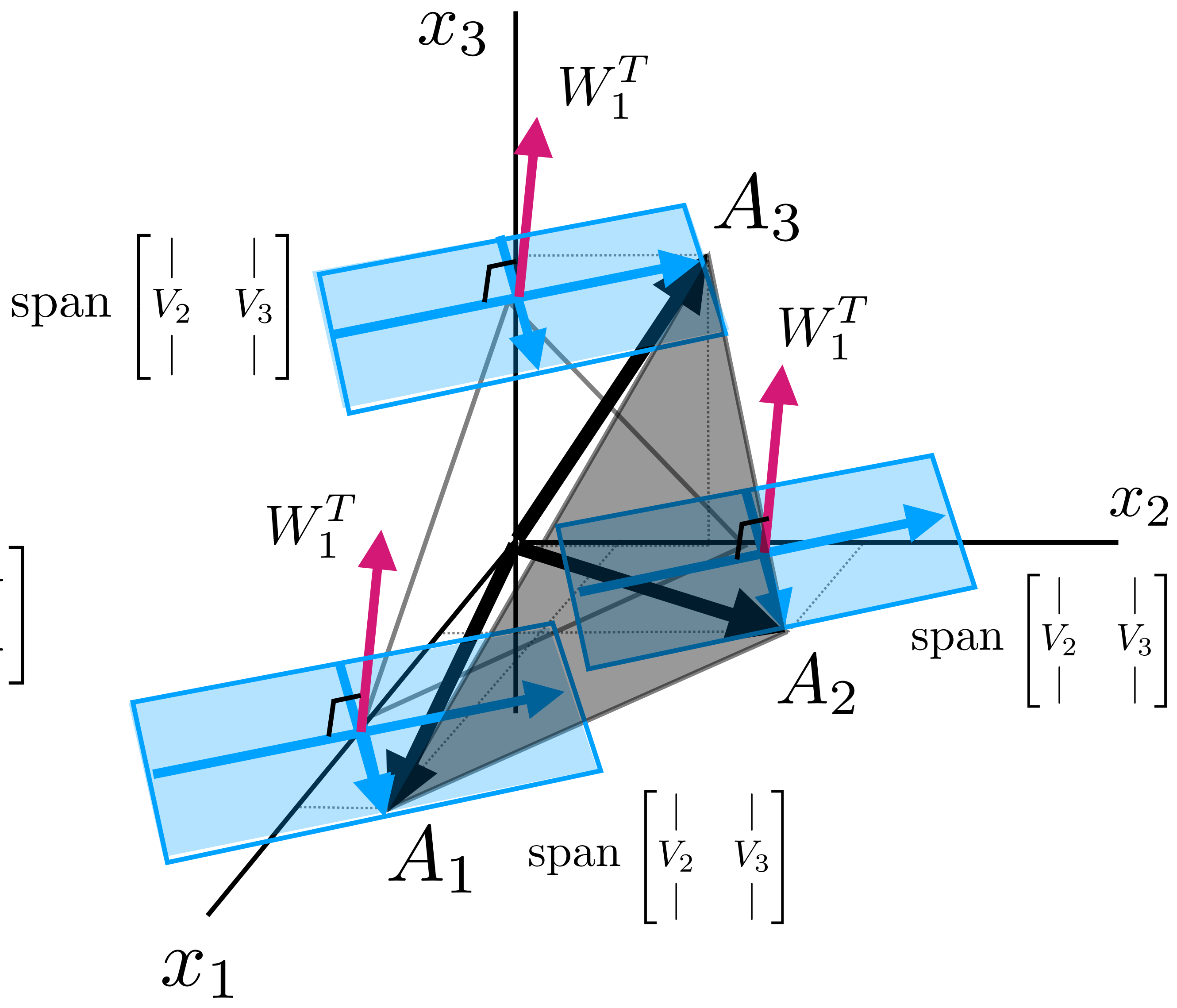
$$A \in \mathbb{R}^{3\times 3}$$

$$A = \begin{bmatrix} | & | & | \\ A_1 & A_2 & A_3 \\ | & | & | \end{bmatrix} = \begin{bmatrix} - & a_1^T & - \\ - & a_2^T & - \\ - & a_3^T & - \end{bmatrix} = \begin{bmatrix} | & | & | \\ V_1 & V_2 & V_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \\ - & W_3^T & - \end{bmatrix}$$

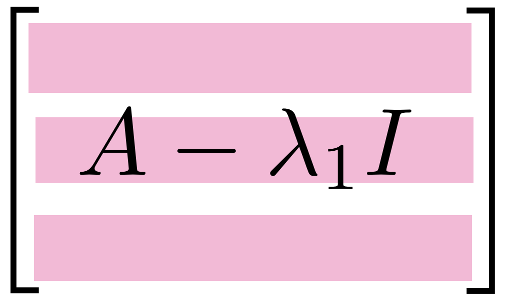
COLUMN GEOMETRY



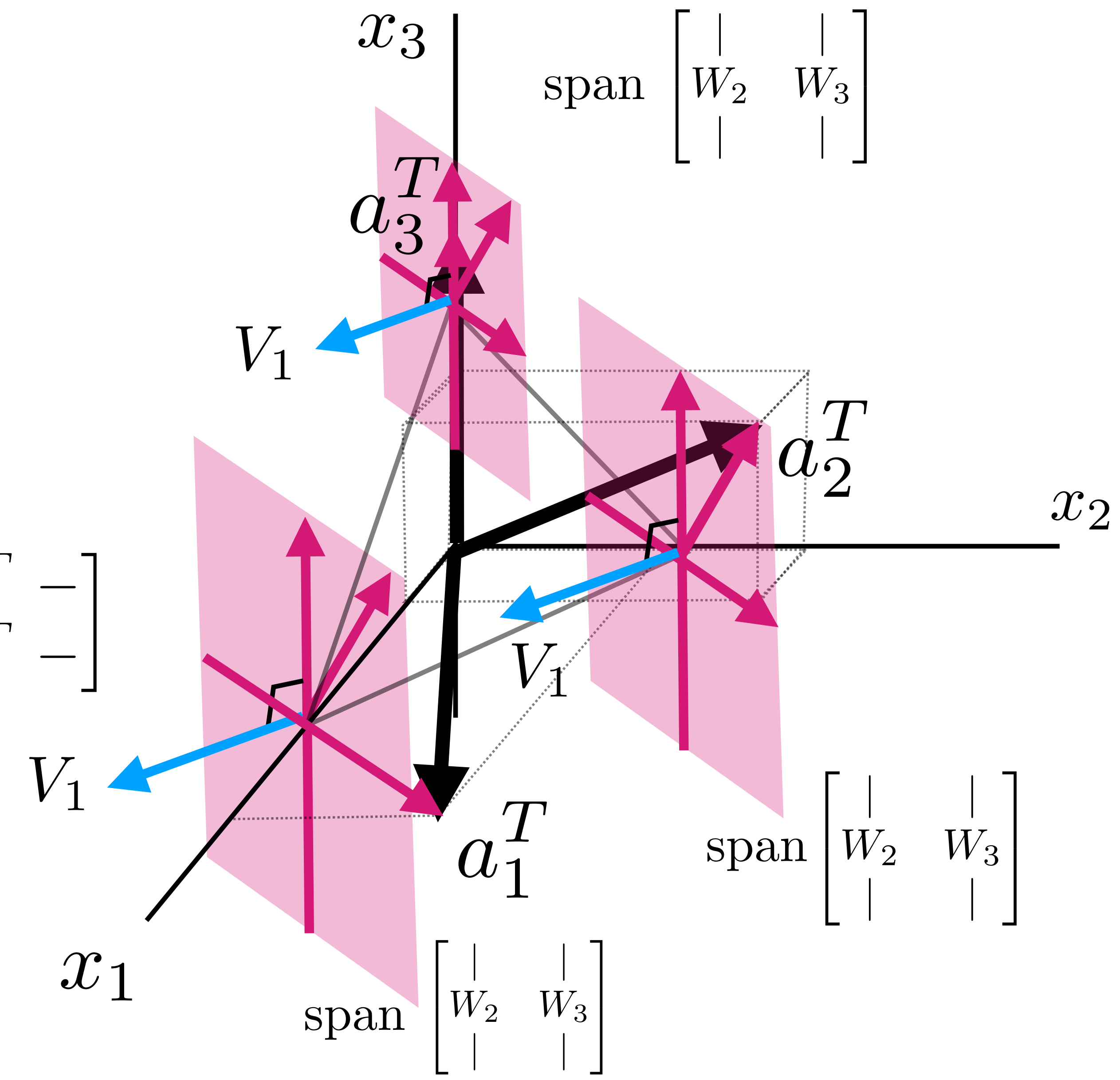
$$\begin{bmatrix} | & | \\ V_2 & V_3 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_2 - \lambda_1 & 0 \\ 0 & \lambda_3 - \lambda_1 \end{bmatrix} \begin{bmatrix} - & W_2^T & - \\ - & W_3^T & - \end{bmatrix}$$



ROW GEOMETRY



$$\begin{bmatrix} | & | \\ V_2 & V_3 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_2 - \lambda_1 & 0 \\ 0 & \lambda_3 - \lambda_1 \end{bmatrix} \begin{bmatrix} - & W_2^T & - \\ - & W_3^T & - \end{bmatrix}$$



Eigenvector/Eigenvalue Picture

For any eigenvalue $\lambda \in \mathbb{C}$

Eigenvectors exist only for values of s where $A - sI$ drops rank…

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Characteristic Polynomial

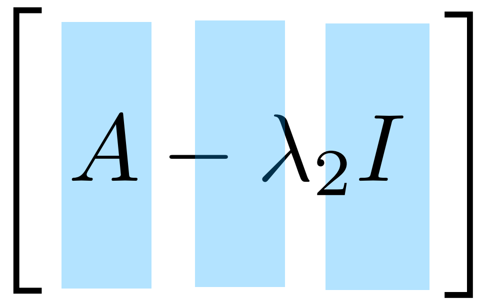
$sI - A$ drops rank only when

$$\mathrm{char}_A(s) = \det(sI - A) = 0$$

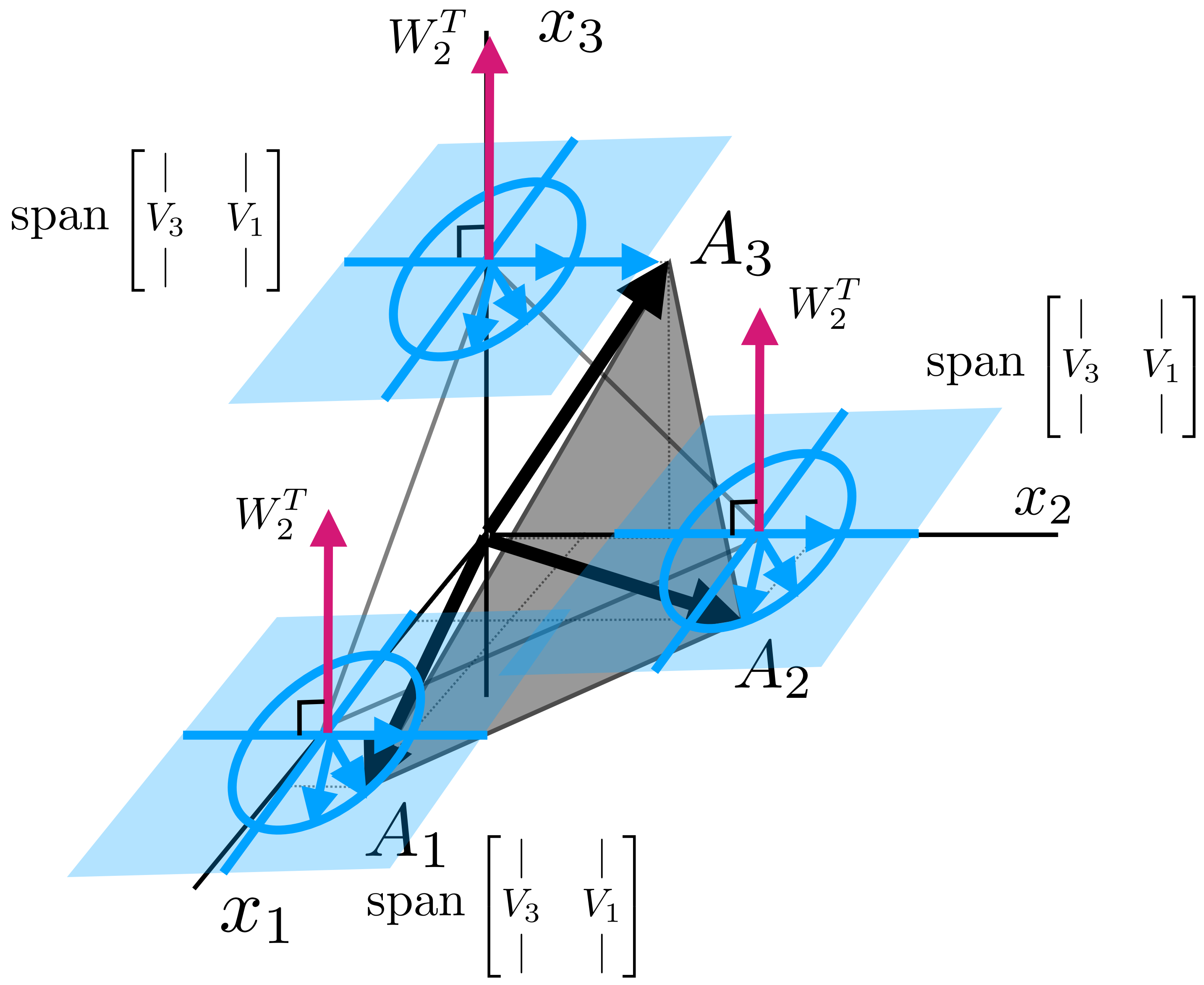
$$A \in \mathbb{R}^{3\times 3}$$

$$A = \begin{bmatrix} | & | & | \\ A_1 & A_2 & A_3 \\ | & | & | \end{bmatrix} = \begin{bmatrix} - & a_1^T & - \\ - & a_2^T & - \\ - & a_3^T & - \end{bmatrix} = \begin{bmatrix} | & | & | \\ V_1 & V_2 & V_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \\ - & W_3^T & - \end{bmatrix}$$

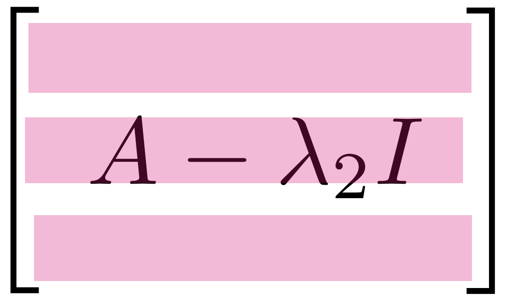
COLUMN GEOMETRY



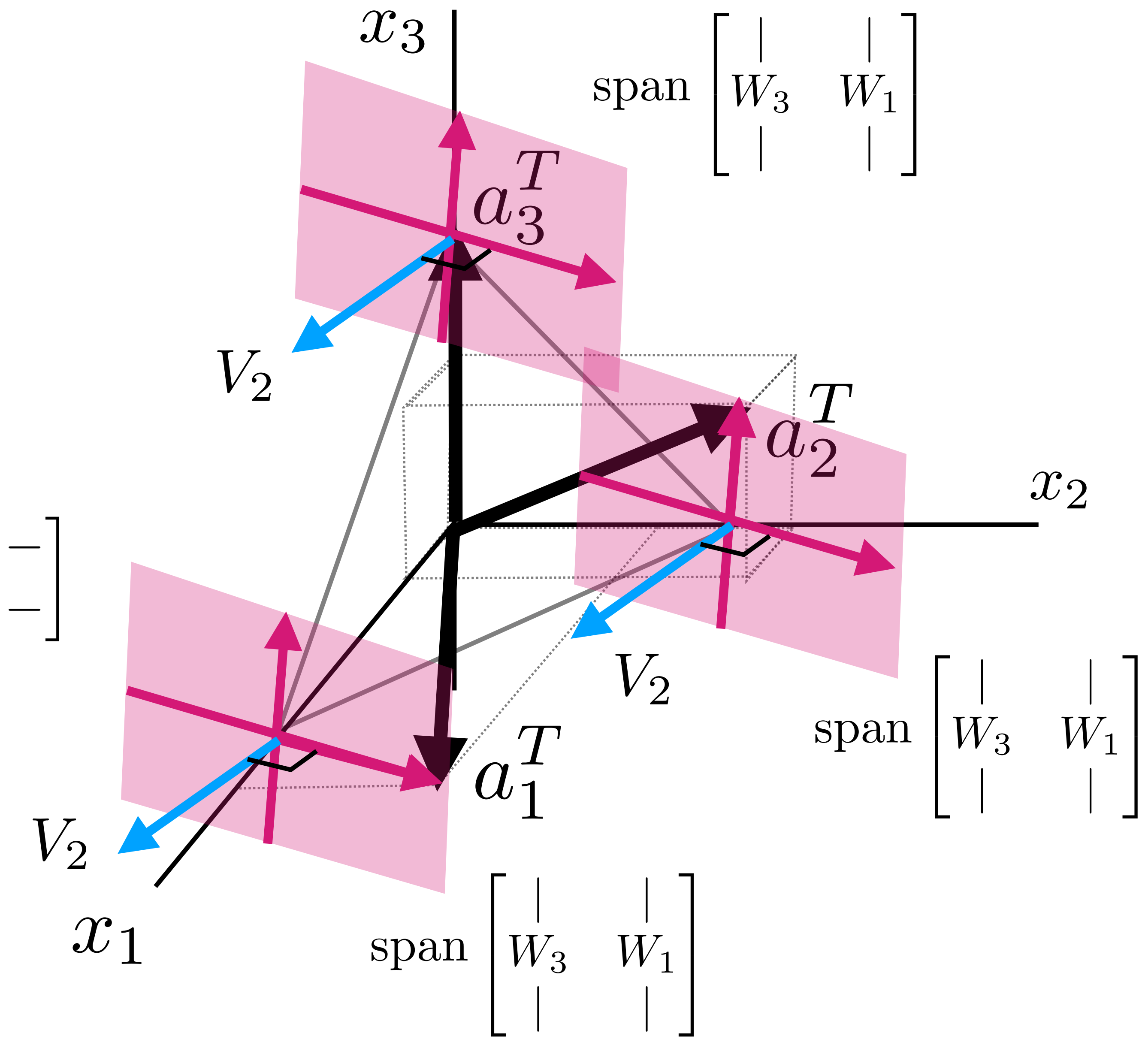
$$\begin{bmatrix} | & | \\ V_1 & V_3 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 - \lambda_2 & 0 \\ 0 & \lambda_3 - \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_3^T & - \end{bmatrix}$$



ROW GEOMETRY



$$\begin{bmatrix} | & | \\ V_1 & V_3 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 - \lambda_2 & 0 \\ 0 & \lambda_3 - \lambda_2 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_3^T & - \end{bmatrix}$$



Eigenvector/Eigenvalue Picture

For any eigenvalue $\lambda \in \mathbb{C}$

Right Eigenvector: $v \in \mathbb{C}^n$

$$Av = v\lambda \qquad (A - \lambda I)v = 0$$

Left Eigenvectors: $w \in \mathbb{C}^n$

$$w^* A = w^* \lambda \qquad w^*(A - \lambda I) = 0$$

Eigenvectors exist only for values of s where $A - sI$ drops rank...

Characteristic Polynomial

$sI - A$ drops rank only when

$$\text{char}_A(s) = \det(sI - A) = 0$$

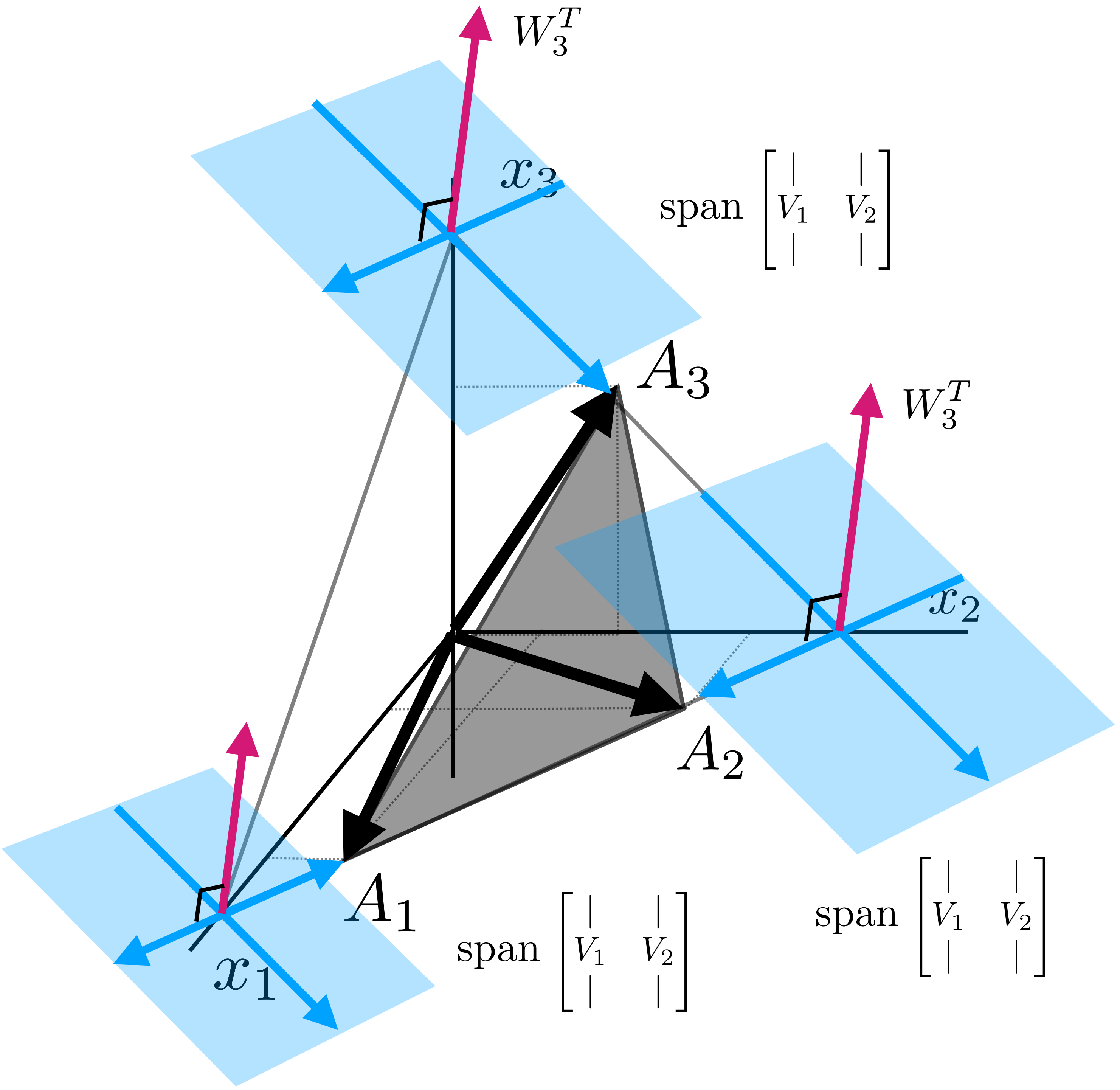
$$A \in \mathbb{R}^{3\times 3}$$

$$A = \begin{bmatrix} | & | & | \\ A_1 & A_2 & A_3 \\ | & | & | \end{bmatrix} = \begin{bmatrix} - & a_1^T & - \\ - & a_2^T & - \\ - & a_3^T & - \end{bmatrix} = \begin{bmatrix} | & | & | \\ V_1 & V_2 & V_3 \\ | & | & | \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \\ - & W_3^T & - \end{bmatrix}$$

COLUMN GEOMETRY

$$\begin{bmatrix} A - \lambda_3 I \end{bmatrix}$$

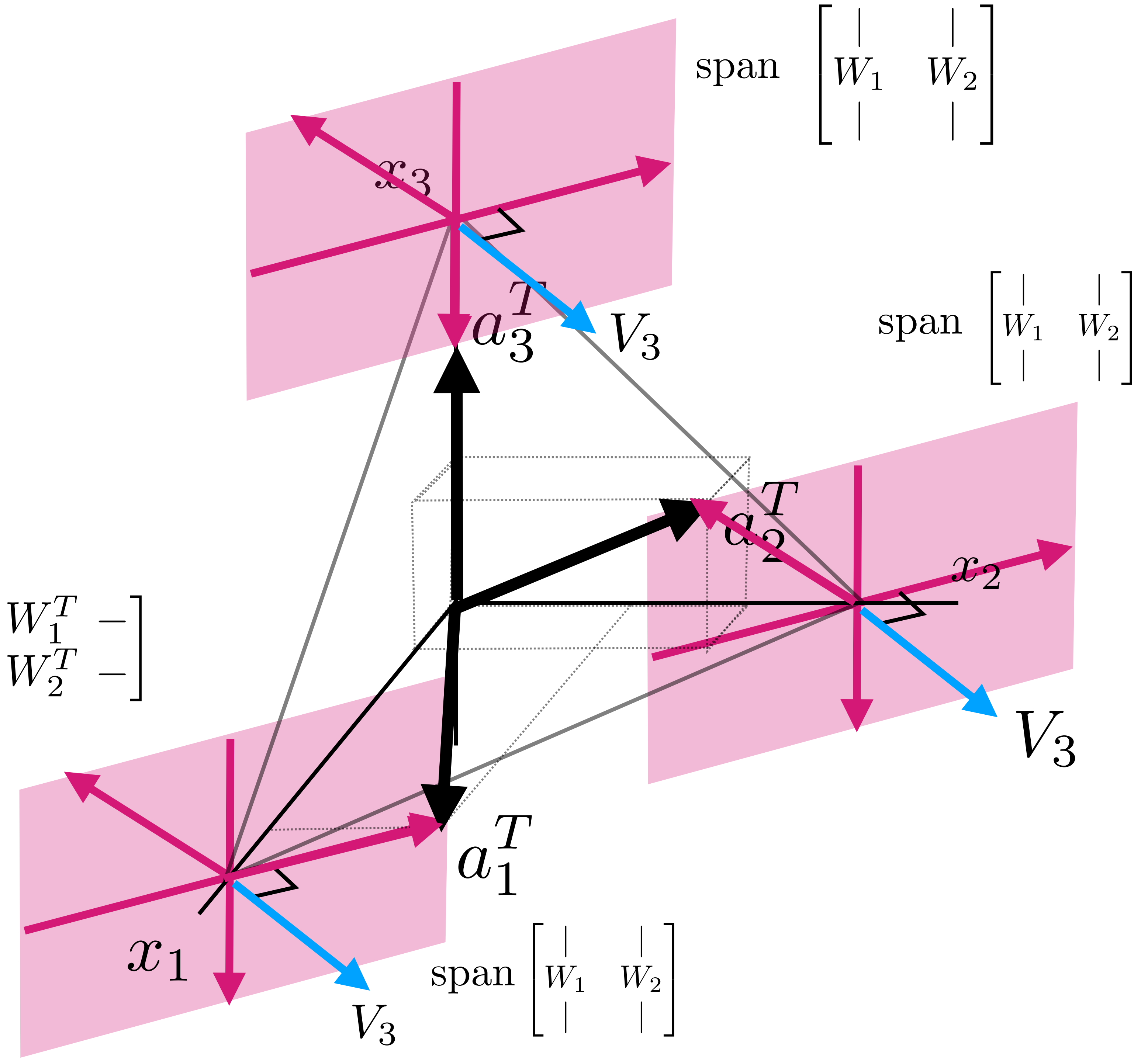
$$\begin{bmatrix} | & | \\ V_1 & V_2 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 - \lambda_3 & 0 \\ 0 & \lambda_2 - \lambda_3 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \end{bmatrix}$$



ROW GEOMETRY

$$\begin{bmatrix} A - \lambda_3 I \end{bmatrix}$$

$$\begin{bmatrix} | & | \\ V_1 & V_2 \\ | & | \end{bmatrix} \begin{bmatrix} \lambda_1 - \lambda_3 & 0 \\ 0 & \lambda_2 - \lambda_3 \end{bmatrix} \begin{bmatrix} - & W_1^T & - \\ - & W_2^T & - \end{bmatrix}$$



Diagonalization

Square matrix: $A \in \mathbb{R}^{n\times n}$

Assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Right Eigenvectors:

$$V = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \qquad AV = \begin{bmatrix} AV_1 \cdots AV_n \end{bmatrix} = \begin{bmatrix} V_1\lambda_1 \cdots V_n\lambda_n \end{bmatrix} = \begin{bmatrix} V_1 \cdots V_n \end{bmatrix} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{D} = VD$$

$$AV = VD$$

$$\Rightarrow \quad A = VDV^{-1}$$

Left Eigenvectors:

$$W = \begin{bmatrix} -W_1^*- \\ \vdots \\ -W_n^*- \end{bmatrix} \qquad WA = \begin{bmatrix} -W_1^*A- \\ \vdots \\ -W_n^*A- \end{bmatrix} = \begin{bmatrix} -\lambda_1 W_1^*- \\ \vdots \\ -\lambda_n W_n^*- \end{bmatrix} = \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{D} \begin{bmatrix} -W_1^*- \\ \vdots \\ -W_n^*- \end{bmatrix} = DW$$

$$WA = DW$$

$$\Rightarrow \quad A = W^{-1}DW$$

Assuming V & W are chosen with compatible orderings and lengths of columns/rows…

$$V^{-1} = W$$

Diagonalization

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V D V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \underbrace{\begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}}_{\text{Right eigen-vectors}} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{\text{Eigen-values (on diagonal)}} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}}_{\text{Left eigen-vectors}}$$

Right eigen-vectors

Eigen-values (on diagonal)

Left eigen-vectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

$$V^{-1}V = \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}$$

$$= \begin{bmatrix} W_1^* V_1 & \cdots & W_1^* V_n \\ \vdots & & \vdots \\ W_n^* V_1 & \cdots & W_n^* V_n \end{bmatrix} = \begin{bmatrix} 1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & 1 \end{bmatrix}$$

…from off diagonal terms $W_j^* V_i = 0 \quad j \neq i$

V_i orthogonal to all other W_j

…from diagonal terms $W_i^* V_i = 1$

V_i, W_i can be scaled so that $W_i^* V_i = 1$

Diagonalization - Similarity Transform

Square matrix: $A \in \mathbb{R}^{n\times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V D V^{-1}$$

$$\begin{bmatrix} & A & \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}$$

Right eigen-vectors | **Eigen-values** (on diagonal) | **Left eigen-vectors**

$$\begin{bmatrix} & A & \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} [\lambda_i] [- \quad W_i^* \quad -]$$

Sum of rank-1 matrices

Dyadic Expansion

A is similar to a diagonal matrix

…transform into eigenvector coordinates

$$x = Vx' \qquad y = Vy'$$

$$y = Ax$$
$$Vy' = AVx'$$
$$y' = V^{-1}AVx'$$
$$y' = V^{-1}VDV^{-1}Vx'$$
$$y' = Dx'$$

$$\begin{bmatrix} y_1' \\ \vdots \\ y_n' \end{bmatrix} = \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} x_1' \\ \vdots \\ x_n' \end{bmatrix} = \begin{bmatrix} \lambda_1 x_1' \\ \vdots \\ \lambda_n x_n' \end{bmatrix}$$

Diagonalization - Matrix Multiplication

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} & A & \end{bmatrix} = \underbrace{\begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}}_{\text{Right eigen-vectors}} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{\text{Eigen-values (on diagonal)}} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}}_{\text{Left eigen-vectors}} =$$

Right eigen-vectors

Eigen-values (on diagonal)

Left eigen-vectors

$$\begin{bmatrix} & A & \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

Interpretation of Matrix Multiplication Ax

$$\begin{bmatrix} & A & \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix}}$$

$$\begin{bmatrix} W_1^* x \\ \vdots \\ W_n^* x \end{bmatrix}$$ transforming into eigen-vector coords

Diagonalization - Matrix Multiplication

Square matrix: $A \in \mathbb{R}^{n\times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \underbrace{\begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}}_{\textbf{Right eigen-vectors}} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{\textbf{Eigen-values} \text{ (on diagonal)}} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}}_{\textbf{Left eigen-vectors}} =$$

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

Interpretation of Matrix Multiplication Ax

$$\begin{bmatrix} A \end{bmatrix}\begin{bmatrix} | \\ x \\ | \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix}$$

$\begin{bmatrix} W_1^* x \\ \vdots \\ W_n^* x \end{bmatrix}$ transforming into eigen-vector coords

$\begin{bmatrix} \lambda_1 W_1^* x \\ \vdots \\ \lambda_n W_n^* x \end{bmatrix}$ Scaling each coord by eigenvalue

Diagonalization - Matrix Multiplication

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \underbrace{\begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}}_{\text{Right eigen-vectors}} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{\text{Eigen-values (on diagonal)}} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}}_{\text{Left eigen-vectors}} =$$

Right eigen-vectors

Eigen-values (on diagonal)

Left eigen-vectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

Interpretation of Matrix Multiplication Ax

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix}$$

$\begin{bmatrix} W_1^* x \\ \vdots \\ W_n^* x \end{bmatrix}$ transforming into eigen-vector coords

$\begin{bmatrix} \lambda_1 W_1^* x \\ \vdots \\ \lambda_n W_n^* x \end{bmatrix}$ Scaling each coord by eigenvalue

$V_1 \lambda_1 W_1^* x + \cdots + V_n \lambda_n W_n^* x$ Transforming back into regular coordinates

Diagonalization - Matrix Multiplication

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \underbrace{\begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}}_{\text{Right eigen-vectors}} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{\text{Eigen-values (on diagonal)}} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}}_{\text{Left eigen-vectors}} =$$

Right eigen-vectors

Eigen-values (on diagonal)

Left eigen-vectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

If x is an eigenvector…

Interpretation of Matrix Multiplication AV_i

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix}}$$

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

Orthogonal to all other left eigenvectors

Diagonalization - Matrix Multiplication

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \underbrace{\begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}}_{\text{Right eigenvectors}} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{\text{Eigenvalues (on diagonal)}} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}}_{\text{Left eigenvectors}} =$$

Right eigen-vectors

Eigen-values (on diagonal)

Left eigen-vectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} [\lambda_i] \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

If x is an eigenvector…

Interpretation of Matrix Multiplication AV_i

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix}$$

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

Orthogonal to all other left eigenvectors

$$\begin{bmatrix} 0 \\ \vdots \\ \lambda_i \\ \vdots \\ 0 \end{bmatrix}$$

Scaled by specific eigenvalue

Diagonalization - Matrix Multiplication

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \underbrace{\begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix}}_{\text{Right eigenvectors}} \underbrace{\begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix}}_{\text{Eigenvalues (on diagonal)}} \underbrace{\begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}}_{\text{Left eigenvectors}} =$$

Right eigen-vectors

Eigen-values (on diagonal)

Left eigen-vectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} [\lambda_i] \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

If x is an eigenvector…

Interpretation of Matrix Multiplication AV_i

$$\begin{bmatrix} A \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} \begin{bmatrix} | \\ x \\ | \end{bmatrix}$$

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

Orthogonal to all other left eigenvectors

$$\begin{bmatrix} 0 \\ \vdots \\ \lambda_i \\ \vdots \\ 0 \end{bmatrix}$$

Scaled by specific eigenvalue

$$\lambda_i V_i$$

Select out that specific eigenvector

Diagonalization (non-unique) case 1: ordering

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Permutation Matrix $P \in \mathbb{R}^{n \times n}$

Shuffle columns (or rows) of identity…

Ex. $P = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ $P^T P = I$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}$$

Right eigen-vectors | **Eigen-values** (on diagonal) | **Left eigen-vectors**

Shuffling eigenvalues and eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

← Order of sum does not matter…

Diagonalization (non-unique) case 1: ordering

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Permutation Matrix $P \in \mathbb{R}^{n \times n}$

Shuffle columns (or rows) of identity…

Ex. $P = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ $P^T P = I$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} P \end{bmatrix} \begin{bmatrix} P^T \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} P \end{bmatrix} \begin{bmatrix} P^T \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}$$

Right eigen-vectors | **Eigen-values** (on diagonal) | **Left eigen-vectors**

Shuffling eigenvalues and eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

← Order of sum does not matter…

Diagonalization (non-unique) case 1: ordering

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Permutation Matrix $P \in \mathbb{R}^{n \times n}$

Shuffle columns (or rows) of identity…

Ex. $P = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ $\quad P^T P = I$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} P \end{bmatrix} \begin{bmatrix} P^T \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} P \end{bmatrix} \begin{bmatrix} P^T \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}$$

Right eigen-vectors | **Eigen-values** (on diagonal) | **Left eigen-vectors**

Shuffling eigenvalues and eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

← Order of sum does not matter…

Diagonalization (non-unique) case 1: ordering

Square matrix: $A \in \mathbb{R}^{n\times n}$ assume $\mathrm{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\mathrm{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Permutation Matrix $P \in \mathbb{R}^{n\times n}$

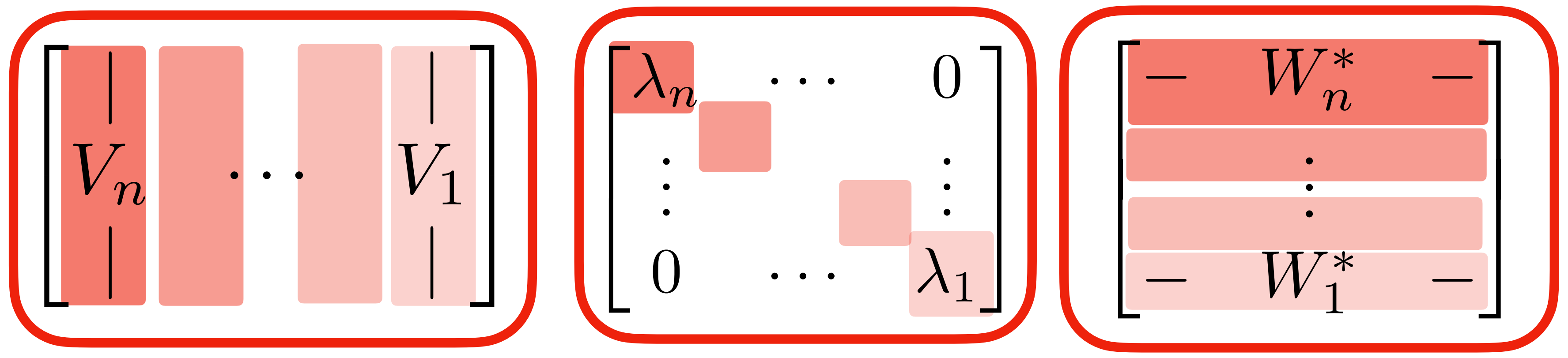
Shuffle columns (or rows) of identity…

Ex. $P = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ $\quad P^T P = I$

Diagonalization

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} =$$



Right eigen-vectors | **Eigen-values** (on diagonal) | **Left eigen-vectors**

Shuffling eigenvalues and eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

Order of sum does not matter…

Diagonalization (non-unique) case 1: ordering

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\mathrm{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\mathrm{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

$$A = V D V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} =$$

Right eigen-vectors | **Eigen-values** (on diagonal) | **Left eigen-vectors**

Permutation Matrix $P \in \mathbb{R}^{n \times n}$

Shuffle columns (or rows) of identity…

Ex. $P = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ $P^T P = I$

$$\begin{bmatrix} | & & | \\ V_n & \cdots & V_1 \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_n & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_1 \end{bmatrix} \begin{bmatrix} - & W_n^* & - \\ & \vdots & \\ - & W_1^* & - \end{bmatrix}$$

Shuffling eigenvalues and eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

← Order of sum does not matter…

Diagonalization (non-unique) case 2: scaling

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

diagonal matrices commute…

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 \frac{\gamma_1}{\gamma_1} & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \frac{\gamma_n}{\gamma_n} \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}$$

Right eigen-vectors | **Eigen-values** (on diagonal) | **Left eigen-vectors**

Scaling eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

← Order of sum does not matter…

Diagonalization (non-unique) case 2: scaling

Square matrix: $A \in \mathbb{R}^{n\times n}$ assume $\mathrm{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\mathrm{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

diagonal matrices commute…

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \gamma_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \gamma_n \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} \frac{1}{\gamma_1} & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \frac{1}{\gamma_n} \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix}$$

Right eigen-vectors

Eigen-values (on diagonal)

Left eigen-vectors

Scaling eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

← Order of sum does not matter…

Diagonalization (non-unique) case 2: scaling

Square matrix: $A \in \mathbb{R}^{n\times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization

diagonal matrices commute…

$$A = V \quad D \quad V^{-1}$$

$$\begin{bmatrix} A \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1 & \cdots & V_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & W_1^* & - \\ & \vdots & \\ - & W_n^* & - \end{bmatrix} = \begin{bmatrix} | & & | \\ V_1\gamma_1 & \cdots & V_n\gamma_n \\ | & & | \end{bmatrix} \begin{bmatrix} \lambda_1 & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n \end{bmatrix} \begin{bmatrix} - & \frac{1}{\gamma_1} W_1^* & - \\ & \vdots & \\ - & \frac{1}{\gamma_n} W_n^* & - \end{bmatrix}$$

Right eigen-vectors **Eigen-values** (on diagonal) **Left eigen-vectors**

$$V' \qquad V'^{-1}$$

Scaling eigenvectors

$$\begin{bmatrix} A \end{bmatrix} = \sum_i \begin{bmatrix} | \\ V_i \\ | \end{bmatrix} \begin{bmatrix} \lambda_i \end{bmatrix} \begin{bmatrix} - & W_i^* & - \end{bmatrix}$$

Sum of rank-1 matrices

Dyadic Expansion

← Order of sum does not matter…

Spectral Mapping Theorem

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization $A = VDV^{-1}$

Powers of A

$$A^k = VDV^{-1} \times VDV^{-1} \times \cdots \times VDV^{-1}$$
$$= VDV^{-1}VDV^{-1} \cdots VDV^{-1}$$
$$= VD^kV^{-1}$$

$$A^k = VD^kV^{-1}$$

$$= \begin{bmatrix} & V & \end{bmatrix} \begin{bmatrix} \lambda_1^k & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n^k \end{bmatrix} \begin{bmatrix} & V^{-1} & \end{bmatrix}$$

Polynomials of A

polynomial $\Psi(s) = \alpha_k s^k + \alpha_{k-1}s^{k-1} + \alpha_{k-2}s^{k-2} + \cdots + \alpha_1 s + \alpha_0 1$

plugging in A…

$$\Psi(A) = \alpha_k A^k + \alpha_{k-1}A^{k-1} + \alpha_{k-2}A^{k-2} + \cdots + \alpha_1 A + \alpha_0 I$$
$$= \alpha_k VD^kV^{-1} + \alpha_{k-1}VD^{k-1}V^{-1} + \alpha_{k-2}VD^{k-2}V^{-1} + \cdots + \alpha_1 VDV^{-1} + \alpha_0 VV^{-1}$$
$$= V\Big(\alpha_k D^k + \alpha_{k-1}D^{k-1} + \alpha_{k-2}D^{k-2} + \cdots + \alpha_1 D + \alpha_0 I\Big)V^{-1}$$

$$\Psi(A) = V\Psi(D)V^{-1}$$

$$= \begin{bmatrix} & V & \end{bmatrix} \begin{bmatrix} \Psi(\lambda_1) & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \Psi(\lambda_n) \end{bmatrix} \begin{bmatrix} & V^{-1} & \end{bmatrix}$$

Spectral Mapping Theorem

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization $A = VDV^{-1}$

Powers of A

$$A^k = VDV^{-1} \times VDV^{-1} \times \cdots \times VDV^{-1}$$
$$= VDV^{-1}VDV^{-1} \cdots VDV^{-1}$$
$$= VD^kV^{-1}$$

$$A^k = VD^kV^{-1}$$
$$= \begin{bmatrix} & & \\ & V & \\ & & \end{bmatrix} \begin{bmatrix} \lambda_1^k & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n^k \end{bmatrix} \begin{bmatrix} & & \\ & V^{-1} & \\ & & \end{bmatrix}$$

Polynomials of A

polynomial $\Psi(s) = \alpha_k s^k + \alpha_{k-1} s^{k-1} + \alpha_{k-2} s^{k-2} + \cdots + \alpha_1 s + \alpha_0 1$

$$\Psi(A) = V\Big(\alpha_k D^k + \alpha_{k-1} D^{k-1} + \alpha_{k-2} D^{k-2} + \cdots + \alpha_1 D + \alpha_0 I\Big)V^{-1}$$

$$\Psi(A) = V\Psi(D)V^{-1}$$
$$= \begin{bmatrix} & & \\ & V & \\ & & \end{bmatrix} \begin{bmatrix} \Psi(\lambda_1) & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \Psi(\lambda_n) \end{bmatrix} \begin{bmatrix} & & \\ & V^{-1} & \\ & & \end{bmatrix}$$

Spectral Mapping Theorem for f(s) analytic

$\lambda \in \text{eig}(A)$ ➡ $f(\lambda) \in \text{eig}\big(f(A)\big)$

$A, f(A)$ have the same eigenvectors

Spectral Mapping Theorem

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\text{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\text{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization $A = VDV^{-1}$

Powers of A

$$A^k = VDV^{-1} \times VDV^{-1} \times \cdots \times VDV^{-1}$$
$$= VDV^{-1}VDV^{-1} \cdots VDV^{-1}$$
$$= VD^kV^{-1}$$

$$A^k = VD^kV^{-1}$$
$$= \begin{bmatrix} & V & \end{bmatrix} \begin{bmatrix} \lambda_1^k & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n^k \end{bmatrix} \begin{bmatrix} & V^{-1} & \end{bmatrix}$$

Polynomials of A

polynomial $\Psi(s) = \alpha_k s^k + \alpha_{k-1} s^{k-1} + \alpha_{k-2} s^{k-2} + \cdots + \alpha_1 s + \alpha_0 1$

$$\Psi(A) = V\Big(\alpha_k D^k + \alpha_{k-1} D^{k-1} + \alpha_{k-2} D^{k-2} + \cdots + \alpha_1 D + \alpha_0 I\Big)V^{-1}$$

Spectral Mapping Theorem for f(s) analytic

$\lambda \in \text{eig}(A)$ ➡ $f(\lambda) \in \text{eig}\big(f(A)\big)$

$A, f(A)$ have the same eigenvectors

Specific Useful Case: Matrix Exponential

$$e^{At} = I + At + \tfrac{1}{2!}A^2t^2 + \tfrac{1}{3!}A^3t^3 + \cdots$$
$$= \sum_{k=0}^{\infty} \tfrac{1}{k!} A^k t^k$$

Derivative: $\frac{d}{dt}\left(e^{At}\right) = Ae^{At}$

- can see from polynomial definition
- related to definition of e

Spectral Mapping Theorem

Square matrix: $A \in \mathbb{R}^{n \times n}$ assume $\mathrm{char}_A(s) = \det(sI - A)$ has **n distinct roots**

Eigenvalues: $\mathrm{eig}(A) = \{\lambda_1, \cdots, \lambda_n\}$ with $\lambda_1 \neq \lambda_2 \neq \cdots \neq \lambda_n$

Diagonalization $A = VDV^{-1}$

Powers of A

$$A^k = VDV^{-1} \times VDV^{-1} \times \cdots \times VDV^{-1}$$
$$= VDV^{-1}VDV^{-1} \cdots VDV^{-1}$$
$$= VD^kV^{-1}$$

$$A^k = VD^kV^{-1}$$

$$= \begin{bmatrix} & V & \end{bmatrix} \begin{bmatrix} \lambda_1^k & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & \lambda_n^k \end{bmatrix} \begin{bmatrix} & V^{-1} & \end{bmatrix}$$

Polynomials of A

polynomial $\Psi(s) = \alpha_k s^k + \alpha_{k-1} s^{k-1} + \alpha_{k-2} s^{k-2} + \cdots + \alpha_1 s + \alpha_0 1$

$$\Psi(A) = V\Big(\alpha_k D^k + \alpha_{k-1} D^{k-1} + \alpha_{k-2} D^{k-2} + \cdots + \alpha_1 D + \alpha_0 I\Big)V^{-1}$$

Spectral Mapping Theorem for f(s) analytic

$\lambda \in \mathrm{eig}(A)$ ➡ $f(\lambda) \in \mathrm{eig}\big(f(A)\big)$

$A, f(A)$ have the same eigenvectors

Specific Useful Case: Matrix Exponential

$$e^{At} = I + At + \tfrac{1}{2!}A^2t^2 + \tfrac{1}{3!}A^3t^3 + \cdots$$
$$= \sum_{k=0}^{\infty} \tfrac{1}{k!} A^k t^k$$

$$e^{At} = Ve^{Dt}V^{-1}$$
$$= \begin{bmatrix} & V & \end{bmatrix} \begin{bmatrix} e^{\lambda_1 t} & \cdots & 0 \\ \vdots & & \vdots \\ 0 & \cdots & e^{\lambda_n t} \end{bmatrix} \begin{bmatrix} & V^{-1} & \end{bmatrix}$$