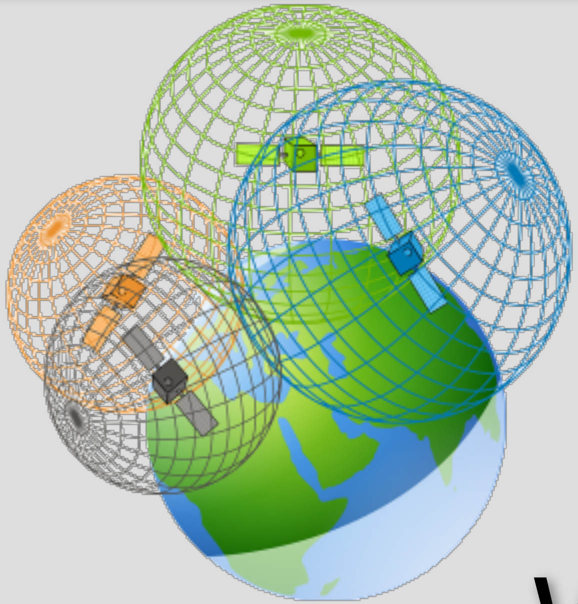
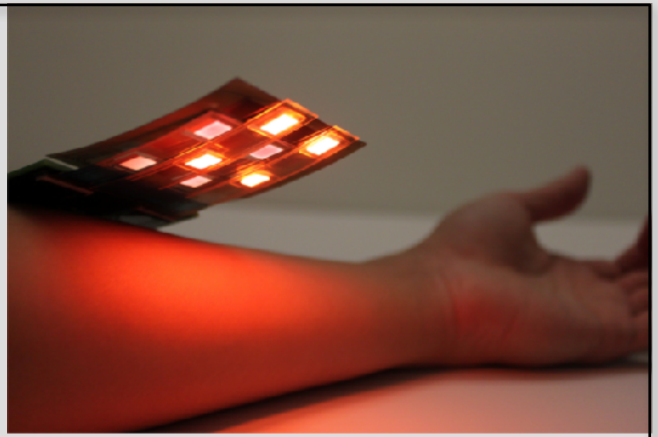




Welcome to EECS 16A!

Designing Information Devices and Systems I

Ana Arias and Miki Lustig

Fa 2022

Lecture 5A

Eigen Values and Vectors

Announcements

- Last time:
  - Vector spaces
  - Subspaces
  - Null spaces
- Today:
  - Computing the determinant
  - Eigen Values and Eigen Vectors of a Matrix
    - Example via page-rank

Jargon from Last time

- **Rank** a matrix A is the number of linearly independent columns
- **Nullspace** of a matrix A is the set of solutions to $A\vec{x} = 0$
- A **vector space** is a set of vectors connected by two operators (+,x)
- A vector **subspace** is a subset of vectors that have “nice properties”
- A **basis** for a vector space is a minimum set of vectors needed to represent all vectors in the space
- **Dimension** of a vector space is the number of basis vectors
- **Column space** is the span (range) of the columns of a matrix
- **Row space** is the span of the rows of a matrix

Null Space

- Definition: The null-space of $A \in \mathbb{R}^{N \times M}$ is the set of all vectors $\overrightarrow{x} \in \mathbb{R}^{M}$ such that: $A\overrightarrow{x} = 0$

$$A\overrightarrow{x} = 0$$

Examples

$$\begin{bmatrix} 1 & 0 \\ 0 & -2 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Linearly independent!

$$\vec{x} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

$\vec{0}$ is always in the null space — trivial Null space

Examples

$$\begin{bmatrix} 1 & -2 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Linearly dependent!

Gaussian elimination:

$$\left[\begin{array}{cc|c} 1 & -2 & 0 \\ 0 & 0 & 0 \end{array}\right] \Rightarrow x_1 = 2x_2$$

$$\Rightarrow \vec{x} = \begin{bmatrix} 2\alpha \\ \alpha \end{bmatrix}$$

$$\vec{x} = \alpha \begin{bmatrix} 2 \\ 1 \end{bmatrix}$$

A has a non-trivial null-space, $\text{span} \left\{ \begin{bmatrix} 2 \\ 1 \end{bmatrix} \right\}$

Example

$$A\overrightarrow{x} = \overrightarrow{b}$$

We know that $\overrightarrow{v}_0 \in \mathrm{Null}(A)$

$$\rightarrow A\overrightarrow{v}_0 = \overrightarrow{0}$$

We know 1 solution: $\overrightarrow{x}_0$

$$\rightarrow A\overrightarrow{x}_0 = b$$

Example

$$A\overrightarrow{x} = \overrightarrow{b}$$

We know that $\overrightarrow{v}_0 \in \mathrm{Null}(A)$

$$\rightarrow A\overrightarrow{v}_0 = \overrightarrow{0}$$

We know 1 solution: $\overrightarrow{x}_0$

$$\rightarrow A\overrightarrow{x}_0 = b$$

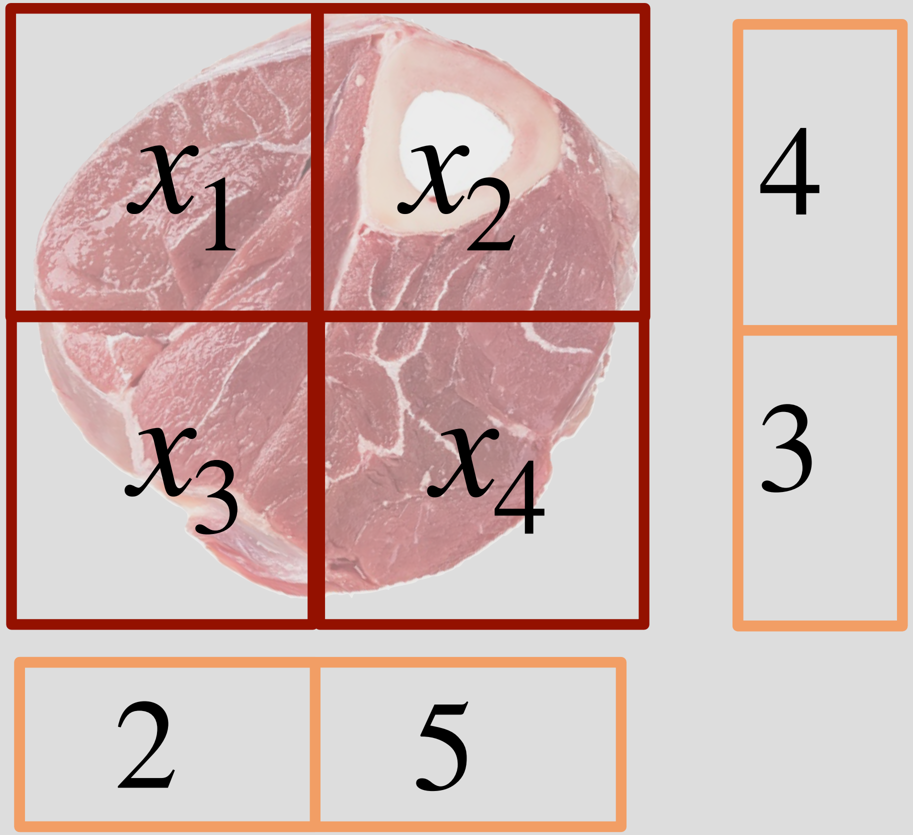
Then: $\overrightarrow{x}_0 + \alpha\overrightarrow{v}_0$ is also a solution

$$\rightarrow A(\overrightarrow{x}_0 + \alpha\overrightarrow{v}_0) = A\overrightarrow{x}_0 + A(\alpha\overrightarrow{v}_0)$$

$$= \overrightarrow{b} + \alpha A\overrightarrow{v}_0$$

$$= \overrightarrow{b}$$

Back to Tomography



$$1 \cdot x_1 + 1 \cdot x_2 + 0 \cdot x_3 + 0 \cdot x_4 = 4$$
$$0 \cdot x_1 + 0 \cdot x_2 + 1 \cdot x_3 + 1 \cdot x_4 = 3$$
$$1 \cdot x_1 + 0 \cdot x_2 + 1 \cdot x_3 + 0 \cdot x_4 = 2$$
$$0 \cdot x_1 + 1 \cdot x_2 + 0 \cdot x_3 + 1 \cdot x_4 = 5$$

A

$$\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 4 \\ 0 & 0 & 1 & 1 & 3 \\ 1 & 0 & 1 & 0 & 2 \\ 0 & 1 & 0 & 1 & 5 \end{array}\right]$$

Null Space of the Tomography System (4 measur.)

Step I

$$\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \end{array}\right]$$

Step II

$(3)-(1)$

$$\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \end{array}\right]$$

Step III

$$\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \end{array}\right]$$

Step IV

$(3)+(2)$

$$\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \end{array}\right]$$

Step V

$(4)-(3)$

$$\left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

Step VI

$(1)-(2)$

$$\left[\begin{array}{cccc|c} 1 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

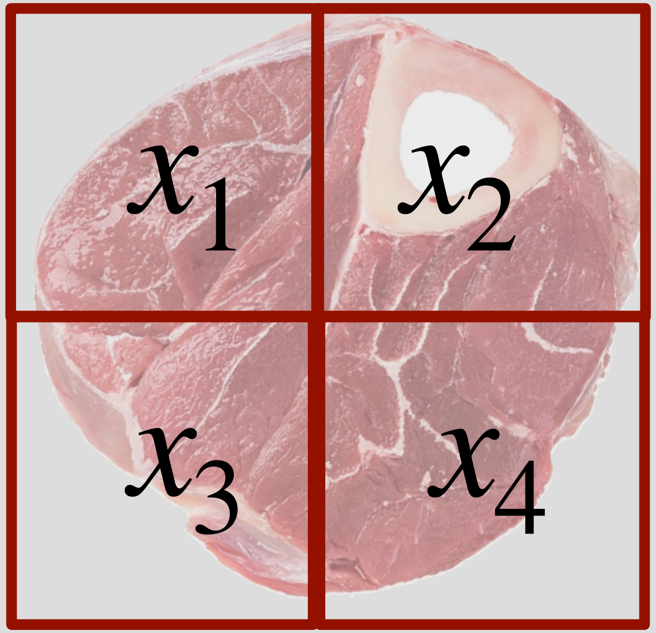
Null Space of the Tomography System (4 measur.)

$$\left[\begin{array}{cccc|c} 1 & 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

x_4 is the free variable:

$$\Rightarrow \vec{x} = \alpha \begin{bmatrix} 1 \\ -1 \\ -1 \\ 1 \end{bmatrix}$$

Possible reconstruction



$$= \begin{bmatrix} 1 & 3 \\ 1 & 2 \end{bmatrix} + \alpha \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}$$

Rank

- $A \in \mathbb{R}^{N \times M}$, $\text{Rank}\{A\} = \dim\left\{\text{Span}\{A\}\right\}$

- $\text{Rank}\{A\} = \dim\left\{\text{Span}\{A\}\right\} \leq \min(M, N)$

- $\text{Rank} = L$, mean the matrix $A \in \mathbb{R}^{N \times M}$ has L independent rows&columns

- $\text{Rank}\{A\} + \dim\left\{\text{Null}\{A\}\right\} = M$

Equivalent Statements

- Matrix A is **invertible**
- $A\overrightarrow{x} = \overrightarrow{b}$ has a unique solution
- A has linearly independent columns (A is **full rank**)
- A has a **trivial nullspace**
- The **determinant** of A is not zero

The Determinant

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

$$\det(A) = \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix}\right) = ad - bc$$

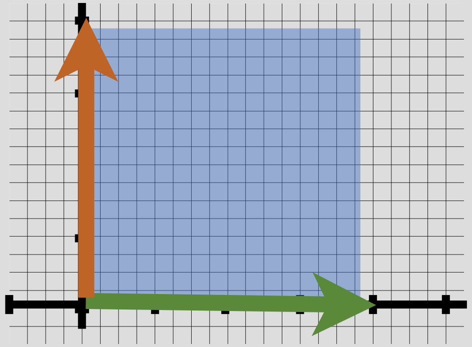
When $\det(A) \neq 0$, A is invertible

Recall:

$$A^{-1} = \frac{1}{ad - bc}\begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$$

Interpretation of Determinant of a Matrix in $\mathbb{R}^{2\times2}$

- Area of a parallelogram



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

$$\det(A) = \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix}\right) = ad - bc$$

Interpretation of Determinant of a Matrix in $\mathbb{R}^{2\times 2}$

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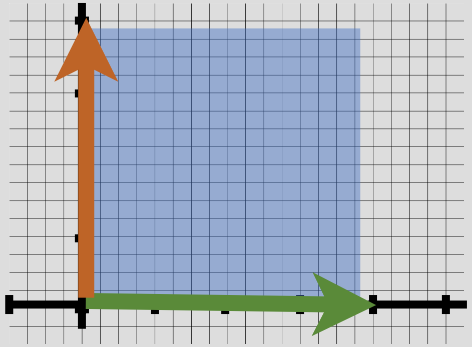
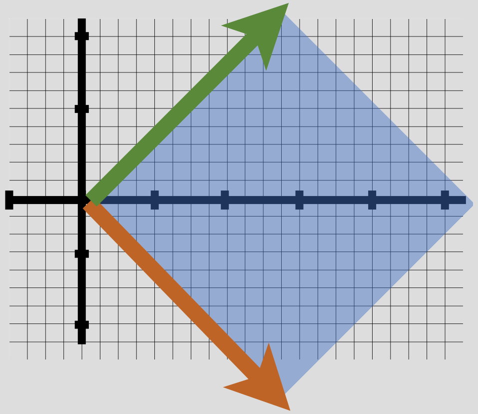


$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$ Area $\neq 0$



$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$ Area $\neq 0$

Interpretation of Determinant of a Matrix in $\mathbb{R}^{2\times 2}$

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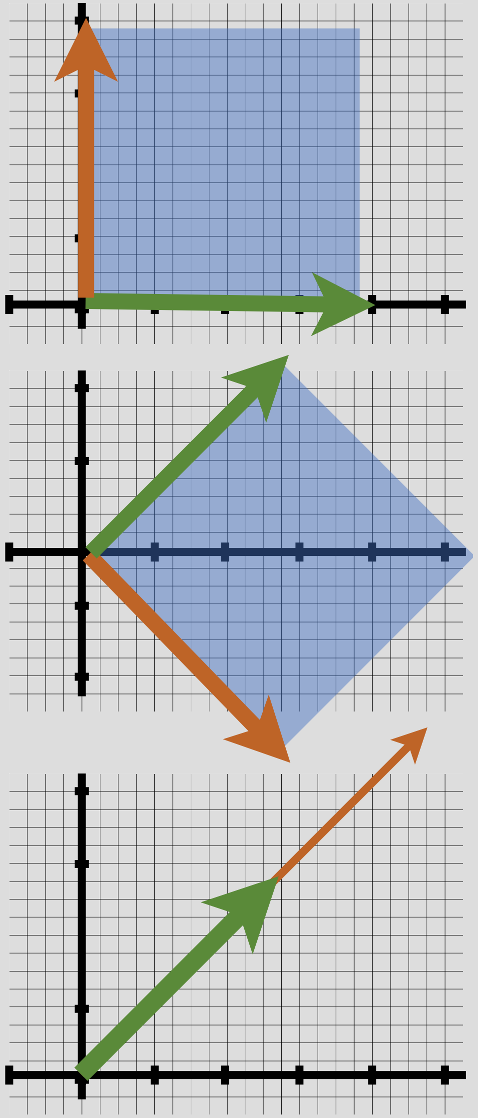


$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$ Area≠0

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$$ Area≠0

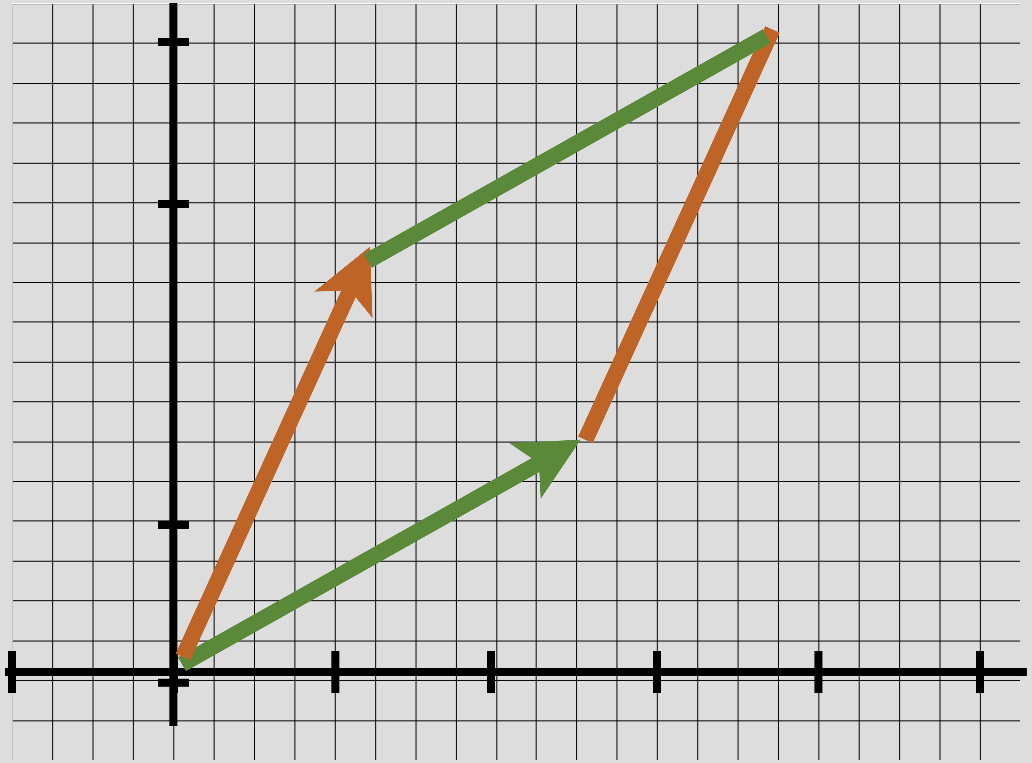
$$\begin{bmatrix} 1 & 2 \\ 1 & 2 \end{bmatrix}$$ Area=0

$$\det(A) = 1 \cdot 2 - 1 \cdot 2 = 0$$

Interpretation of Determinant of a Matrix in $\mathbb{R}^{2\times 2}$

- Area of a parallelogram

$$\det(A) = \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix} \right) = ad - bc$$



Interpretation of Determinant of a Matrix in $\mathbb{R}^{2\times2}$

- Area of a parallelogram

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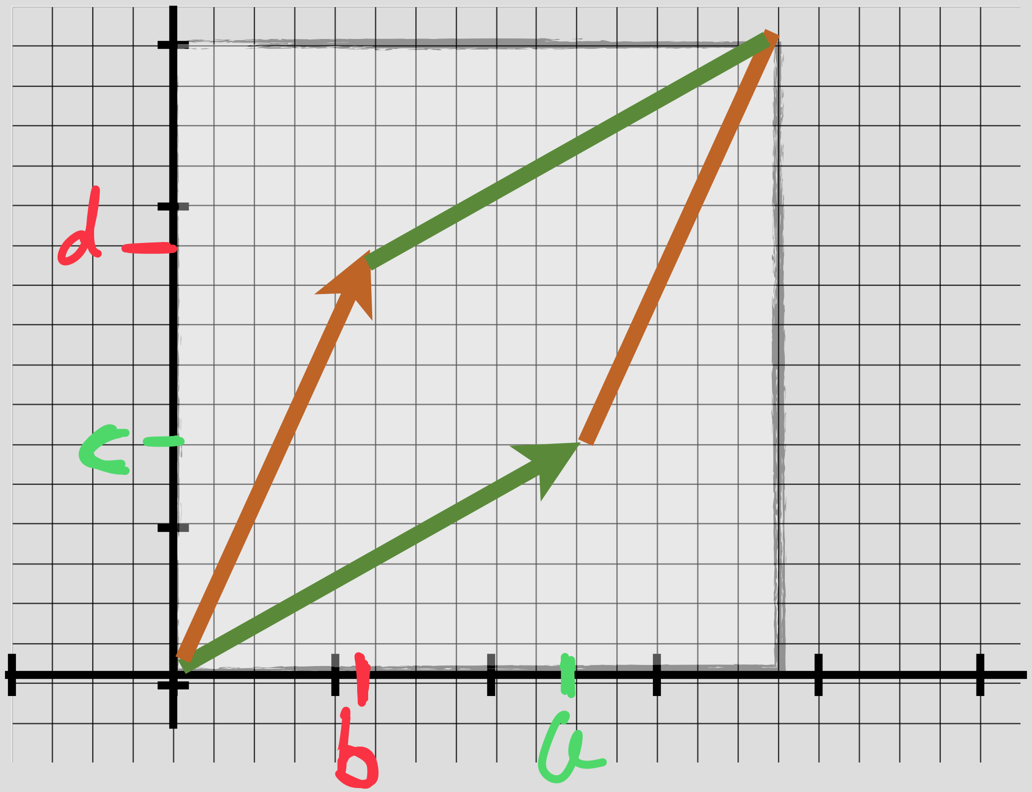
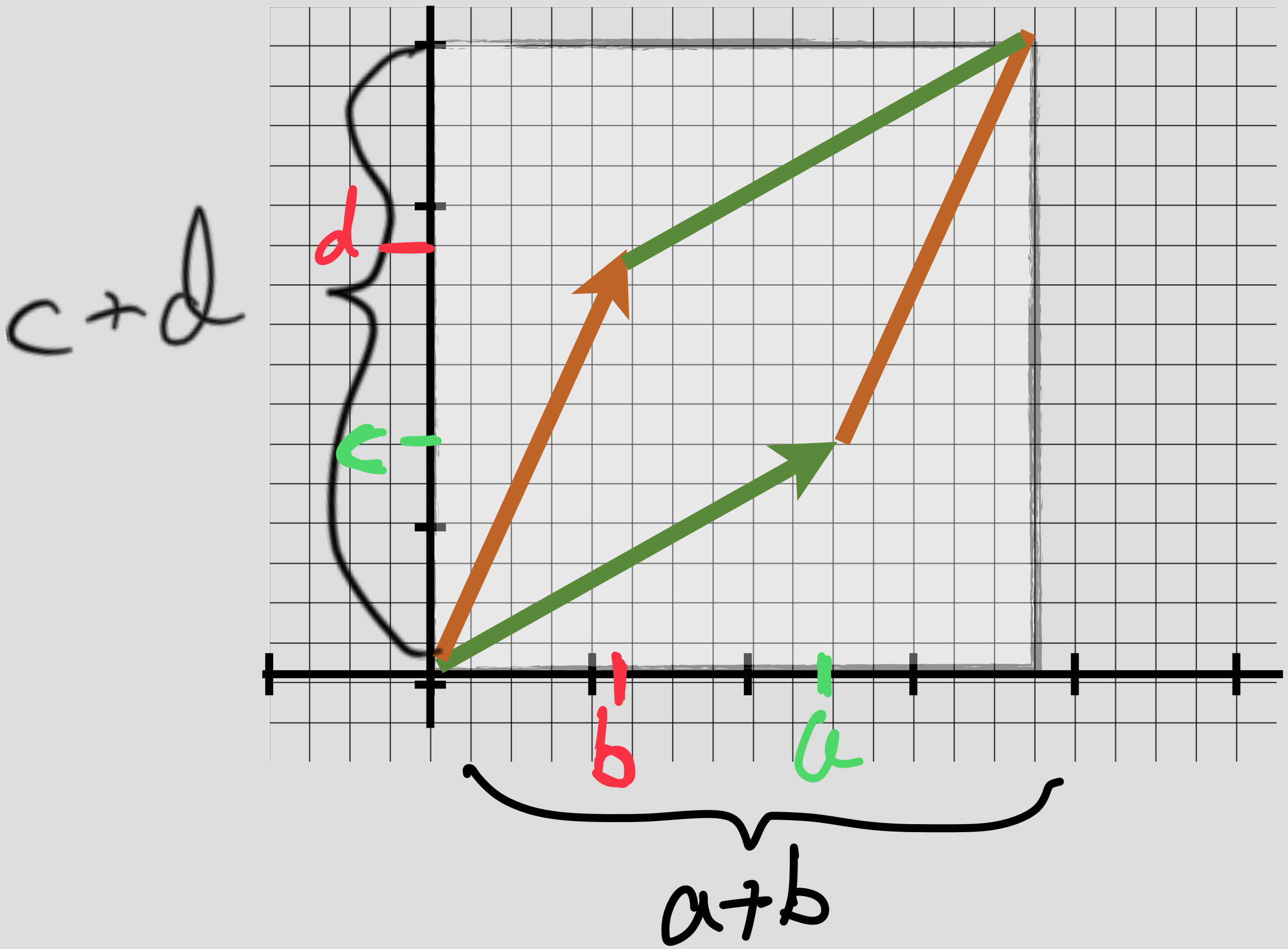


Interpretation of Determinant of a Matrix in $\mathbb{R}^{2\times2}$

- Area of a parallelogram

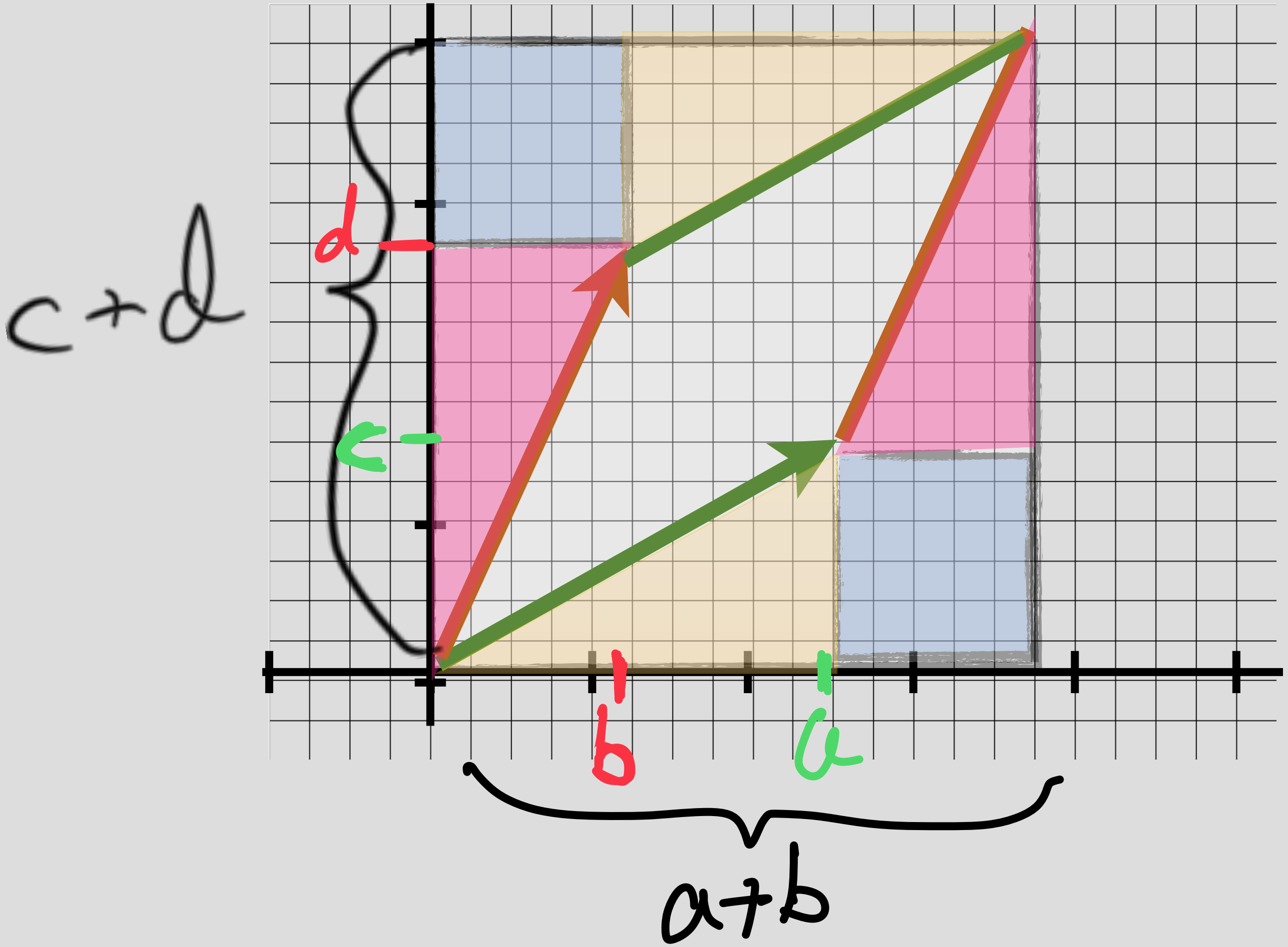
$$\det(A) = \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix} \right) = ad - bc$$

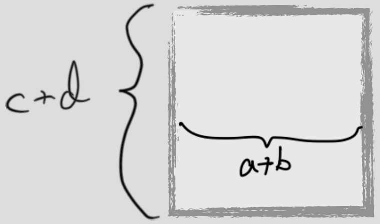


Interpretation of Determinant of a Matrix in $\mathbb{R}^{2\times 2}$

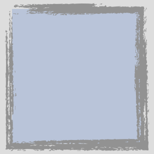
- Area of a parallelogram

$$\det(A) = \left(\begin{bmatrix} a & b \\ c & d \end{bmatrix}\right) = ad - bc$$



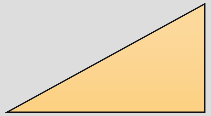


$$(c+d)(a+b)$$



x2

$$bc \times 2$$

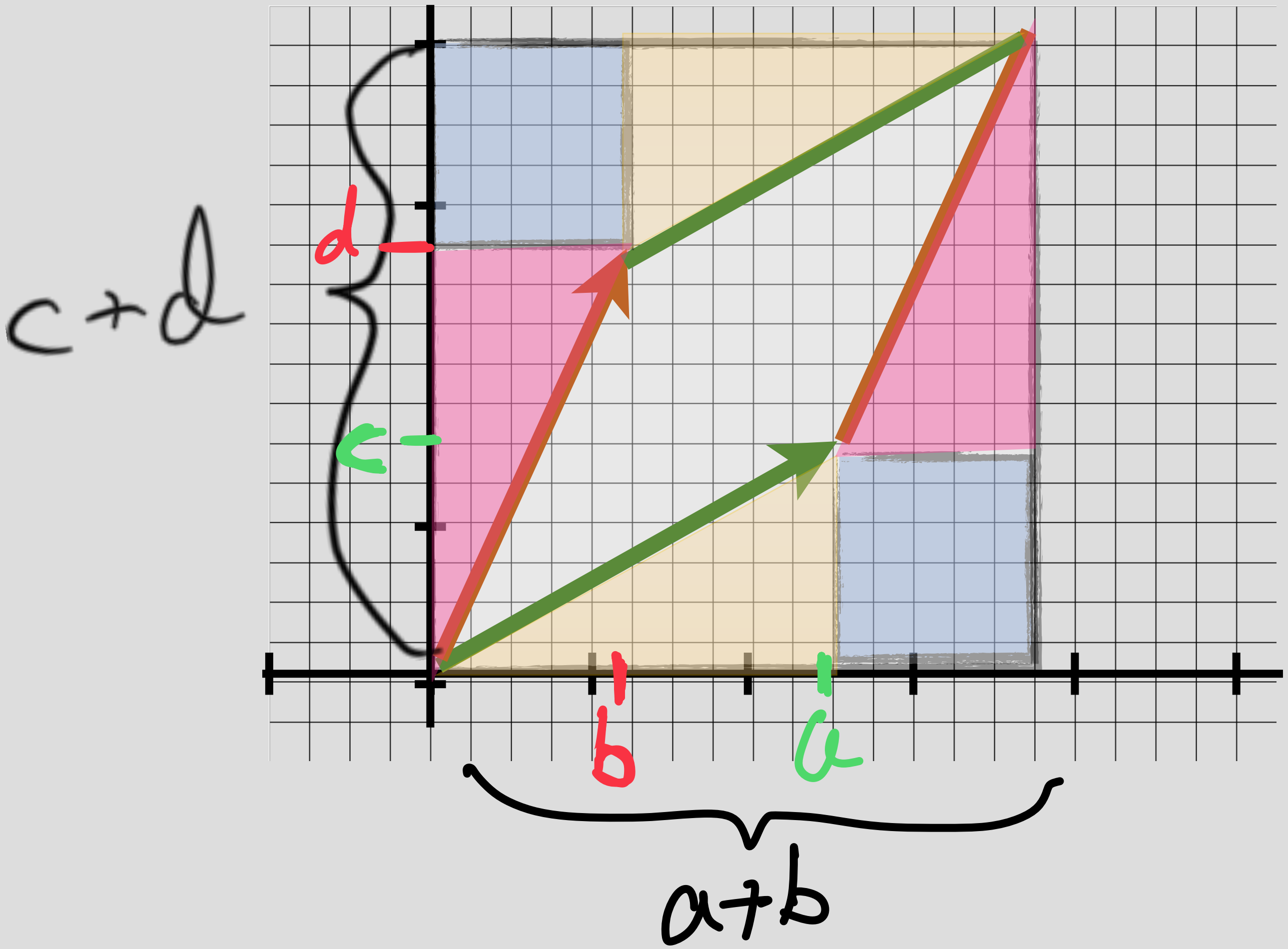


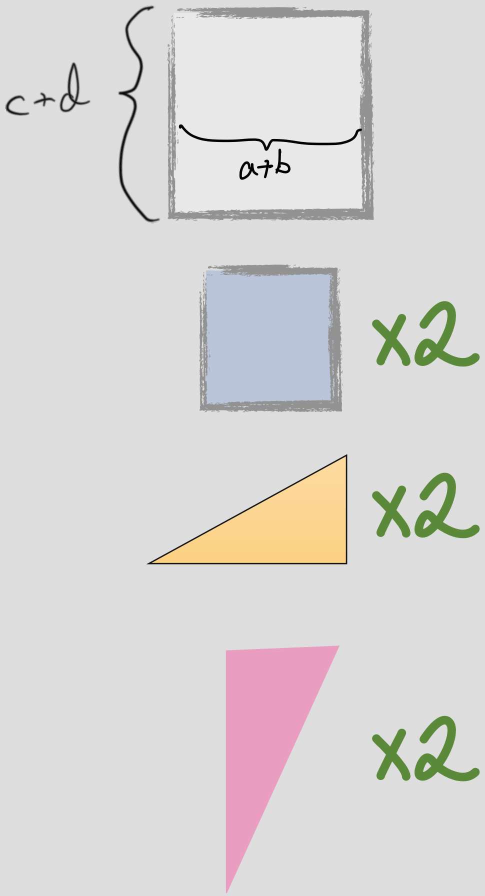
x2

$$\frac{1}{2}ac \times 2$$

x2

$$\frac{1}{2}bd \times 2$$



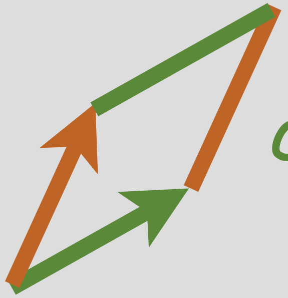


$(c+d)(a+b)$

$2bc$

ac

bd



area= $(c+d)(a+b) \; -2bc \; -ac \; -bd$

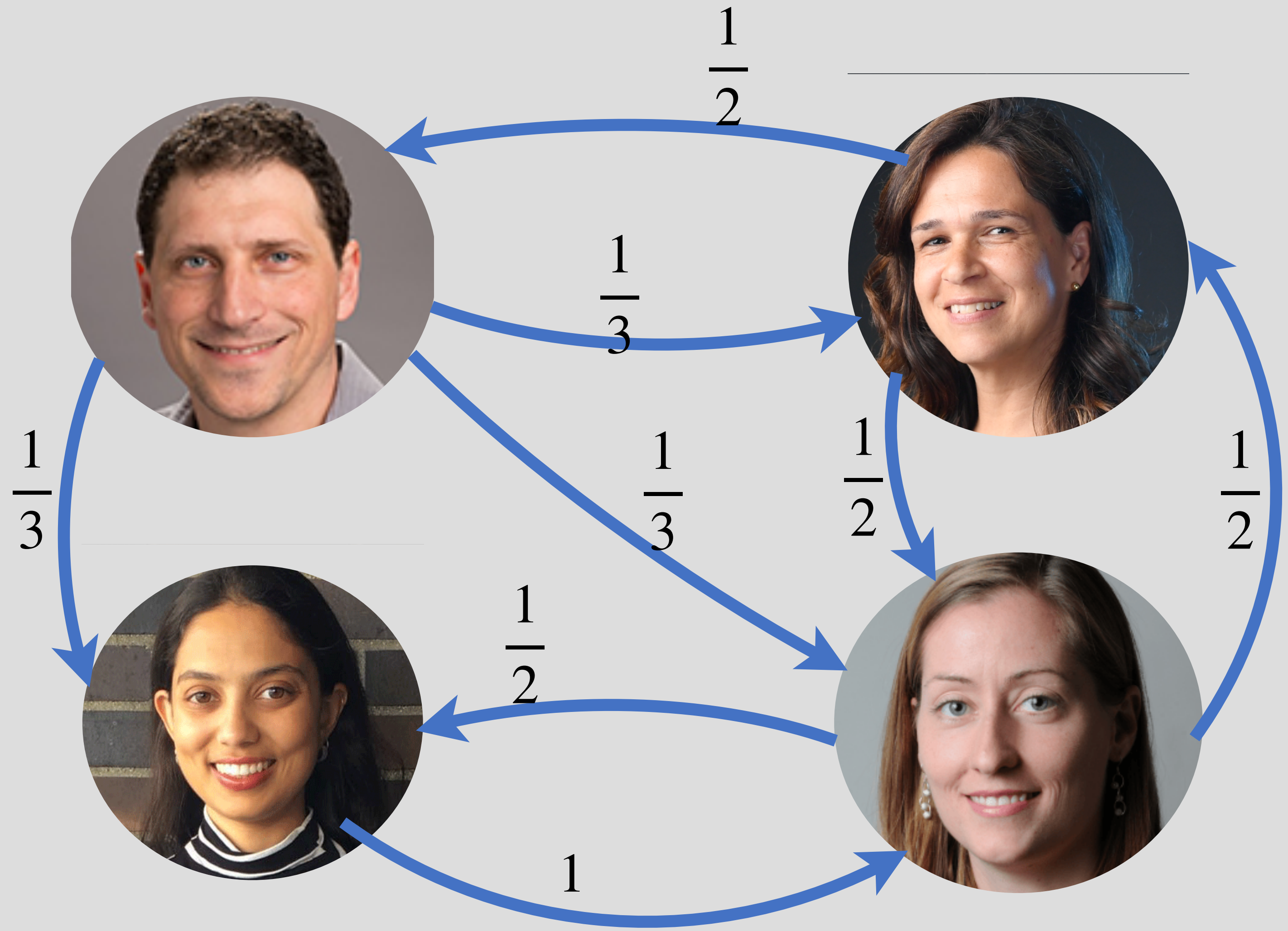
$= \cancel{c}a + \cancel{c}b + da + \cancel{d}b - \cancel{2}bc - \cancel{a}c - \cancel{b}d = ad - bc$

Determinant in $\mathbb{R}^3$

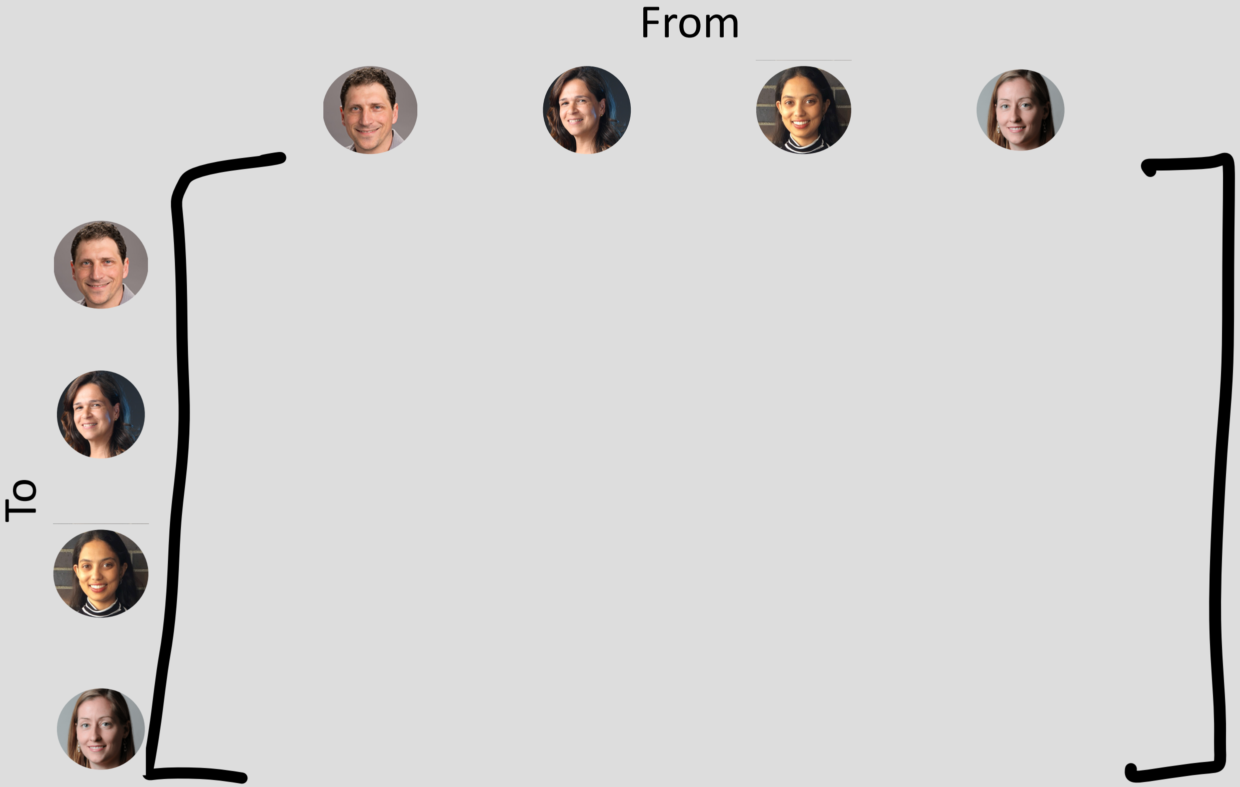
$$\det\left(\begin{bmatrix} a & b & c \\ d & e & f \\ g & h & i \end{bmatrix}\right) = \left[a \times \begin{vmatrix} e & f \\ h & i \end{vmatrix} \right] - \left[b \times \begin{vmatrix} d & f \\ g & i \end{vmatrix} \right] + \left[c \times \begin{vmatrix} d & e \\ g & h \end{vmatrix} \right]$$

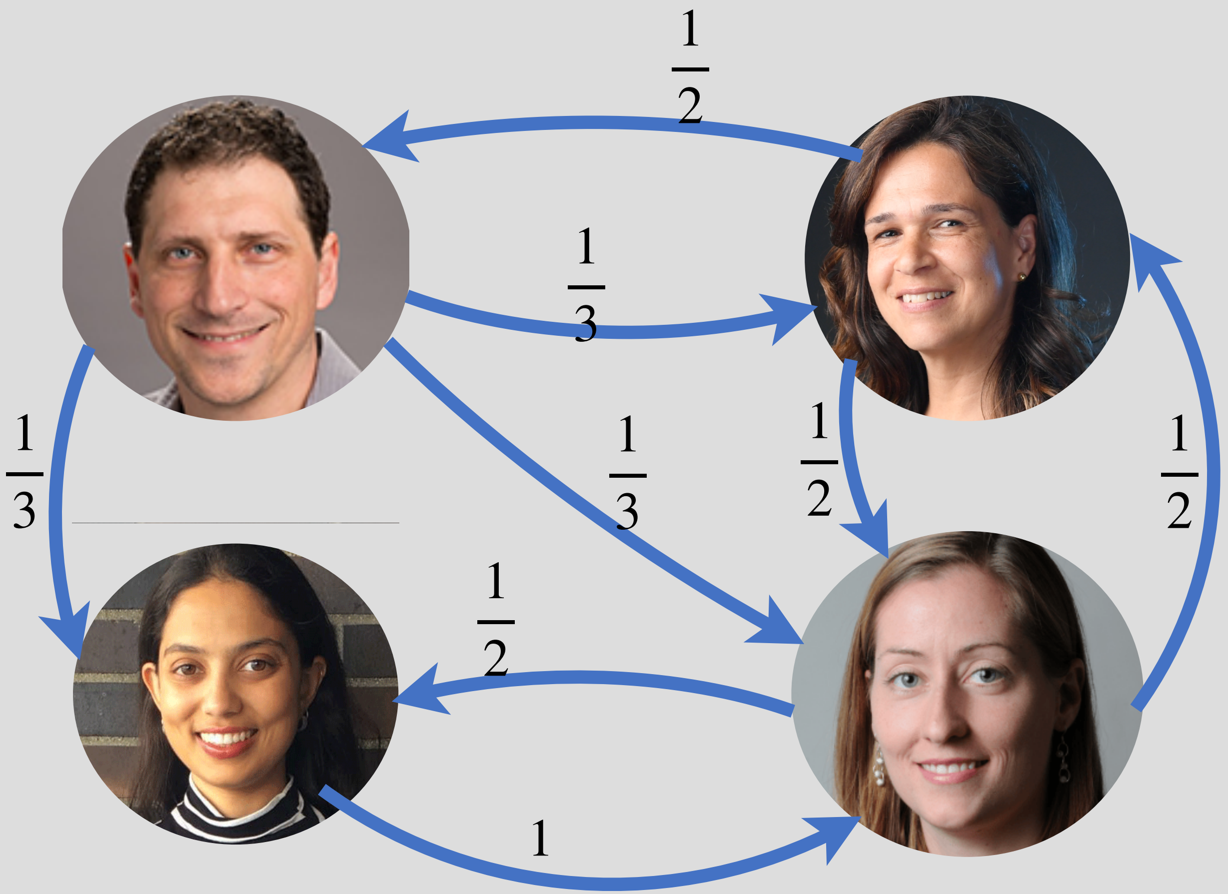
PageRank

- Ranks websites based on how many high-ranked pages link to them



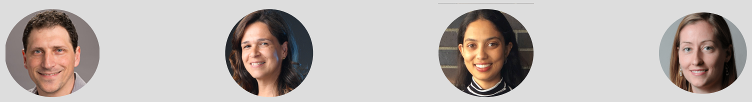
PageRank



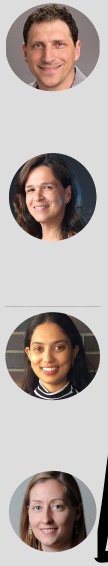


PageRank

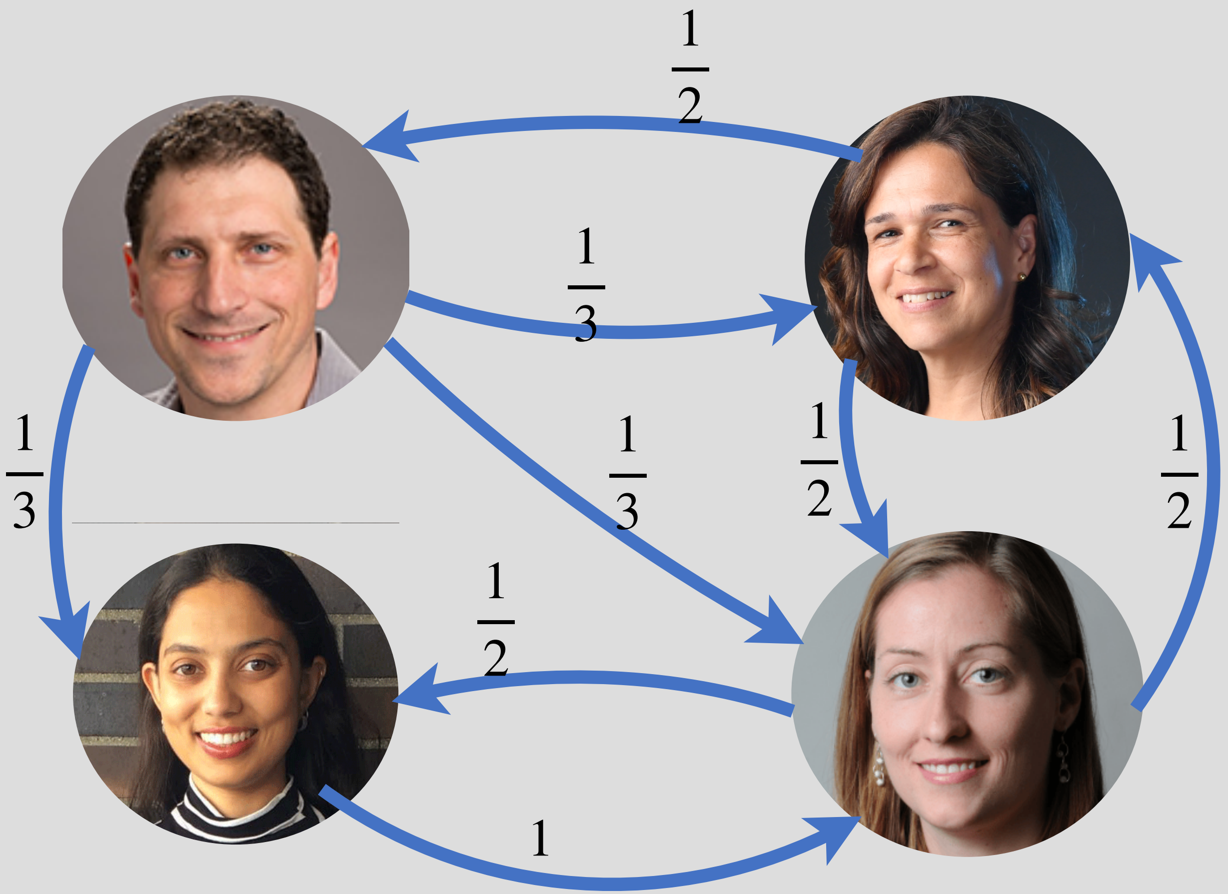
From



To



$$\begin{bmatrix} 0 \\ \frac{1}{3} \\ \frac{1}{3} \\ \frac{1}{3} \end{bmatrix}$$

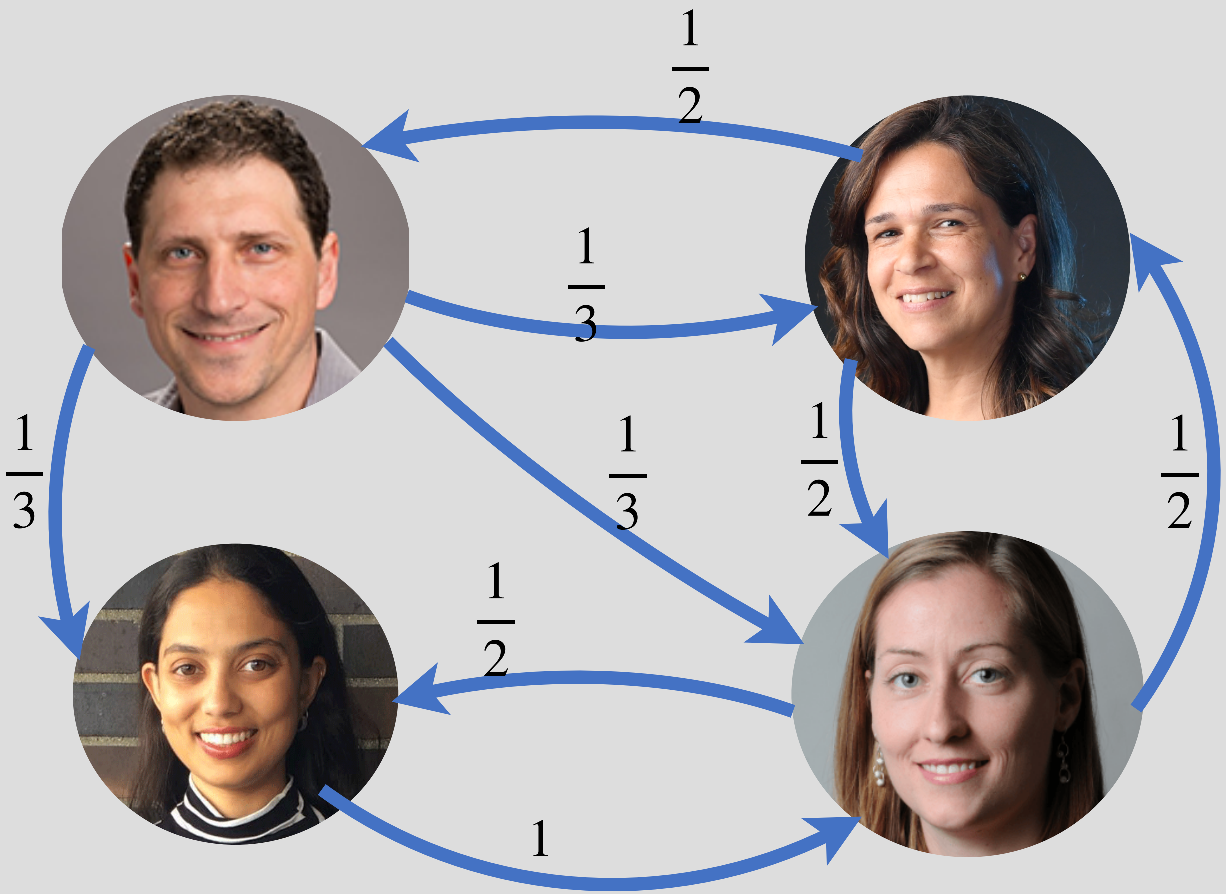


PageRank

From

To

0	$\frac{1}{2}$		
$\frac{1}{3}$	0		
$\frac{1}{3}$	0		
$\frac{1}{3}$	$\frac{1}{2}$		

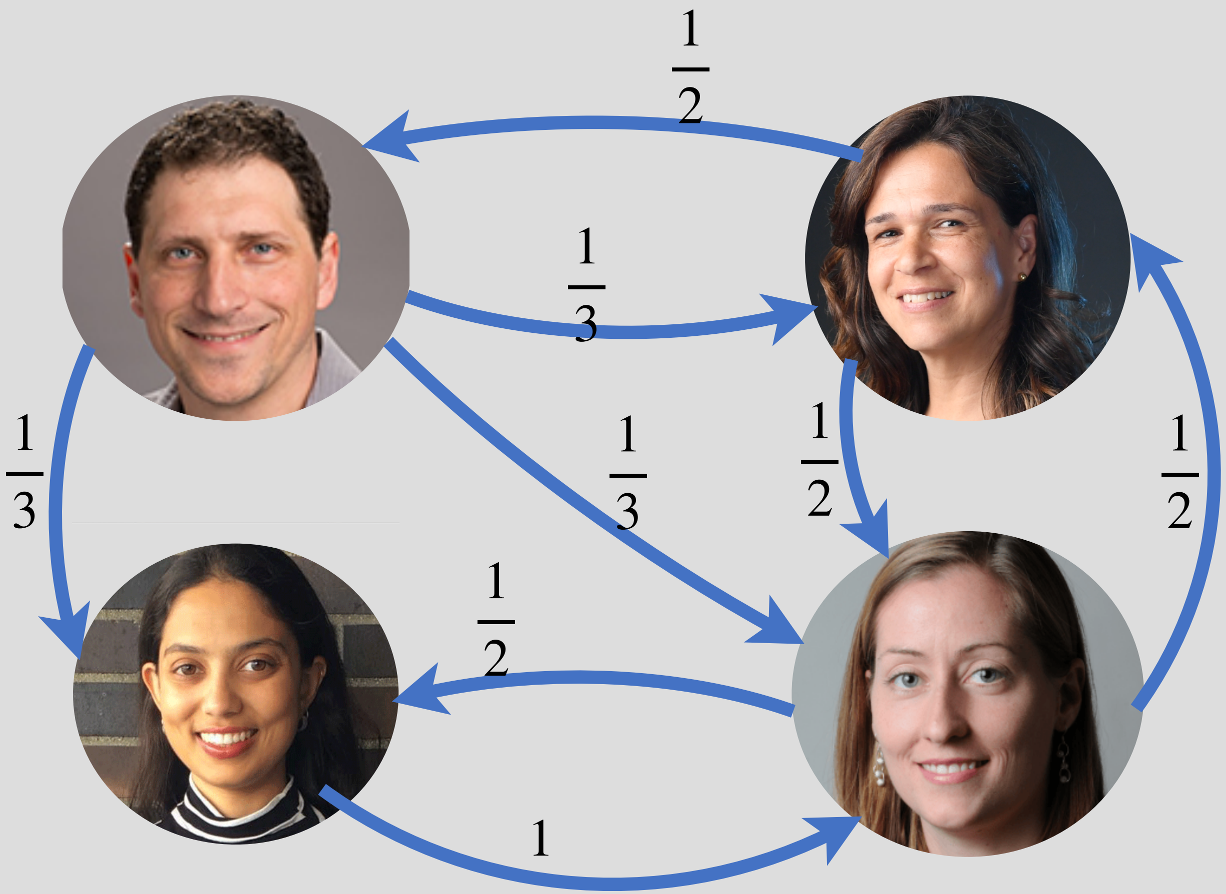


PageRank

From

To

0	$\frac{1}{2}$	0	
$\frac{1}{3}$	0	0	
$\frac{1}{3}$	0	0	
$\frac{1}{3}$	$\frac{1}{2}$	1	

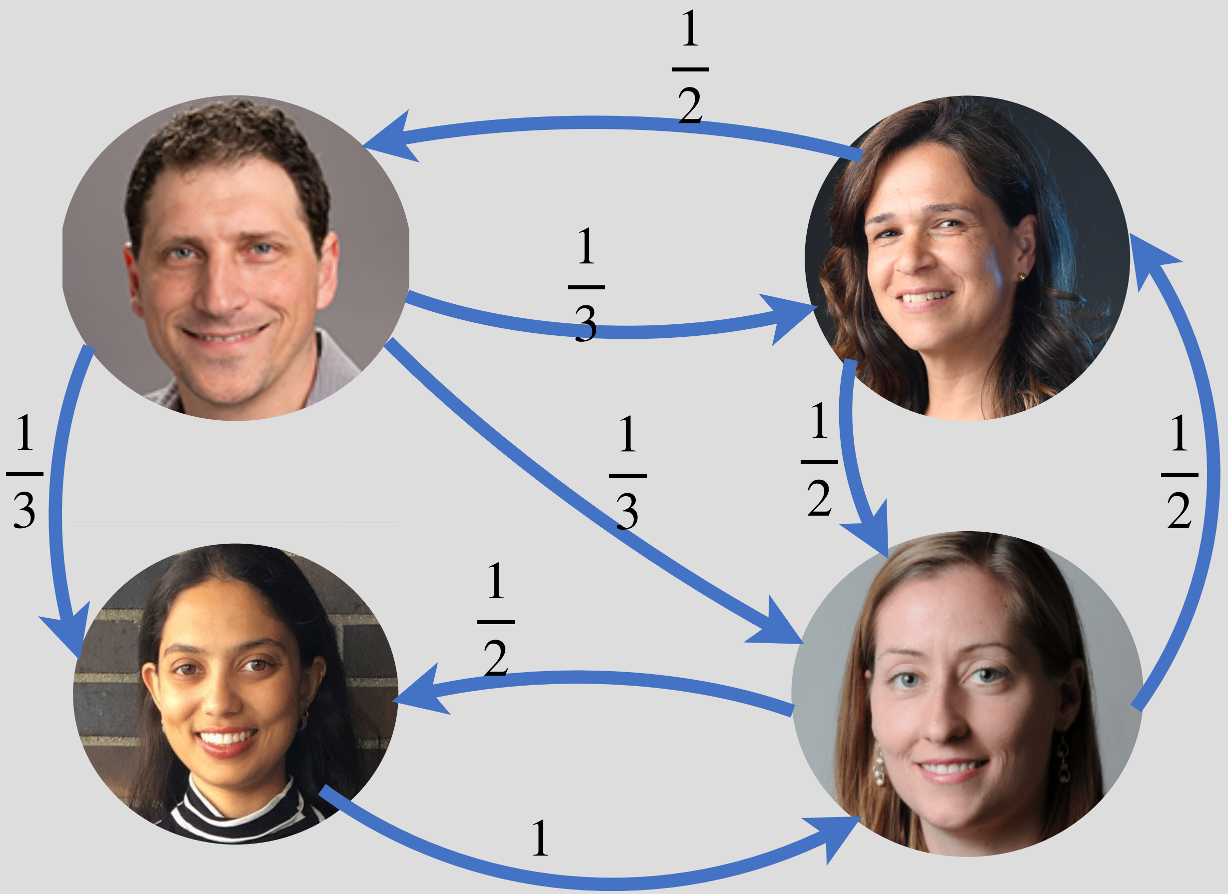


PageRank

From

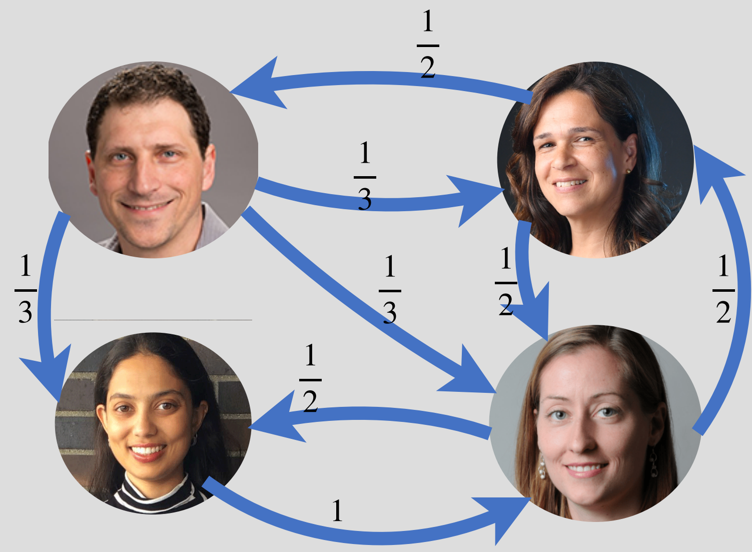
To

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



PageRank

$$\vec{x}(t+1) = \begin{bmatrix} 0 & 1/2 & 0 & 0 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 1/2 & 1 & 0 \end{bmatrix} \vec{x}(t)$$



$\vec{x}(t) \Rightarrow$ Page ranking

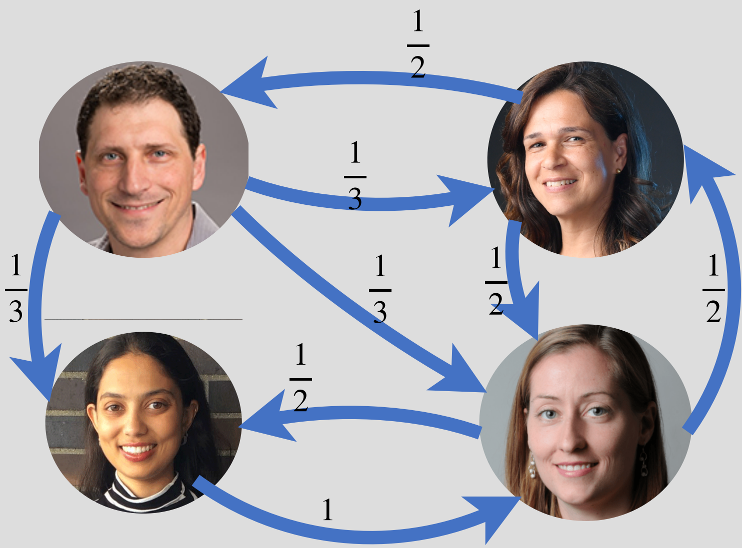
$$\vec{x}(0) = \begin{bmatrix} 1/4 \\ 1/4 \\ 1/4 \\ 1/4 \end{bmatrix}$$

$\Downarrow$

equal Ranking

PageRank

$$\vec{x}(t+1) = \begin{bmatrix} 0 & 1/2 & 0 & 0 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 1/2 & 1 & 0 \end{bmatrix} \vec{x}(t)$$



$\vec{x}(t) \Rightarrow$ Page ranking

$$\vec{x}(0) = \begin{bmatrix} 1/4 \\ 1/4 \\ 1/4 \\ 1/4 \end{bmatrix}$$

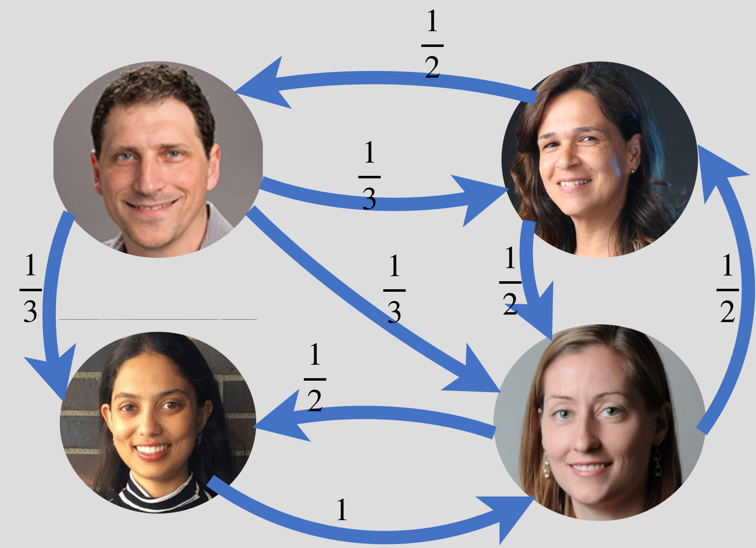
$\Downarrow$

equal Ranking

$t=1$

PageRank

$$\vec{x}(t+1) = \begin{bmatrix} 0 & 1/2 & 0 & 0 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 1/2 & 1 & 0 \end{bmatrix} \vec{x}(t)$$



$\vec{x}(t) \Rightarrow$ Page ranking

$$\vec{x}(0) = \begin{bmatrix} 1/4 \\ 1/4 \\ 1/4 \\ 1/4 \end{bmatrix}$$

$\Downarrow$

equal Ranking

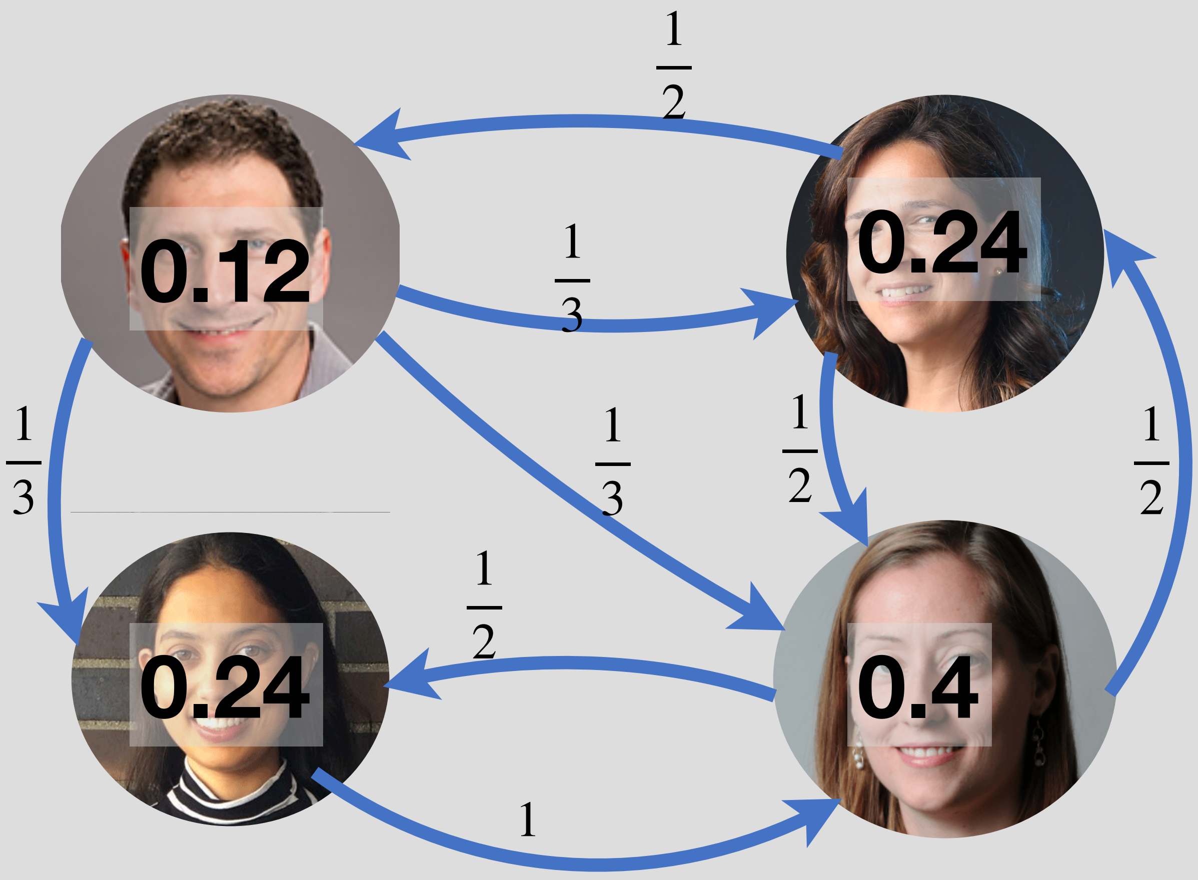
$t=1$

$$\begin{bmatrix} 0.125 \\ 0.208 \\ 0.208 \\ 0.458 \end{bmatrix}$$

Page Rank

$$\begin{bmatrix} 0.12 \\ 0.24 \\ 0.24 \\ 0.4 \end{bmatrix} = \begin{bmatrix} 0 & 1/2 & 0 & 0 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 0 & 0 & 1/2 \\ 1/3 & 1/2 & 1 & 0 \end{bmatrix} \begin{bmatrix} 0.12 \\ 0.24 \\ 0.24 \\ 0.4 \end{bmatrix}$$

steady state!




Judge me by my PageRank, do you?
Pirillo & Fitz
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General Steady-state solution

$$\overrightarrow{x}_{ss} = Q \cdot \overrightarrow{x}_{ss}$$

$$Q \cdot \overrightarrow{x}_{ss} - \overrightarrow{x}_{ss} = \overrightarrow{0}$$

$$(Q - ?)\overrightarrow{x}_{ss} = \overrightarrow{0}$$

$$Q \cdot \overrightarrow{x}_{ss} - I\overrightarrow{x}_{ss} = \overrightarrow{0}$$

$$(Q - I)\overrightarrow{x}_{ss} = \overrightarrow{0}$$

The $\mathrm{Null}(Q - I)$ is the steady state solution

Find via Gauss elimination!

Eigen Values

We saw an example for a steady-state vector

$$Q \cdot \overrightarrow{x}_{\text{ss}} = 1 \cdot \overrightarrow{x}_{\text{ss}}$$

Direction, and size of the vector did not change!

We will now look at the more general case

$$Q \cdot \overrightarrow{x} = \lambda \cdot \overrightarrow{x}$$

In this case, we say that
$\overrightarrow{x}$ is an Eigen Vector of Q with Eigen Value λ
and $\text{span}\{\overrightarrow{x}\}$ is the associated Eigen-space

Eigen Values

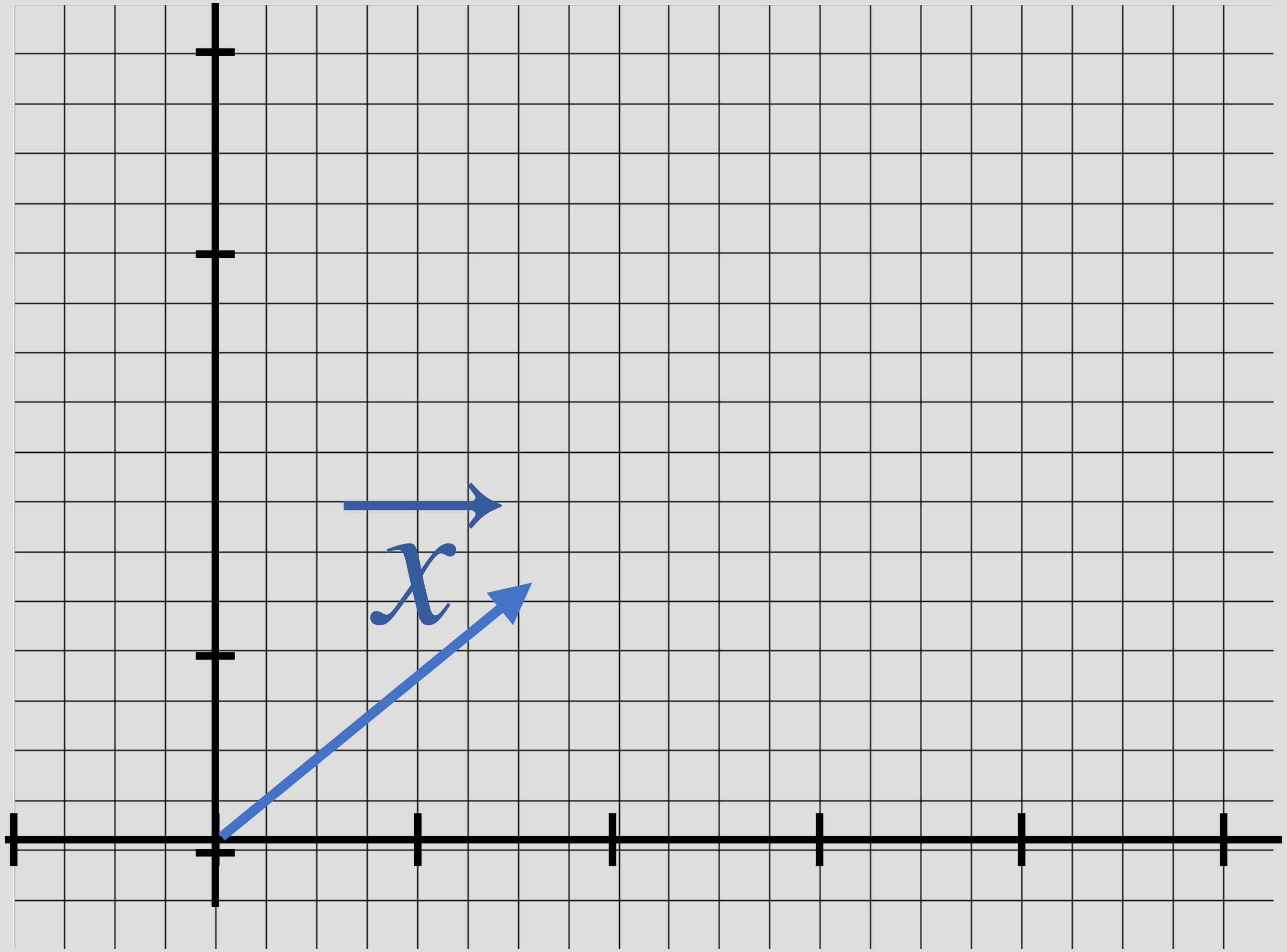
$$Q \cdot \overrightarrow{x} = \lambda \cdot \overrightarrow{x}$$

What happens if,

$\lambda = 1$?

$\lambda > 1$?

$\lambda < 1$?



Eigen Values and Eigen Vectors

- Definition: Let $Q \in \mathbb{R}^{N \times N}$ be a square matrix, and $^{**}\lambda \in \mathbb{R}$

  if $\exists \overrightarrow{x} \neq \overrightarrow{0}$ such that $Q\overrightarrow{x} = \lambda\overrightarrow{x}$,

  then λ is an eigenvalue of Q, $\overrightarrow{x}$ is an eigenvector

  and $\mathrm{Null}(Q - \lambda I)$ is its eigenspace.

**In general $\lambda \in \mathbb{C}$

Computing eigenvalues and vectors via determinant

Consider :

$$Q = \begin{bmatrix} \frac{1}{2} & 0 \\ \frac{1}{2} & 1 \end{bmatrix}$$, we want to find $\lambda, \vec{x}$ such that $Q\vec{x} = \lambda\vec{x}$

$$Q\vec{x} - \lambda\vec{x} = \vec{0}$$

$$(Q - \lambda I)\vec{x} = \vec{0}$$

Find $\vec{x} \in \text{Null}(Q - \lambda I)$:

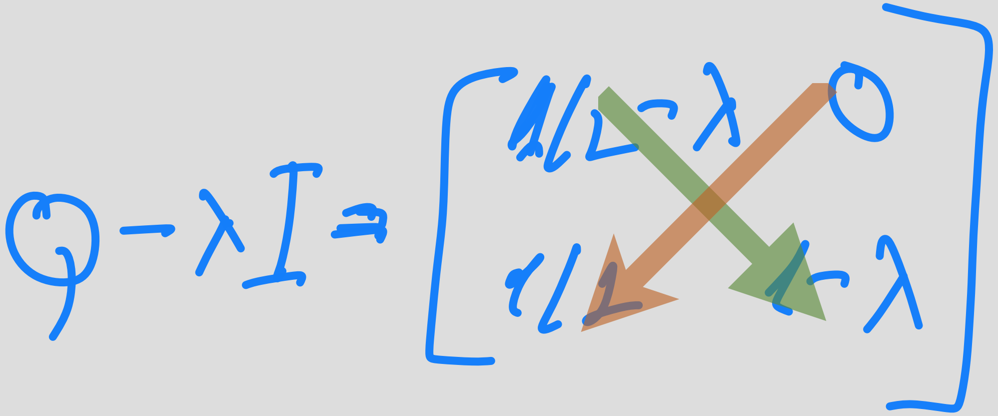
$$Q - \lambda I = \begin{bmatrix} 1/2 & 0 \\ 1/2 & 1 \end{bmatrix} - \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} = \begin{bmatrix} 1/2-\lambda & 0 \\ 1/2 & 1-\lambda \end{bmatrix}$$

① find λ

② find $\vec{x}$

Computing eigenvalues and vectors via determinant

Find $\vec{x} \in \text{Null}(Q - \lambda I)$:



① find λ

② find $\vec{x}$

Find λ that results in a non-trivial null space

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

$$(1/2 - \lambda)(1 - \lambda) - (0) \cdot 1/2 = 0$$

Characteristic polynomial

$$(1/2 - \lambda)(1 - \lambda) = 0$$

$$\lambda_1 = 1/2, \lambda_2 = 1$$

Computing eigenvalues and vectors via determinant

Find $\vec{x} \in \text{Null}(Q - \lambda I)$:

$$Q - \lambda I = \begin{bmatrix} 1/2 - \lambda & 0 \\ 1/2 & 1 - \lambda \end{bmatrix}$$

① find λ $\lambda_1 = 1/2,\ \lambda_2 = 1$

② find $\vec{x}$

$$\lambda_1 = 1/2$$

$$\begin{bmatrix} 1/2 - 1/2 & 0 \\ 1/2 & 1 - 1/2 \end{bmatrix} \vec{x} = 0$$

$$\begin{bmatrix} 0 & 0 \\ 1/2 & 1/2 \end{bmatrix} \vec{x} = 0$$

$$\left[\begin{array}{cc|c} 1/2 & 1/2 & 0 \\ 0 & 0 & 0 \end{array}\right] \quad x_1 = -x_2$$

$$\Downarrow$$

$$\left[\begin{array}{cc|c} 1 & 1 & 0 \\ 0 & 0 & 0 \end{array}\right] \nearrow \quad \vec{x}_1 \in \text{span}\left\{\begin{bmatrix} 1 \\ -1 \end{bmatrix}\right\}$$

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$x_1 = -x_2$

$\vec{x}_1 \in \text{span}\left\{\begin{bmatrix} 1 \\ -1 \end{bmatrix}\right\}$

$\lambda_2 = 1$

$$\begin{bmatrix} 1/2 - 1 & 0 \\ 1/2 & 1 - 1 \end{bmatrix} \vec{x} = 0$$

$$\begin{bmatrix} -1/2 & 0 \\ 1/2 & 0 \end{bmatrix} \vec{x} = 0$$

$$\left[\begin{array}{cc|c} 1/2 & 0 & 0 \\ -1/2 & 0 & 0 \end{array}\right] \Downarrow \left[\begin{array}{cc|c} 1 & 0 & 0 \\ 0 & 0 & 0 \end{array}\right]$$

$x_1 = 0$

$\vec{x}_2 \in \text{span}\left\{\begin{bmatrix} 0 \\ 1 \end{bmatrix}\right\}$

Eigen-vals/vectors/spaces

$$Q = \begin{bmatrix} 1/2 & 0 \\ 1/2 & 1 \end{bmatrix}$$

The matrix Q has the Eigen-vector

$$\vec{x}_1 \in \operatorname{span}\left\{ \begin{bmatrix} 1 \\ -1 \end{bmatrix} \right\}$$

eigenspace

Associated with eigenvalue $\lambda_1 = 1/2$

$$\vec{v} = \begin{bmatrix} 2 \\ -2 \end{bmatrix}$$

$$\begin{bmatrix} 1/2 & 0 \\ 1/2 & 1 \end{bmatrix} \begin{bmatrix} 2 \\ -2 \end{bmatrix} = \begin{bmatrix} 1/2 \cdot 2 + 0(-2) \\ 1/2 \cdot 2 + 1(-2) \end{bmatrix} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$Q\vec{v} = 1/2\vec{v}$$

Eigen-vals/vectors/spaces

$$Q = \begin{bmatrix} 1/2 & 0 \\ 1/2 & 1 \end{bmatrix}$$

The matrix Q has the Eigen-vector

$$\vec{x}_1 \in span\left\{\begin{bmatrix} 1 \\ -1 \end{bmatrix}\right\}$$ eigenspace

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$$Q\vec{v} = 1/2\vec{v}$$

and,

has the Eigen-vector

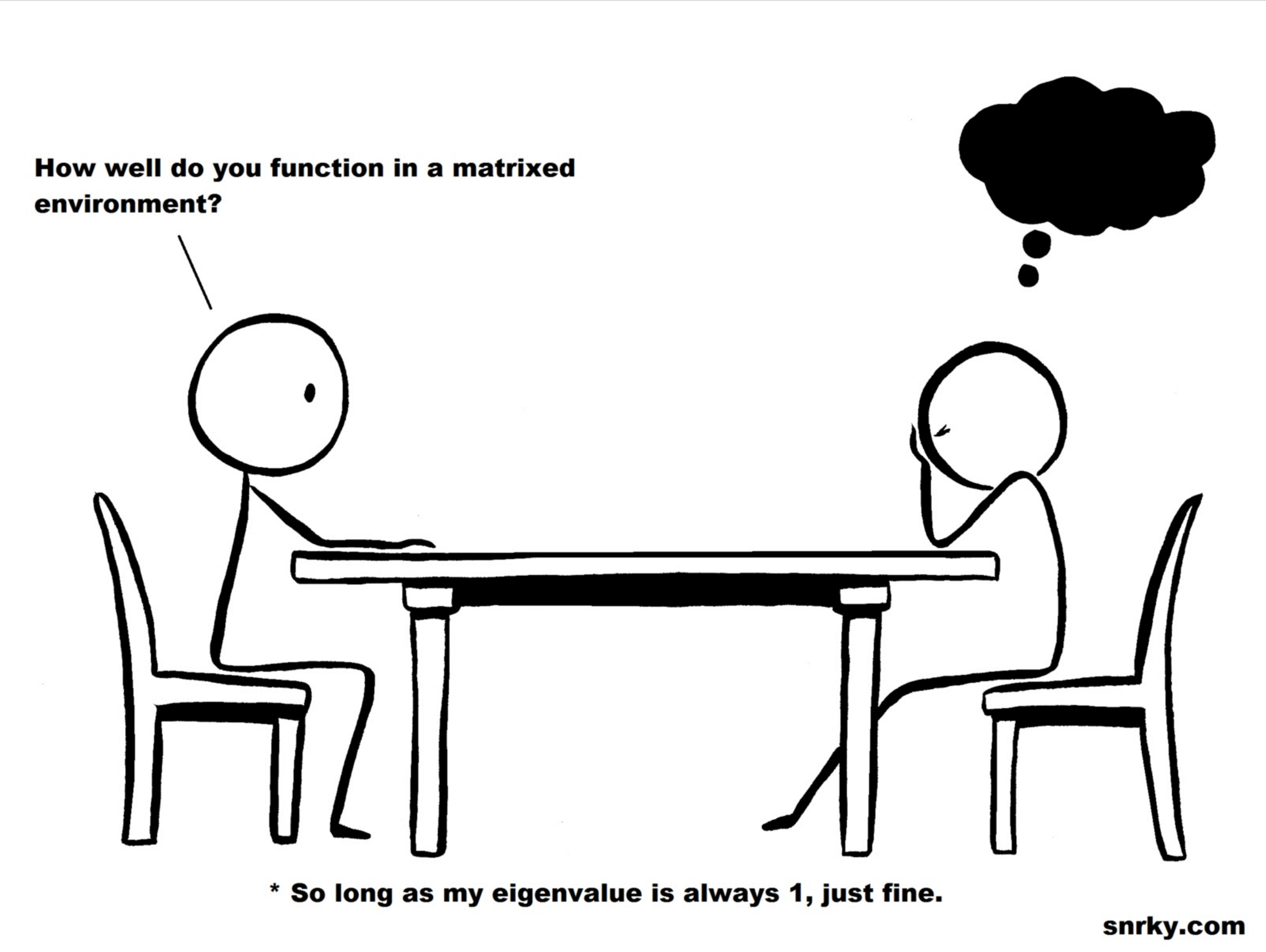
$$\vec{x}_2 \in span\left\{\begin{bmatrix} 0 \\ 1 \end{bmatrix}\right\}$$ eigenspace

Associated with eigenvalue $\lambda_2 = 1$

$$\vec{u} = \begin{bmatrix} 0 \\ 2 \end{bmatrix}$$

$$\begin{bmatrix} 1/2 & 0 \\ 1/2 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ 2 \end{bmatrix} = \begin{bmatrix} 1/2 \cdot 0 + 0(2) \\ 1/2 \cdot 0 + 1 \cdot 2 \end{bmatrix} = \begin{bmatrix} 0 \\ 2 \end{bmatrix}$$

$$Q\vec{u} = 1 \cdot \vec{u}$$



How well do you function in a matrixed environment?
* So long as my eigenvalue is always 1, just fine.
snrky.com

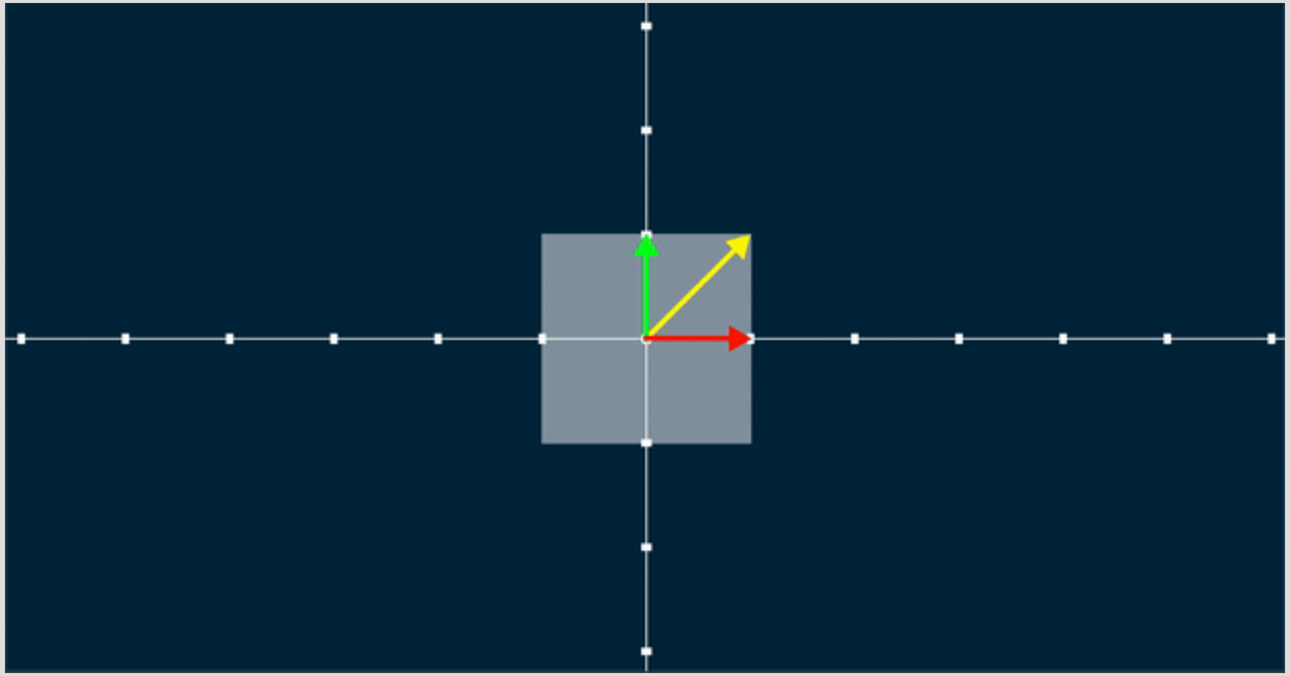
Matrix transformations

What does the matrix do?

What is the A matrix?

What are its eigenvectors?

What are its eigenvalues?



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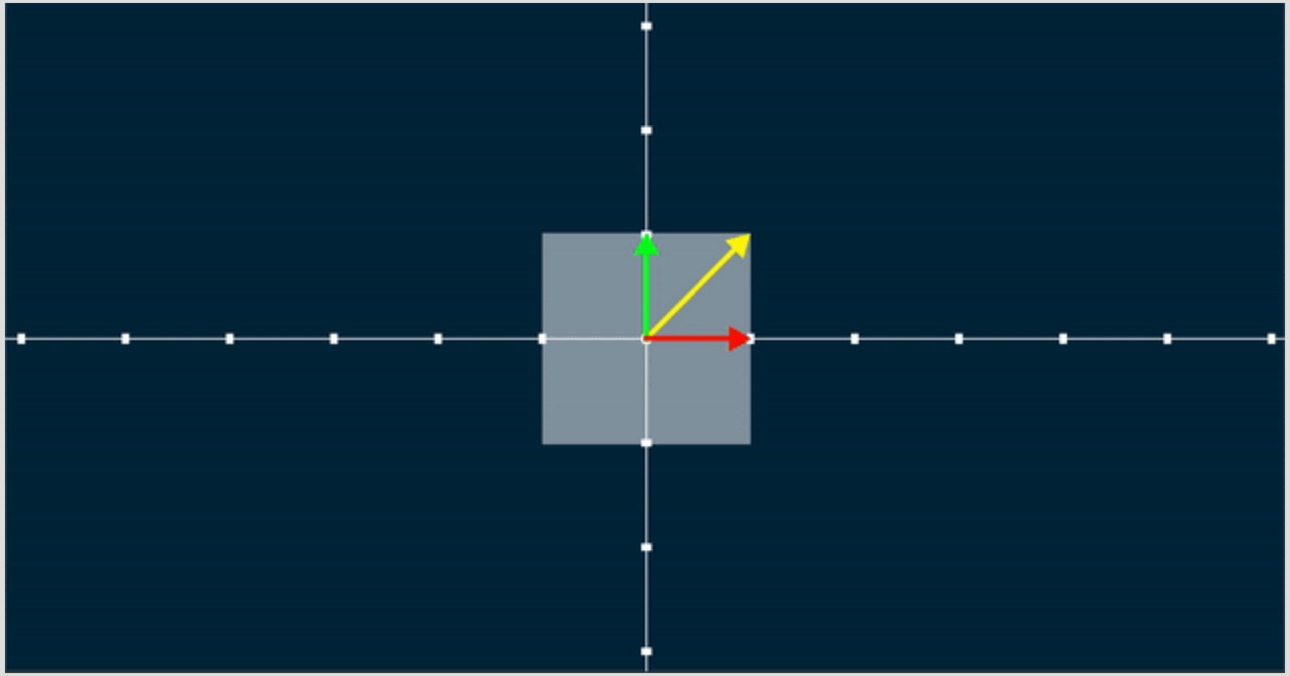

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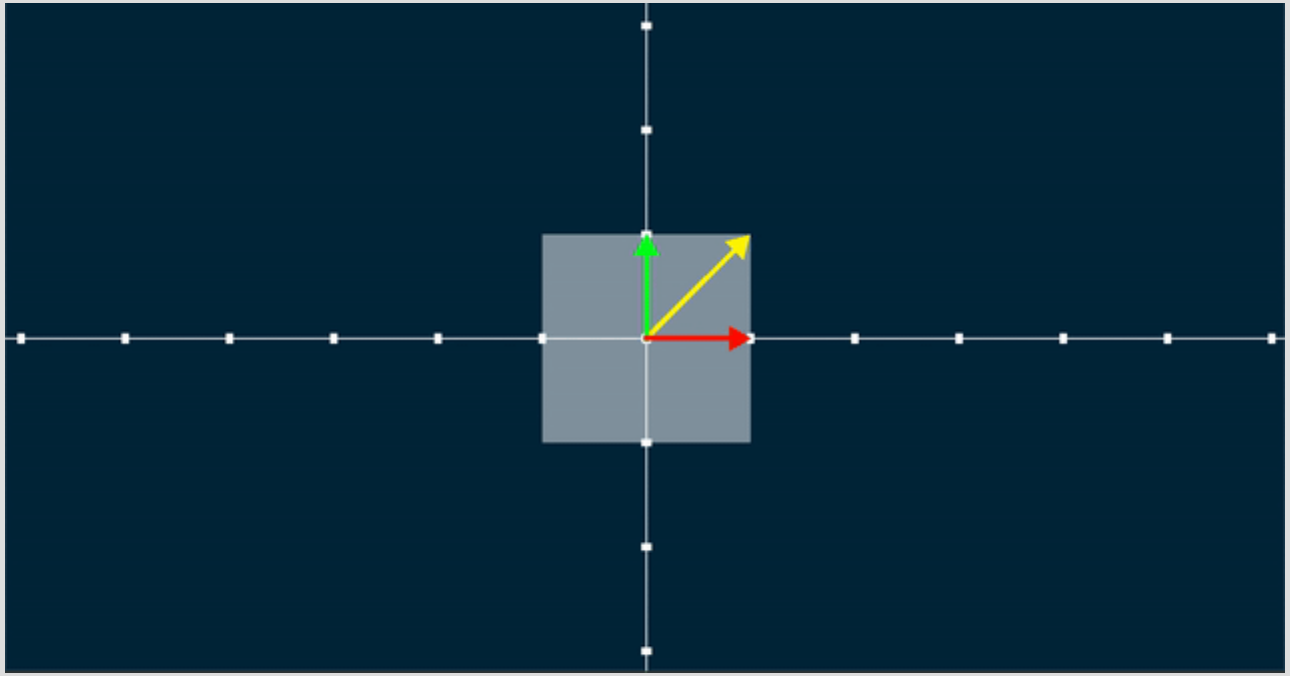

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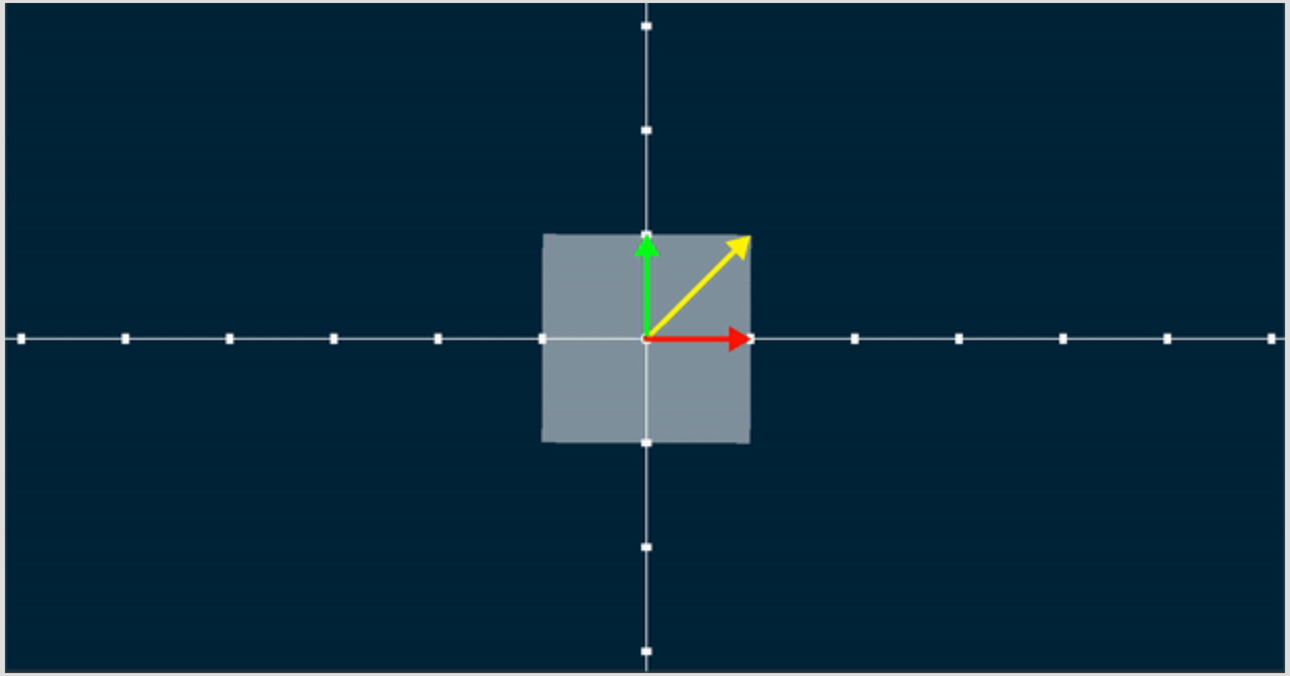

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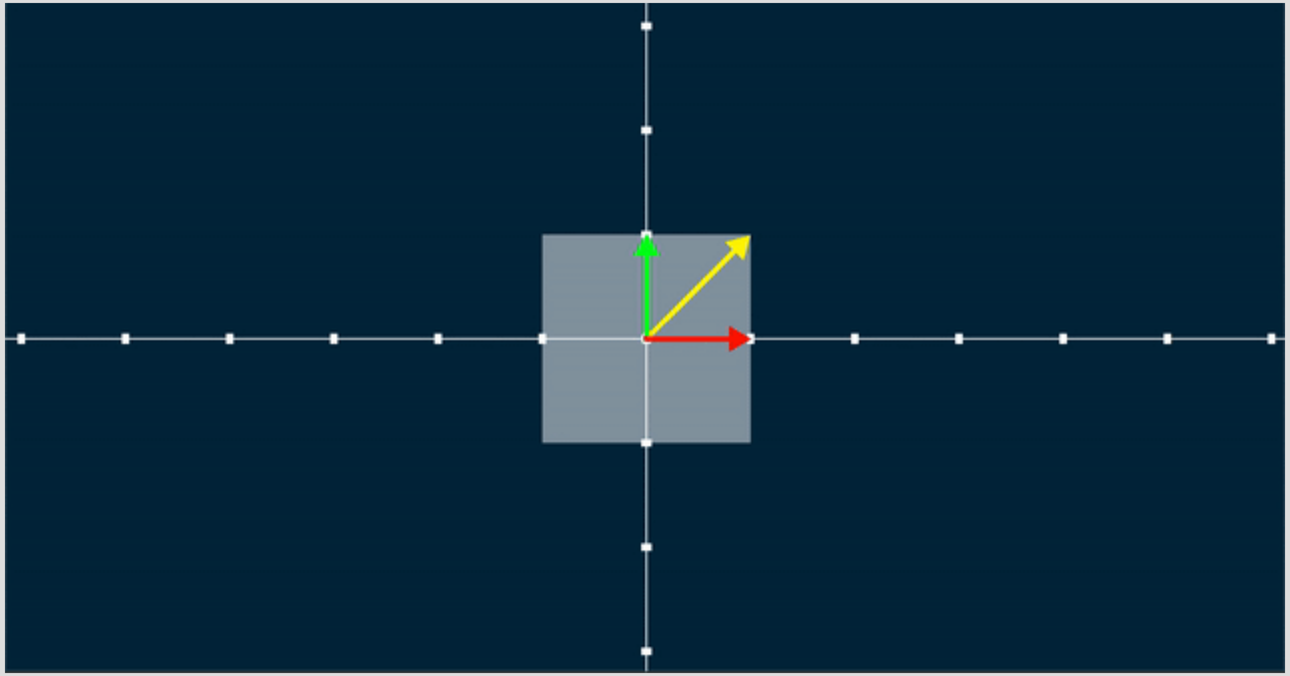

Matrix transformations

For a matrix that flips (reflects) vectors along a line:

What is the A matrix?

What are its eigenvectors?

What are its eigenvalues?