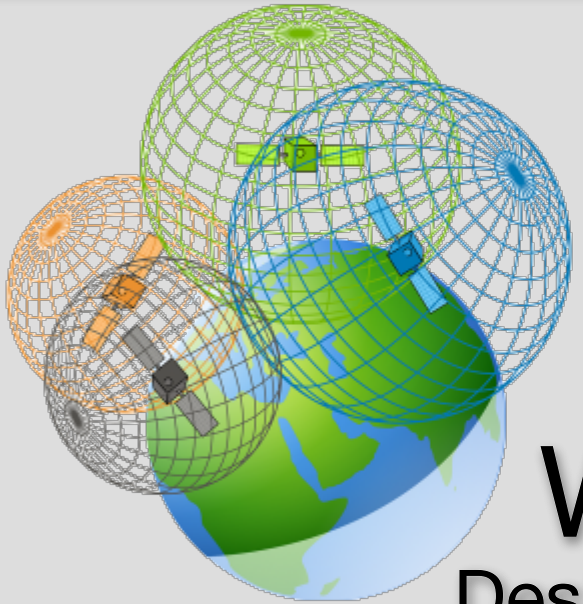
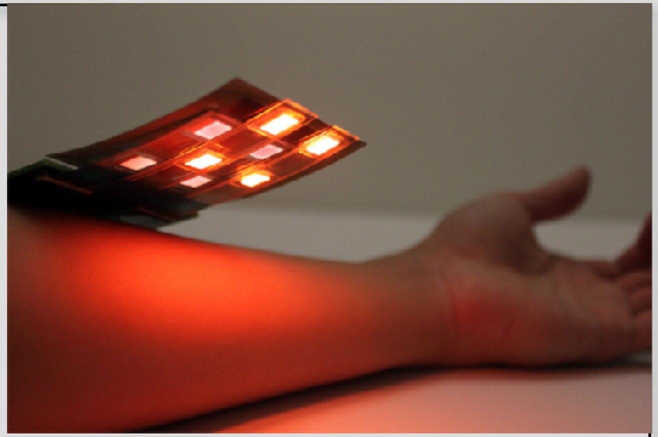




Welcome to EECS 16A!

Designing Information Devices and Systems I

Ana Arias and Miki Lustig

Fa 2022

Lecture 2B

Span, Proofs

Linear (in)dependance

Announcements

- Last time:
  - Continue vectors
  - Matrix-Matrix and Matrix-vector Multiplications
  - Matrix-Vector Multiplications as linear set of equations
- Today:
  - Span
  - Proofs
  - Linear (in)dependance

Matrix-Vector Form of Systems of Linear Equations

- Consider the matrix equation: $A\vec{x} = \vec{b}$

$$A\vec{x} = \underbrace{\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} \\ a_{21} & a_{22} & \cdots & a_{2N} \\ & & \vdots & \\ a_{M1} & a_{M2} & \cdots & a_{MN} \end{bmatrix}}_{M \times N} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_N \end{bmatrix}}_{N \times 1} = \underbrace{\begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1N}x_N \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2N}x_N \\ \vdots \\ a_{M1}x_1 + a_{M2}x_2 + \cdots + a_{MN}x_N \end{bmatrix}}_{M \times 1} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_M \end{bmatrix}$$

Same as the Augmented Matrix!

$$\left[\begin{array}{cccc|c} a_{11} & a_{12} & \cdots & a_{1N} & b_1 \\ a_{21} & a_{22} & \cdots & a_{2N} & b_2 \\ \vdots & & \vdots & & \vdots \\ a_{M1} & a_{M2} & \cdots & a_{MN} & b_M \end{array}\right]$$

$A\vec{x} = \vec{b}$ is another way to write
A linear set of equations!

Row vs Column Perspective

- Row / Measurement Perspective of $A\overrightarrow{x} = \overrightarrow{b}$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

$$\begin{bmatrix} \\ \\ \end{bmatrix} = \begin{bmatrix} \\ \\ \end{bmatrix}$$

Row vs Column Perspective

- Row / Measurement Perspective of $A\overrightarrow{x} = \overrightarrow{b}$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

$$\begin{bmatrix} a_{11}x_1 + a_{12}x_2 + a_{13}x_3 \\ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

Q: What does a row mean?

A: How each variable affect a particular measurement

Row vs Column Perspective

- Column Perspective of $A\overrightarrow{x} = \overrightarrow{b}$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

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

Row vs Column Perspective

- Column Perspective of $A\overrightarrow{x} = \overrightarrow{b}$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

$$\begin{bmatrix} \vec{a}_1 & \vec{a}_2 & \vec{a}_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} =$$

Row vs Column Perspective

- Column Perspective of $A\overrightarrow{x} = \overrightarrow{b}$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

$$\begin{bmatrix} \vec{a}_1 & \vec{a}_2 & \vec{a}_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \quad x_1\vec{a}_1 + x_2\vec{a}_2 + x_3\vec{a}_3 =$$

Row vs Column Perspective

- Column Perspective of $A\overrightarrow{x} = \overrightarrow{b}$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

$$\begin{bmatrix} \vec{a}_1 & \vec{a}_2 & \vec{a}_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \quad x_1\vec{a}_1 + x_2\vec{a}_2 + x_3\vec{a}_3 =$$

$$= \begin{bmatrix} a_{11}x_1 \\ a_{21}x_1 \end{bmatrix} + \begin{bmatrix} a_{12}x_2 \\ a_{22}x_2 \end{bmatrix} + \begin{bmatrix} a_{13}x_3 \\ a_{23}x_3 \end{bmatrix} = \begin{bmatrix} a_{11}x_1 + a_{12}x_2 + a_{13}x_3 \\ a_{21}x_1 + a_{22}x_2 + a_{23}x_3 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

Q: What does a column mean?

A: How a particular variable affects all measurements.

Linear combination of vectors

- Given set of vectors $\{\overrightarrow{a}_1, \overrightarrow{a}_2, \cdots, \overrightarrow{a}_M\} \in \mathbb{R}^N$, and coefficients $\{\alpha_1, \alpha_2, \cdots, \alpha_M\} \in \mathbb{R}$
- A linear combination of vectors is defined as: $\overrightarrow{b} \triangleq \alpha_1 \overrightarrow{a}_1 + \alpha_2 \overrightarrow{a}_2 + \cdots + \alpha_M \overrightarrow{a}_M$

Recall: $A\overrightarrow{x}$:

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} \vec{a}_1 & \vec{a}_2 & \vec{a}_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

$$= x_1\vec{a}_1 + x_2\vec{a}_2 + x_3\vec{a}_3$$

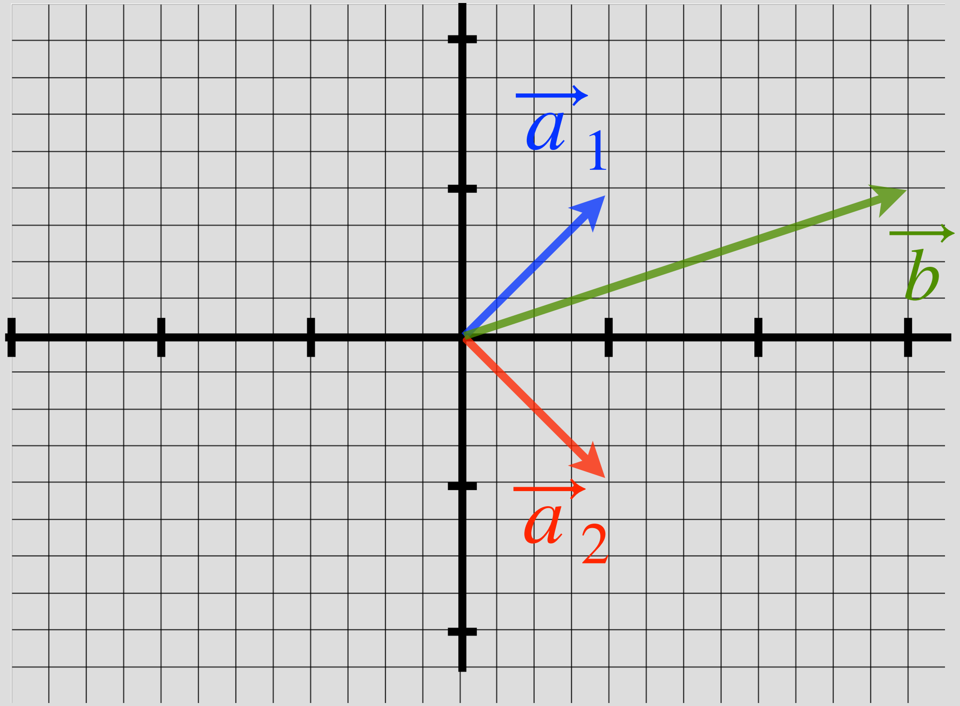
Matrix-vector multiplication is a linear combination of the columns of A!

Linear Set of Equations as a Linear Combination

- Consider the problem: $A\overrightarrow{x} = \overrightarrow{b}$:

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \end{bmatrix}$$

$\overrightarrow{a}_1$ $\overrightarrow{a}_2$ $\overrightarrow{b}$



Linear Set of Equations as a Linear Combination

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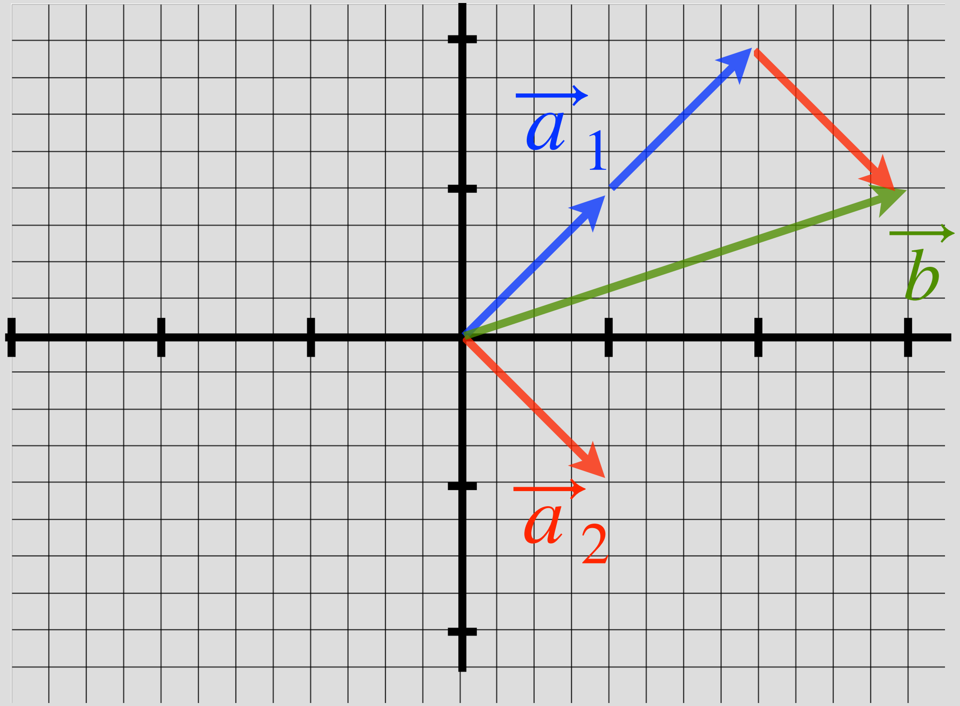
$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \end{bmatrix}$$

$$\overrightarrow{a}_1 \quad \overrightarrow{a}_2 \quad \overrightarrow{b}$$

Q: What linear combination of $\overrightarrow{a}_1, \overrightarrow{a}_2$ will give $\overrightarrow{b}$?



Linear Set of Equations as a Linear Combination

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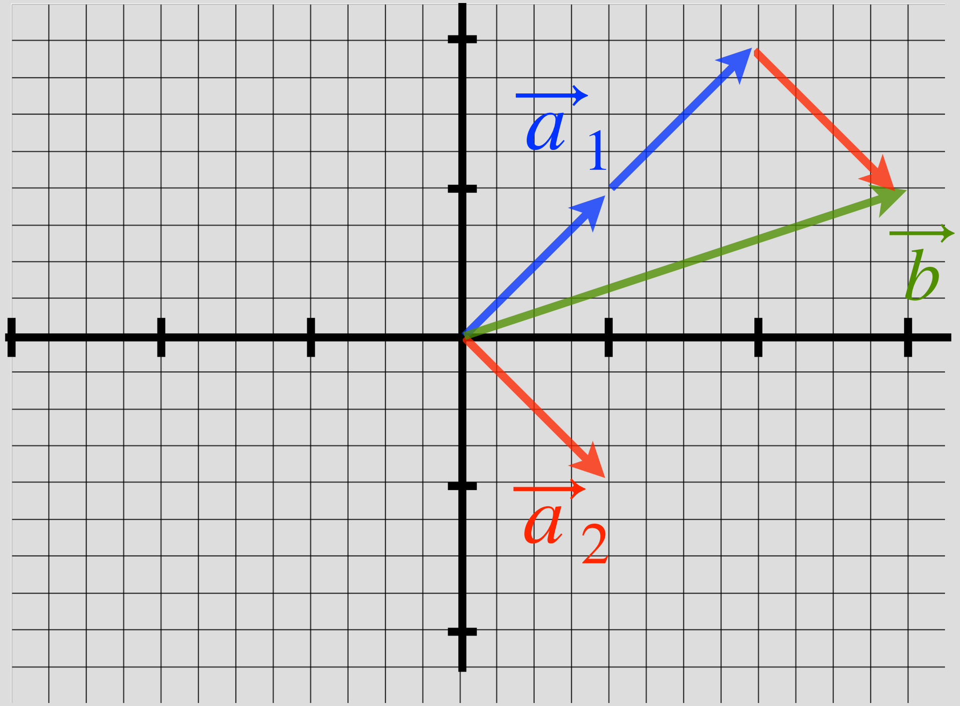
$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \end{bmatrix}$$

$$\overrightarrow{a}_1 \quad \overrightarrow{a}_2 \qquad\qquad \overrightarrow{b}$$

Q: What linear combination of $\overrightarrow{a}_1, \overrightarrow{a}_2$ will give $\overrightarrow{b}$?

A: $2\overrightarrow{a}_1 + 1\overrightarrow{a}_2$

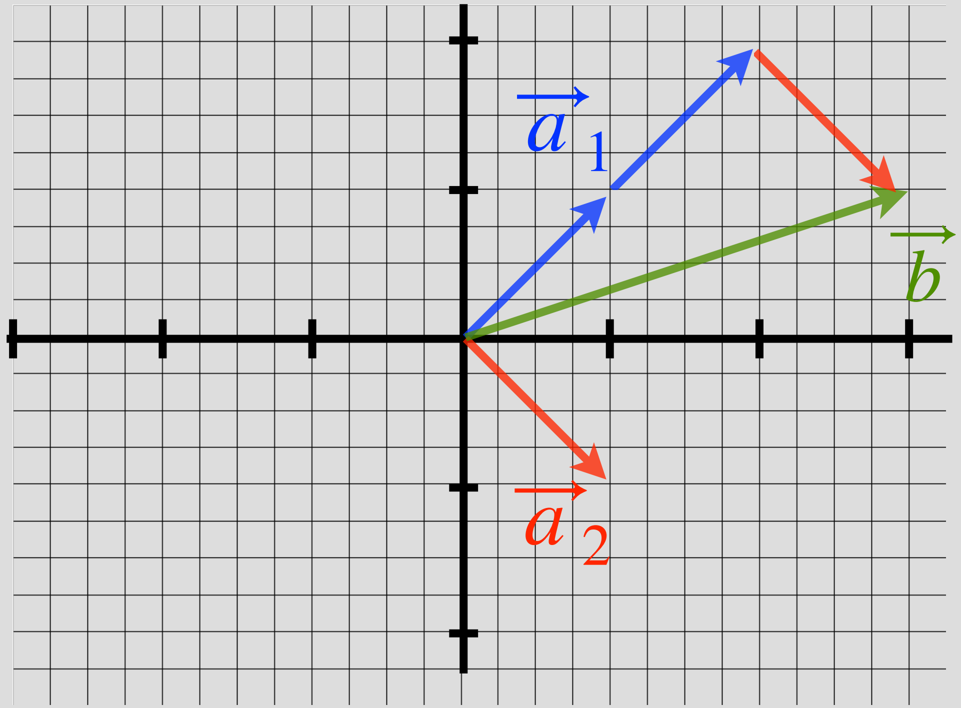


Linear Set of Equations as a Linear Combination

- Consider the problem: $A\vec{x} = \vec{b}$:

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \end{bmatrix}$$

$\vec{a}_1$ $\vec{a}_2$ $\vec{b}$



Q: What linear combination of $\vec{a}_1, \vec{a}_2$ will give $\vec{b}$?

A: $2\vec{a}_1 + 1\vec{a}_2$

Gaussian Elimination:

$$\left[\begin{array}{cc|c} 1 & 1 & 3 \\ 1 & -1 & 1 \end{array}\right] \quad \left[\begin{array}{cc|c} 1 & 1 & 3 \\ 0 & 1 & 1 \end{array}\right]$$

$$\left[\begin{array}{cc|c} 1 & 1 & 3 \\ 0 & -2 & -2 \end{array}\right] \quad \left[\begin{array}{cc|c} 1 & 0 & 2 \\ 0 & 1 & 1 \end{array}\right] \rightarrow$$

$x_1 = 2$
$x_2 = 1$

same as

$\Rightarrow \vec{b} = \underline{2}\vec{a}_1 + \underline{1} \cdot \vec{a}_2$!

Linear Set of Equations as a Linear Combination

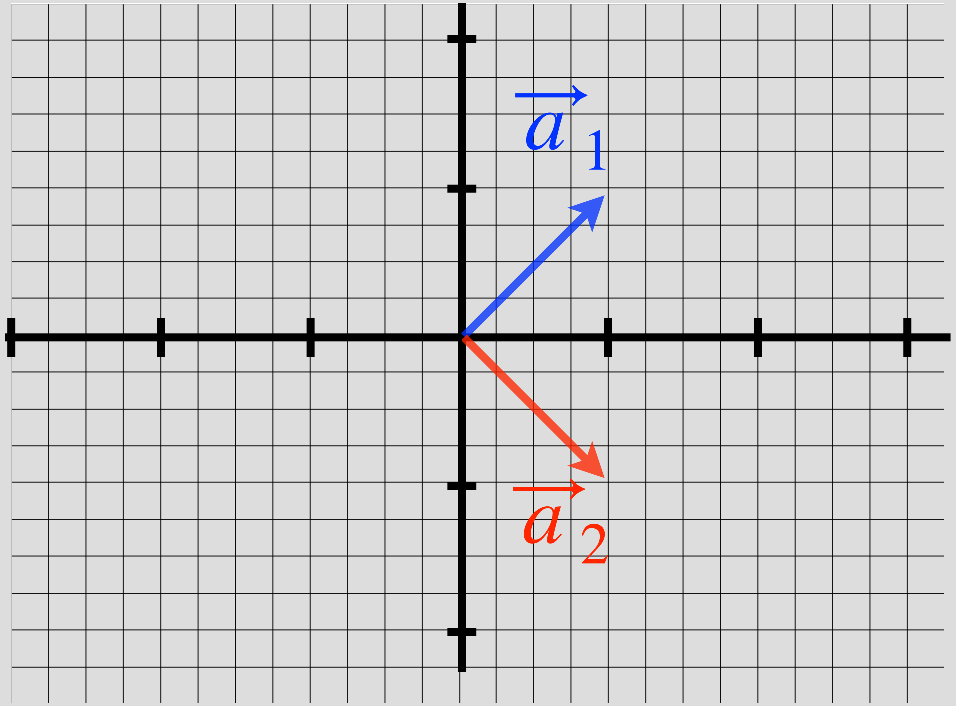
- Consider the problem: $A\overrightarrow{x} = \overrightarrow{b}$:

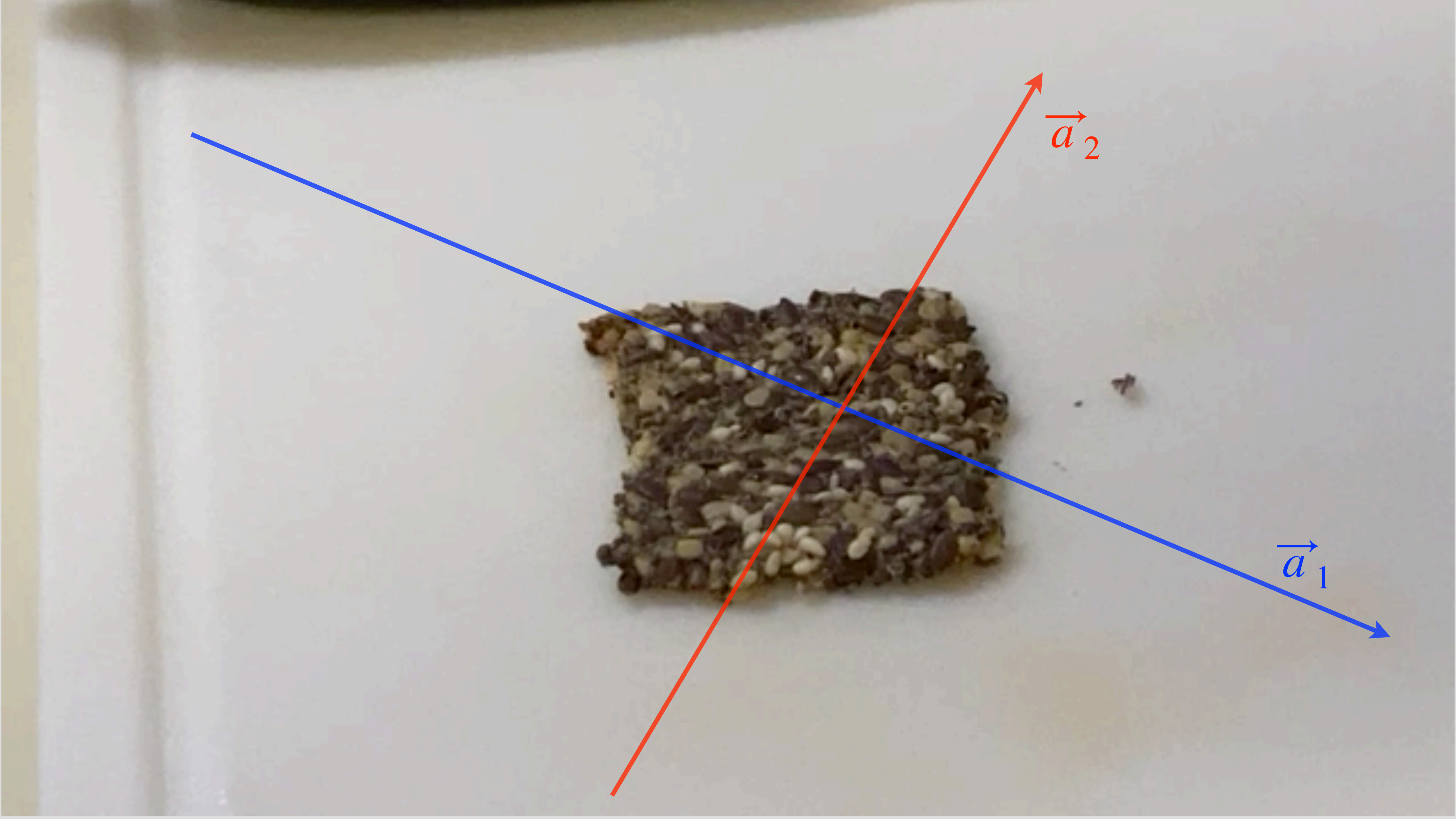
$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \vec{b}$$

$$\overrightarrow{a}_1 \qquad \overrightarrow{a}_2$$

Q: Can linear combination of $\overrightarrow{a}_1, \overrightarrow{a}_2$ give any $\overrightarrow{b}$?

A: Hmmm….I think so….




$\vec{a}_2$
$\vec{a}_1$

Linear Set of Equations as a Linear Combination

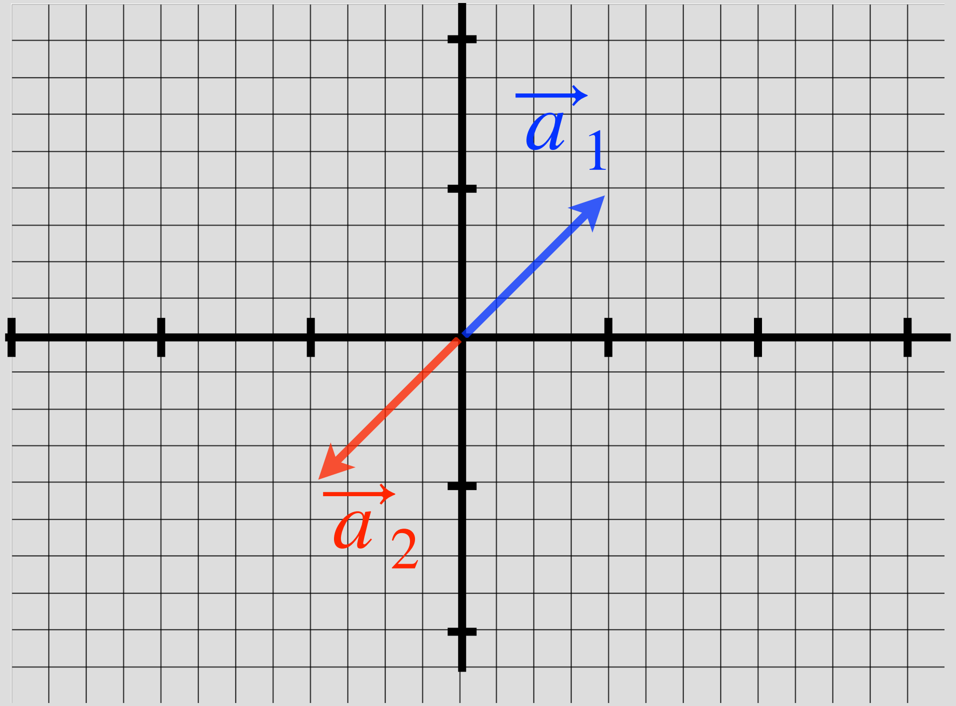
- Consider the problem: $A\overrightarrow{x} = \overrightarrow{b}$:

$$\begin{bmatrix} 1 & -1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \vec{b}$$

$$\overrightarrow{a}_1 \qquad \overrightarrow{a}_2$$

Q: Can linear combination of $\overrightarrow{a}_1, \overrightarrow{a}_2$ give any $\overrightarrow{b}$?

A: Hmmm….I don't think so…. Unless its along the line $\overrightarrow{a}_1$



Linear Set of Equations as a Linear Combination

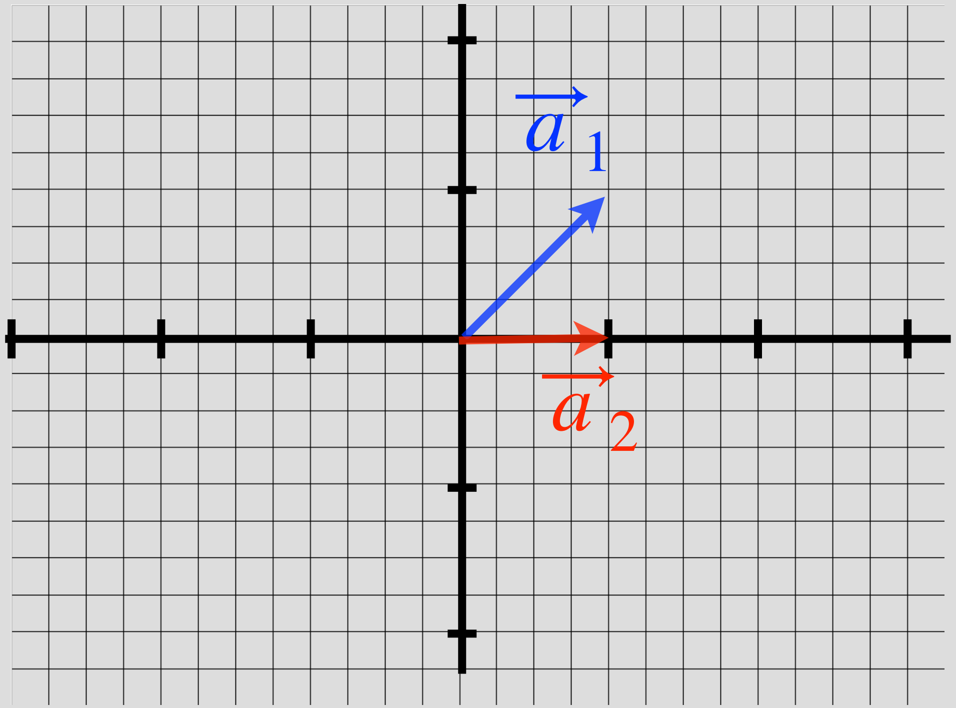
- Consider the problem: $A\overrightarrow{x} = \overrightarrow{b}$:

$$\begin{bmatrix} 1 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \vec{b}$$

$$\overrightarrow{a}_1 \quad \overrightarrow{a}_2$$

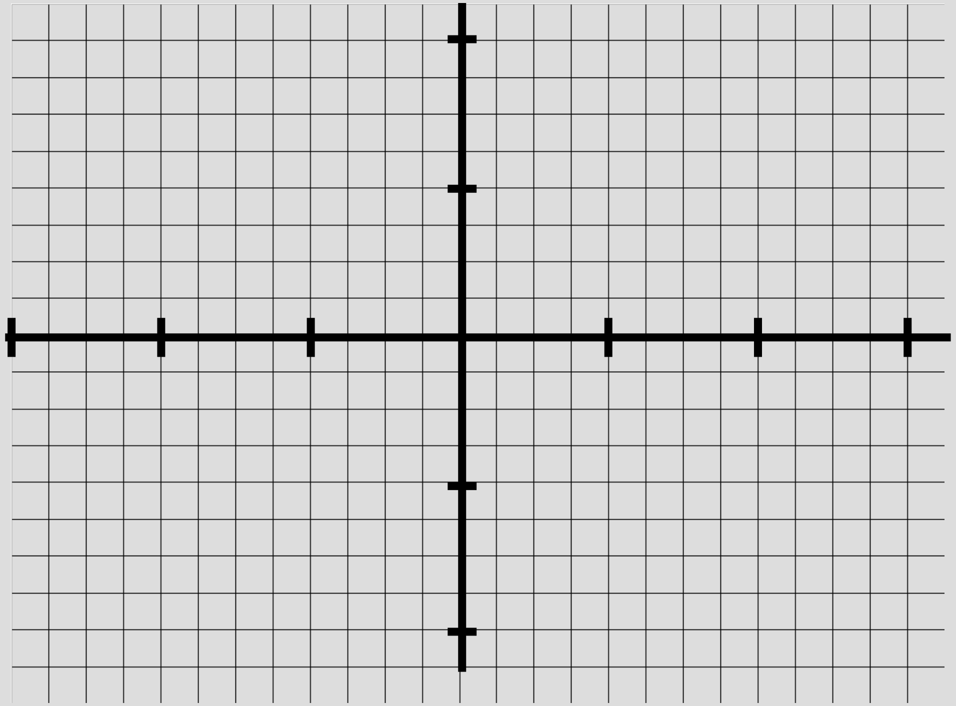
Q: Can linear combination of $\overrightarrow{a}_1, \overrightarrow{a}_2$ give any $\overrightarrow{b}$?

A: Hmmm….yes!



Span / Column Space / Range

- Span of the columns of A is the set of all vectors $\overrightarrow{b}$ such that $A\overrightarrow{x} = \overrightarrow{b}$ has a solution
  - i.e. the set of all vectors that can be reached by all possible linear combinations of the columns of A



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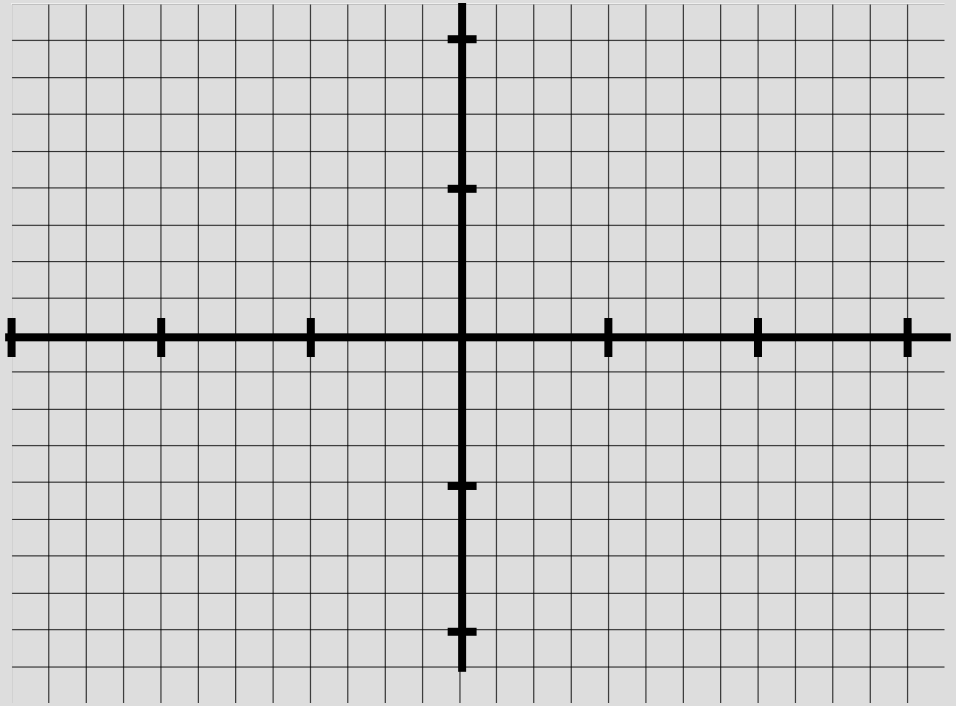
Example: What is the span of the cols of A?

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



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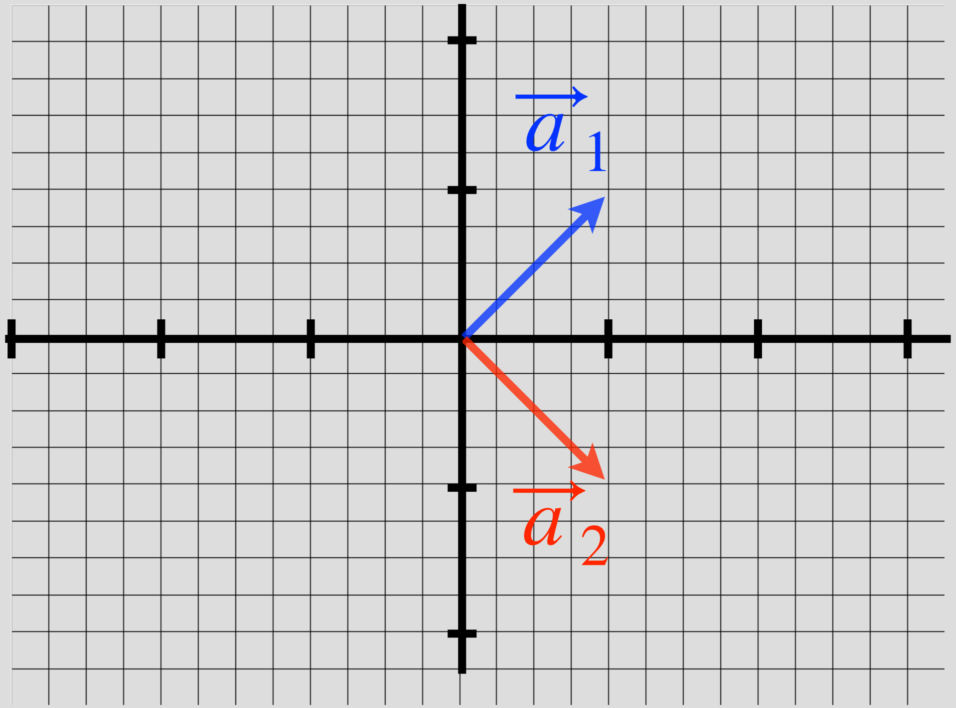
Example: What is the span of the cols of A?

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

A: $\mathbb{R}^2$!



Span / Column Space / Range

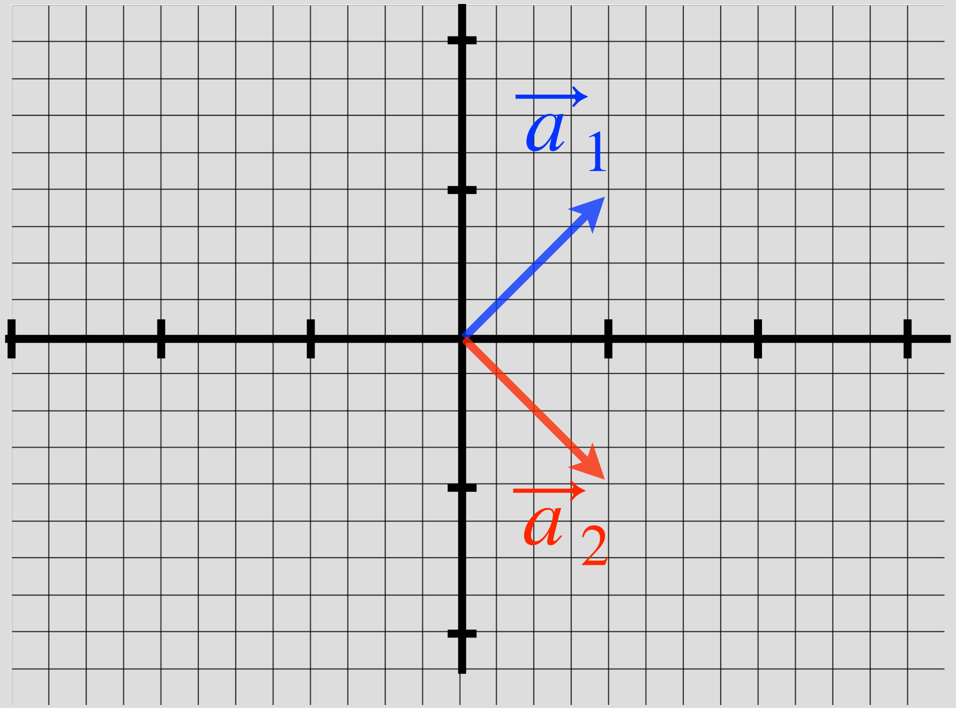
- Span of the columns of A is the set of all vectors $\vec{b}$ such that $A\vec{x} = \vec{b}$ has a solution
  - i.e. the set of all vectors that can be reached by all possible linear combinations of the columns of A

Example: What is the span of the cols of A?

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

A: $\mathbb{R}^2$!

$$\text{span}(\text{cols of } A) = \left\{ \vec{v} \,\middle|\, \vec{v} = \alpha \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \beta \begin{bmatrix} 1 \\ -1 \end{bmatrix} \quad \alpha, \beta \in \mathbb{R} \right\}$$



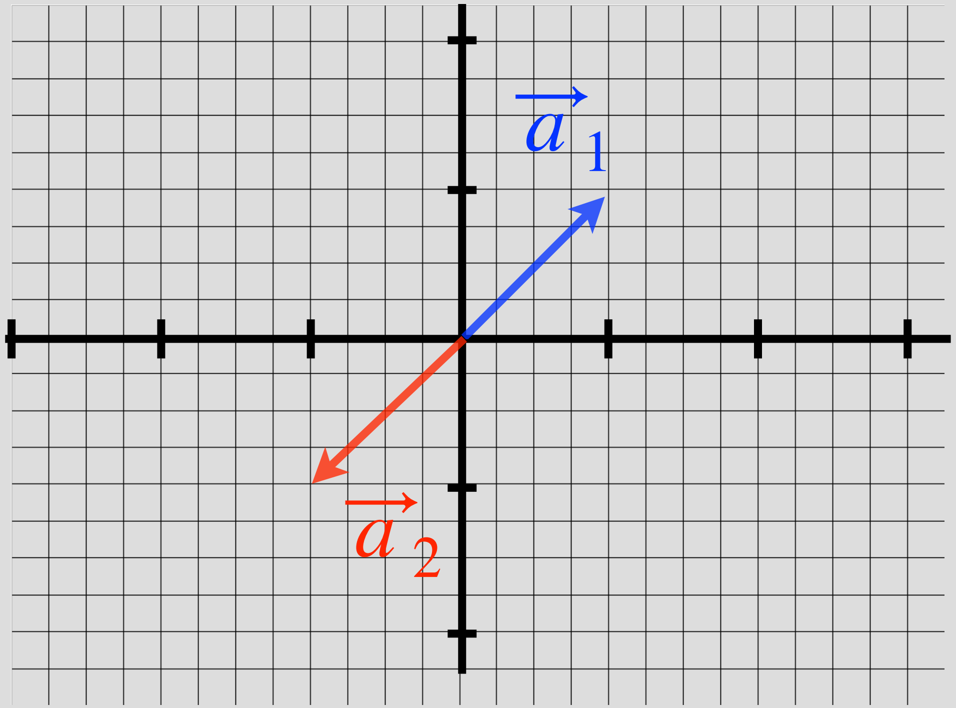
Span / Column Space / Range

Example 2: What is the span of the cols of A?

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

A: The line $x_1 = x_2$

$$\text{span}(\text{cols of } A) = \left\{ \vec{v} \,\middle|\, \vec{v} = \alpha \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad \alpha \in \mathbb{R} \right\}$$



Span / Column Space / Range

- Definition:

  If $\exists \overrightarrow{x}$ s.t. $A\overrightarrow{x} = \overrightarrow{b}$ then $\overrightarrow{b} \in \text{span}\{\text{cols}(A)\}$

Q: What if $\overrightarrow{b} \notin \text{span}\{\text{cols}(A)\}$?

A: There is no solution for $A\overrightarrow{x} = \overrightarrow{b}$

- What are the values of a, b, c such that the Span{Cols of A) = $\mathbb{R}^3$

$$A = \begin{bmatrix} 1 & 1 & a \\ -1 & 1 & b \\ 0 & 0 & c \end{bmatrix}$$

Responses

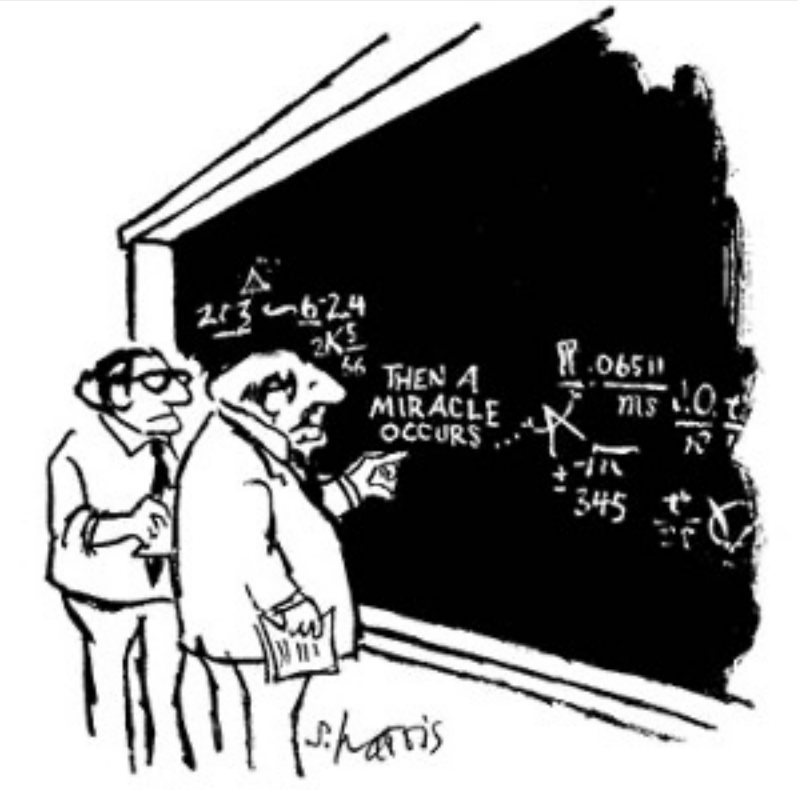
Steps for a proof

- Write out the statement, note direction (“if” → “then”)

- Try a simple example (to see a pattern)
  - Use what is known, definitions and other theorems

- Manipulate both sides of the arguments
  - Must justify each step

- Know the different styles of proofs to try
  - Constructive
  - Proof by contradiction



“I think you should be more explicit here in step two.”

Algorithm for solving linear equations

- Three basic operations that don't change a solution:
  1. Multiply an equation with *nonzero* scalar

$2x + 3y = 4$ has the same solution as: $4x + 6y = 8$

Proof for N=2:

Let $ax + by = c$, with solution x_0, y_0
$\Rightarrow ax_0 + by_0 = c$

Show that $\beta ax + \beta by = \beta c$,
has the same solution.

Substitute x_0, y_0 for x, y:

$$\beta ax_0 + \beta by_0 = \beta c$$

$$\beta(ax_0 + by_0) = \beta c$$

$$\beta c = \beta c$$

But is it the only solution?

$\beta ax + \beta by = \beta c$, with solution: x_1, y_1
$\Rightarrow \beta ax_1 + \beta by_1 = \beta c$

Show that $ax + by = c$,
has the same solution.....

Since $\beta \neq 0$....

$$\beta ax_1 + \beta by_1 = \beta c \Rightarrow ax_1 + by_1 = c$$

SOLUTION OF ONE, IMPLIES THE OTHER
AND VICE-VERSA!

Algorithm for solving linear equations

- Three basic operations that don't change a solution:
  1. Multiply an equation with *nonzero* scalar
  2. Adding a scalar constant multiple of one equation to another

$$\begin{array}{rrcrcr} (1) & x & + & y & = & 2 \\ (2) & 3x & + & 2y & = & 5 \end{array}$$

and

$$\begin{array}{rrcrcr} (1) & x & + & y & = & 2 \\ 3 \times (1) + (2) & 6x & + & 5y & = & 11 \end{array}$$

Have the same solution

Concept of proof: look at explicit solution, show they are the same

Also show the reverse — by applying the reverse operations

Span / Column Space / Range

- Span of the columns of A is the set of all vectors $\overrightarrow{b}$ such that $A\overrightarrow{x} = \overrightarrow{b}$ has a solution
  - i.e. the set of all vectors that can be reached by all possible linear combinations of the columns of A

- Definition:

  If $\exists \overrightarrow{x}$ s.t. $A\overrightarrow{x} = \overrightarrow{b}$ then $\overrightarrow{b} \in \mathrm{span}\{\mathrm{cols}(A)\}$

Proof: Span

Theorem: $\text{span}\left\{\begin{bmatrix}1\\1\end{bmatrix},\begin{bmatrix}1\\-1\end{bmatrix}\right\} = \mathbb{R}^2$

Know:

$$\text{span}\left\{\begin{bmatrix}1\\1\end{bmatrix},\begin{bmatrix}1\\-1\end{bmatrix}\right\} \Rightarrow \left\{\vec{v}\,\middle|\,\vec{v} = \alpha\begin{bmatrix}1\\1\end{bmatrix} + \beta\begin{bmatrix}1\\-1\end{bmatrix}\quad, \alpha, \beta \in \mathbb{R}\right\} = \mathbb{S}$$

Need to show:

$$\text{span}\left\{\begin{bmatrix}1\\1\end{bmatrix},\begin{bmatrix}1\\-1\end{bmatrix}\right\} = \mathbb{R}^2$$

Concept: pick some specific $\vec{b} = \begin{bmatrix}b_1\\b_2\end{bmatrix} \in R^2$, and show that it belongs to $\mathbb{S}$

Need to solve:

Proof: Span

Theorem: $\text{span}\left\{\begin{bmatrix}1\\1\end{bmatrix},\begin{bmatrix}1\\-1\end{bmatrix}\right\}=\mathbb{R}^2$

Know:

$$\text{span}\left\{\begin{bmatrix}1\\1\end{bmatrix},\begin{bmatrix}1\\-1\end{bmatrix}\right\}\Rightarrow\left\{\vec{v}\,\middle|\,\vec{v}=\alpha\begin{bmatrix}1\\1\end{bmatrix}+\beta\begin{bmatrix}1\\-1\end{bmatrix}\quad,\alpha,\beta\in\mathbb{R}\right\}=\mathbb{S}$$

Need to show:

$$\text{span}\left\{\begin{bmatrix}1\\1\end{bmatrix},\begin{bmatrix}1\\-1\end{bmatrix}\right\}=\mathbb{R}^2$$

Concept: pick some specific $\vec{b}=\begin{bmatrix}b_1\\b_2\end{bmatrix}\in R^2$, and show that it belongs to $\mathbb{S}$

Need to solve:

$$\underbrace{\alpha}_{\text{unknown}}\begin{bmatrix}1\\1\end{bmatrix}+\underbrace{\beta}_{\text{unknown}}\begin{bmatrix}1\\-1\end{bmatrix}=\underbrace{\begin{bmatrix}b_1\\b_2\end{bmatrix}}_{\text{Known and }\in\mathbb{R}^2}\qquad\Rightarrow\begin{bmatrix}1&1\\1&-1\end{bmatrix}\begin{bmatrix}\alpha\\\beta\end{bmatrix}=\begin{bmatrix}b_1\\b_2\end{bmatrix}$$

Proof: Span

Need to solve:

$$\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

Gaussian Elimination:

Proof: Span

$$\frac{b_1+b_2}{2}\begin{bmatrix}1\\1\end{bmatrix}+\frac{b_1-b_2}{2}\begin{bmatrix}1\\-1\end{bmatrix}=\begin{bmatrix}b_1\\b_2\end{bmatrix}$$

Need to solve:

$$\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}\begin{bmatrix}\alpha\\\beta\end{bmatrix}=\begin{bmatrix}b_1\\b_2\end{bmatrix}$$

Constructive proof

Gaussian Elimination:

$$\left[\begin{array}{cc|c}1 & 1 & b_1\\1 & -1 & b_2\end{array}\right] \quad \left[\begin{array}{cc|c}1 & 1 & b_1\\0 & -2 & b_2-b_1\end{array}\right] \quad \left[\begin{array}{cc|c}1 & 1 & b_1\\0 & 1 & \frac{b_1-b_2}{2}\end{array}\right]$$

$$\left[\begin{array}{cc|c}1 & 0 & \frac{b_1+b_2}{2}\\0 & 1 & \frac{b_1-b_2}{2}\end{array}\right] \Rightarrow \alpha=\frac{b_1+b_2}{2}, \beta=\frac{b_1-b_2}{2},$$

Every $\overrightarrow{b} \in \mathbb{R}^2$ can be written as linear combinations!

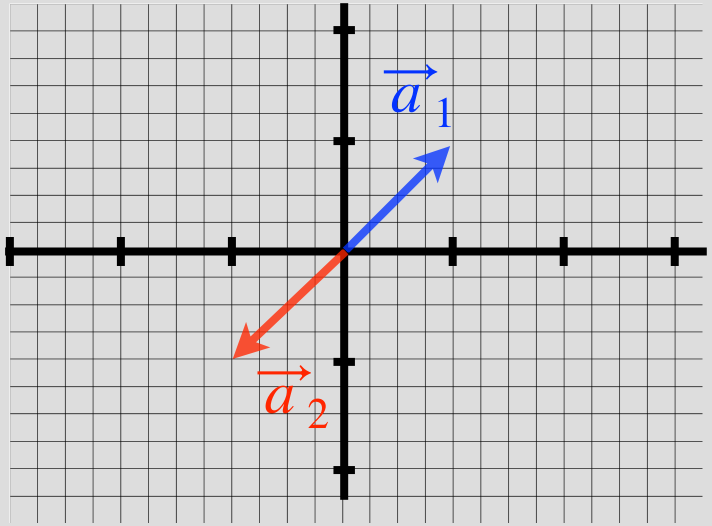
So also, $\overrightarrow{b} \in \mathbb{S}$

Linear Dependence

Recall:

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

$$\vec{a}_1 \quad \vec{a}_2$$



$\vec{a}_1$ and $\vec{a}_2$ are linearly dependent

$$\vec{a}_1 = -\vec{a}_2$$

Linear Dependence

- Definition 1:
  A set of vectors $\{\vec{a}_1, \vec{a}_2, \cdots, \vec{a}_N\}$ are linearly dependent if $\exists \{\alpha_1, \alpha_2, \cdots, \alpha_N\} \in \mathbb{R}$, such that:

$$\vec{a}_i = \sum_{j \neq i} \alpha_j \vec{a}_j \qquad 1 \leq i, j \leq N$$

$\downarrow$

$\vec{a}_i$ in the span of all $\vec{a}_j$s

For example: if $\vec{a}_2 = 3\vec{a}_1 - 2\vec{a}_5 + 6\vec{a}_7$

Linear Dependence

Are these linearly dependent?

$$\left\{ \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \end{bmatrix} \right\}$$

Need to solve:

Linear Dependence

Are these linearly dependent?

$$\left\{ \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \end{bmatrix} \right\}$$

Are linearly dependent

Need to solve:

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

but we showed that….

$$\frac{b_1+b_2}{2} \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \frac{b_1-b_2}{2} \begin{bmatrix} 1 \\ -1 \end{bmatrix} = \begin{bmatrix} b_1 \\ b_2 \end{bmatrix}$$

So….

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

Linear dependence / independence

$$\left\{ \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \end{bmatrix} \right\} \quad \Rightarrow 2 \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \begin{bmatrix} 1 \\ -1 \end{bmatrix} - \begin{bmatrix} 3 \\ 1 \end{bmatrix} = 0$$

- Definition 2:
  A set of vectors $\left\{ \overrightarrow{a}_1, \overrightarrow{a}_2, \cdots, \overrightarrow{a}_N \right\}$ are linearly dependent if $\exists \left\{ \alpha_1, \alpha_2, \cdots, \alpha_N \right\} \in \mathbb{R}$, such that:
  $$\sum_{i=1}^{N} \alpha_i \overrightarrow{a}_i = 0$$
  As long as not all $a_i = 0$

- Definition:
  A set of vectors $\left\{ \overrightarrow{a}_1, \overrightarrow{a}_2, \cdots, \overrightarrow{a}_N \right\}$ are linearly independent if they are not dependent

Linear dependence / independence

Are these linearly dependent?

$$\Bigg\{ \underbrace{\begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix}}_{span = \mathbb{R}^2}, \begin{bmatrix} \pi \\ \sqrt{2} \end{bmatrix} \Bigg\}$$

linearly dependent!

$\in \mathbb{R}^2$

Solutions for linear equations

- Theorem: if the columns of the matrix A are linearly dependent then, $A\overrightarrow{x} = \overrightarrow{b}$ does <u>not</u> have a unique solution

PROOF Consider the counter-example $\mathbb{S} \triangleq \{\circ, \bullet\}$, $\tau \triangleq \{\langle \bullet, \bullet \rangle, \langle \bullet, \circ \rangle, \langle \circ, \circ \rangle\}$ so that $\mathcal{M}_\tau = \{\langle i, \lambda \ell \cdot \bullet \rangle, \langle j, \lambda \ell \cdot \circ \rangle, \langle k, \lambda \ell \cdot (\ell < m \mathrel{?} \bullet \mathrel{¿} \circ) \rangle\}$. We let $\mathcal{X} \triangleq \{\langle i, \sigma \rangle \mid \forall j < i : \sigma_j = \bullet\}$ so that $\neg FD(\mathcal{X})$. We have $\mathcal{M}_{\tau\downarrow\bullet} = \{\langle i, \lambda \ell \cdot \bullet \rangle, \langle k, \lambda \ell \cdot (\ell < m \mathrel{?} \bullet \mathrel{¿} \circ) \rangle \mid k < m\}$, $\mathcal{M}_{\tau\downarrow\circ} = \{\langle j, \lambda \ell \cdot \circ \rangle, \langle k, \lambda \ell \cdot (\ell < m \mathrel{?} \bullet \mathrel{¿} \circ) \rangle \mid k \geq m\}$ and $\oplus\{\!\{\mathcal{X}\}\!\} = \{\langle i, \sigma \rangle \mid \forall j \leq i : \sigma_j = \bullet\}$. We have $\alpha^{\vee}_{\mathcal{M}_\tau}(\oplus\{\!\{\mathcal{X}\}\!\}) = \{s \mid \mathcal{M}_{\tau\downarrow s} \subseteq \oplus\{\!\{\mathcal{X}\}\!\}\} = \{\bullet\}$ whereas $\widetilde{pre}[\tau](\alpha^{\vee}_{\mathcal{M}_\tau}(\mathcal{X})) = \widetilde{pre}[\tau](\{s \mid \mathcal{M}_{\tau\downarrow s} \subseteq \mathcal{X}\}) = \widetilde{pre}[\tau](\{\bullet\}) = \{s \mid \forall s' : t(s, s') \Rightarrow s' = \bullet\} = \emptyset$ since $t(s, \bullet)$ implies $s = \bullet$ and $t(\bullet, \circ)$ holds. ■

Solutions for linear equations

- Theorem: if the columns of the matrix A are linearly dependent then, $A\vec{x} = \vec{b}$ does <u>not</u> have a unique solution

Proof for $A \in \mathbb{R}^{3\times3}$

know: columns are linearly ~~in~~dependent

show: more than 1 solution

Concept: pick some specific solution $\vec{x}^*$, and show that there's another one

Let: $A\vec{x}^* = \vec{b}$ and $A = [\vec{a}_1 \quad \vec{a}_2 \quad \vec{a}_3]$

From linear dependence Def 2:

$$\alpha_1\vec{a}_1 + \alpha_2\vec{a}_2 + \alpha_3\vec{a}_3 = 0$$

Solutions for linear equations

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From linear dependence Def 2:

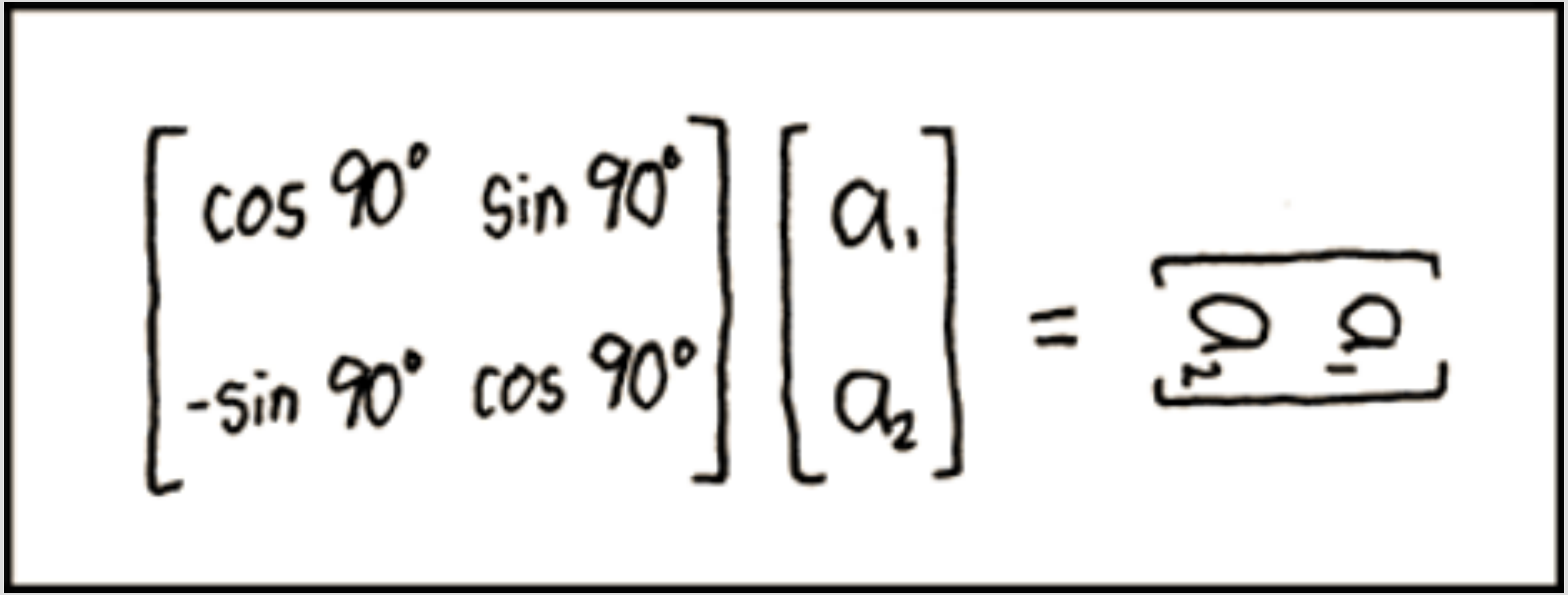
$$\alpha_1\overrightarrow{a}_1 + \alpha_2\overrightarrow{a}_2 + \alpha_3\overrightarrow{a}_3 = 0 \longrightarrow \begin{bmatrix}\vec{a}_1 & \vec{a}_2 & \vec{a}_3\end{bmatrix}\underbrace{\begin{bmatrix}\alpha_1\\ \alpha_2\\ \alpha_3\end{bmatrix}}_{\overrightarrow{\alpha}} = 0 \qquad \Rightarrow A\overrightarrow{\alpha} = 0$$

Set $\overrightarrow{x}^\dagger = \overrightarrow{x}^* + \overrightarrow{\alpha}$

$$\Rightarrow A\overrightarrow{x}^\dagger = A(\overrightarrow{x}^* + \overrightarrow{\alpha}) = A\overrightarrow{x}^* + A\overrightarrow{\alpha} = \overrightarrow{b} + 0$$

So $\overrightarrow{x}^\dagger$ is another solution!

Matrix Transformations

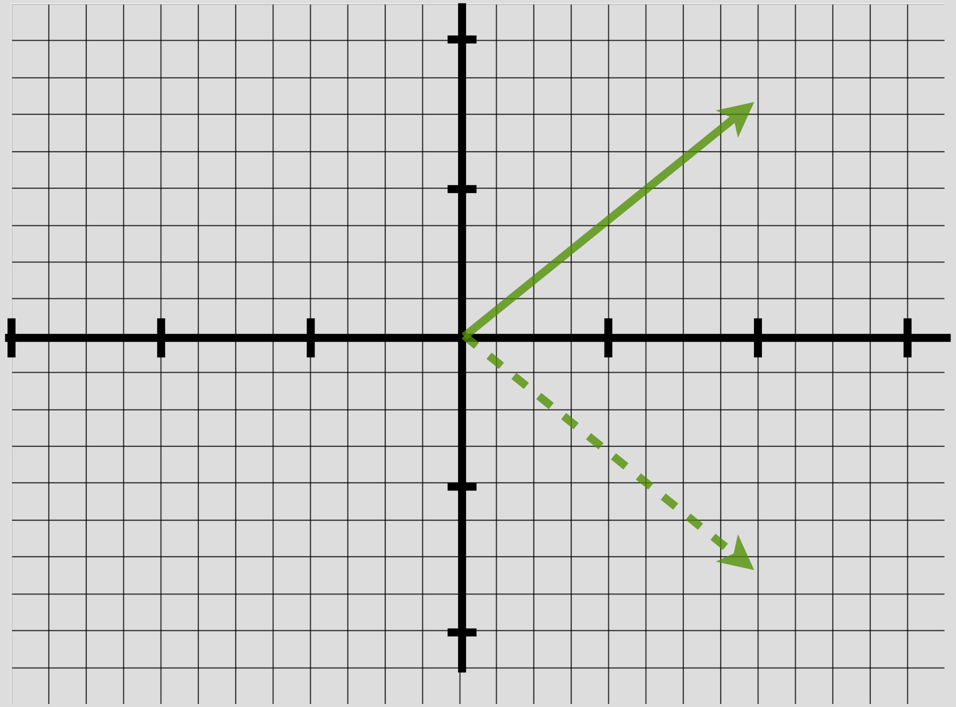


Matrices are operators that transform vectors

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

Example:

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



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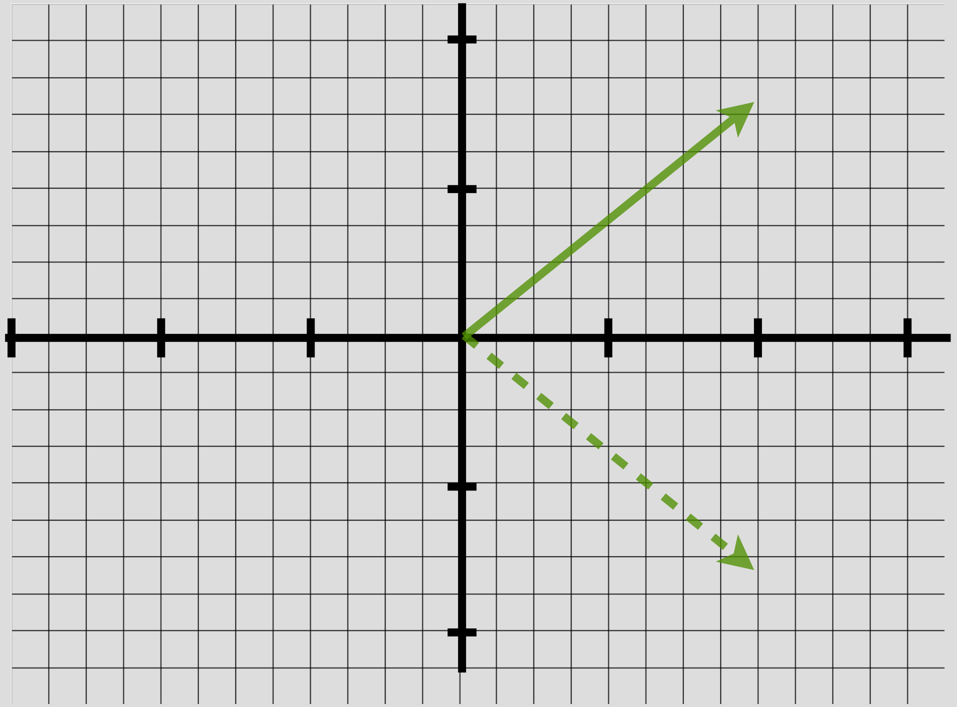

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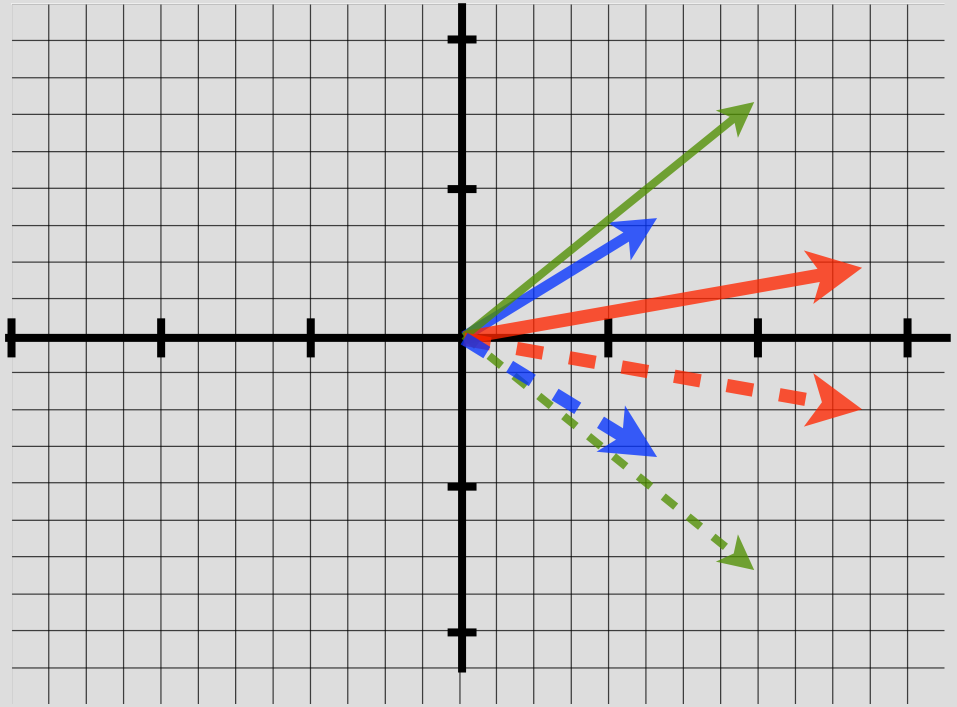
Reflection Matrix!



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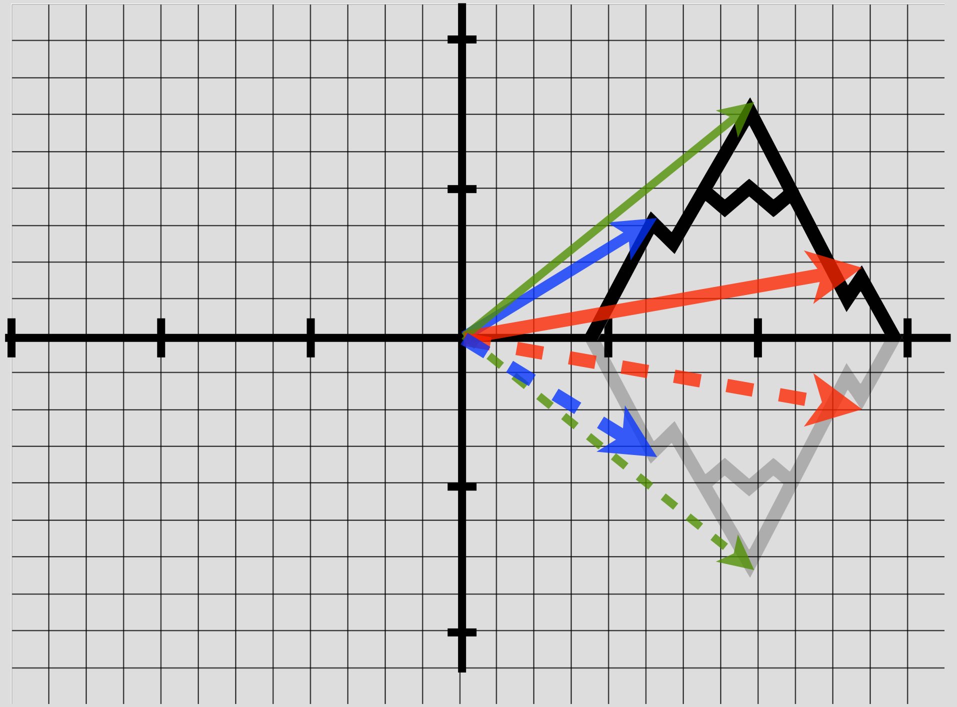
Reflection Matrix!



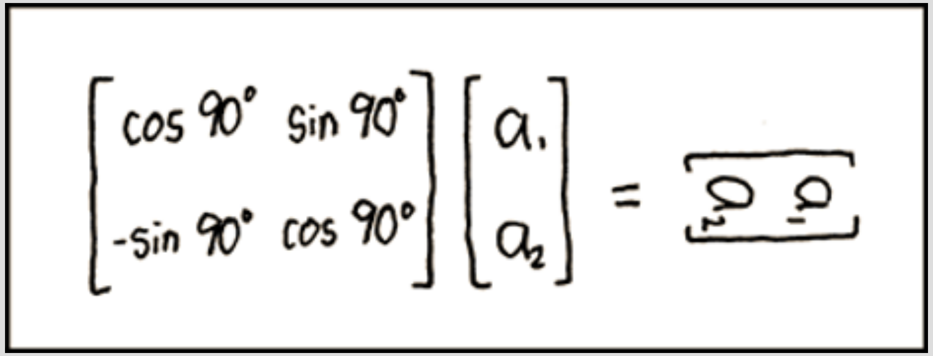
Matrices are operators that transform vectors

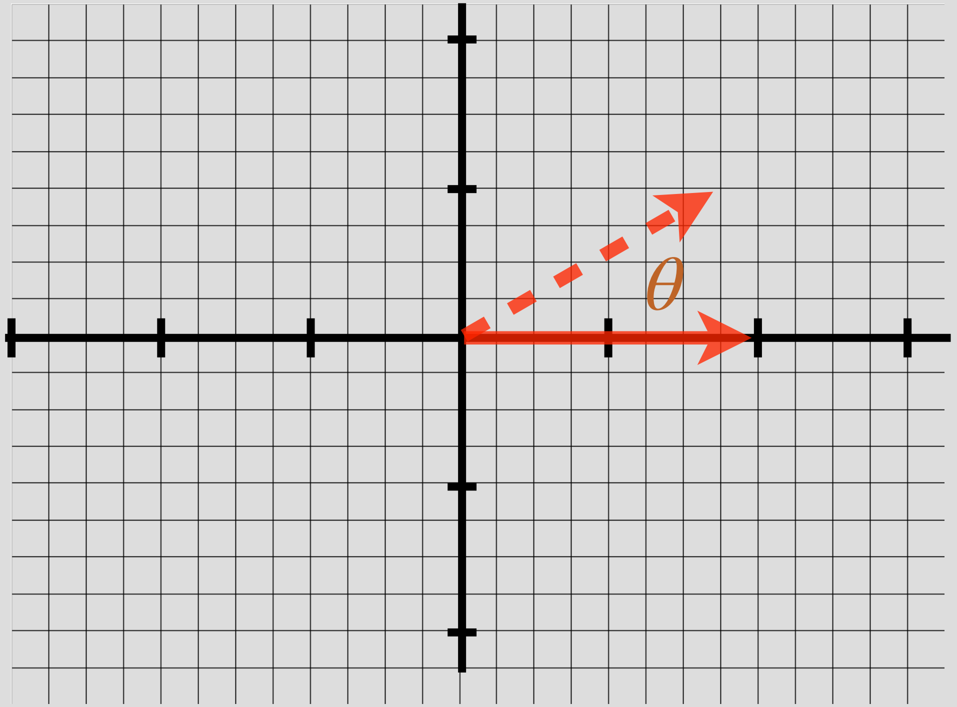
Example 2:

$$\begin{bmatrix}\cos(\theta) & -\sin(\theta)\\ \sin(\theta) & \cos(\theta)\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} = \begin{bmatrix}\cos(\theta)x_1 - \sin(\theta)x2\\ \sin(\theta)x_1 + \cos(\theta)x_2\end{bmatrix}$$

$$\begin{bmatrix}\cos(\theta) & -\sin(\theta)\\ \sin(\theta) & \cos(\theta)\end{bmatrix}\begin{bmatrix}1\\ 0\end{bmatrix} = \begin{bmatrix}\cos(\theta)\\ \sin(\theta)\end{bmatrix}$$

Rotation Matrix!





Linear Transformation of vectors

f: is a linear transformation if:

$$f(\alpha \overrightarrow{x}) = \alpha f(\overrightarrow{x}) \qquad \alpha \in \mathbb{R}$$

$$f(\overrightarrow{x} + \overrightarrow{y}) = f(\overrightarrow{x}) + f(\overrightarrow{y})$$

Claim: Matrix-vector multiplications satisfy linear transformation

$$A \cdot (\alpha \overrightarrow{x}) = \alpha A \overrightarrow{x}$$

Proof via explicitly writing the elements

$$A \cdot (\overrightarrow{x} + \overrightarrow{y}) = A \overrightarrow{x} + A \overrightarrow{y}$$