Linear Algebra

Math 314 Fall 2025

Lecture 4

Today's poll code:

4LHPXC

Office hours

Mondays 5–6 pm
Wednesdays 2–3 pm
in Avery 339 (Dr. Grifo)

Tuesdays 11–noon
Thursdays 1–2 pm
in Avery 337 (Kara)

To do list:

- WeBWorK 1.3 and 2.1 due tomorrow
- WebWork 2.2 due Friday
- Webwork 2.3 due Tuesday September 16

Quiz 3 on Friday
on lectures 4—5

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Quick Recap

Let $v_1, \ldots, v_p$ be vectors in $\mathbb{R}^n$.

span of $v_1, \ldots, v_p$ = set of all linear combinations of $v_1, \ldots, v_p$

$$\operatorname{span}\{v_1, \ldots, v_p\} = \{c_1 v_1 + \cdots + c_p v_p \mid c_i \in \mathbb{R}\}$$

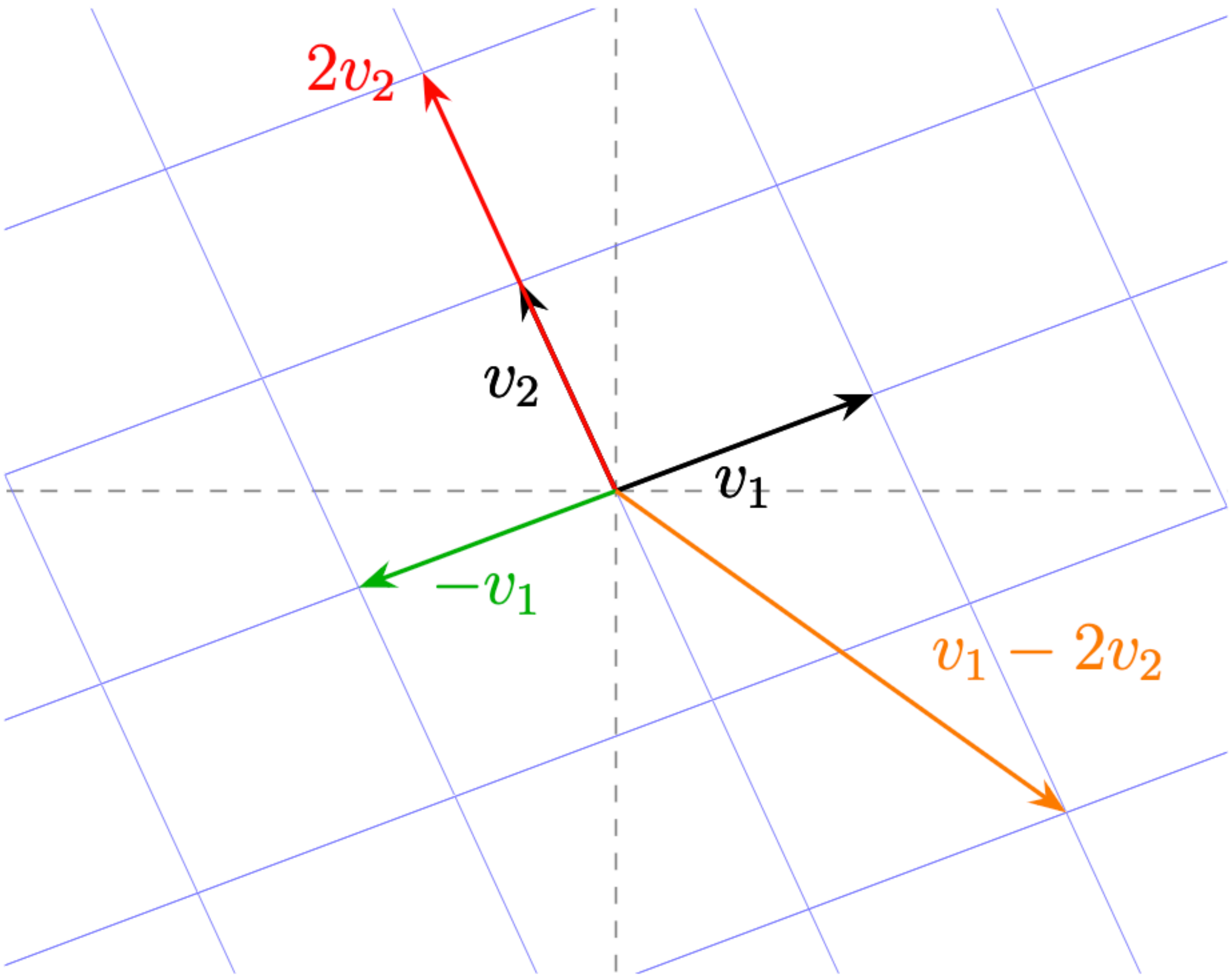
if $v_1 \neq 0$

$$\begin{aligned} \operatorname{span}(\{v_1\}) &= \text{line determined by } v_1 \\ &= \text{all multiples of } v_1 \end{aligned}$$

Let $v_1, \ldots, v_p$ be vectors in $\mathbb{R}^n$.

span of $v_1, \ldots, v_p$ = set of all linear combinations of $v_1, \ldots, v_p$

$$\text{span}\{v_1, \ldots, v_p\} = \{c_1 v_1 + \cdots + c_p v_p \mid c_i \in \mathbb{R}\}$$



$\text{span}(\{v_1, v_2\})$ = plane determined by v_1 and v_2

if $v_1 \neq 0$ and $v_2 \neq 0$ and v_1 and v_2 not multiples of each other

Let $v_1, \ldots, v_p$ be vectors in $\mathbb{R}^n$.

span of $v_1, \ldots, v_p$ = set of all linear combinations of $v_1, \ldots, v_p$

$$\operatorname{span}\{v_1, \ldots, v_p\} = \{c_1 v_1 + \cdots + c_p v_p \mid c_i \in \mathbb{R}\}$$

$$\operatorname{span}\left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 3 \end{bmatrix} \right\} =$$

Let $v_1, \ldots, v_p$ be vectors in $\mathbb{R}^n$.

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$$\text{span}\{v_1, \ldots, v_p\} = \{c_1 v_1 + \cdots + c_p v_p \mid c_i \in \mathbb{R}\}$$

$$\text{span}\left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 3 \end{bmatrix} \right\} = \mathbb{R}^2$$

Question:

$$\text{Is } \begin{bmatrix} 7 \\ 4 \\ -3 \end{bmatrix} \text{ a linear combination of } \begin{bmatrix} 1 \\ -2 \\ -5 \end{bmatrix} \text{ and } \begin{bmatrix} 2 \\ 5 \\ 6 \end{bmatrix}?$$

Equivalently:

$$\text{Does the system } x_1 \begin{bmatrix} 1 \\ -2 \\ -5 \end{bmatrix} + x_2 \begin{bmatrix} 2 \\ 5 \\ 6 \end{bmatrix} = \begin{bmatrix} 7 \\ 4 \\ -3 \end{bmatrix} \text{ have a solution?}$$

$$\begin{bmatrix} 1 & 2 & 7 \\ -2 & 5 & 4 \\ -5 & 6 & -3 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & 3 \\ 0 & 1 & 2 \\ 0 & 0 & 0 \end{bmatrix}$$

No pivots in the last column

system is consistent

Answer: yes.

Question:

$$\text{Is } \begin{bmatrix} 7 \\ 4 \\ -3 \end{bmatrix} \text{ in span} \left\{ \begin{bmatrix} 1 \\ -2 \\ -5 \end{bmatrix}, \begin{bmatrix} 2 \\ 5 \\ 6 \end{bmatrix} \right\}?$$

Equivalently:

Does the system $x_1 \begin{bmatrix} 1 \\ -2 \\ -5 \end{bmatrix} + x_2 \begin{bmatrix} 2 \\ 5 \\ 6 \end{bmatrix} = \begin{bmatrix} 7 \\ 4 \\ -3 \end{bmatrix}$ have a solution?

$$\begin{bmatrix} 1 & 2 & 7 \\ -2 & 5 & 4 \\ -5 & 6 & -3 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & 3 \\ 0 & 1 & 2 \\ 0 & 0 & 0 \end{bmatrix}$$

No pivots in the last column

system is consistent

Answer: yes.

Question:

$$\text{Is } \begin{bmatrix} 7 \\ 4 \\ -3 \end{bmatrix} \text{ in span} \left\{ \begin{bmatrix} 1 \\ -2 \\ -5 \end{bmatrix}, \begin{bmatrix} 2 \\ 5 \\ 6 \end{bmatrix} \right\}?$$

$$\begin{bmatrix} 1 & 2 & 7 \\ -2 & 5 & 4 \\ -5 & 6 & -3 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & 3 \\ 0 & 1 & 2 \\ 0 & 0 & 0 \end{bmatrix}$$

No pivots in the last column

system is consistent

Answer: yes.

Solution set:

$\{(3, 2)\}$

$$3 \begin{bmatrix} 1 \\ -2 \\ -5 \end{bmatrix} + 2 \begin{bmatrix} 2 \\ 5 \\ 6 \end{bmatrix} = \begin{bmatrix} 7 \\ 4 \\ -3 \end{bmatrix}.$$

Today's poll code:

4LHPXC

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$$\text{Fact: } \begin{bmatrix} 3 & -1 & 1 & 3 \\ 0 & 1 & 2 & 6 \\ 1 & 2 & 2 & 9 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 1 & 2 \end{bmatrix}$$

$$\text{Is } \begin{bmatrix} 3 \\ 6 \\ 9 \end{bmatrix} \text{ in span} \left\{ \begin{bmatrix} 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \\ 2 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 2 \end{bmatrix} \right\}?$$

A. Yes

B. No

Today's poll code:

4LHPXC

$$\text{What is }\operatorname{span}\left\{\begin{bmatrix}1\\0\end{bmatrix},\begin{bmatrix}0\\1\end{bmatrix}\right\}?$$

A. $\left\{\begin{bmatrix}a\\a\end{bmatrix} : a \text{ is any value}\right\}$

B. $\left\{\begin{bmatrix}1\\0\end{bmatrix},\begin{bmatrix}0\\1\end{bmatrix}\right\}$

C. $\mathbb{R}^2$

Matrix Equations

$$Ax = \overbrace{\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}}^{x}$$

$$Ax = \overbrace{\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}}^{x} = x_1 \begin{bmatrix} a_{11} \\ a_{21} \\ \vdots \\ a_{m1} \end{bmatrix} + x_2 \begin{bmatrix} a_{12} \\ a_{22} \\ \vdots \\ a_{m2} \end{bmatrix} + \cdots + x_n \begin{bmatrix} a_{1n} \\ a_{2n} \\ \vdots \\ a_{mn} \end{bmatrix}$$

$$= \begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \end{bmatrix}.$$

$$
\begin{aligned}
Ax = \overbrace{\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}}^{A} \overbrace{\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}}^{x} &= x_1 \begin{bmatrix} a_{11} \\ a_{21} \\ \vdots \\ a_{m1} \end{bmatrix} + x_2 \begin{bmatrix} a_{12} \\ a_{22} \\ \vdots \\ a_{m2} \end{bmatrix} + \cdots + x_n \begin{bmatrix} a_{1n} \\ a_{2n} \\ \vdots \\ a_{mn} \end{bmatrix} \\
&= \begin{bmatrix} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n \end{bmatrix}. \\
&= x_1 a_1 + \cdots + x_n a_n
\end{aligned}
$$

Theorem. Let c be a scalar, let $u, v \in \mathbb{R}^n$, and let A be an $m \times n$ matrix. Then

$$A(u+v) = Au + Av \qquad \text{and} \qquad A(cu) = c(Au).$$

$$\begin{cases} a_{11}x_1 + \cdots + a_{1n}x_n = b_1 \\ \vdots \\ a_{m1}x_1 + \cdots + a_{mn}x_n = b_m \end{cases}$$

coefficient matrix

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix}$$

constant vector

$$\mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix} \qquad x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}$$

matrix equation $\quad Ax = b$

$$\begin{cases} \quad x_1 + 3x_2 = 4 \\ -x_1 + x_2 = 1 \end{cases}$$

$$\Big\downarrow$$

matrix equation

$$\begin{bmatrix} 1 & 3 \\ -1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 4 \\ 1 \end{bmatrix}$$

The system $Ax = b$ has a solution

if and only if

b is a linear combination of the columns of A.

Theorem. Fix an $m \times n$ matrix A. The following are equivalent:

1. The system $Ax = b$ has a solution for *every* vector $b \in \mathbb{R}^m$.
2. Every vector $b \in \mathbb{R}^m$ is a linear combination of the columns of A.
3. The columns of A span $\mathbb{R}^m$.
4. The coefficient matrix A has a pivot in every row.

The last statement is about A, the coefficient matrix of the system, **not** the augmented matrix.

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ pivot in every row

$$\Downarrow$$

$Ax = b$ has solutions for every $b \in \mathbb{R}^2$

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{pivot in every row}$$

$$\Downarrow$$

$Ax = b$ has solutions for every $b \in \mathbb{R}^2$

$$\text{span}\left\{ \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix} \right\} = \mathbb{R}^2$$

Homogeneous systems

A linear system is **homogeneous** if we can write it as

$$Ax = 0.$$

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A homogeneous system always has a solution:

the **trivial solution** $x = 0$.

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the **trivial solution** $x = 0$.

A solution $x \neq 0$ is called **nontrivial**.

$$\begin{cases} 3x_1 + 5x_2 - 4x_3 = 0 \\ -3x_1 - 2x_2 + 4x_3 = 0 \\ 6x_1 + x_2 - 8x_3 = 0 \end{cases}$$

homogeneous system

$$\begin{cases} 3x_1 + 5x_2 - 4x_3 = 0 \\ -3x_1 - 2x_2 + 4x_3 = 0 \\ 6x_1 + x_2 - 8x_3 = 0 \end{cases}$$

homogeneous system

$$\underbrace{\begin{bmatrix} 3 & 5 & -4 \\ -3 & -2 & 4 \\ 6 & 1 & -8 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}}_{x} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}}_{b}$$

matrix equation

$$\begin{cases} 3x_1 + 5x_2 - 4x_3 = 0 \\ -3x_1 - 2x_2 + 4x_3 = 0 \\ 6x_1 + x_2 - 8x_3 = 0 \end{cases}$$

homogeneous system

$$\left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ -3 & -2 & 4 & 0 \\ 6 & 1 & -8 & 0 \end{array}\right] \xrightarrow{R_2 \to R_2 + R_1} \left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ 0 & 3 & 0 & 0 \\ 6 & 1 & -8 & 0 \end{array}\right] \xrightarrow{R_3 \to R_3 - 2R_1} \left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & -9 & 0 & 0 \end{array}\right]$$

$$\xrightarrow{R_2 \to \frac{1}{3} R_2} \left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -9 & 0 & 0 \end{array}\right] \xrightarrow{R_1 \to R_1 - 5R_2} \left[\begin{array}{ccc|c} 3 & 0 & -4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -9 & 0 & 0 \end{array}\right] \xrightarrow{R_3 \to R_3 + 9R_2} \left[\begin{array}{ccc|c} 3 & 0 & -4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array}\right]$$

$$\xrightarrow{R1 \to \frac{1}{3} R1} \left[\begin{array}{ccc|c} 1 & 0 & -\frac{4}{3} & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array}\right].$$

Note that the last column doesn't really add any information!

When the system is homogeneous, can row reduce A instead.

$$\begin{cases} 3x_1 + 5x_2 - 4x_3 = 0 \\ -3x_1 - 2x_2 + 4x_3 = 0 \\ 6x_1 + x_2 - 8x_3 = 0 \end{cases}$$

homogeneous system

$$\begin{bmatrix} 3 & 5 & -4 \\ -3 & -2 & 4 \\ 6 & 1 & -8 \end{bmatrix} \xrightarrow{R_2 \to R_2 + R_1} \begin{bmatrix} 3 & 5 & -4 \\ 0 & 3 & 0 \\ 6 & 1 & -8 \end{bmatrix} \xrightarrow{R_3 \to R_3 - 2R_1} \begin{bmatrix} 3 & 5 & -4 \\ 0 & 3 & 0 \\ 0 & -9 & 0 \end{bmatrix}$$

$$\xrightarrow{R_2 \to \frac{1}{3} R_2} \begin{bmatrix} 3 & 5 & -4 \\ 0 & 1 & 0 \\ 0 & -9 & 0 \end{bmatrix} \xrightarrow{R_1 \to R_1 - 5R_2} \begin{bmatrix} 3 & 0 & -4 \\ 0 & 1 & 0 \\ 0 & -9 & 0 \end{bmatrix} \xrightarrow{R_3 \to R_3 + 9R_2} \begin{bmatrix} 3 & 0 & -4 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\xrightarrow{R1 \to \frac{1}{3} R1} \begin{bmatrix} 1 & 0 & -\frac{4}{3} \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

$$\begin{cases} 3x_1 + 5x_2 - 4x_3 = 0 \\ -3x_1 - 2x_2 + 4x_3 = 0 \\ 6x_1 + x_2 - 8x_3 = 0 \end{cases}$$

homogeneous system

$$\left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ -3 & -2 & 4 & 0 \\ 6 & 1 & -8 & 0 \end{array}\right] \xrightarrow{R_2 \to R_2 + R_1} \left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ 0 & 3 & 0 & 0 \\ 6 & 1 & -8 & 0 \end{array}\right] \xrightarrow{R_3 \to R_3 - 2R_1} \left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ 0 & 3 & 0 & 0 \\ 0 & -9 & 0 & 0 \end{array}\right]$$

$$\xrightarrow{R_2 \to \frac{1}{3} R_2} \left[\begin{array}{ccc|c} 3 & 5 & -4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -9 & 0 & 0 \end{array}\right] \xrightarrow{R_1 \to R_1 - 5R_2} \left[\begin{array}{ccc|c} 3 & 0 & -4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -9 & 0 & 0 \end{array}\right] \xrightarrow{R_3 \to R_3 + 9R_2} \left[\begin{array}{ccc|c} 3 & 0 & -4 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array}\right]$$

$$\xrightarrow{R1 \to \frac{1}{3} R1} \left[\begin{array}{ccc|c} 1 & 0 & -\frac{4}{3} & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array}\right].$$

x_3 is free $\qquad x_1 = \frac{4}{3} x_3 \qquad x_2 = 0$

$$\underbrace{\begin{bmatrix} 3 & 5 & -4 \\ -3 & -2 & 4 \\ 6 & 1 & -8 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}}_{x} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}}_{b}$$

homogeneous system

x_3 is free $\qquad x_1 = \frac{4}{3}x_3 \qquad x_2 = 0$

General solution: $\quad x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = x_3 \begin{bmatrix} \frac{4}{3} \\ 0 \\ 1 \end{bmatrix}$ or $t \begin{bmatrix} \frac{4}{3} \\ 0 \\ 1 \end{bmatrix}$

$t = 0$ gives the trivial solution

Each choice of $t \neq 0$ gives a nontrivial particular solution the general solution to a homogeneous system is

a linear combination of vectors with the free variables as coefficients

$$\underbrace{\begin{bmatrix} 3 & 5 & -4 \\ -3 & -2 & 4 \\ 6 & 1 & -8 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}}_{x} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}}_{b}$$

homogeneous system

General solution in parametric vector form

$$x = x_3 \begin{bmatrix} \frac{4}{3} \\ 0 \\ 1 \end{bmatrix} \qquad \text{or} \qquad x = t \begin{bmatrix} \frac{4}{3} \\ 0 \\ 1 \end{bmatrix}$$

A **nonhomogeneous linear system** is a linear system of the form

$$Ax = b \qquad \text{with } b \neq 0$$

Theorem. The general solution to the nonhomogeneous system $Ax = b$ is

$$x = \text{one particular solution} + \begin{matrix}\text{general solution to the} \\ \text{homogeneous system } Ax = 0\end{matrix}$$

A homogeneous system always has a solution:

the **trivial solution** $x = 0$.

A nonhomogeneous system might not have a solution.

$$\begin{bmatrix} 3 & 5 & -4 \\ -3 & -2 & 4 \\ 6 & 1 & 8 \end{bmatrix} x = \begin{bmatrix} 7 \\ 1 \\ -4 \end{bmatrix}$$

$$\begin{bmatrix} 3 & 5 & -4 & 7 \\ -3 & -2 & 4 & 1 \\ 6 & 1 & 8 & -4 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & -\frac{4}{3} & -1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

A

$$\begin{bmatrix} 3 & 5 & -4 \\ -3 & -2 & 4 \\ 6 & 1 & 8 \end{bmatrix} x = \begin{bmatrix} 7 \\ 1 \\ -4 \end{bmatrix}$$

$$\begin{bmatrix} 3 & 5 & -4 & 7 \\ -3 & -2 & 4 & 1 \\ 6 & 1 & 8 & -4 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & -\frac{4}{3} & -1 \\ 0 & 1 & 0 & 2 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

General solution in parametric vector form

$$x = \underbrace{\begin{bmatrix} -1 \\ 2 \\ 0 \end{bmatrix}}_{\text{particular solution}} + x_3 \underbrace{\begin{bmatrix} \frac{4}{3} \\ 0 \\ 1 \end{bmatrix}}_{\text{solution to } Ax = 0}$$

Important

To write the solution set of a consistent system:

1) Row-reduce the augmented matrix into reduced echelon form.
2) Write each non-free variable in terms of the free ones.
3) Write the general solution x as a vector whose entries depend on the free variables (if there are free variables).
4) Decompose this as a linear combination of vectors where each coefficient is a free variable (plus possibly one term with coefficient 1 for a particular solution).

Important

Caution! Given a linear system $Ax = b$, there is a big difference between

the coefficient matrix A and the augmented matrix $\begin{bmatrix} A & b \end{bmatrix}$.

- Is the system $Ax = b$ consistent? $\Longrightarrow$ look at the augmented matrix.
- The system $Ax = 0$ is always consistent.

  We can solve the system by focusing only on A and then finding a particular solution, but if we do so we must remember A is *not* the augmented matrix of the system.

Today’s poll code:

4LHPXC

Today's poll code:

4LHPXC

A homogeneous linear system is always consistent.

A. True

B. False

Today's poll code:

4LHPXC

A non-homogeneous linear system is always consistent.

A. True

B. False

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- WebWork 2.2 due Friday
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On Friday:

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at the beginning

of the recitation

on Lectures 4-5

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