Linear Algebra

Math 314 Fall 2025

Lecture 1

Lectures:

Mondays and Wednesdays 11:30—12:20
Bessey Hall 117

Recitations: Fridays
Time and location vary

Instructor: Dr. Eloísa Grifo
Teaching assistant: Kara Fagerstrom

Download the Nebraska App

Office hours

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

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

To do list:

- Download the Nebraska App

- Do the first bonus assignment, so we can learn your name

- Read the syllabus! (see Canvas)

- First WeBWorK assignment due September 2

Download the Nebraska App

Leiria, Portugal

source: wikipedia

The textbook is free (see Canvas)

Also on Canvas:
class notes
lecture slides (after class)

Final grades	
Polls	10%
Webwork	10%
Quizzes	15%
Labs	10%
Midterms	30%
Final Exam	25%

Nebraska App

Polls: Every lecture we will have poll questions. These will be primarily multiple choice questions designed to help you think through the new concepts we are learning, and to give both you and me a better picture of how well you are following the lecture.

While answering poll questions, you cannot use any sources besides your class notes or the textbook.

Nebraska App

Polls

Will drop **3** lowest lectures

+1 point per class
for answering all or
all but one question

Each question = 3 points

2 points for answering

(Even if incorrectly)

1 point for correct answer

$$\text{Poll grade} = \frac{\text{Total poll points obtained}}{\text{Total poll points possible}}$$

Final poll grades

Last time I taught Linear Algebra

Clicker stats

Minimum grade	85%
Maximum grade	100.00%
Median	97.88%

Download the Nebraska App

Today's poll code:

3WEARF

What class is this?

A. **Linear Algebra**

B. Calc 1

C. Bio 101

D. Tuesday

E. This is a class?

WeBWorK

Due on Tuesdays and Fridays

WeBWorK 1.1 due Tuesday September 2

Link on Canvas (see Assignments)

Drop lowest score

Quizzes

Every Friday in recitation

Quiz 1 this Friday

No makeups

Drop **2** lowest scores

Midterms and Final Exam

Midterms tentative dates:

Monday, October 6

Monday, November 3

Final exam date: 10 to noon on Thursday, December 18

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Linear Algebra

A **linear equation** in the variables $x_1, x_2, \ldots, x_n$ is an equation that can be written in the form:

$$a_1x_1 + a_2x_2 + \cdots + a_nx_n = b$$

where $a_1, \ldots, a_n, b$ are constants (real numbers).

The constant a_i is the **coefficient** of x_i, and b is the **constant term**.

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Poll: Select <u>all</u> the linear equations:

A. $x_1 + \sqrt{x_2} = 7$

B. $\pi x_2 = 2(\sqrt{6} - x_1) + x_3$

C. $x_1 - 7x_2 + 2 = x_1$

D. $x_1 x_2 = 7$

E. $x_1^2 = 42$

A **system of linear equations** or **linear system** is a collection of one or more linear equations.

Example:

$$\begin{cases} x_1 = 4 \\ 2x_1 + x_2 = 0 \end{cases}$$

A **system of linear equations** or **linear system** is a collection of one or more linear equations.

A **solution** to a system of equations in the variables $x_1, \ldots, x_n$ is a list $s = (s_1, \ldots, s_n)$ of numbers that satisfy every equation in the system, meaning that if we replace x_1 by s_1, x_2 by s_2, and so on, then we obtain a true equality.

The **solution set** of a system is the set of all possible solutions.

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Solutions: only one, $(4, -8)$

Solution set: $\{(4, -8)\}$

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Example:

$$\begin{cases} x_1 = 4 \\ x_1 = 7 \end{cases}$$

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The **solution set** of a system is the set of all possible solutions.

Example:

$$\begin{cases} x_1 = 4 \\ x_1 = 7 \end{cases}$$

Solutions: There are none!

Solution set: $\varnothing$

The system is impossible

A **system of linear equations** or **linear system** is a collection of one or more linear equations.

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The **solution set** of a system is the set of all possible solutions.

Example: $x_1 = x_2$

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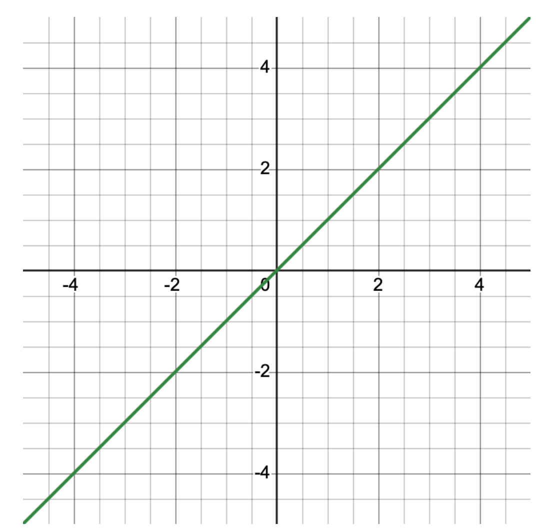
Example: $x_1 = x_2$



Solutions: infinitely many!

Solution set: a line

In general, a system of linear equations may have:

- No solutions,
- Exactly one solution, or
- Infinitely many solutions.

But it can **never** have a finite number of solutions greater than one.

Two systems of linear equations in the same variables $x_1, \ldots, x_n$ are **equivalent** if they have the same solution set.

To study linear systems of equations, we keep replacing our system by an equivalent system, until the solution set becomes easy to find. To do this, we will use matrices.

An $m \times n$ (read m *by* n) matrix is a rectangular array of numbers with m rows and n columns.

Example:

$$\begin{bmatrix} 2 & 5 & 0 \\ 7 & -3 & 13 \end{bmatrix}$$

An $m \times n$ (read m *by* n) matrix is a rectangular array of numbers with m rows and n columns.

Example: $$\begin{bmatrix} 2 & 5 & 0 \\ 7 & -3 & 13 \end{bmatrix}$$ is a 2x3 matrix

A system of linear equations

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

has

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

coefficient matrix

$$\mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

constant vector

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

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constant vector

$$\mathbf{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

$$[A|\mathbf{b}] = \begin{bmatrix} a_{11} & \cdots & a_{1n} & b_1 \\ \vdots & \ddots & \vdots & \vdots \\ a_{m1} & \cdots & a_{mn} & b_m \end{bmatrix}$$

augmented matrix

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augmented matrix

$$[A|\mathbf{b}] = \begin{bmatrix} a_{11} & \cdots & a_{1n} & b_1 \\ \vdots & \ddots & \vdots & \vdots \\ a_{m1} & \cdots & a_{mn} & b_m \end{bmatrix}$$

also written

$$\left[\begin{array}{ccc:c} a_{11} & \cdots & a_{1n} & b_1 \\ \vdots & \ddots & \vdots & \vdots \\ a_{m1} & \cdots & a_{mn} & b_m \end{array}\right]$$

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

coefficient matrix A

number of rows = number of equations

number of columns = number of variables.

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

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

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

coefficient matrix

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

augmented matrix

Theorem. Any system of linear equations can be solved using the following **elementary row operations** on the augmented matrix:

1. Replace: Replace one row by the sum of itself and a multiple of another row.

2. Swap: Swap two rows.

3. Scale: Multiply all entries of a row by a nonzero constant.

$$\begin{cases} x_1 - 2x_2 + x_3 = 0 \\ 2x_2 - 8x_2 = 8 \\ 5x_1 - 5x_3 = 10. \end{cases}$$

$$\begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{bmatrix}$$

$$\begin{cases} x_1 - 2x_2 + x_3 = 0 \\ 2x_2 - 8x_2 = 8 \\ 5x_1 - 5x_3 = 10. \end{cases}$$

$$\begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{bmatrix} \xrightarrow{R_3 \to R_3 - 5R_1}$$

$$\begin{cases} x_1 - 2x_2 + x_3 = 0 \\ 2x_2 - 8x_2 = 8 \\ 5x_1 - 5x_3 = 10. \end{cases} \iff \begin{cases} x_1 - 2x_2 + x_3 = 0 \\ 2x_2 - 8x_2 = 8 \\ 0 + 10x_2 - 10x_3 = 10 \end{cases}$$

$$\begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{bmatrix} \xrightarrow{R_3 \to R_3 - 5R_1} \begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 0 & 10 & -10 & 10 \end{bmatrix}$$

We say two $n \times m$ matrices A and B are **row equivalent** if there exists a finite sequence of row operations that converts A into B.
We will write $A \sim B$ to say that A and B are equivalent.

$$\begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{bmatrix} \xrightarrow{R_3 \to R_3 - 5R_1} \begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 0 & 10 & -10 & 10 \end{bmatrix}$$

so the matrices are equivalent!

$$\begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{bmatrix} \sim \begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 0 & 10 & -10 & 10 \end{bmatrix}$$

Theorem. If the augmented matrices of two linear systems are row equivalent, then the systems have the same solution set.

$$\begin{cases} 2x_2 - 8x_3 = 8 \\ x_1 - 2x_2 = 0 \\ 5x_1 - 5x_3 = 10 \end{cases} \qquad \begin{bmatrix} 0 & 2 & -8 & 8 \\ 1 & -2 & 0 & 0 \\ 5 & 0 & -5 & 10 \end{bmatrix}$$

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$$\left[\begin{array}{ccc:c} 0 & 2 & -8 & 8 \\ 1 & -2 & 0 & 0 \\ 5 & 0 & -5 & 10 \end{array}\right] \xrightarrow{R_1 \leftrightarrow R_2} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{array}\right] \xrightarrow[R_3 \to \frac{1}{5} R_3]{R_2 \to \frac{1}{2} R_2} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 1 & 0 & -1 & 10 \end{array}\right]$$

$$\xrightarrow{R_3 \to R_3 - R_1} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 2 & -1 & 10 \end{array}\right] \xrightarrow{R_3 \to R_3 - 2R_2} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 7 & 2 \end{array}\right].$$

$$\begin{cases} 2x_2 - 8x_3 = 8 \\ x_1 - 2x_2 = 0 \\ 5x_1 - 5x_3 = 10 \end{cases} \qquad \begin{bmatrix} 0 & 2 & -8 & 8 \\ 1 & -2 & 0 & 0 \\ 5 & 0 & -5 & 10 \end{bmatrix}$$

$$\left[\begin{array}{ccc:c} 0 & 2 & -8 & 8 \\ 1 & -2 & 0 & 0 \\ 5 & 0 & -5 & 10 \end{array}\right] \xrightarrow{R_1 \leftrightarrow R_2} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{array}\right] \xrightarrow[R_3 \to \frac{1}{5} R_3]{R_2 \to \frac{1}{2} R_2} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 1 & 0 & -1 & 10 \end{array}\right]$$

$$\xrightarrow{R_3 \to R_3 - R_1} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 2 & -1 & 10 \end{array}\right] \xrightarrow{R_3 \to R_3 - 2R_2} \left[\begin{array}{ccc:c} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 7 & 2 \end{array}\right].$$

so $$\begin{bmatrix} 0 & 2 & -8 & 8 \\ 1 & -2 & 0 & 0 \\ 5 & 0 & -5 & 10 \end{bmatrix} \sim \begin{bmatrix} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 7 & 2 \end{bmatrix}$$

Solve $\begin{cases} 2x_2 - 8x_3 = 8 \\ x_1 - 2x_2 = 0 \\ 5x_1 - 5x_3 = 10 \end{cases}$

$$\begin{bmatrix} 0 & 2 & -8 & 8 \\ 1 & -2 & 0 & 0 \\ 5 & 0 & -5 & 10 \end{bmatrix} \sim \begin{bmatrix} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 7 & 2 \end{bmatrix}$$

$$\begin{cases} 2x_2 - 8x_3 = 8 \\ x_1 - 2x_2 = 0 \\ 5x_1 - 5x_3 = 10 \end{cases}$$

$$\begin{bmatrix} 0 & 2 & -8 & 8 \\ 1 & -2 & 0 & 0 \\ 5 & 0 & -5 & 10 \end{bmatrix} \sim \begin{bmatrix} 1 & -2 & 0 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 7 & 2 \end{bmatrix}$$

$$x_3 = \tfrac{2}{7}$$

$$x_2 = 4x_3 + 4 = \tfrac{8}{7} + 4 = \tfrac{36}{7}$$

$$x_1 = 2x_2 = \tfrac{72}{7}$$

The solution set is $\{(\frac{72}{7}, \frac{36}{7}, \frac{2}{7})\}$.

Given a matrix, the **leading entry** of a particular row is the first nonzero entry in that row (from the left).

A rectangular matrix is in **row echelon form** if:

- Any rows consisting entirely of zeros are at the bottom.
- The leading entry of each nonzero row is to the right of the leading entry of the row above.
- All entries below a leading entry (in the same column) are zero.

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

$$\begin{bmatrix} 2 & -3 \\ 1 & 4 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 3 & -3 \\ 0 & 0 & 0 \\ 0 & 3 & 4 \end{bmatrix}$$

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

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

in row echelon form

$$\begin{bmatrix} 2 & -3 \\ 1 & 4 \end{bmatrix}$$

not in row echelon form

$$\begin{bmatrix} 1 & 3 & -3 \\ 0 & 0 & 0 \\ 0 & 3 & 4 \end{bmatrix}$$

not in row echelon form

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

not in row echelon form

A matrix is in **reduced row echelon form (RREF)** if it is in row echelon form and:

- The leading entry in each nonzero row is 1.
- Each leading 1 is the only nonzero entry in its column.

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

$$\begin{bmatrix} 1 & -3 & 0 & 1 \\ 0 & 1 & 4 & 8 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 0 & -4 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 29 \\ 0 & 1 & 0 & 36 \\ 0 & 0 & 1 & 7 \end{bmatrix}$$

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

row echelon form
not reduced

$$\begin{bmatrix} 1 & -3 & 0 & 1 \\ 0 & 1 & 4 & 8 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

row echelon form
not reduced

$$\begin{bmatrix} 2 & 0 & 0 & 0 \\ 0 & 1 & 0 & -4 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

row echelon form
not reduced

$$\begin{bmatrix} 1 & 0 & 0 & 29 \\ 0 & 1 & 0 & 36 \\ 0 & 0 & 1 & 7 \end{bmatrix}$$

reduced row echelon form

Theorem. Each matrix is row equivalent to one and only one matrix in reduced echelon form.

To solve a linear system of equations, we are going to:

1. Write out the augmented matrix corresponding to the system.
2. Get the augmented matrix in row reduced echelon form.

   Remember: there is only <u>one</u> possible row reduced echelon form.
3. Read the solution to the system from the row reduced echelon form.

A **pivot position** in a matrix, often shortened to **pivot**, is a position that corresponds to a leading 1 in the reduced echelon form of the matrix.

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A **pivot column** is a column that contains a pivot position.

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A **pivot column** is a column that contains a pivot position.

$$\begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

A **pivot position** in a matrix, often shortened to **pivot**, is a position that corresponds to a leading 1 in the reduced echelon form of the matrix.

A **pivot column** is a column that contains a pivot position.

$$\begin{bmatrix} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 5 & 0 & -5 & 10 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -1 \end{bmatrix}$$

pivot columns

Gauss Elimination:

0. Start with the leftmost nonzero column.

   This will be the first pivot column, with a pivot at the very top.

1. Choose a nonzero entry in this pivot column; swap rows if needed

   to move it into the top position, and do nothing if it

   the pivot is already in place. From this point on, we will <u>not</u> switch this row with another ever again.

2. Use row operations to eliminate all other entries in this pivot column.

3. Move (right) to the next pivot column and repeat.

4. Scale pivot rows so that each pivot is 1. This can be done together with the previous steps, or all together at the end.

5. Eliminate all entries *above* each pivot.

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