

# Lecture Notes for Math 307: Linear Algebra and Differential Equations

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## About this document

These lecture notes were prepared by Max Hill for a 16-week linear algebra course (MATH 307) at University of Hawaii at Manoa in Fall 2025.

The textbook used is *Linear Algebra and Differential Equations* (2002) by G. Peterson S. Sochacki, in which we cover primarily Chapters 1,2,5, and 6

## 0 Tentative Course Outline

- **Weeks 1-3: Matrices and determinants.** (*Systems of linear equations, matrices, matrix operations, inverse matrices, special matrices and their properties, and determinants.*)
  - Section 1.1: Systems of Linear Equations
  - Section 1.2: Matrices and Matrix Operations
  - Section 1.3: Inverses of Matrices
  - Section 1.4: Special Matrices and Additional Properties of Matrices
  - Section 1.5: Determinants
  - Section 1.6: Further Properties of Determinants
  - Section 1.7: Proofs of Theorems on Determinants
- **Weeks 4-6: Vector spaces.** (*Vector spaces, subspaces, spanning sets, linear independence, bases, dimension, null space, row and column spaces, Wronskian.*)
  - Section 2.1: Vector Spaces
  - Section 2.2: Subspaces and Spanning Sets
  - Section 2.3: Linear Independence and Bases
  - Section 2.4: Dimension; Nullspace, Row space, and Column Space
  - Section 2.5: Wronskians
- **Weeks 7-11: Linear transformations, spectral theory.** (*Linear transformation, eigenvalues and eigenvectors, algebra of linear transformations, matrices for linear transformations, eigenvalues and eigenvectors, similar matrices, diagonalization, Jordan normal form.*)
  - Section 5.1: Linear Transformations
  - Section 5.2: The Algebra of Linear Transformations
  - Section 5.3: Matrices for Linear Transformations
  - Section 5.4: Eigenvalues and Eigenvectors of Matrices
  - Section 5.5: Similar Matrices, Diagonalization, and Jordan Canonical Form
  - Section 5.6: Eigenvectors and Eigenvalues of Linear Transformations
- **Midterm Exam**
- **Weeks 12-14: Systems of differential equations.** (*Theory of systems of linear differential equations, homogeneous systems with constant coefficients, the diagonalizable case, nondiagonalizable case, nonhomogeneous linear systems, applications to  $2 \times 2$  and  $3 \times 3$  systems of nonlinear differential equations.*)
  - Section 6.1: The Theory of Systems of Linear Differential Equations
  - Section 6.2: Homogenous Systems with Constant Coefficients: The Diagonalizable Case
  - Section 6.3: Homogenous Systems with Constant Coefficients: The Nondiagonalizable Case
  - Section 6.4: Nonhomogeneous Linear Systems
  - Section 6.6: Applications Involving Systems of Linear Differential Equations
  - Section 6.7:  $2 \times 2$  Systems of Nonlinear Differential Equations
- **Weeks 14-16: Other stuff if time allows.** (*Converting differential equations to first order systems (section 6.5), linearization of  $2 \times 2$  nonlinear systems (??), stability and instability (section 6.7), predator-prey equations (section 6.7.1).*)
- **Final Exam**

# 1 2025-08-25 | Week 01 | Lecture 01

This lecture is based on textbook section 1.1. Introduction to Systems of Linear Equations

*The nexus question of this lecture: What is a system of linear equations, and what does it mean to ‘solve’ a system of linear equations?*

## 1.1 A first example of a system of linear equations

We begin with something concrete.

**Example 1** (A first example of a *system of linear equations*). Consider the following word problem:

*A boat travels between two ports on a river 48 miles apart. When traveling downstream (i.e., with the current), the trip takes 4 hours, but when traveling upstream (i.e., fighting the current), the trip takes 6 hours.*

*Assume that the boat and the current are both moving at a constant speed. What is the speed of the boat in still water, and what is the speed of the current?*

This problem is hard to reason through without writing something down, but becomes much simpler when we formalize it mathematically with equations. The unknowns are (1) **the speed of the boat in still water** and (2) **the speed of the current**. So let

$x :=$  (the speed of the boat in still water)

$y :=$  (the speed of the current).

The speed of the boat going downstream is  $x + y$ . Therefore, since  $(\text{speed}) \times (\text{time}) = (\text{distance travelled})$ , we have

$$4(x + y) = 48, \quad \text{or equivalently} \quad x + y = 12.$$

Similarly, the speed of the boat going upstream is  $x - y$ , so

$$6(x - y) = 48, \quad \text{or equivalently} \quad x - y = 8$$

Thus, we have the following *system of linear equations*:

$$\begin{cases} x + y = 12 \\ x - y = 8. \end{cases} \quad (1)$$

This system has **two equations** and **two variables** ( $x$  and  $y$ ). You have encountered systems of equations like this many times. With the help of the technology of algebra, solving this problem (namely, solving System (1)) is much easier than solving the original word problem.

- In this case, the problem can be easily solved **algebraically** using a substitution (e.g., plug  $x = 8 + y$  into the first equation and solve for  $y$ , then solve for  $x$  after finding  $y$ ). This gives the solution  $(x, y) = (10, 2)$ . The speed of the boat in still water is 10mph. The speed of the river current is 2mph.
- We can conceive of another type of solution, which uses a **geometric**, rather than algebraic perspective: observe that each equation  $x + y = 12$  and  $x - y = 8$  represents a line on the  $xy$ -plane. Plot the lines. Their intersection is the point  $(10, 2)$ , which is the solution.
- However, solving systems of equations like in (1) becomes more cumbersome when there are lots of variables and equations. Doing substitutions and algebraic manipulations will still work, but will be tedious and difficult if you have many equations and variables.

Later, we will introduce a general algorithm which can solve any such system. This algorithm is called **Gauss-Jordan elimination**, and it will be one of the core techniques that we will use to solve many types of problems in this class.

End of Example 1.  $\square$

## 1.2 Key definitions: linear systems and their solutions

In this section, we formalize the mathematical objects we are studying.

**Definition 2** (Linear equation). A **linear equation** in the variables  $x_1, \dots, x_n$  is an equation that can be written in the form

$$a_1x_1 + a_2x_2 + \dots + a_nx_n = b,$$

where  $a_1, \dots, a_n$  and  $b$  are constants (e.g., fixed real numbers). The numbers  $a_1, \dots, a_n$  are called **coefficients**.

Note that the variables  $x_1, \dots, x_n$  are not raised to any powers. That's what makes the equation *linear*. If we had squares or cubes of some of the  $x_i$ 's, or products like  $x_1x_3$ , then the equation would be quadratic or cubic, or something else, but not linear.

**Example 3** (Examples of linear equations).

- The equation

$$2x - 3y = 1$$

is a linear equation in the variables  $x$  and  $y$ . Its graph is a line on the  $xy$ -plane.

- The equation

$$3x - y + 2z = 9$$

is a linear equation in the variables  $x, y$  and  $z$ . Its graph is a plane in 3-dimensional space (denoted  $\mathbb{R}^3$ ).

- The equation

$$-x_1 + 5x_2 + \pi^2x_3 + \sqrt{2}x_4 = e^2$$

is a linear equation in the variables  $x_1, x_2, x_3$ , and  $x_4$ . The coefficients are

$$a_1 = -1, \quad a_2 = 5, \quad a_3 = \pi, \quad \text{and} \quad a_4 = \sqrt{2}.$$

The graph of this linear system is a 3-dimensional hyperplane in 4d-space (i.e.,  $\mathbb{R}^4$ ).

**Observation:** In these examples, we observe a simple relationship between the number of variables and the dimension of the graph:

$$(\text{dimension of graph}) = (\# \text{ of variables}) - 1.$$

Here, the term **dimension** refers to the number of free variables. In the first equation (which is  $2x - 3y = 1$ ), it's easy to see that if we know one of the variables, then the other one is automatically determined. So it makes sense that the graph of this equation is of dimension 1 (which it is, because it's a line). For the second equation, if we know any 2 of the variables, then the third variable is automatically determined, so it makes sense that the dimension of the graph is 2 (which it is, because planes are 2-dimensional). Etc.

End of Example 3.  $\square$

**Definition 4** (Linear system, solution of a linear system). When considered together, a collection of  $m$  linear equations

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = b_2 \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = b_m \end{cases} \quad (2)$$

is called a **system of linear equations**, or **linear system** for short. A **solution** to a system of linear equations is a set of values for  $x_1, \dots, x_n$  which satisfy all equations in system (2).

**Example 5** (A system of linear equations). An example of a system of linear equations is

$$\begin{cases} x - y + z = 0 \\ 2x - 3y + 4z = -2 \\ -2x - y + z = 7 \end{cases}$$

When a linear system like this walks in the door, we always first ask two basic questions: (1) ‘how many equations does it have?’ and (2) ‘how many variables does it have?’. In this case, we have  $m = 3$  equations and  $n = 3$  variables.

End of Example 5.  $\square$

### 1.3 How to understand solutions of linear systems geometrically

Here is a very useful geometric perspective. In system (2), we have a system of  $m$  equations expressed in  $n$  variables  $x_1, \dots, x_n$ . Each of the  $m$  equations is the equation of some hyperplane<sup>1</sup> which lives in  $n$ -dimensional space ( $\mathbb{R}^n$ ). *The solution to the linear system is the intersection of these hyperplanes.*

For example, in Example 5, the ‘hyperplanes’ were lines, and their intersection was the point  $(x, y) = (10, 2)$ .

We will spend a lot of time understanding what hyperplanes look like, and what intersections of hyperplanes look like.

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<sup>1</sup>Note: Hyperplanes will be defined more formally later, but for now can be thought of as generalized lines or planes, since a 1-dimensional hyperplane is a *line* and a 2-dimensional hyperplane is a *plane*.

## 2 2025-08-27 | Week 01 | Lecture 02

*The nexus question of this lecture: What do solutions to linear systems look like?*

### 2.1 How to understand solutions of linear systems geometrically

Here is a very useful geometric perspective. In system (2), we have a system of  $m$  equations expressed in  $n$  variables  $x_1, \dots, x_n$ . Each of the  $m$  equations is the equation of some hyperplane<sup>2</sup> which lives in  $n$ -dimensional space ( $\mathbb{R}^n$ ). *The solution to the linear system is the intersection of these hyperplanes.*

The clearest example of this can be seen in the linear system:

**Example 6** (The case with two variables).

$$\begin{cases} a_{11}x + a_{12}y = b_1 \\ a_{21}x + a_{22}y = b_2 \end{cases} \quad (3)$$

where  $a_{12}, a_{22} \neq 0$ . (In this case, the “hyperplanes” are simply lines.) Here, the solutions to the first equation are the points on the line

$$y = -\frac{a_{11}}{a_{12}}x + \frac{b_1}{a_{12}} \quad (4)$$

Similarly, the solutions to the second equation are the points on the line

$$y = -\frac{a_{21}}{a_{22}}x + \frac{b_2}{a_{22}}. \quad (5)$$

There are three possible things that can happen when we intersect the two lines in Eqs. (4) and (5):

- **Case 1.** The two line equations Eqs. (4) and (5) represent distinct lines and are not parallel. In this case, their intersection consists of a unique point, like this:



In this case, the system (3) has **exactly one solution**—namely, the intersection of the two lines, just like we saw in the boat example.

- **Case 2.** The two line equations Eqs. (4) and (5) represent two parallel but different lines. In this case, the two lines never intersect each other (i.e., there is no point that lies on both lines), so the system (3) has **no solutions**.
- **Case 3.** The two equations of lines are the same, so they represent the same line. Therefore the intersection of the two lines is the entire line. Therefore, there are **infinitely many solutions** to the linear system (3). Namely, any point  $(x, y)$  on the line is a solution to the linear system.

End of Example 6.  $\square$

These three cases described in Example 6 constitute the following trichotomy:

**Theorem 7.** *A system of linear equations either has (1) exactly one solution, (2) no solution, or (3) infinitely many solutions.*

We haven’t proven this fact, only illustrated it for systems of linear equations like (3) that have 2 equations and 2 variables. In fact, as we shall see, this fact always holds for all linear systems of the form given in (2), no matter how many equations and variables.

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<sup>2</sup>Note: Hyperplanes will be defined more formally later, but for now can be thought of as generalized lines or planes, since a 1-dimensional hyperplane is a *line* and a 2-dimensional hyperplane is a *plane*.

## 2.2 The planar case

Recall that, geometrically, a line is determined by two features:

1. A slope  $m$  which determines the direction of the line
2. A point  $(x_0, y_0)$  which the line passes through, as this determines where the line lives on the  $xy$ -plane

It is easy to see that these two things determine everything about a line because the equation of a line can be expressed as

$$y - y_0 = m(x - x_0)$$

and to write this down, all we need are  $m$  and  $(x_0, y_0)$ .

Just like a line, a plane is determined by two things:

1. A normal vector  $n = \langle A, B, C \rangle$  which determines the tilt of the plane. (Here,  $A, B$ , and  $C$  are fixed constants)
2. A point  $(x_0, y_0, z_0)$  which the plane passes through, as this determines where in 3-d space ( $\mathbb{R}^3$ ) the plane lives.

To be precise, a plane  $\mathbb{P}$  consists of the set of points  $(x, y, z)$  satisfying the following equation:

$$A(x - x_0) + B(y - y_0) + C(z - z_0) = 0 \quad (6)$$

This is the standard form equation of a plane, and we can write it down if we know both  $n = \langle A, B, C \rangle$  and  $(x_0, y_0, z_0)$ . So if we know those two things, then we know the equation of the plane, meaning we know everything about it.

By a little bit of algebra, we can rewrite Eq. (6) as

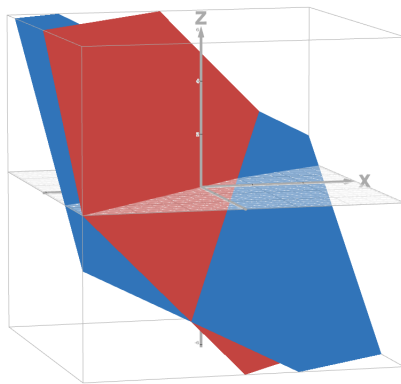
$$Ax + By + Cz = D$$

where  $D = Ax_0 + By_0 + Cz_0$ . This is a linear equation. Just like how the solutions to a linear equation with 2 variables form a line, the solutions to a linear equation with 3 variables form a plane.

**Example 8** (A system with three variables). Suppose we wish to solve the linear system

$$\begin{cases} x - y + z = 0 \\ 2x - 3y + 4z = -2 \\ -2x - y + z = 7 \end{cases}$$

In this case, each equation is the equation of a plane. The planes for the first two equations are the following:



The plane for the first equation is in red. The plane for the second equation is blue. Any point on the red plane is a solution to the first equation  $x - y + z = 0$ . Any point on the blue plane is a solution to the second equation  $2x - 3y + 4z = -2$ . The two planes intersect in a line. If I pick any point on this line, then it satisfies both equations.

But our system has three equations, so we have a third plane, and the intersection of all three planes is a point, as shown:

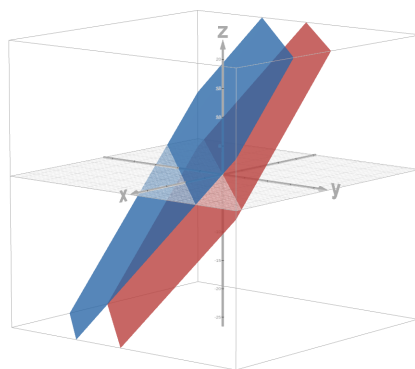




In this case, the system of equations has a unique solution, which is the unique point of intersection of the planes. Here's the desmos link to see the plots of these three planes, if you want to play around with them:

<https://www.desmos.com/3d/gpgtw2rjaf>

Of course there are other ways that three planes could have intersected. For example, two of the planes might be parallel, like the following picture, in which case the system will have no solutions:



Or the three planes could intersect in a line, like the following picture, in which case there are infinitely many solutions (credit Noah C. for the observation and picture):



There are other ways that three planes could intersect as well, but the trichotomy stated earlier always holds: their intersection either consists of (1) exactly one point, (2) infinitely many points, or (3) zero points.

End of Example 8.  $\square$

We've seen in this lecture that for systems of linear equations with two variables, the solutions are the intersection of lines. For systems of linear equations with three variables, the solutions are the intersections of planes. ... And for systems with  $n > 3$  variables, the solutions are the intersections of hyperplanes.

### 3 2025-08-29 | Week 01 | Lecture 03

This lecture is based on section 1.1 in the textbook

**The nexus question of this lecture:** How can we solve a linear system without resorting to substitution?

Recall in the boat example (Example 1), we had the system

$$\begin{cases} x + y = 12 \\ x - y = 8 \end{cases}$$

And we could solve this using substitution. Another thing we could have done, would be to add the second equation to the first, giving us a new, simpler but equivalent system:

$$\begin{cases} 2x = 20 \\ x - y = 8 \end{cases}$$

Then divide the first equation by two

$$\begin{cases} x = 10 \\ x - y = 8 \end{cases}$$

Then subtract the first equation from the second:

$$\begin{cases} x = 10 \\ -y = -2 \end{cases}$$

Then multiply the second equation by  $-1$

$$\begin{cases} x = 10 \\ y = 2 \end{cases}$$

And tada! We have found our solution without doing substitution. But this example was very simple, so maybe it's special and we can't always do this sort of thing? Actually, we can. In the rest of the lecture, I'll try to formalize these sorts of steps we used here and apply them to a more complicated problem.

The reason I'm doing this is because, in the next lecture, I will begin to present **Gauss-Jordan elimination** (aka **row reduction**), a general method which can be used to find the solutions of any system of linear equation which does not use substitution. For now, we will work out an example which motivates the main ideas that will be used by Gauss-Jordan elimination.

#### 3.1 Solving a linear system using via simplifying transformations

**Example 9** (Solving a linear system with elementary operations). Suppose we wish to solve the following system:

$$\begin{cases} x - y + z = 0 & (E_1) \\ 2x - 3y + 4z = -2 & (E_2) \\ -2x - y + z = 7 & (E_3) \end{cases} \quad (7)$$

This system has 3 equations, labeled  $E_1, E_2, E_3$ , and 3 variables  $x, y$  and  $z$ . Suppose that we know ahead of time that this system has a unique solution (we showed this graphically in Example 8). Then, in principle, we could solve this using substitution, but that would suck. Instead, I will illustrate an approach in which we iteratively transform this linear system into successively simpler systems until we get to a point where the solution is obvious.

To do this, we will play a game where there are three 'moves' available to us. The three moves are:

1. Interchange two equations in the system.
2. Multiply an equation by a nonzero number.

3. Replace an equation by itself plus a multiple of another equation.

These moves are called **elementary operations**, and if we use them intelligently, they will allow us to transform the linear system into a simpler system.

Two systems of equations are said to be **equivalent** if they have the same solutions. Applying elementary operations always results in an equivalent system. Our goal will be to use some combination of elementary operations to produce a system of the form

$$\begin{cases} x = * \\ y = * \\ z = * \end{cases}$$

where each  $*$  is a constant which we will have computed. This will be our solution to the linear system (7), because the two systems will be equivalent.

First, let's apply operation 3: specifically, by replacing  $E_2$  with  $E_2 - 2E_1$ :

$$\begin{cases} x - y + z = 0 \\ -y + 2z = -2 \\ -2x - y + z = 7 \end{cases}$$

We have eliminated the  $x$  from the second equation, yielding a simpler system. Let's keep doing this. To eliminate  $x$  from equation 3, let's apply operation 3 again: This time, replace  $E_3$  with  $E_3 + 2E_1$ :

$$\begin{cases} x - y + z = 0 \\ -y + 2z = -2 \\ -3y + 3z = 7 \end{cases}$$

Apply operation 3, replace  $E_1$  with  $E_1 - E_2$ . This will allow us to eliminate  $y$  from  $E_1$ :

$$\begin{cases} x - z = 2 \\ -y + 2z = -2 \\ -3y + 3z = 7 \end{cases}$$

Apply operation 3, replace  $E_3$  with  $E_3 - 3E_2$ . This will allow us to eliminate  $y$  from  $E_3$ :

$$\begin{cases} x - z = 2 \\ -y + 2z = -2 \\ -3z = 13 \end{cases}$$

Apply operation 2 twice: multiply both the first and second equations by 3:

$$\begin{cases} 3x - 3z = 6 \\ -3y + 6z = -6 \\ -3z = 13 \end{cases}$$

Apply operation 3, twice. First, replace  $E_1$  with  $E_1 - E_3$ . Then replace  $E_2$  with  $E_2 + 2E_3$ . Doing both of these, we get:

$$\begin{cases} 3x = -7 \\ -3y = 20 \\ -3z = 13 \end{cases}$$

Apply operation 2 by multiplying the first equation by  $1/3$ . Then multiply the second and third equations both by  $-1/3$ :

$$\begin{cases} x = -7/3 \\ y = -20/3 \\ z = -13/3 \end{cases}$$

This is the solution to the original equation. We have used elementary operations to reduce our original linear system Eq. (7) to the above system, which is equivalent to the original system.

While solving this system was still a lot of (tedious) work, it was still probably simpler than doing substitution.

End of Example 9.  $\square$

### 3.2 Representing a linear system as an augmented matrix

In the procedure presented in Example 9, we didn't really need to track the variables, only the *coefficients* and the *quantities on the right hand sides* of the equations. Instead of working with the equations directly, it will be simpler to work with the following matrix, called the **augmented matrix** corresponding to Eq. (7):

$$\left[ \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 2 & -3 & 4 & -2 \\ -2 & -1 & 1 & 7 \end{array} \right].$$

Comparing this with system (7), it becomes clear that the augmented matrix was obtained essentially by just erasing the variables  $x, y$ , and  $z$  in (7), and then placing what remains into an array. We also drew a vertical line to separate the left- and right-hand sides of the equations. Inside the augmented matrix, the  $3 \times 3$  submatrix of coefficients

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

is called the **coefficient matrix** of the system.

More precise definitions are as follows:

**Definition 10** (Augmented Matrix). Given a linear system of the form (2), the **augmented matrix** is

$$\left[ \begin{array}{cccc|c} a_{11} & a_{12} & \dots & a_{1n} & b_1 \\ a_{21} & a_{22} & \dots & a_{2n} & b_2 \\ \vdots & \vdots & & \vdots & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} & b_m \end{array} \right]$$

and the **coefficient matrix** is the matrix

$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}.$$

This is our first application of

## 4 2025-09-03 | Week 02 | Lecture 04

*The nexus question of this lecture: What is Gauss-Jordan elimination (aka: row reduction) and how do we use it to solve linear systems?*

Now I will present **Gauss-Jordan elimination**. This is also called **Gaussian elimination**, or more commonly, **row reduction**. I will illustrate it by means of an example.

### 4.1 Using row reduction to solve a linear system with a unique solution

Suppose we wish to solve

$$\begin{cases} x - y + z = 0 \\ -y + 2z = -2 \\ -2x - y + z = 7 \end{cases} \quad (8)$$

**Steps:** We initialize the algorithm by setting up an **augmented matrix** corresponding to the system. For the system in (8), the augmented matrix is

$$\left[ \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 2 & -3 & 4 & -2 \\ -2 & -1 & 1 & 7 \end{array} \right].$$

- The matrix to the left of the vertical row is the **coefficient matrix**.
- A line of numbers going from left to right is called a **row** of the matrix. A line of numbers going down the matrix is a **column**.

Gauss-Jordan elimination is like a game where the player has three possible moves, called **row operations**.

1. Interchange two rows.
2. Multiply a row by a nonzero number.
3. Replace a row by itself plus a multiple of another row.

The player does row operations with the **goal** of making the diagonal entries of the coefficient matrix 1's and making as many of the other numbers zero, if possible. Here are the row operations for this example:

$$\begin{aligned} & \left[ \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 2 & -3 & 4 & -2 \\ -2 & -1 & 1 & 7 \end{array} \right] \xrightarrow{R_2 - 2R_1 \rightarrow R_2} \left[ \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ \mathbf{0} & -1 & \mathbf{2} & -2 \\ -2 & -1 & 1 & 7 \end{array} \right] \xrightarrow{R_3 + 2R_1 \rightarrow R_3} \left[ \begin{array}{ccc|c} 1 & -1 & 1 & 0 \\ 0 & -1 & 2 & -2 \\ \mathbf{0} & -\mathbf{3} & \mathbf{3} & \mathbf{7} \end{array} \right] \\ & \xrightarrow{R_1 - R_2 \rightarrow R_1} \left[ \begin{array}{ccc|c} \mathbf{1} & \mathbf{0} & -1 & \mathbf{2} \\ 0 & -1 & 2 & -2 \\ 0 & -3 & 3 & 7 \end{array} \right] \xrightarrow{R_3 - 3R_2 \rightarrow R_3} \left[ \begin{array}{ccc|c} 1 & 0 & -1 & 2 \\ 0 & -1 & 2 & -2 \\ \mathbf{0} & \mathbf{0} & -\mathbf{3} & \mathbf{13} \end{array} \right] \xrightarrow{(-1) \cdot R_2 \rightarrow R_2} \left[ \begin{array}{ccc|c} 1 & 0 & -1 & 2 \\ \mathbf{0} & \mathbf{1} & -2 & \mathbf{2} \\ 0 & 0 & -3 & 13 \end{array} \right] \\ & \xrightarrow{(-\frac{1}{3}) \cdot R_3 \rightarrow R_3} \left[ \begin{array}{ccc|c} 1 & 0 & -1 & 2 \\ 0 & 1 & -2 & 2 \\ \mathbf{0} & \mathbf{0} & \mathbf{1} & -\mathbf{13/3} \end{array} \right] \xrightarrow{R_2 + 2R_3 \rightarrow R_2} \left[ \begin{array}{ccc|c} 1 & 0 & -1 & 2 \\ \mathbf{0} & \mathbf{1} & \mathbf{0} & -\mathbf{20/3} \\ 0 & 0 & 1 & -13/3 \end{array} \right] \xrightarrow{R_1 + R_3 \rightarrow R_1} \left[ \begin{array}{ccc|c} \mathbf{1} & \mathbf{0} & \mathbf{0} & -\mathbf{7/3} \\ 0 & 1 & 0 & -20/3 \\ 0 & 0 & 1 & -13/3 \end{array} \right] \end{aligned}$$

We now convert the augmented matrix back to a system of linear equations:

$$\begin{cases} 1x - 0y + 0z = -7/3 \\ 0x - 1y + 0z = -20/3 \\ 0x - 0y + 1z = -13/3 \end{cases}$$

or more simply,

$$\begin{aligned}x &= -7/3 \\y &= -20/3 \\z &= -13/3\end{aligned}$$

We can check that this is a solution to the original system of equations (8).

## 4.2 The goal when doing row reduction

In the previous example, we used row reduction Gauss-Jordan elimination to solve a linear system. The example we did had a unique solution. When that happens we can reduce the coefficient matrix to a matrix like

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

possibly with one or more rows of zeros at the bottom. (It may be larger or smaller depending on the number of equations and variables).

But in general, as we've seen, a linear system either has (1) one solution, (2) no solutions, or (3) infinitely many solutions. And if cases (2) or (3) happen, then we won't be able to do that. So we need to relax our "goal" when doing row reduction.

**Our new goal** is to reduce the coefficient matrix to **reduced row-echelon form**, which in the case of a linear system with three equations and three variables, means it should look like one of these

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & 0 & \# \\ 0 & 1 & \# \\ 0 & 0 & 0 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & \# & \# \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

where # denotes any arbitrary number.

**Definition 11.** More precisely, a coefficient matrix

$$\begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}.$$

is said to be in **reduced row echelon form** if

1. Any rows of zeros appear at the bottom
2. The leftmost nonzero entry of all other rows equals 1 (the "leading 1's")
3. Each leading 1 of a nonzero row appears to the right of the leading row above it
4. All the other entries of a column containing a leading 1 are zero

This definition is *general*: it applies to any system with  $m$  equations and  $n$  variables. The pattern will become natural once you've worked a few (dozen?) examples.

## 4.3 Using row reduction to solve a system with infinitely many solutions

Here's an example which shows what happens when we try to solve a linear system with infinitely many solutions:

**Example 12** (Using row reduction to solve a system with infinitely many solutions). We wish to solve the system

$$\begin{cases} 2x + 3y - z = 3 \\ -x - y + 3z = 0 \\ x + 2y + 2z = 3 \\ y + 5z = 3 \end{cases}$$

This system has 4 equations and 3 variables. Each equation represents a plane. The solutions, if there are any, will be the intersection of these four planes. I've plotted the planes in Desmos:



It looks like the four planes intersect in a line. So we should expect infinitely many solutions.

**Step 1.** Write down the augmented matrix of the system.

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

**Step 2.** Do some combination or row reduction steps until the coefficient matrix is in reduced row echelon form. (This is Example 3 in the textbook, refer there for the steps.)

**Step 3.** Our matrix is now in reduced row echelon form:

$$\left[ \begin{array}{ccc|c} 1 & 0 & -8 & -3 \\ 0 & 1 & 5 & 3 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array} \right]$$

Let's convert it back into a linear system of equations:

$$\begin{aligned} x - 8z &= -3 \\ y + 5z &= 3 \\ 0 &= 0 \\ 0 &= 0 \end{aligned}$$

Therefore, we have

$$\begin{cases} x = -3 + 8z \\ y = 3 - 5z \end{cases} \quad (9)$$

where  $z$  is any real number. There are no restrictions on the value of  $z$ . Any choice of  $z$  gives us a valid solution to our original system of equations. If  $z = 0$ , we have the solution  $(x, y, z) = (-3, 3, 0)$ . If  $z = 1$ , then we have the solution  $(x, y, z) = (5, -2, 1)$ , and so forth.

**Interpretation:** In this case,  $z$  is called a *free variable* and  $x$  and  $y$  are called *dependent variables*. The solutions to the original linear system consist of all points on a line which cuts through 3-dimensional space  $\mathbb{R}^3$ . Eq. (9) gives us a parametric equation of the line. The set of solutions is 1-dimensional, because it is a line.

End of Example 12.  $\square$

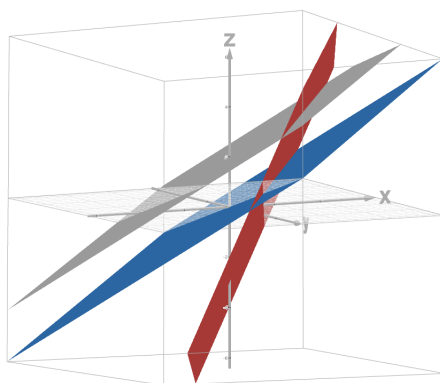
We've covered two of the three cases. For the last case, we consider the question *what happens if we attempt to solve a linear system that has no solutions?*

#### 4.4 Using row reduction to attempt to solve a system with no solutions

**Example 13** (Using row reduction to attempt to solve a system with no solutions). Suppose we wish to solve the system

$$\begin{aligned} 2x + y - z &= 3 \\ -x - y + 2z &= 0 \\ -x - y + 2z &= 4 \end{aligned}$$

Here's a plot of the planes:



Their intersection if the three planes is *empty*: there is no point which lies on all three planes. So this system has no solution. What happens when we try to use row reduction?

**Step 1.** Write down the augmented matrix:

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

**Step 2.** Do row reduction to get to reduced row echelon form (I'm skipping steps here):

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

**Step 3.** Convert back to a linear system:

$$\begin{cases} x + z = 3 \\ x - y + 3z = 3 \\ 0 = 4 \end{cases}$$



The last equation is never true, no matter what values we choose for  $x, y$  and  $z$ . So the system has no solution

End of Example 13.  $\square$

## 4.5 Notes and resources for learning row reduction

**NOTE:** I'm not going to do a lot of examples of row reduction because it's so time consuming that it's not a great use of lecture time. So I expect you to teach yourself how to do row reduction. If you want to see more examples, some good online videos are

<https://www.youtube.com/watch?v=OP2aQU0evhI>  
<https://www.youtube.com/watch?v=eDb6iugi6Uk>

There are also some nice online tools to help with row reduction, for example:

<https://textbooks.math.gatech.edu/ila/demos/rrinter.html>  
<https://www.math.odu.edu/~bogacki/cgi-bin/lat.cgi?c=roc>

### General advice:

1. Of course I'm going to ask you to row-reduce matrices on your exams, and for that you'll need to be able to do it by hand, without a calculator.
2. Write down all your steps, including a new matrix at every step in an organized way.
3. Use the notation  $R_i \leftrightarrow R_j$  to indicate a swap of rows  $i$  and  $j$ ;  $cR_i \rightarrow R_i$  to indicate a multiplication of row  $i$  by a constant  $c$ ; and,  $R_i + cR_j \rightarrow R_i$  to indicate that you've added  $c$  times row  $j$  to row  $i$ .
4. Work left to right, top to bottom. Start by making the top left entry 1. Then use it to make all the numbers below it zero. Then go to the second column, second row, and make that 1. Then make everything beneath it zero. Etc.

## 5 2025-09-05 | Week 02 | Lecture 05

*The nexus question of this lecture: What is a matrix, and what are the fundamental algebraic operations we can do with it?*

This lecture is based on section 1.2 in the textbook.

### 5.1 Matrices and matrix notation

A **matrix** is a rectangular array of objects, usually numbers, which are called **entries**. If the number of rows and the number of columns are equal, the matrix is said to be a **square matrix**.

For example,

$$\begin{bmatrix} 1 & 0 & 3 \\ 2 & 5 & -3 \end{bmatrix} \quad \text{or} \quad \underbrace{\begin{bmatrix} 1 & 0 & -7 & 5 \end{bmatrix}}_{\text{a row vector}} \quad \text{or} \quad \underbrace{\begin{bmatrix} 1 \\ 4 \\ 0 \end{bmatrix}}_{\text{a column vector}} \quad \text{or} \quad \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

A matrix with  $m$  rows and  $n$  columns takes the form

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}.$$

Such a matrix is said to be an  $m \times n$  **matrix**. The pair  $(m, n)$  is called the **dimensions** of the matrix (i.e., the number of rows and number of columns). If  $m = n$ , then the matrix is said to be a **square matrix**.

The set of all  $m \times n$  matrices with real entries is denoted

$$M_{m \times n}(\mathbb{R})$$

For example, in set notation

$$M_{2 \times 3}(\mathbb{R}) = \left\{ \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \end{bmatrix} : a_{11}, a_{12}, a_{13}, a_{21}, a_{22}, a_{23} \in \mathbb{R} \right\}$$

**Notation 14.** It is common to denote a matrix compactly using the notation

$$A = [a_{ij}] \quad \text{or} \quad A = (a_{ij})$$

To denote the entry at row  $i$ , column  $j$ , we write either

$$\text{ent}_{ij}(A) \quad \text{or more simply,} \quad a_{ij}$$

For example, if

$$A = (a_{ij}) = \begin{bmatrix} -1 & 2 & 1 \\ 5 & 4 & -9 \\ 3 & -4 & 7 \end{bmatrix}$$

then  $a_{23} = \text{ent}_{23}(A) = -9$ , and  $a_{21} = \text{ent}_{21}(A) = 5$ .

Vectors are a special case of matrices. An  $n$ -dimensional vector is an  $n \times 1$  matrices (a column matrix, typically).

## 5.2 Matrix operations: scaling, addition and multiplication

We can **multiply matrices by a scalar**, in the obvious way:  $10 \times \begin{bmatrix} 3 & 4 \\ -2 & 0 \end{bmatrix} = \begin{bmatrix} 30 & 40 \\ -20 & 0 \end{bmatrix}$ .

We can **add matrices**, also in the obvious way:

$$\begin{bmatrix} 3 & 4 \\ -2 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 5 \\ 2 & 10 \end{bmatrix} = \begin{bmatrix} 4 & 9 \\ 0 & 10 \end{bmatrix}.$$

But note that we can only add two matrices if they have the same dimensions:

$$\begin{bmatrix} 5 & 2 \\ -2 & -1 \end{bmatrix} + \begin{bmatrix} -1 & 10 \\ 4 & 7 \\ 2 & 5 \end{bmatrix} = \text{undefined}.$$

We can also **multiply** matrices, but before defining matrix multiplication, it will be helpful to recall the notion of dot product. Suppose we have two vectors of the same length:

$$X = [x_1 \ x_2 \ \cdots \ x_n] \quad \text{and} \quad Y = [y_1 \ y_2 \ \cdots \ y_n],$$

then the **dot product** of  $X$  and  $Y$ , denoted  $X \cdot Y$ , is

$$X \cdot Y = x_1 y_1 + x_2 y_2 + \cdots + x_n y_n = \sum_{i=1}^n x_i y_i.$$

**Matrix multiplication** is defined in the following way:

### Matrix Multiplication

If  $A = (a_{ij})$  is a  $p \times n$  matrix and  $B = (b_{ij})$  is an  $n \times q$  matrix, then we can think of  $A$  and  $B$  as

$$A = \begin{bmatrix} \text{---} A_1 \text{---} \\ \text{---} A_2 \text{---} \\ \vdots \\ \text{---} A_p \text{---} \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} \begin{array}{c|c|c|c} B_1 & B_2 & \cdots & B_q \\ \hline \end{array} \end{bmatrix}$$

where  $A_1, \dots, A_p$  are the  $1 \times n$  row vectors

$$A_i = [a_{i1} \ a_{i2} \ \cdots \ a_{in}] \quad (i = 1, \dots, p)$$

and  $B_1, \dots, B_q$  are  $n \times 1$  column vectors:

$$B_j = \begin{bmatrix} b_{1j} \\ b_{2j} \\ \vdots \\ b_{nj} \end{bmatrix} \quad (j = 1, 2, \dots, q)$$

Then the product  $P = AB$  is a  $p \times q$  matrix  $P = (p_{ij})$ , whose entries are

$$\begin{aligned} p_{ij} &= A_i \cdot B_j \\ &= \sum_{k=1}^n a_{ik} b_{kj}. \end{aligned}$$

For example,

$$\begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 5 & 6 \\ 7 & 8 \end{bmatrix} = \begin{bmatrix} 1 \cdot 5 + 2 \cdot 7 & 1 \cdot 6 + 2 \cdot 8 \\ 3 \cdot 5 + 4 \cdot 7 & 3 \cdot 6 + 4 \cdot 8 \end{bmatrix} = \begin{bmatrix} 19 & 22 \\ 43 & 50 \end{bmatrix}$$

**Dimensionality requirement for matrix multiplication:** we can only multiply two matrices if their dimensions match in the right way. If  $A$  is a  $p \times n$  matrix, and  $B$  is an  $\tilde{n} \times q$  matrix, then the product  $AB$  is defined if and only if  $n = \tilde{n}$ . That is,

$$AB \text{ is } \begin{cases} \text{a } p \times q \text{ matrix} & \text{if } n = \tilde{n} \\ \text{undefined} & \text{if } n \neq \tilde{n} \end{cases}$$

**Properties of matrix multiplication:** Perhaps surprisingly, despite matrix multiplication's complicated definition, it nonetheless behaves sort of like regular multiplication in that the **associative property** and **distributed property** both hold. That is,

$$ABC = (AB)C = A(BC) \quad (\text{associative property})$$

and

$$\begin{aligned} A(B + C) &= AB + AC & (\text{left distributive property}) \\ (B + C)A &= BA + CA & (\text{right distributive property}) \end{aligned}$$

It's not obvious why the properties always hold; they require proof. For now, we will take them as a given.

## 5.3 Special classes of matrices

### 5.3.1 Diagonal matrices

If  $A = (a_{ij})$  is a square (i.e.,  $n \times n$ ) matrix, then the entries  $a_{11}, a_{22}, a_{33}, \dots, a_{nn}$  are called the **diagonal entries**. A square matrix of the form

$$A = \begin{bmatrix} a_{11} & 0 & 0 & \dots & 0 \\ 0 & a_{22} & 0 & \dots & 0 \\ 0 & 0 & a_{33} & \dots & 0 \\ \vdots & \vdots & & \ddots & \\ 0 & 0 & 0 & \dots & a_{nn} \end{bmatrix}.$$

is called a **diagonal** matrix, and the notation used for such matrices is  $A = \text{diag}(a_{11}, \dots, a_{nn})$ .

### 5.3.2 Identity matrix

An **identity matrix** is a diagonal matrix with 1's on its diagonal (and 0's everywhere else). For example,

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{et cetera}$$

Identity matrices are always square. The notation for an  $n \times n$  identity matrix is  $I_n$ , or more simply  $I$ .

An identity matrix has the property that when you multiply it by another matrix, it doesn't change the other matrix. For example,

$$\begin{bmatrix} 5 & 6 \\ 2 & 7 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 5 & 6 \\ 2 & 7 \end{bmatrix}$$

It's like multiplying a number by 1.

### 5.3.3 Zero matrices

A matrix whose entries are all zeros is called a *zero matrix*, like

$$\begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad \text{et cetera}$$

The book uses the notation  $\mathbf{O}_{m \times n}$  to denote an  $m \times n$  zero matrix, or sometimes even just  $\mathbf{O}$ .

## 6 2025-09-08 | Week 03 | Lecture 06

*The nexus question of this lecture: How do we encode a linear system using matrices? And once thus encoded, what can we say about the solutions to the linear system just by looking at the matrix?*

*This lecture is based on sections 1.2 and 1.3 of the textbook.*

### 6.1 Inverting matrices

We begin this lecture by introducing the idea of a matrix inverse, which we will use to help answer the main question of the lecture.

Recall that the identity matrix is a matrix of the form

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad \text{or} \quad \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad \text{et cetera}$$

and we usually denote an identity matrix by the letter  $I_n$  (or just  $I$  if the dimensions are clear from context). Such a matrix behaves like the number 1, in the sense that  $AI = A$  and  $IA = A$  for any matrix  $A$ .

Every nonzero number  $a$  has an inverse  $a^{-1} = \frac{1}{a}$  such that

$$a \cdot a^{-1} = a^{-1}a = 1.$$

It would be natural to conjecture that every nonzero matrix  $A$  also has an inverse  $A^{-1}$  such that

$$AA^{-1} = A^{-1}A = I$$

In fact, this conjecture is false: we cannot do this with every matrix, but sometimes we can.

To be precise, if two matrices satisfy the property that  $AB = BA = I$ , then they are said to be **inverses**. In this case, we write  $B = A^{-1}$  (which doesn't mean  $1/A$ ). This is analogous to when we multiply two numbers like  $3 \cdot \frac{1}{3} = \frac{1}{3} \cdot 3 = 1$ .

**Example 15** (Matrix inverses). An example are the matrices

$$A = \begin{bmatrix} 1 & 2 \\ 3 & 5 \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} -5 & 2 \\ 3 & -1 \end{bmatrix}$$

Because

$$\begin{aligned} AB &= \begin{bmatrix} 1 & 2 \\ 3 & 5 \end{bmatrix} \begin{bmatrix} -5 & 2 \\ 3 & -1 \end{bmatrix} \\ &= \begin{bmatrix} 1(-5) + 2 \cdot 3 & 1 \cdot 2 + 2(-1) \\ 3(-5) + 5 \cdot 3 & 2 \cdot 2 + 5(-1) \end{bmatrix} \\ &= \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &= I_2 \end{aligned}$$

And similarly,  $BA = I_2$ . Therefore  $A^{-1} = B$ .

End of Example 15.  $\square$

As noted, not every matrix has an inverse. A matrix that doesn't have an inverse is called **singular** or **noninvertible**. A matrix that has an inverse, is called **nonsingular** or **invertible**. Generally in mathematics, "singular" means "bad".

Moreover, note that it is possible for  $AB = I$  but  $BA \neq I$ , as the following example shows.

**Example 16.** Let

$$A = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \quad \text{and} \quad B = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \\ 0 & 1 \end{bmatrix}$$

Then

$$AB = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad \text{but} \quad BA = \frac{1}{2} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix}$$

End of Example 16.  $\square$

Incidentally this example illustrates one important way that matrix multiplication is not like multiplication of numbers.

## 6.2 An aside about commutativity

Consider two real numbers  $a, b \in \mathbb{R}$ . Then

$$ab = ba.$$

This property is called **commutativity**. One way that matrix multiplication differs from multiplication of real numbers is that if we consider two matrices  $A, B$ , then it is usually not the case that  $AB = BA$ . Whenever it is the case that  $AB = BA$ , we say that the matrices  $A$  and  $B$  **commute**, but again, this usually doesn't happen. Here are some examples:

**Example 17** (Commutativity and noncommutativity of matrix multiplication). Let

$$A = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} 2 & 3 \\ 0 & 2 \end{bmatrix} \quad \text{and} \quad C = \begin{bmatrix} 2 & 0 \\ 3 & 1 \end{bmatrix}.$$

Direct computation shows that

$$AB = BA = \begin{bmatrix} 2 & 5 \\ 0 & 2 \end{bmatrix}.$$

In this case, we say that the matrices  $A$  and  $B$  commute.

On the other hand, the matrices  $A$  and  $C$  do not commute because

$$AC = \begin{bmatrix} 5 & 1 \\ 3 & 1 \end{bmatrix} \quad \text{but} \quad CA = \begin{bmatrix} 2 & 2 \\ 3 & 4 \end{bmatrix}$$

so  $AC \neq CA$ .

End of Example 17.  $\square$

## 6.3 Encoding a linear system via matrix equations

In this section, we answer the first part of the main question of lecture. Consider the  $2 \times 2$  linear system

$$\begin{aligned} 3x_1 + 7x_2 &= 5 \\ 2x_1 - 6x_2 &= 1 \end{aligned}$$

Using matrix multiplication, we can write this system as

$$\begin{bmatrix} 3 & 7 \\ 2 & -6 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 5 \\ 1 \end{bmatrix}$$

In fact, we can do something similar with any linear system, as we now show:

Suppose we have any linear system, like this:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = b_2 \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = b_m \end{cases}$$

Define the three matrices

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{bmatrix}, \quad X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} \quad \text{and} \quad B = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix}$$

Then we can represent the linear system compactly as the matrix equation

$$AX = B.$$

This answers the question “*how can we encode a linear system using matrices?*” (It also provides us with the beginnings of an answer to the question “*why is matrix multiplication defined the way it is?*”, which is that matrix multiplication allows us to compactly represent linear systems, though a more compelling answer to this question will come later in the course.)

## 6.4 What does $A$ tell us about the linear system $AX = B$ ?

For the remainder of the lecture, we consider the question, “*What can we tell about the solutions to the linear system  $AX = B$ , just by looking at the matrix  $A$ ?*” It is not obvious that we should be able to tell anything at all about the solutions just by looking at  $A$ —after all, that’s, like trying to say something about the solutions to a system of equations *by only looking at the left-hand sides of the equations*.

Observe that if we know  $A^{-1}$ , then we can multiply both sides of this equation on the left by

$$A^{-1}AX = A^{-1}B$$

which simplifies to

$$X = A^{-1}B. \tag{10}$$

Thus,  $X$  is the unique solution to our original system. This motivates the following theorem:

**Theorem 18.** *A linear system  $AX = B$  with  $n$  equations and  $n$  variables has exactly one solution if and only if  $A$  is invertible.*

This theorem provides a partial answer to the main question of the lecture. What is remarkable is that it says we don’t need to know anything at all about the vector  $B$  to know whether the system has a unique solution. We only need to know whether  $A$  is singular or nonsingular. This hints a deeper structure in linear algebra that we will explore more fully throughout this course.

As an aside, note that when doing computations, it is usually easier to solve a linear system  $AX = B$  directly using row reduction, rather than (1) finding the inverse of  $A$  and then (2) multiplying both sides by  $A^{-1}$ . So the latter approach isn’t recommended for solving a system of linear equations. Just use row reduction.

We can actually push our answer to the lecture question a little bit further, by drawing a connection with one of your homework problems (homework 1, problem 3). In that problem, you showed that for the matrix  $A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$ , the linear system

$$AX = B$$

has a unique solution if and only if the determinant of  $A$  (defined as  $a_{11}a_{22} - a_{12}a_{21}$ ) is nonzero. That is,

$$\text{determinant of } A \text{ is nonzero} \iff AX = B \text{ has a unique solution}$$



Connecting this with Theorem 18, we have:

$$\text{determinant of } A \text{ is nonzero} \iff AX = B \text{ has a unique solution} \iff A \text{ is invertible}$$

Putting it together, we have the following theorem, which gives us an answer to the main question of the lecture:

**Theorem 19.** *Let  $A$  be an  $n \times n$  matrix. Then the following are equivalent:*

- (i.)  $A$  is invertible.*
- (ii.) The determinant of  $A$  is nonzero.*
- (iii.) For any vector  $B \in \mathbb{R}^n$  the linear system  $AX = B$  has exactly one solution.*

We haven't proved this theorem for all matrices; we've only shown that it holds for  $2 \times 2$  matrices. In fact, it holds for all matrices, as we'll see later.

## 7 2025-09-10 | Week 03 | Lecture 07

*This lecture isn't really based on any textbook section, but sections 1.5 and 1.6 cover determinants. Please read sections 1.3 and 1.4 for Friday.*

*The nexus question of this lecture: What is a determinant, geometrically?*

### 7.1 The determinant of $2 \times 2$ matrix

Recall that the determinant of a  $2 \times 2$  matrix is defined as the quantity

$$\det \begin{bmatrix} a & b \\ c & d \end{bmatrix} = ad - bc.$$

Later we'll see how to define determinants for  $n \times n$  matrices, but for this lecture I'm going to focus on the  $2 \times 2$  case in order to hopefully demonstrate why you should even care about determinants at all.

### 7.2 A matrix is a transformation of space

Consider the  $2 \times 2$  matrix

$$A = \begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix}.$$

**Preliminaries: Some elementary properties of  $A$**

Let us consider what this matrix does to the standard basis vectors  $e_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$  and  $e_2 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$ :

$$Ae_1 = \begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \end{bmatrix} \quad \text{and} \quad Ae_2 = \begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$$

In other words, multiplication by  $A$  sends the vector  $e_1$  to the vector  $\begin{bmatrix} 3 \\ 1 \end{bmatrix}$ . It sends the vector  $e_2$  to  $\begin{bmatrix} 1 \\ 2 \end{bmatrix}$ .

Let's give these vectors names and compute some values that will be useful later:

$$u = \begin{bmatrix} 3 \\ 1 \end{bmatrix} \quad \text{and} \quad v = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$$

- The magnitudes of  $u$  and  $v$  are

$$|u| = \sqrt{3^2 + 1^2} = \sqrt{10} \quad \text{and} \quad |v| = \sqrt{1^2 + 2^2} = \sqrt{5}$$

- The cosine of angle  $\theta$  between  $u$  and  $v$  can be computed using the dot product, by the formula

$$u \cdot v = |u||v|\cos(\theta).$$

Doing the computation, we get

$$\cos(\theta) = \frac{1}{\sqrt{2}}. \tag{11}$$

#### The key idea

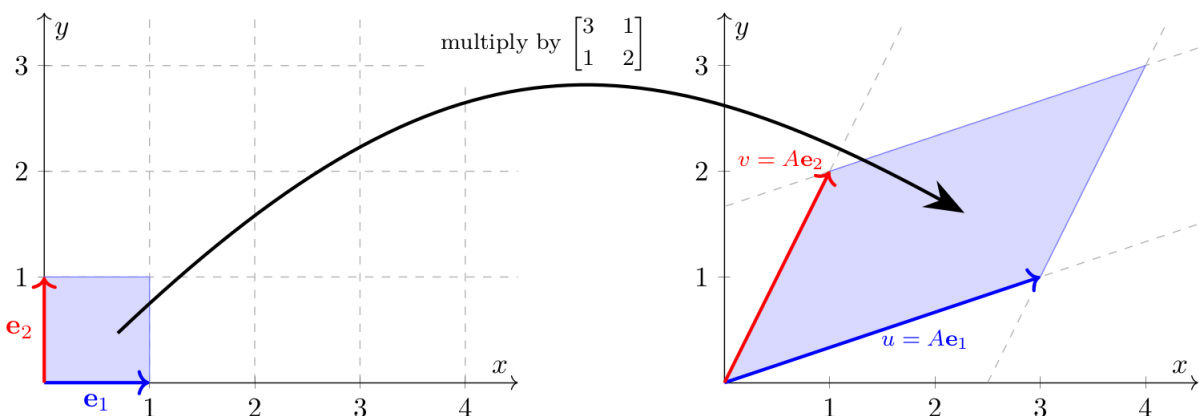
Suppose we decided to multiply *every* vector in the plane by the matrix  $\begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix}$ . In that case, we could conceive of the matrix transforming space (i.e., the plane) in some way. For a general vector in the plane  $\begin{bmatrix} x \\ y \end{bmatrix}$ , the action of  $A$  is the following:

$$\begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 3x + y \\ x + 2y \end{bmatrix}$$

If we use “ $\mapsto$ ” to mean “gets sent to”, then we have

$$\begin{bmatrix} x \\ y \end{bmatrix} \mapsto \begin{bmatrix} 3x + y \\ x + 2y \end{bmatrix}$$

The following plot shows the effect of multiplying *all* vectors in the unit square by  $A$ :

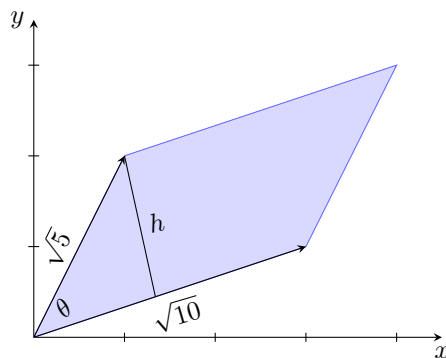


The effect of applying  $A$  is to transform space (i.e., the plane) by stretching it in some way. For this particular matrix, the unit square get mapped to the shown parallelogram. Squares adjacent to the unit square get sent to adjacent parallelograms.

### 7.3 The “volume scaling factor” of a transformation

**Question:** By what factor does the matrix  $\begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix}$  scale the area of a region in space?

**Answer:** The unit square has area 1. What about the parallelogram?



The parallelogram has area

$$(\text{area of parallelogram}) = (\text{base}) \times (\text{height}) \tag{12}$$

In this case, the base of the parallelogram is  $|u| = \sqrt{10}$ . To find the height  $h$ , use the definition of  $\sin(\theta)$ :

$$\sin(\theta) = \frac{\text{opposite}}{\text{hypotenuse}} = \frac{h}{\sqrt{5}}.$$

which implies

$$h = \sqrt{5} \sin(\theta)$$

We already know that  $\cos(\theta) = \frac{1}{\sqrt{2}}$  by Eq. (11). Therefore

$$\begin{aligned}\sin^2(\theta) &= 1 - \cos^2(\theta) && (\text{since } \sin^2(\theta) + \cos^2(\theta) = 1) \\ &= 1 - \frac{1}{2} \\ &= \frac{1}{2}.\end{aligned}$$

Taking square roots, we get  $\sin(\theta) = \frac{1}{\sqrt{2}}$ . Hence  $h = \frac{\sqrt{5}}{\sqrt{2}}$ . Therefore, by Eq. (12),

$$(\text{area of parallelogram}) = (\sqrt{10}) \left( \frac{\sqrt{5}}{\sqrt{2}} \right) = 5.$$

To conclude, the linear transformation of space obtained by multiplying every vector by the matrix  $A = \begin{bmatrix} 1 & 3 \\ 2 & 1 \end{bmatrix}$  took a region of area 1 (the unit square) and mapped it to a parallelogram of area 5. The scaling is uniform throughout the plane, so every region of area 1 gets mapped to a region of area 5. In other words, the transformation scales the volume by a factor 5.

Now let's look at the determinant of the matrix:

$$\det \begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix} = 3 \cdot 2 - 1 \cdot 1 = 5$$

The determinant is also 5. This is not a coincidence. **The determinant tells us how much space gets scaled by the linear transformation induced by the matrix.**

## 7.4 How do we interpret the determinant when it's zero or negative?

The determinant measures how much the linear transformation scales volume. But then what does it mean geometrically for a matrix to have determinant zero or negative?

- If the determinant is zero, that means regions with positive area get mapped to regions of zero area. **This always occurs as a result of dimension collapse.** For example, the following matrix has determinant zero:

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

Note that

$$\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} x \\ 0 \end{bmatrix}$$

Geometrically, this matrix projects every point in the plane to its location on the  $x$ -axis. This means that every point in the plane (a 2-dimensional surface) gets mapped to the  $x$ -axis (a 1-dimensional line with zero area). The dimension collapse here is the reduction in dimension from 2D to 1D.

Another example would be a transformation that projects every point in 3D space onto a specified plane; this is because mapping a 3D region onto a 2D plane destroys volume. An example of such a transformation is obtained from the matrix

$$P = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

which projects points in 3D space onto the  $xy$ -plane. We haven't discussed how to define the determinant for  $3 \times 3$  matrices, but based on our geometric intuition, we'd expect  $P$  to have determinant zero (it does).

- If the determinant is negative, that means the transformation reverses the orientation of space in the same way a mirror changes left and right hands. In 2D, this occurs when the transformation reflects the plane across a line. For example, the matrix

$$R = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

reflects the  $xy$ -plane across the line  $y = x$ , but doesn't stretch space at all. The determinant is  $-1$ . Under this transformation, regions don't stretch or shrink, but they do get flipped.

Another example can be obtained if we decided to *combine* two transformations:

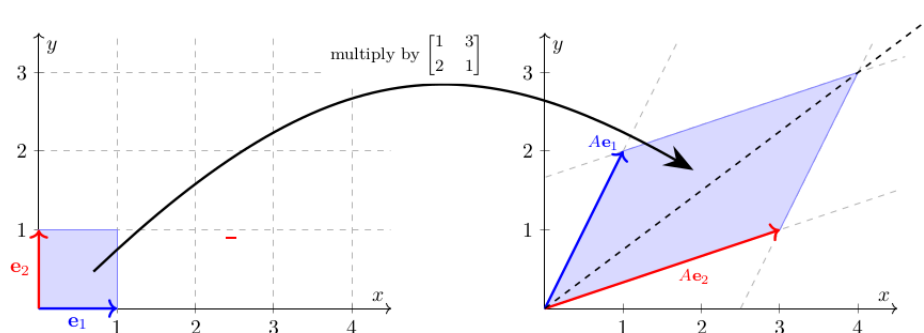
- **First**, flip the  $xy$ -plane using  $R$ .
- **Then**, transform space using the matrix  $A$ .

To combine these two transformations, we multiply the matrices like this:

$$AR = \underbrace{\begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix}}_{2^{\text{nd}}} \underbrace{\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}}_{1^{\text{st}}} = \begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix}$$

This new matrix has determinant  $-5$ . It is similar to the matrix  $A$  we considered earlier, but the columns are swapped. Geometrically, this matrix transforms space by first reflecting the plane across the line  $y = x$  and then doing the same stretchy thing done by the previous matrix.

The picture is almost the same as the previous one, but note how the red and blue vectors swapped compared to the first picture. The orientation has changed, which is why the determinant is negative.



## 8 2025-09-12 | Week 03 | Lecture 08

This lecture is based on sections 1.3 and 1.4 in your textbook

*The nexus question of this lecture: Something about inverses?*

### 8.1 What is a matrix inverse?

**Definition 20** (Matrix Inverse). The matrix  $A$  is **invertible** if there is a matrix  $A^{-1}$  such that

$$A^{-1}A = I \quad \text{and} \quad AA^{-1} = I$$

If so we call  $A^{-1}$  the **inverse** of  $A$ .

**Note:**

- Invertible matrices are always square. Nonsquare matrices are not invertible.
- Whatever  $A$  does,  $A^{-1}$  undoes. If  $A$  stretches spaces,  $A^{-1}$  compresses it back. If  $A$  flips space,  $A^{-1}$  flips it back. If  $A$  rotates spaces,  $A^{-1}$  rotates it back, etc.

**Theorem 21** (The socks and shoes property). *If  $A$  and  $B$  are invertible then so is  $AB$ . The inverse of a product  $AB$  is*

$$(AB)^{-1} = B^{-1}A^{-1}$$

If you put on socks and then shoes, what is the inverse of that? Take off the shoes, and then the socks.

*Proof of Theorem 21.* It is sufficient to show that  $B^{-1}A^{-1}$  is the inverse of  $AB$ , which we can do by direct computation:

$$(AB)(B^{-1}A^{-1}) = A(BB^{-1})A^{-1} = A(I)A^{-1} = AA^{-1} = I.$$

and

$$(B^{-1}A^{-1})(AB) = B^{-1}(A^{-1}A)B = B^{-1}B = I$$

□

**Theorem 22.** *Suppose that  $A$  and  $B$  are square matrices such that either  $AB = I$  or  $BA = I$ . Then  $A$  is an invertible matrix and  $A^{-1} = B$*

I'm going to omit the proof of this theorem, but I will introduce the general framework that that is used to prove it and results like it, because it is based on an important idea.

### 8.2 Row reduction is multiplication by elementary matrices

Section 1.3 in the textbook provides a powerful framework, based on row reduction, for deducing properties of inverses. Recall that in row reduction, you have three basic operations:

- swapping two rows
- multiplying a row by a number
- adding a multiple of a row to another row.

These operations can all be done using matrix multiplication, using matrices called **elementary matrices**. Here are some examples:

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} c & d \\ a & b \end{bmatrix} \qquad R_1 \leftrightarrow R_2$$

$$\begin{bmatrix} 5 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} 5a & 5b \\ c & d \end{bmatrix} \quad 5R_1 \rightarrow R_1$$

$$\begin{bmatrix} 1 & 0 \\ 3 & 1 \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} c & d \\ 3a+c & 3b+d \end{bmatrix} \quad 3R_1 + R_2 \rightarrow R_2$$

If you can row reduce a matrix  $A$  to  $I$ , that means there exists some sequence of elementary matrices  $E_1, \dots, E_m$  such that

$$E_1 E_2 E_3 \cdots E_m A = I.$$

Letting  $M = E_1 E_2 E_3 \cdots E_m$ , we have

$$MA = I.$$

By Theorem 22, this is enough to conclude that  $A$  is invertible and

$$A^{-1} = M.$$

We've just proven part of the following theorem:

**Theorem 23.** *Let  $A$  be a square matrix. The following are equivalent:*

(i.)  *$A$  can be row-reduced to the identity matrix  $I$ .*

(ii.)  *$A$  is invertible.*

In particular, we've shown that (i.) implies (ii.). The reverse direction (that (ii.) implies (i.)) can also be proved using this framework of elementary matrices, but I'd rather just illustrate it by showing examples of how a matrix inverse can be computed using row reduction.

### 8.3 Computing matrix inverses using row-reduction

The next example will illustrate a general approach for computing a matrix inverse.

**Example 24** (Computing the inverse of a matrix). In the previous lecture, we considered the matrix

$$A = \begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix}$$

which stretches space in some way, scaling area by a factor of 5. Suppose we wish to find  $A^{-1}$ .

Let

$$X = \begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{bmatrix}$$

We need  $X$  to satisfy

$$AX = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Writing out  $AX$ , we have

$$AX = \begin{bmatrix} 3 & 1 \\ 1 & 2 \end{bmatrix} \begin{bmatrix} x_{11} & x_{12} \\ x_{21} & x_{22} \end{bmatrix} = \begin{bmatrix} 3x_{11} + x_{21} & 3x_{12} + x_{22} \\ x_{11} + 2x_{21} & x_{12} + 2x_{22} \end{bmatrix} \stackrel{\text{set}}{=} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

By setting  $AX$  equal to  $I$ , we have a system of four linear equations in four variables  $x_{11}, x_{12}, x_{21}, x_{22}$ .

We have a nice way to solve linear systems: row reduction. Moreover, for finding inverses, there is a clever way to do it, as I now show. The augmented matrix we will use is the following:

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

Row reducing this, we get:

$$\left[ \begin{array}{cc|cc} 1 & 0 & 2/5 & -1/5 \\ 0 & 1 & -1/5 & 3/5 \end{array} \right]$$

and  $A^{-1}$  is the the matrix to the right of the bar:

$$A^{-1} = \begin{bmatrix} 2/5 & -1/5 \\ -1/5 & 3/5 \end{bmatrix}$$

Recall that  $A$  somehow stretched space in a way that scaled area by a factor of 5, because  $\det(A) = 5$ . The transformation of  $A^{-1}$  undoes whatever  $A$  did, so it must shrink space by a factor of 5. Indeed,

$$\det(A^{-1}) = \begin{pmatrix} 2 \\ 5 \end{pmatrix} \begin{pmatrix} 3 \\ 5 \end{pmatrix} - \begin{pmatrix} -1 \\ 5 \end{pmatrix} \begin{pmatrix} -1 \\ 5 \end{pmatrix} = \frac{6}{25} - \frac{1}{25} = \frac{1}{5}.$$

End of Example 24.  $\square$

Before doing another example, I want to note that Example 24 illustrates the following theorem:

**Theorem 25.** *If  $A^{-1}$  exists then*

$$\det(A^{-1}) = \frac{1}{\det(A)}.$$

Now that we know the determinant of a matrix measures how space is scaled by the transformation, the geometric reason why this theorem is true is obvious: the matrix  $A$  transforms space in some way, and then  $A^{-1}$  undoes that transformation. So we are left with the **identity transformation**, which doesn't change space at all. So if  $A$  scales space by a factor of  $a$  then  $A^{-1}$  must scale it by a factor of  $\frac{1}{a}$ . We'll probably give an actual proof later, but that's the idea.

The approach in Example 24 works for larger matrices as well, see Example 1 in Section 1.3 of the textbook (p.31).

**Example 26** (Example 1 in section 1.3). Find the inverse of the matrix

$$A = \begin{bmatrix} 2 & 1 & 3 \\ 2 & 1 & 1 \\ 4 & 5 & 1 \end{bmatrix}$$

We set up the augmented matrix

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

After row reduction, we obtain

$$\left[ \begin{array}{ccc|ccc} 1 & 0 & 0 & -1/3 & 7/6 & -1/6 \\ 0 & 1 & 0 & 1/6 & -5/6 & 1/3 \\ 0 & 0 & 1 & 1/2 & -1/2 & 0 \end{array} \right].$$

Then the inverse of  $A$  is given by

$$A^{-1} = \begin{bmatrix} -1/3 & 7/6 & -1/6 \\ 1/6 & -5/6 & 1/3 \\ 1/2 & -1/2 & 0 \end{bmatrix}.$$

End of Example 26.  $\square$



## 9 2025-09-15 | Week 04 | Lecture 09

### 9.1 Transpose

Given an  $m \times n$  matrix  $A = (a_{ij})$ , the **transpose** of  $A$ , denoted  $A^\top$ , is the  $n \times m$  matrix  $A^\top = (a_{ji})$ . For example,

$$A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix} \quad \text{and} \quad A^\top = \begin{bmatrix} 1 & 4 \\ 2 & 5 \\ 3 & 6 \end{bmatrix}$$

**Theorem 27** (Properties of Transpose). *Suppose  $A, B$  are matrices. Then whenever defined, the following properties hold:*

1.  $(A^\top)^\top = A$
2.  $(A + B)^\top = A^\top + B^\top$
3.  $(cA)^\top = cA^\top$
4.  $(AB)^\top = B^\top A^\top$
5.  $(A^\top)^{-1} = (A^{-1})^\top$

*Proof.* Maybe prove properties 4 and 5. The proof is kind of neat, just uses the definition of matrix multiplication.  $\square$

### 9.2 Symmetric Matrices

If  $A = A^\top$ , then we say that  $A$  is **symmetric**. An example:

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

Symmetric matrices are always square. If  $A, B$  are symmetric, then  $A + B$  is also symmetric.

**Theorem 28.** *Let  $A$  be any matrix. Then  $A^\top A$  and  $AA^\top$  are both symmetric.*

*Proof.* Uses matrix multiplication.  $\square$

**Theorem 29.** *If  $A$  is an invertible symmetric matrix, then  $A^{-1}$  is also symmetric.*

*Proof.* Using the fact that  $(A^{-1})^\top = (A^\top)^{-1}$ , we have

$$\begin{aligned} (A^{-1})^\top &= (A^\top)^{-1} \\ &= (A)^{-1} \\ &= A^{-1}. \end{aligned}$$

This calculation shows that  $A^{-1}$  is symmetric, since it equals its transpose.  $\square$