

# Linear Algebra for Team-Based Inquiry Learning

2024 Edition PREVIEW

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October 25, 2023

**Website:** [Linear Algebra for Team-Based Inquiry Learning](https://linear.tbil.org)<sup>1</sup>

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# Chapter 1

# Systems of Linear Equations (LE)

## Learning Outcomes

How can we solve systems of linear equations?

By the end of this chapter, you should be able to...

1. Translate back and forth between a system of linear equations, a vector equation, and the corresponding augmented matrix.
2. Explain why a matrix isn't in reduced row echelon form, and put a matrix in reduced row echelon form.
3. Determine the number of solutions for a system of linear equations or a vector equation.
4. Compute the solution set for a system of linear equations or a vector equation with infinitely many solutions.

## 1.1 Linear Systems, Vector Equations, and Augmented Matrices (LE1)

### Learning Outcomes

- Translate back and forth between a system of linear equations, a vector equation, and the corresponding augmented matrix.



## Linear Systems, Vector Equations, and Augmented Matrices (LE1)

**Definition 1.1.1** A **linear equation** is an equation of the variables  $x_i$  of the form

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

A **solution** for a linear equation is a Euclidean vector

$$\begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix}$$

that satisfies

$$a_1s_1 + a_2s_2 + \cdots + a_ns_n = b$$

(that is, a Euclidean vector that can be plugged into the equation).  $\diamond$

## Linear Systems, Vector Equations, and Augmented Matrices (LE1)

**Remark 1.1.2** In previous classes you likely used the variables  $x, y, z$  in equations. However, since this course often deals with equations of four or more variables, we will often write our variables as  $x_i$ , and assume  $x = x_1, y = x_2, z = x_3, w = x_4$  when convenient.

**Definition 1.1.3** A **system of linear equations** (or a **linear system** for short) is a collection of one or more linear equations.

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

Its **solution set** is given by

$$\left\{ \left[ \begin{array}{c} s_1 \\ s_2 \\ \vdots \\ s_n \end{array} \right] \middle| \left[ \begin{array}{c} s_1 \\ s_2 \\ \vdots \\ s_n \end{array} \right] \text{ is a solution to all equations in the system} \right\}.$$

◇

## Linear Systems, Vector Equations, and Augmented Matrices (LE1)

**Remark 1.1.4** When variables in a large linear system are missing, we prefer to write the system in one of the following standard forms:

Original linear system:    Verbose standard form:    Concise standard form:

$$\begin{array}{lll} x_1 + 3x_3 = 3 & 1x_1 + 0x_2 + 3x_3 = 3 & x_1 \quad \quad + 3x_3 = 3 \\ 3x_1 - 2x_2 + 4x_3 = 0 & 3x_1 - 2x_2 + 4x_3 = 0 & 3x_1 - 2x_2 + 4x_3 = 0 \\ -x_2 + x_3 = -2 & 0x_1 - 1x_2 + 1x_3 = -2 & \quad - x_2 + x_3 = -2 \end{array}$$

**Remark 1.1.5** It will often be convenient to think of a system of equations as a vector equation.

By applying vector operations and equating components, it is straightforward to see that the vector equation

$$x_1 \begin{bmatrix} 1 \\ 3 \\ 0 \end{bmatrix} + x_2 \begin{bmatrix} 0 \\ -2 \\ -1 \end{bmatrix} + x_3 \begin{bmatrix} 3 \\ 4 \\ 1 \end{bmatrix} = \begin{bmatrix} 3 \\ 0 \\ -2 \end{bmatrix}$$

is equivalent to the system of equations

$$\begin{array}{rcrcrcrcrcrcl} x_1 & & & & & + 3x_3 & = & 3 \\ 3x_1 & - 2x_2 & + 4x_3 & = & 0 \\ & - & x_2 & + & x_3 & = & -2 \end{array}$$

**Definition 1.1.6** A linear system is **consistent** if its solution set is non-empty (that is, there exists a solution for the system). Otherwise it is **inconsistent**.  $\diamond$

**Fact 1.1.7** *All linear systems are one of the following:*

1. Consistent with one solution: *its solution set contains a single vector,*

*e.g.*  $\left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \right\}$

2. Consistent with infinitely-many solutions: *its solution set contains in-*

*finitely many vectors, e.g.*  $\left\{ \begin{bmatrix} 1 \\ 2 - 3a \\ a \end{bmatrix} \mid a \in \mathbb{R} \right\}$

3. Inconsistent: *its solution set is the empty set, denoted by either  $\{\}$  or  $\emptyset$ .*

**Activity 1.1.8** All inconsistent linear systems contain a logical **contradiction**. Find a contradiction in this system to show that its solution set is the empty set.

$$-x_1 + 2x_2 = 5$$

$$2x_1 - 4x_2 = 6$$



**Activity 1.1.9** Consider the following consistent linear system.

$$-x_1 + 2x_2 = -3$$

$$2x_1 - 4x_2 = 6$$

- (a) Find three different solutions for this system.
- (b) Let  $x_2 = a$  where  $a$  is an arbitrary real number, then find an expression for  $x_1$  in terms of  $a$ . Use this to write the solution set  $\left\{ \begin{bmatrix} ? \\ a \end{bmatrix} \middle| a \in \mathbb{R} \right\}$  for the linear system.

**Activity 1.1.10** Consider the following linear system.

$$\begin{array}{rcl} x_1 + 2x_2 & - & x_4 = 3 \\ x_3 + 4x_4 & = & -2 \end{array}$$

Describe the solution set

$$\left\{ \left[ \begin{array}{c} ? \\ a \\ ? \\ b \end{array} \right] \middle| a, b \in \mathbb{R} \right\}$$

to the linear system by setting  $x_2 = a$  and  $x_4 = b$ , and then solving for  $x_1$  and  $x_3$ .

## Linear Systems, Vector Equations, and Augmented Matrices (LE1)

**Observation 1.1.11** Solving linear systems of two variables by graphing or substitution is reasonable for two-variable systems, but these simple techniques won't usually cut it for equations with more than two variables or more than two equations. For example,

$$-2x_1 - 4x_2 + x_3 - 4x_4 = -8$$

$$x_1 + 2x_2 + 2x_3 + 12x_4 = -1$$

$$x_1 + 2x_2 + x_3 + 8x_4 = 1$$

has the exact same solution set as the system in the previous activity, but we'll want to learn new techniques to compute these solutions efficiently.

## Linear Systems, Vector Equations, and Augmented Matrices (LE1)

**Remark 1.1.12** The only important information in a linear system are its coefficients and constants.

Original linear system:    Verbose standard form:    Coefficients/constants:

$$\begin{array}{rclcl} x_1 + 3x_3 = 3 & 1x_1 + 0x_2 + 3x_3 = 3 & 1 & 0 & 3 \mid 3 \\ 3x_1 - 2x_2 + 4x_3 = 0 & 3x_1 - 2x_2 + 4x_3 = 0 & 3 & -2 & 4 \mid 0 \\ -x_2 + x_3 = -2 & 0x_1 - 1x_2 + 1x_3 = -2 & 0 & -1 & 1 \mid -2 \end{array}$$

## Linear Systems, Vector Equations, and Augmented Matrices (LE1)

**Definition 1.1.13** A system of  $m$  linear equations with  $n$  variables is often represented by writing its coefficients and constants in an **augmented matrix**.

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

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



## Linear Systems, Vector Equations, and Augmented Matrices (LE1)

**Example 1.1.14** The corresponding augmented matrix for this system is obtained by simply writing the coefficients and constants in matrix form.

Linear system:

Augmented matrix:

$$\begin{array}{rcrcrcrcl} x_1 & & & + & 3x_3 & = & 3 \\ 3x_1 & - & 2x_2 & + & 4x_3 & = & 0 \\ & - & x_2 & + & x_3 & = & -2 \end{array} \qquad \left[ \begin{array}{ccc|c} 1 & 0 & 3 & 3 \\ 3 & -2 & 4 & 0 \\ 0 & -1 & 1 & -2 \end{array} \right]$$

Vector equation:

$$x_1 \begin{bmatrix} 1 \\ 3 \\ 0 \end{bmatrix} + x_2 \begin{bmatrix} 0 \\ -2 \\ -1 \end{bmatrix} + x_3 \begin{bmatrix} 3 \\ 4 \\ 1 \end{bmatrix} = \begin{bmatrix} 3 \\ 0 \\ -2 \end{bmatrix}$$

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## 1.2 Row Reduction of Matrices (LE2)

### Learning Outcomes

- Explain why a matrix isn't in reduced row echelon form, and put a matrix in reduced row echelon form.

## Row Reduction of Matrices (LE2)

**Definition 1.2.1** Two systems of linear equations (and their corresponding augmented matrices) are said to be **equivalent** if they have the same solution set.

For example, both of these systems share the same solution set  $\left\{ \begin{bmatrix} 1 \\ 1 \end{bmatrix} \right\}$ .

$$3x_1 - 2x_2 = 1$$

$$x_1 + 4x_2 = 5$$

$$3x_1 - 2x_2 = 1$$

$$4x_1 + 2x_2 = 6$$

Therefore these augmented matrices are equivalent (even though they're not *equal*), which we denote with  $\sim$ :

$$\left[ \begin{array}{cc|c} 3 & -2 & 1 \\ 1 & 4 & 5 \end{array} \right] \neq \left[ \begin{array}{cc|c} 3 & -2 & 1 \\ 4 & 2 & 6 \end{array} \right]$$

$$\left[ \begin{array}{cc|c} 3 & -2 & 1 \\ 1 & 4 & 5 \end{array} \right] \sim \left[ \begin{array}{cc|c} 3 & -2 & 1 \\ 4 & 2 & 6 \end{array} \right]$$

◇



## Row Reduction of Matrices (LE2)

**Activity 1.2.2** Consider whether these matrix manipulations (A) *must keep* or (B) *could change* the solution set for the corresponding linear system.

(a) Swapping two rows, for example:

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 4 & 5 & 6 \\ 1 & 2 & 3 \end{array} \right] \quad \begin{array}{l} x + 2y = 3 \\ 4x + 5y = 6 \end{array} \quad \begin{array}{l} 4x + 5y = 6 \\ x + 2y = 3 \end{array}$$

(b) Swapping two columns, for example:

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 2 & 1 & 3 \\ 5 & 4 & 6 \end{array} \right] \quad \begin{array}{l} x + 2y = 3 \\ 4x + 5y = 6 \end{array} \quad \begin{array}{l} 2x + y = 6 \\ 5x + 4y = 3 \end{array}$$

(c) Add a constant to every term of a row, for example:

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 1+6 & 2+6 & 3+6 \\ 4 & 5 & 6 \end{array} \right] \quad \begin{array}{l} x + 2y = 3 \\ 4x + 5y = 6 \end{array} \quad \begin{array}{l} 7x + 8y = 9 \\ 4x + 5y = 3 \end{array}$$

(d) Multiply a row by a nonzero constant, for example:

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 3 & 6 & 9 \\ 4 & 5 & 6 \end{array} \right] \quad \begin{array}{l} x + 2y = 3 \\ 4x + 5y = 6 \end{array} \quad \begin{array}{l} 3x + 6y = 9 \\ 4x + 5y = 3 \end{array}$$

(e) Add a constant multiple of one row to another row, for example:

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4+3 & 5+6 & 6+9 \end{array} \right] \quad \begin{array}{l} x + 2y = 3 \\ 4x + 5y = 6 \end{array} \quad \begin{array}{l} ?x + ?y = ? \\ ?x + ?y = ? \end{array}$$

(f) Replace a column with zeros, for example:

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 1 & 0 & 3 \\ 4 & 0 & 6 \end{array} \right] \quad \begin{array}{l} x + 2y = 3 \\ 4x + 5y = 6 \end{array} \quad \begin{array}{l} ?x + ?y = ? \\ ?x + ?y = ? \end{array}$$

(g) Replace a row with zeros, for example:

Row Reduction of Matrices (LE2)

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 0 & 0 & 0 \end{array} \right]$$

$$\begin{array}{lcl} x + 2y = 3 & ?x + ?y = ? \\ 4x + 5y = 6 & ?x + ?y = ? \end{array}$$

## Row Reduction of Matrices (LE2)

**Definition 1.2.3** The following three **row operations** produce equivalent augmented matrices.

1. Swap two rows, for example,  $R_1 \leftrightarrow R_2$ :

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 4 & 5 & 6 \\ 1 & 2 & 3 \end{array} \right]$$

2. Multiply a row by a nonzero constant, for example,  $2R_1 \rightarrow R_1$ :

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 2(1) & 2(2) & 2(3) \\ 4 & 5 & 6 \end{array} \right]$$

3. Add a constant multiple of one row to another row, for example,  $R_2 - 4R_1 \rightarrow R_2$ :

$$\left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 & 5 & 6 \end{array} \right] \sim \left[ \begin{array}{cc|c} 1 & 2 & 3 \\ 4 - 4(1) & 5 - 4(2) & 6 - 4(3) \end{array} \right]$$

Observe that we will use the following notation: (Combination of old rows)  $\rightarrow$  (New row).  $\diamond$

## Row Reduction of Matrices (LE2)

**Activity 1.2.4** Each of the following linear systems has the same solution set.

A)

$$\begin{aligned}x + 2y + z &= 3 \\ -x - y + z &= 1 \\ 2x + 5y + 3z &= 7\end{aligned}$$

B)

$$\begin{aligned}2x + 5y + 3z &= 7 \\ -x - y + z &= 1 \\ x + 2y + z &= 3\end{aligned}$$

C)

$$\begin{aligned}x - z &= 1 \\ y + 2z &= 4 \\ y + z &= 1\end{aligned}$$

D)

$$\begin{aligned}x + 2y + z &= 3 \\ y + 2z &= 4 \\ 2x + 5y + 3z &= 7\end{aligned}$$

E)

$$\begin{aligned}x - z &= 1 \\ y + z &= 1 \\ z &= 3\end{aligned}$$

F)

$$\begin{aligned}x + 2y + z &= 3 \\ y + 2z &= 4 \\ y + z &= 1\end{aligned}$$

Sort these six equivalent linear systems from most complicated to simplest (in your opinion).

## Row Reduction of Matrices (LE2)

**Activity 1.2.5** Here we've written the sorted linear systems from [Activity 1.2.4](#) as augmented matrices.

$$\begin{aligned} & \left[ \begin{array}{ccc|c} 2 & 5 & 3 & 7 \\ -1 & -1 & 1 & 1 \\ 1 & 2 & 1 & 3 \end{array} \right] \sim \left[ \begin{array}{ccc|c} \boxed{1} & 2 & 1 & 3 \\ -1 & -1 & 1 & 1 \\ 2 & 5 & 3 & 7 \end{array} \right] \sim \left[ \begin{array}{ccc|c} \boxed{1} & 2 & 1 & 3 \\ 0 & 1 & 2 & 4 \\ 2 & 5 & 3 & 7 \end{array} \right] \sim \\ & \sim \left[ \begin{array}{ccc|c} \boxed{1} & 2 & 1 & 3 \\ 0 & \boxed{1} & 2 & 4 \\ 0 & 1 & 1 & 1 \end{array} \right] \sim \left[ \begin{array}{ccc|c} \boxed{1} & 0 & -1 & 1 \\ 0 & \boxed{1} & 2 & 4 \\ 0 & 1 & 1 & 1 \end{array} \right] \sim \left[ \begin{array}{ccc|c} \boxed{1} & 0 & -1 & 1 \\ 0 & \boxed{1} & 1 & 1 \\ 0 & 0 & -1 & -3 \end{array} \right] \end{aligned}$$

Assign the following row operations to each step used to manipulate each matrix to the next:

$$R_3 - 1R_2 \rightarrow R_3$$

$$R_2 + 1R_1 \rightarrow R_2$$

$$R_1 \leftrightarrow R_3$$

$$R_3 - 2R_1 \rightarrow R_3$$

$$R_1 - 2R_3 \rightarrow R_1$$

## Row Reduction of Matrices (LE2)

**Definition 1.2.6** A matrix is in **reduced row echelon form (RREF)** if

1. The leftmost nonzero term of each row is 1. We call these terms **pivots**.
2. Each pivot is to the right of every higher pivot.
3. Each term that is either above or below a pivot is 0.
4. All zero rows (rows whose terms are all 0) are at the bottom of the matrix.

Every matrix has a unique reduced row echelon form. If  $A$  is a matrix, we write  $\text{RREF}(A)$  for the reduced row echelon form of that matrix.  $\diamond$

## Row Reduction of Matrices (LE2)

**Activity 1.2.7** Recall that a matrix is in **reduced row echelon form (RREF)** if

1. The leftmost nonzero term of each row is 1. We call these terms **pivots**.
2. Each pivot is to the right of every higher pivot.
3. Each term that is either above or below a pivot is 0.
4. All zero rows (rows whose terms are all 0) are at the bottom of the matrix.

For each matrix, mark the leading terms, and label it as RREF or not RREF. For the ones not in RREF, determine which rule is violated and how it might be fixed.

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

## Row Reduction of Matrices (LE2)

**Activity 1.2.8** Recall that a matrix is in **reduced row echelon form (RREF)** if

1. The leftmost nonzero term of each row is 1. We call these terms **pivots**.
2. Each pivot is to the right of every higher pivot.
3. Each term that is either above or below a pivot is 0.
4. All zero rows (rows whose terms are all 0) are at the bottom of the matrix.

For each matrix, mark the leading terms, and label it as RREF or not RREF. For the ones not in RREF, determine which rule is violated and how it might be fixed.

$$D = \left[ \begin{array}{ccc|c} 1 & 0 & 2 & -3 \\ 0 & 3 & 3 & -3 \\ 0 & 0 & 0 & 0 \end{array} \right] \quad E = \left[ \begin{array}{ccc|c} 0 & 1 & 0 & 7 \\ 1 & 0 & 0 & 4 \\ 0 & 0 & 0 & 0 \end{array} \right] \quad F = \left[ \begin{array}{ccc|c} 1 & 0 & 0 & 4 \\ 0 & 1 & 0 & 7 \\ 0 & 0 & 1 & 0 \end{array} \right]$$



## Row Reduction of Matrices (LE2)

**Remark 1.2.9** In practice, if we simply need to convert a matrix into reduced row echelon form, we use technology to do so.

However, it is also important to understand the **Gauss-Jordan elimination** algorithm that a computer or calculator uses to convert a matrix (augmented or not) into reduced row echelon form. Understanding this algorithm will help us better understand how to interpret the results in many applications we use it for in [Chapter 2](#).

## Row Reduction of Matrices (LE2)

**Activity 1.2.10** Consider the matrix

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

Which row operation is the best choice for the first move in converting to RREF?

- A. Add row 3 to row 2 ( $R_2 + R_3 \rightarrow R_2$ )
- B. Add row 2 to row 3 ( $R_3 + R_2 \rightarrow R_3$ )
- C. Swap row 1 to row 2 ( $R_1 \leftrightarrow R_2$ )
- D. Add -2 row 2 to row 1 ( $R_1 - 2R_2 \rightarrow R_1$ )

## Row Reduction of Matrices (LE2)

**Activity 1.2.11** Consider the matrix

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

Which row operation is the best choice for the next move in converting to RREF?

- A. Add row 1 to row 3 ( $R_3 + R_1 \rightarrow R_3$ )
- B. Add -2 row 1 to row 2 ( $R_2 - 2R_1 \rightarrow R_2$ )
- C. Add 2 row 2 to row 3 ( $R_3 + 2R_2 \rightarrow R_3$ )
- D. Add 2 row 3 to row 2 ( $R_2 + 2R_3 \rightarrow R_2$ )

## Row Reduction of Matrices (LE2)

**Activity 1.2.12** Consider the matrix

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

Which row operation is the best choice for the next move in converting to RREF?

- A. Add row 1 to row 2 ( $R_2 + R_1 \rightarrow R_2$ )
- B. Add -1 row 3 to row 2 ( $R_2 - R_3 \rightarrow R_2$ )
- C. Add -1 row 2 to row 3 ( $R_3 - R_2 \rightarrow R_3$ )
- D. Add row 2 to row 1 ( $R_1 + R_2 \rightarrow R_1$ )

## Row Reduction of Matrices (LE2)

**Observation 1.2.13** The steps for the Gauss-Jordan elimination algorithm may be summarized as follows:

1. Ignoring any rows that already have marked pivots, identify the leftmost column with a nonzero entry.
2. Use row operations to obtain a pivot of value 1 in the topmost row that does not already have a marked pivot.
3. Mark this pivot, then use row operations to change all values above and below the marked pivot to 0.
4. Repeat these steps until the matrix is in RREF.

In particular, *once a pivot is marked, it should remain in the same position*. This will keep you from undoing your progress towards an RREF matrix.

## Row Reduction of Matrices (LE2)

**Activity 1.2.14** Complete the following RREF calculation (multiple row operations may be needed for certain steps):

$$\begin{aligned}
 A = \begin{bmatrix} 2 & 3 & 2 & 3 \\ -2 & 1 & 6 & 1 \\ -1 & -3 & -4 & 1 \end{bmatrix} &\sim \begin{bmatrix} \boxed{1} & ? & ? & ? \\ -2 & 1 & 6 & 1 \\ -1 & -3 & -4 & 1 \end{bmatrix} \sim \begin{bmatrix} \boxed{1} & ? & ? & ? \\ 0 & ? & ? & ? \\ 0 & ? & ? & ? \end{bmatrix} \\
 &\sim \begin{bmatrix} \boxed{1} & ? & ? & ? \\ 0 & \boxed{1} & ? & ? \\ 0 & ? & ? & ? \end{bmatrix} \sim \begin{bmatrix} \boxed{1} & 0 & ? & ? \\ 0 & \boxed{1} & ? & ? \\ 0 & 0 & ? & ? \end{bmatrix} \sim \dots \sim \begin{bmatrix} \boxed{1} & 0 & -2 & 0 \\ 0 & \boxed{1} & 2 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}
 \end{aligned}$$

## Row Reduction of Matrices (LE2)

**Activity 1.2.15** Consider the matrix

$$A = \begin{bmatrix} 2 & 4 & 2 & -4 \\ -2 & -4 & 1 & 1 \\ 3 & 6 & -1 & -4 \end{bmatrix}.$$

Compute  $\text{RREF}(A)$ .

## Row Reduction of Matrices (LE2)

**Activity 1.2.16** Consider the non-augmented and augmented matrices

$$A = \begin{bmatrix} 2 & 4 & 2 & -4 \\ -2 & -4 & 1 & 1 \\ 3 & 6 & -1 & -4 \end{bmatrix} \quad B = \left[ \begin{array}{ccc|c} 2 & 4 & 2 & -4 \\ -2 & -4 & 1 & 1 \\ 3 & 6 & -1 & -4 \end{array} \right].$$

Can  $\text{RREF}(A)$  be used to find  $\text{RREF}(B)$ ?

- A. Yes,  $\text{RREF}(A)$  and  $\text{RREF}(B)$  are exactly the same.
- B. Yes,  $\text{RREF}(A)$  may be slightly modified to find  $\text{RREF}(B)$ .
- C. No, a new calculation is required.



## Row Reduction of Matrices (LE2)

**Activity 1.2.17** Free browser-based technologies for mathematical computation are available online.

- Go to <https://sagecell.sagemath.org/>.
- In the dropdown on the right, you can select a number of different languages. Select "Octave" for the Matlab-compatible syntax used by this text.
- Type `rref([1,3,2;2,5,7])` and then press the Evaluate button to compute the RREF of  $\begin{bmatrix} 1 & 3 & 2 \\ 2 & 5 & 7 \end{bmatrix}$ .

## Row Reduction of Matrices (LE2)

**Activity 1.2.18** In the HTML version of this text, code cells are often embedded for your convenience when RREFs need to be computed.

Try this out to compute RREF  $\left[ \begin{array}{cc|c} 2 & 3 & 1 \\ 3 & 0 & 6 \end{array} \right]$ .

## 1.3 Counting Solutions for Linear Systems (LE3)

### Learning Outcomes

- Determine the number of solutions for a system of linear equations or a vector equation.

### Counting Solutions for Linear Systems (LE3)

**Remark 1.3.1** We will frequently need to know the reduced row echelon form of matrices during the remainder of this course, so unless you're told otherwise, feel free to use technology (see [Activity 1.2.17](#)) to compute RREFs efficiently.

### Counting Solutions for Linear Systems (LE3)

**Activity 1.3.2** Consider the following system of equations.

$$3x_1 - 2x_2 + 13x_3 = 6$$

$$2x_1 - 2x_2 + 10x_3 = 2$$

$$-x_1 + 3x_2 - 6x_3 = 11.$$

- (a) Convert this to an augmented matrix and use technology to compute its reduced row echelon form:

$$\text{RREF} \left[ \begin{array}{ccc|c} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{array} \right] = \left[ \begin{array}{ccc|c} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{array} \right]$$

- (b) Use the RREF matrix to write a linear system equivalent to the original system.
- (c) How many solutions must this system have?

A. Zero

B. Only one

C. Infinitely-many

### Counting Solutions for Linear Systems (LE3)

**Activity 1.3.3** Consider the vector equation

$$x_1 \begin{bmatrix} 3 \\ 2 \\ -1 \end{bmatrix} + x_2 \begin{bmatrix} -2 \\ -2 \\ 0 \end{bmatrix} + x_3 \begin{bmatrix} 13 \\ 10 \\ -3 \end{bmatrix} = \begin{bmatrix} 6 \\ 2 \\ 1 \end{bmatrix}$$

- (a) Convert this to an augmented matrix and use technology to compute its reduced row echelon form:

$$\text{RREF} \left[ \begin{array}{ccc|c} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{array} \right] = \left[ \begin{array}{ccc|c} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{array} \right]$$

- (b) Use the RREF matrix to write a linear system equivalent to the original system.
- (c) How many solutions must this system have?

A. Zero

B. Only one

C. Infinitely-many

### Counting Solutions for Linear Systems (LE3)

**Activity 1.3.4** What contradictory equations besides  $0 = 1$  may be obtained from the RREF of an augmented matrix?

- A.  $x = 0$  is an obtainable contradiction
- B.  $x = y$  is an obtainable contradiction
- C.  $0 = 17$  is an obtainable contradiction
- D.  $0 = 1$  is the only obtainable contradiction

### Counting Solutions for Linear Systems (LE3)

**Activity 1.3.5** Consider the following linear system.

$$x_1 + 2x_2 + 3x_3 = 1$$

$$2x_1 + 4x_2 + 8x_3 = 0$$

- (a) Find its corresponding augmented matrix  $A$  and find  $\text{RREF}(A)$ .
- (b) Use the RREF matrix to write a linear system equivalent to the original system.
- (c) How many solutions must this system have?
  - A. Zero
  - B. One
  - C. Infinitely-many



### Counting Solutions for Linear Systems (LE3)

**Fact 1.3.6** *We will see in [Section 1.4](#) that the intuition established here generalizes: a consistent system with more variables than equations (ignoring  $0 = 0$ ) will always have infinitely many solutions.*

### Counting Solutions for Linear Systems (LE3)

**Fact 1.3.7** *By finding  $\text{RREF}(A)$  from a linear system's corresponding augmented matrix  $A$ , we can immediately tell how many solutions the system has.*

- *If the linear system given by  $\text{RREF}(A)$  includes the contradiction  $0 = 1$ , that is, the row  $\left[ \begin{array}{ccc|c} 0 & \cdots & 0 & 1 \end{array} \right]$ , then the system is inconsistent, which means it has zero solutions and its solution set is written as  $\emptyset$  or  $\{\}$ .*
- *If the linear system given by  $\text{RREF}(A)$  sets each variable of the system to a single value; that is,  $x_1 = s_1$ ,  $x_2 = s_2$ , and so on; then the system is consistent with exactly one solution  $\begin{bmatrix} s_1 \\ s_2 \\ \vdots \end{bmatrix}$ , and its solution set is  $\left\{ \begin{bmatrix} s_1 \\ s_2 \\ \vdots \end{bmatrix} \right\}$ .*
- *Otherwise, the system must have more variables than non-trivial equations (equations other than  $0 = 0$ ). This means it is consistent with infinitely-many different solutions. We'll learn how to find such solution sets in [Section 1.4](#).*

### Counting Solutions for Linear Systems (LE3)

**Activity 1.3.8** For each vector equation, write an explanation for whether each solution set has no solutions, one solution, or infinitely-many solutions. If the set is finite, describe it using set notation.

(a)

$$x_1 \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix} + x_2 \begin{bmatrix} 4 \\ -3 \\ 1 \end{bmatrix} + x_3 \begin{bmatrix} 7 \\ -6 \\ 4 \end{bmatrix} = \begin{bmatrix} 10 \\ -6 \\ 4 \end{bmatrix}$$

(b)

$$x_1 \begin{bmatrix} -2 \\ -1 \\ -2 \end{bmatrix} + x_2 \begin{bmatrix} 3 \\ 1 \\ 1 \end{bmatrix} + x_3 \begin{bmatrix} -2 \\ -2 \\ -5 \end{bmatrix} = \begin{bmatrix} 1 \\ 4 \\ 13 \end{bmatrix}$$

(c)

$$x_1 \begin{bmatrix} -1 \\ -2 \\ 1 \end{bmatrix} + x_2 \begin{bmatrix} -5 \\ -5 \\ 4 \end{bmatrix} + x_3 \begin{bmatrix} -7 \\ -9 \\ 6 \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \\ -2 \end{bmatrix}$$

## 1.4 Linear Systems with Infinitely-Many Solutions (LE4)

### Learning Outcomes

- Compute the solution set for a system of linear equations or a vector equation with infinitely many solutions.

### Linear Systems with Infinitely-Many Solutions (LE4)

**Activity 1.4.1** Consider this simplified linear system found to be equivalent to the system from [Activity 1.3.5](#):

$$\begin{aligned}x_1 + 2x_2 &= 4 \\ x_3 &= -1\end{aligned}$$

Earlier, we determined this system has infinitely-many solutions.

(a) Let  $x_1 = a$  and write the solution set in the form  $\left\{ \begin{bmatrix} a \\ ? \\ ? \end{bmatrix} \mid a \in \mathbb{R} \right\}$ .

(b) Let  $x_2 = b$  and write the solution set in the form  $\left\{ \begin{bmatrix} ? \\ b \\ ? \end{bmatrix} \mid b \in \mathbb{R} \right\}$ .

(c) Which of these was easier? What features of the RREF matrix  $\left[ \begin{array}{ccc|c} \boxed{1} & 2 & 0 & 4 \\ 0 & 0 & \boxed{1} & -1 \end{array} \right]$  caused this?

## Linear Systems with Infinitely-Many Solutions (LE4)

**Definition 1.4.2** Recall that the pivots of a matrix in RREF form are the leading 1s in each non-zero row.

The pivot columns in an augmented matrix correspond to the **bound variables** in the system of equations ( $x_1, x_3$  below). The remaining variables are called **free variables** ( $x_2$  below).

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

To efficiently solve a system in RREF form, assign letters to the free variables, and then solve for the bound variables.  $\diamond$

# Linear Systems with Infinitely-Many Solutions (LE4)

**Activity 1.4.3** Find the solution set for the system

$$\begin{array}{rcl} 2x_1 - 2x_2 - 6x_3 + x_4 - x_5 & = & 3 \\ -x_1 + x_2 + 3x_3 - x_4 + 2x_5 & = & -3 \\ x_1 - 2x_2 - x_3 + x_4 + x_5 & = & 2 \end{array}$$

by doing the following.

(a) Row-reduce its augmented matrix.

(b) Assign letters to the free variables (given by the non-pivot columns):

$$? = a$$

$$? = b$$

(c) Solve for the bound variables (given by the pivot columns) to show that

$$? = 1 + 5a + 2b$$

$$? = 1 + 2a + 3b$$

$$? = 3 + 3b$$

(d) Replace  $x_1$  through  $x_5$  with the appropriate expressions of  $a, b$  in the following set-builder notation.

$$\left\{ \left[ \begin{array}{c} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{array} \right] \middle| a, b \in \mathbb{R} \right\}$$

## Linear Systems with Infinitely-Many Solutions (LE4)

**Remark 1.4.4** Don't forget to correctly express the solution set of a linear system. Systems with zero or one solutions may be written by listing their elements, while systems with infinitely-many solutions may be written using set-builder notation.

- *Inconsistent*:  $\emptyset$  or  $\{\}$

- (not  $0$  or  $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ )

- *Consistent with one solution*: e.g.  $\left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \right\}$

- (not just  $\begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}$ )

- *Consistent with infinitely-many solutions*: e.g.  $\left\{ \begin{bmatrix} 1 \\ 2 - 3a \\ a \end{bmatrix} \mid a \in \mathbb{R} \right\}$

- (not just  $\begin{bmatrix} 1 \\ 2 - 3a \\ a \end{bmatrix}$ )



### Linear Systems with Infinitely-Many Solutions (LE4)

**Activity 1.4.5** Consider the following system of linear equations.

$$x_1 \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} + x_2 \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} + x_3 \begin{bmatrix} -1 \\ 5 \\ -5 \end{bmatrix} + x_4 \begin{bmatrix} -3 \\ 13 \\ -13 \end{bmatrix} = \begin{bmatrix} -3 \\ 12 \\ -12 \end{bmatrix}.$$

- (a) Explain how to find a simpler system or vector equation that has the same solution set.
- (b) Explain how to describe this solution set using set notation.

### Linear Systems with Infinitely-Many Solutions (LE4)

**Activity 1.4.6** Consider the following system of linear equations.

$$\begin{array}{rcccccl} x_1 & & & - & 2x_3 & = & -3 \\ 5x_1 & + & x_2 & - & 7x_3 & = & -18 \\ 5x_1 & - & x_2 & - & 13x_3 & = & -12 \\ x_1 & + & 3x_2 & + & 7x_3 & = & -12 \end{array}$$

- (a) Explain how to find a simpler system or vector equation that has the same solution set.
- (b) Explain how to describe this solution set using set notation.

# Chapter 2

## Euclidean Vectors (EV)

### Learning Outcomes

What is a space of Euclidean vectors?

By the end of this chapter, you should be able to...

1. Determine if a Euclidean vector can be written as a linear combination of a given set of Euclidean vectors by solving an appropriate vector equation.
2. Determine if a set of Euclidean vectors spans  $\mathbb{R}^n$  by solving appropriate vector equations.
3. Determine if a subset of  $\mathbb{R}^n$  is a subspace or not.
4. Determine if a set of Euclidean vectors is linearly dependent or independent by solving an appropriate vector equation.
5. Explain why a set of Euclidean vectors is or is not a basis of  $\mathbb{R}^n$ .
6. Compute a basis for the subspace spanned by a given set of Euclidean vectors, and determine the dimension of the subspace.
7. Find a basis for the solution set of a homogeneous system of equations.

## 2.1 Linear Combinations (EV1)

### Learning Outcomes

- Determine if a Euclidean vector can be written as a linear combination of a given set of Euclidean vectors by solving an appropriate vector equation.

## Linear Combinations (EV1)

**Definition 2.1.1** A **linear combination** of a set of vectors  $\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_m\}$  is given by  $c_1\vec{v}_1 + c_2\vec{v}_2 + \dots + c_m\vec{v}_m$  for any choice of scalar multiples  $c_1, c_2, \dots, c_m$ .

For example, we can say  $\begin{bmatrix} 3 \\ 0 \\ 5 \end{bmatrix}$  is a linear combination of the vectors

$\begin{bmatrix} 1 \\ -1 \\ 2 \end{bmatrix}$  and  $\begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}$  since

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

◇

## Linear Combinations (EV1)

**Definition 2.1.2** The **span** of a set of vectors is the collection of all linear combinations of that set:

$$\text{span}\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_m\} = \{c_1\vec{v}_1 + c_2\vec{v}_2 + \dots + c_m\vec{v}_m \mid c_i \in \mathbb{R}\}.$$

For example:

$$\text{span}\left\{\begin{bmatrix} 1 \\ -1 \\ 2 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}\right\} = \left\{a \begin{bmatrix} 1 \\ -1 \\ 2 \end{bmatrix} + b \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} \mid a, b \in \mathbb{R}\right\}.$$

◇

## Linear Combinations (EV1)

**Activity 2.1.3** Consider  $\text{span} \left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right\}$ .

(a) Sketch the four Euclidean vectors

$$1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \quad 3 \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 3 \\ 6 \end{bmatrix}, \quad 0 \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad -2 \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} -2 \\ -4 \end{bmatrix}$$

in the  $xy$  plane by placing a dot at the  $(x, y)$  coordinate associated with each vector.

(b) Sketch a representation of all the vectors belonging to

$$\text{span} \left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right\} = \left\{ a \begin{bmatrix} 1 \\ 2 \end{bmatrix} \mid a \in \mathbb{R} \right\}$$

in the  $xy$  plane by plotting their  $(x, y)$  coordinates as dots. What best describes this sketch?

- A. A line                      B. A plane                      C. A parabola                      D. A circle

## Linear Combinations (EV1)

**Remark 2.1.4** It is important to remember that

$$\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_m\} \neq \text{span}\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_m\}.$$

For example,

$$\left\{ \begin{bmatrix} 1 \\ -1 \\ 2 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} \right\}$$

is a set containing exactly two vectors, while

$$\text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 2 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} \right\} = \left\{ a \begin{bmatrix} 1 \\ -1 \\ 2 \end{bmatrix} + b \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} \mid a, b \in \mathbb{R} \right\}$$

is a set containing infinitely-many vectors.



## Linear Combinations (EV1)

**Activity 2.1.5** Consider  $\text{span} \left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix} \right\}$ .

(a) Sketch the following five Euclidean vectors in the  $xy$  plane.

$$\begin{aligned} 1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 0 \begin{bmatrix} -1 \\ 1 \end{bmatrix} &= ? & 0 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1 \begin{bmatrix} -1 \\ 1 \end{bmatrix} &= ? & 1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1 \begin{bmatrix} -1 \\ 1 \end{bmatrix} &= ? \\ -2 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1 \begin{bmatrix} -1 \\ 1 \end{bmatrix} &= ? & -1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + -2 \begin{bmatrix} -1 \\ 1 \end{bmatrix} &= ? \end{aligned}$$

(b) Sketch a representation of all the vectors belonging to

$$\text{span} \left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix} \right\} = \left\{ a \begin{bmatrix} 1 \\ 2 \end{bmatrix} + b \begin{bmatrix} -1 \\ 1 \end{bmatrix} \mid a, b \in \mathbb{R} \right\}$$

in the  $xy$  plane. What best describes this sketch?

- A. A line                      B. A plane                      C. A parabola                      D. A circle

### Linear Combinations (EV1)

**Activity 2.1.6** Sketch a representation of all the vectors belonging to  $\text{span} \left\{ \begin{bmatrix} 6 \\ -4 \end{bmatrix}, \begin{bmatrix} -3 \\ 2 \end{bmatrix} \right\}$  in the  $xy$  plane. What best describes this sketch?

- A. A line
- B. A plane
- C. A parabola
- D. A cube

## Linear Combinations (EV1)

**Activity 2.1.7** Consider the following questions to discover whether a Euclidean vector belongs to a span.

- (a) The Euclidean vector  $\begin{bmatrix} -1 \\ -6 \\ 1 \end{bmatrix}$  belongs to  $\text{span} \left\{ \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix} \right\}$  exactly when there exists a solution to which of these vector equations?

A.  $x_1 \begin{bmatrix} -1 \\ -6 \\ 1 \end{bmatrix} + x_2 \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix} = \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix}$

B.  $x_1 \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix} + x_2 \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix} = \begin{bmatrix} -1 \\ -6 \\ 1 \end{bmatrix}$

C.  $x_1 \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix} + x_2 \begin{bmatrix} -1 \\ -6 \\ 1 \end{bmatrix} + x_3 \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix} = 0$

- (b) Use technology to find RREF of the corresponding augmented matrix, and then use that matrix to find the solution set of the vector equation.

- (c) Given this solution set, does  $\begin{bmatrix} -1 \\ -6 \\ 1 \end{bmatrix}$  belong to  $\text{span} \left\{ \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix} \right\}$ ?

## Linear Combinations (EV1)

**Observation 2.1.8** The following are all equivalent statements:

- The vector  $\vec{b}$  belongs to  $\text{span}\{\vec{v}_1, \dots, \vec{v}_n\}$ .
- The vector  $\vec{b}$  is a linear combination of the vectors  $\vec{v}_1, \dots, \vec{v}_n$ .
- The vector equation  $x_1\vec{v}_1 + \dots + x_n\vec{v}_n = \vec{b}$  is consistent.
- The linear system corresponding to  $\left[\vec{v}_1 \dots \vec{v}_n \mid \vec{b}\right]$  is consistent.
- RREF  $\left[\vec{v}_1 \dots \vec{v}_n \mid \vec{b}\right]$  doesn't have a row  $[0 \dots 0 \mid 1]$  representing the contradiction  $0 = 1$ .

## Linear Combinations (EV1)

**Activity 2.1.9** Consider this claim about a vector equation:

$\begin{bmatrix} -6 \\ 2 \\ -6 \end{bmatrix}$  is a linear combination of the vectors  $\begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix}$ ,  $\begin{bmatrix} 3 \\ 0 \\ 6 \end{bmatrix}$ ,  $\begin{bmatrix} 2 \\ 0 \\ 4 \end{bmatrix}$ , and  $\begin{bmatrix} -4 \\ 1 \\ -5 \end{bmatrix}$ .

(a) Write a statement involving the solutions of a vector equation that's equivalent to this claim.

(b) Explain why the statement you wrote is true.

(c) Since your statement was true, use the solution set to describe a linear combination of  $\begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix}$ ,  $\begin{bmatrix} 3 \\ 0 \\ 6 \end{bmatrix}$ ,  $\begin{bmatrix} 2 \\ 0 \\ 4 \end{bmatrix}$ , and  $\begin{bmatrix} -4 \\ 1 \\ -5 \end{bmatrix}$  that equals  $\begin{bmatrix} -6 \\ 2 \\ -6 \end{bmatrix}$ .

## Linear Combinations (EV1)

**Activity 2.1.10** Consider this claim about a vector equation:

$$\begin{bmatrix} -5 \\ -1 \\ -7 \end{bmatrix} \text{ belongs to span } \left\{ \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix}, \begin{bmatrix} 3 \\ 0 \\ 6 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 4 \end{bmatrix}, \begin{bmatrix} -4 \\ 1 \\ -5 \end{bmatrix} \right\}.$$

- (a) Write a statement involving the solutions of a vector equation that's equivalent to this claim.
- (b) Explain why the statement you wrote is false, to conclude that the vector does not belong to the span.

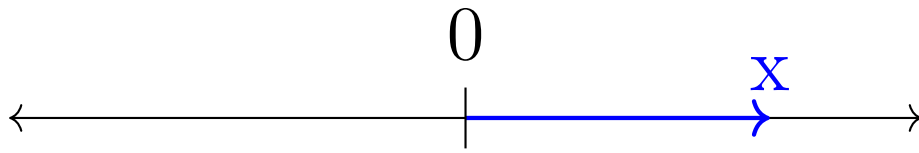
## 2.2 Spanning Sets (EV2)

### Learning Outcomes

- Determine if a set of Euclidean vectors spans  $\mathbb{R}^n$  by solving appropriate vector equations.

## Spanning Sets (EV2)

**Observation 2.2.1** Any single non-zero vector/number  $x$  in  $\mathbb{R}^1$  spans  $\mathbb{R}^1$ , since  $\mathbb{R}^1 = \{cx \mid c \in \mathbb{R}\}$ .

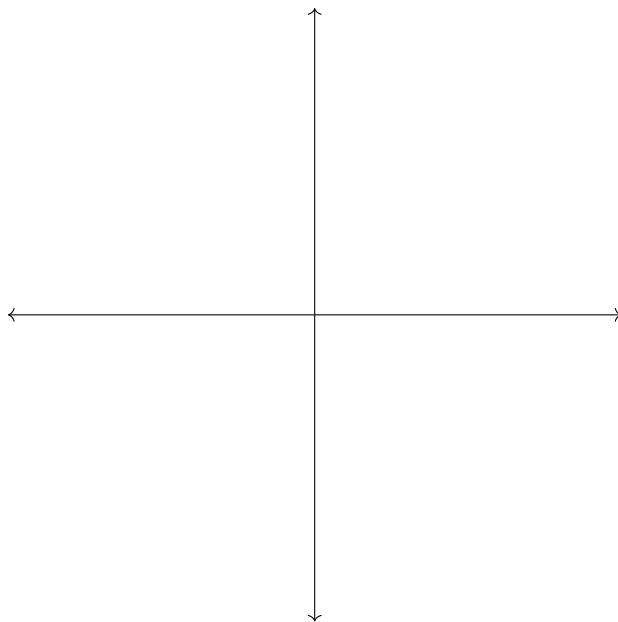


**Figure 1** An  $\mathbb{R}^1$  vector



## Spanning Sets (EV2)

**Activity 2.2.2** How many vectors are required to span  $\mathbb{R}^2$ ? Sketch a drawing in the  $xy$  plane to support your answer.



**Figure 2** The  $xy$  plane  $\mathbb{R}^2$

A. 1

B. 2

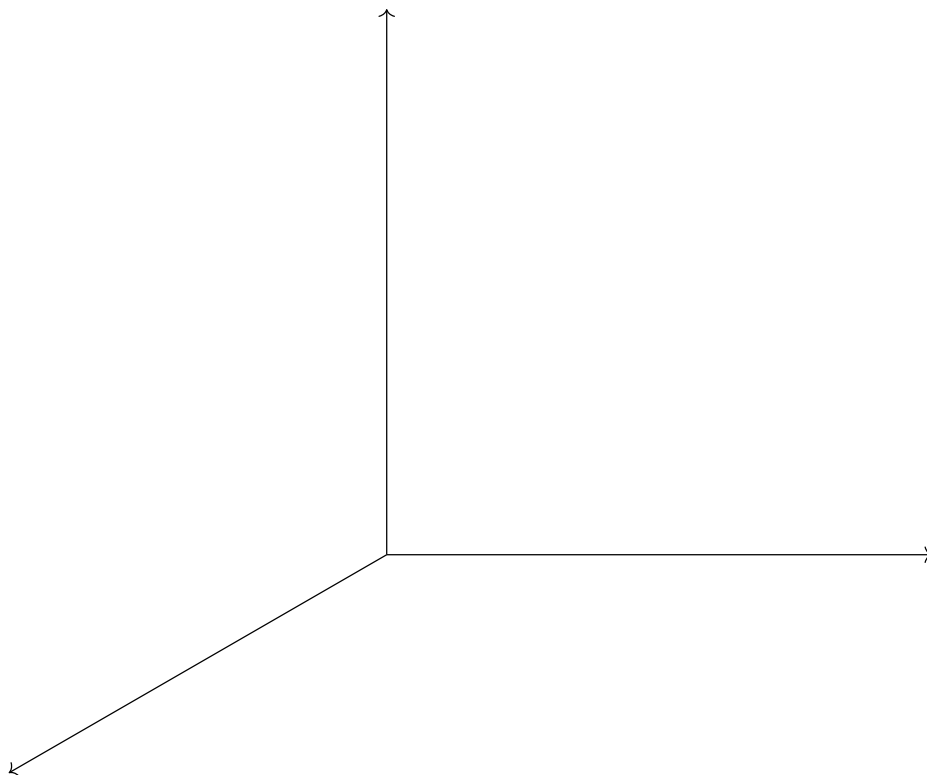
C. 3

D. 4

E. Infinitely Many

## Spanning Sets (EV2)

**Activity 2.2.3** How many vectors are required to span  $\mathbb{R}^3$ ?



**Figure 3**  $\mathbb{R}^3$  space

A. 1

B. 2

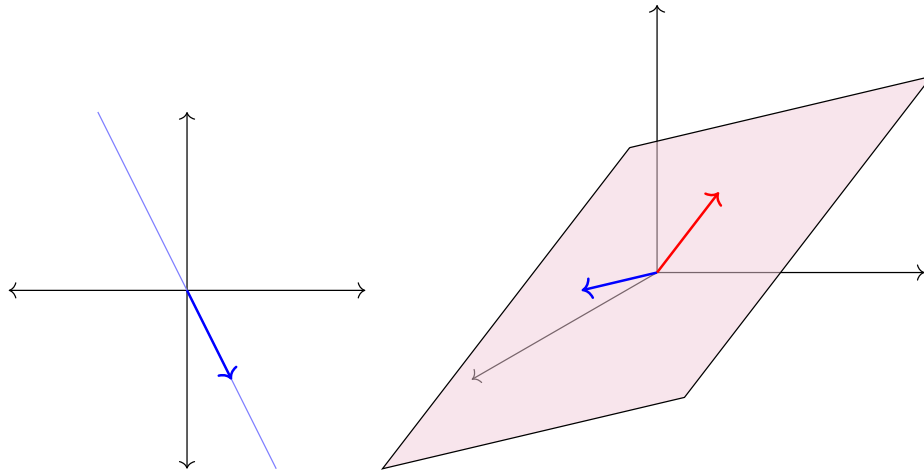
C. 3

D. 4

E. Infinitely Many

## Spanning Sets (EV2)

**Fact 2.2.4** *At least  $n$  vectors are required to span  $\mathbb{R}^n$ .*



**Figure 4** *Failed attempts to span  $\mathbb{R}^n$  by  $< n$  vectors*

## Spanning Sets (EV2)

**Activity 2.2.5** Consider the question: Does every vector in  $\mathbb{R}^3$  belong to  $\text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -2 \\ -2 \\ 2 \end{bmatrix} \right\}$ ?

(a) Determine if  $\begin{bmatrix} 7 \\ -3 \\ -2 \end{bmatrix}$  belongs to  $\text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -2 \\ -2 \\ 2 \end{bmatrix} \right\}$ .

(b) Determine if  $\begin{bmatrix} 2 \\ 5 \\ 7 \end{bmatrix}$  belongs to  $\text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -2 \\ -2 \\ 2 \end{bmatrix} \right\}$ .

(c) An arbitrary vector  $\begin{bmatrix} ? \\ ? \\ ? \end{bmatrix}$  belongs to

$\text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} -2 \\ -2 \\ 2 \end{bmatrix} \right\}$  provided the equation

$$x_1 \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix} + x_2 \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix} + x_3 \begin{bmatrix} -2 \\ -2 \\ 2 \end{bmatrix} = \begin{bmatrix} ? \\ ? \\ ? \end{bmatrix}$$

has...

- A. no solutions.
- B. exactly one solution.
- C. at least one solution.
- D. infinitely-many solutions.

(d) We're guaranteed at least one solution if the RREF of the corresponding augmented matrix has no contradictions; likewise, we have no solutions if the RREF corresponds to the contradiction  $0 = 1$ . Given

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

we may conclude that the set does not span all of  $\mathbb{R}^3$  because...

### Spanning Sets (EV2)

- A. the row  $[0 \ 1 \ 2 \mid ?]$  prevents a contradiction.
- B. the row  $[0 \ 1 \ 2 \mid ?]$  allows a contradiction.
- C. the row  $[0 \ 0 \ 0 \mid ?]$  prevents a contradiction.
- D. the row  $[0 \ 0 \ 0 \mid ?]$  allows a contradiction.

## Spanning Sets (EV2)

**Fact 2.2.6** *The set  $\{\vec{v}_1, \dots, \vec{v}_m\}$  spans all of  $\mathbb{R}^n$  exactly when the vector equation*

$$x_1\vec{v}_1 + \cdots x_m\vec{v}_m = \vec{w}$$

*is consistent for every vector  $\vec{w}$ .*

*Likewise, the set  $\{\vec{v}_1, \dots, \vec{v}_m\}$  fails to span all of  $\mathbb{R}^n$  exactly when the vector equation*

$$x_1\vec{v}_1 + \cdots x_m\vec{v}_m = \vec{w}$$

*is inconsistent for some vector  $\vec{w}$ .*

*Note these two possibilities are decided based on whether or not  $\text{RREF}[\vec{v}_1 \dots \vec{v}_m]$  has either all pivot rows, or at least one non-pivot row (a row of zeroes):*

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

## Spanning Sets (EV2)

**Activity 2.2.7** Consider the set of vectors  $S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ -4 \\ 3 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 7 \\ -3 \\ -1 \end{bmatrix}, \begin{bmatrix} 0 \\ 3 \\ 5 \\ 7 \end{bmatrix}, \begin{bmatrix} 3 \\ 13 \\ 7 \\ 16 \end{bmatrix} \right\}$  and the question “Does  $\mathbb{R}^4 = \text{span } S$ ?”

- (a) Rewrite this question in terms of the solutions to a vector equation.
- (b) Answer your new question, and use this to answer the original question.

## Spanning Sets (EV2)

**Activity 2.2.8** Let  $\vec{v}_1, \vec{v}_2, \vec{v}_3 \in \mathbb{R}^7$  be three Euclidean vectors, and suppose  $\vec{w}$  is another vector with  $\vec{w} \in \text{span}\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$ . What can you conclude about  $\text{span}\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$ ?

- A.  $\text{span}\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$  is larger than  $\text{span}\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$ .
- B.  $\text{span}\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$  is the same as  $\text{span}\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$ .
- C.  $\text{span}\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$  is smaller than  $\text{span}\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$ .



## 2.3 Subspaces (EV3)

### Learning Outcomes

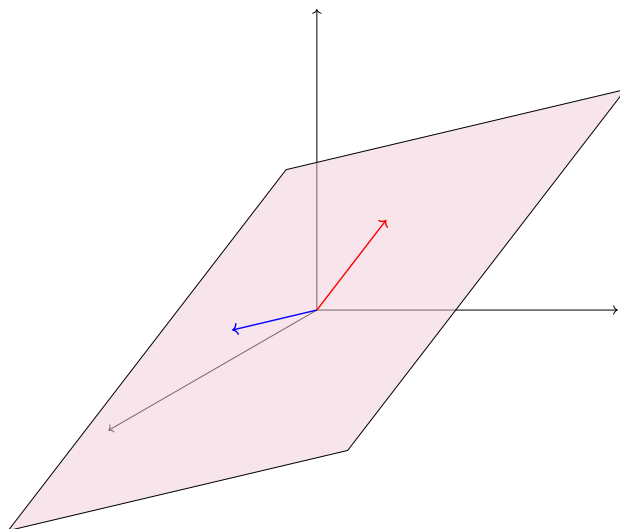
- Determine if a subset of  $\mathbb{R}^n$  is a subspace or not.

### Subspaces (EV3)

**Definition 2.3.1** A subset  $S$  of a vector space is called a **subspace** provided it is equal to the span of a set of vectors from that space.  $\diamond$

### Subspaces (EV3)

**Activity 2.3.2** Consider two non-colinear vectors in  $\mathbb{R}^3$ . If we look at all linear combinations of those two vectors (that is, their span), we end up with a planar subspace within  $\mathbb{R}^3$ . Call this plane  $S$ .



(a) For any unspecified  $\vec{u}, \vec{v} \in S$ , is it the case that  $\vec{u} + \vec{v} \in S$ ?

A. Yes.

B. No.

(b) For any unspecified  $\vec{u} \in S$  and  $c \in \mathbb{R}$ , is it the case that  $\vec{u} + \begin{bmatrix} c \\ c \\ c \end{bmatrix} \in S$ ?

A. Yes.

B. No.

(c) For any unspecified  $\vec{u} \in S$  and  $c \in \mathbb{R}$ , is it the case that  $c\vec{u} \in S$ ?

A. Yes.

B. No.

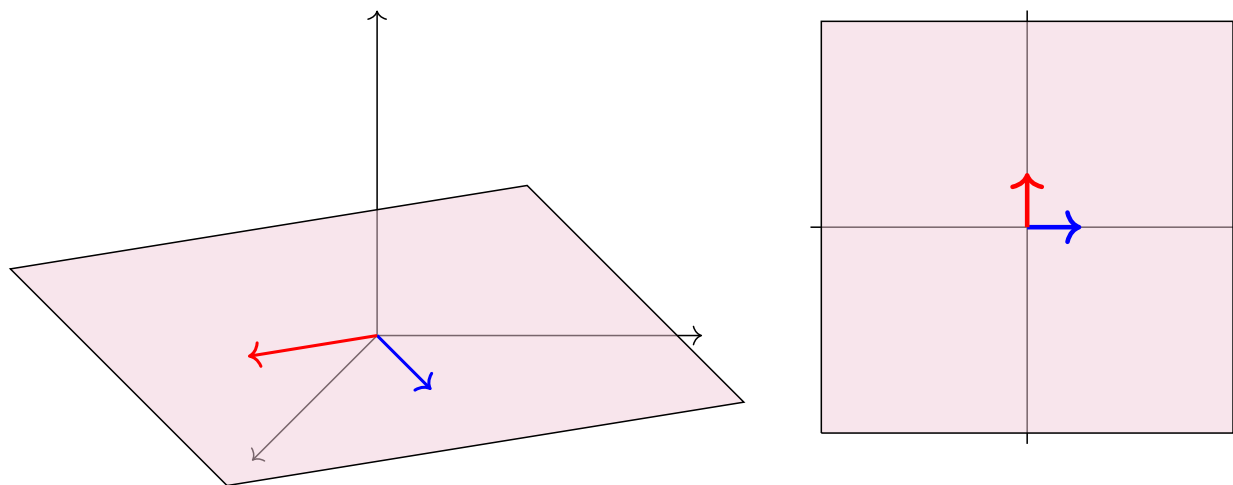
### Subspaces (EV3)

**Fact 2.3.3** *A subset  $S$  of a vector space is a subspace provided:*

- *the subset is **closed under addition**: for any  $\vec{u}, \vec{v} \in S$ , the sum  $\vec{u} + \vec{v}$  is also in  $S$ .*
- *the subset is **closed under scalar multiplication**: for any  $\vec{u} \in S$  and scalar  $c \in \mathbb{R}$ , the product  $c\vec{u}$  is also in  $S$ .*

### Subspaces (EV3)

**Observation 2.3.4** Note the similarities between a planar subspace spanned by two non-colinear vectors in  $\mathbb{R}^3$ , and the Euclidean plane  $\mathbb{R}^2$ . While they are not the same thing (and shouldn't be referred to interchangeably), algebraists call such similar spaces **isomorphic**; we'll learn what this means more carefully in a later chapter.



**Figure 5** A planar subset of  $\mathbb{R}^3$  compared with the plane  $\mathbb{R}^2$ .

### Subspaces (EV3)

**Activity 2.3.5** Let  $S = \left\{ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \mid x + 2y + z = 0 \right\}$ .

(a) Let's assume that  $\vec{v} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$  and  $\vec{w} = \begin{bmatrix} a \\ b \\ c \end{bmatrix}$  are in  $S$ . What are we allowed to assume?

A.  $x + 2y + z = 0$ .

C. Both of these.

B.  $a + 2b + c = 0$ .

D. Neither of these.

(b) Which equation must be verified to show that  $\vec{v} + \vec{w} = \begin{bmatrix} x + a \\ y + b \\ z + c \end{bmatrix}$  also belongs to  $S$ ?

A.  $(x + a) + 2(y + b) + (z + c) = 0$ .

B.  $x + a + 2y + b + z + c = 0$ .

C.  $x + 2y + z = a + 2b + c$ .

(c) Use the assumptions from (a) to verify the equation from (b).

(d) Is  $S$  a subspace of  $\mathbb{R}^3$ ?

A. Yes

B. No

C. Not enough information

(e) Show that  $k\vec{v} = \begin{bmatrix} kx \\ ky \\ kz \end{bmatrix}$  also belongs to  $S$  for any  $k \in \mathbb{R}$  by verifying  $(kx) + 2(ky) + (kz) = 0$  under these assumptions.

(f) Is  $S$  a subspace of  $\mathbb{R}^3$ ?

A. Yes

B. No

C. Not enough information

### Subspaces (EV3)

**Activity 2.3.6** Let  $S = \left\{ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \mid x + 2y + z = 4 \right\}$ .

(a) Which of these statements is valid?

- A.  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , and  $\begin{bmatrix} 2 \\ 2 \\ 2 \end{bmatrix} \in S$ , so  $S$  is a subspace.
- B.  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , and  $\begin{bmatrix} 2 \\ 2 \\ 2 \end{bmatrix} \in S$ , so  $S$  is not a subspace.
- C.  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , but  $\begin{bmatrix} 2 \\ 2 \\ 2 \end{bmatrix} \notin S$ , so  $S$  is a subspace.
- D.  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , but  $\begin{bmatrix} 2 \\ 2 \\ 2 \end{bmatrix} \notin S$ , so  $S$  is not a subspace.

(b) Which of these statements is valid?

- (a)  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , and  $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \in S$ , so  $S$  is a subspace.
- (b)  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , and  $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \in S$ , so  $S$  is not a subspace.
- (c)  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , but  $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \notin S$ , so  $S$  is a subspace.
- (d)  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \in S$ , but  $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \notin S$ , so  $S$  is not a subspace.

### Subspaces (EV3)

**Remark 2.3.7** In summary, *any one* of the following is enough to prove that a nonempty subset  $W$  is *not* a subspace:

- Find specific values for  $\vec{u}, \vec{v} \in W$  such that  $\vec{u} + \vec{v} \notin W$ .
- Find specific values for  $c \in \mathbb{R}, \vec{v} \in W$  such that  $c\vec{v} \notin W$ .
- Show that  $\vec{0} \notin W$ .

If you cannot do any of these, then  $W$  can be proven to be a subspace by doing *both* of the following:

1. For all  $\vec{v}, \vec{w} \in W$  (not just specific values),  $\vec{u} + \vec{v} \in W$ .
2. For all  $\vec{v} \in W$  and  $c \in \mathbb{R}$  (not just specific values),  $c\vec{v} \in W$ .



### Subspaces (EV3)

**Activity 2.3.8** Consider these subsets of  $\mathbb{R}^3$ :

$$R = \left\{ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \middle| y = z + 1 \right\} \quad S = \left\{ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \middle| y = |z| \right\} \quad T = \left\{ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \middle| z = xy \right\}.$$

- (a) Show  $R$  isn't a subspace by showing that  $\vec{0} \notin R$ .
- (b) Show  $S$  isn't a subspace by finding two vectors  $\vec{u}, \vec{v} \in S$  such that  $\vec{u} + \vec{v} \notin S$ .
- (c) Show  $T$  isn't a subspace by finding a vector  $\vec{v} \in T$  such that  $2\vec{v} \notin T$ .

### Subspaces (EV3)

**Activity 2.3.9** Consider the following two sets of Euclidean vectors:

$$U = \left\{ \begin{bmatrix} x \\ y \end{bmatrix} \middle| 7x + 4y = 0 \right\} \quad W = \left\{ \begin{bmatrix} x \\ y \end{bmatrix} \middle| 3xy^2 = 0 \right\}$$

Explain why one of these sets is a subspace of  $\mathbb{R}^2$  and one is not.

### Subspaces (EV3)

**Activity 2.3.10** Consider the following attempted proof that

$$U = \left\{ \begin{bmatrix} x \\ y \end{bmatrix} \middle| x + y = xy \right\}$$

is closed under scalar multiplication.

Let  $\begin{bmatrix} x \\ y \end{bmatrix} \in U$ , so we know that  $x + y = xy$ . We want to show  $k \begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} kx \\ ky \end{bmatrix} \in U$ , that is,  $(kx) + (ky) = (kx)(ky)$ . This is verified by the following calculation:

$$(kx) + (ky) = (kx)(ky)$$

$$k(x + y) = k^2xy$$

$$0[k(x + y)] = 0[k^2xy]$$

$$0 = 0$$

Is this reasoning valid?

A. Yes

B. No

### Subspaces (EV3)

**Remark 2.3.11** Proofs of an equality  $\text{LEFT} = \text{RIGHT}$  should generally be of one of these forms:

1. Using a chain of equalities:

$$\begin{aligned}\text{LEFT} &= \dots \\ &= \dots \\ &= \dots \\ &= \text{RIGHT}\end{aligned}$$

Alternatively:

$\text{LEFT} = \dots$	$\text{RIGHT} = \dots$
$= \dots$	$= \dots$
$= \dots$	$= \dots$
$= \text{SAME}$	$= \text{SAME}$

2. When the assumption  $\text{THIS} = \text{THAT}$  is already known or assumed to be true :

	$\text{THIS} = \text{THAT}$
$\Rightarrow$	$\dots = \dots$
$\Rightarrow$	$\dots = \dots$
$\Rightarrow$	$\text{LEFT} = \text{RIGHT}$

## 2.4 Linear Independence (EV4)

### Learning Outcomes

- Determine if a set of Euclidean vectors is linearly dependent or independent by solving an appropriate vector equation.

## Linear Independence (EV4)

**Activity 2.4.1** Consider the two sets

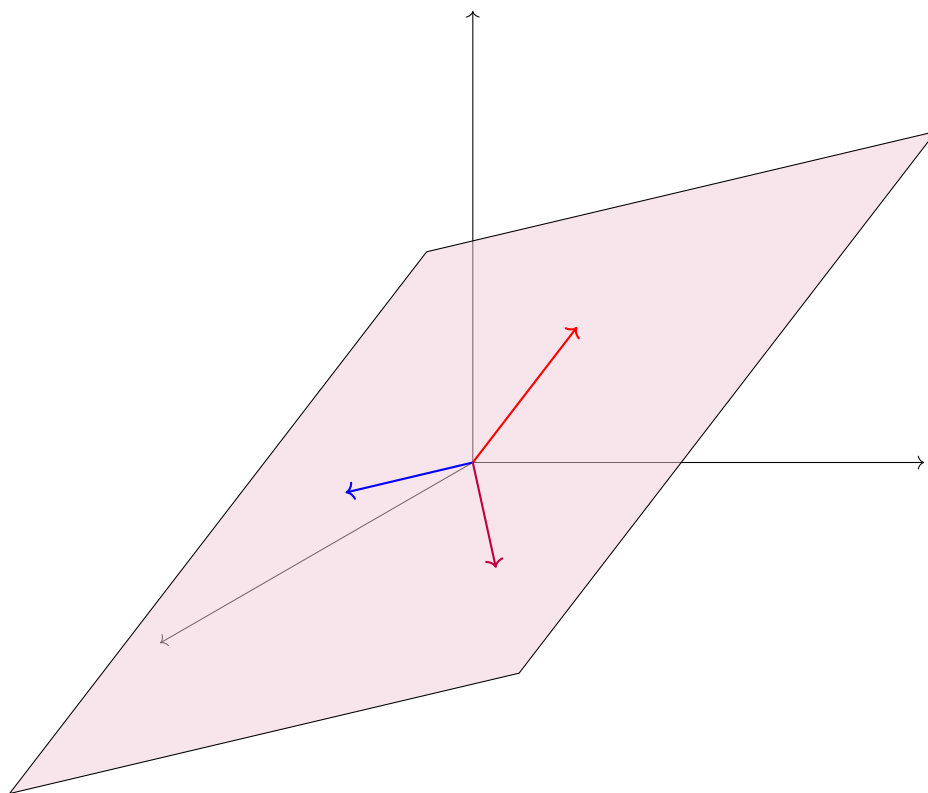
$$S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 4 \end{bmatrix} \right\} \quad T = \left\{ \begin{bmatrix} 2 \\ 3 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 4 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ -11 \end{bmatrix} \right\}.$$

Which of the following is true?

- A.  $\text{span } S$  is bigger than  $\text{span } T$ .
- B.  $\text{span } S$  and  $\text{span } T$  are the same size.
- C.  $\text{span } S$  is smaller than  $\text{span } T$ .

## Linear Independence (EV4)

**Definition 2.4.2** We say that a set of vectors is **linearly dependent** if one vector in the set belongs to the span of the others. Otherwise, we say the set is **linearly independent**.



**Figure 6** A linearly dependent set of three vectors

You can think of linearly dependent sets as containing a redundant vector, in the sense that you can drop a vector out without reducing the span of the set. In the above image, all three vectors lay in the same planar subspace, but only two vectors are needed to span the plane, so the set is linearly dependent.



## Linear Independence (EV4)

**Activity 2.4.3** Consider the following three vectors in  $\mathbb{R}^3$ :

$$\vec{v}_1 = \begin{bmatrix} -2 \\ 0 \\ 0 \end{bmatrix}, \vec{v}_2 = \begin{bmatrix} 1 \\ 3 \\ 0 \end{bmatrix}, \text{ and } \vec{v}_3 = \begin{bmatrix} -2 \\ 5 \\ 4 \end{bmatrix}.$$

(a) Let  $\vec{w} = 3\vec{v}_1 - \vec{v}_2 - 5\vec{v}_3 = \begin{bmatrix} ? \\ ? \\ ? \end{bmatrix}$ . The set  $\{\vec{v}_1, \vec{v}_2, \vec{v}_3, \vec{w}\}$  is...

- A. linearly dependent: at least one vector is a linear combination of others
- B. linearly independent: no vector is a linear combination of others

(b) Find

$$\text{RREF} \begin{bmatrix} \vec{v}_1 & \vec{v}_2 & \vec{v}_3 & \vec{w} \end{bmatrix} = \text{RREF} \begin{bmatrix} -2 & 1 & -2 & ? \\ 0 & 3 & 5 & ? \\ 0 & 0 & 4 & ? \end{bmatrix} = ?.$$

What does this tell you about solution set for the vector equation  $x_1\vec{v}_1 + x_2\vec{v}_2 + x_3\vec{v}_3 + x_4\vec{w} = \vec{0}$ ?

- A. It is inconsistent.
- B. It is consistent with one solution.
- C. It is consistent with infinitely many solutions.

(c) Which of these might explain the connection?

- A. A pivot column establishes linear independence and creates a contradiction.
- B. A non-pivot column both describes a linear combination and reveals the number of solutions.
- C. A pivot row describes the bound variables and prevents a contradiction.
- D. A non-pivot row prevents contradictions and makes the vector equation solvable.



## Linear Independence (EV4)

**Fact 2.4.4** *For any vector space, the set  $\{\vec{v}_1, \dots, \vec{v}_n\}$  is linearly dependent if and only if the vector equation  $x_1\vec{v}_1 + x_2\vec{v}_2 + \dots + x_n\vec{v}_n = \vec{0}$  is consistent with infinitely many solutions.*

*Likewise, the set of vectors  $\{\vec{v}_1, \dots, \vec{v}_n\}$  is linearly independent if and only if the vector equation*

$$x_1\vec{v}_1 + x_2\vec{v}_2 + \dots + x_n\vec{v}_n = \vec{0}$$

*has exactly one solution:* 
$$\begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ 0 \end{bmatrix}.$$

## Linear Independence (EV4)

**Activity 2.4.5** Find

$$\text{RREF} \left[ \begin{array}{ccccc|c} 2 & 2 & 3 & -1 & 4 & 0 \\ 3 & 0 & 13 & 10 & 3 & 0 \\ 0 & 0 & 7 & 7 & 0 & 0 \\ -1 & 3 & 16 & 14 & 1 & 0 \end{array} \right]$$

and mark the part of the matrix that demonstrates that

$$S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ 13 \\ 7 \\ 16 \end{bmatrix}, \begin{bmatrix} -1 \\ 10 \\ 7 \\ 14 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 1 \end{bmatrix} \right\}$$

is linearly dependent (the part that shows its linear system has infinitely many solutions).

## Linear Independence (EV4)

**Observation 2.4.6** Compare the following results:

- A set of  $\mathbb{R}^m$  vectors  $\{\vec{v}_1, \dots, \vec{v}_n\}$  is linearly independent if and only if  $\text{RREF} \begin{bmatrix} \vec{v}_1 & \dots & \vec{v}_n \end{bmatrix}$  has all pivot *columns*.
- A set of  $\mathbb{R}^m$  vectors  $\{\vec{v}_1, \dots, \vec{v}_n\}$  is linearly dependent if and only if  $\text{RREF} \begin{bmatrix} \vec{v}_1 & \dots & \vec{v}_n \end{bmatrix}$  has at least one non-pivot *column*.
- A set of  $\mathbb{R}^m$  vectors  $\{\vec{v}_1, \dots, \vec{v}_n\}$  spans  $\mathbb{R}^m$  if and only if  $\text{RREF} \begin{bmatrix} \vec{v}_1 & \dots & \vec{v}_n \end{bmatrix}$  has all pivot *rows*.
- A set of  $\mathbb{R}^m$  vectors  $\{\vec{v}_1, \dots, \vec{v}_n\}$  fails to span  $\mathbb{R}^m$  if and only if  $\text{RREF} \begin{bmatrix} \vec{v}_1 & \dots & \vec{v}_n \end{bmatrix}$  has at least one non-pivot *row*.

## Linear Independence (EV4)

### Activity 2.4.7

- (a) Write a statement involving the solutions of a vector equation that's equivalent to each claim:

(i) “The set of vectors  $\left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 5 \\ 5 \\ 3 \\ 1 \end{bmatrix}, \begin{bmatrix} 9 \\ 11 \\ 6 \\ 3 \end{bmatrix} \right\}$  is linearly *independent*.”

(ii) “The set of vectors  $\left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 5 \\ 5 \\ 3 \\ 1 \end{bmatrix}, \begin{bmatrix} 9 \\ 11 \\ 6 \\ 3 \end{bmatrix} \right\}$  is linearly *dependent*.”

- (b) Explain how to determine which of these statements is true.

### Linear Independence (EV4)

**Activity 2.4.8** What is the largest number of  $\mathbb{R}^4$  vectors that can form a linearly independent set?

- A. 3
- B. 4
- C. 5
- D. You can have infinitely many vectors and still be linearly independent.

### Linear Independence (EV4)

**Activity 2.4.9** Is it possible for the set of Euclidean vectors  $\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_n, \vec{0}\}$  to be linearly independent?

A. Yes

B. No

## 2.5 Identifying a Basis (EV5)

### Learning Outcomes

- Explain why a set of Euclidean vectors is or is not a basis of  $\mathbb{R}^n$ .

# Identifying a Basis (EV5)

**Activity 2.5.1** Consider the set of vectors

$$S = \left\{ \begin{bmatrix} 3 \\ -2 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 4 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 0 \\ -16 \\ -5 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 3 \\ 0 \end{bmatrix}, \begin{bmatrix} 3 \\ 3 \\ 0 \\ 1 \end{bmatrix} \right\}.$$

- (a) Express the vector  $\begin{bmatrix} 5 \\ 2 \\ 0 \\ 1 \end{bmatrix}$  as a linear combination of the vectors in  $S$ ,  
i.e. find scalars such that

$$\begin{bmatrix} 5 \\ 2 \\ 0 \\ 1 \end{bmatrix} = ? \begin{bmatrix} 3 \\ -2 \\ -1 \\ 0 \end{bmatrix} + ? \begin{bmatrix} 2 \\ 4 \\ 1 \\ 1 \end{bmatrix} + ? \begin{bmatrix} 0 \\ -16 \\ -5 \\ -3 \end{bmatrix} + ? \begin{bmatrix} 1 \\ 2 \\ 3 \\ 0 \end{bmatrix} + ? \begin{bmatrix} 3 \\ 3 \\ 0 \\ 1 \end{bmatrix}.$$

- (b) Find a *different* way to express the vector  $\begin{bmatrix} 5 \\ 2 \\ 0 \\ 1 \end{bmatrix}$  as a linear combination  
of the vectors in  $S$ .

- (c) Consider another vector  $\begin{bmatrix} 8 \\ 6 \\ 7 \\ 5 \end{bmatrix}$ . Without computing the RREF of another matrix, how many ways can this vector be written as a linear combination of the vectors in  $S$ ?

- A. Zero.
- B. One.
- C. Infinitely-many.
- D. Computing a new matrix RREF is necessary.



### Identifying a Basis (EV5)

**Activity 2.5.2** Let's review some of the terminology we've been dealing with...

- (a) If every vector in a space can be constructed as one or more linear combination of vectors in a set  $S$ , we can say...
- A. the set  $S$  spans the space.
  - B. the set  $S$  fails to span the space.
  - C. the set  $S$  is linearly independent.
  - D. the set  $S$  is linearly dependent.
- (b) If the zero vector  $\vec{0}$  can be constructed as a *unique* linear combination of vectors in a set  $S$  (the combination multiplying every vector by the scalar value 0), we can say...
- A. the set  $S$  spans the space.
  - B. the set  $S$  fails to span the space.
  - C. the set  $S$  is linearly independent.
  - D. the set  $S$  is linearly dependent.
- (c) If every vector of a space can either be constructed as a *unique* linear combination of vectors in a set  $S$ , or not at all, we can say...
- A. the set  $S$  spans the space.
  - B. the set  $S$  fails to span the space.
  - C. the set  $S$  is linearly independent.
  - D. the set  $S$  is linearly dependent.

### Identifying a Basis (EV5)

**Definition 2.5.3** A **basis** of a vector space  $V$  is a set of vectors  $S$  contained in  $V$  for which

1. *Every* vector of the space can be expressed as a linear combination of the vectors in  $S$ .
2. For each vector  $\vec{v}$  in the space, there is only *one* way to write it as a linear combination of the vectors in  $S$ .

These two properties may be expressed more succinctly as the statement "Every vector in  $V$  can be expressed *uniquely* as a linear combination of the vectors in  $S$ ".  $\diamond$

### Identifying a Basis (EV5)

**Observation 2.5.4** In terms of a vector equation, a set  $S = \{\vec{v}_1, \dots, \vec{v}_n\}$  is a basis of a space if the vector equation

$$x_1\vec{v}_1 + \cdots + x_n\vec{v}_n = \vec{w}$$

has a *unique* solution for *every* vector  $\vec{w}$  in the space.

Put another way, a basis may be thought of as a minimal set of “building blocks” that can be used to construct any other vector of the space.

### Identifying a Basis (EV5)

**Activity 2.5.5** Let  $S$  be a basis ([Definition 2.5.3](#)) for a space. Then...

- A. the set  $S$  must both span the space and be linearly independent.
- B. the set  $S$  must span the space but could be linearly dependent.
- C. the set  $S$  must be linearly independent but could fail to span the space.
- D. the set  $S$  could fail to span the space and could be linearly dependent.

### Identifying a Basis (EV5)

**Activity 2.5.6** The vectors

$$\hat{i} = (1, 0, 0) = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \quad \hat{j} = (0, 1, 0) = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \quad \hat{k} = (0, 0, 1) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

form a basis  $\{\hat{i}, \hat{j}, \hat{k}\}$  used frequently in multivariable calculus.

Find the unique linear combination of these vectors

$$? \hat{i} + ? \hat{j} + ? \hat{k}$$

that equals the vector

$$(3, -2, 4) = \begin{bmatrix} 3 \\ -2 \\ 4 \end{bmatrix}$$

in  $xyz$  space.

### Identifying a Basis (EV5)

**Definition 2.5.7** The **standard basis** of  $\mathbb{R}^n$  is the set  $\{\vec{e}_1, \dots, \vec{e}_n\}$  where

$$\vec{e}_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad \vec{e}_2 = \begin{bmatrix} 0 \\ 1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \quad \dots \quad \vec{e}_n = \begin{bmatrix} 0 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}.$$

In particular, the standard basis for  $\mathbb{R}^3$  is  $\{\vec{e}_1, \vec{e}_2, \vec{e}_3\} = \{\hat{i}, \hat{j}, \hat{k}\}$ .  $\diamond$

### Identifying a Basis (EV5)

**Activity 2.5.8** Take the RREF of an appropriate matrix to determine if each of the following sets is a basis for  $\mathbb{R}^4$ .

(a)

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

- A. A basis, because it both spans  $\mathbb{R}^4$  and is linearly independent.
- B. Not a basis, because while it spans  $\mathbb{R}^4$ , it is linearly dependent.
- C. Not a basis, because while it is linearly independent, it fails to span  $\mathbb{R}^4$ .
- D. Not a basis, because not only does it fail to span  $\mathbb{R}^4$ , it's also linearly dependent.

(b)

$$\left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 2 \end{bmatrix}, \begin{bmatrix} -3 \\ 0 \\ 1 \\ 3 \end{bmatrix} \right\}$$

- A. A basis, because it both spans  $\mathbb{R}^4$  and is linearly independent.
- B. Not a basis, because while it spans  $\mathbb{R}^4$ , it is linearly dependent.
- C. Not a basis, because while it is linearly independent, it fails to span  $\mathbb{R}^4$ .
- D. Not a basis, because not only does it fail to span  $\mathbb{R}^4$ , it's also linearly dependent.

(c)

$$\left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ 13 \\ 7 \\ 16 \end{bmatrix}, \begin{bmatrix} -1 \\ 10 \\ 7 \\ 14 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 2 \end{bmatrix} \right\}$$

- A. A basis, because it both spans  $\mathbb{R}^4$  and is linearly independent.
- B. Not a basis, because while it spans  $\mathbb{R}^4$ , it is linearly dependent.

### Identifying a Basis (EV5)

- C. Not a basis, because while it is linearly independent, it fails to span  $\mathbb{R}^4$ .
- D. Not a basis, because not only does it fail to span  $\mathbb{R}^4$ , it's also linearly dependent.

(d)

$$\left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 2 \end{bmatrix}, \begin{bmatrix} -3 \\ 0 \\ 1 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ 6 \\ 1 \\ 5 \end{bmatrix} \right\}$$

- A. A basis, because it both spans  $\mathbb{R}^4$  and is linearly independent.
- B. Not a basis, because while it spans  $\mathbb{R}^4$ , it is linearly dependent.
- C. Not a basis, because while it is linearly independent, it fails to span  $\mathbb{R}^4$ .
- D. Not a basis, because not only does it fail to span  $\mathbb{R}^4$ , it's also linearly dependent.

(e)

$$\left\{ \begin{bmatrix} 5 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} -2 \\ 1 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 4 \\ 5 \\ 1 \\ 3 \end{bmatrix} \right\}$$

- A. A basis, because it both spans  $\mathbb{R}^4$  and is linearly independent.
- B. Not a basis, because while it spans  $\mathbb{R}^4$ , it is linearly dependent.
- C. Not a basis, because while it is linearly independent, it fails to span  $\mathbb{R}^4$ .
- D. Not a basis, because not only does it fail to span  $\mathbb{R}^4$ , it's also linearly dependent.



### Identifying a Basis (EV5)

**Activity 2.5.9** If  $\{\vec{v}_1, \vec{v}_2, \vec{v}_3, \vec{v}_4\}$  is a basis for  $\mathbb{R}^4$ , that means  $\text{RREF}[\vec{v}_1 \ \vec{v}_2 \ \vec{v}_3 \ \vec{v}_4]$  has a pivot in every row (because it spans), and has a pivot in every column (because it's linearly independent).

What is  $\text{RREF}[\vec{v}_1 \ \vec{v}_2 \ \vec{v}_3 \ \vec{v}_4]$ ?

$$\text{RREF}[\vec{v}_1 \ \vec{v}_2 \ \vec{v}_3 \ \vec{v}_4] = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix}$$

### Identifying a Basis (EV5)

**Fact 2.5.10** *The set  $\{\vec{v}_1, \dots, \vec{v}_m\}$  is a basis for  $\mathbb{R}^n$  if and only if  $m = n$  and*

$$\text{RREF}[\vec{v}_1 \ \dots \ \vec{v}_n] = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}.$$

*That is, a basis for  $\mathbb{R}^n$  must have exactly  $n$  vectors and its square matrix must row-reduce to the so-called **identity matrix** containing all zeros except for a downward diagonal of ones. (We will learn where the identity matrix gets its name in a later module.)*

## 2.6 Subspace Basis and Dimension (EV6)

### Learning Outcomes

- Compute a basis for the subspace spanned by a given set of Euclidean vectors, and determine the dimension of the subspace.

## Subspace Basis and Dimension (EV6)

**Observation 2.6.1** Recall from section [Section 2.3](#) that a **subspace** of a vector space is the result of spanning a set of vectors from that space.

Recall also that a linearly dependent set contains “redundant” vectors. For example, only two of the three vectors in [Figure 14](#) are needed to span the planar subspace.

## Subspace Basis and Dimension (EV6)

**Activity 2.6.2** Consider the subspace of  $\mathbb{R}^4$  given by  $W = \text{span} \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix} \right\}.$

(a) Mark the column of RREF  $\begin{bmatrix} 2 & 2 & 2 & 1 \\ 3 & 0 & -3 & 5 \\ 0 & 1 & 2 & -1 \\ 1 & -1 & -3 & 0 \end{bmatrix}$  that shows that  $W$ 's spanning set is linearly dependent.

(b) What would be the result of removing the vector that gave us this column?

- A. The set still spans  $W$ , and remains linearly dependent.
- B. The set still spans  $W$ , but is now also linearly independent.
- C. The set no longer spans  $W$ , and remains linearly dependent.
- D. The set no longer spans  $W$ , but is now linearly independent.

## Subspace Basis and Dimension (EV6)

**Definition 2.6.3** Let  $W$  be a subspace of a vector space. A **basis** for  $W$  is a linearly independent set of vectors that spans  $W$  (but not necessarily the entire vector space).  $\diamond$

## Subspace Basis and Dimension (EV6)

**Observation 2.6.4** So given a set  $S = \{\vec{v}_1, \dots, \vec{v}_m\}$ , to compute a basis for the subspace  $\text{span } S$ , simply remove the vectors corresponding to the non-pivot columns of  $\text{RREF}[\vec{v}_1 \dots \vec{v}_m]$ . For example, since

$$\text{RREF} \begin{bmatrix} 1 & 2 & 0 & 1 \\ 2 & 4 & -2 & 2 \\ 3 & 6 & -2 & 1 \end{bmatrix} = \begin{bmatrix} \boxed{1} & 2 & 0 & 1 \\ 0 & 0 & \boxed{1} & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

the subspace  $W = \text{span} \left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, \begin{bmatrix} 2 \\ 4 \\ 6 \end{bmatrix}, \begin{bmatrix} 0 \\ -2 \\ -2 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} \right\}$  has

$\left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, \begin{bmatrix} 0 \\ -2 \\ -2 \end{bmatrix} \right\}$  as a basis.

## Subspace Basis and Dimension (EV6)

### Activity 2.6.5

(a) Find a basis for  $\text{span } S$  where

$$S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix} \right\}.$$

(b) Find a basis for  $\text{span } T$  where

$$T = \left\{ \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix} \right\}.$$



### Subspace Basis and Dimension (EV6)

**Observation 2.6.6** Even though we found different bases for them,  $\text{span } S$  and  $\text{span } T$  are exactly the same subspace of  $\mathbb{R}^4$ , since

$$S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix} \right\} = \left\{ \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix} \right\} = T.$$

Thus the basis for a subspace is not unique in general.

## Subspace Basis and Dimension (EV6)

**Fact 2.6.7** *Any non-trivial real vector space has infinitely-many different bases, but all the bases for a given vector space are exactly the same size.*

*For example,*

$$\{\vec{e}_1, \vec{e}_2, \vec{e}_3\} \text{ and } \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \right\} \text{ and } \left\{ \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} 2 \\ -2 \\ 1 \end{bmatrix}, \begin{bmatrix} 3 \\ -2 \\ 5 \end{bmatrix} \right\}$$

*are all valid bases for  $\mathbb{R}^3$ , and they all contain three vectors.*

## Subspace Basis and Dimension (EV6)

**Definition 2.6.8** The **dimension** of a vector space or subspace is equal to the size of any basis for the vector space.

As you'd expect,  $\mathbb{R}^n$  has dimension  $n$ . For example,  $\mathbb{R}^3$  has dimension 3 because any basis for  $\mathbb{R}^3$  such as

$$\{\vec{e}_1, \vec{e}_2, \vec{e}_3\} \text{ and } \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \right\} \text{ and } \left\{ \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} 2 \\ -2 \\ 1 \end{bmatrix}, \begin{bmatrix} 3 \\ -2 \\ 5 \end{bmatrix} \right\}$$

contains exactly three vectors.

◇

### Subspace Basis and Dimension (EV6)

**Activity 2.6.9** Consider the following subspace  $W$  of  $\mathbb{R}^4$ :

$$W = \text{span} \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 0 \\ 2 \end{bmatrix}, \begin{bmatrix} -3 \\ 1 \\ -5 \\ 5 \end{bmatrix}, \begin{bmatrix} 12 \\ -3 \\ 15 \\ -18 \end{bmatrix} \right\}.$$

- (a) Explain and demonstrate how to find a basis of  $W$ .
- (b) Explain and demonstrate how to find the dimension of  $W$ .

### Subspace Basis and Dimension (EV6)

**Activity 2.6.10** The dimension of a subspace may be found by doing what with an appropriate RREF matrix?

- A. Count the rows.
- B. Count the non-pivot columns.
- C. Count the pivots.
- D. Add the number of pivot rows and pivot columns.

## 2.7 Homogeneous Linear Systems (EV7)

### Learning Outcomes

- Find a basis for the solution set of a homogeneous system of equations.

## Homogeneous Linear Systems (EV7)

**Definition 2.7.1** A **homogeneous** system of linear equations is one of the form:

$$\begin{array}{ccccccc} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n & = & 0 \\ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n & = & 0 \\ \vdots & & \vdots & & \vdots & & \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n & = & 0 \end{array}$$

This system is equivalent to the vector equation:

$$x_1\vec{v}_1 + \dots + x_n\vec{v}_n = \vec{0}$$

and the augmented matrix:

$$\left[ \begin{array}{cccc|c} a_{11} & a_{12} & \cdots & a_{1n} & 0 \\ a_{21} & a_{22} & \cdots & a_{2n} & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} & 0 \end{array} \right]$$

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## Homogeneous Linear Systems (EV7)

**Activity 2.7.2** Consider the homogeneous vector equation  $x_1\vec{v}_1 + \cdots + x_n\vec{v}_n = \vec{0}$ .

(a) Note that if  $\begin{bmatrix} a_1 \\ \vdots \\ a_n \end{bmatrix}$  and  $\begin{bmatrix} b_1 \\ \vdots \\ b_n \end{bmatrix}$  are both solutions, we know that

$$a_1\vec{v}_1 + \cdots + a_n\vec{v}_n = \vec{0} \text{ and } b_1\vec{v}_1 + \cdots + b_n\vec{v}_n = \vec{0}.$$

Therefore by adding these equations,

$$(a_1 + b_1)\vec{v}_1 + \cdots + (a_n + b_n)\vec{v}_n = \vec{0}$$

shows that  $\begin{bmatrix} a_1 + b_1 \\ \vdots \\ a_n + b_n \end{bmatrix}$  is also a solution. Thus the solution set of a homogeneous system is...

- A. Closed under addition.
- B. Not closed under addition.
- C. Linearly dependent.
- D. Linearly independent.

(b) Similarly, if  $c \in \mathbb{R}$ ,  $\begin{bmatrix} ca_1 \\ \vdots \\ ca_n \end{bmatrix}$  is a solution. Thus the solution set of a homogeneous system is also closed under scalar multiplication, and therefore...

- A. A basis for  $\mathbb{R}^n$ .
- B. A subspace of  $\mathbb{R}^n$ .
- C. All of  $\mathbb{R}^n$ .
- D. The empty set.



### Homogeneous Linear Systems (EV7)

**Activity 2.7.3** Consider the homogeneous system of equations

$$\begin{aligned}x_1 + 2x_2 + x_4 &= 0 \\ 2x_1 + 4x_2 - x_3 - 2x_4 &= 0 \\ 3x_1 + 6x_2 - x_3 - x_4 &= 0\end{aligned}$$

- (a) Find its solution set (a subspace of  $\mathbb{R}^4$ ).
- (b) Rewrite this solution space in the form

$$\left\{ a \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix} + b \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix} \mid a, b \in \mathbb{R} \right\}.$$

- (c) Rewrite this solution space in the form

$$\text{span} \left\{ \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix}, \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix} \right\}.$$

- (d) Which of these choices best describes the set of two vectors

$$\left\{ \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix}, \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix} \right\} \text{ used in this span?}$$

- A. The set is linearly dependent.
- B. The set is linearly independent.
- C. The set spans all of  $\mathbb{R}^4$ .
- D. The set fails to span the solution space.

## Homogeneous Linear Systems (EV7)

**Fact 2.7.4** *The coefficients of the free variables in the solution space of a linear system always yield linearly independent vectors that span the solution space.*

*Thus if*

$$\left\{ a \begin{bmatrix} -2 \\ 1 \\ 0 \\ 0 \end{bmatrix} + b \begin{bmatrix} -1 \\ 0 \\ -4 \\ 1 \end{bmatrix} \mid a, b \in \mathbb{R} \right\} = \text{span} \left\{ \begin{bmatrix} -2 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ -4 \\ 1 \end{bmatrix} \right\}$$

*is the solution space for a homogeneous system, then*

$$\left\{ \begin{bmatrix} -2 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 0 \\ -4 \\ 1 \end{bmatrix} \right\}$$

*is a basis for the solution space.*

## Homogeneous Linear Systems (EV7)

**Activity 2.7.5** Consider the homogeneous system of equations

$$\begin{aligned}2x_1 + 4x_2 + 2x_3 - 4x_4 &= 0 \\ -2x_1 - 4x_2 + x_3 + x_4 &= 0 \\ 3x_1 + 6x_2 - x_3 - 4x_4 &= 0\end{aligned}$$

Find a basis for its solution space.

### Homogeneous Linear Systems (EV7)

**Activity 2.7.6** Consider the homogeneous vector equation

$$x_1 \begin{bmatrix} 2 \\ -2 \\ 3 \end{bmatrix} + x_2 \begin{bmatrix} 4 \\ -4 \\ 6 \end{bmatrix} + x_3 \begin{bmatrix} 2 \\ 1 \\ -1 \end{bmatrix} + x_4 \begin{bmatrix} -4 \\ 1 \\ -4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

Find a basis for its solution space.

## Homogeneous Linear Systems (EV7)

**Activity 2.7.7** Consider the homogeneous system of equations

$$x_1 - 3x_2 + 2x_3 = 0$$

$$2x_1 + 6x_2 + 4x_3 = 0$$

$$x_1 + 6x_2 - 4x_3 = 0$$

(a) Find its solution space.

(b) Which of these is the best choice of basis for this solution space?

A  $\{\}$

B  $\{\vec{0}\}$

C The basis does  
not exist

## Homogeneous Linear Systems (EV7)

**Activity 2.7.8** To create a computer-animated film, an animator first models a scene as a subset of  $\mathbb{R}^3$ . Then to transform this three-dimensional visual data for display on a two-dimensional movie screen or television set, the computer could apply a linear transformation that maps visual information at the point  $(x, y, z) \in \mathbb{R}^3$  onto the pixel located at  $(x + y, y - z) \in \mathbb{R}^2$ .

- (a) What homogeneous linear system describes the positions  $(x, y, z)$  within the original scene that would be aligned with the pixel  $(0, 0)$  on the screen?
- (b) Solve this system to describe these locations.

## Chapter 3

# Algebraic Properties of Linear Maps (AT)

### Learning Outcomes

How can we understand linear maps algebraically?

By the end of this chapter, you should be able to...

1. Determine if a map between Euclidean vector spaces is linear or not.
2. Translate back and forth between a linear transformation of Euclidean spaces and its standard matrix, and perform related computations.
3. Compute a basis for the kernel and a basis for the image of a linear map, and verify that the rank-nullity theorem holds for a given linear map.
4. Determine if a given linear map is injective and/or surjective.
5. Explain why a given set with defined addition and scalar multiplication does satisfy a given vector space property, but nonetheless isn't a vector space.
6. Answer questions about vector spaces of polynomials or matrices.

## 3.1 Linear Transformations (AT1)

### Learning Outcomes

- Determine if a map between Euclidean vector spaces is linear or not.



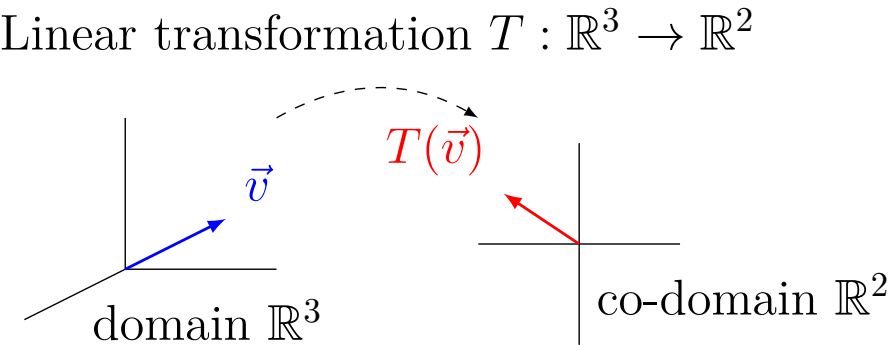
## Linear Transformations (AT1)

**Definition 3.1.1** A **linear transformation** (also called a **linear map**) is a map between vector spaces that preserves the vector space operations. More precisely, if  $V$  and  $W$  are vector spaces, a map  $T : V \rightarrow W$  is called a linear transformation if

1.  $T(\vec{v} + \vec{w}) = T(\vec{v}) + T(\vec{w})$  for any  $\vec{v}, \vec{w} \in V$ , and
2.  $T(c\vec{v}) = cT(\vec{v})$  for any  $c \in \mathbb{R}$ , and  $\vec{v} \in V$ .

In other words, a map is linear when vector space operations can be applied before or after the transformation without affecting the result.  $\diamond$

**Definition 3.1.2** Given a linear transformation  $T : V \rightarrow W$ ,  $V$  is called the **domain** of  $T$  and  $W$  is called the **co-domain** of  $T$ .

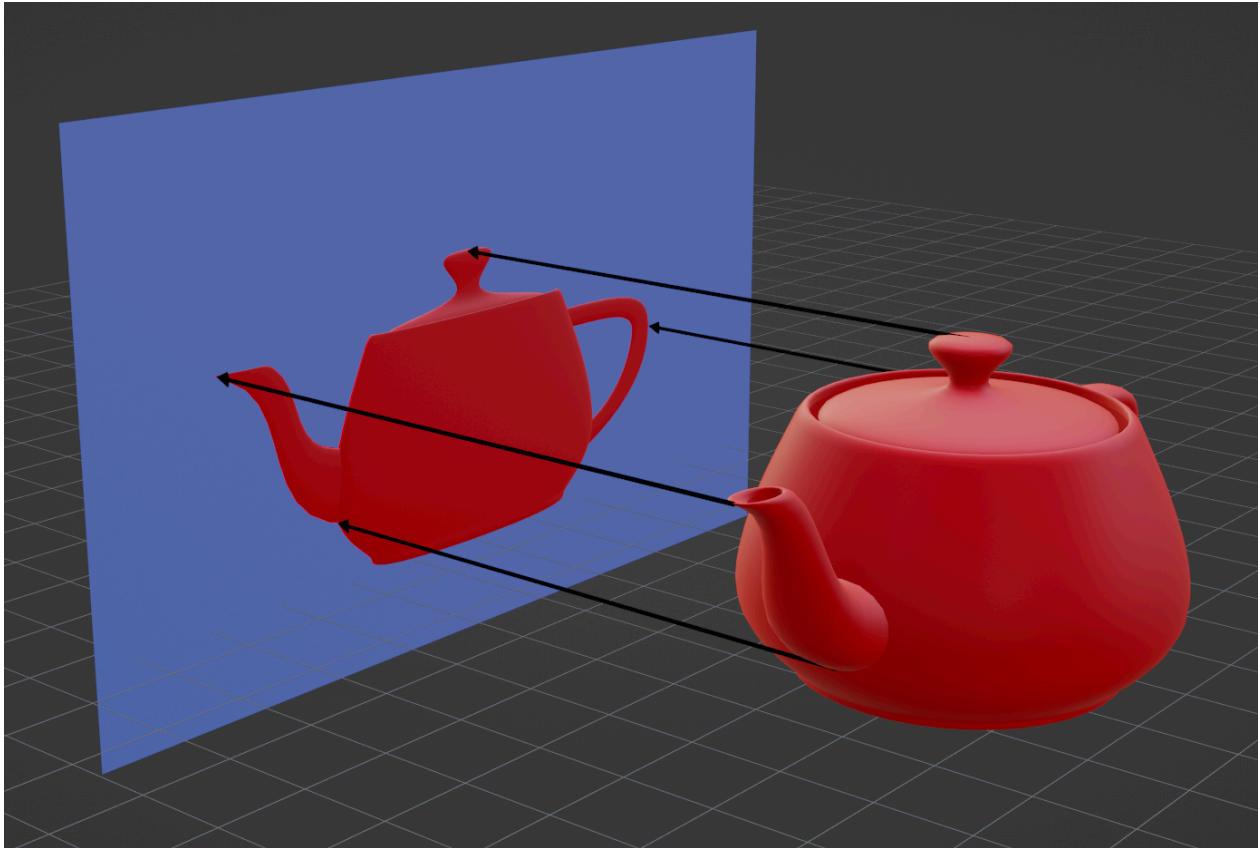


**Figure 7** A linear transformation with a domain of  $\mathbb{R}^3$  and a co-domain of  $\mathbb{R}^2$

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## Linear Transformations (AT1)

**Observation 3.1.3** One example of a linear transformation  $\mathbb{R}^3 \rightarrow \mathbb{R}^2$  is the projection of three-dimensional data onto a two-dimensional screen, as is necessary for computer animation in film or video games.



**Figure 8** A projection of a 3D teapot onto a 2D screen

### Linear Transformations (AT1)

**Activity 3.1.4** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be given by

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} x - z \\ 3y \end{bmatrix}.$$

(a) Compute the result of adding vectors before a  $T$  transformation:

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} u \\ v \\ w \end{bmatrix} \right) = T \left( \begin{bmatrix} x + u \\ y + v \\ z + w \end{bmatrix} \right)$$

A.  $\begin{bmatrix} x - u + z - w \\ 3y - 3v \end{bmatrix}$

C.  $\begin{bmatrix} x + u \\ 3y + 3v \\ z + w \end{bmatrix}$

B.  $\begin{bmatrix} x + u - z - w \\ 3y + 3v \end{bmatrix}$

D.  $\begin{bmatrix} x - u \\ 3y - 3v \\ z - w \end{bmatrix}$

(b) Compute the result of adding vectors after a  $T$  transformation:

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) + T \left( \begin{bmatrix} u \\ v \\ w \end{bmatrix} \right) = \begin{bmatrix} x - z \\ 3y \end{bmatrix} + \begin{bmatrix} u - w \\ 3v \end{bmatrix}$$

A.  $\begin{bmatrix} x - u + z - w \\ 3y - 3v \end{bmatrix}$

C.  $\begin{bmatrix} x + u \\ 3y + 3v \\ z + w \end{bmatrix}$

B.  $\begin{bmatrix} x + u - z - w \\ 3y + 3v \end{bmatrix}$

D.  $\begin{bmatrix} x - u \\ 3y - 3v \\ z - w \end{bmatrix}$

(c) Is  $T$  a linear transformation?

A. Yes.

B. No.

C. More work is necessary to know.

### Linear Transformations (AT1)

(d) Compute the result of scalar multiplication before a  $T$  transformation:

$$T \left( c \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = T \left( \begin{bmatrix} cx \\ cy \\ cz \end{bmatrix} \right)$$

A.  $\begin{bmatrix} cx - cz \\ 3cy \end{bmatrix}$

C.  $\begin{bmatrix} x + c \\ 3y + c \\ z + c \end{bmatrix}$

B.  $\begin{bmatrix} cx + cz \\ -3cy \end{bmatrix}$

D.  $\begin{bmatrix} x - c \\ 3y - c \\ z - c \end{bmatrix}$

(e) Compute the result of scalar multiplication after a  $T$  transformation:

$$cT \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = c \begin{bmatrix} x - z \\ 3y \end{bmatrix}$$

A.  $\begin{bmatrix} cx - cz \\ 3cy \end{bmatrix}$

C.  $\begin{bmatrix} x + c \\ 3y + c \\ z + c \end{bmatrix}$

B.  $\begin{bmatrix} cx + cz \\ -3cy \end{bmatrix}$

D.  $\begin{bmatrix} x - c \\ 3y - c \\ z - c \end{bmatrix}$

(f) Is  $T$  a linear transformation?

A. Yes.

B. No.

C. More work is necessary to know.

# Linear Transformations (AT1)

**Activity 3.1.5** Let  $S : \mathbb{R}^2 \rightarrow \mathbb{R}^4$  be given by

$$S\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} x + y \\ x^2 \\ y + 3 \\ y - 2^x \end{bmatrix}$$

(a) Compute

$$S\left(\begin{bmatrix} 0 \\ 1 \end{bmatrix} + \begin{bmatrix} 2 \\ 3 \end{bmatrix}\right) = S\left(\begin{bmatrix} 2 \\ 4 \end{bmatrix}\right)$$

A.  $\begin{bmatrix} 6 \\ 4 \\ 7 \\ 0 \end{bmatrix}$

B.  $\begin{bmatrix} -3 \\ 0 \\ 1 \\ 5 \end{bmatrix}$

C.  $\begin{bmatrix} -3 \\ -1 \\ 7 \\ 5 \end{bmatrix}$

D.  $\begin{bmatrix} 6 \\ 4 \\ 10 \\ -1 \end{bmatrix}$

(b) Compute

$$S\left(\begin{bmatrix} 0 \\ 1 \end{bmatrix}\right) + S\left(\begin{bmatrix} 2 \\ 3 \end{bmatrix}\right) = \begin{bmatrix} 0 + 1 \\ 0^2 \\ 1 + 3 \\ 1 - 2^0 \end{bmatrix} + \begin{bmatrix} 2 + 3 \\ 2^2 \\ 3 + 3 \\ 3 - 2^2 \end{bmatrix}$$

A.  $\begin{bmatrix} 6 \\ 4 \\ 7 \\ 0 \end{bmatrix}$

B.  $\begin{bmatrix} -3 \\ 0 \\ 1 \\ 5 \end{bmatrix}$

C.  $\begin{bmatrix} -3 \\ -1 \\ 7 \\ 5 \end{bmatrix}$

D.  $\begin{bmatrix} 6 \\ 4 \\ 10 \\ -1 \end{bmatrix}$

(c) Is  $T$  a linear transformation?

A. Yes.

B. No.

C. More work is necessary to know.

### Linear Transformations (AT1)

**Activity 3.1.6** Fill in the ?s, assuming  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  is linear:

$$T\left(\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}\right) = T\left(\begin{matrix} ? & \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \end{matrix}\right) = ? T\left(\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} ? \\ ? \\ ? \end{bmatrix}$$

## Linear Transformations (AT1)

**Remark 3.1.7** In summary, *any one* of the following is enough to prove that  $T : V \rightarrow W$  is *not* a linear transformation:

- Find specific values for  $\vec{v}, \vec{w} \in V$  such that  $T(\vec{v} + \vec{w}) \neq T(\vec{v}) + T(\vec{w})$ .
- Find specific values for  $\vec{v} \in V$  and  $c \in \mathbb{R}$  such that  $T(c\vec{v}) \neq cT(\vec{v})$ .
- Show  $T(\vec{0}) \neq \vec{0}$ .

If you cannot do any of these, then  $T$  can be proven to be a linear transformation by doing *both* of the following:

1. For all  $\vec{v}, \vec{w} \in V$  (not just specific values),  $T(\vec{v} + \vec{w}) = T(\vec{v}) + T(\vec{w})$ .
2. For all  $\vec{v} \in V$  and  $c \in \mathbb{R}$  (not just specific values),  $T(c\vec{v}) = cT(\vec{v})$ .

(Note the similarities between this process and showing that a subset of a vector space is or is not a subspace: [Remark 2.3.7.](#))



## Linear Transformations (AT1)

### Activity 3.1.8

- (a) Consider the following maps of Euclidean vectors  $P : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  and  $Q : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  defined by

$$P \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} -2x - 3y - 3z \\ 3x + 4y + 4z \\ 3x + 4y + 5z \end{bmatrix} \quad \text{and} \quad Q \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} x - 4y + 9z \\ y - 2z \\ 8y^2 - 3xz \end{bmatrix}.$$

Which do you *suspect*?

- A.  $P$  is linear, but  $Q$  is not.                      C. Both maps are linear.  
B.  $Q$  is linear, but  $P$  is not.                      D. Neither map is linear.
- (b) Consider the following map of Euclidean vectors  $S : \mathbb{R}^2 \rightarrow \mathbb{R}^2$

$$S \left( \begin{bmatrix} x \\ y \end{bmatrix} \right) = \begin{bmatrix} x + 2y \\ 9xy \end{bmatrix}.$$

Prove that  $S$  *is not* a linear transformation.

- (c) Consider the following map of Euclidean vectors  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$

$$T \left( \begin{bmatrix} x \\ y \end{bmatrix} \right) = \begin{bmatrix} 8x - 6y \\ 6x - 4y \end{bmatrix}.$$

Prove that  $T$  *is* a linear transformation.

## 3.2 Standard Matrices (AT2)

### Learning Outcomes

- Translate back and forth between a linear transformation of Euclidean spaces and its standard matrix, and perform related computations.

## Standard Matrices (AT2)

**Remark 3.2.1** Recall that a linear map  $T : V \rightarrow W$  satisfies

1.  $T(\vec{v} + \vec{w}) = T(\vec{v}) + T(\vec{w})$  for any  $\vec{v}, \vec{w} \in V$ .
2.  $T(c\vec{v}) = cT(\vec{v})$  for any  $c \in \mathbb{R}, \vec{v} \in V$ .

In other words, a map is linear when vector space operations can be applied before or after the transformation without affecting the result.

Standard Matrices (AT2)

**Activity 3.2.2** Suppose  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  is a linear map, and you know  $T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$  and  $T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$ . What is  $T\left(\begin{bmatrix} 3 \\ 0 \\ 0 \end{bmatrix}\right)$ ?

A.  $\begin{bmatrix} 6 \\ 3 \end{bmatrix}$

C.  $\begin{bmatrix} -4 \\ -2 \end{bmatrix}$

B.  $\begin{bmatrix} -9 \\ 6 \end{bmatrix}$

D.  $\begin{bmatrix} 6 \\ -4 \end{bmatrix}$

Standard Matrices (AT2)

**Activity 3.2.3** Suppose  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  is a linear map, and you know  $T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$  and  $T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$ . What is  $T\left(\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}\right)$ ?

A.  $\begin{bmatrix} 2 \\ 1 \end{bmatrix}$

C.  $\begin{bmatrix} -1 \\ 3 \end{bmatrix}$

B.  $\begin{bmatrix} 3 \\ -1 \end{bmatrix}$

D.  $\begin{bmatrix} 5 \\ -8 \end{bmatrix}$

Standard Matrices (AT2)

**Activity 3.2.4** Suppose  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  is a linear map, and you know  $T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$  and  $T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$ . What is  $T\left(\begin{bmatrix} -2 \\ 0 \\ -3 \end{bmatrix}\right)$ ?

A.  $\begin{bmatrix} 2 \\ 1 \end{bmatrix}$

C.  $\begin{bmatrix} -1 \\ 3 \end{bmatrix}$

B.  $\begin{bmatrix} 3 \\ -1 \end{bmatrix}$

D.  $\begin{bmatrix} 5 \\ -8 \end{bmatrix}$

### Standard Matrices (AT2)

**Activity 3.2.5** Suppose  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  is a linear map, and you know  $T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$  and  $T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$ . What piece of information would help you compute  $T\left(\begin{bmatrix} 0 \\ 4 \\ -1 \end{bmatrix}\right)$ ?

- |   |  |
|---|--|
| <p>A. The value of <math>T\left(\begin{bmatrix} 0 \\ -4 \\ 0 \end{bmatrix}\right)</math>.</p> | <p>C. The value of <math>T\left(\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}\right)</math>.</p> |
| <p>B. The value of <math>T\left(\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}\right)</math>.</p>  | <p>D. Any of the above.</p>  |

## Standard Matrices (AT2)

**Fact 3.2.6** Consider any basis  $\{\vec{b}_1, \dots, \vec{b}_n\}$  for  $V$ . Since every vector  $\vec{v}$  can be written as a linear combination of basis vectors,  $\vec{v} = x_1\vec{b}_1 + \dots + x_n\vec{b}_n$ , we may compute  $T(\vec{v})$  as follows:

$$T(\vec{v}) = T(x_1\vec{b}_1 + \dots + x_n\vec{b}_n) = x_1T(\vec{b}_1) + \dots + x_nT(\vec{b}_n).$$

Therefore any linear transformation  $T : V \rightarrow W$  can be defined by just describing the values of  $T(\vec{b}_i)$ .

Put another way, the images of the basis vectors completely **determine** the transformation  $T$ .



## Standard Matrices (AT2)

**Definition 3.2.7** Since a linear transformation  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  is determined by its action on the standard basis  $\{\vec{e}_1, \dots, \vec{e}_n\}$ , it is convenient to store this information in an  $m \times n$  matrix, called the **standard matrix** of  $T$ , given by  $[T(\vec{e}_1) \cdots T(\vec{e}_n)]$ .

For example, let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be the linear map determined by the following values for  $T$  applied to the standard basis of  $\mathbb{R}^3$ .

$$T(\vec{e}_1) = T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 3 \\ 2 \end{bmatrix} \quad T(\vec{e}_2) = T\left(\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} -1 \\ 4 \end{bmatrix} \quad T(\vec{e}_3) = T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} 5 \\ 0 \end{bmatrix}$$

Then the standard matrix corresponding to  $T$  is

$$\begin{bmatrix} T(\vec{e}_1) & T(\vec{e}_2) & T(\vec{e}_3) \end{bmatrix} = \begin{bmatrix} 3 & -1 & 5 \\ 2 & 4 & 0 \end{bmatrix}.$$

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### Standard Matrices (AT2)

**Activity 3.2.8** Let  $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$  be the linear transformation given by

$$T(\vec{e}_1) = \begin{bmatrix} 0 \\ 3 \\ -2 \end{bmatrix} \quad T(\vec{e}_2) = \begin{bmatrix} -3 \\ 0 \\ 1 \end{bmatrix} \quad T(\vec{e}_3) = \begin{bmatrix} 4 \\ -2 \\ 1 \end{bmatrix} \quad T(\vec{e}_4) = \begin{bmatrix} 2 \\ 0 \\ 0 \end{bmatrix}$$

Write the standard matrix  $[T(\vec{e}_1) \cdots T(\vec{e}_n)]$  for  $T$ .

### Standard Matrices (AT2)

**Activity 3.2.9** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be the linear transformation given by

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} x + 3z \\ 2x - y - 4z \end{bmatrix}$$

- (a) Compute  $T(\vec{e}_1)$ ,  $T(\vec{e}_2)$ , and  $T(\vec{e}_3)$ .
- (b) Find the standard matrix for  $T$ .

## Standard Matrices (AT2)

**Fact 3.2.10** *Because every linear map  $T : \mathbb{R}^m \rightarrow \mathbb{R}^n$  has a linear combination of the variables in each component, and thus  $T(\vec{e}_i)$  yields exactly the coefficients of  $x_i$ , the standard matrix for  $T$  is simply an array of the coefficients of the  $x_i$ :*

$$T\left(\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}\right) = \begin{bmatrix} ax + by + cz + dw \\ ex + fy + gz + hw \end{bmatrix} \quad A = \begin{bmatrix} a & b & c & d \\ e & f & g & h \end{bmatrix}$$

### Standard Matrices (AT2)

**Activity 3.2.11** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  be the linear transformation given by the standard matrix

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

(a) Compute  $T \left( \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \right)$ .

(b) Compute  $T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right)$ .

### Standard Matrices (AT2)

**Activity 3.2.12** Compute the following linear transformations of vectors given their standard matrices.

(a)

$$T_1 \left( \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right) \text{ for the standard matrix } A_1 = \begin{bmatrix} 4 & 3 \\ 0 & -1 \\ 1 & 1 \\ 3 & 0 \end{bmatrix}$$

(b)

$$T_2 \left( \begin{bmatrix} 1 \\ 1 \\ 0 \\ -3 \end{bmatrix} \right) \text{ for the standard matrix } A_2 = \begin{bmatrix} 4 & 3 & 0 & -1 \\ 1 & 1 & 3 & 0 \end{bmatrix}$$

(c)

$$T_3 \left( \begin{bmatrix} 0 \\ -2 \\ 0 \end{bmatrix} \right) \text{ for the standard matrix } A_3 = \begin{bmatrix} 4 & 3 & 0 \\ 0 & -1 & 3 \\ 5 & 1 & 1 \\ 3 & 0 & 0 \end{bmatrix}$$

## 3.3 Image and Kernel (AT3)

### Learning Outcomes

- Compute a basis for the kernel and a basis for the image of a linear map, and verify that the rank-nullity theorem holds for a given linear map.

### Image and Kernel (AT3)

**Activity 3.3.1** Let  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$  be given by

$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} \quad \text{with standard matrix} \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$$

Which of these subspaces of  $\mathbb{R}^2$  describes the set of all vectors that transform into  $\vec{0}$ ?

A.  $\left\{ \begin{bmatrix} a \\ a \end{bmatrix} \mid a \in \mathbb{R} \right\}$

C.  $\left\{ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right\}$

B.  $\left\{ \begin{bmatrix} a \\ 0 \end{bmatrix} \mid a \in \mathbb{R} \right\}$

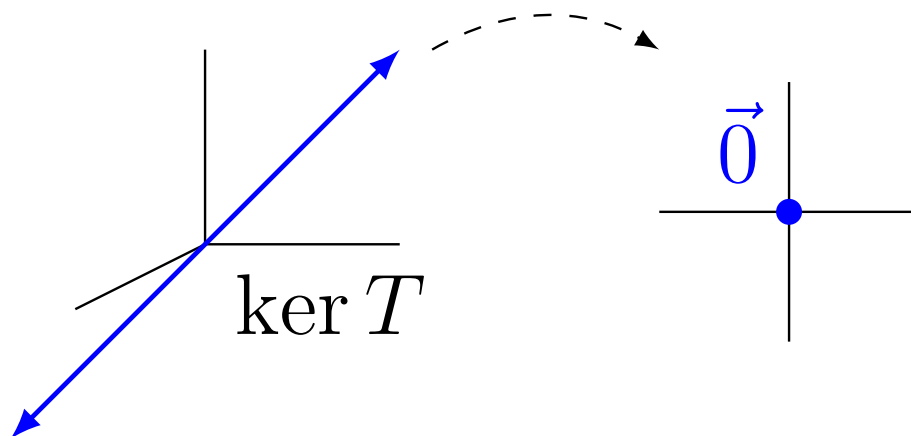
D.  $\left\{ \begin{bmatrix} a \\ b \end{bmatrix} \mid a, b \in \mathbb{R} \right\}$



### Image and Kernel (AT3)

**Definition 3.3.2** Let  $T : V \rightarrow W$  be a linear transformation, and let  $\vec{z}$  be the additive identity (the “zero vector”) of  $W$ . The **kernel** of  $T$  is an important subspace of  $V$  defined by

$$\ker T = \{ \vec{v} \in V \mid T(\vec{v}) = \vec{z} \}$$



**Figure 9** The kernel of a linear transformation



### Image and Kernel (AT3)

**Activity 3.3.3** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be given by

$$T\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}\right) = \begin{bmatrix} x \\ y \end{bmatrix} \quad \text{with standard matrix} \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

Which of these subspaces of  $\mathbb{R}^3$  describes  $\ker T$ , the set of all vectors that transform into  $\vec{0}$ ?

A.  $\left\{ \begin{bmatrix} 0 \\ 0 \\ a \end{bmatrix} \mid a \in \mathbb{R} \right\}$

C.  $\left\{ \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \right\}$

B.  $\left\{ \begin{bmatrix} a \\ a \\ 0 \end{bmatrix} \mid a \in \mathbb{R} \right\}$

D.  $\left\{ \begin{bmatrix} a \\ b \\ c \end{bmatrix} \mid a, b, c \in \mathbb{R} \right\}$

### Image and Kernel (AT3)

**Activity 3.3.4** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be the linear transformation given by the standard matrix

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} 3x + 4y - z \\ x + 2y + z \end{bmatrix}$$

- (a) Set  $T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$  to find a linear system of equations whose solution set is the kernel.
- (b) Use  $\text{RREF}(A)$  to solve this homogeneous system of equations and find a basis for the kernel of  $T$ .

### Image and Kernel (AT3)

**Activity 3.3.5** Let  $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$  be the linear transformation given by

$$T \left( \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \right) = \begin{bmatrix} 2x + 4y + 2z - 4w \\ -2x - 4y + z + w \\ 3x + 6y - z - 4w \end{bmatrix}.$$

Find a basis for the kernel of  $T$ .

### Image and Kernel (AT3)

**Activity 3.3.6** Let  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$  be given by

$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} \quad \text{with standard matrix} \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$$

Which of these subspaces of  $\mathbb{R}^3$  describes the set of all vectors that are the result of using  $T$  to transform  $\mathbb{R}^2$  vectors?

A.  $\left\{ \begin{bmatrix} 0 \\ 0 \\ a \end{bmatrix} \mid a \in \mathbb{R} \right\}$

C.  $\left\{ \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \right\}$

B.  $\left\{ \begin{bmatrix} a \\ b \\ 0 \end{bmatrix} \mid a, b \in \mathbb{R} \right\}$

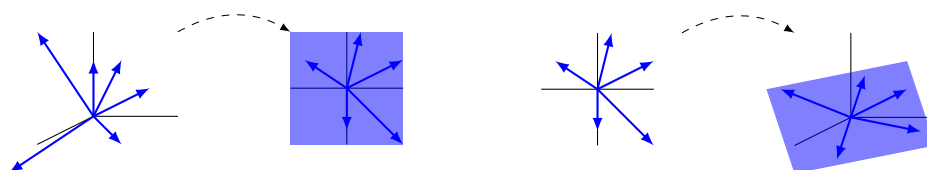
D.  $\left\{ \begin{bmatrix} a \\ b \\ c \end{bmatrix} \mid a, b, c \in \mathbb{R} \right\}$

### Image and Kernel (AT3)

**Definition 3.3.7** Let  $T : V \rightarrow W$  be a linear transformation. The **image** of  $T$  is an important subspace of  $W$  defined by

$$\text{Im } T = \{ \vec{w} \in W \mid \text{there is some } \vec{v} \in V \text{ with } T(\vec{v}) = \vec{w} \}$$

In the examples below, the left example's image is all of  $\mathbb{R}^2$ , but the right example's image is a planar subspace of  $\mathbb{R}^3$ .



**Figure 10** The image of a linear transformation

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### Image and Kernel (AT3)

**Activity 3.3.8** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be given by

$$T\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}\right) = \begin{bmatrix} x \\ y \end{bmatrix} \quad \text{with standard matrix} \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

Which of these subspaces of  $\mathbb{R}^2$  describes  $\text{Im } T$ , the set of all vectors that are the result of using  $T$  to transform  $\mathbb{R}^3$  vectors?

A.  $\left\{ \begin{bmatrix} a \\ a \end{bmatrix} \mid a \in \mathbb{R} \right\}$

C.  $\left\{ \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right\}$

B.  $\left\{ \begin{bmatrix} a \\ 0 \end{bmatrix} \mid a \in \mathbb{R} \right\}$

D.  $\left\{ \begin{bmatrix} a \\ b \end{bmatrix} \mid a, b \in \mathbb{R} \right\}$

### Image and Kernel (AT3)

**Activity 3.3.9** Let  $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$  be the linear transformation given by the standard matrix

$$A = \begin{bmatrix} 3 & 4 & 7 & 1 \\ -1 & 1 & 0 & 2 \\ 2 & 1 & 3 & -1 \end{bmatrix} = \begin{bmatrix} T(\vec{e}_1) & T(\vec{e}_2) & T(\vec{e}_3) & T(\vec{e}_4) \end{bmatrix}.$$

Since for a vector  $\vec{v} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}$ ,  $T(\vec{v}) = T(x_1\vec{e}_1 + x_2\vec{e}_2 + x_3\vec{e}_3 + x_4\vec{e}_4)$ , which of the following best describes the set of vectors

$$\left\{ \begin{bmatrix} 3 \\ -1 \\ 2 \end{bmatrix}, \begin{bmatrix} 4 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 7 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ -1 \end{bmatrix} \right\}?$$

- A. The set of vectors spans  $\text{Im } T$  but is not linearly independent.
- B. The set of vectors is a linearly independent subset of  $\text{Im } T$  but does not span  $\text{Im } T$ .
- C. The set of vectors is linearly independent and spans  $\text{Im } T$ ; that is, the set of vectors is a basis for  $\text{Im } T$ .



### Image and Kernel (AT3)

**Observation 3.3.10** Let  $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$  be the linear transformation given by the standard matrix

$$A = \begin{bmatrix} 3 & 4 & 7 & 1 \\ -1 & 1 & 0 & 2 \\ 2 & 1 & 3 & -1 \end{bmatrix}.$$

Since the set  $\left\{ \begin{bmatrix} 3 \\ -1 \\ 2 \end{bmatrix}, \begin{bmatrix} 4 \\ 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 7 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ -1 \end{bmatrix} \right\}$  spans  $\text{Im } T$ , we can obtain a basis for  $\text{Im } T$  by finding RREF  $A = \begin{bmatrix} 1 & 0 & 1 & -1 \\ 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}$  and only using the vectors corresponding to pivot columns:

$$\left\{ \begin{bmatrix} 3 \\ -1 \\ 2 \end{bmatrix}, \begin{bmatrix} 4 \\ 1 \\ 1 \end{bmatrix} \right\}$$

### Image and Kernel (AT3)

**Fact 3.3.11** *Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear transformation with standard matrix  $A$ .*

- *The kernel of  $T$  is the solution set of the homogeneous system given by the augmented matrix  $\left[ A \mid \vec{0} \right]$ . Use the coefficients of its free variables to get a basis for the kernel.*
- *The image of  $T$  is the span of the columns of  $A$ . Remove the vectors creating non-pivot columns in RREF  $A$  to get a basis for the image.*

### Image and Kernel (AT3)

**Activity 3.3.12** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^4$  be the linear transformation given by the standard matrix

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

Find a basis for the kernel and a basis for the image of  $T$ .

### Image and Kernel (AT3)

**Activity 3.3.13** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear transformation with standard matrix  $A$ . Which of the following is equal to the dimension of the kernel of  $T$ ?

- A. The number of pivot columns
- B. The number of non-pivot columns
- C. The number of pivot rows
- D. The number of non-pivot rows

### Image and Kernel (AT3)

**Activity 3.3.14** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear transformation with standard matrix  $A$ . Which of the following is equal to the dimension of the image of  $T$ ?

- A. The number of pivot columns
- B. The number of non-pivot columns
- C. The number of pivot rows
- D. The number of non-pivot rows

### Image and Kernel (AT3)

**Observation 3.3.15** Combining these with the observation that the number of columns is the dimension of the domain of  $T$ , we have the **rank-nullity theorem**:

The dimension of the domain of  $T$  equals  $\dim(\ker T) + \dim(\operatorname{Im} T)$ .

The dimension of the image is called the **rank** of  $T$  (or  $A$ ) and the dimension of the kernel is called the **nullity**.

### Image and Kernel (AT3)

**Activity 3.3.16** Let  $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$  be the linear transformation given by

$$T \left( \begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix} \right) = \begin{bmatrix} x - y + 5z + 3w \\ -x - 4z - 2w \\ y - 2z - w \end{bmatrix}.$$

- (a) Explain and demonstrate how to find the image of  $T$  and a basis for that image.
- (b) Explain and demonstrate how to find the kernel of  $T$  and a basis for that kernel.
- (c) Explain and demonstrate how to find the rank and nullity of  $T$ , and why the rank-nullity theorem holds for  $T$ .

## 3.4 Injective and Surjective Linear Maps (AT4)

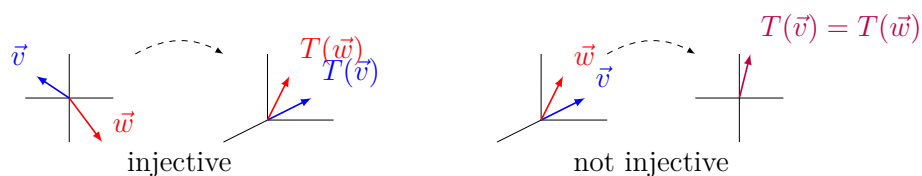
### Learning Outcomes

- Determine if a given linear map is injective and/or surjective.



## Injective and Surjective Linear Maps (AT4)

**Definition 3.4.1** Let  $T : V \rightarrow W$  be a linear transformation.  $T$  is called **injective** or **one-to-one** if  $T$  does not map two distinct vectors to the same place. More precisely,  $T$  is injective if  $T(\vec{v}) \neq T(\vec{w})$  whenever  $\vec{v} \neq \vec{w}$ .



**Figure 11** An injective transformation and a non-injective transformation



### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.2** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be given by

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} x \\ y \end{bmatrix} \quad \text{with standard matrix} \quad \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

Is  $T$  injective?

A. Yes, because  $T(\vec{v}) = T(\vec{w})$  whenever  $\vec{v} = \vec{w}$ .

B. Yes, because  $T(\vec{v}) \neq T(\vec{w})$  whenever  $\vec{v} \neq \vec{w}$ .

C. No, because  $T \left( \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) \neq T \left( \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} \right)$ .

D. No, because  $T \left( \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) = T \left( \begin{bmatrix} 0 \\ 0 \\ 2 \end{bmatrix} \right)$ .

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.3** Let  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$  be given by

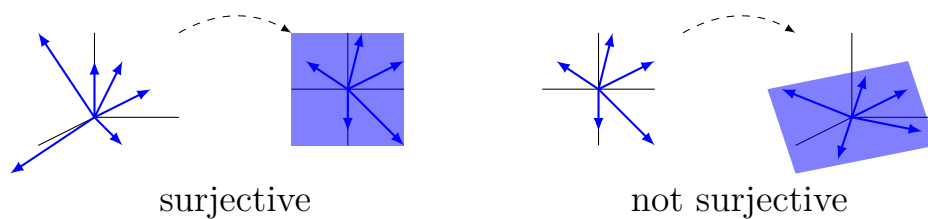
$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} \quad \text{with standard matrix} \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$$

Is  $T$  injective?

- A. Yes, because  $T(\vec{v}) = T(\vec{w})$  whenever  $\vec{v} = \vec{w}$ .
- B. Yes, because  $T(\vec{v}) \neq T(\vec{w})$  whenever  $\vec{v} \neq \vec{w}$ .
- C. No, because  $T\left(\begin{bmatrix} 1 \\ 2 \end{bmatrix}\right) \neq T\left(\begin{bmatrix} 3 \\ 4 \end{bmatrix}\right)$ .
- D. No, because  $T\left(\begin{bmatrix} 1 \\ 2 \end{bmatrix}\right) = T\left(\begin{bmatrix} 3 \\ 4 \end{bmatrix}\right)$ .

## Injective and Surjective Linear Maps (AT4)

**Definition 3.4.4** Let  $T : V \rightarrow W$  be a linear transformation.  $T$  is called **surjective** or **onto** if every element of  $W$  is mapped to by an element of  $V$ . More precisely, for every  $\vec{w} \in W$ , there is some  $\vec{v} \in V$  with  $T(\vec{v}) = \vec{w}$ .



**Figure 12** A surjective transformation and a non-surjective transformation

◇

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.5** Let  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$  be given by

$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix} \quad \text{with standard matrix} \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$$

Is  $T$  surjective?

A. Yes, because for every  $\vec{w} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \in \mathbb{R}^3$ , there exists  $\vec{v} = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^2$  such that  $T(\vec{v}) = \vec{w}$ .

B. No, because  $T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right)$  can never equal  $\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$ .

C. No, because  $T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right)$  can never equal  $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ .

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.6** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be given by

$$T\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}\right) = \begin{bmatrix} x \\ y \end{bmatrix} \quad \text{with standard matrix } \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

Is  $T$  surjective?

- A. Yes, because for every  $\vec{w} = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^2$ , there exists  $\vec{v} = \begin{bmatrix} x \\ y \\ 42 \end{bmatrix} \in \mathbb{R}^3$  such that  $T(\vec{v}) = \vec{w}$ .
- B. Yes, because for every  $\vec{w} = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^2$ , there exists  $\vec{v} = \begin{bmatrix} 0 \\ 0 \\ z \end{bmatrix} \in \mathbb{R}^3$  such that  $T(\vec{v}) = \vec{w}$ .
- C. No, because  $T\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}\right)$  can never equal  $\begin{bmatrix} 3 \\ -2 \end{bmatrix}$ .

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.7** Let  $T : V \rightarrow W$  be a linear transformation where  $\ker T$  contains multiple vectors. What can you conclude?

A.  $T$  is injective

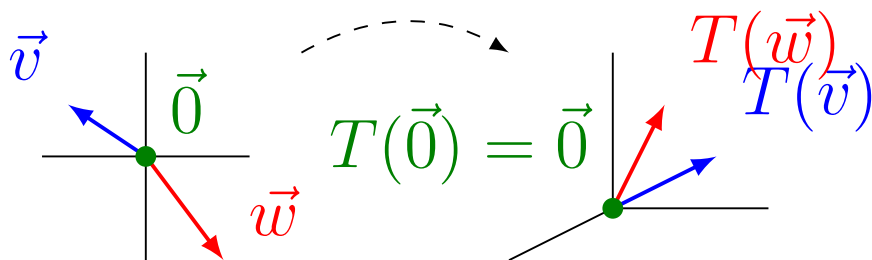
C.  $T$  is surjective

B.  $T$  is not injective

D.  $T$  is not surjective

## Injective and Surjective Linear Maps (AT4)

**Fact 3.4.8** *A linear transformation  $T$  is injective if and only if  $\ker T = \{\vec{0}\}$ . Put another way, an injective linear transformation may be recognized by its **trivial** kernel.*



**Figure 13** *A linear transformation with trivial kernel, which is therefore injective*



### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.9** Let  $T : V \rightarrow \mathbb{R}^3$  be a linear transformation where  $\text{Im } T$  may be spanned by only two vectors. What can you conclude?

A.  $T$  is injective

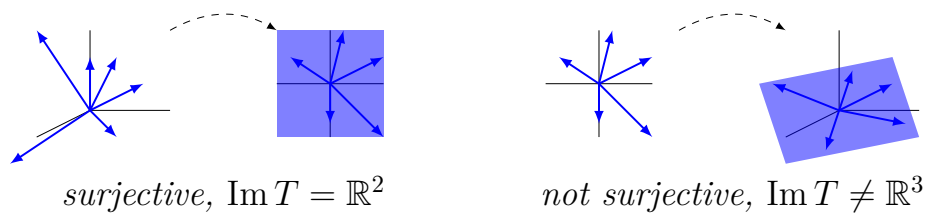
C.  $T$  is surjective

B.  $T$  is not injective

D.  $T$  is not surjective

## Injective and Surjective Linear Maps (AT4)

**Fact 3.4.10** *A linear transformation  $T : V \rightarrow W$  is surjective if and only if  $\text{Im } T = W$ . Put another way, a surjective linear transformation may be recognized by its identical codomain and image.*



**Figure 14** *A linear transformation with identical codomain and image, which is therefore surjective; and a linear transformation with an image smaller than the codomain  $\mathbb{R}^3$ , which is therefore not surjective.*

## Injective and Surjective Linear Maps (AT4)

**Definition 3.4.11** A transformation that is both injective and surjective is said to be **bijective**.  $\diamond$

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.12** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear map with standard matrix  $A$ . Determine whether each of the following statements means  $T$  is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

1. The kernel of  $T$  is trivial, i.e.  $\ker T = \{\vec{0}\}$ .
2. The image of  $T$  equals its codomain, i.e.  $\text{Im } T = \mathbb{R}^m$ .
3. For every  $\vec{w} \in \mathbb{R}^m$ , the set  $\{\vec{v} \in \mathbb{R}^n | T(\vec{v}) = \vec{w}\}$  contains exactly one vector.

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.13** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear map with standard matrix  $A$ . Determine whether each of the following statements means  $T$  is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

1. The columns of  $A$  span  $\mathbb{R}^m$ .
2. The columns of  $A$  form a basis for  $\mathbb{R}^m$ .
3. The columns of  $A$  are linearly independent.

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.14** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear map with standard matrix  $A$ . Determine whether each of the following statements means  $T$  is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

1.  $\text{RREF}(A)$  is the identity matrix.
2. Every column of  $\text{RREF}(A)$  has a pivot.
3. Every row of  $\text{RREF}(A)$  has a pivot.

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.15** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear map with standard matrix  $A$ . Determine whether each of the following statements means  $T$  is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

1. The system of linear equations given by the augmented matrix  $\left[ A \mid \vec{b} \right]$  has a solution for all  $\vec{b} \in \mathbb{R}^m$ .
2. The system of linear equations given by the augmented matrix  $\left[ A \mid \vec{b} \right]$  has exactly one solution for all  $\vec{b} \in \mathbb{R}^m$ .
3. The system of linear equations given by the augmented matrix  $\left[ A \mid \vec{0} \right]$  has exactly one solution.

## Injective and Surjective Linear Maps (AT4)

**Observation 3.4.16** The easiest way to determine if the linear map with standard matrix  $A$  is injective is to see if  $\text{RREF}(A)$  has a pivot in each column.

The easiest way to determine if the linear map with standard matrix  $A$  is surjective is to see if  $\text{RREF}(A)$  has a pivot in each row.



### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.17** What can you conclude about the linear map  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$  with standard matrix  $\begin{bmatrix} a & b \\ c & d \\ e & f \end{bmatrix}$ ?

- A. Its standard matrix has more columns than rows, so  $T$  is not injective.
- B. Its standard matrix has more columns than rows, so  $T$  is injective.
- C. Its standard matrix has more rows than columns, so  $T$  is not surjective.
- D. Its standard matrix has more rows than columns, so  $T$  is surjective.

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.18** What can you conclude about the linear map  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  with standard matrix  $\begin{bmatrix} a & b & c \\ d & e & f \end{bmatrix}$ ?

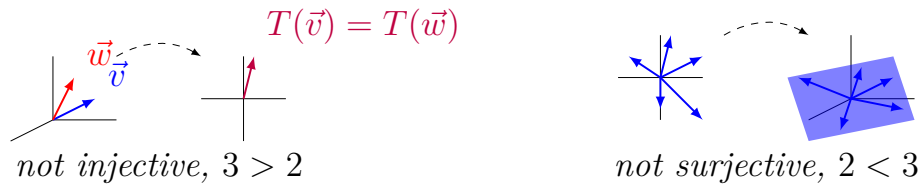
- A. Its standard matrix has more columns than rows, so  $T$  is not injective.
- B. Its standard matrix has more columns than rows, so  $T$  is injective.
- C. Its standard matrix has more rows than columns, so  $T$  is not surjective.
- D. Its standard matrix has more rows than columns, so  $T$  is surjective.

## Injective and Surjective Linear Maps (AT4)

**Fact 3.4.19** *The following are true for any linear map  $T : V \rightarrow W$ :*

- *If  $\dim(V) > \dim(W)$ , then  $T$  is not injective.*
- *If  $\dim(V) < \dim(W)$ , then  $T$  is not surjective.*

*Basically, a linear transformation cannot reduce dimension without collapsing vectors into each other, and a linear transformation cannot increase dimension from its domain to its image.*



**Figure 15** *A linear transformation whose domain has a larger dimension than its codomain, and is therefore not injective; and a linear transformation whose domain has a smaller dimension than its codomain, and is therefore not surjective.*

*But dimension arguments cannot be used to prove a map is injective or surjective.*

## Injective and Surjective Linear Maps (AT4)

**Activity 3.4.20** Suppose  $T : \mathbb{R}^n \rightarrow \mathbb{R}^4$  with standard matrix  $A =$

$$\begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & a_{3n} \\ a_{41} & a_{42} & \cdots & a_{4n} \end{bmatrix}$$

is bijective.

- (a) How many pivot rows must RREF  $A$  have?
- (b) How many pivot columns must RREF  $A$  have?
- (c) What is RREF  $A$ ?

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.21** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$  be a bijective linear map with standard matrix  $A$ . Label each of the following as true or false.

- A.  $\text{RREF}(A)$  is the identity matrix.
- B. The columns of  $A$  form a basis for  $\mathbb{R}^n$ .
- C. The system of linear equations given by the augmented matrix  $\left[ A \mid \vec{b} \right]$  has exactly one solution for each  $\vec{b} \in \mathbb{R}^n$ .

## Injective and Surjective Linear Maps (AT4)

**Observation 3.4.22** The easiest way to show that the linear map with standard matrix  $A$  is bijective is to show that  $\text{RREF}(A)$  is the identity matrix.

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.23** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  be given by the standard matrix

$$A = \begin{bmatrix} 2 & 1 & -1 \\ 4 & 1 & 1 \\ 6 & 2 & 1 \end{bmatrix}.$$

Which of the following must be true?

- |  |  |
|--|--|
| A. $T$ is neither injective nor surjective | C. $T$ is surjective but not injective |
| B. $T$ is injective but not surjective     | D. $T$ is bijective.                   |

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.24** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  be given by

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} 2x + y - z \\ 4x + y + z \\ 6x + 2y \end{bmatrix}.$$

Which of the following must be true?

- |  |  |
|--|--|
| A. $T$ is neither injective nor surjective | C. $T$ is surjective but not injective |
| B. $T$ is injective but not surjective     | D. $T$ is bijective.                   |



### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.25** Let  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$  be given by

$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} 2x + 3y \\ x - y \\ x + 3y \end{bmatrix}.$$

Which of the following must be true?

- |  |  |
|--|--|
| A. $T$ is neither injective nor surjective | C. $T$ is surjective but not injective |
| B. $T$ is injective but not surjective     | D. $T$ is bijective.                   |

### Injective and Surjective Linear Maps (AT4)

**Activity 3.4.26** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be given by

$$T \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} 2x + y - z \\ 4x + y + z \end{bmatrix}.$$

Which of the following must be true?

- |  |  |
|--|--|
| A. $T$ is neither injective nor surjective | C. $T$ is surjective but not injective |
| B. $T$ is injective but not surjective     | D. $T$ is bijective.                   |

## 3.5 Vector Spaces (AT5)

### Learning Outcomes

- Determine if a map between Euclidean vector spaces is linear or not.

## Vector Spaces (AT5)

**Observation 3.5.1** Consider the following applications of properties of the real numbers  $\mathbb{R}$ :

1.  $1 + (2 + 3) = (1 + 2) + 3$ .
2.  $7 + 4 = 4 + 7$ .
3. There exists some  $?$  where  $5 + ? = 5$ .
4. There exists some  $?$  where  $9 + ? = 0$ .
5.  $\frac{1}{2}(1 + 7)$  is the only number that is equally distant from 1 and 7.

### Vector Spaces (AT5)

**Activity 3.5.2** Which of the following properties of  $\mathbb{R}^2$  Euclidean vectors is NOT true?

A.  $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \left( \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \right) = \left( \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \right) + \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}.$

B.  $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} + \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$

C. There exists some  $\begin{bmatrix} ? \\ ? \end{bmatrix}$  where  $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} ? \\ ? \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$

D. There exists some  $\begin{bmatrix} ? \\ ? \end{bmatrix}$  where  $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} ? \\ ? \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}.$

E.  $\frac{1}{2} \left( \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \right)$  is the only vector whose endpoint is equally distant from the endpoints of  $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$  and  $\begin{bmatrix} y_1 \\ y_2 \end{bmatrix}.$

## Vector Spaces (AT5)

**Observation 3.5.3** Consider the following applications of properties of the real numbers  $\mathbb{R}$ :

1.  $3(2(7)) = (3 \cdot 2)(7)$ .
2.  $1(19) = 19$ .
3. There exists some  $x$  such that  $x \cdot 4 = 9$ .
4.  $3 \cdot (2 + 8) = 3 \cdot 2 + 3 \cdot 8$ .
5.  $(2 + 7) \cdot 4 = 2 \cdot 4 + 7 \cdot 4$ .

### Vector Spaces (AT5)

**Activity 3.5.4** Which of the following properties of  $\mathbb{R}^2$  Euclidean vectors is NOT true?

A.  $a \left( b \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \right) = ab \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$

B.  $1 \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$

C. There exists some  $\lambda$  such that  $\lambda \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}.$

D.  $a(\vec{u} + \vec{v}) = a\vec{u} + a\vec{v}.$

E.  $(a + b)\vec{v} = a\vec{v} + b\vec{v}.$

## Vector Spaces (AT5)

**Fact 3.5.5** *Every Euclidean vector space  $\mathbb{R}^n$  satisfies the following properties, where  $\vec{u}, \vec{v}, \vec{w}$  are Euclidean vectors and  $a, b$  are scalars.*

1. *Vector addition is associative:  $\vec{u} + (\vec{v} + \vec{w}) = (\vec{u} + \vec{v}) + \vec{w}$ .*
2. *Vector addition is commutative:  $\vec{u} + \vec{v} = \vec{v} + \vec{u}$ .*
3. *An additive identity exists: There exists some  $\vec{z}$  where  $\vec{v} + \vec{z} = \vec{v}$ .*
4. *Additive inverses exist: There exists some  $-\vec{v}$  where  $\vec{v} + (-\vec{v}) = \vec{z}$ .*
5. *Scalar multiplication is associative:  $a(b\vec{v}) = (ab)\vec{v}$ .*
6. *1 is a multiplicative identity:  $1\vec{v} = \vec{v}$ .*
7. *Scalar multiplication distributes over vector addition:  $a(\vec{u} + \vec{v}) = (a\vec{u}) + (a\vec{v})$ .*
8. *Scalar multiplication distributes over scalar addition:  $(a + b)\vec{v} = (a\vec{v}) + (b\vec{v})$ .*



## Vector Spaces (AT5)

**Definition 3.5.6** A **vector space**  $V$  is any set of mathematical objects, called **vectors**, and a set of numbers, called **scalars**, with associated addition  $\oplus$  and scalar multiplication  $\odot$  operations that satisfy the following properties. Let  $\vec{u}, \vec{v}, \vec{w}$  be vectors belonging to  $V$ , and let  $a, b$  be scalars.

We always assume the codomain of our operations is  $V$ , i.e. that addition is a map  $V \times V \rightarrow V$  and that scalar multiplication is a map  $\mathbb{R} \times V \rightarrow V$ .

Likewise, we only consider “real” vector spaces, i.e. those whose scalars come from  $\mathbb{R}$ . However, one can similarly define vector spaces with scalars from other fields like the complex or rational numbers.

1. Vector addition is associative:  $\vec{u} \oplus (\vec{v} \oplus \vec{w}) = (\vec{u} \oplus \vec{v}) \oplus \vec{w}$ .
2. Vector addition is commutative:  $\vec{u} \oplus \vec{v} = \vec{v} \oplus \vec{u}$ .
3. An additive identity exists: There exists some  $\vec{z}$  where  $\vec{v} \oplus \vec{z} = \vec{v}$ .
4. Additive inverses exist: There exists some  $-\vec{v}$  where  $\vec{v} \oplus (-\vec{v}) = \vec{z}$ .
5. Scalar multiplication is associative:  $a \odot (b \odot \vec{v}) = (ab) \odot \vec{v}$ .
6. 1 is a multiplicative identity:  $1 \odot \vec{v} = \vec{v}$ .
7. Scalar multiplication distributes over vector addition:  $a \odot (\vec{u} \oplus \vec{v}) = (a \odot \vec{u}) \oplus (a \odot \vec{v})$ .
8. Scalar multiplication distributes over scalar addition:  $(a + b) \odot \vec{v} = (a \odot \vec{v}) \oplus (b \odot \vec{v})$ .

◇

## Vector Spaces (AT5)

**Remark 3.5.7** Consider the set  $\mathbb{C}$  of complex numbers with the usual definition for addition:  $(a + b\mathbf{i}) \oplus (c + d\mathbf{i}) = (a + c) + (b + d)\mathbf{i}$ .

Let  $\vec{u} = a + b\mathbf{i}$ ,  $\vec{v} = c + d\mathbf{i}$ , and  $\vec{w} = e + f\mathbf{i}$ . Then

$$\begin{aligned}\vec{u} \oplus (\vec{v} \oplus \vec{w}) &= (a + b\mathbf{i}) \oplus ((c + d\mathbf{i}) \oplus (e + f\mathbf{i})) \\ &= (a + b\mathbf{i}) \oplus ((c + e) + (d + f)\mathbf{i}) \\ &= (a + c + e) + (b + d + f)\mathbf{i}\end{aligned}$$

$$\begin{aligned}(\vec{u} \oplus \vec{v}) \oplus \vec{w} &= ((a + b\mathbf{i}) \oplus (c + d\mathbf{i})) \oplus (e + f\mathbf{i}) \\ &= ((a + c) + (b + d)\mathbf{i}) \oplus (e + f\mathbf{i}) \\ &= (a + c + e) + (b + d + f)\mathbf{i}\end{aligned}$$

This proves that complex addition is associative:  $\vec{u} \oplus (\vec{v} \oplus \vec{w}) = (\vec{u} \oplus \vec{v}) \oplus \vec{w}$ . The seven other vector space properties may also be verified, so  $\mathbb{C}$  is an example of a non-Euclidean vector space.

## Vector Spaces (AT5)

**Remark 3.5.8** The following sets are just a few examples of vector spaces, with the usual/natural operations for addition and scalar multiplication.

- $\mathbb{R}^n$ : Euclidean vectors with  $n$  components.
- $\mathbb{C}$ : Complex numbers.
- $M_{m,n}$ : Matrices of real numbers with  $m$  rows and  $n$  columns.
- $\mathcal{P}_n$ : Polynomials of degree  $n$  or less.
- $\mathcal{P}$ : Polynomials of any degree.
- $C(\mathbb{R})$ : Real-valued continuous functions.

### Vector Spaces (AT5)

**Activity 3.5.9** Consider the set  $V = \{(x, y) \mid y = 2^x\}$ .

Which of the following vectors is not in  $V$ ?

A.  $(0, 0)$

C.  $(2, 4)$

B.  $(1, 2)$

D.  $(3, 8)$

### Vector Spaces (AT5)

**Activity 3.5.10** Consider the set  $V = \{(x, y) \mid y = 2^x\}$  with the operation  $\oplus$  defined by

$$(x_1, y_1) \oplus (x_2, y_2) = (x_1 + x_2, y_1 y_2).$$

Let  $\vec{u}, \vec{v}$  be in  $V$  with  $\vec{u} = (1, 2)$  and  $\vec{v} = (2, 4)$ . Using the operations defined for  $V$ , which of the following is  $\vec{u} \oplus \vec{v}$ ?

A.  $(2, 6)$

C.  $(3, 6)$

B.  $(2, 8)$

D.  $(3, 8)$

### Vector Spaces (AT5)

**Activity 3.5.11** Consider the set  $V = \{(x, y) \mid y = 2^x\}$  with operations  $\oplus, \odot$  defined by

$$(x_1, y_1) \oplus (x_2, y_2) = (x_1 + x_2, y_1 y_2) \qquad c \odot (x, y) = (cx, y^c).$$

Let  $a = 2, b = -3$  be scalars and  $\vec{u} = (1, 2) \in V$ .

(a) Verify that

$$(a + b) \odot \vec{u} = \left(-1, \frac{1}{2}\right).$$

(b) Compute the value of

$$(a \odot \vec{u}) \oplus (b \odot \vec{u}).$$

### Vector Spaces (AT5)

**Activity 3.5.12** Consider the set  $V = \{(x, y) \mid y = 2^x\}$  with operations  $\oplus, \odot$  defined by

$$(x_1, y_1) \oplus (x_2, y_2) = (x_1 + x_2, y_1 y_2) \qquad c \odot (x, y) = (cx, y^c).$$

Let  $a, b$  be unspecified scalars in  $\mathbb{R}$  and  $\vec{u} = (x, y)$  be an unspecified vector in  $V$ .

(a) Show that both sides of the equation

$$(a + b) \odot (x, y) = (a \odot (x, y)) \oplus (b \odot (x, y))$$

simplify to the expression  $(ax + bx, y^a y^b)$ .

(b) Show that  $V$  contains an additive identity element  $\vec{z} = (?, ?)$  satisfying

$$(x, y) \oplus (?, ?) = (x, y)$$

for all  $(x, y) \in V$ .

That is, pick appropriate values for  $\vec{z} = (?, ?)$  and then simplify  $(x, y) \oplus (?, ?)$  into just  $(x, y)$ .

(c) Is  $V$  a vector space?

A. Yes

B. No

C. More work is required

## Vector Spaces (AT5)

**Remark 3.5.13** It turns out  $V = \{(x, y) \mid y = 2^x\}$  with operations  $\oplus, \odot$  defined by

$$(x_1, y_1) \oplus (x_2, y_2) = (x_1 + x_2, y_1 y_2) \qquad c \odot (x, y) = (cx, y^c)$$

satisfies all eight properties from [Definition 3.5.6](#).

Thus,  $V$  is a vector space.



### Vector Spaces (AT5)

**Activity 3.5.14** Let  $V = \{(x, y) \mid x, y \in \mathbb{R}\}$  have operations defined by

$$(x_1, y_1) \oplus (x_2, y_2) = (x_1 + y_1 + x_2 + y_2, x_1^2 + x_2^2)$$

$$c \odot (x, y) = (x^c, y + c - 1).$$

- (a) Show that 1 is the scalar multiplication identity element by simplifying  $1 \odot (x, y)$  to  $(x, y)$ .
- (b) Show that  $V$  does not have an additive identity element  $\vec{z} = (z, w)$  by showing that  $(0, -1) \oplus (z, w) \neq (0, -1)$  no matter what the values of  $z, w$  are.
- (c) Is  $V$  a vector space?
  - A. Yes
  - B. No
  - C. More work is required

### Vector Spaces (AT5)

**Activity 3.5.15** Let  $V = \{(x, y) \mid x, y \in \mathbb{R}\}$  have operations defined by

$$(x_1, y_1) \oplus (x_2, y_2) = (x_1 + x_2, y_1 + 3y_2) \qquad c \odot (x, y) = (cx, cy).$$

(a) Show that scalar multiplication distributes over vector addition, i.e.

$$c \odot ((x_1, y_1) \oplus (x_2, y_2)) = c \odot (x_1, y_1) \oplus c \odot (x_2, y_2)$$

for *all*  $c \in \mathbb{R}$ ,  $(x_1, y_1), (x_2, y_2) \in V$ .

(b) Show that vector addition is not associative, i.e.

$$(x_1, y_1) \oplus ((x_2, y_2) \oplus (x_3, y_3)) \neq ((x_1, y_1) \oplus (x_2, y_2)) \oplus (x_3, y_3)$$

for *some* vectors  $(x_1, y_1), (x_2, y_2), (x_3, y_3) \in V$ .

(c) Is  $V$  a vector space?

A. Yes

B. No

C. More work is required

## 3.6 Polynomial and Matrix Spaces (AT6)

### Learning Outcomes

- Answer questions about vector spaces of polynomials or matrices.

## Polynomial and Matrix Spaces (AT6)

**Observation 3.6.1** Nearly every term we've defined for Euclidean vector spaces  $\mathbb{R}^n$  was actually defined for all kinds of vector spaces:

- [Definition 2.1.2](#)
- [Definition 2.1.3](#)
- [Definition 2.3.1](#)
- [Definition 2.4.2](#)
- [Definition 2.5.3](#)
- [Definition 3.1.1](#)
- [Definition 3.1.2](#)
- [Definition 3.3.2](#)
- [Definition 3.3.7](#)
- [Definition 3.4.1](#)
- [Definition 3.4.4](#)
- [Definition 3.4.11](#)

Polynomial and Matrix Spaces (AT6)

**Activity 3.6.2** Let  $V$  be a vector space with the basis  $\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$ . Which of these completes the following definition for a bijective linear map  $T : V \rightarrow \mathbb{R}^3$ ?

$$T(\vec{v}) = T(a\vec{v}_1 + b\vec{v}_2 + c\vec{v}_3) = \begin{bmatrix} ? \\ ? \\ ? \end{bmatrix}$$

A.  $\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$

B.  $\begin{bmatrix} a + b + c \\ 0 \\ 0 \end{bmatrix}$

C.  $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$

## Polynomial and Matrix Spaces (AT6)

**Fact 3.6.3** *Every vector space with finite dimension, that is, every vector space  $V$  with a basis of the form  $\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_n\}$  has a linear bijection  $T$  with Euclidean space  $\mathbb{R}^n$  that simply swaps its basis with the standard basis  $\{\vec{e}_1, \vec{e}_2, \dots, \vec{e}_n\}$  for  $\mathbb{R}^n$ :*

$$T(c_1\vec{v}_1 + c_2\vec{v}_2 + \cdots + c_n\vec{v}_n) = c_1\vec{e}_1 + c_2\vec{e}_2 + \cdots + c_n\vec{e}_n = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix}$$

*This transformation (in fact, any linear bijection between vector spaces) is called an **isomorphism**, and  $V$  is said to be **isomorphic** to  $\mathbb{R}^n$ .*

### Polynomial and Matrix Spaces (AT6)

**Activity 3.6.4** The matrix space  $M_{2,2} = \left\{ \begin{bmatrix} a & b \\ c & d \end{bmatrix} \mid a, b, c, d \in \mathbb{R} \right\}$  has the basis

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

(a) Which Euclidean space is  $M_{2,2}$  isomorphic to?

A.  $\mathbb{R}^2$

C.  $\mathbb{R}^4$

B.  $\mathbb{R}^3$

D.  $\mathbb{R}^5$

(b) Describe an isomorphism  $T : M_{2,2} \rightarrow \mathbb{R}^?$ :

$$T\left(\begin{bmatrix} a & b \\ c & d \end{bmatrix}\right) = \begin{bmatrix} ? \\ \vdots \\ ? \end{bmatrix}$$

# Polynomial and Matrix Spaces (AT6)

**Activity 3.6.5** The polynomial space  $\mathcal{P}^4 = \{a + bx + cx^2 + dx^3 + ex^4 \mid a, b, c, d, e \in \mathbb{R}\}$  has the basis

$$\{1, x, x^2, x^3, x^4\}.$$

(a) Which Euclidean space is  $\mathcal{P}^4$  isomorphic to?

A.  $\mathbb{R}^2$

C.  $\mathbb{R}^4$

B.  $\mathbb{R}^3$

D.  $\mathbb{R}^5$

(b) Describe an isomorphism  $T : \mathcal{P}^4 \rightarrow \mathbb{R}^?$ :

$$T(a + bx + cx^2 + dx^3 + ex^4) = \begin{bmatrix} ? \\ \vdots \\ ? \end{bmatrix}$$



## Polynomial and Matrix Spaces (AT6)

**Remark 3.6.6** Since any finite-dimensional vector space is isomorphic to a Euclidean space  $\mathbb{R}^n$ , one approach to answering questions about such spaces is to answer the corresponding question about  $\mathbb{R}^n$ .

### Polynomial and Matrix Spaces (AT6)

**Activity 3.6.7** Consider how to construct the polynomial  $x^3 + x^2 + 5x + 1$  as a linear combination of polynomials from the set

$$\{x^3 - 2x^2 + x + 2, 2x^2 - 1, -x^3 + 3x^2 + 3x - 2, x^3 - 6x^2 + 9x + 5\}.$$

- (a) Describe the vector space involved in this problem, and an isomorphic Euclidean space and relevant Euclidean vectors that can be used to solve this problem.
- (b) Show how to construct an appropriate Euclidean vector from an appropriate set of Euclidean vectors.
- (c) Use this result to answer the original question.

## Polynomial and Matrix Spaces (AT6)

**Observation 3.6.8** The space of polynomials  $\mathcal{P}$  (of *any* degree) has the basis  $\{1, x, x^2, x^3, \dots\}$ , so it is a natural example of an infinite-dimensional vector space.

Since  $\mathcal{P}$  and other infinite-dimensional spaces cannot be treated as an isomorphic finite-dimensional Euclidean space  $\mathbb{R}^n$ , vectors in such spaces cannot be studied by converting them into Euclidean vectors. Fortunately, most of the examples we will be interested in for this course will be finite-dimensional.

# Chapter 4

## Matrices (MX)

### Learning Outcomes

What algebraic structure do matrices have?

By the end of this chapter, you should be able to...

1. Multiply matrices.
2. Determine if a matrix is invertible, and if so, compute its inverse.
3. Invert an appropriate matrix to solve a system of linear equations.
4. Express row operations through matrix multiplication.

## 4.1 Matrices and Multiplication (MX1)

### Learning Outcomes

- Multiply matrices.

## Matrices and Multiplication (MX1)

**Observation 4.1.1** If  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  and  $S : \mathbb{R}^m \rightarrow \mathbb{R}^k$  are linear maps, then the composition map  $S \circ T$  computed as  $(S \circ T)(\vec{v}) = S(T(\vec{v}))$  is a linear map from  $\mathbb{R}^n \rightarrow \mathbb{R}^k$ .

$$\begin{array}{ccccc} \mathbb{R}^n & \xrightarrow{T} & \mathbb{R}^m & \xrightarrow{S} & \mathbb{R}^k \\ & & \searrow & \nearrow & \\ & & S \circ T & & \end{array}$$

**Figure 16** The composition of two linear maps.

## Matrices and Multiplication (MX1)

**Activity 4.1.2** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be defined by the  $2 \times 3$  standard matrix  $B$  and  $S : \mathbb{R}^2 \rightarrow \mathbb{R}^4$  be defined by the  $4 \times 2$  standard matrix  $A$ :

$$B = \begin{bmatrix} 2 & 1 & -3 \\ 5 & -3 & 4 \end{bmatrix} \quad A = \begin{bmatrix} 1 & 2 \\ 0 & 1 \\ 3 & 5 \\ -1 & -2 \end{bmatrix}.$$

(a) What are the domain and codomain of the composition map  $S \circ T$ ?

- |  |  |
|--|--|
| A. The domain is $\mathbb{R}^3$ and the codomain is $\mathbb{R}^2$ | C. The domain is $\mathbb{R}^3$ and the codomain is $\mathbb{R}^4$ |
| B. The domain is $\mathbb{R}^2$ and the codomain is $\mathbb{R}^4$ | D. The domain is $\mathbb{R}^4$ and the codomain is $\mathbb{R}^3$ |

(b) What size will the standard matrix of  $S \circ T$  be?

- |                                  |                                  |
|----------------------------------|----------------------------------|
| A. 4 (rows) $\times$ 3 (columns) | C. 3 (rows) $\times$ 2 (columns) |
| B. 3 (rows) $\times$ 4 (columns) | D. 2 (rows) $\times$ 4 (columns) |

(c) Compute

$$(S \circ T)(\vec{e}_1) = S(T(\vec{e}_1)) = S\left(\begin{bmatrix} 2 \\ 5 \end{bmatrix}\right) = \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix}.$$

(d) Compute  $(S \circ T)(\vec{e}_2)$ .

(e) Compute  $(S \circ T)(\vec{e}_3)$ .

(f) Use  $(S \circ T)(\vec{e}_1)$ ,  $(S \circ T)(\vec{e}_2)$ ,  $(S \circ T)(\vec{e}_3)$  to write the standard matrix for  $S \circ T$ .

## Matrices and Multiplication (MX1)

**Definition 4.1.3** We define the **product**  $AB$  of a  $m \times n$  matrix  $A$  and a  $n \times k$  matrix  $B$  to be the  $m \times k$  standard matrix of the composition map of the two corresponding linear functions.

For the previous activity,  $T$  was a map  $\mathbb{R}^3 \rightarrow \mathbb{R}^2$ , and  $S$  was a map  $\mathbb{R}^2 \rightarrow \mathbb{R}^4$ , so  $S \circ T$  gave a map  $\mathbb{R}^3 \rightarrow \mathbb{R}^4$  with a  $4 \times 3$  standard matrix:

$$AB = \begin{bmatrix} 1 & 2 \\ 0 & 1 \\ 3 & 5 \\ -1 & -2 \end{bmatrix} \begin{bmatrix} 2 & 1 & -3 \\ 5 & -3 & 4 \end{bmatrix}$$
$$= [(S \circ T)(\vec{e}_1) \quad (S \circ T)(\vec{e}_2) \quad (S \circ T)(\vec{e}_3)] = \begin{bmatrix} 12 & -5 & 5 \\ 5 & -3 & 4 \\ 31 & -12 & 11 \\ -12 & 5 & -5 \end{bmatrix}.$$

◇



### Matrices and Multiplication (MX1)

**Activity 4.1.4** Let  $S : \mathbb{R}^3 \rightarrow \mathbb{R}^2$  be given by the matrix  $A = \begin{bmatrix} -4 & -2 & 3 \\ 0 & 1 & 1 \end{bmatrix}$

and  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$  be given by the matrix  $B = \begin{bmatrix} 2 & 3 \\ 1 & -1 \\ 0 & -1 \end{bmatrix}$ .

- (a) Write the dimensions (rows  $\times$  columns) for  $A$ ,  $B$ ,  $AB$ , and  $BA$ .
- (b) Find the standard matrix  $AB$  of  $S \circ T$ .
- (c) Find the standard matrix  $BA$  of  $T \circ S$ .

## Matrices and Multiplication (MX1)

**Activity 4.1.5** Consider the following three matrices.

$$A = \begin{bmatrix} 1 & 0 & -3 \\ 3 & 2 & 1 \end{bmatrix} \quad B = \begin{bmatrix} 2 & 2 & 1 & 0 & 1 \\ 1 & 1 & 1 & -1 & 0 \\ 0 & 0 & 3 & 2 & 1 \\ -1 & 5 & 7 & 2 & 1 \end{bmatrix} \quad C = \begin{bmatrix} 2 & 2 \\ 0 & -1 \\ 3 & 1 \\ 4 & 0 \end{bmatrix}$$

- (a) Find the domain and codomain of each of the three linear maps corresponding to  $A$ ,  $B$ , and  $C$ .
- (b) Only one of the matrix products  $AB$ ,  $AC$ ,  $BA$ ,  $BC$ ,  $CA$ ,  $CB$  can actually be computed. Compute it.

### Matrices and Multiplication (MX1)

**Activity 4.1.6** Let  $B = \begin{bmatrix} 3 & -4 & 0 \\ 2 & 0 & -1 \\ 0 & -3 & 3 \end{bmatrix}$ , and let  $A = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$ .

- (a) Compute the product  $BA$  by hand.
- (b) Check your work using technology. Using Octave:

```
B = [3 -4 0 ; 2 0 -1 ; 0 -3 3]
A = [2 7 -1 ; 0 3 2 ; 1 1 -1]
B*A
```

### Matrices and Multiplication (MX1)

**Activity 4.1.7** Of the following three matrices, only two may be multiplied.

$$A = \begin{bmatrix} -1 & 3 & -2 & -3 \\ 1 & -4 & 2 & 3 \end{bmatrix} \quad B = \begin{bmatrix} 1 & -6 & -1 \\ 0 & 1 & 0 \end{bmatrix} \quad C = \begin{bmatrix} 1 & -1 & -1 \\ 0 & 1 & -2 \\ -2 & 4 & -1 \\ -2 & 3 & -1 \end{bmatrix}$$

Explain which two can be multiplied and why. Then show how to find their product.

## 4.2 The Inverse of a Matrix (MX2)

### Learning Outcomes

- Determine if a matrix is invertible, and if so, compute its inverse.

## The Inverse of a Matrix (MX2)

**Activity 4.2.1** Let  $A = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$ . Find a  $3 \times 3$  matrix  $B$  such that  $BA = A$ , that is,

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$$

Check your guess using technology.

## The Inverse of a Matrix (MX2)

**Definition 4.2.2** The identity matrix  $I_n$  (or just  $I$  when  $n$  is obvious from context) is the  $n \times n$  matrix

$$I_n = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 \end{bmatrix}.$$

It has a 1 on each diagonal element and a 0 in every other position. ◇

## The Inverse of a Matrix (MX2)

**Fact 4.2.3** *For any square matrix  $A$ ,  $IA = AI = A$ :*

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$$



## The Inverse of a Matrix (MX2)

**Activity 4.2.4** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$  be a linear map with standard matrix  $A$ . Sort the following items into three groups of statements: a group that means  $T$  is *injective*, a group that means  $T$  is *surjective*, and a group that means  $T$  is *bijective*.

- A.  $A\vec{x} = \vec{b}$  has a solution for all  $\vec{b} \in \mathbb{R}^m$
- B.  $A\vec{x} = \vec{b}$  has a unique solution for all  $\vec{b} \in \mathbb{R}^m$
- C.  $A\vec{x} = \vec{0}$  has a unique solution.
- D. The columns of  $A$  span  $\mathbb{R}^m$
- E. The columns of  $A$  are linearly independent
- F. The columns of  $A$  are a basis of  $\mathbb{R}^m$
- G. Every column of  $\text{RREF}(A)$  has a pivot
- H. Every row of  $\text{RREF}(A)$  has a pivot
- I.  $m = n$  and  $\text{RREF}(A) = I$

## The Inverse of a Matrix (MX2)

**Activity 4.2.5** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  be the linear transformation given by the standard matrix  $A = \begin{bmatrix} 2 & -1 & 0 \\ 2 & 1 & 4 \\ 1 & 1 & 3 \end{bmatrix}$ .

Write an augmented matrix representing the system of equations given by  $T(\vec{x}) = \vec{0}$ , that is,  $A\vec{x} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$ . Then solve  $T(\vec{x}) = \vec{0}$  to find the kernel of  $T$ .

## The Inverse of a Matrix (MX2)

**Definition 4.2.6** Let  $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$  be a linear map with standard matrix  $A$ .

- If  $T$  is a bijection and  $\vec{b}$  is any  $\mathbb{R}^n$  vector, then  $T(\vec{x}) = A\vec{x} = \vec{b}$  has a unique solution.
- So we may define an **inverse map**  $T^{-1} : \mathbb{R}^n \rightarrow \mathbb{R}^n$  by setting  $T^{-1}(\vec{b})$  to be this unique solution.
- Let  $A^{-1}$  be the standard matrix for  $T^{-1}$ . We call  $A^{-1}$  the **inverse matrix** of  $A$ , so we also say that  $A$  is **invertible**.

◇

## The Inverse of a Matrix (MX2)

**Activity 4.2.7** Let  $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$  be the linear transformation given by the standard matrix  $A = \begin{bmatrix} 2 & -1 & -6 \\ 2 & 1 & 3 \\ 1 & 1 & 4 \end{bmatrix}$ .

(a) Write an augmented matrix representing the system of equations given

by  $T(\vec{x}) = \vec{e}_1$ , that is,  $A\vec{x} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$ . Then solve  $T(\vec{x}) = \vec{e}_1$  to find  $T^{-1}(\vec{e}_1)$ .

(b) Solve  $T(\vec{x}) = \vec{e}_2$  to find  $T^{-1}(\vec{e}_2)$ .

(c) Solve  $T(\vec{x}) = \vec{e}_3$  to find  $T^{-1}(\vec{e}_3)$ .

(d) Write  $A^{-1}$ , the standard matrix for  $T^{-1}$ .

## The Inverse of a Matrix (MX2)

**Observation 4.2.8** We could have solved these three systems simultaneously by row reducing the matrix  $[A \mid I]$  at once.

$$\left[ \begin{array}{ccc|ccc} 2 & -1 & -6 & 1 & 0 & 0 \\ 2 & 1 & 3 & 0 & 1 & 0 \\ 1 & 1 & 4 & 0 & 0 & 1 \end{array} \right] \sim \left[ \begin{array}{ccc|ccc} 1 & 0 & 0 & 1 & -2 & 3 \\ 0 & 1 & 0 & -5 & 14 & -18 \\ 0 & 0 & 1 & 1 & -3 & 4 \end{array} \right]$$

## The Inverse of a Matrix (MX2)

**Activity 4.2.9** Find the inverse  $A^{-1}$  of the matrix  $A = \begin{bmatrix} 1 & 3 \\ 0 & -2 \end{bmatrix}$  by row-reducing  $[A \mid I]$ .

## The Inverse of a Matrix (MX2)

**Activity 4.2.10** Is the matrix  $\begin{bmatrix} 2 & 3 & 1 \\ -1 & -4 & 2 \\ 0 & -5 & 5 \end{bmatrix}$  invertible? Give a reason for your answer.

## The Inverse of a Matrix (MX2)

**Observation 4.2.11** An  $n \times n$  matrix  $A$  is invertible if and only if  $\text{RREF}(A) = I_n$ .



## The Inverse of a Matrix (MX2)

**Activity 4.2.12** Let  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  be the bijective linear map defined by  $T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} 2x - 3y \\ -3x + 5y \end{bmatrix}$ , with the inverse map  $T^{-1}\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} 5x + 3y \\ 3x + 2y \end{bmatrix}$ .

(a) Compute  $(T^{-1} \circ T)\left(\begin{bmatrix} -2 \\ 1 \end{bmatrix}\right)$ .

(b) If  $A$  is the standard matrix for  $T$  and  $A^{-1}$  is the standard matrix for  $T^{-1}$ , find the  $2 \times 2$  matrix

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

## The Inverse of a Matrix (MX2)

**Observation 4.2.13**  $T^{-1} \circ T = T \circ T^{-1}$  is the identity map for any bijective linear transformation  $T$ . Therefore  $A^{-1}A = AA^{-1}$  equals the identity matrix  $I$  for any invertible matrix  $A$ .

## 4.3 Solving Systems with Matrix Inverses (MX3)

### Learning Outcomes

- Invert an appropriate matrix to solve a system of linear equations.

# Solving Systems with Matrix Inverses (MX3)

**Activity 4.3.1** Consider the following linear system with a unique solution:

$$\begin{array}{ccccrccl} 3x_1 & - & 2x_2 & - & 2x_3 & - & 4x_4 & = & -7 \\ 2x_1 & - & x_2 & - & x_3 & - & x_4 & = & -1 \\ -x_1 & & & + & x_3 & & & = & -1 \\ & - & x_2 & & & - & 2x_4 & = & -5 \end{array}$$

(a) Define

$$T\left(\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}\right) = \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix}$$

so that  $T(\vec{x}) = \begin{bmatrix} -7 \\ -1 \\ -1 \\ -5 \end{bmatrix}$  has the same solution set as this system.

(b) Define

$$A = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix}$$

so that  $A\vec{x} = \begin{bmatrix} -7 \\ -1 \\ -1 \\ -5 \end{bmatrix}$  has the same solution set as this system.

(c) Find

$$B = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix}$$

so that  $BA\vec{x} = \vec{x}$ .

(d) Find  $\vec{x} = BA\vec{x} = B \begin{bmatrix} -7 \\ -1 \\ -1 \\ -5 \end{bmatrix}$  to solve the system.

### Solving Systems with Matrix Inverses (MX3)

**Remark 4.3.2** The linear system described by the augmented matrix  $[A \mid \vec{w}]$  has exactly the same solution set as the matrix equation  $A\vec{x} = \vec{w}$ .

### Solving Systems with Matrix Inverses (MX3)

**Activity 4.3.3** Let  $A\vec{x} = \vec{w}$  describe a linear system. When will this linear system have exactly one solution?

- A. When  $A$  is invertible.
- B. When  $A$  is not invertible.
- C. When RREF  $A$  has a non-pivot column.
- D. When RREF  $A$  has a non-pivot row.

### Solving Systems with Matrix Inverses (MX3)

**Fact 4.3.4** *When  $A\vec{x} = \vec{w}$  has exactly one solution, this solution is given by  $\vec{x} = A^{-1}\vec{w}$ .*

### Solving Systems with Matrix Inverses (MX3)

**Activity 4.3.5** Consider the vector equation

$$x_1 \begin{bmatrix} 1 \\ 2 \\ -2 \end{bmatrix} + x_2 \begin{bmatrix} -2 \\ -3 \\ 3 \end{bmatrix} + x_3 \begin{bmatrix} 1 \\ 4 \\ -3 \end{bmatrix} = \begin{bmatrix} -3 \\ 5 \\ -1 \end{bmatrix}$$

with a unique solution.

- (a) Explain and demonstrate how this problem can be restated using matrix multiplication.
- (b) Use the properties of matrix multiplication to find the unique solution.



## 4.4 Row Operations as Matrix Multiplication (MX4)

### Learning Outcomes

- Express row operations through matrix multiplication.

## Row Operations as Matrix Multiplication (MX4)

**Activity 4.4.1** Tweaking the identity matrix slightly allows us to write row operations in terms of matrix multiplication.

(a) Create a matrix that doubles the third row of  $A$ :

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 2 & 2 & -2 \end{bmatrix}$$

(b) Create a matrix that swaps the second and third rows of  $A$ :

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 1 & 1 & -1 \\ 0 & 3 & 2 \end{bmatrix}$$

(c) Create a matrix that adds 5 times the third row of  $A$  to the first row:

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 + 5(1) & 7 + 5(1) & -1 + 5(-1) \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$$

## Row Operations as Matrix Multiplication (MX4)

**Fact 4.4.2** *If  $R$  is the result of applying a row operation to  $I$ , then  $RA$  is the result of applying the same row operation to  $A$ .*

- *Scaling a row:*  $R = \begin{bmatrix} c & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

- *Swapping rows:*  $R = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

- *Adding a row multiple to another row:*  $R = \begin{bmatrix} 1 & 0 & c \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

*Such matrices can be chained together to emulate multiple row operations. In particular,*

$$\text{RREF}(A) = R_k \dots R_2 R_1 A$$

*for some sequence of matrices  $R_1, R_2, \dots, R_k$ .*

### Row Operations as Matrix Multiplication (MX4)

**Activity 4.4.3** Consider the two row operations  $R_2 \leftrightarrow R_3$  and  $R_1 + R_2 \rightarrow R_1$  applied as follows to show  $A \sim B$ :

$$\begin{aligned} A = \begin{bmatrix} -1 & 4 & 5 \\ 0 & 3 & -1 \\ 1 & 2 & 3 \end{bmatrix} &\sim \begin{bmatrix} -1 & 4 & 5 \\ 1 & 2 & 3 \\ 0 & 3 & -1 \end{bmatrix} \\ &\sim \begin{bmatrix} -1+1 & 4+2 & 5+3 \\ 1 & 2 & 3 \\ 0 & 3 & -1 \end{bmatrix} = \begin{bmatrix} 0 & 6 & 8 \\ 1 & 2 & 3 \\ 0 & 3 & -1 \end{bmatrix} = B \end{aligned}$$

Express these row operations as matrix multiplication by expressing  $B$  as the product of two matrices and  $A$ :

$$B = \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} A$$

Check your work using technology.

## Chapter 5

# Geometric Properties of Linear Maps (GT)

### Learning Outcomes

How do we understand linear maps geometrically?

By the end of this chapter, you should be able to...

1. Describe how a row operation affects the determinant of a matrix.
2. Compute the determinant of a  $4 \times 4$  matrix.
3. Find the eigenvalues of a  $2 \times 2$  matrix.
4. Find a basis for the eigenspace of a  $4 \times 4$  matrix associated with a given eigenvalue.

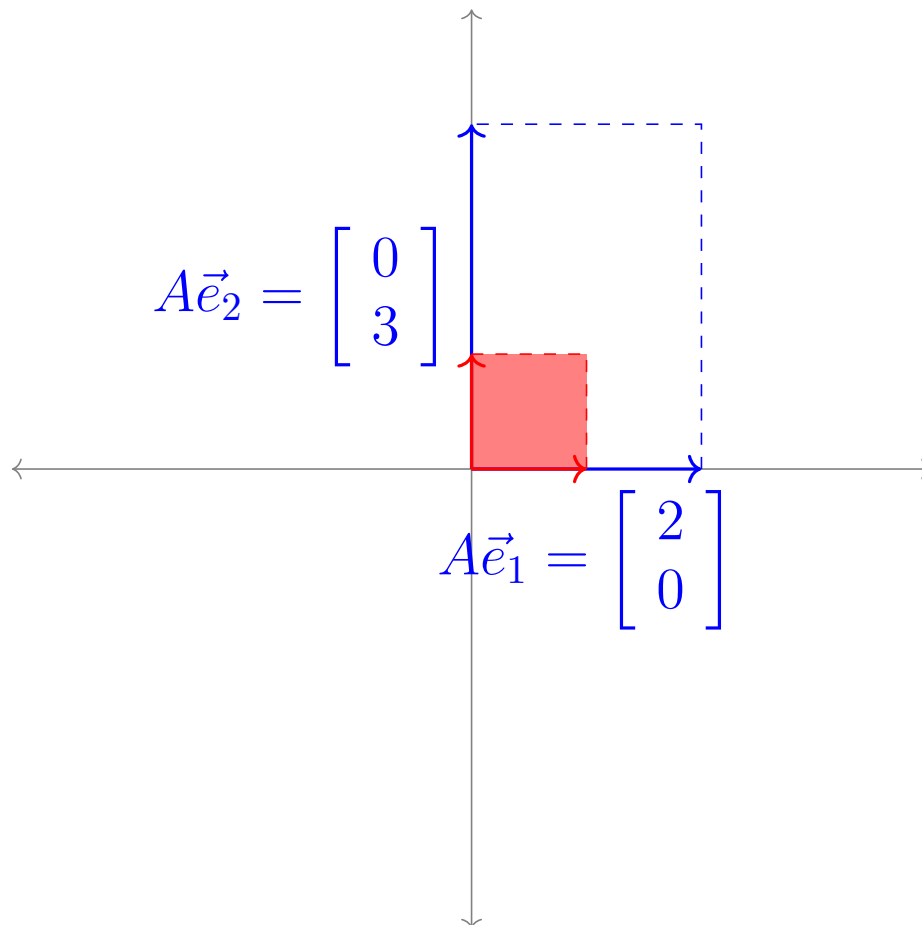
## 5.1 Row Operations and Determinants (GT1)

### Learning Outcomes

- Describe how a row operation affects the determinant of a matrix.

## Row Operations and Determinants (GT1)

**Activity 5.1.1** The image in [Figure 46](#) illustrates how the linear transformation  $T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the standard matrix  $A = \begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}$  transforms the unit square.

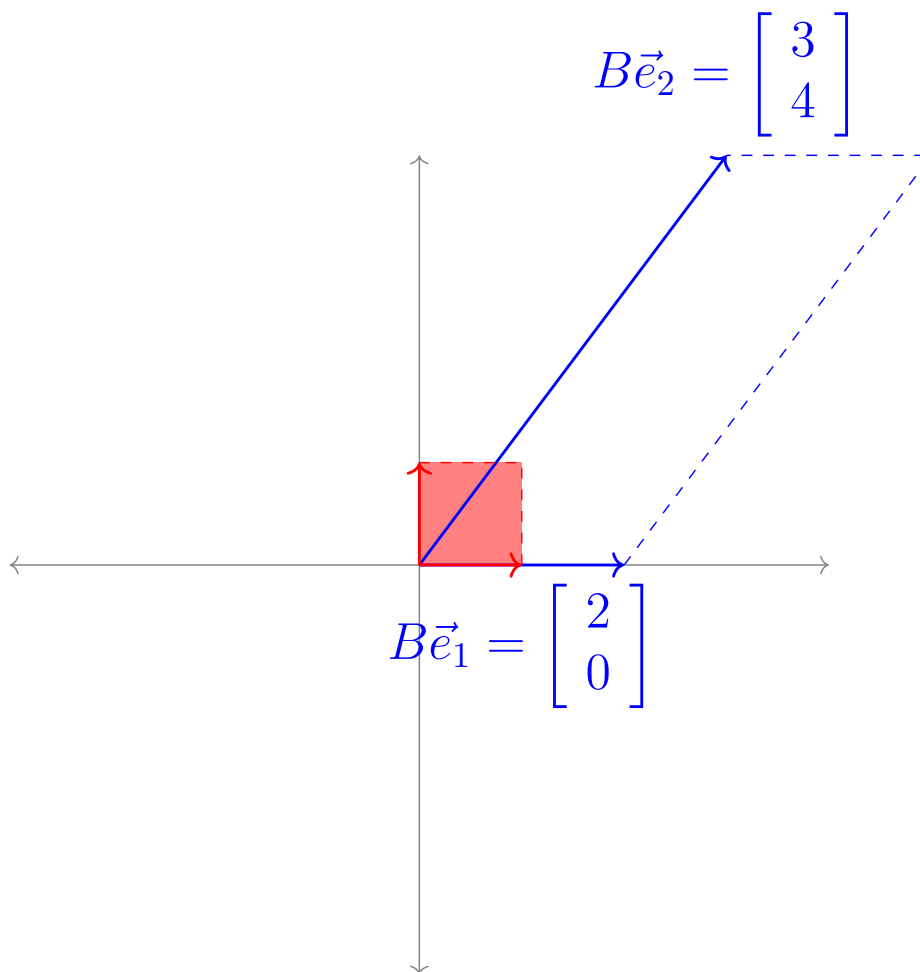


**Figure 17** Transformation of the unit square by the matrix  $A$ .

- (a) What are the lengths of  $A\vec{e}_1$  and  $A\vec{e}_2$ ?
- (b) What is the area of the transformed unit square?

## Row Operations and Determinants (GT1)

**Activity 5.1.2** The image below illustrates how the linear transformation  $S : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the standard matrix  $B = \begin{bmatrix} 2 & 3 \\ 0 & 4 \end{bmatrix}$  transforms the unit square.



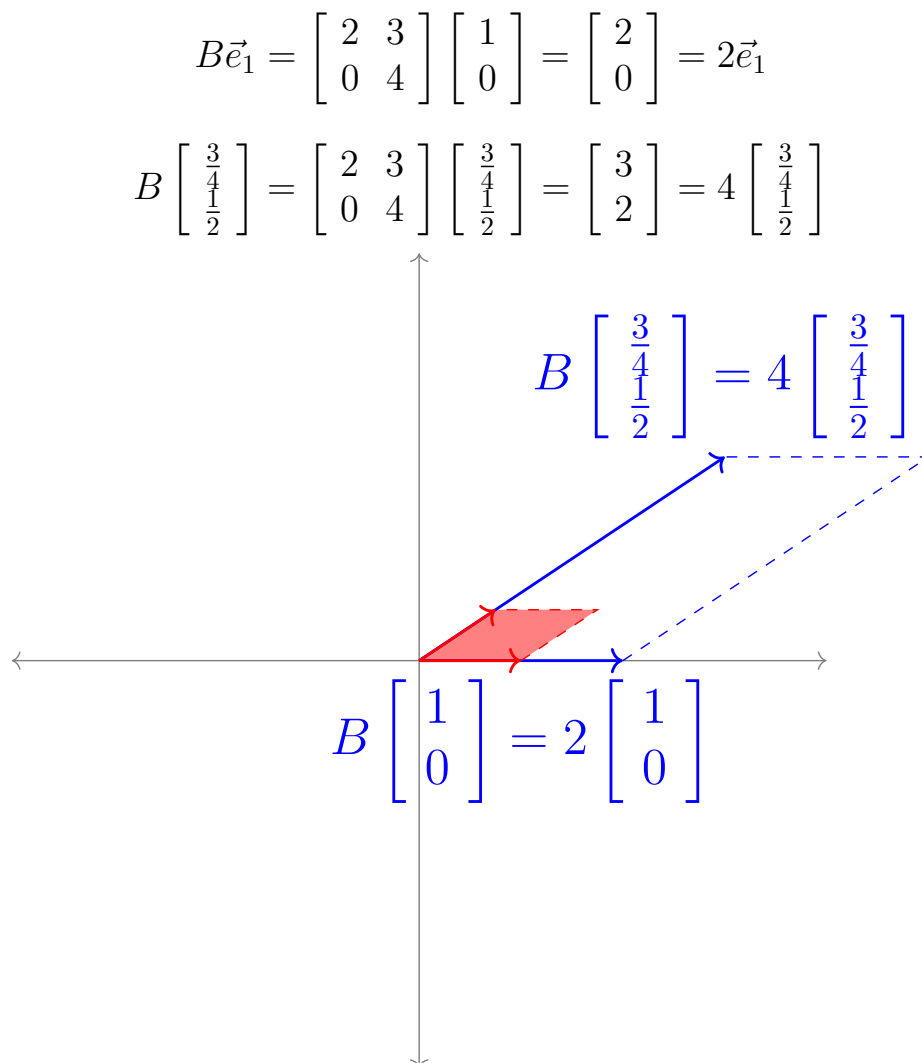
**Figure 18** Transformation of the unit square by the matrix  $B$

- (a) What are the lengths of  $B\vec{e}_1$  and  $B\vec{e}_2$ ?
- (b) What is the area of the transformed unit square?



## Row Operations and Determinants (GT1)

**Observation 5.1.3** It is possible to find two nonparallel vectors that are scaled but not rotated by the linear map given by  $B$ .

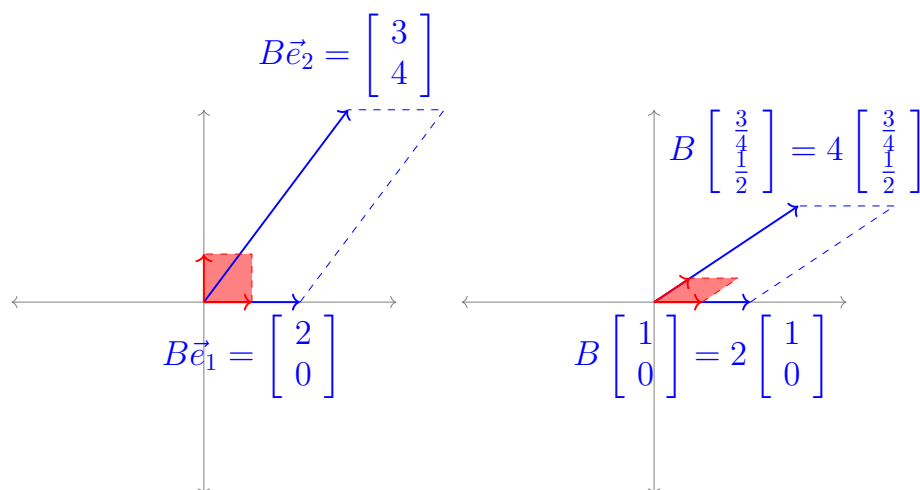


**Figure 19** Certain vectors are stretched out without being rotated.

The process for finding such vectors will be covered later in this chapter.

## Row Operations and Determinants (GT1)

**Observation 5.1.4** Notice that while a linear map can transform vectors in various ways, linear maps always transform parallelograms into parallelograms, and these areas are always transformed by the same factor: in the case of  $B = \begin{bmatrix} 2 & 3 \\ 0 & 4 \end{bmatrix}$ , this factor is 8.

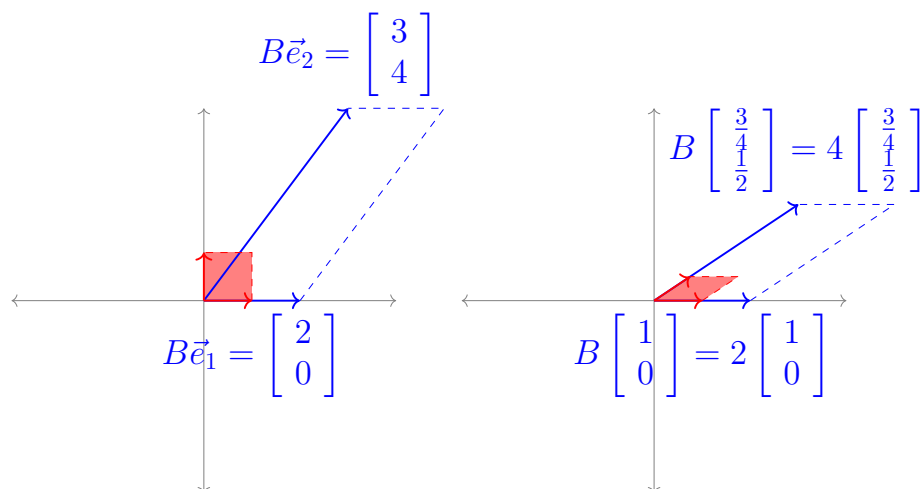


**Figure 20** A linear map transforming parallelograms into parallelograms.

Since this change in area is always the same for a given linear map, it will be equal to the value of the transformed unit square (which begins with area 1).

## Row Operations and Determinants (GT1)

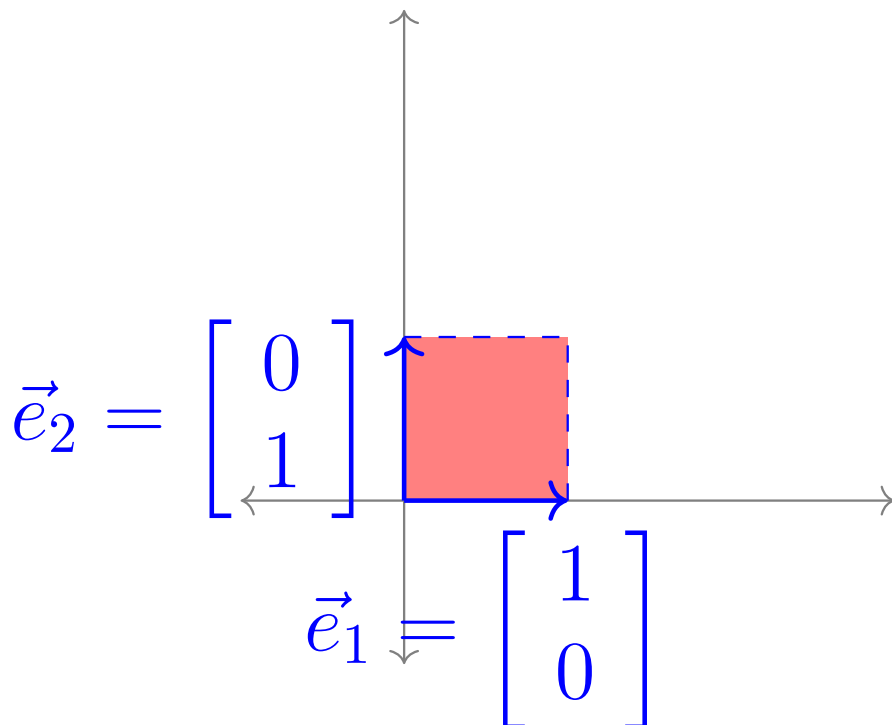
**Remark 5.1.5** We will define the **determinant** of a square matrix  $B$ , or  $\det(B)$  for short, to be the factor by which  $B$  scales areas. In order to figure out how to compute it, we first figure out the properties it must satisfy.



**Figure 21** The linear transformation  $B$  scaling areas by a constant factor, which we call the **determinant**

# Row Operations and Determinants (GT1)

**Activity 5.1.6** The transformation of the unit square by the standard matrix  $[\vec{e}_1 \ \vec{e}_2] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = I$  is illustrated below. If  $\det([\vec{e}_1 \ \vec{e}_2]) = \det(I)$  is the area of resulting parallelogram, what is the value of  $\det([\vec{e}_1 \ \vec{e}_2]) = \det(I)$ ?



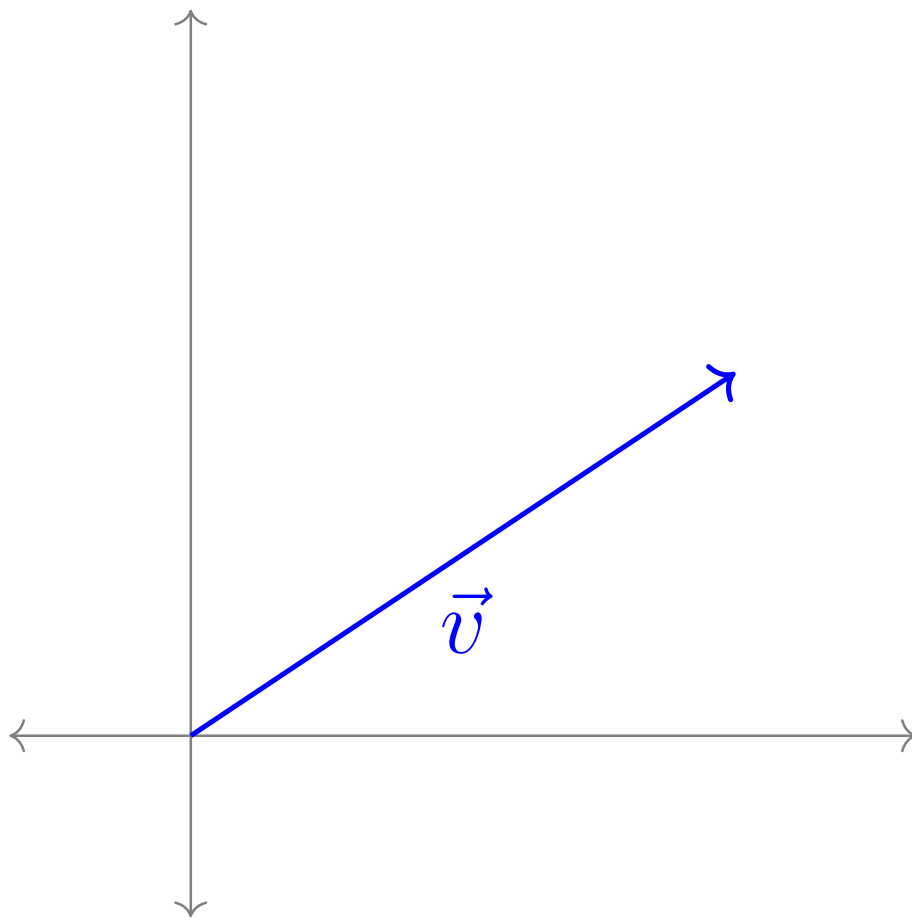
**Figure 22** The transformation of the unit square by the identity matrix.

The value for  $\det([\vec{e}_1 \ \vec{e}_2]) = \det(I)$  is:

- |      |      |
|------|------|
| A. 0 | C. 2 |
| B. 1 | D. 4 |

## Row Operations and Determinants (GT1)

**Activity 5.1.7** The transformation of the unit square by the standard matrix  $[\vec{v} \ \vec{v}]$  is illustrated below: both  $T(\vec{e}_1) = T(\vec{e}_2) = \vec{v}$ . If  $\det([\vec{v} \ \vec{v}])$  is the area of the generated parallelogram, what is the value of  $\det([\vec{v} \ \vec{v}])$ ?



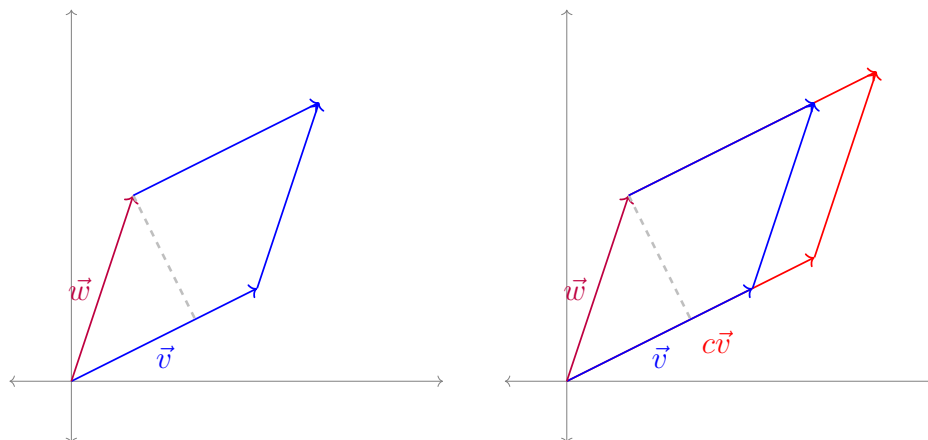
**Figure 23** Transformation of the unit square by a matrix with identical columns.

The value of  $\det([\vec{v} \ \vec{v}])$  is:

- |      |      |
|------|------|
| A. 0 | C. 2 |
| B. 1 | D. 4 |

## Row Operations and Determinants (GT1)

**Activity 5.1.8** The transformations of the unit square by the standard matrices  $[\vec{v} \ \vec{w}]$  and  $[c\vec{v} \ \vec{w}]$  are illustrated below. Describe the value of  $\det([c\vec{v} \ \vec{w}])$ .



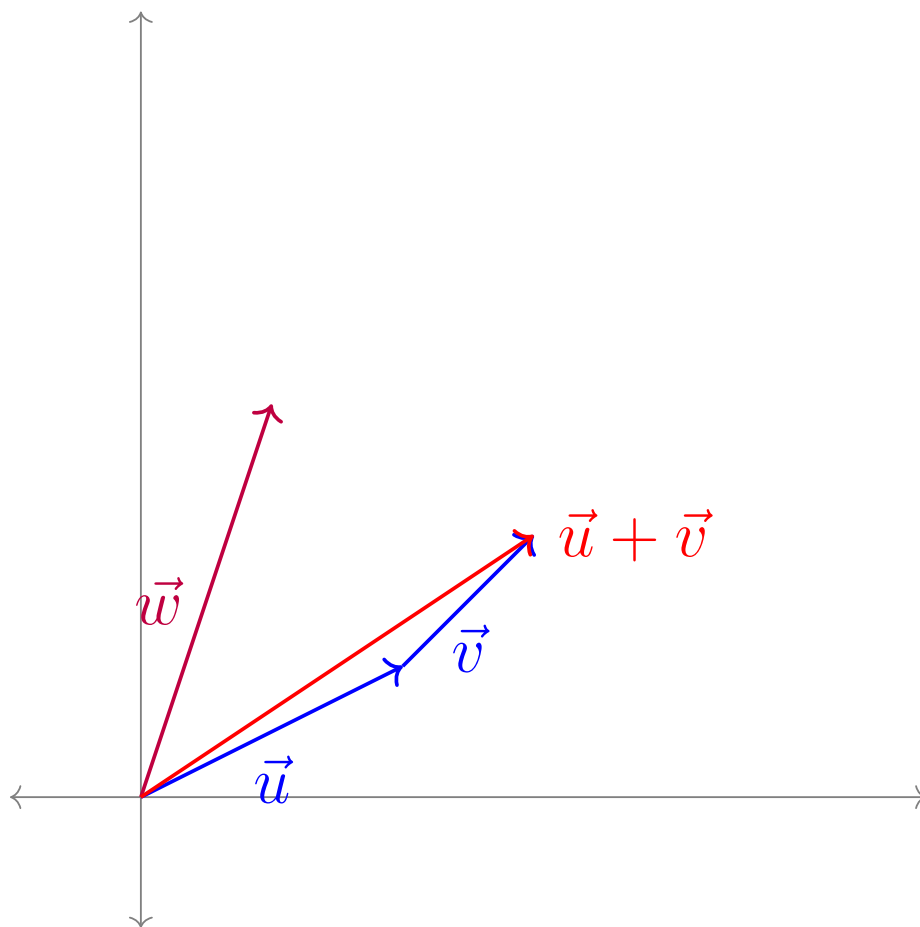
**Figure 24** The parallelograms generated by  $\vec{v}$  and  $\vec{w}/c\vec{w}$

Describe the value of  $\det([c\vec{v} \ \vec{w}])$ :

- |                                  |  |
|----------------------------------|--|
| A. $\det([\vec{v} \ \vec{w}])$   | C. $c^2 \det([\vec{v} \ \vec{w}])$             |
| B. $c \det([\vec{v} \ \vec{w}])$ | D. Cannot be determined from this information. |

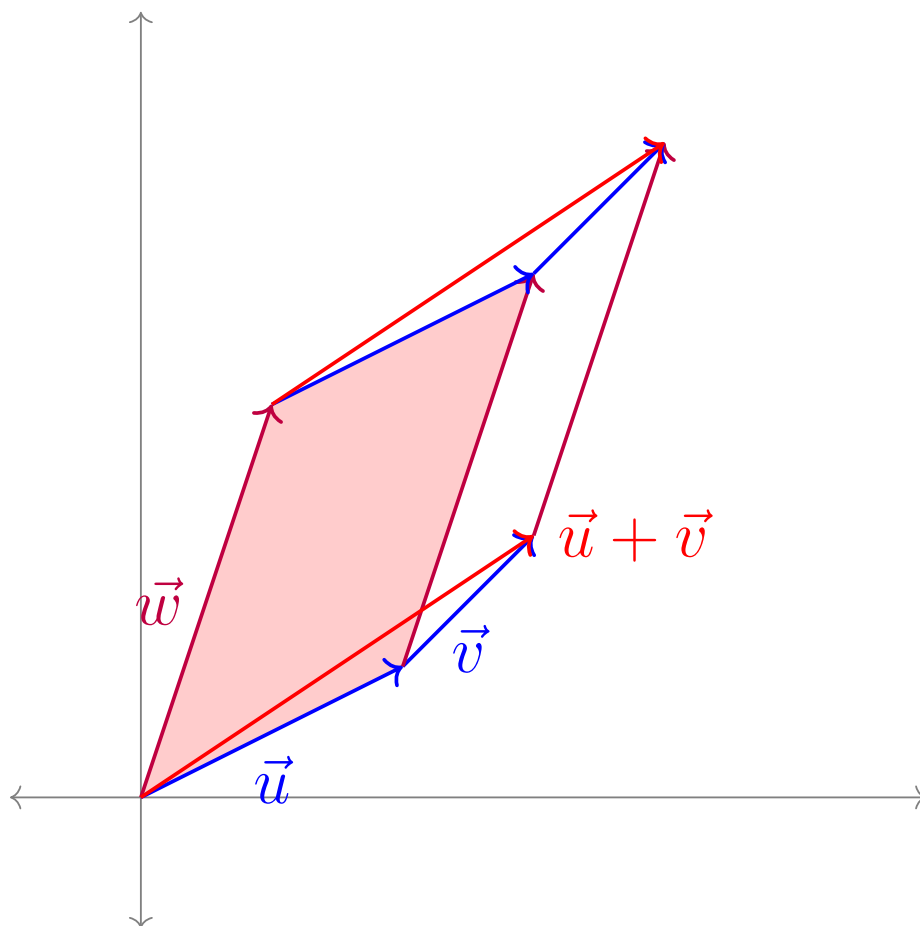
## Row Operations and Determinants (GT1)

**Remark 5.1.9** Consider the vectors  $\vec{u}$ ,  $\vec{v}$ ,  $\vec{u} + \vec{v}$ , and  $\vec{w}$  displayed below. Each pair of vectors generates a parallelogram, and the area of each parallelogram can be described in terms of determinants.



**Figure 25** The vectors  $\vec{u}$ ,  $\vec{v}$ ,  $\vec{u} + \vec{v}$  and  $\vec{w}$

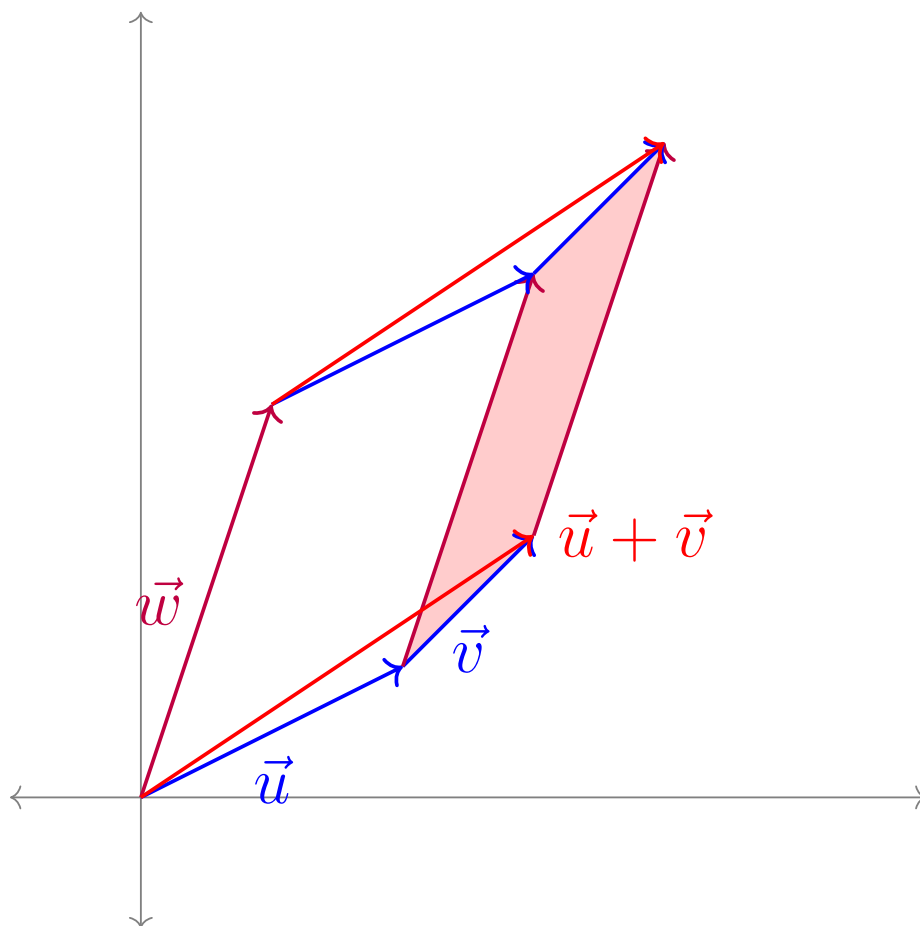
**Remark 5.1.10** For example,  $\det([\vec{u} \ \vec{w}])$  represents the shaded area shown below.



**Figure 26** Parallelogram generated by  $\vec{u}$  and  $\vec{w}$



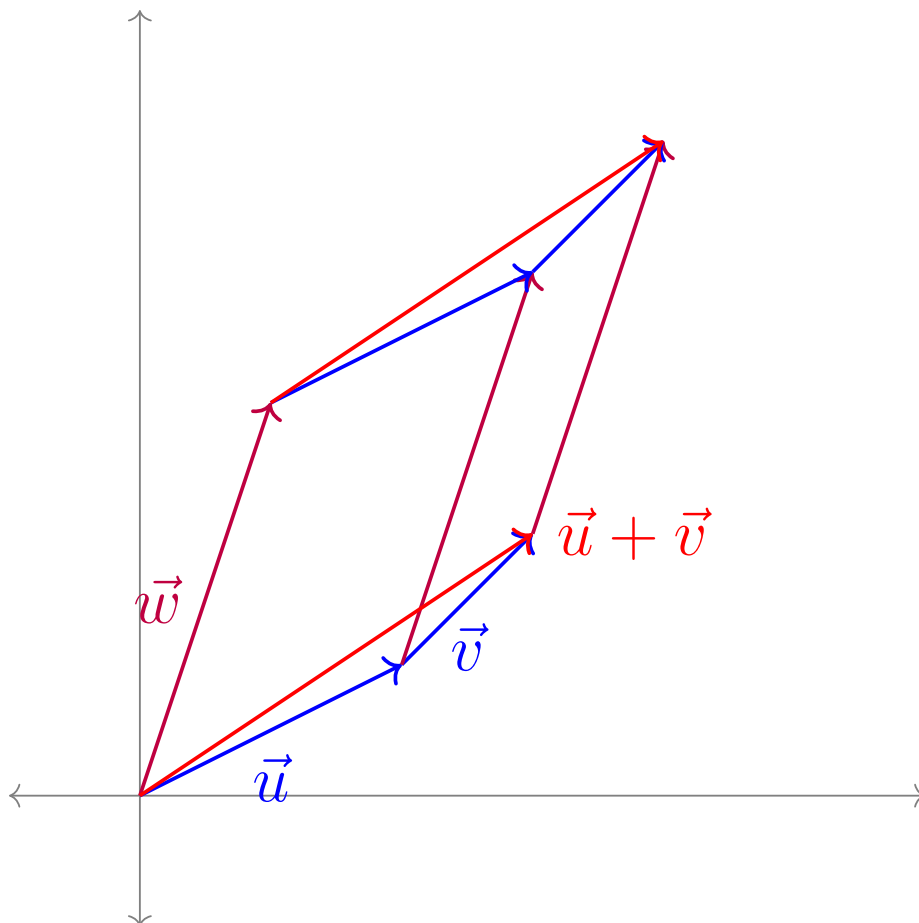
**Remark 5.1.11** Similarly,  $\det([\vec{v} \ \vec{w}])$  represents the shaded area shown below.



**Figure 27** Parallelogram generated by  $\vec{v}$  and  $\vec{w}$

## Row Operations and Determinants (GT1)

**Activity 5.1.12** The parallelograms generated by the standard matrices  $[\vec{u} \ \vec{w}]$ ,  $[\vec{v} \ \vec{w}]$  and  $[\vec{u} + \vec{v} \ \vec{w}]$  are illustrated below.



**Figure 28** Parallelogram generated by  $\vec{u} + \vec{v}$  and  $\vec{w}$

Describe the value of  $\det([\vec{u} + \vec{v} \ \vec{w}])$ .

- |  |  |
|--|--|
| A. $\det([\vec{u} \ \vec{w}]) = \det([\vec{v} \ \vec{w}])$ | C. $\det([\vec{u} \ \vec{w}]) \det([\vec{v} \ \vec{w}])$ |
| B. $\det([\vec{u} \ \vec{w}]) + \det([\vec{v} \ \vec{w}])$ | D. Cannot be determined from this information.           |

## Row Operations and Determinants (GT1)

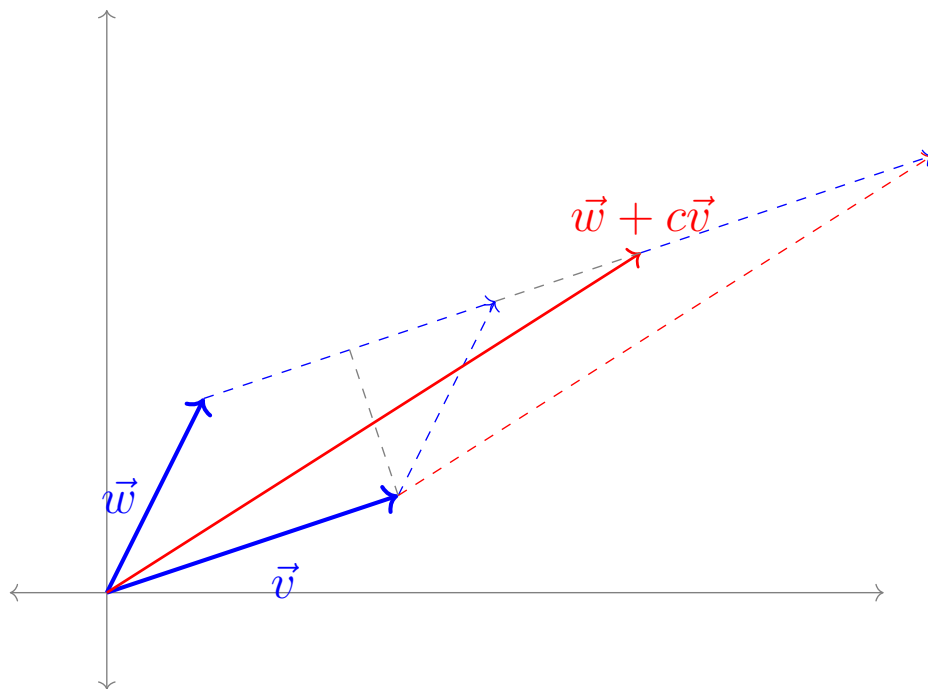
**Definition 5.1.13** The **determinant** is the unique function  $\det : M_{n,n} \rightarrow \mathbb{R}$  satisfying these properties:

1.  $\det(I) = 1$
2.  $\det(A) = 0$  whenever two columns of the matrix are identical.
3.  $\det[\cdots \ c\vec{v} \ \cdots] = c \det[\cdots \ \vec{v} \ \cdots]$ , assuming no other columns change.
4.  $\det[\cdots \ \vec{v} + \vec{w} \ \cdots] = \det[\cdots \ \vec{v} \ \cdots] + \det[\cdots \ \vec{w} \ \cdots]$ , assuming no other columns change.

Note that these last two properties together can be phrased as “The determinant is linear in each column.”  $\diamond$

## Row Operations and Determinants (GT1)

**Observation 5.1.14** The determinant must also satisfy other properties. Consider  $\det([\vec{v} \quad \vec{w} + c\vec{v}])$  and  $\det([\vec{v} \quad \vec{w}])$ .



**Figure 29** Parallelogram built by  $\vec{w} + c\vec{v}$  and  $\vec{w}$

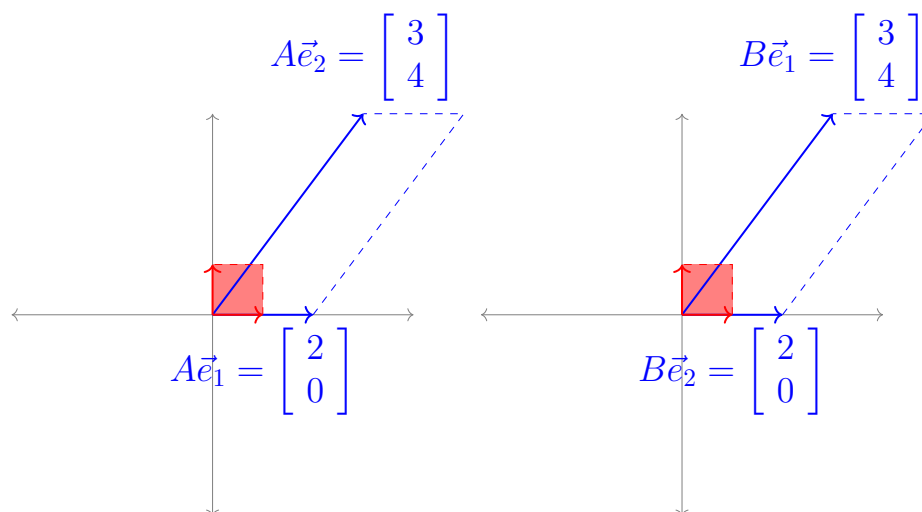
The base of both parallelograms is  $\vec{v}$ , while the height has not changed, so the determinant does not change either. This can also be proven using the other properties of the determinant:

$$\begin{aligned}
 \det([\vec{v} + c\vec{w} \quad \vec{w}]) &= \det([\vec{v} \quad \vec{w}]) + \det([c\vec{w} \quad \vec{w}]) \\
 &= \det([\vec{v} \quad \vec{w}]) + c \det([\vec{w} \quad \vec{w}]) \\
 &= \det([\vec{v} \quad \vec{w}]) + c \cdot 0 \\
 &= \det([\vec{v} \quad \vec{w}])
 \end{aligned}$$

## Row Operations and Determinants (GT1)

**Remark 5.1.15** Swapping columns may be thought of as a reflection, which is represented by a negative determinant. For example, the following matrices transform the unit square into the same parallelogram, but the second matrix reflects its orientation.

$$A = \begin{bmatrix} 2 & 3 \\ 0 & 4 \end{bmatrix} \quad \det A = 8 \qquad B = \begin{bmatrix} 3 & 2 \\ 4 & 0 \end{bmatrix} \quad \det B = -8$$



**Figure 30** Reflection of a parallelogram as a result of swapping columns.

## Row Operations and Determinants (GT1)

**Observation 5.1.16** The fact that swapping columns multiplies determinants by a negative may be verified by adding and subtracting columns.

$$\begin{aligned}\det([\vec{v} \quad \vec{w}]) &= \det([\vec{v} + \vec{w} \quad \vec{w}]) \\ &= \det([\vec{v} + \vec{w} \quad \vec{w} - (\vec{v} + \vec{w})]) \\ &= \det([\vec{v} + \vec{w} \quad -\vec{v}]) \\ &= \det([\vec{v} + \vec{w} - \vec{v} \quad -\vec{v}]) \\ &= \det([\vec{w} \quad -\vec{v}]) \\ &= -\det([\vec{w} \quad \vec{v}])\end{aligned}$$

## Row Operations and Determinants (GT1)

**Fact 5.1.17** *To summarize, we've shown that the column versions of the three row-reducing operations a matrix may be used to simplify a determinant in the following way:*

1. *Multiplying a column by a scalar multiplies the determinant by that scalar:*

$$c \det([\dots \vec{v} \dots]) = \det([\dots c\vec{v} \dots])$$

2. *Swapping two columns changes the sign of the determinant:*

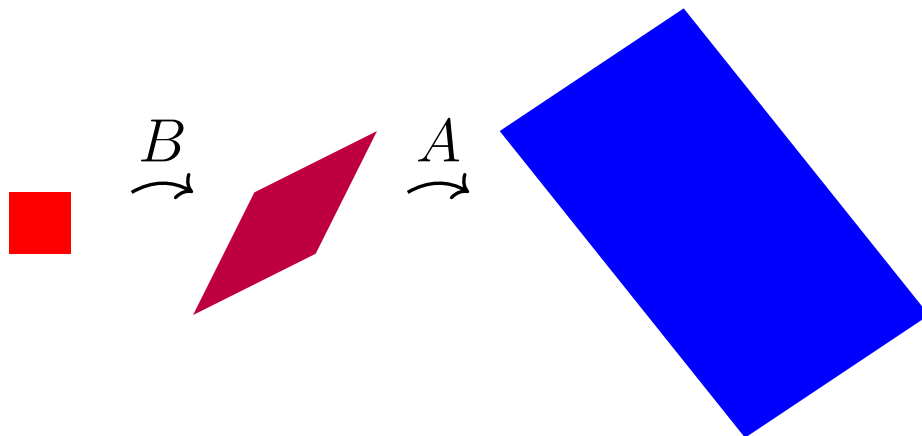
$$\det([\dots \vec{v} \dots \vec{w} \dots]) = -\det([\dots \vec{w} \dots \vec{v} \dots])$$

3. *Adding a multiple of a column to another column does not change the determinant:*

$$\det([\dots \vec{v} \dots \vec{w} \dots]) = \det([\dots \vec{v} + c\vec{w} \dots \vec{w} \dots])$$

## Row Operations and Determinants (GT1)

**Activity 5.1.18** The transformation given by the standard matrix  $A$  scales areas by 4, and the transformation given by the standard matrix  $B$  scales areas by 3. By what factor does the transformation given by the standard matrix  $AB$  scale areas?



**Figure 31** Area changing under the composition of two linear maps

- |      |                         |
|------|-------------------------|
| A. 1 | C. 12                   |
| B. 7 | D. Cannot be determined |



## Row Operations and Determinants (GT1)

**Fact 5.1.19** *Since the transformation given by the standard matrix  $AB$  is obtained by applying the transformations given by  $A$  and  $B$ , it follows that*

$$\det(AB) = \det(A) \det(B) = \det(B) \det(A) = \det(BA).$$

## Row Operations and Determinants (GT1)

**Remark 5.1.20** Recall that row operations may be produced by matrix multiplication.

- Multiply the first row of  $A$  by  $c$ : 
$$\begin{bmatrix} c & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} A$$

- Swap the first and second row of  $A$ : 
$$\begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} A$$

- Add  $c$  times the third row to the first row of  $A$ : 
$$\begin{bmatrix} 1 & 0 & c & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} A$$

## Row Operations and Determinants (GT1)

**Fact 5.1.21** *The determinants of row operation matrices may be computed by manipulating columns to reduce each matrix to the identity:*

- *Scaling a row:*  $\det \begin{bmatrix} c & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = c \det \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = c$

- *Swapping rows:*  $\det \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = -1 \det \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = -1$

- *Adding a row multiple to another row:*  $\det \begin{bmatrix} 1 & 0 & c & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} =$

$$\det \begin{bmatrix} 1 & 0 & c-1c & 0 \\ 0 & 1 & 0-0c & 0 \\ 0 & 0 & 1-0c & 0 \\ 0 & 0 & 0-0c & 1 \end{bmatrix} = \det(I) = 1$$

## Row Operations and Determinants (GT1)

**Activity 5.1.22** Consider the row operation  $R_1 + 4R_3 \rightarrow R_1$  applied as follows to show  $A \sim B$ :

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} \sim \begin{bmatrix} 1 + 4(9) & 2 + 4(10) & 3 + 4(11) & 4 + 4(12) \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} = B$$

(a) Find a matrix  $R$  such that  $B = RA$ , by applying the same row operation

$$\text{to } I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

(b) Find  $\det R$  by comparing with the previous slide.

(c) If  $C \in M_{4,4}$  is a matrix with  $\det(C) = -3$ , find

$$\det(RC) = \det(R) \det(C).$$

### Row Operations and Determinants (GT1)

**Activity 5.1.23** Consider the row operation  $R_1 \leftrightarrow R_3$  applied as follows to show  $A \sim B$ :

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} \sim \begin{bmatrix} 9 & 10 & 11 & 12 \\ 5 & 6 & 7 & 8 \\ 1 & 2 & 3 & 4 \\ 13 & 14 & 15 & 16 \end{bmatrix} = B$$

- (a) Find a matrix  $R$  such that  $B = RA$ , by applying the same row operation to  $I$ .
- (b) If  $C \in M_{4,4}$  is a matrix with  $\det(C) = 5$ , find  $\det(RC)$ .

## Row Operations and Determinants (GT1)

**Activity 5.1.24** Consider the row operation  $3R_2 \rightarrow R_2$  applied as follows to show  $A \sim B$ :

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} \sim \begin{bmatrix} 1 & 2 & 3 & 4 \\ 3(5) & 3(6) & 3(7) & 3(8) \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} = B$$

- (a) Find a matrix  $R$  such that  $B = RA$ .
- (b) If  $C \in M_{4,4}$  is a matrix with  $\det(C) = -7$ , find  $\det(RC)$ .

## Row Operations and Determinants (GT1)

**Activity 5.1.25** Let  $A$  be *any*  $4 \times 4$  matrix with determinant 2.

- (a) Let  $B$  be the matrix obtained from  $A$  by applying the row operation  $R_1 - 5R_3 \rightarrow R_1$ . What is  $\det B$ ?

A -4

B -2

C 2

D 10

- (b) Let  $M$  be the matrix obtained from  $A$  by applying the row operation  $R_3 \leftrightarrow R_1$ . What is  $\det M$ ?

A -4

B -2

C 2

D 10

- (c) Let  $P$  be the matrix obtained from  $A$  by applying the row operation  $2R_4 \rightarrow R_4$ . What is  $\det P$ ?

A -4

B -2

C 2

D 10

## Row Operations and Determinants (GT1)

**Remark 5.1.26** Recall that the column versions of the three row-reducing operations a matrix may be used to simplify a determinant:

1. Multiplying columns by scalars:

$$\det([\cdots \ c\vec{v} \ \cdots]) = c \det([\cdots \ \vec{v} \ \cdots])$$

2. Swapping two columns:

$$\det([\cdots \ \vec{v} \ \cdots \ \vec{w} \ \cdots]) = -\det([\cdots \ \vec{w} \ \cdots \ \vec{v} \ \cdots])$$

3. Adding a multiple of a column to another column:

$$\det([\cdots \ \vec{v} \ \cdots \ \vec{w} \ \cdots]) = \det([\cdots \ \vec{v} + c\vec{w} \ \cdots \ \vec{w} \ \cdots])$$



## Row Operations and Determinants (GT1)

**Remark 5.1.27** The determinants of row operation matrices may be computed by manipulating columns to reduce each matrix to the identity:

- Scaling a row: 
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

- Swapping rows: 
$$\begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

- Adding a row multiple to another row: 
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & c & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

## Row Operations and Determinants (GT1)

**Fact 5.1.28** *Thus we can also use both row operations to simplify determinants:*

- *Multiplying rows by scalars:*

$$\det \begin{bmatrix} \vdots \\ cR \\ \vdots \end{bmatrix} = c \det \begin{bmatrix} \vdots \\ R \\ \vdots \end{bmatrix}$$

- *Swapping two rows:*

$$\det \begin{bmatrix} \vdots \\ R \\ \vdots \\ S \\ \vdots \end{bmatrix} = - \det \begin{bmatrix} \vdots \\ S \\ \vdots \\ R \\ \vdots \end{bmatrix}$$

- *Adding multiples of rows/columns to other rows:*

$$\det \begin{bmatrix} \vdots \\ R \\ \vdots \\ S \\ \vdots \end{bmatrix} = \det \begin{bmatrix} \vdots \\ R + cS \\ \vdots \\ S \\ \vdots \end{bmatrix}$$

## Row Operations and Determinants (GT1)

**Activity 5.1.29** Complete the following derivation for a formula calculating  $2 \times 2$  determinants:

$$\begin{aligned}\det \begin{bmatrix} a & b \\ c & d \end{bmatrix} &= ? \det \begin{bmatrix} 1 & b/a \\ c & d \end{bmatrix} \\ &= ? \det \begin{bmatrix} 1 & b/a \\ c-c & d-bc/a \end{bmatrix} \\ &= ? \det \begin{bmatrix} 1 & b/a \\ 0 & d-bc/a \end{bmatrix} \\ &= ? \det \begin{bmatrix} 1 & b/a \\ 0 & 1 \end{bmatrix} \\ &= ? \det \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &= ? \det I \\ &= ?\end{aligned}$$

## Row Operations and Determinants (GT1)

**Observation 5.1.30** So we may compute the determinant of  $\begin{bmatrix} 2 & 4 \\ 2 & 3 \end{bmatrix}$  by using determinant properties to manipulate its rows/columns to reduce the matrix to  $I$ :

$$\begin{aligned}\det \begin{bmatrix} 2 & 4 \\ 2 & 3 \end{bmatrix} &= 2 \det \begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix} \\ &= 2 \det \begin{bmatrix} 1 & 2 \\ 0 & -1 \end{bmatrix} \\ &= -2 \det \begin{bmatrix} 1 & -2 \\ 0 & 1 \end{bmatrix} \\ &= -2 \det \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &= -2\end{aligned}$$

Or we may use a formula:

$$\det \begin{bmatrix} 2 & 4 \\ 2 & 3 \end{bmatrix} = (2)(3) - (4)(2) = -2$$

## 5.2 Computing Determinants (GT2)

### Learning Outcomes

- Compute the determinant of a  $4 \times 4$  matrix.

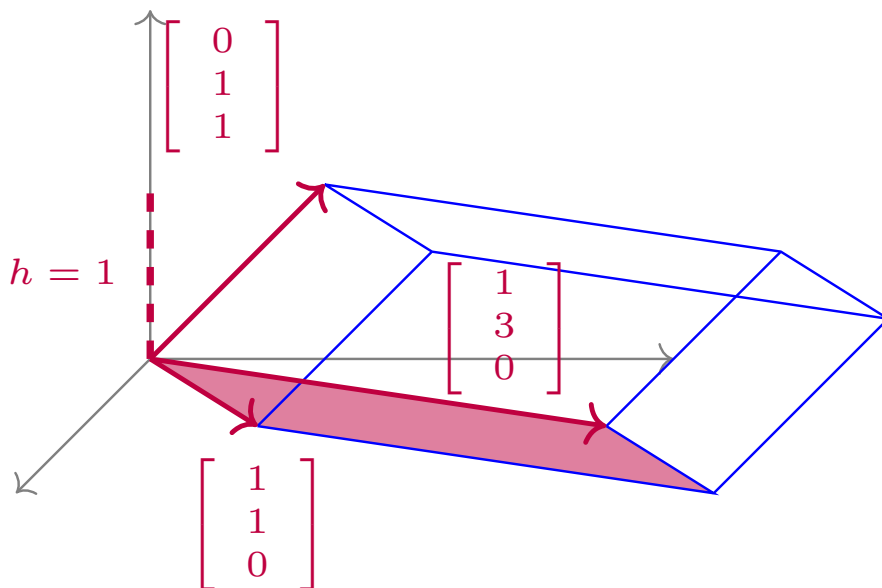
## Computing Determinants (GT2)

**Remark 5.2.1** We've seen that row reducing all the way into RREF gives us a method of computing determinants.

However, we learned in [Chapter 1](#) that this can be tedious for large matrices. Thus, we will try to figure out how to turn the determinant of a larger matrix into the determinant of a smaller matrix.

## Computing Determinants (GT2)

**Activity 5.2.2** The following image illustrates the transformation of the unit cube by the matrix  $\begin{bmatrix} 1 & 1 & 0 \\ 1 & 3 & 1 \\ 0 & 0 & 1 \end{bmatrix}$ .



**Figure 32** Transformation of the unit cube by the linear transformation.

Recall that for this solid  $V = Bh$ , where  $h$  is the height of the solid and  $B$  is the area of its parallelogram base. So what must its volume be?

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

C.  $\det \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$

B.  $\det \begin{bmatrix} 1 & 0 \\ 3 & 1 \end{bmatrix}$

D.  $\det \begin{bmatrix} 1 & 3 \\ 0 & 0 \end{bmatrix}$

## Computing Determinants (GT2)

**Fact 5.2.3** *If row  $i$  contains all zeros except for a 1 on the main (upper-left to lower-right) diagonal, then both column and row  $i$  may be removed without changing the value of the determinant.*

$$\det \begin{bmatrix} 3 & 2 & -1 & 3 \\ 0 & 1 & 0 & 0 \\ -1 & 4 & 1 & 0 \\ 5 & 0 & 11 & 1 \end{bmatrix} = \det \begin{bmatrix} 3 & -1 & 3 \\ -1 & 1 & 0 \\ 5 & 11 & 1 \end{bmatrix}$$

*Since row and column operations affect the determinants in the same way, the same technique works for a column of all zeros except for a 1 on the main diagonal.*

$$\det \begin{bmatrix} 3 & 0 & -1 & 5 \\ 2 & 1 & 4 & 0 \\ -1 & 0 & 1 & 11 \\ 3 & 0 & 0 & 1 \end{bmatrix} = \det \begin{bmatrix} 3 & -1 & 5 \\ -1 & 1 & 11 \\ 3 & 0 & 1 \end{bmatrix}$$

*Put another way, if you have either a column or row from the identity matrix, you can cancel both the column and row containing the 1.*



## Computing Determinants (GT2)

**Activity 5.2.4** Remove an appropriate row and column of  $\det \begin{bmatrix} 1 & 0 & 0 \\ 1 & 5 & 12 \\ 3 & 2 & -1 \end{bmatrix}$  to simplify the determinant to a  $2 \times 2$  determinant.

## Computing Determinants (GT2)

**Activity 5.2.5** Simplify  $\det \begin{bmatrix} 0 & 3 & -2 \\ 2 & 5 & 12 \\ 0 & 2 & -1 \end{bmatrix}$  to a multiple of a  $2 \times 2$  determinant by first doing the following:

- (a) Factor out a 2 from a column.
- (b) Swap rows or columns to put a 1 on the main diagonal.

## Computing Determinants (GT2)

**Activity 5.2.6** Simplify  $\det \begin{bmatrix} 4 & -2 & 2 \\ 3 & 1 & 4 \\ 1 & -1 & 3 \end{bmatrix}$  to a multiple of a  $2 \times 2$  determinant by first doing the following:

- (a) Use row/column operations to create two zeroes in the same row or column.
- (b) Factor/swap as needed to get a row/column of all zeroes except a 1 on the main diagonal.

## Computing Determinants (GT2)

**Observation 5.2.7** Using row/column operations, you can introduce zeros and reduce dimension to whittle down the determinant of a large matrix to a determinant of a smaller matrix.

$$\begin{aligned}
 \det \begin{bmatrix} 4 & 3 & 0 & 1 \\ 2 & -2 & 4 & 0 \\ -1 & 4 & 1 & 5 \\ 2 & 8 & 0 & 3 \end{bmatrix} &= \det \begin{bmatrix} 4 & 3 & 0 & 1 \\ 6 & -18 & 0 & -20 \\ -1 & 4 & 1 & 5 \\ 2 & 8 & 0 & 3 \end{bmatrix} = \det \begin{bmatrix} 4 & 3 & 1 \\ 6 & -18 & -20 \\ 2 & 8 & 3 \end{bmatrix} \\
 &= \dots = -2 \det \begin{bmatrix} 1 & 3 & 4 \\ 0 & 21 & 43 \\ 0 & -1 & -10 \end{bmatrix} = -2 \det \begin{bmatrix} 21 & 43 \\ -1 & -10 \end{bmatrix} \\
 &= \dots = -2 \det \begin{bmatrix} -167 & 21 \\ 0 & 1 \end{bmatrix} = -2 \det[-167] \\
 &= -2(-167) \det(I) = 334
 \end{aligned}$$

## Computing Determinants (GT2)

**Activity 5.2.8** Rewrite

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

as a multiple of a determinant of a  $3 \times 3$  matrix.

## Computing Determinants (GT2)

**Activity 5.2.9** Compute  $\det \begin{bmatrix} 2 & 3 & 5 & 0 \\ 0 & 3 & 2 & 0 \\ 1 & 2 & 0 & 3 \\ -1 & -1 & 2 & 2 \end{bmatrix}$  by using any combination of row/column operations.

## Computing Determinants (GT2)

**Observation 5.2.10** Another option is to take advantage of the fact that the determinant is linear in each row or column. This approach is called **Laplace expansion** or **cofactor expansion**.

For example, since  $\begin{bmatrix} 1 & 2 & 4 \end{bmatrix} = 1 \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} + 2 \begin{bmatrix} 0 & 1 & 0 \end{bmatrix} + 4 \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$ ,

$$\begin{aligned} \det \begin{bmatrix} 2 & 3 & 5 \\ -1 & 3 & 5 \\ 1 & 2 & 4 \end{bmatrix} &= 1 \det \begin{bmatrix} 2 & 3 & 5 \\ -1 & 3 & 5 \\ 1 & 0 & 0 \end{bmatrix} + 2 \det \begin{bmatrix} 2 & 3 & 5 \\ -1 & 3 & 5 \\ 0 & 1 & 0 \end{bmatrix} + 4 \det \begin{bmatrix} 2 & 3 & 5 \\ -1 & 3 & 5 \\ 0 & 0 & 1 \end{bmatrix} \\ &= -1 \det \begin{bmatrix} 5 & 3 & 2 \\ 5 & 3 & -1 \\ 0 & 0 & 1 \end{bmatrix} - 2 \det \begin{bmatrix} 2 & 5 & 3 \\ -1 & 5 & 3 \\ 0 & 0 & 1 \end{bmatrix} + 4 \det \begin{bmatrix} 2 & 3 & 5 \\ -1 & 3 & 5 \\ 0 & 0 & 1 \end{bmatrix} \\ &= - \det \begin{bmatrix} 5 & 3 \\ 5 & 3 \end{bmatrix} - 2 \det \begin{bmatrix} 2 & 5 \\ -1 & 5 \end{bmatrix} + 4 \det \begin{bmatrix} 2 & 3 \\ -1 & 3 \end{bmatrix} \end{aligned}$$

## Computing Determinants (GT2)

**Observation 5.2.11** Recall the formula for a  $2 \times 2$  determinant found in [Observation 5.1.30](#):

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

There are formulas and algorithms for the determinants of larger matrices, but they can be pretty tedious to use. For example, writing out a formula for a  $4 \times 4$  determinant would require 24 different terms!

$$\det \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} = a_{11}(a_{22}(a_{33}a_{44}-a_{43}a_{34})-a_{23}(a_{32}a_{44}-a_{42}a_{34})+\dots)+\dots$$



## Computing Determinants (GT2)

**Activity 5.2.12** Based on the previous activities, which technique is easier for computing determinants?

- A. Memorizing formulas.
- B. Using row/column operations.
- C. Laplace expansion.
- D. Some other technique.

## Computing Determinants (GT2)

**Activity 5.2.13** Use your preferred technique to compute

$$\det \begin{bmatrix} 4 & -3 & 0 & 0 \\ 1 & -3 & 2 & -1 \\ 3 & 2 & 0 & 3 \\ 0 & -3 & 2 & -2 \end{bmatrix}.$$

## 5.3 Eigenvalues and Characteristic Polynomials (GT3)

### Learning Outcomes

- Find the eigenvalues of a  $2 \times 2$  matrix.

### Eigenvalues and Characteristic Polynomials (GT3)

**Activity 5.3.1** An invertible matrix  $M$  and its inverse  $M^{-1}$  are given below:

$$M = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \quad M^{-1} = \begin{bmatrix} -2 & 1 \\ 3/2 & -1/2 \end{bmatrix}$$

Which of the following is equal to  $\det(M) \det(M^{-1})$ ?

A.  $-1$

C.  $1$

B.  $0$

D.  $4$

### Eigenvalues and Characteristic Polynomials (GT3)

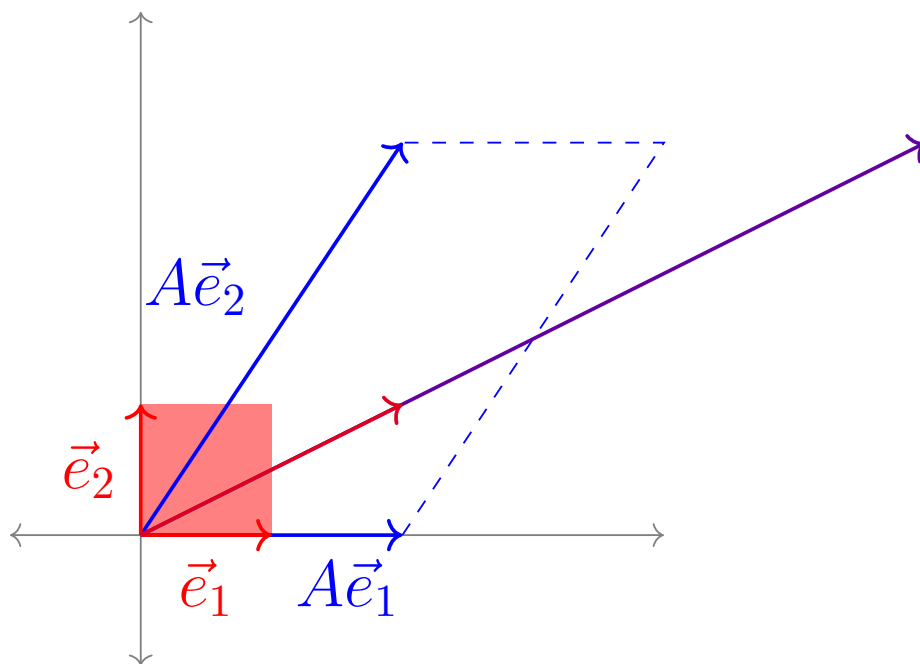
**Fact 5.3.2** *For every invertible matrix  $M$ ,*

$$\det(M) \det(M^{-1}) = \det(I) = 1$$

*so  $\det(M^{-1}) = \frac{1}{\det(M)}$ .*

*Furthermore, a square matrix  $M$  is invertible if and only if  $\det(M) \neq 0$ .*

**Observation 5.3.3** Consider the linear transformation  $A : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the matrix  $A = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix}$ .



**Figure 33** Transformation of the unit square by the linear transformation  $A$

It is easy to see geometrically that

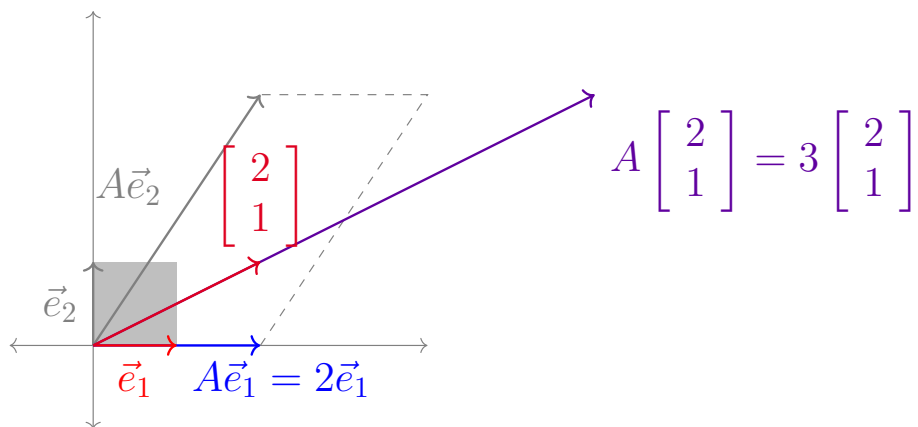
$$A \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \end{bmatrix} = 2 \begin{bmatrix} 1 \\ 0 \end{bmatrix}.$$

It is less obvious (but easily checked once you find it) that

$$A \begin{bmatrix} 2 \\ 1 \end{bmatrix} = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix} \begin{bmatrix} 2 \\ 1 \end{bmatrix} = \begin{bmatrix} 6 \\ 3 \end{bmatrix} = 3 \begin{bmatrix} 2 \\ 1 \end{bmatrix}.$$

## Eigenvalues and Characteristic Polynomials (GT3)

**Definition 5.3.4** Let  $A \in M_{n,n}$ . An **eigenvector** for  $A$  is a vector  $\vec{x} \in \mathbb{R}^n$  such that  $A\vec{x}$  is parallel to  $\vec{x}$ .



**Figure 34** The map  $A$  stretches out the eigenvector  $\begin{bmatrix} 2 \\ 1 \end{bmatrix}$  by a factor of 3 (the corresponding eigenvalue).

In other words,  $A\vec{x} = \lambda\vec{x}$  for some scalar  $\lambda$ . If  $\vec{x} \neq \vec{0}$ , then we say  $\vec{x}$  is a **nontrivial eigenvector** and we call this  $\lambda$  an **eigenvalue** of  $A$ .  $\diamond$

### Eigenvalues and Characteristic Polynomials (GT3)

**Activity 5.3.5** Finding the eigenvalues  $\lambda$  that satisfy

$$A\vec{x} = \lambda\vec{x} = \lambda(I\vec{x}) = (\lambda I)\vec{x}$$

for some nontrivial eigenvector  $\vec{x}$  is equivalent to finding nonzero solutions for the matrix equation

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

(a) If  $\lambda$  is an eigenvalue, and  $T$  is the transformation with standard matrix  $A - \lambda I$ , which of these must contain a non-zero vector?

A. The kernel of  $T$

C. The domain of  $T$

B. The image of  $T$

D. The codomain of  $T$

(b) Therefore, what can we conclude?

A.  $A$  is invertible

C.  $A - \lambda I$  is invertible

B.  $A$  is not invertible

D.  $A - \lambda I$  is not invertible

(c) And what else?

A.  $\det A = 0$

C.  $\det(A - \lambda I) = 0$

B.  $\det A = 1$

D.  $\det(A - \lambda I) = 1$



### Eigenvalues and Characteristic Polynomials (GT3)

**Fact 5.3.6** *The eigenvalues  $\lambda$  for a matrix  $A$  are exactly the values that make  $A - \lambda I$  non-invertible.*

*Thus the eigenvalues  $\lambda$  for a matrix  $A$  are the solutions to the equation*

$$\det(A - \lambda I) = 0.$$

### Eigenvalues and Characteristic Polynomials (GT3)

**Definition 5.3.7** The expression  $\det(A - \lambda I)$  is called **characteristic polynomial** of  $A$ .

For example, when  $A = \begin{bmatrix} 1 & 2 \\ 5 & 4 \end{bmatrix}$ , we have

$$A - \lambda I = \begin{bmatrix} 1 & 2 \\ 5 & 4 \end{bmatrix} - \begin{bmatrix} \lambda & 0 \\ 0 & \lambda \end{bmatrix} = \begin{bmatrix} 1 - \lambda & 2 \\ 5 & 4 - \lambda \end{bmatrix}.$$

Thus the characteristic polynomial of  $A$  is

$$\det \begin{bmatrix} 1 - \lambda & 2 \\ 5 & 4 - \lambda \end{bmatrix} = (1 - \lambda)(4 - \lambda) - (2)(5) = \lambda^2 - 5\lambda - 6$$

and its eigenvalues are the solutions  $-1, 6$  to  $\lambda^2 - 5\lambda - 6 = 0$ .

◇

### Eigenvalues and Characteristic Polynomials (GT3)

**Activity 5.3.8** Let  $A = \begin{bmatrix} 5 & 2 \\ -3 & -2 \end{bmatrix}$ .

- (a) Compute  $\det(A - \lambda I)$  to determine the characteristic polynomial of  $A$ .
- (b) Set this characteristic polynomial equal to zero and factor to determine the eigenvalues of  $A$ .

### Eigenvalues and Characteristic Polynomials (GT3)

**Activity 5.3.9** Find all the eigenvalues for the matrix  $A = \begin{bmatrix} 3 & -3 \\ 2 & -4 \end{bmatrix}$ .

### Eigenvalues and Characteristic Polynomials (GT3)

**Activity 5.3.10** Find all the eigenvalues for the matrix  $A = \begin{bmatrix} 1 & -4 \\ 0 & 5 \end{bmatrix}$ .

### Eigenvalues and Characteristic Polynomials (GT3)

**Activity 5.3.11** Find all the eigenvalues for the matrix  $A = \begin{bmatrix} 3 & -3 & 1 \\ 0 & -4 & 2 \\ 0 & 0 & 7 \end{bmatrix}$ .

## 5.4 Eigenvectors and Eigenspaces (GT4)

### Learning Outcomes

- Find a basis for the eigenspace of a  $4 \times 4$  matrix associated with a given eigenvalue.

## Eigenvectors and Eigenspaces (GT4)

**Activity 5.4.1** It's possible to show that  $-2$  is an eigenvalue for  $\begin{bmatrix} -1 & 4 & -2 \\ 2 & -7 & 9 \\ 3 & 0 & 4 \end{bmatrix}$ .

Compute the kernel of the transformation with standard matrix

$$A - (-2)I = \begin{bmatrix} ? & 4 & -2 \\ 2 & ? & 9 \\ 3 & 0 & ? \end{bmatrix}$$

to find all the eigenvectors  $\vec{x}$  such that  $A\vec{x} = -2\vec{x}$ .



## Eigenvectors and Eigenspaces (GT4)

**Definition 5.4.2** Since the kernel of a linear map is a subspace of  $\mathbb{R}^n$ , and the kernel obtained from  $A - \lambda I$  contains all the eigenvectors associated with  $\lambda$ , we call this kernel the **eigenspace** of  $A$  associated with  $\lambda$ .  $\diamond$

## Eigenvectors and Eigenspaces (GT4)

**Activity 5.4.3** Find a basis for the eigenspace for the matrix  $\begin{bmatrix} 0 & 0 & 3 \\ 1 & 0 & -1 \\ 0 & 1 & 3 \end{bmatrix}$  associated with the eigenvalue 3.

## Eigenvectors and Eigenspaces (GT4)

**Activity 5.4.4** Find a basis for the eigenspace for the matrix

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

associated with the eigenvalue 1.

## Eigenvectors and Eigenspaces (GT4)

**Activity 5.4.5** Find a basis for the eigenspace for the matrix  $\begin{bmatrix} 4 & 3 & 0 & 0 \\ 3 & 3 & 0 & 0 \\ 0 & 0 & 2 & 5 \\ 0 & 0 & 0 & 2 \end{bmatrix}$  associated with the eigenvalue 2.

# Appendix A

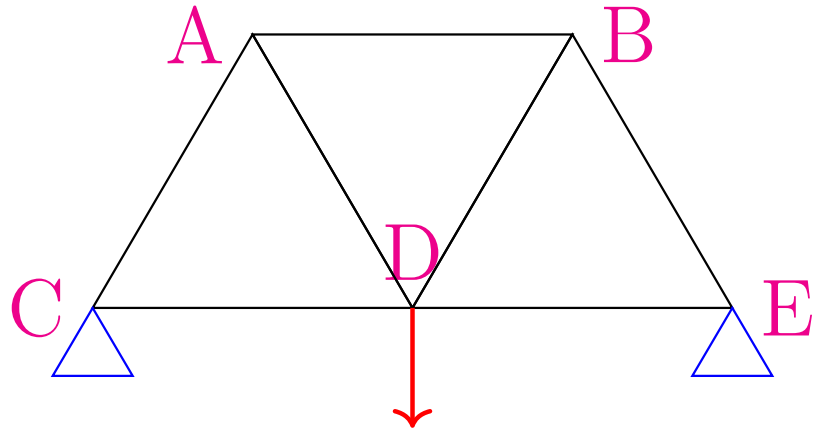
## Applications

### A.1 Civil Engineering: Trusses and Struts

**Definition A.1.1** In engineering, a **truss** is a structure designed from several beams of material called **struts**, assembled to behave as a single object.



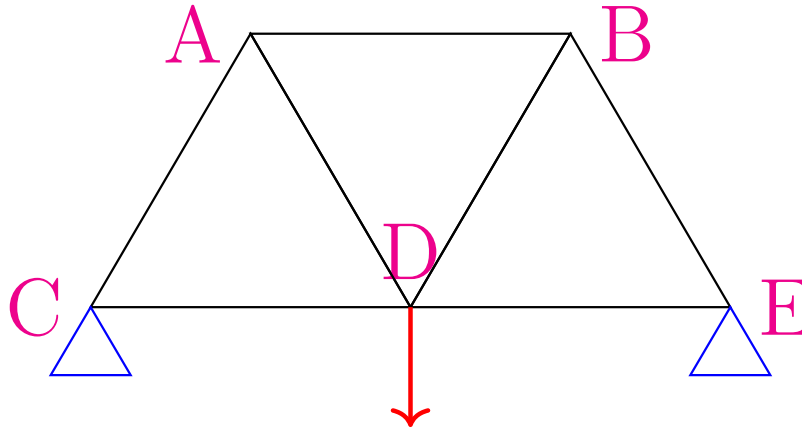
**Figure 35** A simple truss



**Figure 36** A simple truss



**Activity A.1.2** Consider the representation of a simple truss pictured below. All of the seven struts are of equal length, affixed to two anchor points applying a normal force to nodes  $C$  and  $E$ , and with a  $10000N$  load applied to the node given by  $D$ .

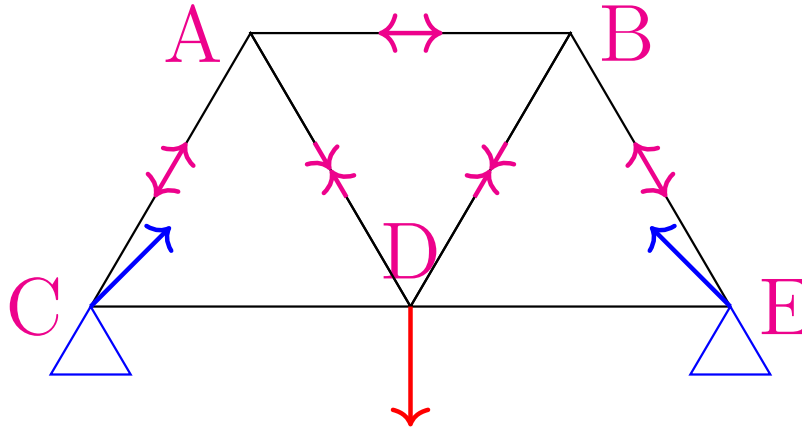


**Figure 37** A simple truss

Which of the following must hold for the truss to be stable?

1. All of the struts will experience compression.
2. All of the struts will experience tension.
3. Some of the struts will be compressed, but others will be tensioned.

**Observation A.1.3** Since the forces must balance at each node for the truss to be stable, some of the struts will be compressed, while others will be tensioned.

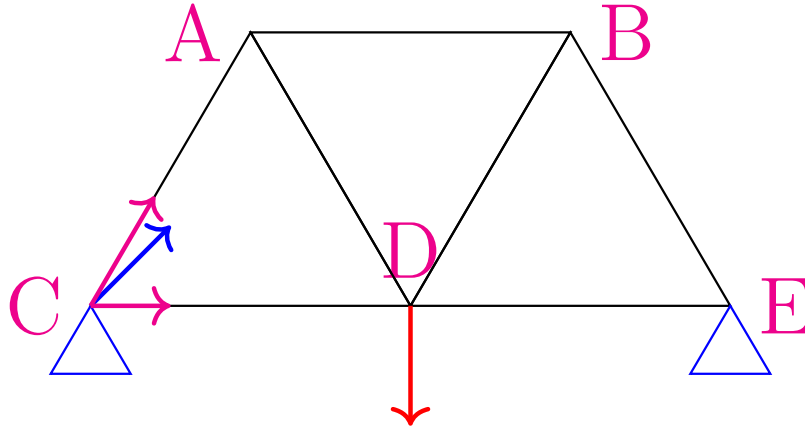


**Figure 38** Completed truss

By finding vector equations that must hold at each node, we may determine many of the forces at play.



**Remark A.1.4** For example, at the bottom left node there are 3 forces acting.



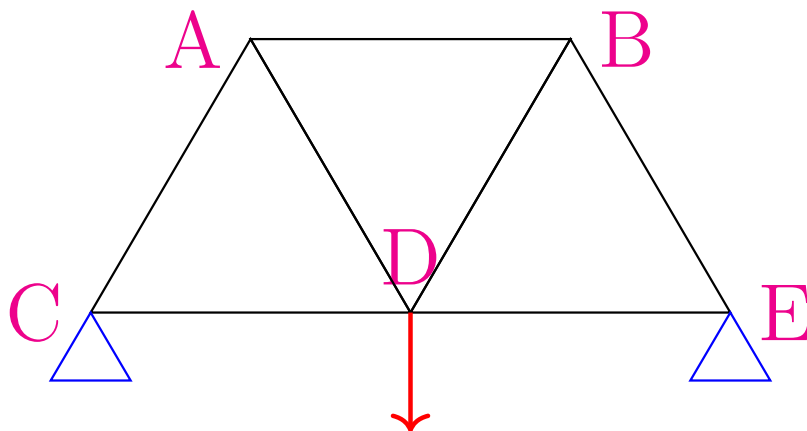
**Figure 39** Truss with forces

Let  $\vec{F}_{CA}$  be the force on  $C$  given by the compression/tension of the strut  $CA$ , let  $\vec{F}_{CD}$  be defined similarly, and let  $\vec{N}_C$  be the normal force of the anchor point on  $C$ .

For the truss to be stable, we must have:

$$\vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$

**Activity A.1.5** Using the conventions of the previous remark, and where  $\vec{L}$  represents the load vector on node  $D$ , find four more vector equations that must be satisfied for each of the other four nodes of the truss.



**Figure 40** A simple truss

$A : ?$

$B : ?$

$$C : \vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$

$D : ?$

$E : ?$

## Civil Engineering: Trusses and Struts

**Remark A.1.6** The five vector equations may be written as follows.

$$A : \vec{F}_{AC} + \vec{F}_{AD} + \vec{F}_{AB} = \vec{0}$$

$$B : \vec{F}_{BA} + \vec{F}_{BD} + \vec{F}_{BE} = \vec{0}$$

$$C : \vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$

$$D : \vec{F}_{DC} + \vec{F}_{DA} + \vec{F}_{DB} + \vec{F}_{DE} + \vec{L} = \vec{0}$$

$$E : \vec{F}_{EB} + \vec{F}_{ED} + \vec{N}_E = \vec{0}$$

## Civil Engineering: Trusses and Struts

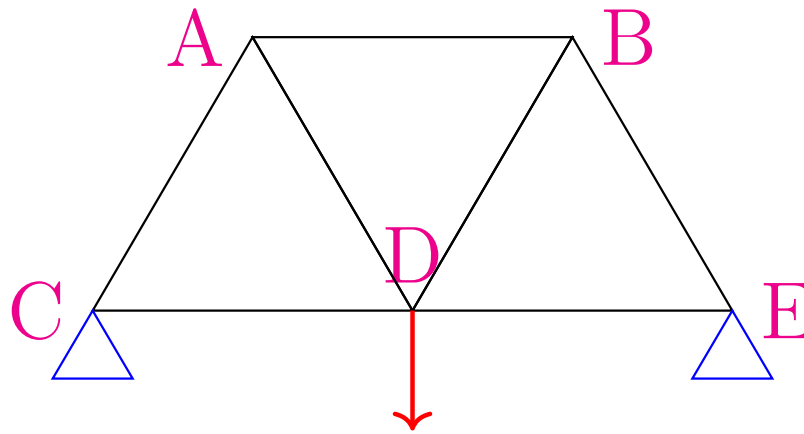
**Observation A.1.7** Each vector has a vertical and horizontal component, so it may be treated as a vector in  $\mathbb{R}^2$ . Note that  $\vec{F}_{CA}$  must have the same magnitude (but opposite direction) as  $\vec{F}_{AC}$ .

$$\vec{F}_{CA} = x \begin{bmatrix} \cos(60^\circ) \\ \sin(60^\circ) \end{bmatrix} = x \begin{bmatrix} 1/2 \\ \sqrt{3}/2 \end{bmatrix}$$

$$\vec{F}_{AC} = x \begin{bmatrix} \cos(-120^\circ) \\ \sin(-120^\circ) \end{bmatrix} = x \begin{bmatrix} -1/2 \\ -\sqrt{3}/2 \end{bmatrix}$$

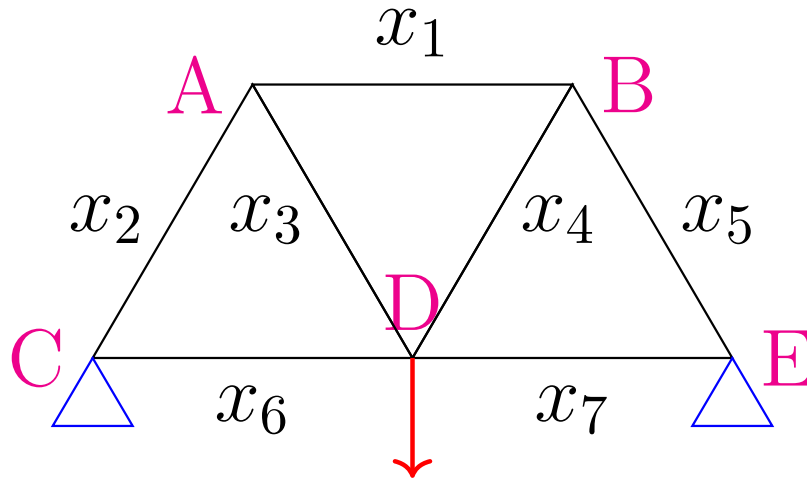
**Activity A.1.8** To write a linear system that models the truss under consideration with constant load 10000 newtons, how many scalar variables will be required?

- 7: 5 from the nodes, 2 from the anchors
- 9: 7 from the struts, 2 from the anchors
- 11: 7 from the struts, 4 from the anchors
- 12: 7 from the struts, 4 from the anchors, 1 from the load
- 13: 5 from the nodes, 7 from the struts, 1 from the load



**Figure 41** A simple truss

**Observation A.1.9** Since the angles for each strut are known, one variable may be used to represent each.



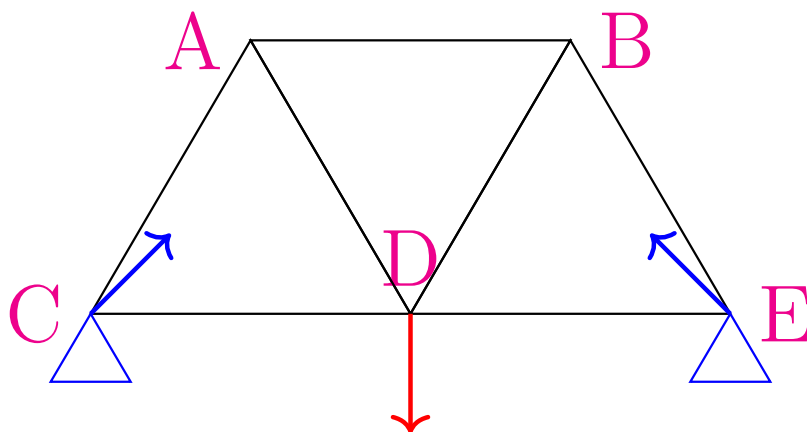
**Figure 42** Variables for the truss

For example:

$$\vec{F}_{AB} = -\vec{F}_{BA} = x_1 \begin{bmatrix} \cos(0) \\ \sin(0) \end{bmatrix} = x_1 \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$\vec{F}_{BE} = -\vec{F}_{EB} = x_5 \begin{bmatrix} \cos(-60^\circ) \\ \sin(-60^\circ) \end{bmatrix} = x_5 \begin{bmatrix} 1/2 \\ -\sqrt{3}/2 \end{bmatrix}$$

**Observation A.1.10** Since the angle of the normal forces for each anchor point are unknown, two variables may be used to represent each.



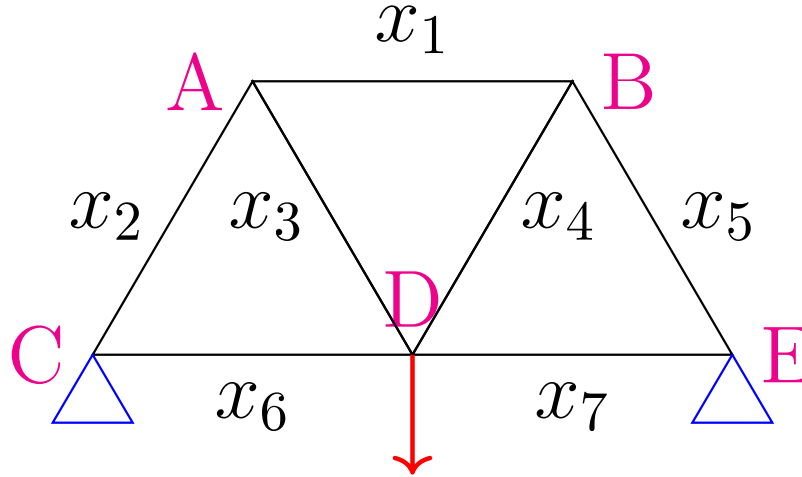
**Figure 43** Truss with normal forces

$$\vec{N}_C = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \quad \vec{N}_D = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}$$

The load vector is constant.

$$\vec{L} = \begin{bmatrix} 0 \\ -10000 \end{bmatrix}$$

**Remark A.1.11** Each of the five vector equations found previously represent two linear equations: one for the horizontal component and one for the vertical.



**Figure 44** Variables for the truss

$$C : \vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$

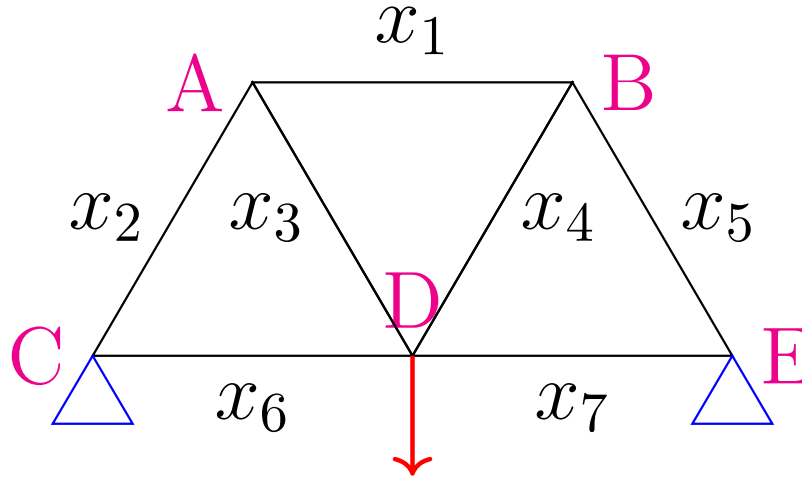
$$\Leftrightarrow x_2 \begin{bmatrix} \cos(60^\circ) \\ \sin(60^\circ) \end{bmatrix} + x_6 \begin{bmatrix} \cos(0^\circ) \\ \sin(0^\circ) \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Using the approximation  $\sqrt{3}/2 \approx 0.866$ , we have

$$\Leftrightarrow x_2 \begin{bmatrix} 0.5 \\ 0.866 \end{bmatrix} + x_6 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + y_1 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + y_2 \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$



**Activity A.1.12** Expand the vector equation given below using sine and cosine of appropriate angles, then compute each component (approximating  $\sqrt{3}/2 \approx 0.866$ ).



**Figure 45** Variables for the truss

$$\begin{aligned}
 D : \vec{F}_{DA} + \vec{F}_{DB} + \vec{F}_{DC} + \vec{F}_{DE} &= -\vec{L} \\
 \Leftrightarrow x_3 \begin{bmatrix} \cos(?) \\ \sin(?) \end{bmatrix} + x_4 \begin{bmatrix} \cos(?) \\ \sin(?) \end{bmatrix} + x_6 \begin{bmatrix} \cos(?) \\ \sin(?) \end{bmatrix} + x_7 \begin{bmatrix} \cos(?) \\ \sin(?) \end{bmatrix} &= \begin{bmatrix} ? \\ ? \end{bmatrix} \\
 \Leftrightarrow x_3 \begin{bmatrix} ? \\ ? \end{bmatrix} + x_4 \begin{bmatrix} ? \\ ? \end{bmatrix} + x_6 \begin{bmatrix} ? \\ ? \end{bmatrix} + x_7 \begin{bmatrix} ? \\ ? \end{bmatrix} &= \begin{bmatrix} ? \\ ? \end{bmatrix}
 \end{aligned}$$

## Civil Engineering: Trusses and Struts

**Observation A.1.13** The full augmented matrix given by the ten equations in this linear system is given below, where the elevent columns correspond to  $x_1, \dots, x_7, y_1, y_2, z_1, z_2$ , and the ten rows correspond to the horizontal and vertical components of the forces acting at  $A, \dots, E$ .

$$\left[ \begin{array}{cccccccccccc|c} 1 & -0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.866 & -0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & -0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -0.866 & -0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -0.5 & 0.5 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.866 & 0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 10000 \\ 0 & 0 & 0 & 0 & -0.5 & 0 & -1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.866 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{array} \right]$$

## Civil Engineering: Trusses and Struts

**Observation A.1.14** This matrix row-reduces to the following.

$$\sim \left[ \begin{array}{cccccccccccc|c} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5773.7 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5773.7 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5773.7 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5773.7 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5773.7 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & -1 & 0 & 2886.8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 2886.8 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 5000 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 5000 \end{array} \right]$$

**Observation A.1.15** Thus we know the truss must satisfy the following conditions.

$$x_1 = x_2 = x_5 = -5882.4$$

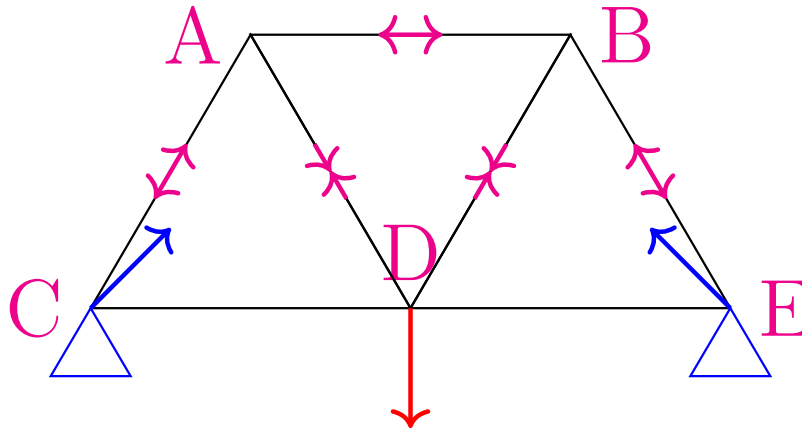
$$x_3 = x_4 = 5882.4$$

$$x_6 = x_7 = 2886.8 + z_1$$

$$y_1 = -z_1$$

$$y_2 = z_2 = 5000$$

In particular, the negative  $x_1, x_2, x_5$  represent tension (forces pointing into the nodes), and the positive  $x_3, x_4$  represent compression (forces pointing out of the nodes). The vertical normal forces  $y_2 + z_2$  counteract the 10000 load.

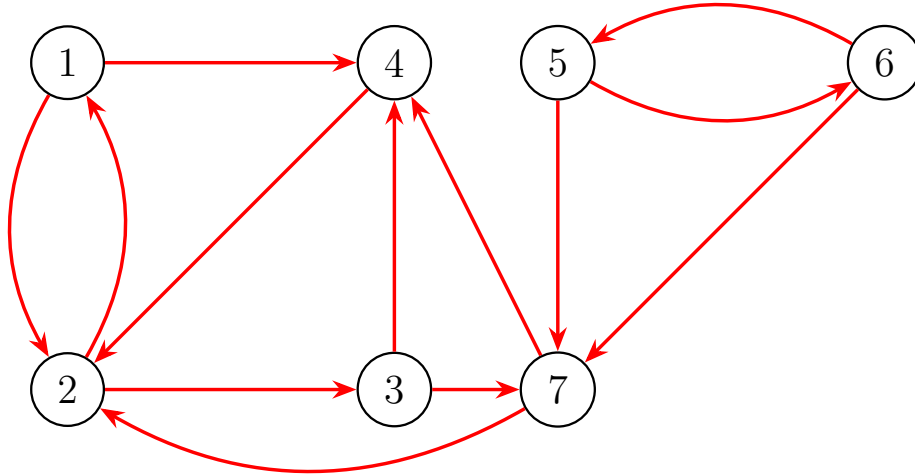


**Figure 46** Completed truss

## A.2 Computer Science: PageRank

### Activity A.2.1 The \$978,000,000,000 Problem.

In the picture below, each circle represents a webpage, and each arrow represents a link from one page to another.



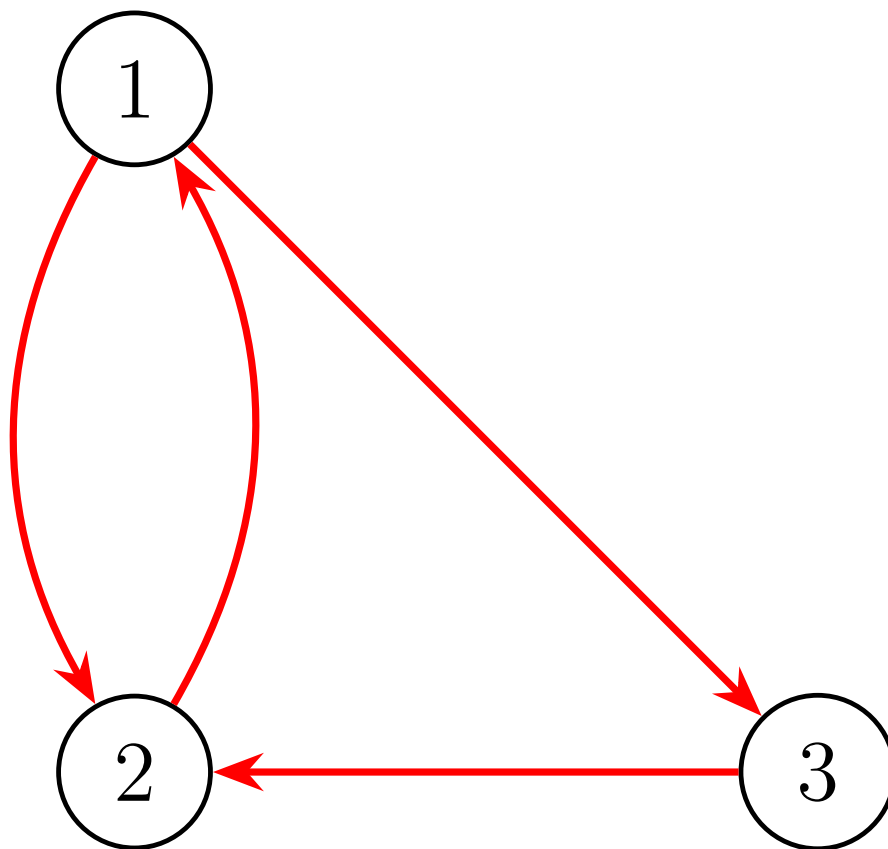
**Figure 47** A seven-webpage network

Based on how these pages link to each other, write a list of the 7 webpages in order from most important to least important.

**Observation A.2.2 The \$978,000,000,000 Idea.** Links are endorsements. That is:

1. A webpage is important if it is linked to (endorsed) by important pages.
2. A webpage distributes its importance equally among all the pages it links to (endorses).

**Example A.2.3** Consider this small network with only three pages. Let  $x_1, x_2, x_3$  be the importance of the three pages respectively.



**Figure 48** A three-webpage network

1.  $x_1$  splits its endorsement in half between  $x_2$  and  $x_3$
2.  $x_2$  sends all of its endorsement to  $x_1$
3.  $x_3$  sends all of its endorsement to  $x_2$ .

This corresponds to the **page rank system**:

$$\begin{aligned}
 x_2 &= x_1 \\
 \frac{1}{2}x_1 + x_3 &= x_2 \\
 \frac{1}{2}x_1 &= x_3
 \end{aligned}$$

□

## Observation A.2.4

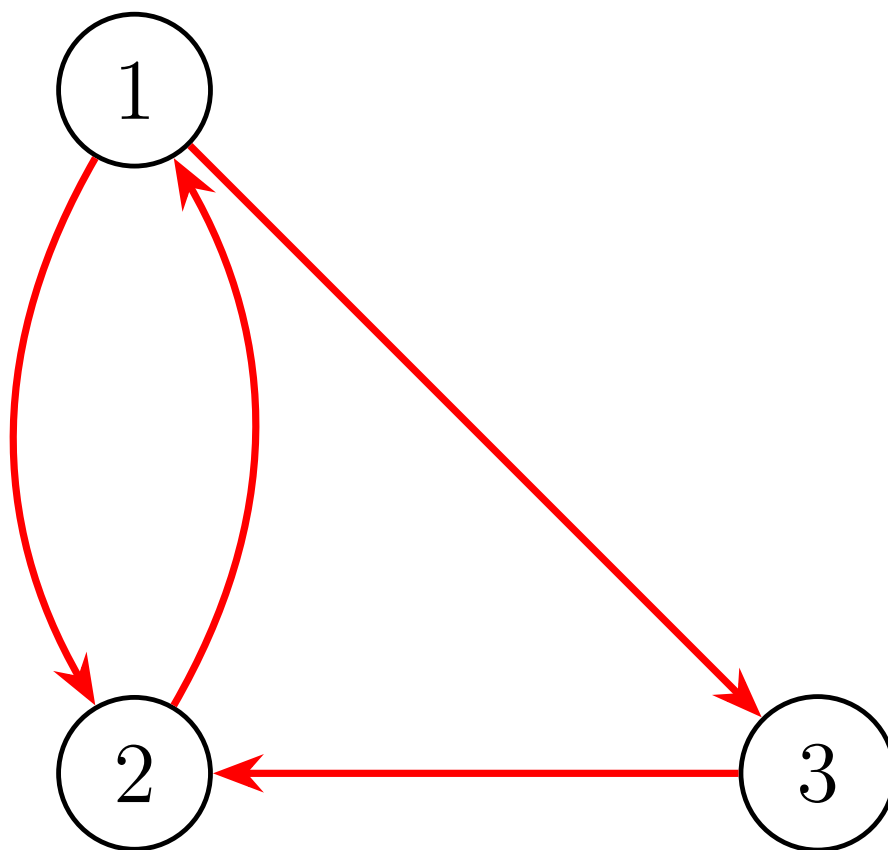


Figure 49 A three-webpage network

$$\begin{array}{rcl}
 x_2 & = & x_1 \\
 \frac{1}{2}x_1 + x_3 & = & x_2 \\
 \frac{1}{2}x_1 & = & x_3
 \end{array}
 \qquad
 \begin{bmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & 1 \\ \frac{1}{2} & 0 & 0 \end{bmatrix}
 \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}
 =
 \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

By writing this linear system in terms of matrix multiplication, we obtain the **page rank matrix**  $A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & 1 \\ \frac{1}{2} & 0 & 0 \end{bmatrix}$  and page rank vector  $\vec{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$ .

Thus, computing the importance of pages on a network is equivalent to solving the matrix equation  $A\vec{x} = \vec{1}\vec{x}$ .



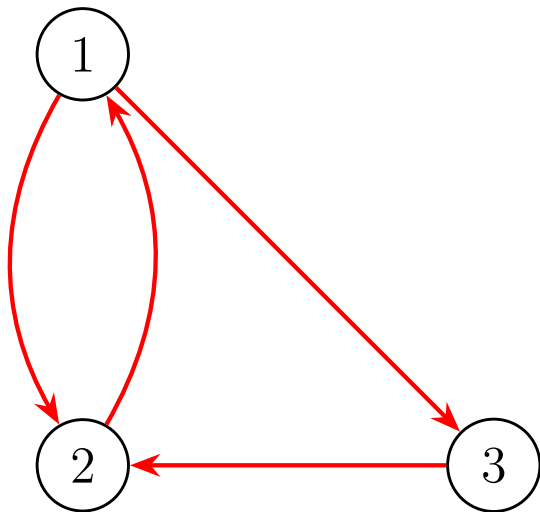
**Activity A.2.5** Thus, our \$978,000,000,000 problem is what kind of problem?

$$\begin{bmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = 1 \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

- A. An antiderivative problem
- B. A bijection problem
- C. A cofactoring problem
- D. A determinant problem
- E. An eigenvector problem

**Activity A.2.6** Find a page rank vector  $\vec{x}$  satisfying  $A\vec{x} = 1\vec{x}$  for the following network's page rank matrix  $A$ .

That is, find the eigenspace associated with  $\lambda = 1$  for the matrix  $A$ , and choose a vector from that eigenspace.



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

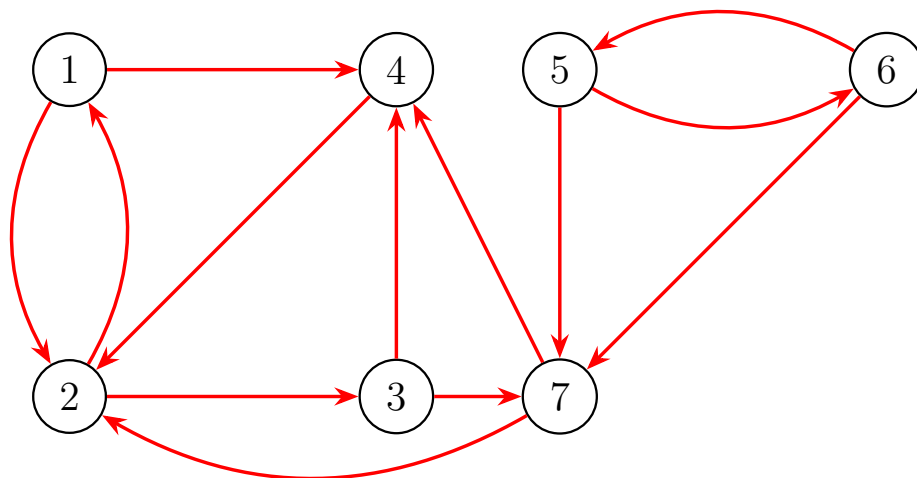
**Figure 50** A three-webpage network

**Observation A.2.7** Row-reducing  $A-I = \begin{bmatrix} -1 & 1 & 0 \\ \frac{1}{2} & -1 & 1 \\ \frac{1}{2} & 0 & -1 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & -2 \\ 0 & 1 & -2 \\ 0 & 0 & 0 \end{bmatrix}$

yields the basic eigenvector  $\begin{bmatrix} 2 \\ 2 \\ 1 \end{bmatrix}$ .

Therefore, we may conclude that pages 1 and 2 are equally important, and both pages are twice as important as page 3.

**Activity A.2.8** Compute the  $7 \times 7$  page rank matrix for the following network.



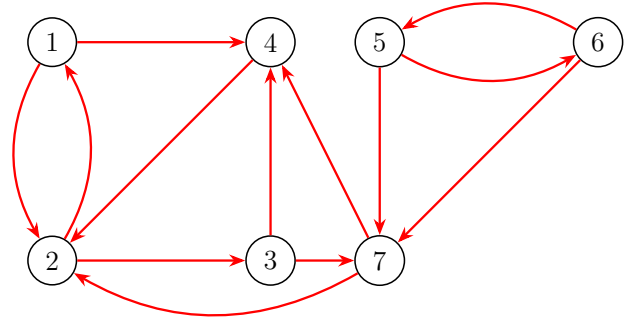
**Figure 51** A seven-webpage network

For example, since website 1 distributes its endorsement equally between

2 and 4, the first column is  $\begin{bmatrix} 0 \\ \frac{1}{2} \\ 0 \\ \frac{1}{2} \\ 0 \\ 0 \\ 0 \end{bmatrix}$ .

**Activity A.2.9** Find a page rank vector for the given page rank matrix.

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



**Figure 52** A seven-webpage network

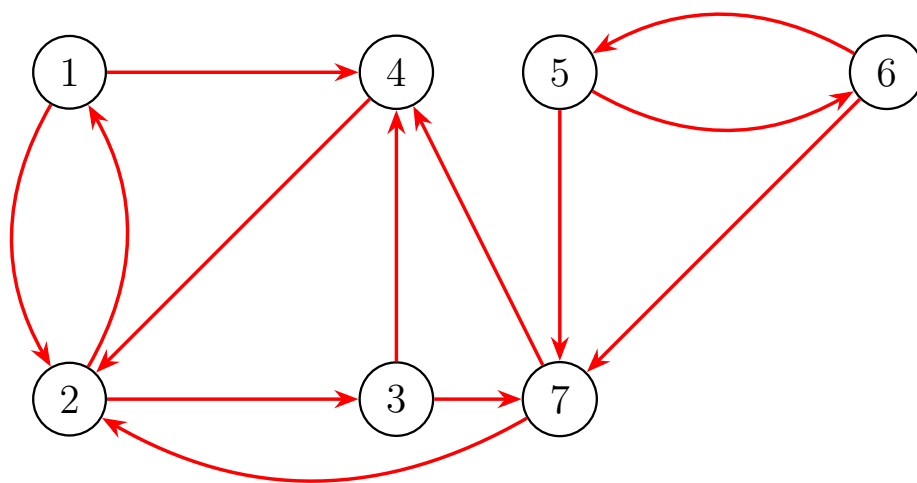
Which webpage is most important?

**Observation A.2.10** Since a page rank vector for the network is given by  $\vec{x}$ , it's reasonable to consider page 2 as the most important page.

$$\vec{x} = \begin{bmatrix} 2 \\ 4 \\ 2 \\ 2.5 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

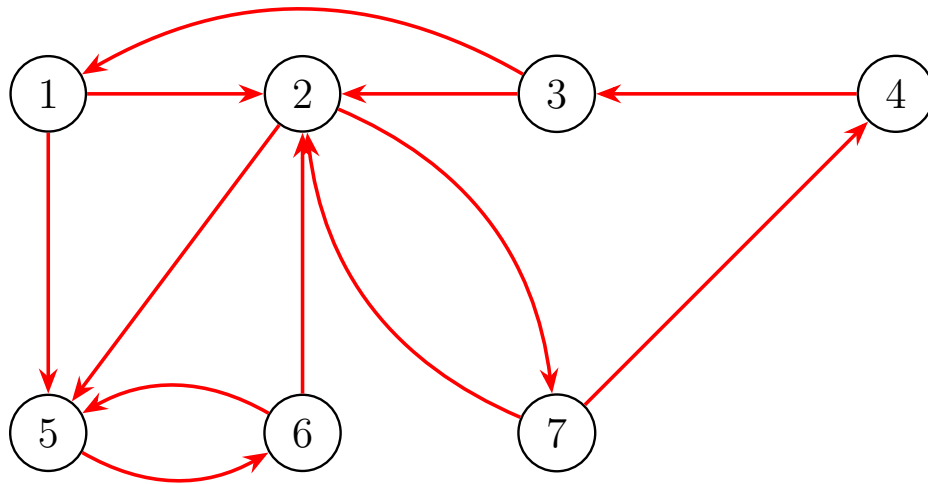
Based upon this page rank vector, here is a complete ranking of all seven pages from most important to least important:

2, 4, 1, 3, 7, 5, 6



**Figure 53** A seven-webpage network

**Activity A.2.11** Given the following diagram, use a page rank vector to rank the pages 1 through 7 in order from most important to least important.



**Figure 54** Another seven-webpage network

## A.3 Geology: Phases and Components

**Definition A.3.1** In geology, a **phase** is any physically separable material in the system, such as various minerals or liquids.

A **component** is a chemical compound necessary to make up the phases; these are usually oxides such as Calcium Oxide ( $\text{CaO}$ ) or Silicon Dioxide ( $\text{SiO}_2$ ).

In a typical application, a geologist knows how to build each phase from the components, and is interested in determining reactions among the different phases.  $\diamond$



## Geology: Phases and Components

**Observation A.3.2** Consider the 3 components

$$\vec{c}_1 = \text{CaO} \quad \vec{c}_2 = \text{MgO} \quad \text{and} \quad \vec{c}_3 = \text{SiO}_2$$

and the 5 phases:

$$\begin{array}{lll} \vec{p}_1 = \text{Ca}_3\text{MgSi}_2\text{O}_8 & \vec{p}_2 = \text{CaMgSiO}_4 & \vec{p}_3 = \text{CaSiO}_3 \\ \vec{p}_4 = \text{CaMgSi}_2\text{O}_6 & \vec{p}_5 = \text{Ca}_2\text{MgSi}_2\text{O}_7 & \end{array}$$

Geologists already know (or can easily deduce) that

$$\begin{array}{lll} \vec{p}_1 = 3\vec{c}_1 + \vec{c}_2 + 2\vec{c}_3 & \vec{p}_2 = \vec{c}_1 + \vec{c}_2 + \vec{c}_3 & \vec{p}_3 = \vec{c}_1 + 0\vec{c}_2 + \vec{c}_3 \\ \vec{p}_4 = \vec{c}_1 + \vec{c}_2 + 2\vec{c}_3 & \vec{p}_5 = 2\vec{c}_1 + \vec{c}_2 + 2\vec{c}_3 & \end{array}$$

since, for example:

$$\vec{c}_1 + \vec{c}_3 = \text{CaO} + \text{SiO}_2 = \text{CaSiO}_3 = \vec{p}_3$$

### Geology: Phases and Components

**Activity A.3.3** To study this vector space, each of the three components  $\vec{c}_1, \vec{c}_2, \vec{c}_3$  may be considered as the three components of a Euclidean vector.

$$\vec{p}_1 = \begin{bmatrix} 3 \\ 1 \\ 2 \end{bmatrix}, \vec{p}_2 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \vec{p}_3 = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \vec{p}_4 = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}, \vec{p}_5 = \begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix}.$$

Determine if the set of phases is linearly dependent or linearly independent.

## Geology: Phases and Components

**Activity A.3.4** Geologists are interested in knowing all the possible chemical reactions among the 5 phases:

$$\vec{p}_1 = \text{Ca}_3\text{MgSi}_2\text{O}_8 = \begin{bmatrix} 3 \\ 1 \\ 2 \end{bmatrix} \quad \vec{p}_2 = \text{CaMgSiO}_4 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad \vec{p}_3 = \text{CaSiO}_3 = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$$

$$\vec{p}_4 = \text{CaMgSi}_2\text{O}_6 = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix} \quad \vec{p}_5 = \text{Ca}_2\text{MgSi}_2\text{O}_7 = \begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix}.$$

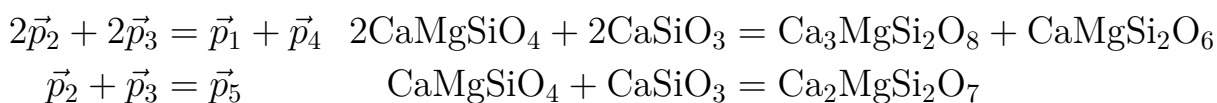
That is, they want to find numbers  $x_1, x_2, x_3, x_4, x_5$  such that

$$x_1\vec{p}_1 + x_2\vec{p}_2 + x_3\vec{p}_3 + x_4\vec{p}_4 + x_5\vec{p}_5 = 0.$$

- (a) Set up a system of equations equivalent to this vector equation.
- (b) Find a basis for its solution space.
- (c) Interpret each basis vector as a vector equation and a chemical equation.

## Geology: Phases and Components

**Activity A.3.5** We found two basis vectors  $\begin{bmatrix} 1 \\ -2 \\ -2 \\ 1 \\ 0 \end{bmatrix}$  and  $\begin{bmatrix} 0 \\ -1 \\ -1 \\ 0 \\ 1 \end{bmatrix}$ , corresponding to the vector and chemical equations



Combine the basis vectors to produce a chemical equation among the five phases that does not involve  $\vec{p}_2 = \text{CaMgSiO}_4$ .