

Standards for this Module

At the end of this module, students will be able to...

- **E1: Systems as matrices.** Translate back and forth between a system of linear equations and the corresponding augmented matrix.
- **E2: Row reduction.** Put a matrix in reduced row echelon form
- **E3: Solving Linear Systems.** Solve a system of linear equations.
- **E4: Homogeneous Systems.** Find a basis for the solution set of a homogeneous linear system.

Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Determine if a system to a two-variable system of linear equations will have zero, one, or infinitely-many solutions by graphing.
- Find the unique solution to a two-variable system of linear equations by back-substitution.

Readiness Assurance Resources

The following resources will help you prepare for this module.

- <https://www.khanacademy.org/math/cc-eighth-grade-math/cc-8th-systems-topic/cc-8th-systems-graphical/a/systems-of-equations-with-graphing>
- <https://www.khanacademy.org/math/algebra/systems-of-linear-equations/solving-systems-of-equations-v/practice-using-substitution-for-systems>

Readiness Assurance Test

Choose the most appropriate response for each question.

- 1) Which of these graphs represents the following system of linear equations?

$$x + 2y = 4$$

$$2x - 3y = 1$$



- 2) How many solutions are there for the system of linear equations represented by the following graph?



- (a) One (b) Two (c) Zero (d) Infinitely-many

- 3) Which of these graphs represents the following system of linear equations?

$$3x + 3y = 6$$

$$x + y = 2$$

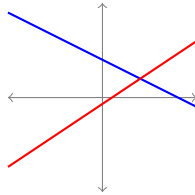


- 4) How many solutions are there for the system of linear equations represented by the following graph?
(This graph represents two completely overlapping lines.)



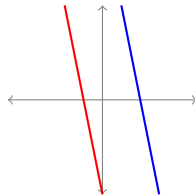
- (a) Zero (b) One (c) Two (d) Infinitely-many

5) How many solutions are there for the system of linear equations represented by the following graph?



- (a) Zero (b) One (c) Two (d) Infinitely-many

6) How many solutions are there for the system of linear equations represented by the following graph?
(This graph represents two non-overlapping parallel lines.)



- (a) Zero (b) One (c) Two (d) Infinitely-many

7) Solve the following system of linear equations.

$$\begin{aligned} y &= 2x + 5 \\ y &= -x + 2 \end{aligned}$$

- (a) $(x, y) = (-1, 3)$ (b) $(x, y) = (4, -2)$ (c) There are no solutions. (d) There are infinitely-many solutions.

8) Solve the following system of linear equations.

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

- (a) $(x, y) = (3, 4)$ (b) $(x, y) = (-5, 1)$ (c) There are no solutions. (d) There are infinitely-many solutions.

9) Solve the following system of linear equations.

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

- (a) There are no solutions. (b) There are infinitely many solutions. (c) $(x, y) = (-1, 4)$ (d) $(x, y) = (2, 1)$

10) Solve the following system of linear equations.

$$\begin{aligned}4x - 8y &= 12 \\ -6x + 12y &= -18\end{aligned}$$

- (a) There are no solutions. (b) There are infinitely many solutions. (c) $(x, y) = (3, 3)$ (d) $(x, y) = (-2, 1)$

Application Activities - Module E Part 1 - Class Day 3

Definition 3.1 A **linear equation** is an equation of the variables x_i of the form

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

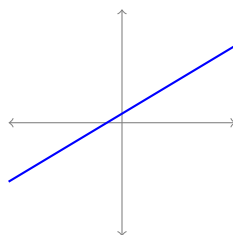
A **solution** for a linear equation is expressed in terms of the Euclidean vectors

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix}$$

and must satisfy

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

Observation 3.2 The linear equation $3x - 5y = -2$ may be graphed as a line in the xy plane.



The linear equation $x + 2y - z = 4$ may be graphed as a plane in xyz space.

Remark 3.3 In previous classes you likely assumed $x = x_1$, $y = x_2$, and $z = x_3$. However, since this course often deals with equations of four or more variables, we will almost always write our variables as x_i .

Definition 3.4 A **system of linear equations** (or a **linear system** for short) is a collection of one or more linear equations.

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

A **solution**

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix} = \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_n \end{bmatrix}$$

for a linear system satisfies

$$a_{i1}s_1 + a_{i2}s_2 + \cdots + a_{in}s_n = b_i$$

for $1 \leq i \leq m$ (that is, the solution satisfies all equations in the system).

Remark 3.5 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:

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

Verbose standard form:

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

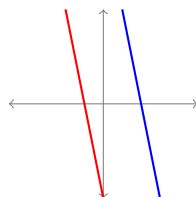
Concise standard form:

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

Definition 3.6 A linear system is **consistent** if there exists a solution for the system. Otherwise it is **inconsistent**.

Fact 3.7 All linear systems are either **consistent with one solution**, **consistent with infinitely-many solutions**, or **inconsistent**.

Activity 3.8 (5 min) Consider the following graphs representing linear systems of two variables. Label each graph with **consistent with one solution**, **consistent with infinitely-many solutions**, or **inconsistent**.



Activity 3.9 (10 min) All inconsistent linear systems contain a logical **contradiction**. Find a contradiction in this system.

$$\begin{aligned}-x_1 + 2x_2 &= 5 \\2x_1 - 4x_2 &= 6\end{aligned}$$

Activity 3.10 (10 min) Consider the following consistent linear system.

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

Part 1: Find three different solutions $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix}, \begin{bmatrix} s_1 \\ s_2 \end{bmatrix}, \begin{bmatrix} t_1 \\ t_2 \end{bmatrix}$ for this system.

Part 2: 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 describe *all* solutions (the **solution set**) $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} ? \\ a \end{bmatrix}$ for the linear system in terms of a .

Activity 3.11 (10 min) Consider the following linear system.

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

Describe the solution set

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} ? \\ a \\ ? \\ b \end{bmatrix} = \begin{bmatrix} t_1 \\ 0 \\ t_3 \\ 0 \end{bmatrix} + a \begin{bmatrix} ? \\ 1 \\ ? \\ 0 \end{bmatrix} + b \begin{bmatrix} ? \\ 0 \\ ? \\ 1 \end{bmatrix}$$

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

Observation 3.12 Solving linear systems of two variables by graphing or substitution is reasonable for two-variable systems, but these simple techniques won't cut it for equations with more than two variables or more than two equations.

Remark 3.13 The only important information in a linear system are its coefficients and constants.

Original linear system:

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

Verbose standard form:

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

Coefficients/constants:

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

Definition 3.14 A system of m linear equations with n variables is often represented by writing its coefficients and constants in an **augmented matrix**.

$$\begin{aligned} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n &= b_1 \\ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n &= b_2 \\ \vdots & \\ a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n &= b_m \end{aligned} \quad \left[\begin{array}{cccc|c} a_{11} & a_{12} & \cdots & a_{1n} & b_1 \\ a_{21} & a_{22} & \cdots & a_{2n} & b_2 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} & b_m \end{array} \right]$$

Definition 3.15 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 have a single solution: $(x_1, x_2) = (1, 1)$.

$$\begin{aligned} 3x_1 - 2x_2 &= 1 \\ x_1 + 4x_2 &= 5 \end{aligned} \quad \begin{aligned} 3x_1 - 2x_2 &= 1 \\ 4x_1 + 2x_2 &= 6 \end{aligned}$$

Therefore these augmented matrices are equivalent:

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

Activity 3.16 (10 min) Following are six procedures used to manipulate an augmented matrix. Label the procedures that would result in an equivalent augmented matrix as **valid**, and label the procedures that would change the solution set of the corresponding linear system as **invalid**.

- | | |
|---|---|
| a) Swap two rows. | d) Multiply a row by a nonzero constant. |
| b) Swap two columns. | e) Add a constant multiple of one row to another row. |
| c) Add a constant to every term in a row. | f) Replace a column with zeros. |

(Instructor Note:) This activity could be ran as a card sort.

Application Activities - Module E Part 2 - Class Day 4

Definition 4.1 The following **row operations** produce equivalent augmented matrices:

1. Swap two rows.
2. Multiply a row by a nonzero constant.
3. Add a constant multiple of one row to another row.

Whenever two matrices A, B are equivalent (so whenever we do any of these operations), we write $A \sim B$.

Activity 4.2 (10 min) Consider the following two linear systems.

$$\begin{array}{rcl} 3x_1 - 2x_2 + 13x_3 & = & 6 \\ 2x_1 - 2x_2 + 10x_3 & = & 2 \\ -1x_1 + 3x_2 - 6x_3 & = & 11 \end{array} \qquad \begin{array}{rcl} x_1 - x_2 + 5x_3 & = & 1 \\ x_2 - 2x_3 & = & 3 \\ x_3 & = & 2 \end{array}$$

Part 1: Show these are equivalent by converting the first system to an augmented matrix, and then performing the following row operations to obtain an augmented matrix equivalent to the second system.

1. Swap R_1 (first row) and R_2 (second row).
2. Multiply R_2 by $\frac{1}{2}$.
3. Add R_1 to R_3 .
4. Add $-3R_1$ to R_2 .
5. Add $-2R_2$ to R_3 .
6. Multiply R_3 by $\frac{1}{3}$.

Part 2: Which linear system would you rather solve?

Definition 4.3 The **leading term** of a matrix row is its first nonzero term. A matrix is in **row echelon form** if all leading terms are 1, the leading term of every row is farther right than every leading term on a higher row, and all zero rows are at the bottom of the matrix. Examples:

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

Activity 4.4 (10 min) Find your own sequence of row operations to manipulate the matrix

$$\left[\begin{array}{ccc|c} 3 & -2 & 13 & 6 \\ 2 & -2 & 10 & 2 \\ -1 & 3 & -6 & 11 \end{array} \right]$$

into row echelon form. (Note that row echelon form is not unique.)

The most efficient way to do this is by circling **pivot positions** in your matrix:

1. Circle the top-left-most cell that (a) is below any existing pivot positions and (b) has a nonzero term either in that position or below it.

2. Ignoring any rows above this pivot position, use row operations to change the value of your pivot position to 1, and the terms below it to 0.
 3. Repeat these two steps as often as possible.
-

Activity 4.5 (10 min) Solve this simplified linear system:

$$\begin{aligned}x_1 - x_2 + 5x_3 &= 1 \\x_2 - 2x_3 &= 3 \\x_3 &= 2\end{aligned}$$

Observation 4.6 The concise standard form of the solution to this linear system corresponds to a simplified row echelon form matrix:

$$\begin{aligned}x_1 &= -2 \\x_2 &= 7 \\x_3 &= 2\end{aligned} \qquad \left[\begin{array}{ccc|c} 1 & 0 & 0 & -2 \\ 0 & 1 & 0 & 7 \\ 0 & 0 & 1 & 2 \end{array} \right]$$

Definition 4.7 A matrix is in **reduced row echelon form** if it is in row echelon form and all terms above leading terms are 0. Examples:

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

Activity 4.8 (10 min) Show that the following two linear systems:

$$\begin{aligned}x_1 - x_2 + 5x_3 &= 1 \\x_2 - 2x_3 &= 3 \\x_3 &= 2\end{aligned} \qquad \begin{aligned}x_1 &= -2 \\x_2 &= 7 \\x_3 &= 2\end{aligned}$$

are equivalent by converting the first system to an augmented matrix, and then zeroing out all terms above pivot positions (the leading terms).

Remark 4.9 We may verify that $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} -2 \\ 7 \\ 2 \end{bmatrix}$ is a solution to the original linear system

$$\begin{aligned}3x_1 - 2x_2 + 13x_3 &= 6 \\2x_1 - 2x_2 + 10x_3 &= 2 \\-1x_1 + 3x_2 - 6x_3 &= 11\end{aligned}$$

by plugging the solution into each equation.

Fact 4.10 Every augmented matrix A reduces to a unique reduced row echelon form matrix. This matrix is denoted as $\text{RREF}(A)$.

Activity 4.11 (10 min) Consider the following matrix.

$$A = \left[\begin{array}{ccc|c} 1 & 2 & 3 & 1 \\ 2 & 4 & 8 & 0 \end{array} \right]$$

Part 1: Find $\text{RREF}(A)$.

Part 2: How many solutions does the corresponding linear system have?

Application Activities - Module E Part 3 - Class Day 5

Definition 5.1 An algorithm that reduces A to $\text{RREF}(A)$ is called **Gauss-Jordan elimination**. For example:

1. Circle the cell that (a) is in the top-most row without a pivot position and (b) is in the left-most column with a nonzero term either in that position or below it. This position (not the number inside) is called a **pivot**.
2. Change the pivot's value to 1 by using row operations involving only the pivot row and rows below it.
3. Add or subtract multiples of the pivot row to zero out above and below the pivot.
4. Return to Step 1 and repeat as needed until the matrix is in row reduced echelon form.

Observation 5.2 Here is an example of applying Gauss-Jordan elimination to a matrix:

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

Definition 5.3 The columns of $\text{RREF}(A)$ without a leading term represent **free variables** of the linear system modeled by A that may be set equal to arbitrary parameters. The other **bounded variables** can then be expressed in terms of those parameters to describe the solution set to the linear system modeled by A .

Example 5.4 Here, x_3 is the free variable set equal to a since its column lacks a pivot, and the other bounded variables are put in terms of a .

$$\begin{array}{rcl}
 \begin{array}{l} 2x_1 - 2x_2 - 6x_3 + x_4 = 3 \\ -x_1 + x_2 + 3x_3 - x_4 = -3 \\ x_1 - 2x_2 - x_3 + x_4 = 1 \end{array} & \begin{array}{l} x_1 - 5x_3 = 1 \\ x_2 - 2x_3 = 1 \\ x_4 = 3 \end{array} & \Rightarrow \begin{array}{l} x_1 = 1 + 5a \\ x_2 = 1 + 2a \\ x_3 = a \\ x_4 = 3 \end{array} \\
 \Downarrow & & \Uparrow \\
 \left[\begin{array}{cccc|c} 2 & -2 & -6 & 1 & 3 \\ -1 & 1 & 3 & -1 & -3 \\ 1 & -2 & -1 & 1 & 2 \end{array} \right] & \sim & \left[\begin{array}{cccc|c} \textcircled{1} & 0 & -5 & 0 & 1 \\ 0 & \textcircled{1} & -2 & 0 & 1 \\ 0 & 0 & 0 & \textcircled{1} & 3 \end{array} \right]
 \end{array}$$

So the solution set is $\left\{ \begin{bmatrix} 1+5a \\ 1+2a \\ a \\ 3 \end{bmatrix} \mid a \in \mathbb{R} \right\}.$

Activity 5.5 (20 min) Solve the system of linear equations, circling the pivot positions in your augmented matrices as you work.

$$\begin{aligned} -x_1 + x_2 - 3x_3 + 2x_4 &= 0 \\ 2x_1 - x_2 + 5x_3 + 3x_4 &= -11 \\ 3x_1 + 2x_2 + 4x_3 + x_4 &= 1 \\ x_2 - x_3 + x_4 &= 1 \end{aligned}$$

Remember to find the solution set of the system by setting the free variable (the column without a pivot position) equal to a , and then express each of the other bounded variables equal to an expression in terms of a .

(Instructor Note:) The resulting RREF matrix is

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

Remark 5.6 From now on, unless specified, there's no need to show your work in finding $\text{RREF}(A)$, so you may use a calculator to speed up your work.

Activity 5.7 (10 min) Solve the linear system

$$\begin{aligned} 2x_1 - 3x_2 &= 17 \\ x_1 + 2x_2 &= -2 \\ -x_1 - x_2 &= 1 \end{aligned}$$

(Instructor Note:) This is an inconsistent solution. Point out to the students that one need not go all the way to RREF to discover a system is inconsistent.

Activity 5.8 (5 min) Show that all linear systems of the form

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

are consistent by finding a quickly verifiable solution.

Definition 5.9 A **homogeneous system** is a linear system satisfying $b_i = 0$, that is, it is a linear system of the form

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

Fact 5.10 Because the zero vector is always a solution, the solution set to any homogeneous system with infinitely-many solutions may be generated by multiplying the parameters representing the free variables by a minimal set of Euclidean vectors, and adding these up. For example:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = a \begin{bmatrix} 3 \\ 1 \\ -1 \\ 0 \end{bmatrix} + b \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Definition 5.11 A minimal set of Euclidean vectors generating the solution set to a homogeneous system is called a **basis** for the solution set of the homogeneous system. For example:

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = a \begin{bmatrix} 3 \\ 1 \\ -1 \\ 0 \end{bmatrix} + b \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \qquad \text{Basis} = \left\{ \begin{bmatrix} 3 \\ 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\}$$

Activity 5.12 (10 min) Find a basis for the solution set of the following homogeneous linear system.

$$\begin{array}{rcl} x_1 + 2x_2 & - & x_4 = 0 \\ & & x_3 + 4x_4 = 0 \\ 2x_1 + 4x_2 + x_3 + 2x_4 & = & 0 \end{array}$$

Standards for this Module

At the end of this module, students will be able to...

- **V1: Vector Spaces.** Determine if a set with given operations forms a vector space.
- **V2: Linear Combinations.** Determine if a vector can be written as a linear combination of a given set of vectors.
- **V3: Spanning Sets.** Determine if a set of vectors spans a vector space.
- **V4: Subspaces.** Determine if a subset of a vector space is a subset or not.

Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Add Euclidean vectors and multiply Euclidean vectors by scalars.
- Add complex numbers and multiply complex numbers by scalars.
- Add polynomials and multiply polynomials by scalars.
- Perform basic manipulations of augmented matrices and linear systems (**Standard(s) E1,E2,E3**).

Readiness Assurance Resources

The following resources will help you prepare for this module.

- <https://www.khanacademy.org/math/precalculus/vectors-prec calc/vector-addition-subtraction/v/adding-and-subtracting-vectors>
- <https://www.khanacademy.org/math/precalculus/vectors-prec calc/combined-vector-operations/v/combined-vector-operations-example>
- <https://www.khanacademy.org/math/precalculus/imaginary-and-complex-numbers/adding-and-subtracting-v/adding-complex-numbers>
- <https://www.khanacademy.org/math/algebra/introduction-to-polynomial-expressions/adding-and-subtracting-polynomials-1>

Readiness Assurance Test

Choose the most appropriate response for each question.

- 11) Simplify the following Euclidean vector expression.

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

(a) $\begin{bmatrix} 0 \\ 4 \\ -8 \end{bmatrix}$

(b) $\begin{bmatrix} 3 \\ 2 \\ -5 \end{bmatrix}$

(c) $\begin{bmatrix} 6 \\ -8 \\ -3 \end{bmatrix}$

(d) $\begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix}$

- 12) Simplify the following Euclidean vector expression.

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

(a) $\begin{bmatrix} 6 \\ -8 \\ -3 \end{bmatrix}$

(b) $\begin{bmatrix} 3 \\ 2 \\ -5 \end{bmatrix}$

(c) $\begin{bmatrix} 0 \\ 4 \\ -8 \end{bmatrix}$

(d) $\begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix}$

- 13) Simplify the complex number expression $-4(3 - 2i) + 2(5 + i)$.

(a) $-2 + 10i$

(b) $3 - 7i$

(c) $4 + i$

(d) $-1 - 5i$

- 14) Which of these complex numbers might be represented by the following Euclidean vector plotted on the complex plane (where the horizontal axis gives the real part and the vertical axis gives the imaginary part)?



(a) $5 + i$

(b) $-3 - 9i$

(c) $-2 + 3i$

(d) $4i$

- 15) Simplify $3f(x) - 2g(x)$ where $f(x) = 7 - x^2$ and $g(x) = 2x^3 + x - 1$.

(a) $-4x^3 - 3x^2 - 2x + 23$

(b) $x^3 + 4x - 5$

(c) $3x^3 + 5x^2 - 3x + 17$

(d) $-x^3 + 19x^2 - 4$

- 16) Express the following system of linear equations as an augmented matrix.

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

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

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

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

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

17) Which of the following matrices is equivalent to the following matrix?

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

(Hint: The correct answer was obtained from a single row operation.)

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

$$(b) \left[\begin{array}{ccc|c} 1 & 2 & 3 & -1 \\ 0 & 4 & -1 & 2 \\ 0 & -1 & -4 & 5 \end{array} \right]$$

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

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

18) Find RREF $\left[\begin{array}{cc|c} 1 & 2 & 3 \\ 0 & 4 & -1 \\ 2 & 3 & 2 \end{array} \right]$.

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

$$(b) \left[\begin{array}{cc|c} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{array} \right]$$

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

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

19) Solve the following system of linear equations.

$$\begin{aligned} 2x_1 + x_2 + 4x_3 &= 0 \\ x_1 + x_2 + x_3 &= 1 \\ -3x_1 + 4x_2 + x_3 &= -7 \end{aligned}$$

$$(a) \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 \\ -6 \\ 1 \end{bmatrix}$$

$$(c) \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 \\ -2 \\ 1 \end{bmatrix} + a \begin{bmatrix} 1 \\ 0 \\ 3 \end{bmatrix} \text{ for all real numbers } a$$

$$(b) \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ -1 \end{bmatrix}$$

(d) No solutions

20) Solve the following system of linear equations.

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

(a) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 4 \\ 1 \\ -5 \end{bmatrix}$

(b) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ -1 \end{bmatrix}$

(c) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = a \begin{bmatrix} -3 \\ 2 \\ 1 \end{bmatrix}$ for all real numbers a

(d) No solutions

Application Activities - Module V Part 1 - Class Day 7

Activity 7.1 (20 min) Consider each of the following vector properties. Label each property with \mathbb{R}^1 , \mathbb{R}^2 , and/or \mathbb{R}^3 if that property holds for Euclidean vectors/scalars $\mathbf{u}, \mathbf{v}, \mathbf{w}$ of that dimension.

1. **Addition associativity.**

$$\mathbf{u} + (\mathbf{v} + \mathbf{w}) = (\mathbf{u} + \mathbf{v}) + \mathbf{w}.$$

2. **Addition commutativity.**

$$\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}.$$

3. **Addition identity.**

There exists some $\mathbf{0}$ where $\mathbf{v} + \mathbf{0} = \mathbf{v}$.

4. **Addition inverse.**

There exists some $-\mathbf{v}$ where $\mathbf{v} + (-\mathbf{v}) = \mathbf{0}$.

5. **Addition midpoint uniqueness.**

There exists a unique \mathbf{m} where the distance from \mathbf{u} to \mathbf{m} equals the distance from \mathbf{m} to \mathbf{v} .

6. **Scalar multiplication associativity.**

$$a(b\mathbf{v}) = (ab)\mathbf{v}.$$

7. **Scalar multiplication identity.**

$$1\mathbf{v} = \mathbf{v}.$$

8. **Scalar multiplication relativity.**

There exists some scalar c where either $c\mathbf{v} = \mathbf{w}$ or $c\mathbf{w} = \mathbf{v}$.

9. **Scalar distribution.**

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

10. **Vector distribution.**

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

11. **Orthogonality.**

There exists a non-zero vector \mathbf{n} such that \mathbf{n} is orthogonal to both \mathbf{u} and \mathbf{v} .

12. **Bidimensionality.**

$$\mathbf{v} = a\mathbf{i} + b\mathbf{j} \text{ for some value of } a, b.$$

Definition 7.2 A **vector space** V is any collection of mathematical objects with associated addition and scalar multiplication operations that satisfy the following properties. Let $\mathbf{u}, \mathbf{v}, \mathbf{w}$ belong to V , and let a, b be scalar numbers.

• **Addition associativity.**

$$\mathbf{u} + (\mathbf{v} + \mathbf{w}) = (\mathbf{u} + \mathbf{v}) + \mathbf{w}.$$

• **Addition commutativity.**

$$\mathbf{u} + \mathbf{v} = \mathbf{v} + \mathbf{u}.$$

• **Addition identity.**

There exists some $\mathbf{0}$ where $\mathbf{v} + \mathbf{0} = \mathbf{v}$.

• **Addition inverse.**

There exists some $-\mathbf{v}$ where $\mathbf{v} + (-\mathbf{v}) = \mathbf{0}$.

• **Scalar multiplication associativity.**

$$a(b\mathbf{v}) = (ab)\mathbf{v}.$$

• **Scalar multiplication identity.**

$$1\mathbf{v} = \mathbf{v}.$$

• **Scalar distribution.**

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

• **Vector distribution.**

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

Definition 7.3 The most important examples of vector spaces are the **Euclidean vector spaces** \mathbb{R}^n , but there are other examples as well.

Activity 7.4 (25 min) Consider the following set that models motion along the curve $y = e^x$. Let $V = \{(x, y) : y = e^x\}$. Let vector addition be defined by $(x_1, y_1) \oplus (x_2, y_2) = (x_1 + x_2, y_1 y_2)$, and let scalar multiplication be defined by $c \odot (x, y) = (cx, y^c)$.

Part 1: Which of the vector space properties are satisfied by V paired with these operations?

- **Addition associativity.**

$$\mathbf{u} \oplus (\mathbf{v} \oplus \mathbf{w}) = (\mathbf{u} \oplus \mathbf{v}) \oplus \mathbf{w}.$$

- **Addition commutativity.**

$$\mathbf{u} \oplus \mathbf{v} = \mathbf{v} \oplus \mathbf{u}.$$

- **Addition identity.**

There exists some $\mathbf{0}$ where $\mathbf{v} \oplus \mathbf{0} = \mathbf{v}$.

- **Addition inverse.**

There exists some $-\mathbf{v}$ where $\mathbf{v} \oplus (-\mathbf{v}) = \mathbf{0}$.

- **Scalar multiplication associativity.**

$$a \odot (b \odot \mathbf{v}) = (ab) \odot \mathbf{v}.$$

- **Scalar multiplication identity.**

$$1 \odot \mathbf{v} = \mathbf{v}.$$

- **Scalar distribution.**

$$a \odot (\mathbf{u} \oplus \mathbf{v}) = (a \odot \mathbf{u}) \oplus (a \odot \mathbf{v}).$$

- **Vector distribution.**

$$(a + b) \odot \mathbf{v} = (a \odot \mathbf{v}) \oplus (b \odot \mathbf{v}).$$

Part 2: Is V a vector space?

Application Activities - Module V Part 2 - Class Day 8

Remark 8.1 The following sets are examples of vector spaces, with the usual/natural operations for addition and scalar multiplication.

- \mathbb{R}^n : Euclidean vectors with n components.
- \mathbb{R}^∞ : Sequences of real numbers (v_1, v_2, \dots) .
- $\mathbb{R}^{m \times n}$: Matrices of real numbers with m rows and n columns.
- \mathbb{C} : Complex numbers.
- \mathcal{P}^n : Polynomials of degree n or less.
- \mathcal{P} : Polynomials of any degree.
- $C(\mathbb{R})$: Real-valued continuous functions.

Activity 8.2 (10 min) Let $V = \{(a, b) : a, b \text{ are real numbers}\}$, where $(a_1, b_1) \oplus (a_2, b_2) = (a_1 + b_1 + a_2 + b_2, b_1^2 + b_2^2)$ and $c \odot (a, b) = (a^c, b + c)$. Show that this is not a vector space by finding a counterexample that does not satisfy one of the vector space properties.

- | | |
|---|--|
| <ul style="list-style-type: none"> • Addition associativity.
$\mathbf{u} \oplus (\mathbf{v} \oplus \mathbf{w}) = (\mathbf{u} \oplus \mathbf{v}) \oplus \mathbf{w}.$ • Addition commutativity.
$\mathbf{u} \oplus \mathbf{v} = \mathbf{v} \oplus \mathbf{u}.$ • Addition identity.
There exists some $\mathbf{0}$ where $\mathbf{v} \oplus \mathbf{0} = \mathbf{v}.$ • Addition inverse.
There exists some $-\mathbf{v}$ where $\mathbf{v} \oplus (-\mathbf{v}) = \mathbf{0}.$ | <ul style="list-style-type: none"> • Scalar multiplication associativity.
$a \odot (b \odot \mathbf{v}) = (ab) \odot \mathbf{v}.$ • Scalar multiplication identity.
$1 \odot \mathbf{v} = \mathbf{v}.$ • Scalar distribution.
$a \odot (\mathbf{u} \oplus \mathbf{v}) = (a \odot \mathbf{u}) \oplus (a \odot \mathbf{v}).$ • Vector distribution.
$(a + b) \odot \mathbf{v} = (a \odot \mathbf{v}) \oplus (b \odot \mathbf{v}).$ |
|---|--|

Definition 8.3 A **linear combination** of a set of vectors $\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_m\}$ is given by $c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \dots + c_m\mathbf{v}_m$ for any choice of scalar multiples c_1, c_2, \dots, c_m .

For example, we 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

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

Definition 8.4 The **span** of a set of vectors is the collection of all linear combinations of that set:

$$\text{span}\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_m\} = \{c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \dots + c_m\mathbf{v}_m : c_i \text{ is a real number}\}$$

Activity 8.5 (10 min) Consider $\text{span}\left\{\begin{bmatrix} 1 \\ 2 \end{bmatrix}\right\}$.

Part 1: Sketch $c\begin{bmatrix} 1 \\ 2 \end{bmatrix}$ in the xy plane for $c = 1, 3, 0, -2$.

Part 2: Sketch a representation of all the vectors given by $\text{span}\left\{\begin{bmatrix} 1 \\ 2 \end{bmatrix}\right\}$ in the xy plane.

Activity 8.6 (10 min) Consider $\text{span}\left\{\begin{bmatrix} 1 \\ 2 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix}\right\}$.

Part 1: Sketch the following linear combinations in the xy plane: $1\begin{bmatrix} 1 \\ 2 \end{bmatrix} + 0\begin{bmatrix} -1 \\ 1 \end{bmatrix}$, $0\begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1\begin{bmatrix} -1 \\ 1 \end{bmatrix}$, $2\begin{bmatrix} 1 \\ 2 \end{bmatrix} + 0\begin{bmatrix} -1 \\ 1 \end{bmatrix}$, $2\begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1\begin{bmatrix} -1 \\ 1 \end{bmatrix}$.

Part 2: Sketch a representation of all the vectors given by $\text{span}\left\{\begin{bmatrix} 1 \\ 2 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix}\right\}$ in the xy plane.

Activity 8.7 (5 min) Sketch a representation of all the vectors given by $\text{span}\left\{\begin{bmatrix} 6 \\ -4 \end{bmatrix}, \begin{bmatrix} -2 \\ 3 \end{bmatrix}\right\}$ in the xy plane.

Activity 8.8 (15 min) The 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 the vector equation

$$x_1\begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix} + x_2\begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix} = \begin{bmatrix} -1 \\ -6 \\ 1 \end{bmatrix} \text{ holds for some scalars } x_1, x_2.$$

Part 1: Reinterpret this vector equation as a system of linear equations.

Part 2: Solve this system. (Remember, you should use a calculator to help find RREF.)

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

Application Activities - Module V Part 3 - Class Day 9

Fact 9.1 A vector \mathbf{b} belongs to $\text{span}\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$ if and only if the linear system corresponding to $[\mathbf{v}_1 \dots \mathbf{v}_n \mid \mathbf{b}]$ is consistent.

Remark 9.2 To determine if \mathbf{b} belongs to $\text{span}\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$, find $\text{RREF}[\mathbf{v}_1 \dots \mathbf{v}_n \mid \mathbf{b}]$.

Activity 9.3 (5 min) Determine if $\begin{bmatrix} 3 \\ -2 \\ 1 \end{bmatrix}$ belongs to $\text{span}\left\{\begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix}\right\}$ by row-reducing an appropriate matrix.

Activity 9.4 (5 min) Determine if $\begin{bmatrix} -1 \\ -9 \\ 0 \end{bmatrix}$ belongs to $\text{span}\left\{\begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix}\right\}$ by row-reducing an appropriate matrix.

Observation 9.5 So far we've only discussed linear combinations of Euclidean vectors. Fortunately, many vector spaces of interest can be reinterpreted as an **isomorphic** Euclidean space \mathbb{R}^n ; that is, a Euclidean space that mirrors the behavior of the vector space exactly.

Activity 9.6 (5 min) We previously checked that $\begin{bmatrix} 3 \\ -2 \\ 1 \end{bmatrix}$ does not belong to $\text{span}\left\{\begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix}\right\}$. Does $f(x) = 3x^2 - 2x + 1$ belong to $\text{span}\{x^2 - 3, -x^2 - 3x + 2\}$?

Activity 9.7 (10 min) Does the matrix $\begin{bmatrix} 6 & 3 \\ 2 & -1 \end{bmatrix}$ belong to $\text{span}\left\{\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \begin{bmatrix} 4 & 3 \\ 2 & 1 \end{bmatrix}\right\}$?

Activity 9.8 (10 min) Does the complex number $2i$ belong to $\text{span}\{-3 + i, 6 - 2i\}$?

Activity 9.9 (10 min) How many vectors are required to span \mathbb{R}^2 ? Sketch a drawing in the xy plane to support your answer.

- (a) 1
 - (b) 2
 - (c) 3
 - (d) 4
 - (e) Infinitely Many
-

Activity 9.10 (*5 min*) How many vectors are required to span \mathbb{R}^3 ?

- (a) 1
 - (b) 2
 - (c) 3
 - (d) 4
 - (e) Infinitely Many
-

Application Activities - Module V Part 4 - Class Day 10

Fact 10.1 At least n vectors are required to span \mathbb{R}^n .



Activity 10.2 (10 min) Choose a vector $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$ in \mathbb{R}^3 that is not in $\text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix} \right\}$ by ensuring

$$\left[\begin{array}{cc|c} 1 & -2 & a \\ -1 & 0 & b \\ 0 & 1 & c \end{array} \right] \sim \left[\begin{array}{cc|c} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{array} \right]. \text{ (Why does this work?)}$$

Fact 10.3 The set $\{\mathbf{v}_1, \dots, \mathbf{v}_m\}$ fails to span all of \mathbb{R}^n exactly when $\text{RREF}[\mathbf{v}_1 \dots \mathbf{v}_m]$ has a row of zeros:

$$\left[\begin{array}{cc} 1 & -2 \\ -1 & 0 \\ 0 & 1 \end{array} \right] \sim \left[\begin{array}{cc} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{array} \right] \Rightarrow \left[\begin{array}{cc|c} 1 & -2 & a \\ -1 & 0 & b \\ 0 & 1 & c \end{array} \right] \sim \left[\begin{array}{cc|c} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{array} \right]$$

Activity 10.4 (5 min) Consider the set of vectors $S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ -4 \\ 3 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 0 \\ 3 \\ 5 \\ 7 \end{bmatrix}, \begin{bmatrix} 3 \\ 13 \\ 7 \\ 16 \end{bmatrix} \right\}$. Does $\mathbb{R}^4 = \text{span } S$?

Activity 10.5 (10 min) Consider the set of third-degree polynomials

$$S = \{2x^3 + 3x^2 - 1, 2x^3 + 3, 3x^3 + 13x^2 + 7x + 16, -x^3 + 10x^2 + 7x + 14, 4x^3 + 3x^2 + 2\}.$$

Does $\mathcal{P}^3 = \text{span } S$?

Definition 10.6 A subset of a vector space is called a **subspace** if it is itself a vector space.

Fact 10.7 If S is a subset of a vector space V , then $\text{span } S$ is a subspace of V .

Remark 10.8 To prove that a subset is a subspace, you need only verify that $c\mathbf{v} + d\mathbf{w}$ belongs to the subset for any choice of vectors \mathbf{v}, \mathbf{w} from the subset and any real scalars c, d .

Activity 10.9 (5 min) Prove that $P = \{ax^2 + b : a, b \text{ are both real numbers}\}$ is a subspace of the vector space of all degree-two polynomials by showing that $c(a_1x^2 + b_1) + d(a_2x^2 + b_2)$ belongs to P .

Activity 10.10 (10 min) Consider the subset of \mathbb{R}^2 where at least one coordinate of each vector is 0.



Find a linear combination $c\mathbf{v} + d\mathbf{w}$ that does not belong to this subset. **(Instructor Note:)** Use this [linear combination to sketch a picture illustrating why this subset is not a subspace](#).

Fact 10.11 Suppose a subset S of V is isomorphic to another vector space W . Then S is a subspace of V .

Activity 10.12 (5 min) Show that the set of 2×2 matrices

$$S = \left\{ \begin{bmatrix} a & b \\ -b & -a \end{bmatrix} : a, b \text{ are real numbers} \right\}$$

is a subspace of $\mathbb{R}^{2 \times 2}$ by identifying a Euclidean space isomorphic to S .

Standards for this Module

At the end of this module, students will be able to...

- **S1. Linear independence** Determine if a set of Euclidean vectors is linearly dependent or independent.
- **S2. Basis verification** Determine if a set of vectors is a basis of a vector space
- **S3. Basis construction** Construct a basis for the subspace spanned by a given set of vectors.
- **S4. Dimension** I can compute the dimension of a vector space.

Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Add Euclidean vectors and multiply Euclidean vectors by scalars.
- Perform basic manipulations of augmented matrices and linear systems (**Standard(s) E1,E2,E3**).
- Apply linear combinations and spanning sets (**Standard(s) V2,V3**).

Readiness Assurance Resources

The following resources will help you prepare for this module.

- <https://www.khanacademy.org/math/precalculus/vectors-prec calc/vector-addition-subtraction/v/adding-and-subtracting-vectors>
- <https://www.khanacademy.org/math/precalculus/vectors-prec calc/combined-vector-operations/v/combined-vector-operations-example>

Readiness Assurance Test

Choose the most appropriate response for each question.

21) Simplify the following Euclidean vector expression.

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

(a) $\begin{bmatrix} 1 \\ -2 \\ -4 \end{bmatrix}$

(b) $\begin{bmatrix} 0 \\ 2 \\ 0 \end{bmatrix}$

(c) $\begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}$

(d) $\begin{bmatrix} 2 \\ 4 \\ 6 \end{bmatrix}$

22) Express the following system of linear equations as an augmented matrix.

$$\begin{aligned} 2x_1 + x_2 + 4x_3 &= 0 \\ x_1 + x_2 + x_3 &= 1 \\ -3x_1 + 4x_2 + x_3 &= -7 \end{aligned}$$

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

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

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

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

23) Find RREF $\left[\begin{array}{cc|c} 1 & 2 & 3 \\ 3 & 2 & 5 \\ -2 & 0 & -2 \end{array} \right]$.

(a) $\left[\begin{array}{cc|c} 1 & 0 & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{array} \right]$

(b) $\left[\begin{array}{cc|c} 1 & 2 & 3 \\ 1 & 3 & 4 \\ 0 & 0 & 0 \end{array} \right]$

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

(d) $\left[\begin{array}{cc|c} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{array} \right]$

24) Solve the following system of linear equations.

$$\begin{aligned} 2x_1 + x_2 + 4x_3 &= 0 \\ x_1 + x_2 + x_3 &= 1 \\ -3x_1 + 4x_2 + x_3 &= -7 \end{aligned}$$

(a) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 \\ -6 \\ 1 \end{bmatrix}$

(c) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 2 \\ 0 \\ -1 \end{bmatrix}$

(b) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 1 \\ -2 \\ 1 \end{bmatrix} + a \begin{bmatrix} 1 \\ 0 \\ 3 \end{bmatrix}$ for all real numbers a

(d) No solutions

25) Solve the following system of linear equations.

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

(a) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ 0 \\ 1 \end{bmatrix}$

(c) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 4 \\ -5 \end{bmatrix} + a \begin{bmatrix} 0 \\ 3 \\ 1 \\ 1 \end{bmatrix}$ for all real numbers a

(b) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 12 \\ -8 \\ 0 \\ 0 \end{bmatrix} + a \begin{bmatrix} -3 \\ 2 \\ 1 \\ 0 \end{bmatrix} + b \begin{bmatrix} -2 \\ 1 \\ 0 \\ 1 \end{bmatrix}$
for all real numbers a, b

(d) No solutions

26) How many vectors are required to span all of \mathbb{R}^4 (the space of Euclidean vectors with four components)?

(a) 3

(b) 4

(c) 5

(d) Infinitely Many

27) How many vectors are required to span all of \mathcal{P}^3 (the space of polynomials of degree three or less)?

(a) 3

(b) 4

(c) 5

(d) Infinitely Many

28) Which vector is a linear combination of $\begin{bmatrix} -3 \\ 2 \\ 1 \\ 0 \end{bmatrix}$ and $\begin{bmatrix} -2 \\ 1 \\ 0 \\ 1 \end{bmatrix}$?

(a) $\begin{bmatrix} 1 \\ 2 \\ 4 \\ 0 \end{bmatrix}$

(b) $\begin{bmatrix} 0 \\ 0 \\ 3 \\ -7 \end{bmatrix}$

(c) $\begin{bmatrix} -5 \\ 3 \\ 1 \\ 1 \end{bmatrix}$

(d) $\begin{bmatrix} 2 \\ 2 \\ 0 \\ 1 \end{bmatrix}$

29) Which vector belongs to $\text{span} \left\{ \begin{bmatrix} -3 \\ 2 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 1 \\ 0 \\ 1 \end{bmatrix} \right\}$?

(a) $\begin{bmatrix} 3 \\ -7 \\ 1 \\ 1 \end{bmatrix}$

(b) $\begin{bmatrix} 4 \\ 1 \\ 2 \\ 3 \end{bmatrix}$

(c) $\begin{bmatrix} 0 \\ 1 \\ 2 \\ -3 \end{bmatrix}$

(d) $\begin{bmatrix} -1 \\ -1 \\ 0 \\ 0 \end{bmatrix}$

30) What best describes $\text{span} \left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \right\}$ in three-dimensional Euclidean space \mathbb{R}^3 ?

(a) a line

(b) a plane

(c) a sphere

(d) all of \mathbb{R}^3

Application Activities - Module S Part 1 - Class Day 12

Activity 12.1 (15 min) In the previous module, we considered

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

and showed that $\text{span } S \neq \mathbb{R}^4$. Find two vectors from this set that are linear combinations of the other three vectors.

(Instructor Note:) Actually, the activity involved the corresponding vectors in \mathcal{P}^3 .

Definition 12.2 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**.

Activity 12.3 (10 min) Suppose $3\mathbf{v}_1 - 5\mathbf{v}_2 = \mathbf{v}_3$, so the set $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3\}$ is linearly dependent. Is the vector equation $x_1\mathbf{v}_1 + x_2\mathbf{v}_2 + x_3\mathbf{v}_3 = \mathbf{0}$ consistent with one solution, consistent with infinitely many solutions, or inconsistent?

Fact 12.4 The set $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$ is linearly dependent if and only if $x_1\mathbf{v}_1 + \dots + x_n\mathbf{v}_n = \mathbf{0}$ is consistent with infinitely many solutions.

Activity 12.5 (10 min) Find

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

and mark the part of the matrix that demonstrates that

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

is linearly dependent.

Fact 12.6 A set of Euclidean vectors $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$ is linearly dependent if and only if $\text{RREF} [\mathbf{v}_1 \ \dots \ \mathbf{v}_n]$ has a column without a pivot position.

Activity 12.7 (5 min) Is the set of Euclidean vectors $\left\{ \begin{bmatrix} -4 \\ 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 1 \\ 10 \\ 10 \\ 2 \\ 6 \end{bmatrix}, \begin{bmatrix} 3 \\ 4 \\ 7 \\ 2 \\ 1 \end{bmatrix} \right\}$ linearly dependent or

linearly independent?

Activity 12.8 (*10 min*) Is the set of polynomials $\{x^3 + 1, x^2 + 2, 4 - 7x, 2x^3 + x\}$ linearly dependent or linearly independent?

Application Activities - Module S Part 2 - Class Day 13

Activity 13.1 (10 min) Last time we saw that $\{x^3 + 1, x^2 + 2, 4 - 7x, 2x^3 + x\}$ is linearly independent. Show that it spans \mathcal{P}^3 .

Definition 13.2 A **basis** is a linearly independent set that spans a vector space.

Observation 13.3 A basis may be thought of as a collection of building blocks for a vector space, since every vector in the space can be expressed as a unique linear combination of basis vectors.

Activity 13.4 (15 min) Which of the following sets are bases for \mathbb{R}^4 ?

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

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

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

Activity 13.5 (10 min) If $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \mathbf{v}_4\}$ is a basis for \mathbb{R}^4 , that means $\text{RREF}[\mathbf{v}_1 \ \mathbf{v}_2 \ \mathbf{v}_3 \ \mathbf{v}_4]$ doesn't have a column without a pivot position, and doesn't have a row of zeros. What is $\text{RREF}[\mathbf{v}_1 \ \mathbf{v}_2 \ \mathbf{v}_3 \ \mathbf{v}_4]$?

Fact 13.6 The set $\{\mathbf{v}_1, \dots, \mathbf{v}_m\}$ is a basis for \mathbb{R}^n if and only if $m = n$ and $\text{RREF}[\mathbf{v}_1 \ \dots \ \mathbf{v}_n] = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{bmatrix}$.

That is, a basis for \mathbb{R}^n must have exactly n vectors and its square matrix must row-reduce to the **identity matrix** containing all zeros except for a downward diagonal of ones.

Activity 13.7 (10 min) Consider the set $\left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix} \right\}$.

Part 1: Use $\text{RREF} \begin{bmatrix} 2 & 2 & 2 & 1 \\ 3 & 0 & -3 & 5 \\ 0 & 1 & 2 & -1 \\ 1 & -1 & -3 & 0 \end{bmatrix}$ to identify which vector may be removed to make the set linearly independent.

Part 2: Find a basis for $\text{span} \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix} \right\}$.

Application Activities - Module S Part 3 - Class Day 14

Fact 14.1 To compute a basis for the subspace $\text{span}\{\mathbf{v}_1, \dots, \mathbf{v}_m\}$, simply remove the vectors corresponding to the non-pivot columns of $\text{RREF}[\mathbf{v}_1 \dots \mathbf{v}_m]$.

Activity 14.2 (10 min) Find all subsets of $S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix} \right\}$ that are a basis for $\text{span } S$ by changing the order of the vectors in S .

Activity 14.3 (10 min) Assume $\mathbf{w}_1 \neq \mathbf{w}_2$ are distinct vectors in V , which has a basis containing a single vector: $\{\mathbf{v}\}$. Could $\{\mathbf{w}_1, \mathbf{w}_2\}$ be a basis?

Fact 14.4 All bases for a vector space are the same size.

Definition 14.5 The **dimension** of a vector space is given by the cardinality/size of any basis for the vector space.

Activity 14.6 (15 min) Find the dimension of each subspace of \mathbb{R}^4 .

$$\begin{aligned} \text{span} \left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\} & \quad \text{span} \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 2 \end{bmatrix}, \begin{bmatrix} -3 \\ 0 \\ 1 \\ 3 \end{bmatrix} \right\} \\ \text{span} \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ 13 \\ 7 \\ 16 \end{bmatrix}, \begin{bmatrix} -1 \\ 10 \\ 7 \\ 14 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 2 \end{bmatrix} \right\} & \quad \text{span} \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 4 \\ 3 \\ 0 \\ 2 \end{bmatrix}, \begin{bmatrix} -3 \\ 0 \\ 1 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ 6 \\ 1 \\ 5 \end{bmatrix} \right\} \\ \text{span} \left\{ \begin{bmatrix} 5 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} -2 \\ 1 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 4 \\ 5 \\ 1 \\ 3 \end{bmatrix} \right\} & \end{aligned}$$

Activity 14.7 (5 min) What is the dimension of the vector space of 7th-degree (or less) polynomials \mathcal{P}^7 ?

- a) 6 b) 7 c) 8 d) infinite
-

Activity 14.8 (5 min) What is the dimension of the vector space of all polynomials \mathcal{P} ?

a) 6

b) 7

c) 8

d) infinite

Observation 14.9 Several interesting vector spaces are infinite-dimensional:

- The space of polynomials \mathcal{P} (consider the set $\{1, x, x^2, x^3, \dots\}$).
- The space of continuous functions $C(\mathbb{R})$ (which contains all polynomials, in addition to other functions like $e^x = 1 + x + x^2/2 + x^3/3 + \dots$).
- The space of real number sequences \mathbb{R}^∞ (consider the set $\{(1, 0, 0, \dots), (0, 1, 0, \dots), (0, 0, 1, \dots), \dots\}$).

Fact 14.10 Every vector space with finite dimension, that is, every vector space with a basis of the form $\{\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n\}$ is isomorphic to a Euclidean space \mathbb{R}^n :

$$c_1 \mathbf{v}_1 + c_2 \mathbf{v}_2 + \dots + c_n \mathbf{v}_n \leftrightarrow \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix}$$

Standards for this Module

At the end of this module, students will be able to...

- **A1. Linear maps as matrices** I can write the standard matrix corresponding to a linear transformation between Euclidean spaces.
- **A2. Linear map verification** I can determine if a map between vector spaces is linear or not.
- **A3. Injectivity and Surjectivity** I can determine if a given linear map is injective and/or surjective
- **A4. Kernel and Image** I can compute the kernel and image of a linear map, including finding bases.

Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Solve a system of linear equations (including finding a basis of the solution space if it is homogeneous) by interpreting as an augmented matrix and row reducing (**Standard(s) E1, E2, E3, E4**).
- State the definition of a spanning set, and determine if a set of vectors spans a vector space or subspace (**Standard(s) V3**).
- State the definition of linear independence, and determine if a set of vectors is linearly dependent or independent (**Standard(s) S1**).
- State the definition of a basis, and determine if a set of vectors is a basis (**Standard(s) S2**).

Readiness Assurance Resources

The following resources will help you prepare for this module.

- Review the supporting Standards listed above.

Readiness Assurance Test

Choose the most appropriate response for each question.

- 31) Which of the following is a solution to the system of linear equations

$$\begin{aligned}x + 3y - z &= 2 \\ 2x + 8y + 3z &= -1 \\ -x - y + 9z &= -10\end{aligned}$$

(a) $\begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}$

(b) $\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}$

(c) $\begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$

(d) $\begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix}$

- 32) Find a basis for the solution set of the following homogeneous system of linear equations

$$\begin{aligned}x + 2y + -z - w &= 0 \\ -2x - 4y + 3z + 5w &= 0\end{aligned}$$

(a) $\left\{ \begin{bmatrix} 1 \\ 2 \\ 0 \\ 2 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 1 \\ 3 \end{bmatrix} \right\}$

(b) $\left\{ \begin{bmatrix} 2 \\ -1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 3 \\ -1 \end{bmatrix} \right\}$

(c) $\left\{ \begin{bmatrix} 2 \\ -1 \\ 3 \\ -1 \end{bmatrix} \right\}$

(d) $\left\{ \begin{bmatrix} 1 \\ 2 \\ 1 \\ 5 \end{bmatrix} \right\}$

- 33) Determine which property applies to the set of vectors

$$\left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \right\} \subset \mathbb{R}^3.$$

- (a) It does not span and is linearly dependent
- (b) It does not span and is linearly independent
- (c) It spans but it is linearly dependent
- (d) It is a basis of \mathbb{R}^3 .

- 34) Determine which property applies to the set of vectors

$$\left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 3 \end{bmatrix} \right\} \subset \mathbb{R}^3.$$

- (a) It does not span and is linearly dependent
- (b) It does not span and is linearly independent
- (c) It spans but it is linearly dependent
- (d) It is a basis of \mathbb{R}^3 .

35) Determine which property applies to the set of vectors

$$\left\{ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ -2 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 3 \\ 3 \\ -3 \end{bmatrix} \right\} \subset \mathbb{R}^3.$$

- (a) It does not span and is linearly dependent
- (b) It does not span and is linearly independent
- (c) It spans but it is linearly dependent
- (d) It is a basis of \mathbb{R}^3 .

36) Determine which property applies to the set of vectors

$$\left\{ \begin{bmatrix} 2 \\ 2 \\ -1 \end{bmatrix}, \begin{bmatrix} -3 \\ 1 \\ -2 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -4 \end{bmatrix} \right\} \subset \mathbb{R}^3.$$

- (a) It spans but it is linearly dependent
- (b) It is a basis of \mathbb{R}^3 .
- (c) It does not span and is linearly independent
- (d) It does not span and is linearly dependent

37) Suppose $\mathbf{v}_1, \dots, \mathbf{v}_n \in \mathbb{R}^5$ and you know that every vector in $\text{span}\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$ can be written uniquely as a linear combination of the vectors $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$. What can you conclude about n ?

- (a) $n \geq 5$
- (b) $n \leq 5$
- (c) $n = 5$
- (d) n could be any positive integer

38) Suppose you know that every vector in \mathbb{R}^5 can be written as a linear combination of the vectors $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$. What can you conclude about n ?

- (a) $n = 5$
- (b) n could be any positive integer
- (c) $n \leq 5$
- (d) $n \geq 5$

39) Suppose you know that every vector in \mathbb{R}^5 can be written uniquely as a linear combination of the vectors $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$. What can you conclude about n ?

- (a) n could be any positive integer
- (b) $n \leq 5$
- (c) $n \geq 5$
- (d) $n = 5$

- 40) Suppose you know that every vector in \mathbb{R}^5 can be written uniquely as a linear combination of the vectors $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$. What can you conclude about the set $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$?
- (a) It does not span and is linearly dependent
 - (b) It does not span and is linearly independent
 - (c) It is a basis of \mathbb{R}^5 .
 - (d) It spans but it is linearly dependent

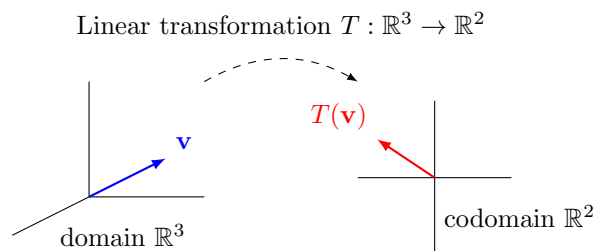
Application Activities - Module A Part 1 - Class Day 17

Definition 17.1 A **linear transformation** 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. $T(\mathbf{v} + \mathbf{w}) = T(\mathbf{v}) + T(\mathbf{w})$ for any $\mathbf{v}, \mathbf{w} \in V$
2. $T(c\mathbf{v}) = cT(\mathbf{v})$ for any $c \in \mathbb{R}, \mathbf{v} \in V$.

In other words, a map is linear if one can do vector space operations before applying the map or after, and obtain the same answer.

Definition 17.2 Given a linear transformation $T : V \rightarrow W$, V is called the **domain** of T and W is called the **co-domain** of T .



Example 17.3 Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by

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

To show that T is linear, we must verify...

$$\begin{aligned} T \left(\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} + \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} \right) &= T \left(\begin{bmatrix} x_1 + x_2 \\ y_1 + y_2 \\ z_1 + z_2 \end{bmatrix} \right) = \begin{bmatrix} (x_1 + x_2) - (z_1 + z_2) \\ (y_1 + y_2) \end{bmatrix} \\ T \left(\begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix} \right) + T \left(\begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} \right) &= \begin{bmatrix} x_1 - z_1 \\ y_1 \end{bmatrix} + \begin{bmatrix} x_2 - z_2 \\ y_2 \end{bmatrix} = \begin{bmatrix} (x_1 + x_2) - (z_1 + z_2) \\ (y_1 + y_2) \end{bmatrix} \end{aligned}$$

And also...

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

Therefore T is a linear transformation.

Activity 17.4 (15 min) Determine if each of the following maps are linear transformations

Part 1: $T_1 : \mathbb{R}^2 \rightarrow \mathbb{R}$ given by $T_1 \left(\begin{bmatrix} x \\ y \end{bmatrix} \right) = \sqrt{x^2 + y^2}$.

Part 2: $T_2 : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ given by $T_2 \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} -x \\ -y \\ -z \end{bmatrix}$

Part 3: $T_3 : \mathcal{P}^d \rightarrow \mathcal{P}^{d-1}$ given by $T_3(f(x)) = f'(x)$.

Part 4: $T_4 : \mathcal{P} \rightarrow \mathcal{P}$ given by $T_4(f(x)) = f(x) + x^2$

Activity 17.5 (5 min) Suppose $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ is a linear transformation, and you know $T \left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$

and $T \left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$. Compute $T \left(\begin{bmatrix} 3 \\ 0 \\ 0 \end{bmatrix} \right)$.

(a) $\begin{bmatrix} 6 \\ 3 \end{bmatrix}$

(c) $\begin{bmatrix} -4 \\ -2 \end{bmatrix}$

(b) $\begin{bmatrix} -9 \\ 6 \end{bmatrix}$

(d) $\begin{bmatrix} 6 \\ -4 \end{bmatrix}$

Activity 17.6 (3 min) Suppose $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ is a linear transformation, and you know $T \left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$

and $T \left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$. Compute $T \left(\begin{bmatrix} 0 \\ 0 \\ -2 \end{bmatrix} \right)$.

(a) $\begin{bmatrix} 6 \\ 3 \end{bmatrix}$

(c) $\begin{bmatrix} -4 \\ -2 \end{bmatrix}$

(b) $\begin{bmatrix} -9 \\ 6 \end{bmatrix}$

(d) $\begin{bmatrix} 6 \\ -4 \end{bmatrix}$

Activity 17.7 (5 min) Suppose $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ is a linear transformation, and you know $T \left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$

and $T \left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$. Compute $T \left(\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \right)$.

(a) $\begin{bmatrix} 2 \\ 1 \end{bmatrix}$

(c) $\begin{bmatrix} -1 \\ 3 \end{bmatrix}$

(b) $\begin{bmatrix} 3 \\ -1 \end{bmatrix}$

(d) $\begin{bmatrix} 5 \\ -8 \end{bmatrix}$

Activity 17.8 (2 min) Suppose $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ is a linear transformation, and you know $T \left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$ and $T \left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$. Compute $T \left(\begin{bmatrix} -2 \\ 0 \\ -3 \end{bmatrix} \right)$.

(a) $\begin{bmatrix} 2 \\ 1 \end{bmatrix}$

(c) $\begin{bmatrix} -1 \\ 3 \end{bmatrix}$

(b) $\begin{bmatrix} 3 \\ -1 \end{bmatrix}$

(d) $\begin{bmatrix} 5 \\ -8 \end{bmatrix}$

Activity 17.9 (5 min) Suppose $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$ is a linear transformation. How many facts of the form $T(\mathbf{v}_i) = \mathbf{w}_i$ do you need to know in order to be able to compute $T(\mathbf{v})$ for *any* $\mathbf{v} \in \mathbb{R}^4$?

(a) 2

(b) 3

(c) 4

(d) 5

(e) You need infinitely many

(In this situation, we say that the vectors $\{\mathbf{v}_1, \dots, \mathbf{v}_n\}$ **determine** T .)

Fact 17.10 Consider any basis $\{\mathbf{b}_1, \dots, \mathbf{b}_n\}$ for V . Since every vector can be written *uniquely* as a linear combination of basis vectors, every linear transformation $T : V \rightarrow W$ is determined by those basis vectors.

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

Definition 17.11 The **standard basis** of \mathbb{R}^n is the (ordered) basis $\{\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_n\}$ where

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

Since linear transformation $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ is determined by the values of each $T(\mathbf{e}_i)$, it's convenient to store this information in the $m \times n$ **standard matrix** $[T(\mathbf{e}_1) \cdots T(\mathbf{e}_n)]$.

Example 17.12 Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be the linear transformation determined by the following values for T applied to the standard basis of \mathbb{R}^3 .

$$T \left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right) = \begin{bmatrix} 3 \\ 2 \end{bmatrix} \qquad T \left(\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \right) = \begin{bmatrix} -1 \\ 4 \end{bmatrix} \qquad T \left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} 5 \\ 0 \end{bmatrix}$$

Then the standard matrix corresponding to T is

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

Activity 17.13 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be the linear transformation given by

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

Write the matrix corresponding to this linear transformation with respect to the standard basis.

Activity 17.14 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be the linear transformation given by the standard matrix

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

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

Activity 17.15 (10 min) Let $D : \mathcal{P}^3 \rightarrow \mathcal{P}^2$ be the derivative map $D(f(x)) = f'(x)$. (Earlier we showed this is a linear transformation.)

Part 1: Write down an equivalent linear transformation $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$ by converting $\{1, x, x^2, x^3\}$ and $\{D(1), D(x), D(x^2), D(x^3)\}$ into appropriate vectors in \mathbb{R}^4 and \mathbb{R}^3 .

Part 2: Write the standard matrix corresponding to T .

Application Activities - Module A Part 2 - Class Day 18

Definition 18.1 Let $T : V \rightarrow W$ be a linear transformation. T is called **injective** or **one-to-one** if T does not map two distinct values to the same place. More precisely, T is injective if $T(\mathbf{v}) \neq T(\mathbf{w})$ whenever $\mathbf{v} \neq \mathbf{w}$.

Activity 18.2 (5 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by

$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix}.$$

The standard matrix of T is thus $\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$.

Is T injective?

Activity 18.3 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by

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

The standard matrix of T is thus $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$.

Is T injective?

Definition 18.4 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 $\mathbf{w} \in W$, there is some $\mathbf{v} \in V$ with $T(\mathbf{v}) = \mathbf{w}$.

Activity 18.5 (5 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by

$$T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} x \\ y \\ 0 \end{bmatrix}.$$

The standard matrix of T is thus $\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$.

Is T surjective?

Activity 18.6 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by

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

The standard matrix of T is thus $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$.

Is T surjective?

Definition 18.7 Let $T : V \rightarrow W$ be a linear transformation. The **kernel** of T is an important subspace of V defined by

$$\ker T = \{\mathbf{v} \in V \mid T(\mathbf{v}) = \mathbf{0}\}$$

Activity 18.8 (5 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the standard matrix $\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$. Find the kernel of T .

Activity 18.9 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the standard matrix $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$. Find the kernel of T .

Activity 18.10 (10 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be the linear transformation given by the standard matrix $A = \begin{bmatrix} 3 & 4 & -1 \\ 1 & 2 & 1 \end{bmatrix}$.

Part 1: Write a system of equations whose solution set is the kernel.

Part 2: Use RREF(A) to solve the system of equations and find the kernel of T .

Part 3: Find a basis for the kernel of T .

Definition 18.11 Let $T : V \rightarrow W$ be a linear transformation. The **image** of T is an important subspace of W defined by

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

Activity 18.12 (5 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the standard matrix $\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$. Find the image of T .

Activity 18.13 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the standard matrix $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$. Find the image of T .

Activity 18.14 (10 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be the linear transformation given by the standard matrix $A = \begin{bmatrix} 3 & 4 & -1 \\ 1 & 2 & 1 \end{bmatrix}$.

Part 1: Find a convenient set of vectors $S \subseteq \mathbb{R}^2$ such that $\operatorname{span} S = \operatorname{Im} T$.

Part 2: Find a convenient basis for the image of T .

Observation 18.15 Let $T : V \rightarrow W$ be a linear transformation with corresponding matrix A .

- If A is a matrix corresponding to T , the kernel is the solution set of the homogeneous system with coefficients given by A .
 - If A is a matrix corresponding to T , the image is the span of the columns of A .
-

Application Activities - Module A Part 3 - Class Day 19

Observation 19.1 Let $T : V \rightarrow W$. We have previously defined the following terms.

- T is called **injective** or **one-to-one** if T does not map two distinct values to the same place.
- T is called **surjective** or **onto** if every element of W is mapped to by some element of V .
- The **kernel** of T is the set of all things that are mapped to $\mathbf{0}$. It is a subspace of V .
- The **image** of T is the set of all things in W that are mapped to by something in V . It is a subspace of W .

Activity 19.2 (5 min) Let $T : V \rightarrow W$ be a linear transformation where $\ker T = \{\mathbf{0}\}$. Can you answer either of the following questions about T ?

(a) Is T injective?

(b) Is T surjective?

(Hint: If $T(\mathbf{v}) = T(\mathbf{w})$, then what is $T(\mathbf{v} - \mathbf{w})$?)

Fact 19.3 A linear transformation T is injective **if and only if** $\ker T = \{\mathbf{0}\}$. Put another way, an injective linear transformation may be recognized by its **trivial** kernel.

Activity 19.4 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be a linear transformation where $\text{Im } T = \text{span} \left\{ \begin{bmatrix} 1 \\ 0 \\ 3 \end{bmatrix}, \begin{bmatrix} 3 \\ -1 \\ -1 \end{bmatrix} \right\}$.

Can you answer either of the following questions about T ?

(a) Is T injective?

(b) Is T surjective?

Fact 19.5 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 same codomain and image.

Activity 19.6 (15 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with standard matrix A . Sort the following claims into two groups of equivalent statements.

- | | |
|---|---|
| (a) T is injective | (g) Every row of $\text{RREF}(A)$ has a pivot. |
| (b) T is surjective | (h) The image of T equals its codomain. |
| (c) The kernel of T is trivial. | (i) The system of linear equations given by the augmented matrix $[A \mid \mathbf{b}]$ has a solution for all $\mathbf{b} \in \mathbb{R}^m$ |
| (d) The columns of A span \mathbb{R}^m | (j) The system of linear equations given by the augmented matrix $[A \mid \mathbf{0}]$ has exactly one solution. |
| (e) The columns of A are linearly independent | |
| (f) Every column of $\text{RREF}(A)$ has a pivot. | |
-

(Instructor Note:) This activity may be ran as a card sort.

Definition 19.7 If $T : V \rightarrow W$ is both injective and surjective, it is called **bijjective**.

Activity 19.8 (5 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a bijective linear map with standard matrix A . Label each of the following as true or false.

- (a) The columns of A form a basis for \mathbb{R}^m
 - (b) $\text{RREF}(A)$ is the identity matrix.
 - (c) The system of linear equations given by the augmented matrix $[A \mid \mathbf{b}]$ has exactly one solution for all $\mathbf{b} \in \mathbb{R}^m$.
-

Activity 19.9 (10 min) 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
 - (b) T is injective but not surjective
 - (c) T is surjective but not injective
 - (d) T is bijective.
-

Activity 19.10 (5 min) 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
 - (b) T is injective but not surjective
 - (c) T is surjective but not injective
 - (d) T is bijective.
-

Activity 19.11 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be given by

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

Which of the following must be true?

- (a) T is neither injective nor surjective
 - (b) T is injective but not surjective
 - (c) T is surjective but not injective
 - (d) T is bijective.
-

Activity 19.12 (5 min) 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
 - (b) T is injective but not surjective
 - (c) T is surjective but not injective
 - (d) T is bijective.
-

Standards for this Module

At the end of this module, students will be able to...

- **M1. Matrix multiplication** Multiply matrices.
- **M2. Invertible matrices** Determine if a square matrix is invertible or not.
- **M3. Matrix inverses** Compute the inverse matrix of an invertible matrix.

Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Compose functions of real numbers
- Solve systems of linear equations (**Standard(s) E3**)
- Find the matrix corresponding to a linear transformation (**Standard(s) A1**)
- Determine if a linear transformation is injective and/or surjective (**Standard(s) A3**)
- Interpret the ideas of injectivity and surjectivity in multiple ways

Readiness Assurance Resources

The following resources will help you prepare for this module.

- <https://www.khanacademy.org/math/algebra2/manipulating-functions/function-composition/v/function-composition>

Readiness Assurance Test

Choose the most appropriate response for each question.

- 41) Suppose $f(x)$ and $g(x)$ are real-valued functions satisfying

$$\begin{array}{ll} f(2) = 4 & g(2) = 4 \\ f(3) = 5 & g(3) = 5 \\ f(4) = 3 & g(4) = 2 \end{array}$$

Compute $(f \circ g)(2)$.

- (a) 2 (b) 3 (c) 4 (d) 5

- 42) Let $f(x) = x^2 - 2$ and $g(x) = x^2 + 1$. Compute the composition function $(f \circ g)(x)$.

- (a) $x^2 - 1$ (b) $x^4 + 2x^2 - 1$ (c) $x^4 - 4x^2 + 5$ (d) $x^4 - x^2 - 2$

- 43) Solve the system of linear equations

$$\begin{array}{l} x + 3y = -2 \\ 2x - 7y = 9 \end{array}$$

- (a) $\begin{bmatrix} -2 \\ 9 \end{bmatrix}$ (b) $\begin{bmatrix} 2 \\ 3 \end{bmatrix}$ (c) $\begin{bmatrix} 1 \\ -1 \end{bmatrix}$ (d) $\begin{bmatrix} 3 \\ 1 \end{bmatrix}$

- 44) Let a, b, c be fixed real numbers. How many solutions does the system of linear equations below have?

$$\begin{array}{l} x + 2y + 3z = a \\ y - z = b \\ y + z = c \end{array}$$

- (a) 0 (b) 1 (c) Infinitely many (d) It depends on the values of a, b , and c .

- 45) What is the standard matrix corresponding to the linear transformation $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ given by $T \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) =$

$$\begin{bmatrix} x + 2y - z \\ y + 3z \\ x + 7y \end{bmatrix} ?$$

- (a) $\begin{bmatrix} 1 & 2 & -1 \\ 1 & 3 & 0 \\ 1 & 7 & 0 \end{bmatrix}$ (b) $\begin{bmatrix} 1 & 1 & 1 \\ 2 & 3 & 7 \\ -1 & 0 & 0 \end{bmatrix}$ (c) $\begin{bmatrix} 1 & 2 & -1 \\ 0 & 1 & 3 \\ 1 & 7 & 0 \end{bmatrix}$ (d) $\begin{bmatrix} 1 & 0 & 1 \\ 2 & 1 & 7 \\ -1 & 3 & 0 \end{bmatrix}$

46) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be the linear transformation with standard matrix $A = \begin{bmatrix} 2 & 3 \\ -1 & -1 \\ 0 & 4 \end{bmatrix}$. Compute

$$T\left(\begin{bmatrix} 2 \\ -1 \end{bmatrix}\right).$$

(a) $\begin{bmatrix} 1 \\ -1 \\ -4 \end{bmatrix}$

(b) $\begin{bmatrix} 2 \\ -1 \\ 0 \end{bmatrix}$

(c) $\begin{bmatrix} 5 \\ 7 \\ 4 \end{bmatrix}$

(d) $\begin{bmatrix} 4 \\ -1 \\ 8 \end{bmatrix}$

47) Which of the following is true of the linear transformation $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ given by

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

- (a) T is neither injective nor surjective
- (b) T is injective but not surjective
- (c) T is surjective but not injective
- (d) T is both injective and surjective

48) Which of the following is true of the linear transformation $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ given by

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

- (a) T is surjective but not injective
- (b) T is injective but not surjective
- (c) T is both injective and surjective
- (d) T is neither injective nor surjective

49) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear transformation with standard matrix A . Which of the following is **not** a characterization of the statement “ T is injective”?

- (a) If $T(\mathbf{v}) = T(\mathbf{w})$ for some $\mathbf{v}, \mathbf{w} \in \mathbb{R}^n$, then $\mathbf{v} = \mathbf{w}$.
- (b) The columns of A are linearly independent
- (c) T has a non-trivial kernel
- (d) $\text{RREF}(A)$ has only pivot columns

50) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear transformation with standard matrix A . Which of the following is **not** a characterization of the statement “ T is surjective”?

- (a) $\text{RREF}(A)$ has a pivot in every row
- (b) $\text{RREF}(A)$ has has a pivot in every column
- (c) $\text{Im } T = \mathbb{R}^m$
- (d) The columns of A span \mathbb{R}^m

Application Activities - Module M Part 1 - Class Day 21

Activity 21.1 (5 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the standard matrix $B = \begin{bmatrix} 2 & 1 & -3 \\ 5 & -3 & 4 \end{bmatrix}$ and $S : \mathbb{R}^2 \rightarrow \mathbb{R}^4$ be given by the standard matrix $A = \begin{bmatrix} 1 & 2 \\ 0 & 1 \\ 3 & 5 \\ -1 & -2 \end{bmatrix}$.

What is the domain of the composition map $S \circ T$?

- (a) \mathbb{R}
 - (b) \mathbb{R}^2
 - (c) \mathbb{R}^3
 - (d) \mathbb{R}^4
-

Activity 21.2 (2 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the standard matrix $B = \begin{bmatrix} 2 & 1 & -3 \\ 5 & -3 & 4 \end{bmatrix}$ and $S : \mathbb{R}^2 \rightarrow \mathbb{R}^4$ be given by the standard matrix $A = \begin{bmatrix} 1 & 2 \\ 0 & 1 \\ 3 & 5 \\ -1 & -2 \end{bmatrix}$.

What is the codomain of the composition map $S \circ T$?

- (a) \mathbb{R}
 - (b) \mathbb{R}^2
 - (c) \mathbb{R}^3
 - (d) \mathbb{R}^4
-

Activity 21.3 (2 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the standard matrix $B = \begin{bmatrix} 2 & 1 & -3 \\ 5 & -3 & 4 \end{bmatrix}$ and $S : \mathbb{R}^2 \rightarrow \mathbb{R}^4$ be given by the standard matrix $A = \begin{bmatrix} 1 & 2 \\ 0 & 1 \\ 3 & 5 \\ -1 & -2 \end{bmatrix}$.

The standard matrix of $S \circ T$ will lie in which matrix space?

- (a) 4×3 matrices
 - (b) 4×2 matrices
 - (c) 3×2 matrices
 - (d) 2×3 matrices
-

(e) 2×4 matrices

(f) 3×4 matrices

Activity 21.4 (15 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the standard matrix $B = \begin{bmatrix} 2 & 1 & -3 \\ 5 & -3 & 4 \end{bmatrix}$ and

$S : \mathbb{R}^2 \rightarrow \mathbb{R}^4$ be given by the standard matrix $A = \begin{bmatrix} 1 & 2 \\ 0 & 1 \\ 3 & 5 \\ -1 & -2 \end{bmatrix}$.

Part 1: Compute $(S \circ T)(\mathbf{e}_1)$

Part 2: Compute $(S \circ T)(\mathbf{e}_2)$

Part 3: Compute $(S \circ T)(\mathbf{e}_3)$.

Part 4: Find the standard matrix of $S \circ T$.

Activity 21.5 (2 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the matrix $B = \begin{bmatrix} 2 & 3 \\ 1 & -1 \\ 0 & -1 \end{bmatrix}$ and $S : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given

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

What is the domain of the composition map $S \circ T$?

(a) \mathbb{R}

(b) \mathbb{R}^2

(c) \mathbb{R}^3

(d) \mathbb{R}^4

Activity 21.6 (2 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the matrix $B = \begin{bmatrix} 2 & 3 \\ 1 & -1 \\ 0 & -1 \end{bmatrix}$ and $S : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given

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

What is the codomain of the composition map $S \circ T$?

(a) \mathbb{R}

(b) \mathbb{R}^2

(c) \mathbb{R}^3

(d) \mathbb{R}^4

Activity 21.7 (2 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the matrix $B = \begin{bmatrix} 2 & 3 \\ 1 & -1 \\ 0 & -1 \end{bmatrix}$ and $S : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given

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

The standard matrix of $S \circ T$ will lie in which matrix space?

- (a) 2×2 matrices
 - (b) 2×3 matrices
 - (c) 3×2 matrices
 - (d) 3×3 matrices
-

Activity 21.8 (10 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the matrix $B = \begin{bmatrix} 2 & 3 \\ 1 & -1 \\ 0 & -1 \end{bmatrix}$ and $S : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given

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

Find the standard matrix of $S \circ T$.

Activity 21.9 (5 min) Let $T : \mathbb{R}^1 \rightarrow \mathbb{R}^4$ be given by the matrix $B = \begin{bmatrix} 3 \\ -2 \\ 1 \\ -1 \end{bmatrix}$ and $S : \mathbb{R}^4 \rightarrow \mathbb{R}^1$ be given by

the matrix $A = \begin{bmatrix} 2 & 3 & 2 & 5 \end{bmatrix}$.

Find the standard matrix of $S \circ T$.

Definition 21.10 We define the product of a $m \times n$ matrix A and a $n \times k$ matrix B to be the $m \times k$ standard matrix (denoted AB) of the composition map of the two corresponding linear functions.

Fact 21.11 If AB is defined, BA need not be defined, and if it is defined, it is in general different from AB .

Activity 21.12 (10 min) Let $A = \begin{bmatrix} 3 & 1 & -1 \\ 2 & 0 & 4 \end{bmatrix}$ and $B = \begin{bmatrix} a & b \\ c & d \\ e & f \end{bmatrix}$. Compute AB .

Activity 21.13 (5 min) Let $A = \begin{bmatrix} 3 & 1 & -1 \\ 2 & 0 & 4 \\ -1 & 3 & 5 \end{bmatrix}$ and $X = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$. Compute AX

Observation 21.14 Consider the system of equations

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

We can interpret this as a **matrix equation** $AX = B$ where

$$A = \begin{bmatrix} 3 & 1 & -1 \\ 2 & 0 & 4 \\ -1 & 3 & 5 \end{bmatrix} \quad X = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad B = \begin{bmatrix} 5 \\ -7 \\ 2 \end{bmatrix}$$

For this reason, we will swap out the use of Euclidean vectors $\mathbf{x} \in \mathbb{R}^n$ and $n \times 1$ matrices X whenever it is convenient.

Application Activities - Module M Part 2 - Class Day 22

Activity 22.1 (5 min) Let $A = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$. Find a 3×3 matrix I such that $IA = A$, that is,

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$$

Definition 22.2 The identity matrix I_n (or just I when n is obvious from context) is the $n \times n$ matrix

$$I_n = \begin{bmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \dots & 0 & 1 \end{bmatrix}.$$

It has a 1 on each diagonal element and a 0 in every other position.

Fact 22.3 For any square matrix A , $IA = AI = A$:

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

Activity 22.4 (15 min) Each row operation can be interpreted as a type of matrix multiplication.

Part 1: Tweak the identity matrix slightly to create a matrix that doubles the third row of A :

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 2 & 2 & -2 \end{bmatrix}$$

Part 2: Create a matrix that swaps the second and third rows of A :

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2 & 7 & -1 \\ 1 & 1 & -1 \\ 0 & 3 & 2 \end{bmatrix}$$

Part 3: Create a matrix that adds 5 times the third row of A to the first row:

$$\begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix} = \begin{bmatrix} 2+5 & 7+5 & -1-5 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$$

Fact 22.5 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 .

This means that for any matrix A , we can find a series of matrices R_1, \dots, R_k corresponding to the row operations such that

$$R_1 R_2 \cdots R_k A = \text{RREF}(A).$$

That is, row reduction can be thought of as the result of matrix multiplication.

Activity 22.6 (15 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with standard matrix A . Sort the following items into groups of statements about T .

- | | |
|--|--|
| (a) T is injective (i.e. one-to-one) | (g) The columns of A span \mathbb{R}^m |
| (b) T is surjective (i.e. onto) | (h) The columns of A are linearly independent |
| (c) T is bijective (i.e. both injective and surjective) | (i) The columns of A are a basis of \mathbb{R}^m |
| (d) $AX = B$ has a solution for all $m \times 1$ matrices B | (j) Every column of $\text{RREF}(A)$ has a pivot |
| (e) $AX = B$ has a unique solution for all $m \times 1$ matrices B | (k) Every row of $\text{RREF}(A)$ has a pivot |
| (f) $AX = 0$ has a unique solution. | (l) $m = n$ and $\text{RREF}(A) = I$ |
-

Activity 22.7 (5 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with matrix A . If T is injective, which of the following cannot be true?

- (a) A has strictly more columns than rows
 - (b) A has the same number of rows as columns (i.e. A is square)
 - (c) A has strictly more rows than columns
-

Activity 22.8 (5 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with matrix A . If T is surjective, which of the following cannot be true?

- (a) A has strictly more columns than rows
 - (b) A has the same number of rows as columns (i.e. A is square)
 - (c) A has strictly more rows than columns
-

Activity 22.9 (5 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with matrix A . If T is bijective, which of the following cannot be true?

- (a) A has strictly more columns than rows
 - (b) A has the same number of rows as columns (i.e. A is square)
 - (c) A has strictly more rows than columns
-

Application Activities - Module M Part 3 - Class Day 23

Definition 23.1 Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$ be a linear map with standard matrix A .

- If T is a bijection and B is any \mathbb{R}^n vector, then $T(X) = AX = B$ has a unique solution X .
- So we may define an **inverse map** $T^{-1} : \mathbb{R}^n \rightarrow \mathbb{R}^n$ by setting $T^{-1}(B) = X$ 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**.

Activity 23.2 (10 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ be the bijective linear map defined by $T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} 2x - 3y \\ -3x + 5y \end{bmatrix}$.

It can be shown that T is bijective and has the inverse map $T^{-1}\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} 5x + 3y \\ 3x + 2y \end{bmatrix}$.

Part 1: Compute $(T^{-1} \circ T)\left(\begin{bmatrix} -2 \\ 1 \end{bmatrix}\right)$.

Part 2: If A is the standard matrix for T and A^{-1} is the standard matrix for T^{-1} , what must $A^{-1}A$ be?

Observation 23.3 $T^{-1} \circ T = T \circ T^{-1}$ is the identity map for any bijective linear transformation T . Therefore $A^{-1}A = AA^{-1} = I$ is the identity matrix for any invertible matrix A .

Activity 23.4 (20 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be given by the matrix $A = \begin{bmatrix} 2 & -1 & -6 \\ 2 & 1 & 3 \\ 1 & 1 & 4 \end{bmatrix}$.

Part 1: Solve $T(X) = \mathbf{e}_1$ to find $T^{-1}(\mathbf{e}_1)$.

Part 2: Solve $T(X) = \mathbf{e}_2$ to find $T^{-1}(\mathbf{e}_2)$.

Part 3: Solve $T(X) = \mathbf{e}_3$ to find $T^{-1}(\mathbf{e}_3)$.

Part 4: Compute A^{-1} , the standard matrix for T^{-1} .

Observation 23.5 We could have solved these three systems simultaneously by row reducing the matrix $[A | I]$ at once.

$$A = \left[\begin{array}{ccc|ccc} 2 & -1 & -6 & 1 & 0 & 0 \\ 2 & 1 & 3 & 0 & 1 & 0 \\ 1 & 1 & 4 & 0 & 0 & 1 \end{array} \right] \sim \left[\begin{array}{ccc|ccc} 1 & 0 & 0 & 1 & -2 & 3 \\ 0 & 1 & 0 & -5 & 14 & -18 \\ 0 & 0 & 1 & 1 & -3 & 4 \end{array} \right]$$

Activity 23.6 (10 min) Find the inverse A^{-1} of the matrix $A = \begin{bmatrix} 1 & 3 \\ 0 & -2 \end{bmatrix}$ by row-reducing $[A | I]$.

Activity 23.7 (10 min) Is the matrix $\begin{bmatrix} 2 & 3 & 1 \\ -1 & -4 & 2 \\ 0 & -5 & 5 \end{bmatrix}$ invertible? Give a reason for your answer.

Observation 23.8 A matrix $A \in \mathbb{R}^{n \times n}$ is invertible if and only if $\text{RREF}(A) = I_n$.

Standards for this Module

At the end of this module, students will be able to...

- **G1. Determinants** Compute the determinant of a square matrix.
- **G2. Eigenvalues** Find the eigenvalues of a square matrix, along with their algebraic multiplicities.
- **G3. Eigenvectors** Find the eigenspace of a square matrix associated to a given eigenvalue.
- **G4. Geometric multiplicity** Compute the geometric multiplicity of an eigenvalue of a square matrix.

Readiness Assurance Outcomes

Before beginning this module, each student should be able to...

- Calculate the area of a parallelogram.
- Find the matrix corresponding to a linear transformation of Euclidean spaces (**Standard(s) A1**).
- Recall and use the definition of a linear transformation (**Standard(s) A2**).
- Find all roots of quadratic polynomials (including complex ones), and be able to use the rational root theorem to find all rational roots of a higher degree polynomial.
- Interpret the statement “ A is an invertible matrix” in many equivalent ways in different contexts.

Readiness Assurance Resources

The following resources will help you prepare for this module.

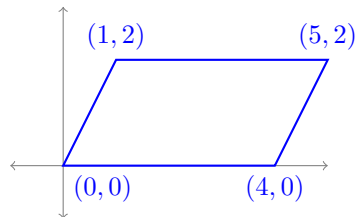
- Finding the area of a parallelogram: <https://www.khanacademy.org/math/basic-geo/basic-geo-area-and-perimeter/parallelogram-area/a/area-of-parallelogram>
- Factoring quadratics: <https://www.khanacademy.org/math/algebra2/polynomial-functions/factoring-polynomials/v/factoring-polynomials-1>
- Finding complex roots of quadratics: <https://www.khanacademy.org/math/algebra2/polynomial-functions/quadratic-equations-with-complex-numbers/v/complex-roots-from-the-quadratic-formula>
- Finding all roots of polynomials: <https://www.khanacademy.org/math/algebra2/polynomial-functions/finding-zeros-of-polynomials/v/finding-roots-or-zeros-of-polynomial-1>
- The Rational Root Theorem: https://artofproblemsolving.com/wiki/index.php?title=Rational_Root_Theorem

Readiness Assurance Test

Choose the most appropriate response for each question.

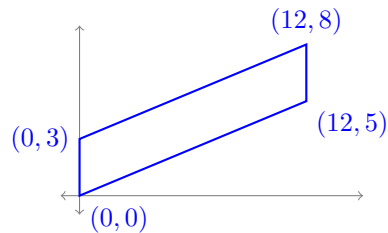
- 1) Find the area of the parallelogram with vertices $(0, 0)$, $(4, 0)$, $(5, 2)$, and $(1, 2)$.

- (a) 8
- (b) 10
- (c) 12
- (d) 14



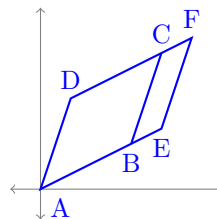
- 2) Find the area of the parallelogram with vertices $(0, 0)$, $(12, 5)$, $(12, 8)$, and $(0, 3)$.

- (a) 36
- (b) 54
- (c) 72
- (d) 96



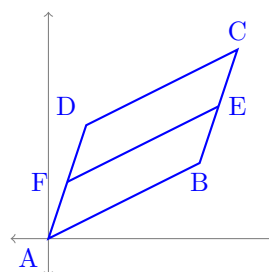
- 3) The parallelogram ABCD has area 6. If AE is 50% longer than AB, what is the area of the parallelogram AEFD?

- (a) 18
- (b) 15
- (c) 12
- (d) 9



- 4) The parallelogram ABCD has area 6. If AD is twice as long as AF, what is the area of the parallelogram ABEF?

- (a) 1
- (b) 2
- (c) 3
- (d) 4



5) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}$ be a linear transformation. Which of the following is equal to $T \left(\begin{bmatrix} a+b \\ a+b \end{bmatrix} \right)$?

- (a) $T \left(\begin{bmatrix} a \\ a \end{bmatrix} \right) + T \left(\begin{bmatrix} a \\ b \end{bmatrix} \right) + T \left(\begin{bmatrix} b \\ a \end{bmatrix} \right) + T \left(\begin{bmatrix} b \\ b \end{bmatrix} \right)$ (c) $T \left(\begin{bmatrix} a \\ b \end{bmatrix} \right)$
(b) $T \left(\begin{bmatrix} a \\ b \end{bmatrix} \right) + T \left(\begin{bmatrix} b \\ a \end{bmatrix} \right)$ (d) $2T \left(\begin{bmatrix} a \\ b \end{bmatrix} \right)$

6) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$ be a linear transformation with standard matrix A . Which of the following is equivalent to the statement “ A is an invertible matrix”?

- (a) T has a non-trivial kernel
(b) The matrix equation $AX = B$ has multiple solutions for all $B \in \mathbb{R}^n$.
(c) The columns of A are linearly dependent
(d) T is surjective

7) What is the matrix corresponding to the linear transformation $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ given by

$$T \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} 3x + 2y - z \\ y + z \\ x + 7z \end{bmatrix} ?$$

- (a) $\begin{bmatrix} 3 & 0 & 1 \\ 2 & 1 & 0 \\ -1 & 1 & 7 \end{bmatrix}$ (b) $\begin{bmatrix} 3 & 2 & -1 \\ 0 & 1 & 1 \\ 1 & 0 & 7 \end{bmatrix}$ (c) $\begin{bmatrix} 3 & 2 & -1 \\ 1 & 1 & 0 \\ 1 & 7 & 0 \end{bmatrix}$ (d) $\begin{bmatrix} 3 & 1 & 1 \\ 2 & 1 & 7 \\ -1 & 0 & 0 \end{bmatrix}$

8) How many distinct real roots does the polynomial $x^4 + 3x^3 + x^2 - 3x - 2$ have?

- (a) 4 (b) 3 (c) 2 (d) 1

9) Which of the following is a root of the polynomial $x^2 - 4x + 13$?

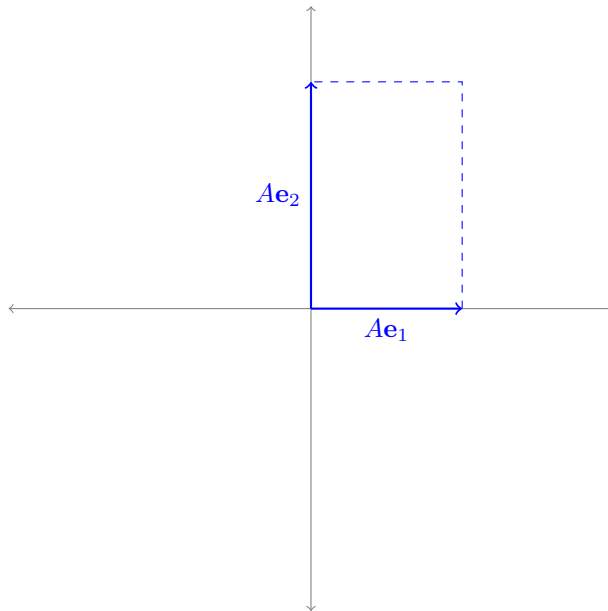
- (a) $2 - 3i$ (b) $3 + 4i$ (c) $4 - 5i$ (d) $5 + 6i$

10) Which of the following conditions imply that the quadratic polynomial $ax^2 + bx + c$ has no real roots?

- (a) $b^2 - 4ac < 0$ (c) $ac - 4b^2 < 0$
(b) $a^2 + 4bc < 0$ (d) $ab + 4c^2 < 0$

Application Activities - Module G Part 1 - Class Day 25

Activity 25.1 (5 min) Consider the linear transformation $A : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ given by the matrix $A = \begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}$



We can summarize the transformation of the unit square into this rectangle by measuring the following:

- How did the area change?
- How was the x -axis stretched?
- How was the y -axis stretched?

Activity 25.2 (15 min) Consider the following linear transformations $A_i : \mathbb{R}^2 \rightarrow \mathbb{R}^2$.

- $A_2 = \begin{bmatrix} 2 & 3 \\ 0 & 1 \end{bmatrix}$
- $A_3 = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$
- $A_4 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
- $A_5 = \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}$

For each linear transformation, do the following:

- Draw a graph showing the image of the unit square.

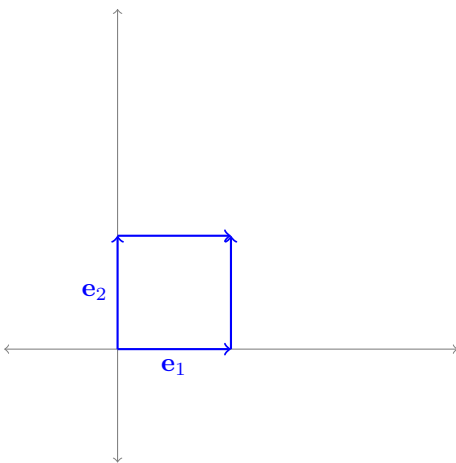
- (b) Compute how much the area was stretched out.
- (c) Determine which axes (or lines) were preserved; how were they stretched out?

Activity 25.3 (10 min) Our goal is to define a function \det that takes a square matrix (linear transformation $\mathbb{R}^n \rightarrow \mathbb{R}^n$) and returns its area stretching factor. This function is called the **determinant**.

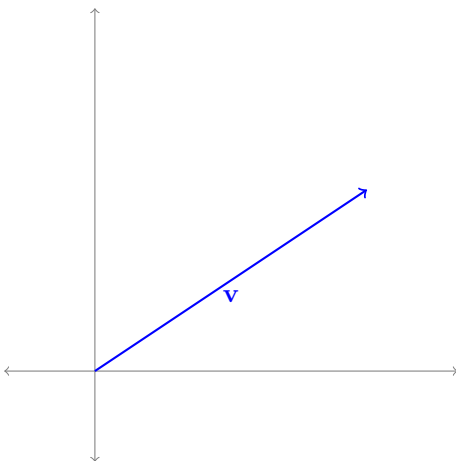
What properties should this function have?

Match the four pictures to the following four expressions

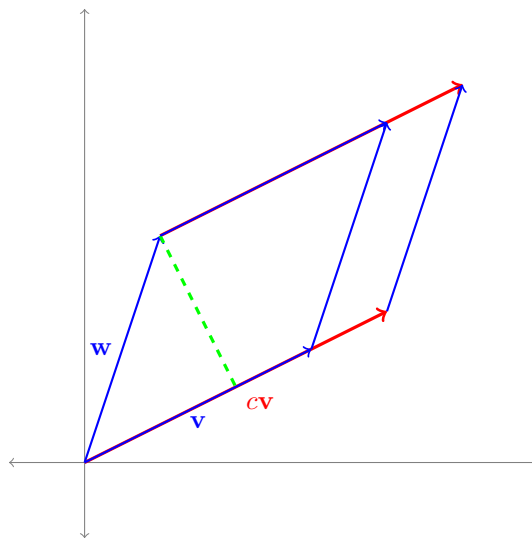
$$\det(\mathbf{e}_1, \mathbf{e}_2)$$



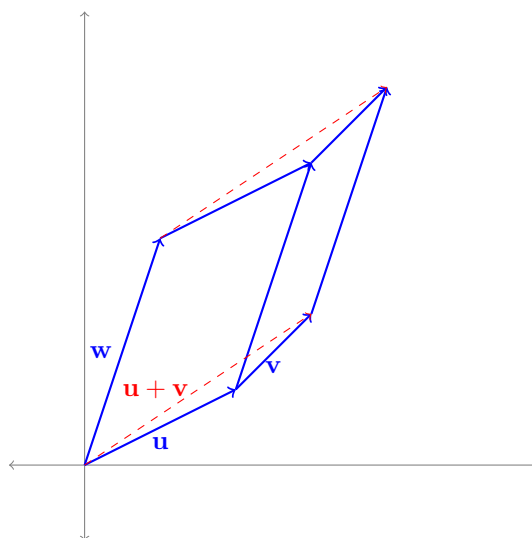
$$\det(\mathbf{v}, \mathbf{v})$$



$$\det(c\mathbf{v}, \mathbf{w})$$



$$\det(\mathbf{u} + \mathbf{v}, \mathbf{w})$$



Activity 25.4 (10 min) What can you conclude about each of the following?

1. $\det(\mathbf{e}_1, \mathbf{e}_2)$
 2. $\det(\mathbf{v}, \mathbf{v})$
 3. $\det(c\mathbf{v}, \mathbf{w})$
 4. $\det(\mathbf{u} + \mathbf{v}, \mathbf{w})$
-

Definition 25.5 To summarize, we have 3 properties (stated here over \mathbb{R}^n)

P1: $\det(\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_n) = 1$

P2: If $\mathbf{v}_i = \mathbf{v}_j$ for some $i \neq j$, then $\det(\mathbf{v}_1, \mathbf{v}_2, \dots, \mathbf{v}_n) = 0$.

P3: The determinant is linear in each column.

These three properties uniquely define the **determinant**, as we shall see.

Observation 25.6 Note that if $\mathbf{v}, \mathbf{w} \in \mathbb{R}^2$ and $A = [\mathbf{v} \ \mathbf{w}]$ we will write either $\det(A)$ or $\det(\mathbf{v}, \mathbf{w})$ as is convenient.

Activity 25.7 (5 min) How are $\det(\mathbf{v}, \mathbf{w})$ and $\det(\mathbf{w}, \mathbf{v})$ related?

- (a) $\det(\mathbf{v}, \mathbf{w}) = \det(\mathbf{w}, \mathbf{v})$
 - (b) $\det(\mathbf{v}, \mathbf{w}) = -\det(\mathbf{w}, \mathbf{v})$
 - (c) They are unrelated
 - (d) They are related, but not by either (a) or (b).
-

Observation 25.8 Note that this implies that the determinant is actually a *signed* area (volume)!

Activity 25.9 (5 min) How are $\det(\mathbf{v} + \mathbf{w}, \mathbf{w})$ and $\det(\mathbf{v}, \mathbf{w})$ related?

- (a) $\det(\mathbf{v} + \mathbf{w}, \mathbf{w}) = \det(\mathbf{v}, \mathbf{w})$
 - (b) $\det(\mathbf{v} + \mathbf{w}, \mathbf{w}) = -\det(\mathbf{v}, \mathbf{w})$
 - (c) They are unrelated
 - (d) They are related, but not by either (a) or (b).
-

Observation 25.10 Note that we now understand the effect of any column operation on the determinant.

Application Activities - Module G Part 2 - Class Day 26

Fact 26.1 By a geometric argument, one can show that the determinant of a matrix and its transpose are the same. Thus, row operations behave like column operations. In particular, we can use row reduction to compute determinants.

Fact 26.2 Row operations change the determinant in the following way

1. Elementary row operations (adding a multiple of one row to another) do not change the determinant.
2. Diagonal operations (multiplying a row by a scalar) multiplies the determinant by the same amount.
3. Swapping two rows multiplies the determinant by -1 .

Activity 26.3 (10 min) Compute $\det \begin{bmatrix} 4 & 5 \\ 2 & 3 \end{bmatrix}$.

Activity 26.4 (10 min) Which of the following is the same as $\det \begin{bmatrix} 3 & -2 & 0 \\ 5 & -1 & 0 \\ -2 & 4 & 1 \end{bmatrix}$?

(a) $\det \begin{bmatrix} 3 & -2 \\ 5 & -1 \end{bmatrix}$

(b) $\det \begin{bmatrix} 3 & -2 \\ -2 & 4 \end{bmatrix}$

(c) $\det \begin{bmatrix} 5 & -1 \\ -2 & 4 \end{bmatrix}$

(d) None of these

Hint: Draw a picture

Activity 26.5 (5 min) Which of the following is the same as $\det \begin{bmatrix} 3 & 0 & 7 \\ 5 & 1 & 2 \\ -2 & 0 & 6 \end{bmatrix}$?

(a) $\det \begin{bmatrix} 3 & 7 \\ 5 & 2 \end{bmatrix}$

(b) $\det \begin{bmatrix} 3 & 7 \\ -2 & 6 \end{bmatrix}$

(c) $\det \begin{bmatrix} 5 & 2 \\ -2 & 6 \end{bmatrix}$

(d) None of these

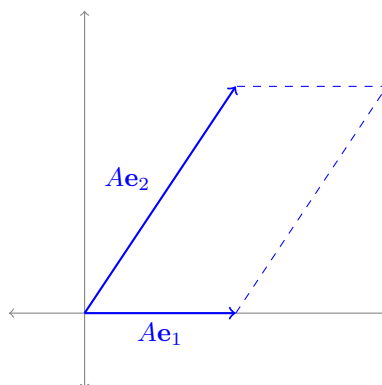
Activity 26.6 (5 min) Compute $\det \begin{bmatrix} 0 & 3 & -2 \\ 1 & 5 & 12 \\ 0 & 2 & -1 \end{bmatrix}$

Activity 26.7 (10 min) Using the fact that $\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$, compute $\det \begin{bmatrix} 1 & 2 & 3 \\ 1 & -2 & 5 \\ 0 & 3 & 3 \end{bmatrix}$.

Activity 26.8 (10 min) Compute $\begin{bmatrix} 2 & 3 & 5 & 0 \\ 0 & 1 & -1 & 0 \\ 1 & 2 & 0 & 3 \\ -1 & -1 & 2 & 2 \end{bmatrix}$

Application Activities - Module G Part 3 - Class Day 27

Activity 27.1 (15 min) Consider the linear transformation $A : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ given by the matrix $A = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix}$



Observe

$$A\mathbf{e}_1 = A \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 2 \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 2\mathbf{e}_1$$

Is there another vector $\mathbf{v} \in \mathbb{R}^2$ such that $A\mathbf{v} = \lambda\mathbf{v}$ for some $\lambda \in \mathbb{R}$?

Definition 27.2 Let $A \in M_n(\mathbb{R})$. An **eigenvector** is a vector $\mathbf{x} \in \mathbb{R}^n$ such that $A\mathbf{x}$ is parallel to \mathbf{x} ; in other words, $A\mathbf{x} = \lambda\mathbf{x}$ for some scalar λ , which is called an **eigenvalue**

Observation 27.3 Observe that $A\mathbf{x} = \lambda\mathbf{x}$ is equivalent to $(A - \lambda I)\mathbf{x} = 0$.

- To find eigenvalues, we need to find values of λ such that $A - \lambda I$ has a nontrivial kernel; equivalently, $A - \lambda I$ is not invertible, which is equivalent to $\det(A - \lambda I) = 0$. $\det(A - \lambda I)$ is called the **characteristic polynomial**.
- Once an eigenvalue is found, the eigenvectors form a subspace called the **eigenspace**, which is simply the kernel of $A - \lambda I$. Each eigenvalue will have an associated eigenspace.

Activity 27.4 (20 min) Let $A = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix}$.

Part 1: Find the eigenvalues of A .

Part 2: Find the eigenspace associated to the eigenvalue 3.

Activity 27.5 (15 min) Find all the eigenvalues and associated eigenspaces for the matrix $\begin{bmatrix} 6 & -2 & 1 \\ 17 & -5 & 5 \\ -4 & 2 & 1 \end{bmatrix}$.

Application Activities - Module G Part 4 - Class Day 28

Activity 28.1 (5 min) If A is a 4×4 matrix, what is the largest number of eigenvalues A can have?

- (a) 3
 - (b) 4
 - (c) 5
 - (d) 6
 - (e) It can have infinitely many
-

Activity 28.2 (10 min) 2 is an eigenvalue of each of the matrices $A = \begin{bmatrix} 1 & -2 & 1 \\ -1 & 0 & 1 \\ -1 & -2 & 3 \end{bmatrix}$ and $B = \begin{bmatrix} -3 & -9 & 5 \\ -2 & -2 & 2 \\ -7 & -13 & 9 \end{bmatrix}$.

Compute the eigenspace associated to 2 for both A and B .

Definition 28.3

- The **algebraic multiplicity** of an eigenvalue is its multiplicity as a root of the characteristic polynomial.
- The **geometric multiplicity** of an eigenvalue is the dimension of the eigenspace.

Activity 28.4 (10 min) How are the algebraic and geometric multiplicities related?

- (a) The algebraic multiplicity is always at least as big as than the geometric multiplicity.
 - (b) The geometric multiplicity is always at least as big as the algebraic multiplicity.
 - (c) Sometimes the algebraic multiplicity is larger and sometimes the geometric multiplicity is larger.
-

Activity 28.5 (15 min) Find the eigenvalues, along with both their algebraic and geometric multiplicities,

for the matrix $\begin{bmatrix} -3 & 1 & 2 & 1 \\ -9 & 5 & -2 & -1 \\ 31 & -17 & 6 & 3 \\ -69 & 39 & -18 & -9 \end{bmatrix}$

Activity 28.6 (10 min) Let $A = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$.

Part 1: Find the eigenvalues of A

Part 2: Describe what this linear transformation is doing geometrically; draw a picture.
