

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.

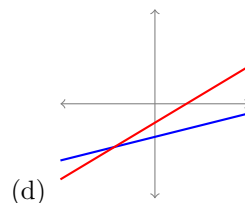
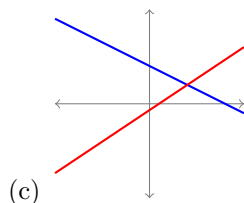
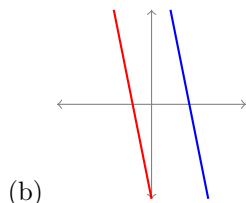
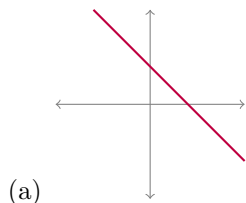
- <https://www.khanacademy.org/math/cc-eighth-grade-math/cc-8th-systems-topic/cc-8th-systems-graphical/a/systems-of-equations-with-graphing>
- <https://www.khanacademy.org/math/algebra/systems-of-linear-equations/solving-systems-of-equations-v/practice-using-substitution-for-systems>

Readiness Assurance Test

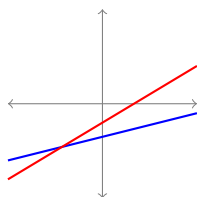
Choose the most appropriate response for each question.

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

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



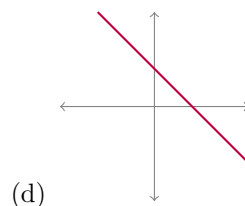
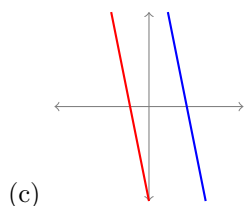
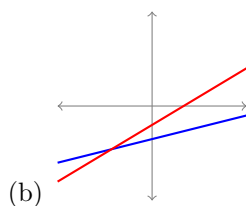
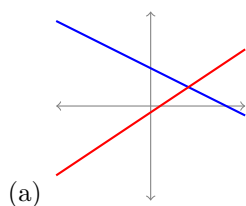
- 2) How many solutions are there for the system of linear equations represented by the following graph?



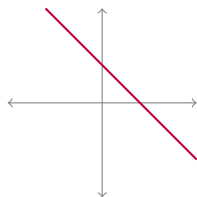
- (a) One (b) Two (c) Zero (d) Infinitely-many

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

$$\begin{aligned}3x + 3y &= 6 \\ x + y &= 2\end{aligned}$$



- 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.

$$y = 2x + 5$$

$$y = -x + 2$$

- (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.

$$y = 3x + 5$$

$$y = 3x + 2$$

- (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.

$$x + 2y = 4$$

$$2x - 3y = 1$$

- (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:

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

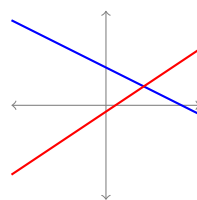
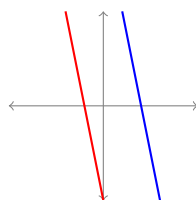
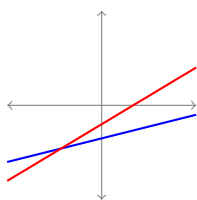
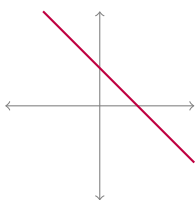
Concise standard form:

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

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.

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

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:

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

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: $(x_1, x_2) = (1, 1)$.

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

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

Therefore these augmented matrices are equivalent:

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

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

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). | 4. Add $-3R_1$ to R_2 . |
| 2. Multiply R_2 by $\frac{1}{2}$. | 5. Add $-2R_2$ to R_3 . |
| 3. Add R_1 to R_3 . | 6. Multiply R_3 by $\frac{1}{3}$. |

Part 2: What is the common solution to these linear systems?

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 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.
4. Finally, zero out any terms above pivot positions.

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

$$\begin{aligned}
 & \left[\begin{array}{ccc|c} \textcircled{3} & -2 & 13 & 6 \\ 2 & -2 & 10 & 2 \\ -1 & 3 & -6 & 11 \end{array} \right] \sim \left[\begin{array}{ccc|c} \textcircled{2} & -2 & 10 & 2 \\ 3 & -2 & 13 & 6 \\ -1 & 3 & -6 & 11 \end{array} \right] \sim \left[\begin{array}{ccc|c} \textcircled{1} & -1 & 5 & 1 \\ 3 & -2 & 13 & 6 \\ -1 & 3 & -6 & 11 \end{array} \right] \\
 & \sim \left[\begin{array}{ccc|c} \textcircled{1} & -1 & 5 & 1 \\ 0 & \textcircled{1} & -2 & 3 \\ 0 & 2 & -1 & 12 \end{array} \right] \sim \left[\begin{array}{ccc|c} \textcircled{1} & -1 & 5 & 1 \\ 0 & \textcircled{1} & -2 & 3 \\ 0 & 0 & \textcircled{3} & 6 \end{array} \right] \sim \left[\begin{array}{ccc|c} \textcircled{1} & -1 & 5 & 1 \\ 0 & \textcircled{1} & -2 & 3 \\ 0 & 0 & \textcircled{1} & 2 \end{array} \right] \\
 & \sim \left[\begin{array}{ccc|c} \textcircled{1} & -1 & 5 & 1 \\ 0 & \textcircled{1} & -2 & 3 \\ 0 & 0 & \textcircled{1} & 2 \end{array} \right] \sim \left[\begin{array}{ccc|c} \textcircled{1} & -1 & 0 & -9 \\ 0 & \textcircled{1} & 0 & 7 \\ 0 & 0 & \textcircled{1} & 2 \end{array} \right] \sim \left[\begin{array}{ccc|c} \textcircled{1} & 0 & 0 & -2 \\ 0 & \textcircled{1} & 0 & 7 \\ 0 & 0 & \textcircled{1} & 2 \end{array} \right]
 \end{aligned}$$

Activity 5.3 (15 min) Find $\text{RREF}(A)$ where

$$A = \left[\begin{array}{cccc|c} -1 & 1 & -3 & 2 & 0 \\ 2 & -1 & 5 & 3 & -11 \\ 3 & 2 & 4 & 1 & 1 \\ 0 & 1 & -1 & 1 & 1 \end{array} \right].$$

Definition 5.4 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 .

Activity 5.5 (10 min) Given the linear system and its equivalent row-reduced matrix

$$\begin{aligned}
 -x_1 + x_2 - 3x_3 + 2x_4 &= 0 \\
 2x_1 - x_2 + 5x_3 + 3x_4 &= -11 \\
 3x_1 + 2x_2 + 4x_3 + x_4 &= 1 \\
 x_2 - x_3 + x_4 &= 1
 \end{aligned}
 \qquad
 \left[\begin{array}{cccc|c} 1 & 0 & 2 & 0 & -1 \\ 0 & 1 & -1 & 0 & 3 \\ 0 & 0 & 0 & 1 & -2 \\ 0 & 0 & 0 & 0 & 0 \end{array} \right]$$

circle the pivot positions and describe the solution set $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} + a \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}$ by setting the free variable (the column without a pivot position) equal to a , and expressing each of the other bounded variables equal to an expression in terms of a .

Remark 5.6 It's not necessary to completely find $\text{RREF}(A)$ to deduce that a linear system is inconsistent.

Activity 5.7 (10 min) Find a contradiction in the inconsistent linear system

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

by considering the following equivalent augmented matrices:

$$\left[\begin{array}{cc|c} 2 & -3 & 17 \\ 1 & 2 & -2 \\ -1 & -1 & 1 \end{array} \right] \sim \left[\begin{array}{cc|c} 1 & 2 & -2 \\ 0 & 1 & 3 \\ 0 & 0 & 2 \end{array} \right].$$

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

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

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.

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

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.

- 1) Simplify the following 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) $\begin{bmatrix} 6 \\ -8 \\ -3 \end{bmatrix}$

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

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

- 2) Simplify the following vector expression.

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

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

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

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

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

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

(a) $3 - 7i$

(b) $4 + i$

(c) $-2 + 10i$

(d) $-1 - 5i$

- 4) Which of these complex numbers might be represented by the following 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) $4i$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

9) Solve the following system of linear equations.

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

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

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

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

(d) No solutions

10) 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 (25 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 vector space that models motion along the curve $y = e^x$. Let $V = \{(x, y) : y = e^x\}$, where $(a_1, b_1) + (a_2, b_2) = (a_1 + a_2, b_1 b_2)$, and $c(a, b) = (ca, b^c)$.

Part 1: Verify that $3((1, e) + (-2, \frac{1}{e^2})) = 3(1, e) + 3(-2, \frac{1}{e^2})$.

(Instructor Note:) Draw a visualization of these vectors by sketching “curved” vectors in the xy plane.

Part 2: Prove the scalar distribution property for this space: $c(\mathbf{u} + \mathbf{v}) = c\mathbf{u} + c\mathbf{v}$.

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 (15 min) Let $V = \{(a, b) : a, b \text{ are real numbers}\}$, where $(a_1, b_1) + (a_2, b_2) = (a_1 + b_1 + a_2 + b_2, b_1^2 + b_2^2)$ and $c(a, b) = (a^c, b + c)$. 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.
$\mathbf{u} + (\mathbf{v} + \mathbf{w}) = (\mathbf{u} + \mathbf{v}) + \mathbf{w}.$ • 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 $\mathbf{v} + (-\mathbf{v}) = \mathbf{0}.$ | <ul style="list-style-type: none"> • 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 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 .

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 $c_1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + c_2 \begin{bmatrix} -1 \\ 1 \end{bmatrix}$ in the xy plane for $\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 1 \end{bmatrix}$.

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 (10 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. (From now on, feel free to use a calculator to solve linear systems.)

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 guess.

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

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 (15 min) Find 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 doing the following.

Part 1: Choose simple values for x, y, z such that $\begin{bmatrix} 1 & 0 & x \\ 0 & 1 & y \\ 0 & 0 & z \end{bmatrix}$ represents an inconsistent linear equation.

Part 2: Use row operations to manipulate $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \sim \begin{bmatrix} 1 & -2 & a \\ -1 & 0 & b \\ 0 & 1 & c \end{bmatrix}$.

Part 3: Write a sentence explaining why $\begin{bmatrix} a \\ b \\ c \end{bmatrix}$ cannot be in $\text{span} \left\{ \begin{bmatrix} 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} -2 \\ 0 \\ 1 \end{bmatrix} \right\}$.

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.

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

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

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

Prove that $\mathcal{P}^3 \neq \text{span } S$.

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.



Part 1: Find a linear combination $c \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} + d \begin{bmatrix} w_1 \\ w_2 \end{bmatrix}$ that does not belong to this subset.

Part 2: 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 finding 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.

- 1) Simplify the following vector expression.

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

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

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

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

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

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

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

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

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

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

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

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

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

(d) No solutions

5) 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) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 12 \\ -8 \\ 0 \\ 0 \end{bmatrix} + a \begin{bmatrix} -3 \\ 2 \\ 1 \\ 0 \end{bmatrix} + b \begin{bmatrix} -2 \\ 1 \\ 0 \\ 1 \end{bmatrix}$ for all real numbers a, b
- (b) $\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 4 \\ -5 \end{bmatrix} + a \begin{bmatrix} 0 \\ 3 \\ 1 \\ 1 \end{bmatrix}$ for all real numbers a (d) No solutions

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

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

7) How many vectors are required to span all of \mathcal{P}^4 (the space of polynomials of degree four or less)?

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

8) 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) $\begin{bmatrix} 2 \\ 2 \\ 0 \\ 1 \end{bmatrix}$ (d) $\begin{bmatrix} -5 \\ 3 \\ 1 \\ 1 \end{bmatrix}$

9) 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) $\begin{bmatrix} -1 \\ -1 \\ 0 \\ 0 \end{bmatrix}$

10) The graphical representation of $\text{span} \left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \right\}$ in three-dimensional Euclidean space \mathbb{R}^3 would be which of the following?

(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 that are in the span 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 $x_1\mathbf{v}_1 + x_2\mathbf{v}_2 = \mathbf{v}_3$, 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 circle 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 (15 min) TODO (compute RREF and label each set of vectors as linearly independent/dependent)

Application Activities - Module S Part 2 - Class Day 13

Activity 13.1 (10 min) (take basis shown to be linearly independent in previous day, and show that it spans)

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 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 (10 min) (given four sets of general vectors, identify which are bases and which aren't)

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 $\text{RREF}[\mathbf{v}_1 \ \dots \ \mathbf{v}_n] =$

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

Activity 13.7 (10 min) (given four sets of \mathbb{R}^5 vectors, identify which are bases and which aren't)

Activity 13.8 (10 min) How can $\{\mathbf{u}, \mathbf{v}, \mathbf{u} + \mathbf{v}\}$ (but with numbers) be changed to make it linearly independent?

Application Activities - Module S Part 3 - Class Day 14

Activity 14.1 (10 min) (discover that the redundant vectors are non-pivot columns)

Fact 14.2 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 14.3 (10 min) (find ALL the bases for $\text{span } S$ that are subsets of S)

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

Activity 14.5 (10 min) Prove that if $\{\mathbf{v}\}$ is a basis for V , then $\{\mathbf{w}_1, \mathbf{w}_2\}$ is linearly dependent (assuming $\mathbf{w}_1 \neq \mathbf{w}_2$).

Fact 14.6 All bases for a vector space are the same size.

Definition 14.7 The **dimension** of a vector space is given by the cardinality/size of any basis for the vector space.

Activity 14.8 (10 min) Reduce a bunch of spans to bases to find their dimension.

Activity 14.9 (5 min) What is the dimension of the vector space of 7th-degree polynomials \mathcal{P}^7 ?

Activity 14.10 (5 min) What is the dimension of the vector space of polynomials \mathcal{P} ?

Observation 14.11 Several interesting vector spaces are infinite-dimensional:

- The space of polynomials \mathcal{P}
- The space of real number sequences \mathbb{R}^∞
- The space of continuous functions $C(\mathbb{R})$

Fact 14.12 Every vector space with dimension $n < \infty$ is isomorphic to \mathbb{R}^n .

Standards for this Module

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

- **A1. Linear maps as matrices** I can write the matrix (with respect to the standard bases) 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.

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

- 2) 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) $\left\{ \begin{bmatrix} 2 \\ 1 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 3 \\ 1 \end{bmatrix} \right\}$ (b) $\left\{ \begin{bmatrix} 2 \\ 2 \\ 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 3 \\ 0 \end{bmatrix} \right\}$ (c) $\left\{ \begin{bmatrix} 2 \\ 1 \\ 3 \\ 1 \end{bmatrix} \right\}$ (d) None of these are a basis.

- 3) 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 .

- 4) 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 .

- 5) 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 .

- 6) 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 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 .

- 7) Find a basis for the subspace of \mathbb{R}^4 spanned by the vectors ...

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

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

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

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

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

- (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 .

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

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

V is called the **domain** of T and W is called the **co-domain** of T .

Activity 17.2 (0 min) Determine if each of the following maps are linear transformations

- (a) $T_1 : \mathbb{R}^2 \rightarrow \mathbb{R}$ given by $T_1 \left(\begin{bmatrix} a \\ b \end{bmatrix} \right) = \sqrt{a^2 + b^2}$
- (b) $T_2 : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ given by $T_2 \left(\begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} x - z \\ y \end{bmatrix}$
- (c) $T_3 : \mathcal{P}_d \rightarrow \mathcal{P}_{d-1}$ given by $T_3(f(x)) = f'(x)$.
- (d) $T_4 : C(\mathbb{R}) \rightarrow C(\mathbb{R})$ given by $T_4(f(x)) = f(-x)$
- (e) $T_5 : \mathcal{P} \rightarrow \mathcal{P}$ given by $T_5(f(x)) = f(x) + x^2$

Activity 17.3 (0 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 each of the following:

- (a) $T \left(\begin{bmatrix} 3 \\ 0 \\ 0 \end{bmatrix} \right)$
- (b) $T \left(\begin{bmatrix} 0 \\ 0 \\ -2 \end{bmatrix} \right)$
- (c) $T \left(\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} \right)$
- (d) $T \left(\begin{bmatrix} -2 \\ 0 \\ 5 \end{bmatrix} \right)$

Activity 17.4 (0 min) Suppose $T : \mathbb{R}^4 \rightarrow \mathbb{R}^3$ is a linear transformation. What is the smallest number of vectors needed to determine T ? In other words, what is the smallest number n such that there are $\vec{v}_1, \dots, \vec{v}_n \in \mathbb{R}^4$ and given $T(\vec{v}_1), \dots, T(\vec{v}_n)$ you can determine $T(\vec{w})$ for *any* $\vec{w} \in \mathbb{R}^4$?

Observation 17.5 Fix an ordered basis for V . Since every vector can be written *uniquely* as a linear combination of basis vectors, a linear transformation $T : V \rightarrow W$ corresponds exactly to a choice of where each basis vector goes. For convenience, we can thus encode a linear transformation as a matrix, with one column for the image of each basis vector (in order).

Activity 17.6 (0 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be a linear transformation with

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

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

Activity 17.7 (0 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be a linear transformation with

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

Write the matrix corresponding to this linear transformation with respect to the ordered basis

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

Activity 17.8 (0 min) Let $D : \mathcal{P}_3 \rightarrow \mathcal{P}_2$ be the derivative map (recall this is a linear transformation). Write the matrix corresponding to D with respect to the ordered basis $\{1, x, x^2, x^3\}$.

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 $T(\vec{v}) \neq T(\vec{w})$ whenever $\vec{v} \neq \vec{w}$.
- T is called **surjective** or **onto** if every element of W is mapped to by an element of V . More precisely, for every $\vec{w} \in W$, there is some $v \in V$ with $T(\vec{v}) = \vec{w}$.

Activity 18.2 (0 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the matrix $\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$. Determine if T is injective, surjective, both, or neither.

Activity 18.3 (0 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the matrix $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$. Determine if T is injective, surjective, both, or neither.

Definition 18.4 We also have two important sets called the **kernel** of T and the **image** of T .

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

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

Activity 18.5 (0 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the matrix $\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}$ (for the standard basis). Find the kernel and image of T .

Activity 18.6 (0 min) Let $T : \mathbb{R}^2 \rightarrow \mathbb{R}^3$ be given by the matrix $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$ (for the standard basis). Find the kernel and image of T .

Activity 18.7 (0 min)

Part 1: Describe surjective linear transformations in terms of the image.

Part 2: Describe injective linear transformations in terms of the kernel.

Activity 18.8 (0 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be the linear transformation given by the matrix $A = \begin{bmatrix} 3 & 4 & -1 \\ 1 & 2 & 1 \end{bmatrix}$ (for the standard basis).

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

- 2) Compute $\text{RREF}(A)$ and solve the system of equations.
 - 3) Compute the kernel of T
 - 4) Find a basis for the kernel of T
-

Activity 18.9 (0 min) Let $S : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be the linear transformation given by the matrix $B = \begin{bmatrix} 3 & 4 & 1 \\ 1 & 2 & 4 \\ 5 & 8 & 9 \end{bmatrix}$ (for the standard basis).

- 1) Write a system of equations whose solution set is the kernel.
 - 2) Compute $\text{RREF}(A)$ and solve the system of equations.
 - 3) Compute the kernel of T
 - 4) Find a basis for the kernel of T
-

Activity 18.10 (0 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be the linear transformation given by the matrix $A = \begin{bmatrix} 3 & 4 & -1 \\ 1 & 2 & 1 \end{bmatrix}$ (for the standard basis).

- 1) Find a set of vectors that span the image of T
 - 2) Find a basis for the image of T .
-

Activity 18.11 (0 min) Let $S : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ be the linear transformation given by the matrix $B = \begin{bmatrix} 3 & 4 & 1 \\ 1 & 2 & 4 \\ 5 & 8 & 9 \end{bmatrix}$ (for the standard basis).

- 1) Find a set of vectors that span the image of T
 - 2) Find a basis for the image of T .
-

Application Activities - Module A Part 3 - Class Day 19

Activity 19.1 (0 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with matrix $A \in M_{m,n}$ (for the standard basis). You have cards containing a number of statements about T and A . Sort them into groups of equivalent statements, and post them on your board.

(Instructor Note:) Card sort activity for 10-15 minutes: cards contain the following

- (a) T is injective
- (b) T is not injective
- (c) T is surjective
- (d) T is not surjective
- (e) The system of linear equations given by the augmented matrix $\begin{bmatrix} A & | & \vec{b} \end{bmatrix}$ has a solution for all $\vec{b} \in \mathbb{R}^m$
- (f) The system of linear equations given by the augmented matrix $\begin{bmatrix} A & | & \vec{b} \end{bmatrix}$ has a unique solution for all $\vec{b} \in \mathbb{R}^m$
- (g) The system of linear equations given by the augmented matrix $\begin{bmatrix} A & | & \vec{0} \end{bmatrix}$ has a non-trivial solution.
- (h) The columns of A span \mathbb{R}^m
- (i) The columns of A are linearly independent
- (j) The columns of A are a basis of \mathbb{R}^m
- (k) Every column of $\text{RREF}(A)$ is a pivot column
- (l) $\text{RREF}(A)$ has a non-pivot column
- (m) $\text{RREF}(A)$ has n pivot columns

Activity 19.2 (0 min) **(Instructor Note:)** Gallery walk Cycle around the room counter-clockwise. If they have two things grouped together that you know are not equivalent, write a reason or counter-example on a sticky note.

Activity 19.3 (0 min) Come up with as many statements as you can, and add them to the appropriate group.

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.

1) 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) $x^4 - x^2 - 2$

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

$$\begin{array}{ll} f(2) = 1 & g(2) = 3 \\ f(3) = 4 & g(3) = 5 \\ f(4) = 3 & g(4) = 6 \end{array}$$

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

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

3) Solve the system of linear equations

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

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

4) 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 .

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

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

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

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

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

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

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

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

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

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

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

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

7) Which of the following is true of the linear transformation $T : ?$

- (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

8) Which of the following is true of the linear transformation $T : ?$

- (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

9) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear transformation with associated matrix $A \in M_{m,n}(\mathbb{R})$. Three of the four answer choices are equivalent to each other; which one is not equivalent to the other three?

- (a) T is injective
- (b) T has a non-trivial kernel
- (c) The columns of A are linearly dependent
- (d) $\text{RREF}(A)$ has a non-pivot column

10) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear transformation with associated matrix $A \in M_{m,n}(\mathbb{R})$. Three of the four answer choices are equivalent to each other; which one is not equivalent to the other three?

- (a) T is surjective
- (b) $\text{Im } T = \mathbb{R}^m$
- (c) The columns of A span \mathbb{R}^m
- (d) $\text{RREF}(A)$ has only pivot columns

Application Activities - Module M Part 1 - Class Day 21

Activity 21.1 (0 min) Let $T : \mathbb{R}^3 \rightarrow \mathbb{R}^2$ be given by the 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 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 (0 min) 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 (0 min) The matrix corresponding to $S \circ T$ will lie in which matrix space?

- (a) $M_{4,3}$
 - (b) $M_{4,2}$
 - (c) $M_{3,2}$
 - (d) $M_{2,3}$
 - (e) $M_{2,4}$
 - (f) $M_{3,4}$
-

Activity 21.4 (0 min) Compute $(S \circ T)(\vec{e}_1)$, $(S \circ T)(\vec{e}_2)$, and $(S \circ T)(\vec{e}_3)$.

Activity 21.5 (0 min) Find the matrix corresponding to $S \circ T$ with respect to the standard bases.

Activity 21.6 (0 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 21.7 (0 min) 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 21.8 (0 min) The matrix corresponding to $S \circ T$ will lie in which matrix space?

- (a) $M_{2,2}$
 - (b) $M_{2,3}$
 - (c) $M_{3,2}$
 - (d) $M_{3,3}$
-

Activity 21.9 (0 min) Compute $(S \circ T)(\vec{e}_1)$ and $(S \circ T)(\vec{e}_2)$

Activity 21.10 (0 min) Find the matrix corresponding to $S \circ T$ with respect to the standard bases.

Activity 21.11 (0 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 $A = \begin{bmatrix} 2 & 3 & 2 & 5 \end{bmatrix}$.

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 21.12 (0 min) 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 21.13 (0 min) The matrix corresponding to $S \circ T$ will lie in which matrix space?

- (a) $M_{1,1}$
 - (b) $M_{1,4}$
 - (c) $M_{4,1}$
 - (d) $M_{4,4}$
-

Activity 21.14 (0 min) Compute $(S \circ T)(\vec{e}_1)$

Activity 21.15 (0 min) Find the matrix corresponding to $S \circ T$ with respect to the standard bases.

Activity 21.16 (0 min) Let $A = \begin{bmatrix} 3 & 1 & -1 \\ 2 & 0 & 4 \\ -1 & 3 & 5 \end{bmatrix}$ and $X = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$

1. Compute AX
2. Interpret the system of equations below as a matrix equation

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

Application Activities - Module M Part 2 - Class Day 22

Activity 22.1 (0 min) Each row operation can be interpreted as a matrix multiplication. Let $A \in M_{4,4}$

- 1) Find a matrix S_1 such that $S_1 A$ is the result of swapping the second and fourth rows of A .
 - 2) Find a matrix S_2 such that $S_2 A$ is the result of adding 5 times the third row of A to the first.
 - 3) Find a matrix S_3 such that $S_3 A$ is the result of doubling the fourth row of A .
-

Activity 22.2 (0 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with matrix $A \in M_{m,n}$ (for the standard basis). Consider the following statements about T

- (a) T is injective
- (b) T is surjective
- (c) T is bijective (i.e. both injective and surjective)
- (d) $AX = B$ has a solution for all $B \in M_{m,1}$
- (e) $AX = B$ has a unique solution for all $B \in M_{m,1}$
- (f) $AX = 0$ has a non-trivial solution.
- (g) The columns of A span \mathbb{R}^m
- (h) The columns of A are linearly independent
- (i) The columns of A are a basis of \mathbb{R}^m
- (j) $\text{RREF}(A)$ has n pivot columns
- (k) $\text{RREF}(A)$ has m pivot columns

Sort these statements into groups of equivalent statements.

Activity 22.3 (0 min) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^m$ be a linear map with matrix $A \in M_{m,n}$ (for the standard basis). If T is injective, what must be true about how m and n are related?

- (a) $m < n$
 - (b) $m \leq n$
 - (c) $m = n$
 - (d) $m \geq n$
 - (e) $m > n$
-

Activity 22.4 (*0 min*) If T is surjective, what must be true about how m and n are related?

- (a) $m < n$
 - (b) $m \leq n$
 - (c) $m = n$
 - (d) $m \geq n$
 - (e) $m > n$
-

Activity 22.5 (*0 min*) If T is bijective, what must be true about how m and n are related?

- (a) $m < n$
 - (b) $m \leq n$
 - (c) $m = n$
 - (d) $m \geq n$
 - (e) $m > n$
-

Application Activities - Module M Part 3 - Class Day 23

Activity 23.1 (*0 min*) Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$ be a linear map with matrix $A \in M_{n,n}$.

If T is a bijection, then $AX = B$ has a unique solution for all $B \in \mathbb{R}^n$. Thus we can define a map $T^{-1} : \mathbb{R}^n \rightarrow \mathbb{R}^n$ by defining $T^{-1}(B)$ to be this solution. It follows immediately that $T \circ T^{-1}$ is the identity map. The matrix corresponding to T^{-1} is denoted A^{-1} .

- 1) Solve $AX = \vec{e}_1$ to determine $T^{-1}(\vec{e}_1)$
- 2) Solve $AX = \vec{e}_2$ to determine $T^{-1}(\vec{e}_2)$
- 3) Solve $AX = \vec{e}_3$ to determine $T^{-1}(\vec{e}_3)$
- 4) Compute A^{-1}

A (square) matrix is called *invertible* if it corresponds to an invertible linear transformation.

- 1) Find the inverse of the matrix $\begin{bmatrix} 1 & 3 \\ 0 & -2 \end{bmatrix}$
 - 2) Find the inverse of the matrix $\begin{bmatrix} 1 & -2 & 1 \\ -3 & 7 & 6 \\ 2 & -3 & 0 \end{bmatrix}$
-