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# Linear Algebra

University of South Alabama

Fall 2017

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# Module E: Solving Systems of Linear Equations

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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.

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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.

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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-graphically/a/systems-of-equations-with-graphing>
- <https://www.khanacademy.org/math/algebra/systems-of-linear-equations/solving-systems-of-equations-with-substitution/v/practice-using-substitution-for-systems>

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# Application Activities - Module E Part 1 - Class Day 3

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## 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

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

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**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.



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## 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  $x_i$ .

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## Definition 3.4

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

$$a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = b_1$$

$$a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = b_2$$

$$\vdots \qquad \qquad \qquad \vdots \qquad \qquad \qquad \vdots \qquad \qquad \qquad \vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = b_m$$

## 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

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

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

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**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:

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

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# Definition 3.6

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

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## Fact 3.7

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

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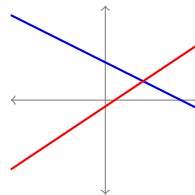
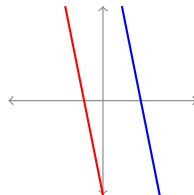
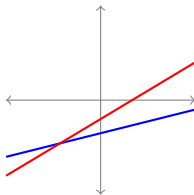
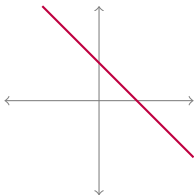
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## Activity 3.8

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**.



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## Activity 3.9

All inconsistent linear systems contain a logical **contradiction**. Find a contradiction in this system.

$$-x_1 + 2x_2 = 5$$

$$2x_1 - 4x_2 = 6$$

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## Activity 3.10

Consider the following consistent linear system.

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

$$2x_1 - 4x_2 = 6$$



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## Activity 3.10

Consider the following consistent linear system.

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

$$2x_1 - 4x_2 = 6$$

*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.

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## Activity 3.10

Consider the following consistent linear system.

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

$$2x_1 - 4x_2 = 6$$

*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  $a$ .

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## Activity 3.11

Consider the following linear system.

$$x_1 + 2x_2 - x_4 = 3$$

$$x_3 + 4x_4 = -2$$

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  $x_3$ .

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## 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.

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Remark 3.13

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

Original linear system:	Verbose standard form:	Coefficients/constants:
$x_1 + 3x_3 = 3$	$1x_1 + 0x_2 + 3x_3 = 3$	$1 \quad 0 \quad 3 \mid 3$
$3x_1 - 2x_2 + 4x_3 = 0$	$3x_1 - 2x_2 + 4x_3 = 0$	$3 \quad -2 \quad 4 \mid 0$
$-x_2 + x_3 = -2$	$0x_1 - 1x_2 + 1x_3 = -2$	$0 \quad -1 \quad 1 \mid -2$

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### 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**.

$$a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = b_1$$

$$a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = b_2$$

$$\vdots \qquad \qquad \qquad \vdots \qquad \qquad \qquad \vdots \qquad \qquad \qquad \vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = b_m$$

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

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

$$3x_1 - 2x_2 = 1$$

$$x_1 + 4x_2 = 5$$

$$3x_1 - 2x_2 = 1$$

$$4x_1 + 2x_2 = 6$$

Therefore these augmented matrices are equivalent:

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

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

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## Activity 3.16

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



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# Application Activities - Module E Part 2 - Class Day 4

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## 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

Consider the following two linear systems.

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

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

$$-1x_1 + 3x_2 - 6x_3 = 11$$

$$x_1 - x_2 + 5x_3 = 1$$

$$x_2 - 2x_3 = 3$$

$$x_3 = 2$$

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### Module S

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### Module A

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### Module G

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## Activity 4.2

Consider the following two linear systems.

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

$$x_1 - x_2 + 5x_3 = 1$$

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

$$x_2 - 2x_3 = 3$$

$$-1x_1 + 3x_2 - 6x_3 = 11$$

$$x_3 = 2$$

*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  $\frac{1}{3}$ .

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## Activity 4.2

Consider the following two linear systems.

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

$$x_1 - x_2 + 5x_3 = 1$$

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

$$x_2 - 2x_3 = 3$$

$$-1x_1 + 3x_2 - 6x_3 = 11$$

$$x_3 = 2$$

*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).

③ Add  $R_1$  to  $R_3$ .

④ Add  $-3R_1$  to  $R_2$ .

⑤ Add  $-2R_2$  to  $R_3$ .

② Multiply  $R_2$  by  $\frac{1}{2}$ .

⑥ Multiply  $R_3$  by  $\frac{1}{3}$ .

*Part 2:* Which linear system would you rather solve?

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Part 1 (Day 25)

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## Module E

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## 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:

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

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

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

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## Activity 4.4

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.

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## Activity 4.5

Solve this simplified linear system:

$$x_1 - x_2 + 5x_3 = 1$$

$$x_2 - 2x_3 = 3$$

$$x_3 = 2$$



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# Observation 4.6

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

$$\begin{array}{rcl} x_1 & = & -2 \\ x_2 & = & 7 \\ x_3 & = & 2 \end{array}$$

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

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**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:

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

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

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

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## Activity 4.8

Show that the following two linear systems:

$$x_1 - x_2 + 5x_3 = 1$$

$$x_2 - 2x_3 = 3$$

$$x_3 = 2$$

$$x_1 = -2$$

$$x_2 = 7$$

$$x_3 = 2$$

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

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**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

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

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

$$-1x_1 + 3x_2 - 6x_3 = 11$$

by plugging the solution into each equation.

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## Fact 4.10

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

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## Activity 4.11

Consider the following matrix.

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

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**Activity 4.11**

Consider the following matrix.

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

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

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**Activity 4.11**

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?



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# Application Activities - Module E Part 3 - Class Day 5

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## 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:

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

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## 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  $A$ .

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**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  $a$ .

$$2x_1 - 2x_2 - 6x_3 + x_4 = 3$$

$$-x_1 + x_2 + 3x_3 - x_4 = -3$$

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

$$x_1 - 5x_3 = 1$$

$$x_2 - 2x_3 = 1$$

$$x_4 = 3$$

$$x_1 = 1 + 5a$$

$$x_2 = 1 + 2a$$

$$x_3 = a$$

$$x_4 = 3$$

 $\Rightarrow$ 

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

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

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## Activity 5.5

Solve the system of linear equations, circling the pivot positions in your augmented matrices as you work.

$$-x_1 + x_2 - 3x_3 + 2x_4 = 0$$

$$2x_1 - x_2 + 5x_3 + 3x_4 = -11$$

$$3x_1 + 2x_2 + 4x_3 + x_4 = 1$$

$$x_2 - x_3 + x_4 = 1$$

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  $a$ .

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**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.

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**Activity 5.7**

Solve the linear system

$$2x_1 - 3x_2 = 17$$

$$x_1 + 2x_2 = -2$$

$$-x_1 - x_2 = 1$$



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# Activity 5.8

Show that all linear systems of the form

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

are consistent by finding a quickly verifiable solution.

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# Definition 5.9

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

$$a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n = 0$$

$$a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n = 0$$

$$\vdots \qquad \qquad \qquad \vdots \qquad \qquad \qquad \vdots \qquad \vdots$$

$$a_{m1}x_1 + a_{m2}x_2 + \dots + a_{mn}x_n = 0$$

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**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:

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

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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:

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

$$\text{Basis} = \left\{ \begin{bmatrix} 3 \\ 1 \\ -1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\}$$

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## Activity 5.12

Find a basis for the solution set of the following homogeneous linear system.

$$x_1 + 2x_2 \quad - \quad x_4 = 0$$

$$x_3 + 4x_4 = 0$$

$$2x_1 + 4x_2 + x_3 + 2x_4 = 0$$

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# Module V: Vector Spaces

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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.

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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).**



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The following resources will help you prepare for this module.

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

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## Activity 7.1

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 commutivity.**

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

**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.**

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

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

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## 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.

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## Activity 7.4

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

$c \odot (x, y) = (cx, y^c)$ .

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## Activity 7.4

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.**

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

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## Activity 7.4

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?



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## 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.
- $\mathbb{R}^\infty$ : 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.

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## Activity 8.2

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.

- **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.**

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

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## 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

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

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## Definition 8.4

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

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

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# Activity 8.5

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

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Part 1 (Day 7)  
**Part 2 (Day 8)**  
Part 3 (Day 9)  
Part 4 (Day 10)

## Module S

Part 1 (Day 12)  
Part 2 (Day 13)  
Part 3 (Day 14)

## Module A

Part 1 (Day 17)  
Part 2 (Day 18)  
Part 3 (Day 19)

## Module M

Part 1 (Day 21)  
Part 2 (Day 22)  
Part 3 (Day 23)

## Module G

Part 1 (Day 25)  
Part 2 (Day 26)  
Part 3 (Day 27)  
Part 4 (Day 28)

## Activity 8.5

Consider span  $\left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right\}$ .

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

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

**Part 2 (Day 8)**

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 8.5**

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.



## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

**Part 2 (Day 8)**

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 8.6

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

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 8.6**

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:  $1 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 0 \begin{bmatrix} -1 \\ 1 \end{bmatrix},$

$$0 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1 \begin{bmatrix} -1 \\ 1 \end{bmatrix}, 2 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 0 \begin{bmatrix} -1 \\ 1 \end{bmatrix}, 2 \begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1 \begin{bmatrix} -1 \\ 1 \end{bmatrix}.$$

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

**Part 2 (Day 8)**

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

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Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 8.6**

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.

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

**Part 2 (Day 8)**

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 8.7

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.

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Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

**Part 2 (Day 8)**

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 8.8**

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

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Part 1 (Day 3)

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Part 3 (Day 5)

## Module V

Part 1 (Day 7)

**Part 2 (Day 8)**

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

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Part 2 (Day 13)

Part 3 (Day 14)

## Module A

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Part 3 (Day 19)

## Module M

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Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 8.8

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

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

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## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 8.8**

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

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

**Part 2 (Day 8)**

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 8.8**

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  $x_1 \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix} + x_2 \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix} = \begin{bmatrix} -1 \\ -6 \\ 1 \end{bmatrix}$  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  $\text{span} \left\{ \begin{bmatrix} 1 \\ 0 \\ -3 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix} \right\}$ ?



Module E

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Module S

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Module A

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Module M

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# Application Activities - Module V Part 3 - Class Day 9

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## Module A

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Part 2 (Day 18)

Part 3 (Day 19)

## Module M

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**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.

Module E

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Module A

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- Part 3 (Day 27)
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# Remark 9.2

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

Module E

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Module S

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Module A

- Part 1 (Day 17)
- Part 2 (Day 18)
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Module M

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Module G

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- Part 3 (Day 27)
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Activity 9.3

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.

Module E

- Part 1 (Day 3)
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- Part 3 (Day 5)

Module V

- Part 1 (Day 7)
- Part 2 (Day 8)
- Part 3 (Day 9)**
- Part 4 (Day 10)

Module S

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- Part 2 (Day 13)
- Part 3 (Day 14)

Module A

- Part 1 (Day 17)
- Part 2 (Day 18)
- Part 3 (Day 19)

Module M

- Part 1 (Day 21)
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Module G

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Activity 9.4

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.

## Module E

Part 1 (Day 3)

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## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

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Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

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Part 3 (Day 27)

Part 4 (Day 28)

## 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.

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Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

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## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 9.6

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  $\text{span}\{x^2 - 3, -x^2 - 3x + 2\}$ ?

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

**Part 3 (Day 9)**

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 9.7**

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



Module E

Part 1 (Day 3)  
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Part 2 (Day 8)  
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Part 4 (Day 10)

Module S

Part 1 (Day 12)  
Part 2 (Day 13)  
Part 3 (Day 14)

Module A

Part 1 (Day 17)  
Part 2 (Day 18)  
Part 3 (Day 19)

Module M

Part 1 (Day 21)  
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Module G

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## Activity 9.8

Does the complex number  $2i$  belong to  $\text{span}\{-3 + i, 6 - 2i\}$ ?

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

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Part 1 (Day 7)

Part 2 (Day 8)

**Part 3 (Day 9)**

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

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Part 3 (Day 27)

Part 4 (Day 28)

## Activity 9.9

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

Module E

Part 1 (Day 3)  
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Part 2 (Day 8)  
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Module S

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Part 2 (Day 13)  
Part 3 (Day 14)

Module A

Part 1 (Day 17)  
Part 2 (Day 18)  
Part 3 (Day 19)

Module M

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Module G

Part 1 (Day 25)  
Part 2 (Day 26)  
Part 3 (Day 27)  
Part 4 (Day 28)

## Activity 9.10

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

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

Module E

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Module S

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Module A

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Part 2 (Day 18)  
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Module M

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# Application Activities - Module V Part 4 - Class Day 10

## Module E

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Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

**Part 4 (Day 10)**

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

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

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 10.2**

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

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

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

**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:

$$\begin{bmatrix} 1 & -2 \\ -1 & 0 \\ 0 & 1 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \Rightarrow \begin{bmatrix} 1 & -2 & | & a \\ -1 & 0 & | & b \\ 0 & 1 & | & c \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & | & 0 \\ 0 & 1 & | & 0 \\ 0 & 0 & | & 1 \end{bmatrix}$$

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

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## Module G

Part 1 (Day 25)

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Part 3 (Day 27)

Part 4 (Day 28)

**Activity 10.4**

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

$\mathbb{R}^4 = \text{span } S$ ?



## Module E

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## Module S

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## Module A

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## Activity 10.5

Consider the set of third-degree polynomials

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

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

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## Definition 10.6

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

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## Fact 10.7

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

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## 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  $c, d$ .

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**Activity 10.9**

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  $P$ .

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**Activity 10.10**

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.

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**Fact 10.11**

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

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## Module A

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**Activity 10.12**

Show that the set of  $2 \times 2$  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  $S$ .



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## Module S: Structure of vector spaces

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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.

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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)**.

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The following resources will help you prepare for this module.

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

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# Application Activities - Module S Part 1 - Class Day 12

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## Activity 12.1

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.

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## 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**.

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## Activity 12.3

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?



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**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

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.

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## Module E

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**Fact 12.6**

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

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**Activity 12.7**

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?

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## Activity 12.8

Is the set of polynomials  $\{x^3 + 1, x^2 + 2, 4 - 7x, 2x^3 + x\}$  linearly dependent or linearly independent?

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# Application Activities - Module S Part 2 - Class Day 13

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## Activity 13.1

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

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# Definition 13.2

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



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# 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

Which of the following sets are bases for  $\mathbb{R}^4$ ?

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

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## Activity 13.5

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  $\text{RREF}[\mathbf{v}_1 \ \mathbf{v}_2 \ \mathbf{v}_3 \ \mathbf{v}_4]$ ?

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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.

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## Activity 13.7

Consider the set  $\left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 2 \\ 0 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \\ 2 \\ -3 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ -1 \\ 0 \end{bmatrix} \right\}.$

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## Activity 13.7

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 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.

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## Module S

Part 1 (Day 12)

**Part 2 (Day 13)**

Part 3 (Day 14)

## Module A

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Part 2 (Day 18)

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## Module M

Part 1 (Day 21)

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**Activity 13.7**

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

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# Application Activities - Module S Part 3 - Class Day 14



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## 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  $\text{RREF}[\mathbf{v}_1 \ \dots \ \mathbf{v}_m]$ .

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# Activity 14.2

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  $S$ .

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## Activity 14.3

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?

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

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## 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**Find the dimension of each subspace of  $\mathbb{R}^4$ .

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

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

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

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

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

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## Module E

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## Activity 14.7

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

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## Activity 14.8

What is the dimension of the vector space of all polynomials  $\mathcal{P}$ ?

a) 6

b) 7

c) 8

d) infinite



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## 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  $\mathbb{R}^\infty$  (consider the set  $\{(1, 0, 0, \dots), (0, 1, 0, \dots), (0, 0, 1, \dots), \dots\}$ ).

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**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  $\mathbb{R}^n$ :

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

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# Module A: Algebraic properties of linear maps

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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.

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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**).

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The following resources will help you prepare for this module.

- Review the supporting Standards listed above.

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## Application Activities - Module A Part 1 - Class Day 17

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## 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.



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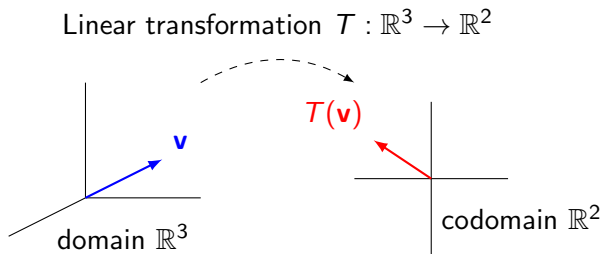
Part 2 (Day 26)

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**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  $T$ .



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## Example 17.3

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

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

**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...

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

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

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**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...

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

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

And also...

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

Therefore  $T$  is a linear transformation.

Determine if each of the following maps are linear transformations

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## Activity 17.4

Determine if each of the following maps are linear transformations

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

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**Activity 17.4**

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  $T_2 \left( \begin{bmatrix} x \\ y \\ z \end{bmatrix} \right) = \begin{bmatrix} -x \\ -y \\ -z \end{bmatrix}$

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## Module G

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Part 2 (Day 26)

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**Activity 17.4**

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  $T_3(f(x)) = f'(x)$ .



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## Module S

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## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

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Part 4 (Day 28)

**Activity 17.4**

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  $T_4(f(x)) = f(x) + x^2$

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## Module G

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## Activity 17.5

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

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**Activity 17.6**

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

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## Activity 17.7

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

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## Activity 17.8

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

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**Activity 17.9**

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**  $T$ .)

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**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.

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

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**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**  $[T(\mathbf{e}_1) \ \dots \ T(\mathbf{e}_n)]$ .



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**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  $\mathbb{R}^3$ .

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

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

$$T \left( \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} 5 \\ 0 \end{bmatrix}$$

Then the standard matrix corresponding to  $T$  is

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

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**Activity 17.13**

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.

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**Activity 17.14**

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

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## Activity 17.15

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.)

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**Activity 17.15**

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  $\mathbb{R}^3$ .

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**Activity 17.15**

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  $T$ .

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# Application Activities - Module A Part 2 - Class Day 18

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## 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  $\mathbf{v} \neq \mathbf{w}$ .



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**Activity 18.2**

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?

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**Activity 18.3**

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

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

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

Is  $T$  injective?

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## 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  $T(\mathbf{v}) = \mathbf{w}$ .

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**Activity 18.5**

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

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

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

Is  $T$  surjective?

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**Activity 18.6**

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

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

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

Is  $T$  surjective?

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## Definition 18.7

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

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

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## Activity 18.8

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  $T$ .

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## Activity 18.9

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  $T$ .



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## Activity 18.10

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

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

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**Activity 18.10**

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.

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**Activity 18.10**

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  $T$ .

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**Activity 18.10**

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  $T$ .

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## Definition 18.11

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

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

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## Activity 18.12

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  $T$ .

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## Activity 18.13

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  $T$ .

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## Activity 18.14

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

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



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**Activity 18.14**

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  $\text{span } S = \text{Im } T$ .

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**Activity 18.14**

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  $\text{span } S = \text{Im } T$ .

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

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**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  $A$ .

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## Application Activities - Module A Part 3 - Class Day 19

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## 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 **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  $W$ .

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## Activity 19.2

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  $T(\mathbf{v} - \mathbf{w})$ ?)

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## 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.

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## Activity 19.4

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?



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## 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.

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**Activity 19.6**

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

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

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## Activity 19.8

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  $\mathbf{b} \in \mathbb{R}^m$ .

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**Activity 19.9**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.

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**Activity 19.10**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.

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**Activity 19.11**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.

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**Activity 19.12**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.



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# Module M: Understanding Matrices Algebraically

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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.

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Part 3 (Day 19)

Module M

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Part 2 (Day 22)  
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Module G

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Part 4 (Day 28)

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

#### Module E

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#### Module V

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#### Module S

Part 1 (Day 12)  
Part 2 (Day 13)  
Part 3 (Day 14)

#### Module A

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#### Module M

Part 1 (Day 21)  
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The following resources will help you prepare for this module.

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

Module E

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Module V

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Module S

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- Part 2 (Day 13)
- Part 3 (Day 14)

Module A

- Part 1 (Day 17)
- Part 2 (Day 18)
- Part 3 (Day 19)

Module M

- Part 1 (Day 21)**
- Part 2 (Day 22)
- Part 3 (Day 23)

Module G

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- Part 4 (Day 28)

# Application Activities - Module M Part 1 - Class Day 21

## Module E

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## Module V

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Part 4 (Day 10)

## Module S

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## Module A

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Part 3 (Day 19)

## Module M

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Part 3 (Day 23)

## Module G

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Part 3 (Day 27)  
Part 4 (Day 28)

## Activity 21.1

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)  $\mathbb{R}^4$

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

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Part 3 (Day 27)

Part 4 (Day 28)

## Activity 21.2

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)  $\mathbb{R}^4$

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 21.3**

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)  $4 \times 3$  matrices

(b)  $4 \times 2$  matrices

(c)  $3 \times 2$  matrices

(d)  $2 \times 3$  matrices

(e)  $2 \times 4$  matrices

(f)  $3 \times 4$  matrices



## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

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Part 2 (Day 8)

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## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 21.4

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

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

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**Activity 21.4**

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  $(S \circ T)(\mathbf{e}_1)$

## Module E

Part 1 (Day 3)

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Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 21.4

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  $(S \circ T)(\mathbf{e}_2)$

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 21.4

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  $(S \circ T)(\mathbf{e}_3)$ .

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 21.4

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  $S \circ T$ .

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

Part 4 (Day 28)

**Activity 21.5**

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)  $\mathbb{R}^4$

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

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Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

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## Module M

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## Module G

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Part 3 (Day 27)

Part 4 (Day 28)

**Activity 21.6**

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)  $\mathbb{R}^4$

## Module E

Part 1 (Day 3)

Part 2 (Day 4)

Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

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Part 3 (Day 23)

## Module G

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Part 3 (Day 27)

Part 4 (Day 28)

**Activity 21.7**

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)  $2 \times 2$  matrices
- (b)  $2 \times 3$  matrices
- (c)  $3 \times 2$  matrices
- (d)  $3 \times 3$  matrices



## Module E

Part 1 (Day 3)

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Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

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## Module M

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Part 3 (Day 23)

## Module G

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Part 3 (Day 27)

Part 4 (Day 28)

## Activity 21.8

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  $S \circ T$ .

## Module E

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Part 3 (Day 5)

## Module V

Part 1 (Day 7)  
Part 2 (Day 8)  
Part 3 (Day 9)  
Part 4 (Day 10)

## Module S

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Part 3 (Day 14)

## Module A

Part 1 (Day 17)  
Part 2 (Day 18)  
Part 3 (Day 19)

## Module M

Part 1 (Day 21)  
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Part 3 (Day 23)

## Module G

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Part 3 (Day 27)  
Part 4 (Day 28)

## Activity 21.9

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  $S \circ T$ .

## Module E

Part 1 (Day 3)

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Part 3 (Day 5)

## Module V

Part 1 (Day 7)

Part 2 (Day 8)

Part 3 (Day 9)

Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

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## Module G

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**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.

## Module E

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## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

**Part 1 (Day 21)**

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

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**Fact 21.11**

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

Module E

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Module V

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Module S

- Part 1 (Day 12)
- Part 2 (Day 13)
- Part 3 (Day 14)

Module A

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- Part 2 (Day 18)
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Module M

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Module G

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- Part 3 (Day 27)
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Activity 21.12

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  $AB$ .

## Module E

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Part 3 (Day 5)

## Module V

Part 1 (Day 7)  
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Part 3 (Day 9)  
Part 4 (Day 10)

## Module S

Part 1 (Day 12)  
Part 2 (Day 13)  
Part 3 (Day 14)

## Module A

Part 1 (Day 17)  
Part 2 (Day 18)  
Part 3 (Day 19)

## Module M

**Part 1 (Day 21)**  
Part 2 (Day 22)  
Part 3 (Day 23)

## Module G

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**Activity 21.13**

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

$$3x + y - z = 5$$

$$2x + 4z = -7$$

$$-x + 3y + 5z = 2$$

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

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

$$X = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

$$B = \begin{bmatrix} 5 \\ -7 \\ 2 \end{bmatrix}$$

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.

Module E

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Module S

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Part 2 (Day 13)  
Part 3 (Day 14)

Module A

Part 1 (Day 17)  
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Part 3 (Day 19)

Module M

Part 1 (Day 21)  
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# Application Activities - Module M Part 2 - Class Day 22



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Module S

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Module A

- Part 1 (Day 17)
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Module M

- Part 1 (Day 21)
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Module G

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Activity 22.1

Let  $A = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$ . Find a  $3 \times 3$  matrix  $I$  such that  $IA = A$ , that is,

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

## Module E

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Part 2 (Day 8)

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Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

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**Definition 22.2**

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

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

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

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## Module S

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Part 3 (Day 14)

## Module A

Part 1 (Day 17)

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Part 3 (Day 19)

## Module M

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## Module G

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**Fact 22.3**

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

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

Module E

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Module A

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Module M

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# Activity 22.4

Each row operation can be interpreted as a type of matrix multiplication.

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## Activity 22.4

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  $A$ :

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

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## Activity 22.4

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  $A$ :

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

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## Activity 22.4

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:

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

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**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.



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**Activity 22.6**

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)
- (b)  $T$  is surjective (i.e. onto)
- (c)  $T$  is bijective (i.e. both injective and surjective)
- (d)  $AX = B$  has a solution for all  $m \times 1$  matrices  $B$
- (e)  $AX = B$  has a unique solution for all  $m \times 1$  matrices  $B$
- (f)  $AX = 0$  has a unique 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) Every column of  $\text{RREF}(A)$  has a pivot
- (k) Every row of  $\text{RREF}(A)$  has a pivot
- (l)  $m = n$  and  $\text{RREF}(A) = I$

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## Activity 22.7

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

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## Activity 22.8

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

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## Activity 22.9

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

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# Application Activities - Module M Part 3 - Class Day 23

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## 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**.

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**Activity 23.2**

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

$$T^{-1} \left( \begin{bmatrix} x \\ y \end{bmatrix} \right) = \begin{bmatrix} 5x + 3y \\ 3x + 2y \end{bmatrix}.$$

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**Activity 23.2**

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



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**Activity 23.2**

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?

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**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  $A$ .

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## Activity 23.4

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

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**Activity 23.4**

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  $T^{-1}(\mathbf{e}_1)$ .

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## Activity 23.4

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  $T^{-1}(\mathbf{e}_2)$ .

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## Activity 23.4

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  $T^{-1}(\mathbf{e}_3)$ .

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## Activity 23.4

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  $T^{-1}$ .

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**Observation 23.5**

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

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



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## Activity 23.6

Find the inverse  $A^{-1}$  of the matrix  $A = \begin{bmatrix} 1 & 3 \\ 0 & -2 \end{bmatrix}$  by row-reducing  $[A \mid I]$ .

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**Activity 23.7**

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

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## Observation 23.8

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

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Part 3 (Day 14)

## Module A

Part 1 (Day 17)

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## Module M

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## Module G

Part 1 (Day 25)

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Part 4 (Day 28)

## Module G: Geometry of Linear Maps

Module E

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Module V

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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.

## Module E

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## Module G

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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.

## Module E

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## Module S

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Part 2 (Day 13)

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## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

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## Module G

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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-quadratic-forms-alg2/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](https://artofproblemsolving.com/wiki/index.php?title=Rational_Root_Theorem)

Module E

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Module G

**Part 1 (Day 25)**  
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Part 4 (Day 28)

# Application Activities - Module G Part 1 - Class Day 25



## Module E

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## Module S

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Part 3 (Day 19)

## Module M

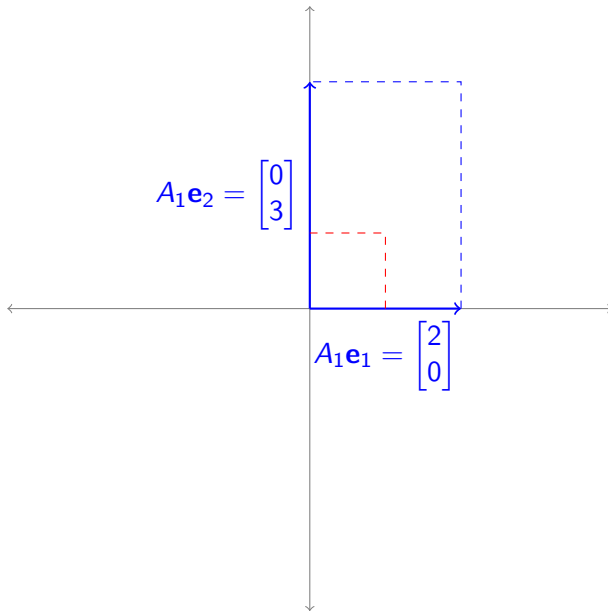
Part 1 (Day 21)  
Part 2 (Day 22)  
Part 3 (Day 23)

## Module G

**Part 1 (Day 25)**  
Part 2 (Day 26)  
Part 3 (Day 27)  
Part 4 (Day 28)

## Observation 25.1

Consider the linear transformation  $A_1 : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the matrix  $A_1 = \begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}$



## Module E

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## Module G

**Part 1 (Day 25)**  
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## Activity 25.2

Consider the linear transformation  $A_2 : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the matrix  $A_2 = \begin{bmatrix} 2 & 3 \\ 0 & 1 \end{bmatrix}$ .

- (a) 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?

## Module E

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## Module A

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## Module M

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## Module G

**Part 1 (Day 25)**

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**Activity 25.3**

Consider the linear transformation  $A_2 : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the matrix

$$A_3 = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$$

- (a) 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?

## Module E

Part 1 (Day 3)  
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## Module G

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## Activity 25.4

Consider the linear transformation  $A_2 : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the matrix  $A_4 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$

- (a) 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?

## Module E

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## Activity 25.5

Consider the linear transformation  $A_2 : \mathbb{R}^2 \rightarrow \mathbb{R}^2$  given by the matrix  $A_5 = \begin{bmatrix} 1 & 1 \\ 0 & 0 \end{bmatrix}$

- (a) 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?

## Module E

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## Definition 25.6

Our goal is to define a function 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**, and we denote it  $\det$ .

What properties should this function have?

**Activity 25.7**

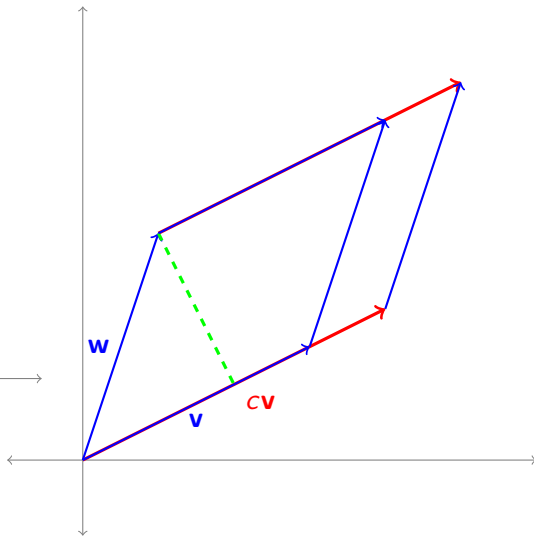
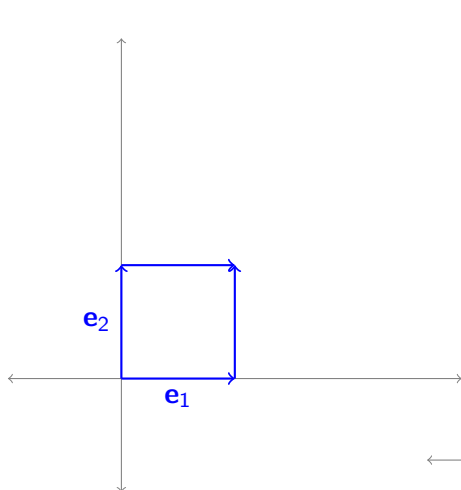
Match the four pictures to the following four expressions

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

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

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

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



## Module E

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## Module G

**Part 1 (Day 25)**

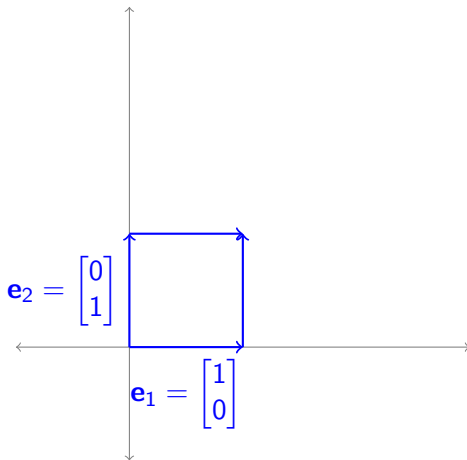
Part 2 (Day 26)

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Part 4 (Day 28)

## Activity 25.8

Based on the picture below, what is  $\det(\mathbf{e}_1, \mathbf{e}_2)$ ?



### Module E

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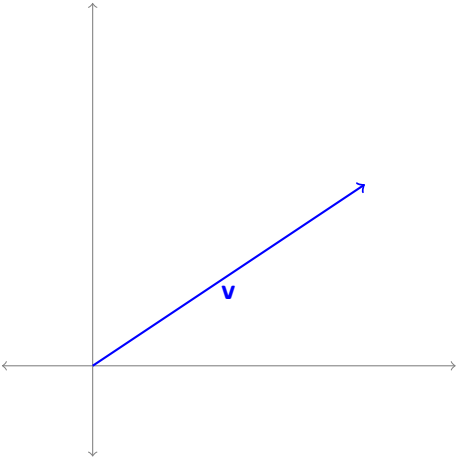
### Module G

- Part 1 (Day 25)**
- Part 2 (Day 26)
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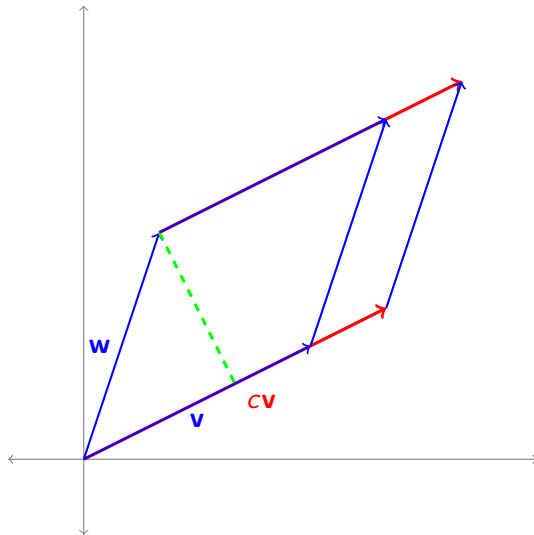
# Activity 25.9

Based on the picture below, what is  $\det(\mathbf{v}, \mathbf{v})$  for any vector  $\mathbf{v}$ ?



## Activity 25.10

Based on the picture below, how are  $\det(\mathbf{v}, \mathbf{w})$  and  $\det(c\mathbf{v}, \mathbf{w})$  related?



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## Module E

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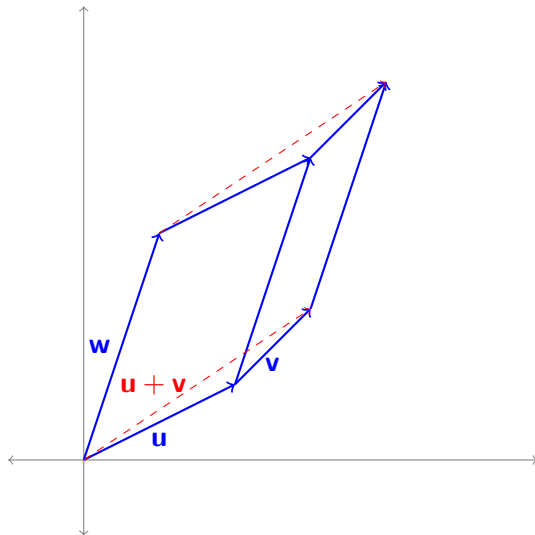
Part 1 (Day 21)  
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## Module G

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## Activity 25.11

Based on the picture below, how is  $\det(\mathbf{u} + \mathbf{v}, \mathbf{w})$  related to  $\det(\mathbf{u}, \mathbf{w})$  and  $\det(\mathbf{v}, \mathbf{w})$ ?



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## Definition 25.12

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.

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## Module G

**Part 1 (Day 25)**

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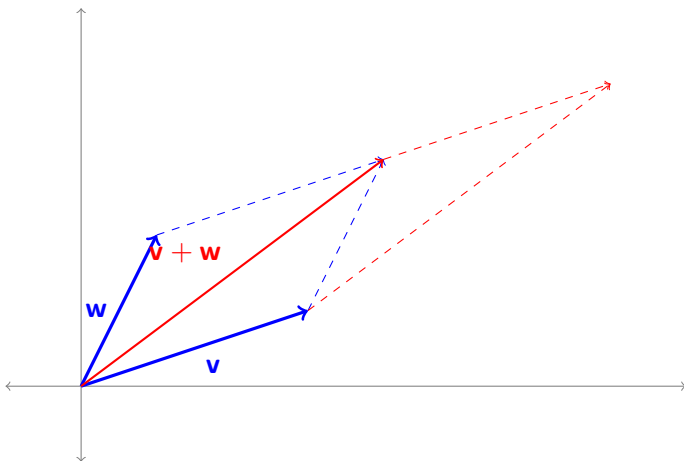
**Observation 25.13**

Note that if  $\mathbf{v}, \mathbf{w} \in \mathbb{R}^2$  and  $A = \begin{bmatrix} \mathbf{v} & \mathbf{w} \end{bmatrix}$  we will write either  $\det(A)$  or  $\det(\mathbf{v}, \mathbf{w})$  as is convenient.

# Activity 25.14

True or false:

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



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## Module E

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## Observation 25.15

$$\det(\mathbf{v}, \mathbf{w}) = \det(\mathbf{v} + \mathbf{w}, \mathbf{w}) = \det(\mathbf{v} + \mathbf{w}, -\mathbf{v}) = \det(\mathbf{w}, -\mathbf{v}).$$

Therefore,  $\det(\mathbf{w}, \mathbf{v}) = -\det(\mathbf{v}, \mathbf{w})$

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

## Module E

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## Observation 25.16

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

- (a) Multiplying a column by a scalar multiplies the determinant by that scalar.
- (b) Adding a multiple of a column to another column does not change the determinant.
- (c) Swapping two columns changes the sign of the determinant.



Module E

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# Application Activities - Module G Part 2 - Class Day 26

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## Module V

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## Module S

Part 1 (Day 12)

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## Module A

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## Module M

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## 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.

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## Fact 26.2

Row operations change the determinant in the following way

- ➊ Adding a multiple of one row to another does not change the determinant.
- ➋ Multiplying a row by a scalar multiplies the determinant by the same amount.
- ➌ Swapping two rows multiplies the determinant by  $-1$ .

Module E

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**Activity 26.3**  
Compute  $\det \begin{bmatrix} 4 & 5 \\ 2 & 3 \end{bmatrix}$  by using row reduction.

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## Activity 26.4

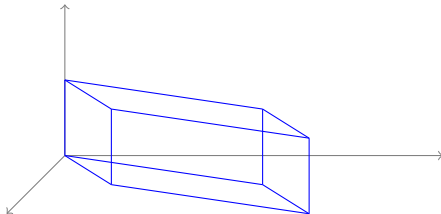
Which of the following is the same as  $\det \begin{bmatrix} 3 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$  ? 2

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

(b)  $\det \begin{bmatrix} 3 & 1 \\ 1 & 0 \end{bmatrix}$

(c)  $\det \begin{bmatrix} 3 & 1 \\ 0 & 1 \end{bmatrix}$

(d) None of these



## Module E

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## Module A

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## Module G

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## Module E

Part 1 (Day 3)

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Part 3 (Day 5)

## Module V

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Part 4 (Day 10)

## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

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## Module G

Part 1 (Day 25)

**Part 2 (Day 26)**

Part 3 (Day 27)

Part 4 (Day 28)

## Activity 26.5

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

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Module S

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Module A

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Module M

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Activity 26.6

Compute  $\det \begin{bmatrix} 0 & 3 & -2 \\ 1 & 5 & 12 \\ 0 & 2 & -1 \end{bmatrix}$



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Module M

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Module G

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Activity 26.7

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

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Module S

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Module A

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Module M

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- Part 3 (Day 27)
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Activity 26.8

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

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- Part 3 (Day 5)

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- Part 4 (Day 10)

- Part 1 (Day 12)
- Part 2 (Day 13)
- Part 3 (Day 14)

Part 1 (Day 17)  
Part 2 (Day 18)  
Part 3 (Day 19)

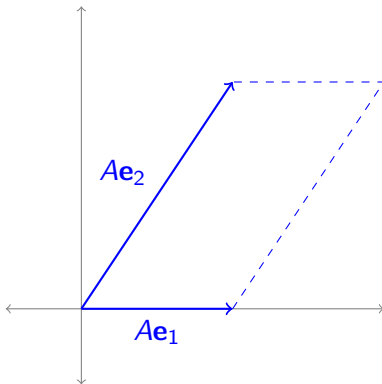
Part 1 (Day 21)  
Part 2 (Day 22)  
Part 3 (Day 23)

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Part 2 (Day 26)  
**Part 3 (Day 27)**  
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## Application Activities - Module X Part 3 - Class Day 27

## Activity 27.1

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

$$Ae_1 = A \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 2 \begin{bmatrix} 1 \\ 0 \end{bmatrix} = 2e_1$$

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

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## Module S

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Part 2 (Day 13)

Part 3 (Day 14)

## Module A

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Part 2 (Day 18)

Part 3 (Day 19)

## Module M

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Part 3 (Day 23)

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Part 2 (Day 26)

**Part 3 (Day 27)**

Part 4 (Day 28)

## 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  $\lambda$ , which is called an **eigenvalue**

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## 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  $\lambda$  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.

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## Activity 27.4

Let  $A = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix}$ .

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## Module V

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## Module S

Part 1 (Day 12)

Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

Part 2 (Day 18)

Part 3 (Day 19)

## Module M

Part 1 (Day 21)

Part 2 (Day 22)

Part 3 (Day 23)

## Module G

Part 1 (Day 25)

Part 2 (Day 26)

**Part 3 (Day 27)**

Part 4 (Day 28)

**Activity 27.4**

Let  $A = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix}$ .

*Part 1:* Find the eigenvalues of  $A$ .



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Part 3 (Day 14)

## Module A

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Part 2 (Day 26)

**Part 3 (Day 27)**

Part 4 (Day 28)

**Activity 27.4**

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.

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# Activity 27.5

Find all the eigenvalues and associated eigenspaces for the matrix

$$\begin{bmatrix} 6 & -2 & 1 \\ 17 & -5 & 5 \\ -4 & 2 & 1 \end{bmatrix}.$$

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## Application Activities - Module X Part 4 - Class Day 28

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## Activity 28.1

If  $A$  is a  $4 \times 4$  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

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## Activity 28.2

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  $B$ .

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## Module S

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Part 2 (Day 13)

Part 3 (Day 14)

## Module A

Part 1 (Day 17)

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## Module M

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## 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.

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## Module S

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## Module A

Part 1 (Day 17)

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## Module M

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## Activity 28.4

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.

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## Activity 28.5

Find the eigenvalues, along with both their algebraic and geometric multiplicities,

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



Module E

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Module A

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Module M

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Module G

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# Activity 28.6

Let  $A = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ .

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Part 4 (Day 10)

## Module S

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Part 3 (Day 14)

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## Module M

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## Module G

Part 1 (Day 25)

Part 2 (Day 26)

Part 3 (Day 27)

**Part 4 (Day 28)**

## Activity 28.6

Let  $A = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ .

*Part 1:* Find the eigenvalues of  $A$

## Module E

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## Activity 28.6

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.