Linear Algebra for Team-Based Inquiry Learning

2024 Edition PREVIEW

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Website: Linear Algebra for Team-Based Inquiry Learning[1]

[1] linear.tbil.org

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TBIL Resource Library

This work is made available as part of the TBIL Resource Library[3], a product of NSF DUE Award #2011807[4].

[3] sites.google.com/southalabama.edu/tbil
[4] nsf.gov/awardsearch/showAward?AWD_ID=2011807

For Instructors

If you are adopting this text in your class, please fill out this short form[5] so we can track usage, let you know about updates, etc.

[5] forms.gle/Ktfbma6iBn2gN1W78

Video Resources

Videos are available at the end of each section. A complete playlist of videos aligned with this text is available on YouTube[6].

[6] www.youtube.com/watch?v=kpOK7RhFEiQ&list=PLwXCBkIf7xBMo3zMnD7WVt39rANLlSdmj

Slideshows

Slides for each section are available in HTML format.

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[7] teambasedinquirylearning.github.io/linear-algebra/2023/LE1.slides.html
[8] teambasedinquirylearning.github.io/linear-algebra/2023/LE2.slides.html
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[16] teambasedinquirylearning.github.io/linear-algebra/2023/EV6.slides.html
[17] teambasedinquirylearning.github.io/linear-algebra/2023/EV7.slides.html
[18] teambasedinquirylearning.github.io/linear-algebra/2023/AT1.slides.html
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[21] teambasedinquirylearning.github.io/linear-algebra/2023/AT4.slides.html
[22] teambasedinquirylearning.github.io/linear-algebra/2023/AT5.slides.html

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[23] teambasedinquirylearning.github.io/linear-algebra/2023/AT6.slides.html
[24] teambasedinquirylearning.github.io/linear-algebra/2023/MX1.slides.html
[25] teambasedinquirylearning.github.io/linear-algebra/2023/MX2.slides.html
[26] teambasedinquirylearning.github.io/linear-algebra/2023/MX3.slides.html
[27] teambasedinquirylearning.github.io/linear-algebra/2023/MX4.slides.html
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[31] teambasedinquirylearning.github.io/linear-algebra/2023/GT4.slides.html
[32] teambasedinquirylearning.github.io/linear-algebra/2023/truss.slides.html
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Chapter 1

Systems of Linear Equations (LE)

Learning Outcomes

How can we solve systems of linear equations?

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

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

Readiness Assurance. Before beginning this chapter, you should be able to...

1. Determine if a system to a two-variable system of linear equations will have zero, one, or infinitely-many solutions by graphing.
   - Review: Khan Academy[1]
2. Find the unique solution to a two-variable system of linear equations by back-substitution.
   - Review: Khan Academy[2]
3. Describe sets using set-builder notation, and check if an element is a member of a set described by set-builder notation.
   - Review: YouTube[3]

[1] bit.ly/2l21etm

[2] www.khanacademy.org/math/algebra-basics/alg-basics-systems-of-equations/alg-basics-solving-systems-with-substitution/v/practice-using-substitution-for-systems

[3] youtu.be/xnfUZ-NTsCE

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

Learning Outcomes

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

1.1.1 Class Activities

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

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

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

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

that satisfies

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

(that is, a Euclidean vector that can be plugged into the equation). ♢

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

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

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

Its **solution set** is given by

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

♢

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

Original linear system:	Verbose standard form:	Concise standard form:
$$\begin{aligned} x_1 + 3x_3 &= 3 \\ 3x_1 - 2x_2 + 4x_3 &= 0 \\ -x_2 + x_3 &= -2 \end{aligned}$$	$$\begin{aligned} 1x_1 + 0x_2 + 3x_3 &= 3 \\ 3x_1 - 2x_2 + 4x_3 &= 0 \\ 0x_1 - 1x_2 + 1x_3 &= -2 \end{aligned}$$	$$\begin{alignedat}{4} x_1 & & &+3x_3 &&= 3 \\ 3x_1 &-2x_2 & &+4x_3 &&= 0 \\ &- x_2 & &+ x_3 &&= -2 \end{alignedat}$$

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

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

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

is equivalent to the system of equations

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

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

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

1. Consistent with one solution: *its solution set contains a single vector, e.g.* $\left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \right\}$
2. Consistent with infinitely-many solutions*: its solution set contains infinitely many vectors, e.g.* $\left\{ \begin{bmatrix} 1 \\ 2-3a \\ a \end{bmatrix} \middle| \, a \in \mathbb{R} \right\}$
3. Inconsistent*: its solution set is the empty set, denoted by either* $\{\}$ *or* $\emptyset$*.*

Activity 1.1.1 All inconsistent linear systems contain a logical **contradiction**. Find a contradiction in this system to show that its solution set is the empty set.

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

Activity 1.1.2 Consider the following consistent linear system.

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

(a) Find three different solutions for this system.

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

Activity 1.1.3 Consider the following linear system.

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

Describe the solution set

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

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

Observation 1.1.8 Solving linear systems of two variables by graphing or substitution is reasonable for two-variable systems, but these simple techniques won't usually cut it for equations with more than two variables or more than two equations. For example,

$$\begin{alignedat}{5} -2x_1 & - 4x_2 & + & x_3 & - & 4x_4 & = & -8 \\ x_1 & + 2x_2 & + & 2x_3 & + & 12x_4 & = & -1 \\ x_1 & + 2x_2 & + & x_3 & + & 8x_4 & = & 1 \end{alignedat}$$

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

Remark 1.1.9 The only important information in a linear system are its coefficients and constants.

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

Definition 1.1.10 A system of m linear equations with n variables is often represented by writing its coefficients and constants in an **augmented matrix**.

$$\begin{alignedat}{5} a_{11}x_1 & + & a_{12}x_2 & + \ldots + & a_{1n}x_n & = & b_1 \\ a_{21}x_1 & + & a_{22}x_2 & + \ldots + & a_{2n}x_n & = & b_2 \\ \vdots & & \vdots & & \vdots & & \vdots \\ a_{m1}x_1 & + & a_{m2}x_2 & + \ldots + & a_{mn}x_n & = & b_m \end{alignedat}$$

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

$\Diamond$

Example 1.1.11 The corresponding augmented matrix for this system is obtained by simply writing the coefficients and constants in matrix form.

Linear system:

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

Augmented matrix:

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

Vector equation:

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

□

1.1.2 Videos

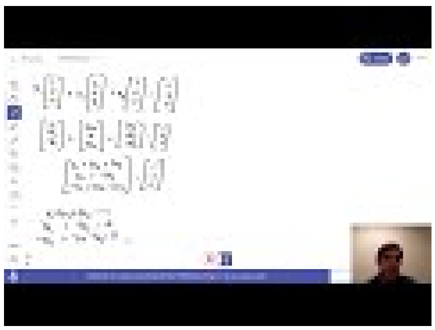


Figure 1 Video: Converting between systems, vector equations, and augmented matrices

1.1.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/LE1.slides.html.

1.1.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/LE1/.

1.1.5 Mathematical Writing Explorations

Exploration 1.1.4 Choose a value for the real constant k such that the following system has one, many, or no solutions. In each case, write the solution set.

Consider the linear system:

$$\begin{aligned} x_1 - x_2 &= 1 \\ 3x_1 - 3x_2 &= k \end{aligned}$$

Exploration 1.1.5 Consider the linear system:

$$\begin{aligned} ax_1 + bx_2 &= j \\ cx_1 + dx_2 &= k \end{aligned}$$

Assume j and k are arbitrary real numbers.

- Choose values for $a, b, c,$ and d, such that $ad - bc = 0$. Show that this system is inconsistent.

- Prove that, if $ad - bc \neq 0$, the system is consistent with exactly one solution.

Exploration 1.1.6 Given a set S, we can define a relation between two arbitrary elements $a, b \in S$. If the two elements are related, we denote this $a \sim b$.

Any relation on a set S that satisfies the properties below is an **equivalence relation**.

- **Reflexive**: For any $a \in S, a \sim a$
- **Symmetric**: For $a, b \in S$, if $a \sim b$, then $b \sim a$
- **Transitive:** for any $a, b, c \in S, a \sim b$ and $b \sim c$ implies $a \sim c$

For each of the following relations, show that it is or is not an equivalence relation.

- For $a, b, \in \mathbb{R}$, $a \sim b$ if an only if $a \leq b$.
- For $a, b, \in \mathbb{R}$, $a \sim b$ if an only if $|a| = |b|$.

1.1.6 Sample Problem and Solution

Sample problem Example B.1.1.

1.2 Row Reduction of Matrices (LE2)

Learning Outcomes

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

1.2.1 Class Activities

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

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

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

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

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

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

$\Diamond$

Activity 1.2.1 Following are seven 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 might 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.

G. Replace a row with zeros.

Definition 1.2.2 The following three **row operations** produce equivalent augmented matrices.

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

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

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

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

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

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

$\Diamond$

Activity 1.2.2 Consider the following (equivalent) linear systems.

A)

$$\begin{alignedat}{4} x &+ 2y &+ z &= 3 \\ -x &- y &+ z &= 1 \\ 2x &+ 5y &+ 3z &= 7 \end{alignedat}$$

B)

$$\begin{alignedat}{4} 2x &+ 5y &+ 3z &= 7 \\ -x &- y &+ z &= 1 \\ x &+ 2y &+ z &= 3 \end{alignedat}$$

C)

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

D)

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

E)

$$\begin{alignedat}{4} x & & - z &= 1 \\ & y &+ z &= 1 \\ & & z &= 3 \end{alignedat}$$

F)

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

Rank the six linear systems from most complicated to simplest.

Activity 1.2.3 We can rewrite the previous in terms of equivalences of augmented matrices

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

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

Determine the row operation(s) necessary in each step to transform the most complicated system's augmented matrix into the simplest.

Definition 1.2.3 A matrix is in **reduced row echelon form** (**RREF**) if

1. The leading term (first nonzero term) of each nonzero row is a 1. Call these terms **pivots**.
2. Each pivot is to the right of every higher pivot.
3. Each term above or below a pivot is zero.
4. All rows of zeroes are at the bottom of the matrix.

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

Activity 1.2.4 Recall that a matrix is in **reduced row echelon form** (**RREF**) if

1. The leading term (first nonzero term) of each nonzero row is a 1. Call these terms **pivots**.
2. Each pivot is to the right of every higher pivot.
3. Each term above or below a pivot is zero.
4. All rows of zeroes are at the bottom of the matrix.

For each matrix, circle the leading terms, and label it as RREF or not RREF. For the ones not in RREF, find their RREF.

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

Activity 1.2.5 Recall that a matrix is in **reduced row echelon form** (**RREF**) if

1. The leading term (first nonzero term) of each nonzero row is a 1. Call these terms **pivots**.
2. Each pivot is to the right of every higher pivot.
3. Each term above or below a pivot is zero.
4. All rows of zeroes are at the bottom of the matrix.

For each matrix, circle the leading terms, and label it as RREF or not RREF. For the ones not in RREF, find their RREF.

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

Remark 1.2.4 In practice, if we simply need to convert a matrix into reduced row echelon form, we use technology to do so.

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

Activity 1.2.6 Consider the matrix

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

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

A. Add row 3 to row 2 ($R_2 + R_3 \to R_2$)

B. Add row 2 to row 3 ($R_3 + R_2 \to R_3$)

C. Swap row 1 to row 2 ($R_1 \leftrightarrow R_2$)

D. Add -2 row 2 to row 1 ($R_1 - 2R_2 \to R_1$)

Activity 1.2.7 Consider the matrix

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

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

A. Add row 1 to row 3 ($R_3 + R_1 \to R_3$)

B. Add -2 row 1 to row 2 ($R_2 - 2R_1 \to R_2$)

C. Add 2 row 2 to row 3 ($R_3 + 2R_2 \to R_3$)

D. Add 2 row 3 to row 2 ($R_2 + 2R_3 \to R_2$)

Activity 1.2.8 Consider the matrix

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

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

A. Add row 1 to row 2 ($R_2 + R_1 \to R_2$)

B. Add -1 row 3 to row 2 ($R_2 - R_3 \to R_2$)

C. Add -1 row 2 to row 3 ($R_3 - R_2 \to R_3$)

D. Add row 2 to row 1 ($R_1 + R_2 \to R_1$)

Activity 1.2.9 Consider the matrix

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

(a) Perform three row operations to produce a matrix closer to RREF.

(b) Finish putting it in RREF.

Activity 1.2.10 Consider the matrix

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

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

Activity 1.2.11 Consider the matrix

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

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

Activity 1.2.12 Consider the matrix

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

which has the same terms as A from the previous activity.

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

A. No, a new calculuation is required.

B. Yes, $\mathrm{RREF}(A)$ and $\mathrm{RREF}(B)$ are exactly the same.

C. Yes, $\mathrm{RREF}(A)$ may be slightly modified to find $\mathrm{RREF}(B)$.

Activity 1.2.13 Free browser-based technologies for mathematical computation are available online.

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

Activity 1.2.14 In the HTML version of this text, code cells are often embedded for your convenience when RREFs need to be computed.

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

```
rref([2,3,1;3,0,6])
```

1.2.2 Videos

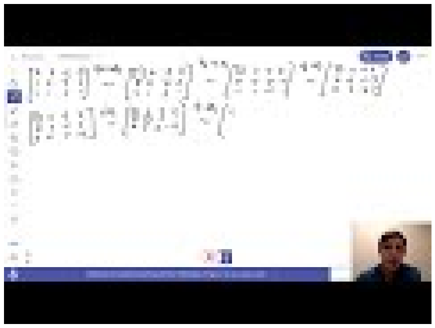


Figure 2 Video: Row reduction

1.2.3 Slideshow

Slideshow of activities available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/LE2.slides.html`.

1.2.4 Exercises

Exercises available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/LE2/`.

1.2.5 Mathematical Writing Explorations

Exploration 1.2.15 Prove that Gauss-Jordan Elimination preserves the solution set of a system of linear equations in n variables. Make sure your proof includes each of the following. Just because I've used bullet points here does not mean you should use bullet points in your proof.

- Write an arbitrary system of linear equations in n variables. Your notation should be unambiguous.
- Label an element of your solution set. You won't know what it is exactly, so you'll have to use a variable. Remember what it means (by definition!) to be in the solution set.
- Describe the three operations used in Gauss-Jordan Elimination.
- Consider all three operations in Gauss-Jordan Elimination. After each one is used, show that the element of the solution set you picked still satisfies the definition.

Exploration 1.2.16 Let $M_{2,2}$ indicate the set of all 2×2 matrices with real entries. Show that equivalence of matrices as defined in this section is an equivalence relation, as in exploration Exploration 1.1.6

1.2.6 Sample Problem and Solution

Sample problem Example B.1.2.

1.3 Counting Solutions for Linear Systems (LE3)

Learning Outcomes

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

1.3.1 Class Activities

Remark 1.3.1 We will frequently need to know the reduced row echelon form of matrices during the remainder of this course, so unless you're told otherwise, feel free to use technology (see Activity 1.2.13) to compute RREFs efficiently.

Activity 1.3.1 Consider the following system of equations.

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

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

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

(b) Use the RREF matrix to write a linear system equivalent to the original system.

(c) How many solutions must this system have?

A. Zero B. Only one C. Infinitely-many

```
rref([3,-2,13,6;2,-2,10,2;-1,3,-6,11])
```

Activity 1.3.2 Consider the vector equation

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

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

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

(b) Use the RREF matrix to write a linear system equivalent to the original system.

(c) How many solutions must this system have?

A. Zero B. Only one C. Infinitely-many

```
rref([3,-2,13,6;2,-2,10,2;-1,0,-3,1])
```

Activity 1.3.3 What contradictory equations besides $0 = 1$ may be obtained from the RREF of an augmented matrix?

A. $x = 0$ is an obtainable contradiction

B. $x = y$ is an obtainable contradiction

C. $0 = 17$ is an obtainable contradiction

D. $0 = 1$ is the only obtainable contradiction

Activity 1.3.4 Consider the following linear system.

$$\begin{aligned} x_1 + 2x_2 + 3x_3 &= 1 \\ 2x_1 + 4x_2 + 8x_3 &= 0 \end{aligned}$$

(a) Find its corresponding augmented matrix A and find $\mathrm{RREF}(A)$.

(b) Use the RREF matrix to write a linear system equivalent to the original system.

(c) How many solutions must this system have?

A. Zero B. One C. Infinitely-many

Fact 1.3.2 *We will see in Section 1.4 that the intuition established here generalizes: a* consistent *system with more variables than equations (ignoring $0 = 0$) will always have infinitely many solutions.*

Fact 1.3.3 *By finding $\mathrm{RREF}(A)$ from a linear system's corresponding augmented matrix A, we can immediately tell how many solutions the system has.*

- *If the linear system given by $\mathrm{RREF}(A)$ includes the contradiction $0 = 1$, that is, the row $\left[\begin{array}{ccc|c} 0 & \cdots & 0 & 1 \end{array}\right]$, then the system is* inconsistent*, which means it has* zero *solutions and its solution set is written as $\emptyset$ or $\{\}$.*

- *If the linear system given by $\mathrm{RREF}(A)$ sets each variable of the system to a single value; that is, $x_1 = s_1$, $x_2 = s_2$, and so on; then the system is* consistent *with exactly* one *solution $\begin{bmatrix} s_1 \\ s_2 \\ \vdots \end{bmatrix}$, and its solution set is $\left\{ \begin{bmatrix} s_1 \\ s_2 \\ \vdots \end{bmatrix} \right\}$.*

- *Otherwise, the system must have more variables than non-trivial equations (equations other than $0 = 0$). This means it is* consistent *with* infinitely-many *different solutions. We'll learn how to find such solution sets in Section 1.4.*

Activity 1.3.5 For each vector equation, write an explanation for whether each solution set has no solutions, one solution, or infinitely-many solutions. If the set is finite, describe it using set notation.

(a)

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

(b)

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

(c)

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

1.3.2 Videos

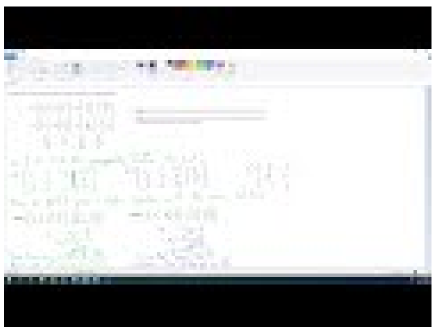


Figure 3 Video: Finding the number of solutions for a system

1.3.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/LE3.slides.html.

1.3.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/LE3/.

1.3.5 Mathematical Writing Explorations

Exploration 1.3.6 A system of equations with all constants equal to 0 is called **homogeneous**. These are addressed in detail in section Section 2.7

- Choose three systems of equations from this chapter that you have already solved. Replace the constants with 0 to make the systems homogeneous. Solve the homogeneous systems and make a conjecture about the relationship between the earlier solutions you found and the associated homogeneous systems.

- Prove or disprove. A system of linear equations is homogeneous if an only if it has the the zero vector as a solution.

1.3.6 Sample Problem and Solution

Sample problem Example B.1.3.

1.4 Linear Systems with Infinitely-Many Solutions (LE4)

Learning Outcomes

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

1.4.1 Class Activities

Activity 1.4.1 Consider this simplified linear system found to be equivalent to the system from Activity 1.3.4:

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

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

(a) Let $x_1 = a$ and write the solution set in the form $\left\{ \left[\begin{array}{c} a \\ ? \\ ? \end{array}\right] \middle| \, a \in \mathbb{R} \right\}$.

(b) Let $x_2 = b$ and write the solution set in the form $\left\{ \left[\begin{array}{c} ? \\ b \\ ? \end{array}\right] \middle| \, b \in \mathbb{R} \right\}$.

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

Definition 1.4.1 Recall that the pivots of a matrix in RREF form are the leading 1s in each non-zero row.

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

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

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

Activity 1.4.2 Find the solution set for the system

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

by doing the following.

(a) Row-reduce its augmented matrix.

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

$? = a$ and $? = b$.

(c) Solve for the bound variables (given by the pivot columns) to show that $? = 1 + 5a + 2b$,

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

and $? = 3 + 3b$.

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

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

Remark 1.4.2 Don't forget to correctly express the solution set of a linear system. Systems with zero or one solutions may be written by listing their elements, while systems with infinitely-many solutions may be written using set-builder notation.

- *Inconsistent*: $\emptyset$ or $\{\}$ (not 0).
- *Consistent* with *one solution*: e.g. $\left\{ \left[\begin{array}{c} 1 \\ 2 \\ 3 \end{array} \right] \right\}$ (not just $\left[\begin{array}{c} 1 \\ 2 \\ 3 \end{array} \right]$).
- *Consistent* with *infinitely-many solutions*: e.g. $\left\{ \left[\begin{array}{c} 1 \\ 2-3a \\ a \end{array} \right] \middle| \, a \in \mathbb{R} \right\}$ (not just $\left[\begin{array}{c} 1 \\ 2-3a \\ a \end{array} \right]$).

Activity 1.4.3 Show how to find the solution set for the vector equation

$$x_1 \left[\begin{array}{c} 1 \\ 0 \\ 1 \end{array} \right] + x_2 \left[\begin{array}{c} 0 \\ 1 \\ -1 \end{array} \right] + x_3 \left[\begin{array}{c} -1 \\ 5 \\ -5 \end{array} \right] + x_4 \left[\begin{array}{c} -3 \\ 13 \\ -13 \end{array} \right] = \left[\begin{array}{c} -3 \\ 12 \\ -12 \end{array} \right].$$

Activity 1.4.4 Consider the following system of linear equations.

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

(a) Explain how to find a simpler system or vector equation that has the same solution set.

(b) Explain how to describe this solution set using set notation.

1.4.2 Videos

Figure 4 Video: Solving a system of linear equations with infinitely-many solutions

1.4.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023LE4.slides.html.

1.4.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/LE4/.

1.4.5 Mathematical Writing Explorations

Exploration 1.4.5 Construct a system of 3 equations in 3 variables having:

- 0 free variables
- 1 free variable
- 2 free variables

In each case, solve the system you have created. Conjecture a relationship between the number of free variables and the type of solution set that can be obtained from a given system.

Exploration 1.4.6 For each of the following, decide if it's true or false. If you think it's true, can we construct a proof? If you think it's false, can we find a counterexample?

- If the coefficient matrix of a system of linear equations has a pivot in the rightmost column, then the system is inconsistent.
- If a system of equations has two equations and four unknowns, then it must be consistent.
- If a system of equations having four equations and three unknowns is consistent, then the solution is unique.
- Suppose that a linear system has four equations and four unknowns and that the coefficient matrix has four pivots. Then the linear system is consistent and has a unique solution.
- Suppose that a linear system has five equations and three unknowns and that the coefficient matrix has a pivot in every column. Then the linear system is consistent and has a unique solution.

1.4.6 Sample Problem and Solution

Sample problem Example B.1.4.

Chapter 2

Euclidean Vectors (EV)

Learning Outcomes

What is a space of Euclidean vectors?

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

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

Readiness Assurance. Before beginning this chapter, you should be able to...

1. Use set builder notation to describe sets of vectors.
   - Review: YouTube[1]
2. Add Euclidean vectors and multiply Euclidean vectors by scalars.
   - Review: Khan Academy (1)[2] (2)[3]
3. Perform basic manipulations of augmented matrices and linear systems.
   - Review: Section 1.1, Section 1.2, Section 1.3

[1] `youtu.be/xnfUZ-NTsCE`
[2] `www.khanacademy.org/math/linear-algebra/vectors-and-spaces/vectors/v/adding-vectors`
[3] `www.khanacademy.org/math/linear-algebra/vectors-and-spaces/vectors/v/multiplying-vector-by-scalar`

2.1 Linear Combinations (EV1)

Learning Outcomes

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

2.1.1 Class Activities

Note 2.1.1 We've implicitly been working with **Euclidean vector spaces** of the form

$$\mathbb{R}^n = \left\{ \left[\begin{array}{c} x_1 \\ x_2 \\ \vdots \\ x_n \end{array}\right] \middle|\, x_1, x_2, \ldots, x_n \in \mathbb{R} \right\}.$$

There are other kinds of vector spaces as well (e.g. polynomials, matrices), which we will investigate in Section 3.5. But understanding the structure of *Euclidean* vectors on their own will be beneficial, even when we turn our attention to other kinds of vectors.

Likewise, when we multiply a vector by a real number, as in $-3 \left[\begin{array}{c} 1 \\ -1 \\ 2 \end{array}\right] = \left[\begin{array}{c} -3 \\ 3 \\ -6 \end{array}\right]$, we refer to this real number as a **scalar**.

Definition 2.1.2 A **linear combination** of a set of vectors $\{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_m\}$ is given by $c_1\vec{v}_1 + c_2\vec{v}_2 + \cdots + c_m\vec{v}_m$ for any choice of scalar multiples $c_1, c_2, \ldots, c_m$.

For example, we can say $\left[\begin{array}{c} 3 \\ 0 \\ 5 \end{array}\right]$ is a linear combination of the vectors $\left[\begin{array}{c} 1 \\ -1 \\ 2 \end{array}\right]$ and $\left[\begin{array}{c} 1 \\ 2 \\ 1 \end{array}\right]$ since

$$\left[\begin{array}{c} 3 \\ 0 \\ 5 \end{array}\right] = 2 \left[\begin{array}{c} 1 \\ -1 \\ 2 \end{array}\right] + 1 \left[\begin{array}{c} 1 \\ 2 \\ 1 \end{array}\right].$$

◊

Definition 2.1.3 The **span** of a set of vectors is the collection of all linear combinations of that set:

$$\operatorname{span}\{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_m\} = \{c_1\vec{v}_1 + c_2\vec{v}_2 + \cdots + c_m\vec{v}_m \,|\, c_i \in \mathbb{R}\}.$$

For example:

$$\operatorname{span}\left\{ \left[\begin{array}{c} 1 \\ -1 \\ 2 \end{array}\right], \left[\begin{array}{c} 1 \\ 2 \\ 1 \end{array}\right] \right\} = \left\{ a \left[\begin{array}{c} 1 \\ -1 \\ 2 \end{array}\right] + b \left[\begin{array}{c} 1 \\ 2 \\ 1 \end{array}\right] \middle|\, a, b \in \mathbb{R} \right\}.$$

◊

Remark 2.1.4 It is important to remember that

$$\{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_m\} \neq \operatorname{span}\{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_m\}.$$

For example,

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

is a set containing exactly two vectors, while

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

is a set containing infinitely-many vectors.

Activity 2.1.1 Consider $\operatorname{span}\left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right\}$.

(a) Sketch the four Euclidean vectors

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

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

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

$$\operatorname{span}\left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix} \right\} = \left\{ a \begin{bmatrix} 1 \\ 2 \end{bmatrix} \middle| a \in \mathbb{R} \right\}$$

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

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

Activity 2.1.2 Consider $\operatorname{span}\left\{ \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \end{bmatrix} \right\}$.

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

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

$$-2\begin{bmatrix} 1 \\ 2 \end{bmatrix} + 1\begin{bmatrix} -1 \\ 1 \end{bmatrix} = ? \qquad -1\begin{bmatrix} 1 \\ 2 \end{bmatrix} + -2\begin{bmatrix} -1 \\ 1 \end{bmatrix} = ?$$

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

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

in the xy plane. What best describes this sketch?

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

Activity 2.1.3 Sketch a representation of all the vectors belonging to $\operatorname{span}\left\{ \begin{bmatrix} 6 \\ -4 \end{bmatrix}, \begin{bmatrix} -3 \\ 2 \end{bmatrix} \right\}$

in the xy plane. What best describes this sketch?

A. A line

B. A plane

C. A parabola

D. A cube

Activity 2.1.4 Consider the following questions to discover whether a Euclidean vector belongs to a span.

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

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

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

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

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

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

Observation 2.1.5 The following are all equivalent statements:

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

Activity 2.1.5 Consider this claim about a vector equation:

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

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

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

(c) Since your statement was true, use the solution set to describe a linear combination of $\left[\begin{array}{c}1\\0\\2\end{array}\right]$, $\left[\begin{array}{c}3\\0\\6\end{array}\right]$, $\left[\begin{array}{c}2\\0\\4\end{array}\right]$, and $\left[\begin{array}{c}-4\\1\\-5\end{array}\right]$ that equals $\left[\begin{array}{c}-5\\-1\\-7\end{array}\right]$.

Activity 2.1.6 Consider this claim about a vector equation:

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

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

(b) Explain why the statement you wrote is false, to conclude that the vector does not belong to the span.

2.1.2 Videos

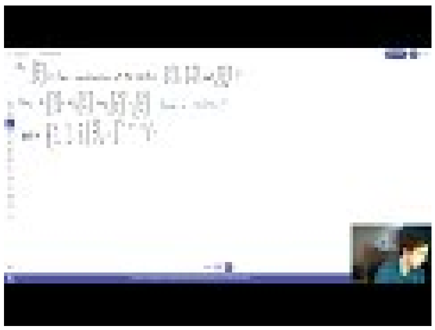


Figure 5 Video: Linear combinations

2.1.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/EV1.slides.html.

2.1.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/EV1/.

2.1.5 Mathematical Writing Explorations

Exploration 2.1.7 Suppose $S = \{\vec{v_1}, \ldots, \vec{v_n}\}$ is a set of vectors. Show that $\vec{v_0}$ is a linear combination of members of S, if an only if there are a set of scalars $\{c_0, c_1, \ldots, c_n\}$ such that $\vec{z} = c_0\vec{v_0} + \cdots + c_n\vec{v_n}$. We can do this in a few parts. I've used bullets here to indicate all that needs to be done. This is an "if and only if" proof, so it needs two parts.

- First, assume that $\vec{0} = c_0\vec{v_0} + \cdots + c_n\vec{v_n}$ has a solution, with $c_0 \neq 0$. Show that $\vec{v_0}$ is a linear combination of elements of S.
- Next, assume that $\vec{v_0}$ is a linear combination of elements of S. Can you find the appropriate $\{c_0, c_1, \ldots, c_n\}$ to make the equation $\vec{z} = c_0\vec{v_0} + \cdots + c_n\vec{v_n}$ true?
- In either of your proofs above, does the case when $\vec{v_0} = \vec{z}$ change your thinking? Explain why or why not.

2.1.6 Sample Problem and Solution

Sample problem Example B.1.5.

2.2 Spanning Sets (EV2)

Learning Outcomes

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

2.2.1 Class Activities

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

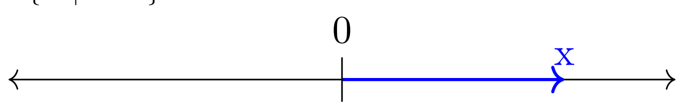


Figure 6 An $\mathbb{R}^1$ vector

Activity 2.2.1 How many vectors are required to span $\mathbb{R}^2$? Sketch a drawing in the xy plane to support your answer.

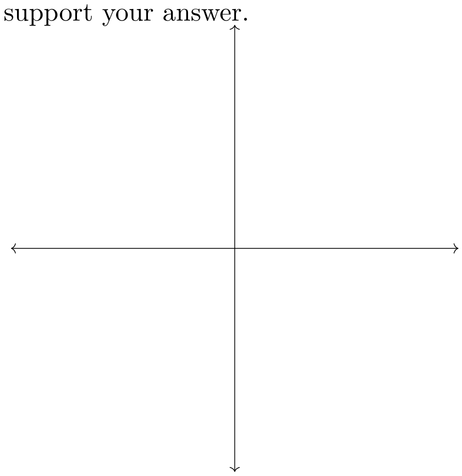


Figure 7 The xy plane $\mathbb{R}^2$

A. 1

B. 2

C. 3

D. 4

E. Infinitely Many

Activity 2.2.2 How many vectors are required to span $\mathbb{R}^3$?

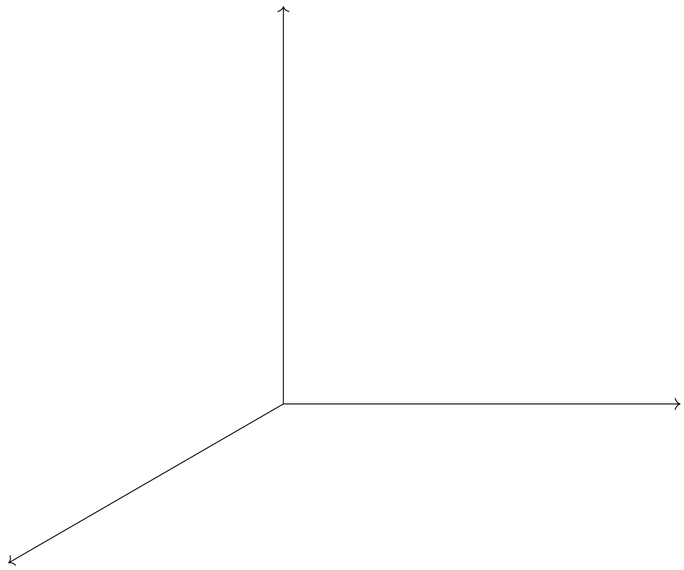


Figure 8 $\mathbb{R}^3$ space

A. 1

B. 2

C. 3

D. 4

E. Infinitely Many

Fact 2.2.2 *At least n vectors are required to span $\mathbb{R}^n$.*

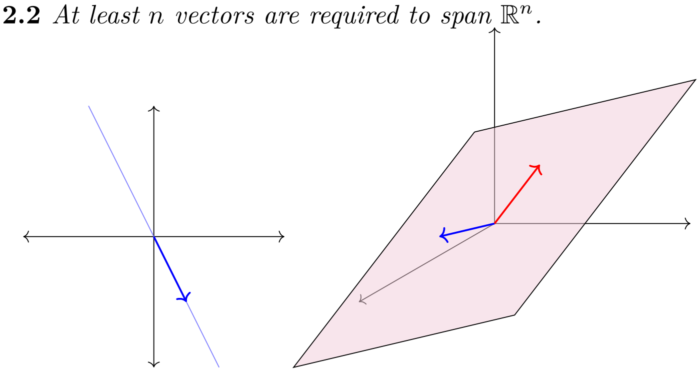


Figure 9 *Failed attempts to span $\mathbb{R}^n$ by $< n$ vectors*

Activity 2.2.3 Consider the question: Does every vector in $\mathbb{R}^3$ belong to $\operatorname{span}\left\{\begin{bmatrix}1\\-1\\0\end{bmatrix},\begin{bmatrix}-2\\0\\1\end{bmatrix},\begin{bmatrix}-2\\-2\\2\end{bmatrix}\right\}$?

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

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

(c) An arbitrary vector $\begin{bmatrix}?\\?\\?\end{bmatrix}$ belongs to $\operatorname{span}\left\{\begin{bmatrix}1\\-1\\0\end{bmatrix},\begin{bmatrix}-2\\0\\1\end{bmatrix},\begin{bmatrix}-2\\-2\\2\end{bmatrix}\right\}$

provided the equation

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

has...

A. no solutions.

B. exactly one solution.

C. at least one solution.

D. infinitely-many solutions.

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

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

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

A. the row $[0\,1\,2\,|\,?]$ prevents a contradiction.

B. the row $[0\,1\,2\,|\,?]$ allows a contradiction.

C. the row $[0\,0\,0\,|\,?]$ prevents a contradiction.

D. the row $[0\,0\,0\,|\,?]$ allows a contradiction.

Fact 2.2.3 *The set $\{\vec{v}_1, \dots, \vec{v}_m\}$ spans all of $\mathbb{R}^n$ exactly when the vector equation*

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

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

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

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

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

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

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

Activity 2.2.4 Consider the set of vectors $S = \left\{ \begin{bmatrix} 2 \\ 3 \\ 0 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ -4 \\ 3 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 \\ 7 \\ -3 \\ -1 \end{bmatrix}, \begin{bmatrix} 0 \\ 3 \\ 5 \\ 7 \end{bmatrix}, \begin{bmatrix} 3 \\ 13 \\ 7 \\ 16 \end{bmatrix} \right\}$ and the question "Does $\mathbb{R}^4 = \operatorname{span} S$?"

(a) Rewrite this question in terms of the solutions to a vector equation.

(b) Answer your new question, and use this to answer the original question.

Activity 2.2.5 Let $\vec{v}_1, \vec{v}_2, \vec{v}_3 \in \mathbb{R}^7$ be three Euclidean vectors, and suppose $\vec{w}$ is another vector with $\vec{w} \in \operatorname{span}\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$. What can you conclude about span $\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$?

A. span $\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$ is larger than span $\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$.

B. span $\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$ is the same as span $\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$.

C. span $\{\vec{w}, \vec{v}_1, \vec{v}_2, \vec{v}_3\}$ is smaller than span $\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$.

2.2.2 Videos

Figure 10 Video: Determining if a set spans a Euclidean space

2.2.3 Slideshow

Slideshow of activities available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/EV2.slides.html`.

2.2.4 Exercises

Exercises available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/EV2/`.

2.2.5 Mathematical Writing Explorations

Exploration 2.2.6 Construct each of the following, or show that it is impossible:

- A set of 2 vectors that spans $\mathbb{R}^3$
- A set of 3 vectors that spans $\mathbb{R}^3$
- A set of 3 vectors that does not span $\mathbb{R}^3$
- A set of 4 vectors that spans $\mathbb{R}^3$

For any of the sets you constructed that did span the required space, are any of the vectors a linear combination of the others in your set?

Exploration 2.2.7 Based on these results, generalize this a conjecture about how a set of $n-1, n$ and $n+1$ vectors would or would not span $\mathbb{R}^n$.

2.2.6 Sample Problem and Solution

Sample problem Example B.1.6.

2.3 Subspaces (EV3)

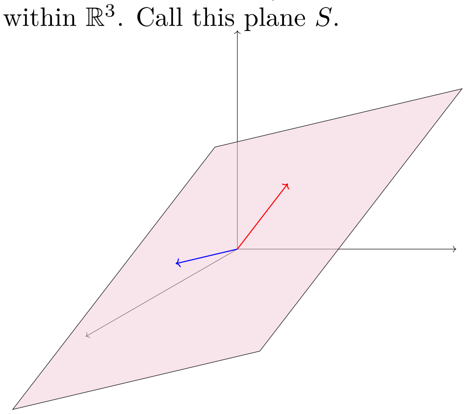
Learning Outcomes

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

2.3.1 Class Activities

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

Activity 2.3.1 Consider two non-colinear vectors in $\mathbb{R}^3$. If we look at all linear combinations of those two vectors (that is, their span), we end up with a planar subspace within $\mathbb{R}^3$. Call this plane S.



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

A. Yes. B. No.

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

A. Yes. B. No.

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

A. Yes. B. No.

Fact 2.3.2 *A* sub*set S of a vector space is a* sub*space provided:*

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

Observation 2.3.3 Note the similarities between a planar subspace spanned by two non-colinear vectors in $\mathbb{R}^3$, and the Euclidean plane $\mathbb{R}^2$. While they are not the same thing (and shouldn't be referred to interchangably), algebraists call such similar spaces **isomorphic**; we'll learn what this means more carefully in a later chapter.

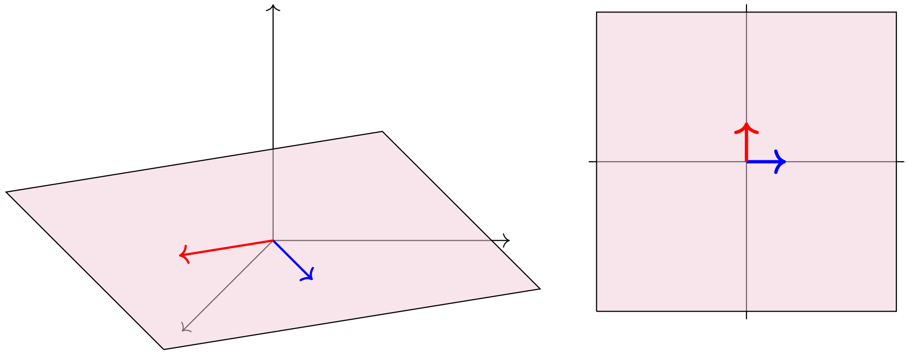


Figure 11 A planar subset of $\mathbb{R}^3$ compared with the plane $\mathbb{R}^2$.

Activity 2.3.2 Let $S = \left\{ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \middle| x + 2y + z = 0 \right\}$.

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

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

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

C. Both of these.

D. Neither of these.

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

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

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

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

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

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

A. Yes

B. No

C. Not enough information

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

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

A. Yes

B. No

C. Not enough information

Activity 2.3.3 Let $S = \left\{ \begin{bmatrix} x \\ y \\ z \end{bmatrix} \middle| x + 2y + z = 4 \right\}$.

(a) Which of these statements is valid?

A. $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *and* $\left[\begin{array}{c}2\\2\\2\end{array}\right] \in S$, so S *is* a subspace.

B. $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *and* $\left[\begin{array}{c}2\\2\\2\end{array}\right] \in S$, so S *is not* a subspace.

C. $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *but* $\left[\begin{array}{c}2\\2\\2\end{array}\right] \notin S$, so S *is* a subspace.

D. $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *but* $\left[\begin{array}{c}2\\2\\2\end{array}\right] \notin S$, so S *is not* a subspace.

(b) Which of these statements is valid?

(a) $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *and* $\left[\begin{array}{c}0\\0\\0\end{array}\right] \in S$, so S *is* a subspace.

(b) $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *and* $\left[\begin{array}{c}0\\0\\0\end{array}\right] \in S$, so S *is not* a subspace.

(c) $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *but* $\left[\begin{array}{c}0\\0\\0\end{array}\right] \notin S$, so S *is* a subspace.

(d) $\left[\begin{array}{c}1\\1\\1\end{array}\right] \in S$, *but* $\left[\begin{array}{c}0\\0\\0\end{array}\right] \notin S$, so S *is not* a subspace.

Remark 2.3.4 In summary, you can check *any* of the following to show that a nonempty subset W isn't a subspace:

- Find $\vec{u}, \vec{v} \in W$ such that $\vec{u} + \vec{v} \notin W$.
- Find $c \in \mathbb{R}, \vec{v} \in W$ such that $c\vec{v} \notin W$.
- Show that $\vec{0} \notin W$ (same as the last step, with $c = 0$).

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

1. Prove that $\vec{u} + \vec{v} \in W$ whenever $\vec{u}, \vec{v} \in W$.
2. Prove that $c\vec{v} \in W$ whenever $c \in \mathbb{R}, \vec{v} \in W$.

Activity 2.3.4 Consider these subsets of $\mathbb{R}^3$:

$$R = \left\{ \left[\begin{array}{c}x\\y\\z\end{array}\right] \middle| \, y = z + 1 \right\} \qquad S = \left\{ \left[\begin{array}{c}x\\y\\z\end{array}\right] \middle| \, y = |z| \right\} \qquad T = \left\{ \left[\begin{array}{c}x\\y\\z\end{array}\right] \middle| \, z = xy \right\}.$$

(a) Show R isn't a subspace by showing that $\vec{0} \notin R$.

(b) Show S isn't a subspace by finding two vectors $\vec{u}, \vec{v} \in S$ such that $\vec{u} + \vec{v} \notin S$.

(c) Show T isn't a subspace by finding a vector $\vec{v} \in T$ such that $2\vec{v} \notin T$.

Activity 2.3.5 Consider the following two sets of Euclidean vectors:

$$U = \left\{ \left[\begin{array}{c} x \\ y \end{array} \right] \middle| 7\,x + 4\,y = 0 \right\} \qquad W = \left\{ \left[\begin{array}{c} x \\ y \end{array} \right] \middle| 3\,xy^2 = 0 \right\}$$

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

Activity 2.3.6 Consider the following attempted proof that

$$U = \left\{ \left[\begin{array}{c} x \\ y \end{array} \right] \middle| x + y = xy \right\}$$

is closed under scalar multiplication.

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

$$\begin{aligned} (kx) + (ky) &= (kx)(ky) \\ k(x + y) &= k^2 xy \\ 0[k(x + y)] &= 0[k^2 xy] \\ 0 &= 0 \end{aligned}$$

Is this reasoning valid?

A. Yes

B. No

Remark 2.3.5 Proofs of an equality LEFT = RIGHT should generally be of one of these forms:

1. Using a chain of equalities:

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

Alternatively:

$$\begin{aligned} \text{LEFT} &= \cdots \\ &= \cdots \\ &= \cdots \\ &= \text{SAME} \end{aligned} \qquad \begin{aligned} \text{RIGHT} &= \cdots \\ &= \cdots \\ &= \cdots \\ &= \text{SAME} \end{aligned}$$

2. When the assumption THIS = THAT is already known or assumed to be true :

$$\begin{array}{lc} & \text{THIS} = \text{THAT} \\ \Rightarrow & \cdots = \cdots \\ \Rightarrow & \cdots = \cdots \\ \Rightarrow & \text{LEFT} = \text{RIGHT} \end{array}$$

Warning 2.3.6 The following proof is *invalid*.

$$\begin{aligned} & \text{LEFT} = \text{RIGHT} \\ \Rightarrow \quad & \cdots = \cdots \\ \Rightarrow \quad & \cdots = \cdots \\ \Rightarrow \quad & 0 = 0 \\ \Rightarrow \quad & \text{ANYTHING} = \text{ANYTHING} \end{aligned}$$

Basically, you cannot prove something is true by assuming it's true, and it's not helpful to prove to someone that zero equals itself (they probably already know that).

2.3.2 Videos

Figure 12 Video: Showing that a subset of a vector space is a subspace

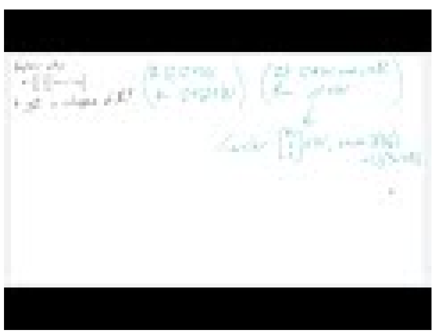


Figure 13 Video: Showing that a subset of a vector space is not a subspace

2.3.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/EV3.slides.html.

2.3.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/EV3/.

2.3.5 Mathematical Writing Explorations

Exploration 2.3.7 A square matrix M is **symmetric**if, for each index i, j, the entries $m_{ij} = m_{ji}$. That is, the matrix is itself when reflected over the diagonal from upper left to lower right. Prove that the set of $n \times n$ symmetric matrices is a subspace of $M_{n\times n}$.

Exploration 2.3.8 The space of all real-valued function of one real variable is a vector space. First, define $\oplus$ and $\odot$ for this vector space. Check that you have closure (both kinds!) and show what the zero vector is under your chosen addition. Decide if each of the following is a subspace. If so, prove it. If not, provide the counterexample.

- The set of even functions, $\{f : \mathbb{R} \to \mathbb{R} : f(-x) = f(x) \text{ for all } x\}$.
- The set of odd functions, $\{f : \mathbb{R} \to \mathbb{R} : f(-x) = -f(x) \text{ for all } x\}$.

Exploration 2.3.9 Give an example of each of these, or explain why it's not possible that such a thing would exist.

- A nonempty subset of $M_{2\times 2}$ that is not a subspace.
- A set of two vectors in $\mathbb{R}^2$ that is not a spanning set.

Exploration 2.3.10 Let V be a vector space and $S = \{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_n\}$ a subset of V. Show that the span of S is a subspace. Is it possible that there is a subset of V containing fewer vectors than S, but whose span contains all of the vectors in the span of S?

2.3.6 Sample Problem and Solution

Sample problem Example B.1.7.

2.4 Linear Independence (EV4)

Learning Outcomes

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

2.4.1 Class Activities

Activity 2.4.1 Consider the two sets

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

Which of the following is true?

A. $\operatorname{span} S$ is bigger than $\operatorname{span} T$.

B. $\operatorname{span} S$ and $\operatorname{span} T$ are the same size.

C. $\operatorname{span} S$ is smaller than $\operatorname{span} T$.

Definition 2.4.1 We say that a set of vectors is **linearly dependent** if one vector in the set belongs to the span of the others. Otherwise, we say the set is **linearly independent**.

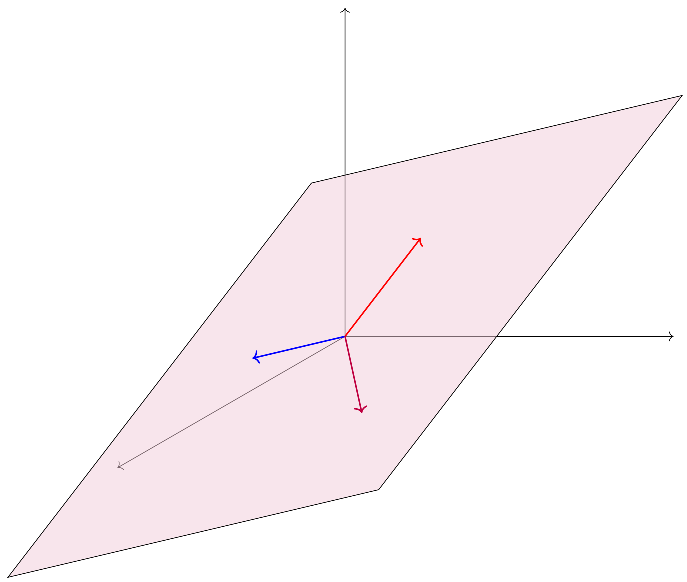


Figure 14 A linearly dependent set of three vectors

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

Activity 2.4.2 Consider the following three vectors in $\mathbb{R}^3$:

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

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

A. linearly dependent: at least one vector is a linear combination of others

B. linearly independent: no vector is a linear combination of others

(b) Find

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

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

A. It is inconsistent.

B. It is consistent with one solution.

C. It is consistent with infinitely many solutions.

(c) Which of these might explain the connection?

A. A pivot column establishes linear independence and creates a contradiction.

B. A non-pivot column both describes a linear combination and reveals the number of solutions.

C. A pivot row describes the bound variables and prevents a contradiction.

D. A non-pivot row prevents contradictions and makes the vector equation solvable.

Fact 2.4.2 *For any vector space, the set $\{\vec{v}_1, \ldots \vec{v}_n\}$ is linearly dependent if and only if the vector equation $x_1\vec{v}_1 + x_2\vec{v}_2 + \cdots + x_n\vec{v}_n = \vec{0}$ is consistent with infinitely many solutions.*

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

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

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

Activity 2.4.3 Find

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

and mark the part of the matrix that demonstrates that

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

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

Observation 2.4.3 Compare the following results:

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

Activity 2.4.4

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

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

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

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

Activity 2.4.5 What is the largest number of $\mathbb{R}^4$ vectors that can form a linearly independent set?

A. 3

B. 4

C. 5

D. You can have infinitely many vectors and still be linearly independent.

Activity 2.4.6 Is is possible for the set of Euclidean vectors $\{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_n, \vec{0}\}$ to be linearly independent?

A. Yes

B. No

2.4.2 Videos

Figure 15 Video: Linear independence

2.4.3 Slideshow

Slideshow of activities available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/EV4.slides.html`.

2.4.4 Exercises

Exercises available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/EV4/`.

2.4.5 Mathematical Writing Explorations

Exploration 2.4.7 Prove the result of Observation 2.4.3, by showing that, given a set $S = \{\vec{v}_1, \vec{v}_2, \ldots, \vec{v}_n\}$ of vectors, S is linearly independent iff the equation $x_1\vec{v}_1 + x_2\vec{v}_2 + \ldots + x_n\vec{v}_n = \vec{0}$ is only true when $x_1 = x_2 = \cdots = x_n = 0$.

2.4.6 Sample Problem and Solution

Sample problem Example B.1.8.

2.5 Identifying a Basis (EV5)

Learning Outcomes

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

2.5.1 Class Activities

Activity 2.5.1 Consider the set of vectors

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

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

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

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

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

A. Zero.

B. One.

C. Infintiely-many.

D. Computing a new matrix RREF is necessary.

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

(a) If every vector in a space can be constructed as one or more linear combination of vectors in a set S, we can say...

A. the set S spans the space.

B. the set S fails to span the space.

C. the set S is linearly independent.

D. the set S is linearly dependent.

(b) If the zero vector $\vec{0}$ can be constructed as a *unique* linear combination of vectors in a set S (the combination multiplying every vector by the scalar value 0), we can say...

A. the set S spans the space.

B. the set S fails to span the space.

C. the set S is linearly independent.

D. the set S is linearly dependent.

(c) If every vector of a space can either be constructed as a *unique* linear combination of vectors in a set S, or not at all, we can say...

A. the set S spans the space.

B. the set S fails to span the space.

C. the set S is linearly independent.

D. the set S is linearly dependent.

Definition 2.5.1 A **basis** of a vector space is a set of vectors S for which

1. *Every* vector of the space can be expressed as a linear combination of the vectors in S.

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

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

Observation 2.5.2 In terms of a vector equation, a set $S = \{\vec{v}_1, \ldots, \vec{v}_n\}$ is a basis of a space if the vector equation

$$x_1\vec{v_1} + \cdots + x_n\vec{v_n} = \vec{w}$$

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

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

Activity 2.5.3 Let S be a basis (Definition 2.5.1) for a space. Then...

A. the set S must both span the space and be linearly independent.

B. the set S must span the space but could be linearly dependent.

C. the set S must be linearly independent but could fail to span the space.

D. the set S could fail to span the space and could be linearly dependent.

Activity 2.5.4 The vectors

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

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

Find the unique linear combination of these vectors

$$?\,\hat{\imath} + \,?\,\hat{\jmath} + \,?\,\hat{k}$$

that equals the vector

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

in xyz space.

Definition 2.5.3 The **standard basis** of $\mathbb{R}^n$ is the set $\{\vec{e}_1,\dots,\vec{e}_n\}$ where

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

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

Activity 2.5.5 Take the RREF of an appropriate matrix to determine if each of the following sets is a basis for $\mathbb{R}^4$.

(a)

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

A. A basis because it both spans and is linearly independent.

B. Spans, but not a basis as it is linearly dependent.

C. Linearly independent, but not a basis as it fails to span.

D. Fails to span and linearly independent, so not a basis.

(b)

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

A. A basis because it both spans and is linearly independent.

B. Spans, but not a basis as it is linearly dependent.

C. Linearly independent, but not a basis as it fails to span.

D. Fails to span and linearly independent, so not a basis.

(c)

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

A. A basis because it both spans and is linearly independent.

B. Spans, but not a basis as it is linearly dependent.

C. Linearly independent, but not a basis as it fails to span.

D. Fails to span and linearly independent, so not a basis.

(d)

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

A. A basis because it both spans and is linearly independent.

B. Spans, but not a basis as it is linearly dependent.

C. Linearly independent, but not a basis as it fails to span.

D. Fails to span and linearly independent, so not a basis.

(e)

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

A. A basis because it both spans and is linearly independent.

B. Spans, but not a basis as it is linearly dependent.

C. Linearly independent, but not a basis as it fails to span.

D. Fails to span and linearly independent, so not a basis.

Activity 2.5.6 If $\{\vec{v}_1, \vec{v}_2, \vec{v}_3, \vec{v}_4\}$ is a basis for $\mathbb{R}^4$, that means $\mathrm{RREF}[\vec{v}_1\ \vec{v}_2\ \vec{v}_3\ \vec{v}_4]$ has a pivot in every row (because it spans), and has a pivot in every column (because it's linearly independent).

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

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

Fact 2.5.4 *The set $\{\vec{v}_1, \ldots, \vec{v}_m\}$ is a basis for $\mathbb{R}^n$ if and only if $m = n$ and* $\mathrm{RREF}[\vec{v}_1\ \ldots\ \vec{v}_n] = \begin{bmatrix} 1 & 0 & \ldots & 0 \\ 0 & 1 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & 1 \end{bmatrix}$.

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

2.5.2 Videos

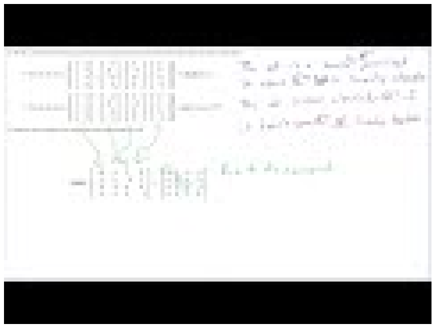


Figure 16 Video: Verifying that a set of vectors is a basis of a vector space

2.5.3 Slideshow

Slideshow of activities available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/EV5.slides.html`.

2.5.4 Exercises

Exercises available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/EV5/`.

2.5.5 Mathematical Writing Explorations

Exploration 2.5.7

- What is a basis for $M_{2,2}$?
- What about $M_{3,3}$?
- Could we write each of these in a way that looks like the standard basis vectors in $\mathbb{R}^m$ for some m? Make a conjecture about the relationship between these spaces of matrices and standard Eulidean space.

Exploration 2.5.8 Recall our earlier definition of symmetric matrices. Find a basis for each of the following:

- The space of 2×2 symmetric matrices.
- The space of 3×3 symmetric matrices.
- The space of $n \times n$ symmetric matrices.

Exploration 2.5.9 Must a basis for the space P_2, the space of all quadratic polynomials, contain a polynomial of each degree less than or equal to 2? Generalize your result to polynomials of arbitrary degree.

2.5.6 Sample Problem and Solution

Sample problem Example B.1.9.

2.6 Subspace Basis and Dimension (EV6)

Learning Outcomes

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

2.6.1 Class Activities

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

Recall also that a linearly dependent set contains "redundant" vectors. For example, only two of the three vectors in Figure 14 are needed to span the planar subspace.

Activity 2.6.1 Consider the subspace of $\mathbb{R}^4$ given by $W = \operatorname{span}\left\{\begin{bmatrix}2\\3\\0\\1\end{bmatrix},\begin{bmatrix}2\\0\\1\\-1\end{bmatrix},\begin{bmatrix}2\\-3\\2\\-3\end{bmatrix},\begin{bmatrix}1\\5\\-1\\0\end{bmatrix}\right\}$.

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

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

A. The set still spans W, and remains linearly dependent.

B. The set still spans W, but is now also linearly independent.

C. The set no longer spans W, and remains linearly dependent.

D. The set no longer spans W, but is now linearly independent.

```
rref([2,2,2,1; 3,0,-3,5; 0,1,2,-1; 1,-1,-3,0])
```

Definition 2.6.2 Let W be a subspace of a vector space. A **basis** for W is a linearly independent set of vectors that spans W (but not necessarily the entire vector space). ♢

Observation 2.6.3 So given a set $S = \{\vec{v}_1, \ldots, \vec{v}_m\}$, to compute a basis for the subspace span S, simply remove the vectors corresponding to the non-pivot columns of $\operatorname{RREF}[\vec{v}_1 \ \ldots \ \vec{v}_m]$. For example, since

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

the subspace $W = \operatorname{span}\left\{\begin{bmatrix}1\\2\\3\end{bmatrix},\begin{bmatrix}2\\4\\6\end{bmatrix},\begin{bmatrix}0\\-2\\-2\end{bmatrix},\begin{bmatrix}1\\2\\1\end{bmatrix}\right\}$ has $\left\{\begin{bmatrix}1\\2\\3\end{bmatrix},\begin{bmatrix}0\\-2\\-2\end{bmatrix}\right\}$ as a basis.

Activity 2.6.2

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

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

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

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

Observation 2.6.4 Even though we found different bases for them, $\operatorname{span} S$ and $\operatorname{span} T$ are exactly the same subspace of $\mathbb{R}^4$, since

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

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

Fact 2.6.5 *Any non-trivial real vector space has infinitely-many different bases, but all the bases for a given vector space are exactly the same size.*

For example,

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

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

Definition 2.6.6 The **dimension** of a vector space or subspace is equal to the size of any basis for the vector space.

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

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

contains exactly three vectors. ◊

Activity 2.6.3 Consider the following subspace W of $\mathbb{R}^4$:

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

(a) Explain and demonstrate how to find a basis of W.

(b) Explain and demonstrate how to find the dimension of W.

Activity 2.6.4 The dimension of a subspace may be found by doing what with an appropriate RREF matrix?

A. Count the rows.

B. Count the non-pivot columns.

C. Count the pivots.

D. Add the number of pivot rows and pivot columns.

2.6.2 Videos

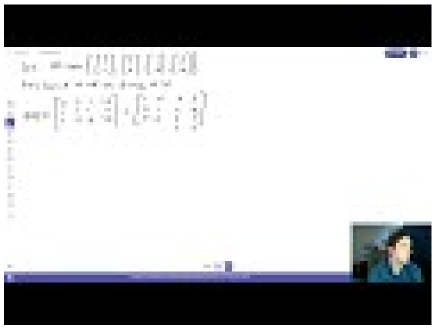


Figure 17 Video: Finding a basis of a subspace and computing the dimension of a subspace

2.6.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/EV6.slides.html.

2.6.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/EV6/.

2.6.5 Mathematical Writing Explorations

Exploration 2.6.5 Prove each of the following statements is true.

- If $\{\vec{b}_1, \vec{b}_2, \ldots, \vec{b}_m\}$ and $\{\vec{c}_1, \vec{c}_2, \ldots, \vec{c}_n\}$ are each a basis for a vector space V, then $m = n$.
- If $\{\vec{v}_1, \vec{v}_2 \ldots, \vec{v}_n\}$ is linearly independent, then so is $\{\vec{v}_1, \vec{v}_1 + \vec{v}_2, \ldots, \vec{v}_1 + \vec{v}_2 + \cdots + \vec{v}_n\}$.
- Let V be a vector space of dimension n, and $\vec{v} \in V$. Then there exists a basis for V which contains $\vec{v}$.

Exploration 2.6.6 Suppose we have the set of all function $f : S \to \mathbb{R}$. We claim that this is a vector space under the usual operation of function addition and scalar multiplication. What is the dimension of this space for each choice of S below:

- $S = \{1\}$
- $S = \{1, 2\}$
- $S = \{1, 2, \ldots, n\}$

- $S = \mathbb{R}$

Exploration 2.6.7 Suppose you have the vector space $V = \left\{ \left(\begin{array}{c} x \\ y \\ z \end{array} \right) \in \mathbb{R}^3 : x+y+z=1 \right\}$ with the operations $\left(\begin{array}{c} x_1 \\ y_1 \\ z_1 \end{array} \right) \oplus \left(\begin{array}{c} x_2 \\ y_2 \\ z_2 \end{array} \right) = \left(\begin{array}{c} x_1+x_2-1 \\ y_1+y_2 \\ z_1+z_2 \end{array} \right)$ and $\alpha \odot \left(\begin{array}{c} x_1 \\ y_1 \\ z_1 \end{array} \right) = \left(\begin{array}{c} \alpha x_1 - \alpha + 1 \\ \alpha y_1 \\ \alpha z_1 \end{array} \right)$. Find a basis for V and determine it's dimension.

2.6.6 Sample Problem and Solution

Sample problem Example B.1.10.

2.7 Homogeneous Linear Systems (EV7)

Learning Outcomes

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

2.7.1 Class Activities

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

$$\begin{alignedat}{4} a_{11}x_1 + {} & a_{12}x_2 + \ldots + {} & a_{1n}x_n & = 0 \\ a_{21}x_1 + {} & a_{22}x_2 + \ldots + {} & a_{2n}x_n & = 0 \\ \vdots \quad & \quad \vdots & \vdots \quad & \ \vdots \\ a_{m1}x_1 + {} & a_{m2}x_2 + \ldots + {} & a_{mn}x_n & = 0 \end{alignedat}$$

This system is equivalent to the vector equation:

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

and the augmented matrix:

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

◊

Activity 2.7.1 Consider the homogeneous vector equation $x_1\vec{v}_1 + \cdots + x_n\vec{v}_n = \vec{0}$.

(a) Note that if $\left[\begin{array}{c} a_1 \\ \vdots \\ a_n \end{array} \right]$ and $\left[\begin{array}{c} b_1 \\ \vdots \\ b_n \end{array} \right]$ are both solutions, we know that

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

Therefore by adding these equations,

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

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

A. Closed under addition.

B. Not closed under addition.

C. Linearly dependent.

D. Linearly independent.

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

A. A basis for $\mathbb{R}^n$.

B. A subspace of $\mathbb{R}^n$.

C. All of $\mathbb{R}^n$.

D. The empty set.

Activity 2.7.2 Consider the homogeneous system of equations

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

(a) Find its solution set (a subspace of $\mathbb{R}^4$).

(b) Rewrite this solution space in the form

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

(c) Rewrite this solution space in the form

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

(d) Which of these choices best describes the set of two vectors $\left\{ \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix}, \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix} \right\}$ used in this span?

A. The set is linearly dependent.

B. The set is linearly independent.

C. The set spans all of $\mathbb{R}^4$.

D. The set fails to span the solution space.

Fact 2.7.2 *The coefficients of the free variables in the solution space of a linear system always yield linearly independent vectors that span the solution space.*

Thus if

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

is the solution space for a homogeneous system, then

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

is a basis for the solution space.

Activity 2.7.3 Consider the homogeneous system of equations

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

Find a basis for its solution space.

Activity 2.7.4 Consider the homogeneous vector equation

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

Find a basis for its solution space.

Activity 2.7.5 Consider the homogeneous system of equations

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

(a) Find its solution space.

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

A $\{\}$ B $\{\vec{0}\}$ C The basis does not exist

Activity 2.7.6 Suppose that in a certain 3D video game, the "camera" aligns the position (x,y,z) within the level onto the pixel located at $(x+y,y-z)$ on the television screen.

(a) What homoegeneous linear system describes the positions within the level that would be aligned with the pixel $(0,0)$ on the screen?

(b) Solve this system to describe these locations.

2.7.2 Videos

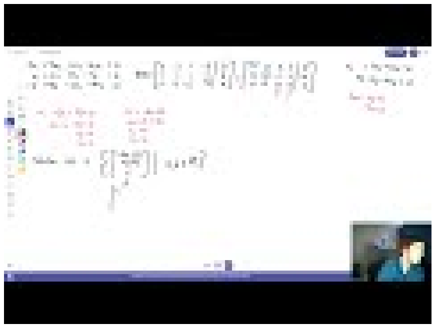


Figure 18 Video: Polynomial and matrix calculations

2.7.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/EV7.slides.html.

2.7.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/EV7/.

2.7.5 Mathematical Writing Explorations

Exploration 2.7.7 An $n \times n$ matrix M is **non-singular** if the associated homogeneous system with coefficient matrix M is consistent with one solution. Assume the matrices in the writing explorations in this section are all non-singular.

- Prove that the reduced row echelon form of M is the identity matrix.
- Prove that, for any column vector $\vec{b} = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix}$, the system of equations given by $\left[\begin{array}{c|c} M & \vec{b} \end{array}\right]$ has a unique solution.
- Prove that the columns of M form a basis for $\mathbb{R}^n$.
- Prove that the rank of M is n.

2.7.6 Sample Problem and Solution

Sample problem Example B.1.11.

Chapter 3

Algebraic Properties of Linear Maps (AT)

Learning Outcomes

How can we understand linear maps algebraically?

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

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

Readiness Assurance. Before beginning this chapter, you should be able to...

1. State the definition of a spanning set, and determine if a set of Euclidean vectors spans $\mathbb{R}^n$.
   - Review: Section 2.2
2. State the definition of linear independence, and determine if a set of Euclidean vectors is linearly dependent or independent.
   - Review: Section 2.4
3. State the definition of a basis, and determine if a set of Euclidean vectors is a basis.
   - Review: Section 2.5, Section 2.6
4. Find a basis of the solution space to a homogeneous system of linear equations.

- Review: Section 2.7

3.1 Linear Transformations (AT1)

Learning Outcomes

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

3.1.1 Class Activities

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

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

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

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

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

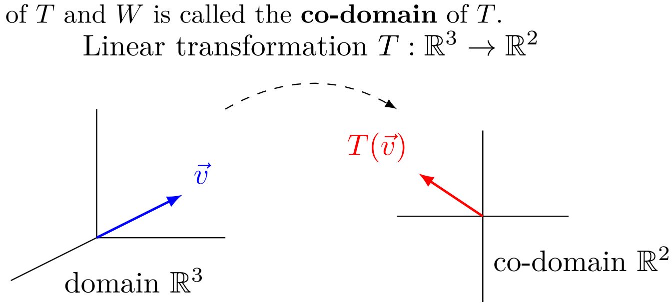


Figure 19 A linear transformation with a domain of $\mathbb{R}^3$ and a co-domain of $\mathbb{R}^2$

$\Diamond$

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

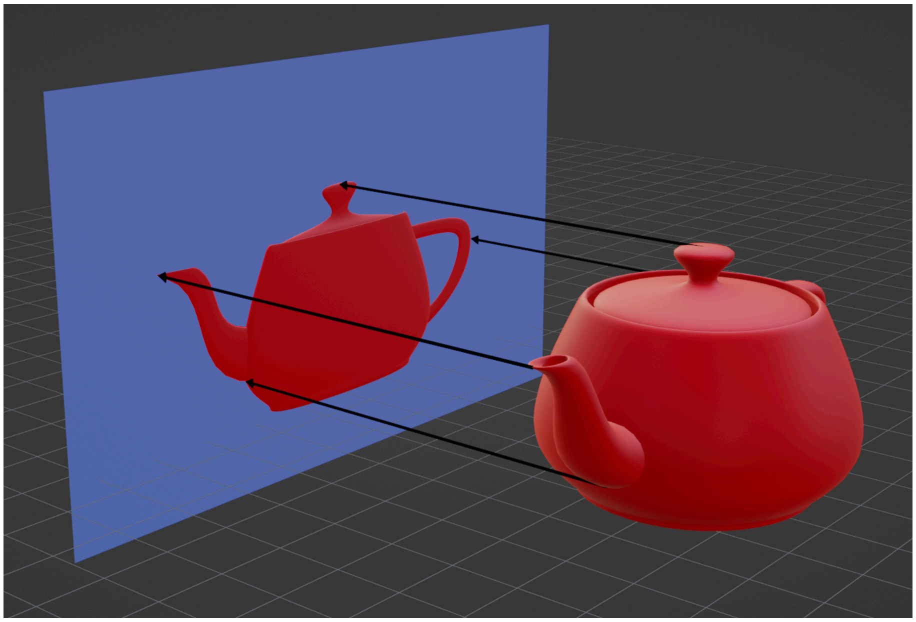


Figure 20 A projection of a $3D$ teapot onto a $2D$ screen

Activity 3.1.1 Let $T : \mathbb{R}^3 \to \mathbb{R}^2$ be given by

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

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

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

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

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

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

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

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

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

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

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

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

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

(c) Is T a linear transformation?

A. Yes.

B. No.

C. More work is necessary to know.

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

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

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

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

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

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

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

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

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

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

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

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

(f) Is T a linear transformation?

A. Yes.

B. No.

C. More work is necessary to know.

Activity 3.1.2 Let $S : \mathbb{R}^2 \to \mathbb{R}^4$ be given by

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

(a) Compute

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

A. $\begin{bmatrix} 6 \\ 4 \\ 7 \\ 0 \end{bmatrix}$ B. $\begin{bmatrix} -3 \\ 0 \\ 1 \\ 5 \end{bmatrix}$ C. $\begin{bmatrix} -3 \\ -1 \\ 7 \\ 5 \end{bmatrix}$ D. $\begin{bmatrix} 6 \\ 4 \\ 10 \\ -1 \end{bmatrix}$

(b) Compute

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

A. $\begin{bmatrix} 6 \\ 4 \\ 7 \\ 0 \end{bmatrix}$ B. $\begin{bmatrix} -3 \\ 0 \\ 1 \\ 5 \end{bmatrix}$ C. $\begin{bmatrix} -3 \\ -1 \\ 7 \\ 5 \end{bmatrix}$ D. $\begin{bmatrix} 6 \\ 4 \\ 10 \\ -1 \end{bmatrix}$

(c) Is T a linear transformation?

A. Yes.

B. No.

C. More work is necessary to know.

Activity 3.1.3 Fill in the ?s, assuming $T : \mathbb{R}^3 \to \mathbb{R}^3$ is linear:

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

Remark 3.1.4 Showing $T : V \to W$ is *not* a linear transformation can be done by finding an example for *any one* of the following.

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

Otherwise, T can be shown to be linear by proving *both* of the following *in general*.

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

Note the similarities between this process and showing that a subset of a vector space is or is not a subspace (Remark 2.3.4).

Activity 3.1.4

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

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

Which do you *suspect*?

A. P is linear, but Q is not.

B. Q is linear, but P is not.

C. Both maps are linear.

D. Neither map is linear.

(b) Consider the following map of Euclidean vectors $S : \mathbb{R}^2 \to \mathbb{R}^2$

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

Prove that S *is not* a linear transformation.

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

$$T\left(\left[\begin{array}{c} x \\ y \end{array}\right]\right) = \left[\begin{array}{c} 8\,x - 6\,y \\ 6\,x - 4\,y \end{array}\right].$$

Prove that T *is* a linear transformation.

3.1.2 Videos

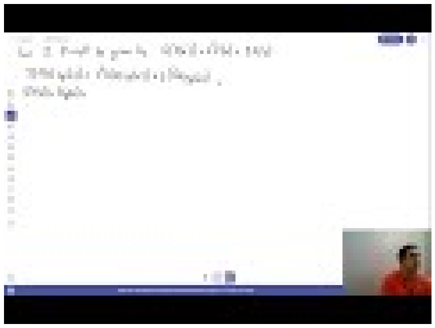


Figure 21 Video: Showing a transformation is linear

Figure 22 Video: Showing a transformation is not linear

3.1.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/AT1.slides.html.

3.1.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/AT1/.

3.1.5 Mathematical Writing Explorations

Exploration 3.1.5 If V, W are vectors spaces, with associated zero vectors $\vec{0}_V$ and $\vec{0}_W$, and $T : V \to W$ is a linear transformation, does $T(\vec{0}_V) = \vec{0}_W$? Prove this is true, or find a counterexample.

Exploration 3.1.6 Assume $f : V \to W$ is a linear transformation between vector spaces. Let $\vec{v} \in V$ with additive inverse $\vec{v}^{-1}$. Prove that $f(\vec{v}^{-1}) = [f(\vec{v})]^{-1}$.

3.1.6 Sample Problem and Solution

Sample problem Example B.1.12.

3.2 Standard Matrices (AT2)

Learning Outcomes

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

3.2.1 Class Activities

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

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

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

Activity 3.2.1 Suppose $T : \mathbb{R}^3 \to \mathbb{R}^2$ is a linear map, and you know $T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$ and $T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$. What is $T\left(\begin{bmatrix} 3 \\ 0 \\ 0 \end{bmatrix}\right)$?

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Activity 3.2.4 Suppose $T : \mathbb{R}^3 \to \mathbb{R}^2$ is a linear map, and you know $T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$ and $T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} -3 \\ 2 \end{bmatrix}$. What piece of information would help you compute $T\left(\begin{bmatrix} 0 \\ 4 \\ -1 \end{bmatrix}\right)$?

A. The value of $T\left(\begin{bmatrix} 0 \\ -4 \\ 0 \end{bmatrix}\right)$.

B. The value of $T\left(\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}\right)$.

C. The value of $T\left(\begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}\right)$.

D. Any of the above.

Fact 3.2.2 *Consider any basis $\{\vec{b}_1, \ldots, \vec{b}_n\}$ for V. Since every vector $\vec{v}$ can be written as a linear combination of basis vectors, $\vec{v} = x_1\vec{b}_1 + \cdots + x_n\vec{b}_n$, we may compute $T(\vec{v})$ as follows:*

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

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

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

Definition 3.2.3 Since a linear transformation $T : \mathbb{R}^n \to \mathbb{R}^m$ is determined by its action on the standard basis $\{\vec{e}_1, \ldots, \vec{e}_n\}$, it is convenient to store this information in an $m \times n$ matrix, called the **standard matrix** of T, given by $[T(\vec{e}_1) \cdots T(\vec{e}_n)]$.

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

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

Then the standard matrix corresponding to T is

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

◊

Activity 3.2.5 Let $T : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by

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

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

Activity 3.2.6 Let $T : \mathbb{R}^3 \to \mathbb{R}^2$ be the linear transformation given by

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

(a) Compute $T(\vec{e}_1)$, $T(\vec{e}_2)$, and $T(\vec{e}_3)$.

(b) Find the standard matrix for T.

Fact 3.2.4 *Because every linear map $T : \mathbb{R}^m \to \mathbb{R}^n$ has a linear combination of the variables in each component, and thus $T(\vec{e}_i)$ yields exactly the coefficients of x_i, the standard matrix for T is simply an array of the coefficients of the x_i:*

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

Activity 3.2.7 Let $T : \mathbb{R}^3 \to \mathbb{R}^3$ be the linear transformation given by the standard matrix

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

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

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

Activity 3.2.8 Compute the following linear transformations of vectors given their standard matrices.

(a)

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

(b)

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

(c)

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

3.2.2 Videos

Figure 23 Video: Using the standard matrix to compute the image of a vector

3.2.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/AT2.slides.html.

3.2.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/AT2/.

3.2.5 Mathematical Writing Explorations

We can represent images in the plane $\mathbb{R}^2$ using vectors, and manipulate those images with linear transformations. We introduce some notation in these explorations that is needed for their completion, but is not essential to the rest of the text. These have a geometric flair to them, and can be understood by thinking of geometric transformations in terms of standard matrices.

Given two vectors $\vec{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix}$ and $\vec{w} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}$, we define the **dot product** as

$$\vec{v} \cdot \vec{w} = v_1 w_1 + v_2 w_2 + \cdots v_n w_n.$$

Exploration 3.2.9 For each of the following properties, determine if it is held by the dot product. Either provide a proof it the property holds, or provide a counter-example if it does not.

- Distributive over addition (e.g., $(\vec{u} + \vec{v}) \cdot \vec{w} = \vec{u} \cdot \vec{w} + \vec{v} \cdot \vec{w}$)?
- Associative?
- Commutative?

Exploration 3.2.10 Given the properties you proved in the last exploration, could the dot product take the place of $\oplus$ as a vector space operation on $\mathbb{R}^n$?

Exploration 3.2.11 Is the dot product a linear operator? That is, given vectors $\vec{u}, \vec{v}, \vec{w} \in \mathbb{R}^n$, and $k, m \in \mathbb{R}$, is it true that

$$\vec{u} \cdot (k\vec{v} + m\vec{w}) = k(\vec{u} \cdot \vec{v}) + m(\vec{u} \cdot \vec{w}).$$

Prove or provide a counter-example.

Exploration 3.2.12 Assume $\vec{v} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix}$ and define the length of a vector by

$$|\vec{v}| = \left(\sum_{i=1}^{n} v_i^2\right)^{1/2}.$$

Prove that $|\vec{u}| = |\vec{v}|$ if an only if $\vec{u}+\vec{v}$ and $\vec{u}-\vec{v}$ are perpendicular. You may use the fact (try and prove it!) that two vectors are perpendicular if and only if their dot product is zero.

Exploration 3.2.13

- A **dilation** is given by by mapping a vector $\vec{v} = \begin{bmatrix} x \\ y \end{bmatrix}$ to some scalar multiple of $\vec{v}$.
- A **rotation** is given by $\vec{v} \mapsto \begin{bmatrix} \cos(\theta)x - \sin(\theta)y \\ \cos(\theta)y + \sin(\theta)x \end{bmatrix}$.
- A **reflection** of $\vec{v}$ over a line l can be found by first finding a vector $\vec{l} = \begin{bmatrix} l_x \\ l_y \end{bmatrix}$ along l, then $\vec{v} \mapsto 2\frac{\vec{l}\cdot\vec{v}}{\vec{l}\cdot\vec{l}}\vec{l} - \vec{v}$.

Represent each of the following transformations with respect to the standard basis in $\mathbb{R}^2$.

- Rotation through an angle θ.
- Reflection over a line l passing through the origin.
- Dilation by some scalar s.

Prove that each transformation is linear, and that your matrix representations are correct.

3.2.6 Sample Problem and Solution

Sample problem Example B.1.13.

3.3 Image and Kernel (AT3)

Learning Outcomes

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

3.3.1 Class Activities

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

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

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

A. $\left\{ \left[\begin{array}{c} a \\ a \end{array}\right] \middle| a \in \mathbb{R} \right\}$

B. $\left\{ \left[\begin{array}{c} a \\ 0 \end{array}\right] \middle| a \in \mathbb{R} \right\}$

C. $\left\{ \left[\begin{array}{c} 0 \\ 0 \end{array}\right] \right\}$

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

Definition 3.3.1 Let $T : V \to W$ be a linear transformation, and let $\vec{z}$ be the additive identity (the "zero vector") of W. The **kernel** of T is an important subspace of V defined by

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

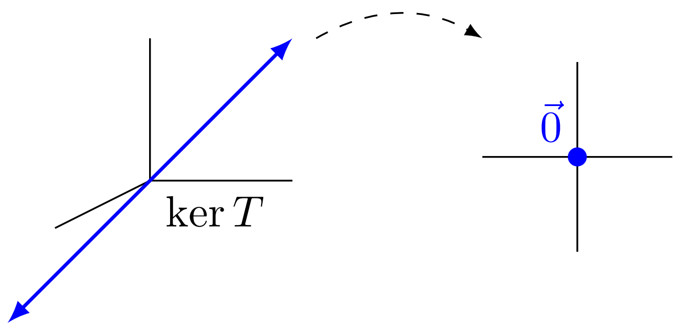


Figure 24 The kernel of a linear transformation

◊

Activity 3.3.2 Let $T : \mathbb{R}^3 \to \mathbb{R}^2$ be given by

$$T\left(\left[\begin{array}{c} x \\ y \\ z \end{array}\right]\right) = \left[\begin{array}{c} x \\ y \end{array}\right] \qquad \text{with standard matrix } \left[\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array}\right]$$

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

A. $\left\{ \left[\begin{array}{c} 0 \\ 0 \\ a \end{array}\right] \middle| a \in \mathbb{R} \right\}$

B. $\left\{ \left[\begin{array}{c} a \\ a \\ 0 \end{array}\right] \middle| a \in \mathbb{R} \right\}$

C. $\left\{ \left[\begin{array}{c} 0 \\ 0 \\ 0 \end{array}\right] \right\}$

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

Activity 3.3.3 Let $T : \mathbb{R}^3 \to \mathbb{R}^2$ be the linear transformation given by the standard matrix

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

(a) Set $T\left(\left[\begin{array}{c} x \\ y \\ z \end{array}\right]\right) = \left[\begin{array}{c} 0 \\ 0 \end{array}\right]$ to find a linear system of equations whose solution set is the kernel.

(b) Use RREF(A) to solve this homogeneous system of equations and find a basis for the kernel of T.

Activity 3.3.4 Let $T : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by

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

Find a basis for the kernel of T.

Activity 3.3.5 Let $T : \mathbb{R}^2 \to \mathbb{R}^3$ be given by

$$T\left(\left[\begin{array}{c} x \\ y \end{array}\right]\right) = \left[\begin{array}{c} x \\ y \\ 0 \end{array}\right] \qquad \text{with standard matrix} \left[\begin{array}{cc} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{array}\right]$$

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

A. $\left\{\left[\begin{array}{c} 0 \\ 0 \\ a \end{array}\right] \middle|\, a \in \mathbb{R}\right\}$

C. $\left\{\left[\begin{array}{c} 0 \\ 0 \\ 0 \end{array}\right]\right\}$

B. $\left\{\left[\begin{array}{c} a \\ b \\ 0 \end{array}\right] \middle|\, a, b \in \mathbb{R}\right\}$

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

Definition 3.3.2 Let $T : V \to W$ be a linear transformation. The **image** of T is an important subspace of W defined by

$$\operatorname{Im} T = \left\{\vec{w} \in W \,\middle|\, \text{there is some } \vec{v} \in V \text{ with } T(\vec{v}) = \vec{w}\right\}$$

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

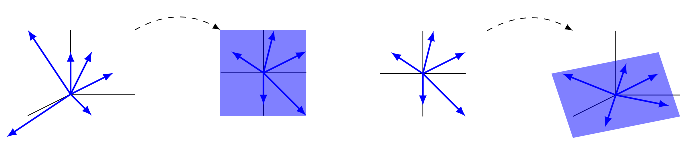


Figure 25 The image of a linear transformation

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

$$T\left(\left[\begin{array}{c} x \\ y \\ z \end{array}\right]\right) = \left[\begin{array}{c} x \\ y \end{array}\right] \qquad \text{with standard matrix} \left[\begin{array}{ccc} 1 & 0 & 0 \\ 0 & 1 & 0 \end{array}\right]$$

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

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

C. $\left\{\left[\begin{array}{c} 0 \\ 0 \end{array}\right]\right\}$

B. $\left\{\left[\begin{array}{c} a \\ 0 \end{array}\right] \middle|\, a \in \mathbb{R}\right\}$

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

Activity 3.3.7 Let $T : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by the standard matrix

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

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

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

A. The set of vectors spans $\operatorname{Im} T$ but is not linearly independent.

B. The set of vectors is a linearly independent subset of $\operatorname{Im} T$ but does not span $\operatorname{Im} T$.

C. The set of vectors is linearly independent and spans $\operatorname{Im} T$; that is, the set of vectors is a basis for $\operatorname{Im} T$.

Observation 3.3.3 Let $T : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by the standard matrix

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

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

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

Fact 3.3.4 *Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear transformation with standard matrix A.*

- *The kernel of T is the solution set of the homogeneous system given by the augmented matrix $\left[\begin{array}{c|c} A & \vec{0} \end{array}\right]$. Use the coefficients of its free variables to get a basis for the kernel.*

- *The image of T is the span of the columns of A. Remove the vectors creating non-pivot columns in* $\operatorname{RREF} A$ *to get a basis for the image.*

Activity 3.3.8 Let $T : \mathbb{R}^3 \to \mathbb{R}^4$ be the linear transformation given by the standard matrix

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

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

Activity 3.3.9 Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear transformation with standard matrix A. Which of the following is equal to the dimension of the kernel of T?

A. The number of pivot columns

B. The number of non-pivot columns

C. The number of pivot rows

D. The number of non-pivot rows

Activity 3.3.10 Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear transformation with standard matrix A. Which of the following is equal to the dimension of the image of T?

A. The number of pivot columns

B. The number of non-pivot columns

C. The number of pivot rows

D. The number of non-pivot rows

Observation 3.3.5 Combining these with the observation that the number of columns is the dimension of the domain of T, we have the **rank-nullity theorem**:

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

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

Activity 3.3.11 Let $T : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by

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

(a) Explain and demonstrate how to find the image of T and a basis for that image.

(b) Explain and demonstrate how to find the kernel of T and a basis for that kernel.

(c) Explain and demonstrate how to find the rank and nullity of T, and why the rank-nullity theorem holds for T.

3.3.2 Videos

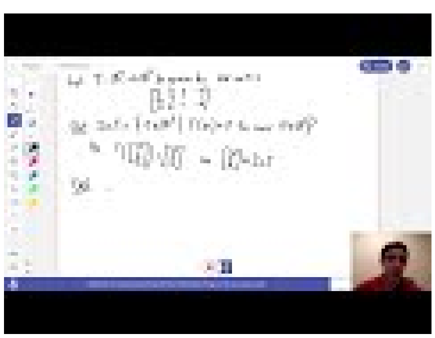

Figure 26 Video: The kernel and image of a linear transformation

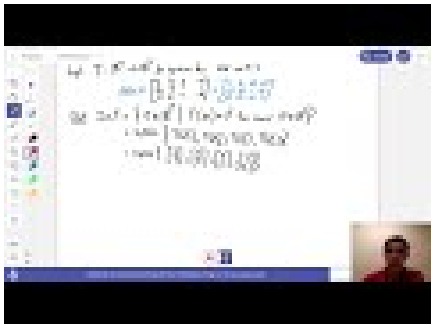

Figure 27 Video: Finding a basis of the image of a linear transformation

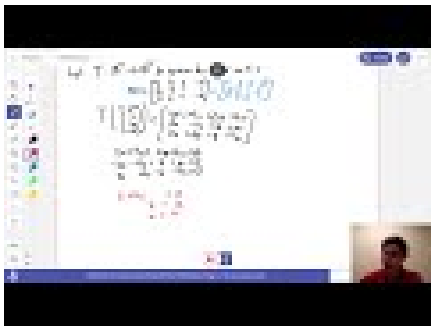

Figure 28 Video: Finding a basis of the kernel of a linear transformation

Figure 29 Video: The rank-nullity theorem

3.3.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/AT3.slides.html.

3.3.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/AT3/.

3.3.5 Mathematical Writing Explorations

Exploration 3.3.12 Assume $f : V \to W$ is a linear map. Let $\{\vec{v_1}, \vec{v_2}, \ldots, \vec{v_n}\}$ be a set of vectors in V, and set $\vec{w_i} = f(\vec{v_i})$.

- If the set $\{\vec{w_1}, \vec{w_2}, \ldots, \vec{w_n}\}$ is linearly independent, must the set $\{\vec{v_1}, \vec{v_2}, \ldots, \vec{v_n}\}$ also be linearly independent?
- If the set $\{\vec{v_1}, \vec{v_2}, \ldots, \vec{v_n}\}$ is linearly independent, must the set $\{\vec{w_1}, \vec{w_2}, \ldots, \vec{w_n}\}$

also be linearly independent?

- If the set $\{\vec{w_1}, \vec{w_2}, \ldots, \vec{w_n}\}$ spans W, must the set $\{\vec{v_1}, \vec{v_2}, \ldots, \vec{v_n}\}$ also span V?
- If the set $\{\vec{v_1}, \vec{v_2}, \ldots, \vec{v_n}\}$ spans V, must the set $\{\vec{w_1}, \vec{w_2}, \ldots, \vec{w_n}\}$ also span W?
- In light of this, is the image of the basis of a vector space always a basis for the codomain?

Exploration 3.3.13 Prove the Rank-Nullity Theorem. Use the steps below to help you.

- The theorem states that, given a linear map $h : V \to W$, with V and W vector spaces, the rank of h, plus the nullity of h, equals the dimension of the domain V. Assume that the dimension of V is n.
- For simplicity, denote the rank of h by $\mathcal{R}(h)$, and the nullity by $\mathcal{N}(h)$.
- Recall that $\mathcal{R}(h)$ is the dimension of the range space of h. State the precise definition.
- Recall that $\mathcal{N}(h)$ is the dimension of the null space of h. State the precise definition.
- Begin with a basis for the null space, denoted $B_N = \{\vec{\beta_1}, \vec{\beta_2}, \ldots, \vec{\beta_k}\}$. Show how this can be extended to a basis B_V for V, with $B_V = \{\vec{\beta_1}, \vec{\beta_2}, \ldots, \vec{\beta_k}, \vec{\beta_{k+1}}, \vec{\beta_{k+2}}, \ldots, \vec{\beta_n}\}$. In this portion, you should assume $k \leq n$, and construct additional vectors which are not linear combinations of vectors in B_N. Prove that you can always do this until you have n total linearly independent vectors.
- Show that $B_R = \{h(\vec{\beta_{k+1}}), h(\vec{\beta_{k+2}}), \ldots, h(\vec{\beta_n})\}$ is a basis for the range space. Start by showing that it is linearly independent, and be sure you prove that each element of the range space can be written as a linear combination of B_R.
- Show that B_R spans the range space.
- State your conclusion.

3.3.6 Sample Problem and Solution

Sample problem Example B.1.14.

3.4 Injective and Surjective Linear Maps (AT4)

Learning Outcomes

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

3.4.1 Class Activities

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

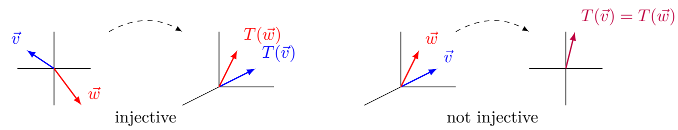

Figure 30 An injective transformation and a non-injective transformation

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Activity 3.4.1 Let $T : \mathbb{R}^3 \to \mathbb{R}^2$ be given by

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

Is T injective?

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

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

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

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

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

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

Is T injective?

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

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

C. No, because $T\left(\begin{bmatrix} 1 \\ 2 \end{bmatrix}\right) \neq T\left(\begin{bmatrix} 3 \\ 4 \end{bmatrix}\right)$.

D. No, because $T\left(\begin{bmatrix} 1 \\ 2 \end{bmatrix}\right) = T\left(\begin{bmatrix} 3 \\ 4 \end{bmatrix}\right)$.

Definition 3.4.2 Let $T : V \to W$ be a linear transformation. T is called **surjective** or **onto** if every element of W is mapped to by an element of V. More precisely, for every $\vec{w} \in W$, there is some $\vec{v} \in V$ with $T(\vec{v}) = \vec{w}$.

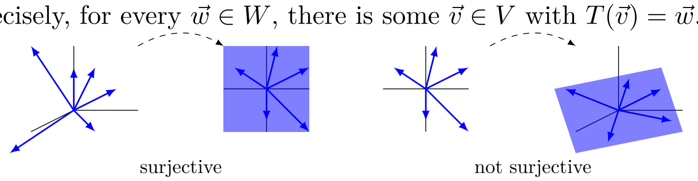

Figure 31 A surjective transformation and a non-surjective transformation

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

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

Is T surjective?

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

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

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

Activity 3.4.4 Let $T : \mathbb{R}^3 \to \mathbb{R}^2$ be given by

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

Is T surjective?

A. Yes, because for every $\vec{w} = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^2$, there exists $\vec{v} = \begin{bmatrix} x \\ y \\ 42 \end{bmatrix} \in \mathbb{R}^3$ such that $T(\vec{v}) = \vec{w}$.

B. Yes, because for every $\vec{w} = \begin{bmatrix} x \\ y \end{bmatrix} \in \mathbb{R}^2$, there exists $\vec{v} = \begin{bmatrix} 0 \\ 0 \\ z \end{bmatrix} \in \mathbb{R}^3$ such that $T(\vec{v}) = \vec{w}$.

C. No, because $T\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}\right)$ can never equal $\begin{bmatrix} 3 \\ -2 \end{bmatrix}$.

Activity 3.4.5 Let $T : V \to W$ be a linear transformation where $\ker T$ contains multiple vectors. What can you conclude?

A. T is injective

B. T is not injective

C. T is surjective

D. T is not surjective

Fact 3.4.3 *A linear transformation T is injective* if and only if $\ker T = \{\vec{0}\}$. *Put another way, an injective linear transformation may be recognized by its **trivial** kernel.*

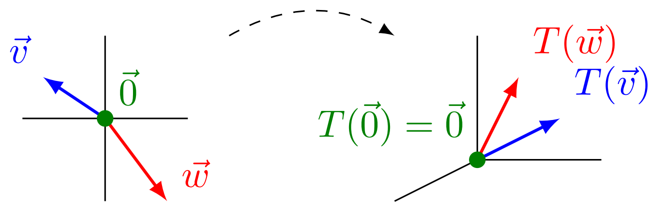

Figure 32 *A linear transformation with trivial kernel, which is therefore injective*

Activity 3.4.6 Let $T : V \to \mathbb{R}^3$ be a linear transformation where $\operatorname{Im} T$ may be spanned by only two vectors. What can you conclude?

A. T is injective

B. T is not injective

C. T is surjective

D. T is not surjective

Fact 3.4.4 *A linear transformation $T : V \to W$ is surjective* if and only if $\operatorname{Im} T = W$. *Put another way, a surjective linear transformation may be recognized by its identical codomain and image.*

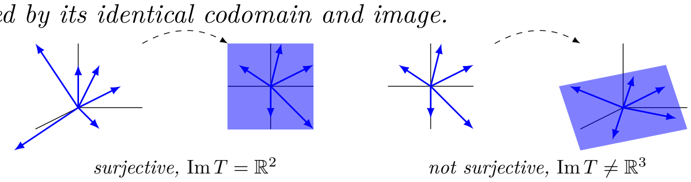

Figure 33 *A linear transformation with identical codomain and image, which is therefore surjective; and a linear transformation with an image smaller than the codomain $\mathbb{R}^3$, which is therefore not surjective.*

Definition 3.4.5 A transformation that is both injective and surjective is said to be **bijective**. ♢

Activity 3.4.7 Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear map with standard matrix A. Determine whether each of the following statements means T is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

1. The kernel of T is trivial, i.e. $\ker T = \{\vec{0}\}$.

2. The image of T equals its codomain, i.e. $\operatorname{Im} T = \mathbb{R}^m$.

3. For every $\vec{w} \in \mathbb{R}^m$, the set $\{\vec{w} \in \mathbb{R}^n | T(\vec{v}) = \vec{w}\}$ contains exactly one vector.

Activity 3.4.8 Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear map with standard matrix A. Determine whether each of the following statements means T is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

1. The columns of A span $\mathbb{R}^m$.

2. The columns of A form a basis for $\mathbb{R}^m$.

3. The columns of A are linearly independent.

Activity 3.4.9 Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear map with standard matrix A. Determine whether each of the following statements means T is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

1. $\operatorname{RREF}(A)$ is the identity matrix.

2. Every column of $\operatorname{RREF}(A)$ has a pivot.

3. Every row of $\operatorname{RREF}(A)$ has a pivot.

Activity 3.4.10 Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear map with standard matrix A. Determine whether each of the following statements means T is (A) *injective*, (B) *surjective*, or (C) *bijective* (both).

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

Observation 3.4.6 The easiest way to determine if the linear map with standard matrix A is injective is to see if $\mathrm{RREF}(A)$ has a pivot in each column.

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

Activity 3.4.11 What can you conclude about the linear map $T : \mathbb{R}^2 \to \mathbb{R}^3$ with standard matrix $\begin{bmatrix} a & b \\ c & d \\ e & f \end{bmatrix}$?

A. Its standard matrix has more columns than rows, so T is not injective.

B. Its standard matrix has more columns than rows, so T is injective.

C. Its standard matrix has more rows than columns, so T is not surjective.

D. Its standard matrix has more rows than columns, so T is surjective.

Activity 3.4.12 What can you conclude about the linear map $T : \mathbb{R}^3 \to \mathbb{R}^2$ with standard matrix $\begin{bmatrix} a & b & c \\ d & e & f \end{bmatrix}$?

A. Its standard matrix has more columns than rows, so T is not injective.

B. Its standard matrix has more columns than rows, so T is injective.

C. Its standard matrix has more rows than columns, so T is not surjective.

D. Its standard matrix has more rows than columns, so T is surjective.

Fact 3.4.7 *The following are true for any linear map $T : V \to W$:*

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

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

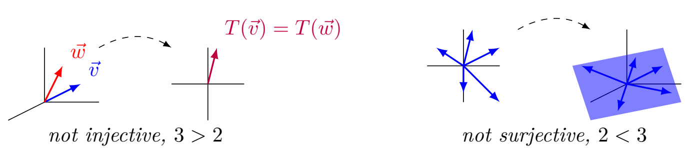

Figure 34 *A linear transformation whose domain has a larger dimension than its codomain, and is therefore not injective; and a linear transformation whose domain has a smaller dimension than its codomain, and is therefore not surjective.*

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

Activity 3.4.13 Suppose $T : \mathbb{R}^n \to \mathbb{R}^4$ with standard matrix $A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & a_{3n} \\ a_{41} & a_{42} & \cdots & a_{4n} \end{bmatrix}$ is both injective and surjective (we call such maps **bijective**).

(a) How many pivot rows must RREF A have?

(b) How many pivot columns must RREF A have?

(c) What is RREF A?

Activity 3.4.14 Let $T : \mathbb{R}^n \to \mathbb{R}^n$ be a bijective linear map with standard matrix A. Label each of the following as true or false.

A. RREF(A) is the identity matrix.

B. The columns of A form a basis for $\mathbb{R}^n$

C. The system of linear equations given by the augmented matrix $\left[\begin{array}{c|c} A & \vec{b} \end{array}\right]$ has exactly one solution for each $\vec{b} \in \mathbb{R}^n$.

Observation 3.4.8 The easiest way to show that the linear map with standard matrix A is bijective is to show that RREF(A) is the identity matrix.

Activity 3.4.15 Let $T : \mathbb{R}^3 \to \mathbb{R}^3$ be given by the standard matrix

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

Which of the following must be true?

A. T is neither injective nor surjective

B. T is injective but not surjective

C. T is surjective but not injective

D. T is bijective.

```
rref([2,1,-1; 4,1,1; 6,2,1])
```

Activity 3.4.16 Let $T : \mathbb{R}^3 \to \mathbb{R}^3$ 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.

```
rref([2,1,-1; 4,1,1; 6,2,0])
```

Activity 3.4.17 Let $T:\mathbb{R}^2\to\mathbb{R}^3$ 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.

```
rref([2,3;1,-1;1,3])
```

Activity 3.4.18 Let $T:\mathbb{R}^3\to\mathbb{R}^2$ 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.

```
rref([2,1,-1;4,1,1])
```

3.4.2 Videos

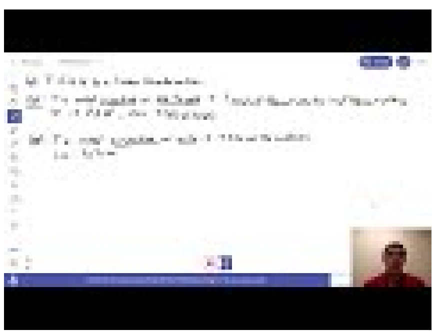

Figure 35 Video: The kernel and image of a linear transformation

Figure 36 Video: Finding a basis of the image of a linear transformation

3.4.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/AT4.slides.html.

3.4.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/AT4/.

3.4.5 Mathematical Writing Explorations

Exploration 3.4.19 Suppose that $f : V \to W$ is a linear transformation between two vector spaces V and W. State carefully what conditions f must satisfy. Let $\vec{0_V}$ and $\vec{0_W}$ be the zero vectors in V and W respectively.

- Prove that f is one-to-one if and only if $f(\vec{0_V}) = \vec{0_W}$, and that $\vec{0_V}$ is the unique element of V which is mapped to $\vec{0_W}$. Remember that this needs to be done in both directions. First prove the if and only if statement, and then show the uniqueness.

- Do not use subtraction in your proof. The only vector space operation we have is addition, and a structure preserving function only preserves addition. If you are writing $\vec{v} - \vec{v} = \vec{0}_V$, what you really mean is that $\vec{v} \oplus \vec{v}^{-1} = \vec{0}_V$, where $\vec{v}^{-1}$ is the additive inverse of $\vec{v}$.

Exploration 3.4.20 Start with an n-dimensional vector space V. We can define the **dual** of V, denoted V^*, by

$$V^* = \{h : V \to \mathbb{R} : h \text{ is linear}\}.$$

Prove that V is isomorphic toV^*. Here are some things to think about as you work through this.

- Start by assuming you have a basis for V. How many basis vectors should you have?

- For each basis vector in V, define a function that returns 1 if it's given that basis vector, and returns 0 if it's given any other basis vector. For example, if $\vec{b_i}$ and $\vec{b_j}$ are each members of the basis for V, and you'll need a function $f_i : V \to \{0, 1\}$, where $f_i(b_i) = 1$ and $f_i(b_j) = 0$ for all $j \neq i$.

- How many of these functions will you need? Show that each of them is in V^*.

- Show that the functions you found in the last part are a basis for V^*? To do this, take an arbitrary function $h \in V^*$ and some vector $\vec{v} \in V$. Write $\vec{v}$ in terms of the basis you chose earlier. How can you write $h(\vec{v})$, with respect to that basis? Pay attention to the fact that all functions in V^* are linear.

- Now that you've got a basis for V and a basis for V^*, can you find an isomorphism?

3.4.6 Sample Problem and Solution

Sample problem Example B.1.15.

3.5 Vector Spaces (AT5)

Learning Outcomes

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

3.5.1 Class Activities

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

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

Activity 3.5.1 Which of the following properites of $\mathbb{R}^2$ Euclidean vectors is NOT true?

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

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

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

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

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

Observation 3.5.2 Consider the following applications of properites of the real numbers $\mathbb{R}$:

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

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

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

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

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

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

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

Fact 3.5.3 *Every Euclidean vector space $\mathbb{R}^n$ satisfies the following properties, where $\vec{u}, \vec{v}, \vec{w}$ are Euclidean vectors and a, b are scalars.*

1. *Vector addition is associative: $\vec{u} + (\vec{v} + \vec{w}) = (\vec{u} + \vec{v}) + \vec{w}$.*

2. *Vector addition is commutative: $\vec{u} + \vec{v} = \vec{v} + \vec{u}$.*

3. *An additive identity exists: There exists some $\vec{z}$ where $\vec{v} + \vec{z} = \vec{v}$.*

4. *Additive inverses exist: There exists some $-\vec{v}$ where $\vec{v} + (-\vec{v}) = \vec{z}$.*

5. *Scalar multiplication is associative: $a(b\vec{v}) = (ab)\vec{v}$.*

6. *1 is a multiplicative identity: $1\vec{v} = \vec{v}$.*

7. *Scalar multiplication distributes over vector addition: $a(\vec{u} + \vec{v}) = (a\vec{u}) + (a\vec{v})$.*

8. *Scalar multiplication distributes over scalar addition: $(a + b)\vec{v} = (a\vec{v}) + (b\vec{v})$.*

Definition 3.5.4 A **vector space** V is any set of mathematical objects, called **vectors**, and a set of numbers, called **scalars**, with associated addition $\oplus$ and scalar multiplication $\odot$ operations that satisfy the following properties. Let $\vec{u}, \vec{v}, \vec{w}$ be vectors belonging to V, and let a, b be scalars.
We always assume the codomain of our operations is V, i.e. that addition is a map $V \times V \to V$ and that scalar multiplication is a map $\mathbb{R} \times V \to V$.

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

1. Vector addition is associative: $\vec{u} \oplus (\vec{v} \oplus \vec{w}) = (\vec{u} \oplus \vec{v}) \oplus \vec{w}$.

2. Vector addition is commutative: $\vec{u} \oplus \vec{v} = \vec{v} \oplus \vec{u}$.

3. An additive identity exists: There exists some $\vec{z}$ where $\vec{v} \oplus \vec{z} = \vec{v}$.

4. Additive inverses exist: There exists some $-\vec{v}$ where $\vec{v} \oplus (-\vec{v}) = \vec{z}$.

5. Scalar multiplication is associative: $a \odot (b \odot \vec{v}) = (ab) \odot \vec{v}$.

6. 1 is a multiplicative identity: $1 \odot \vec{v} = \vec{v}$.

7. Scalar multiplication distributes over vector addition: $a \odot (\vec{u} \oplus \vec{v}) = (a \odot \vec{u}) \oplus (a \odot \vec{v})$.

8. Scalar multiplication distributes over scalar addition: $(a + b) \odot \vec{v} = (a \odot \vec{v}) \oplus (b \odot \vec{v})$.

$\Diamond$

Remark 3.5.5 Consider the set $\mathbb{C}$ of complex numbers with the usual defintion for addition: $(a + b\mathbf{i}) \oplus (c + d\mathbf{i}) = (a + c) + (b + d)\mathbf{i}$.

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

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

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

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

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

Remark 3.5.6 The following sets are just a few examples of vector spaces, with the usual/natural operations for addition and scalar multiplication.

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

Activity 3.5.3 Consider the set $V = \{(x,y)\,|\,y = 2^x\}$.

Which of the following vectors is not in V?

A. $(0,0)$

B. $(1,2)$

C. $(2,4)$

D. $(3,8)$

Activity 3.5.4 Consider the set $V = \{(x,y)\,|\,y = 2^x\}$ with the operation $\oplus$ defined by

$$(x_1,y_1)\oplus(x_2,y_2) = (x_1+x_2, y_1y_2).$$

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

A. $(2,6)$

B. $(2,8)$

C. $(3,6)$

D. $(3,8)$

Activity 3.5.5 Consider the set $V = \{(x,y)\,|\,y = 2^x\}$ with operations $\oplus,\odot$ defined by

$$(x_1,y_1)\oplus(x_2,y_2) = (x_1+x_2, y_1y_2) \qquad c\odot(x,y) = (cx, y^c).$$

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

(a) Verify that

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

(b) Compute the value of

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

Activity 3.5.6 Consider the set $V = \{(x,y)\,|\,y = 2^x\}$ with operations $\oplus,\odot$

defined by

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

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

(a) Show that both sides of the equation

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

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

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

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

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

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

(c) Is V a vector space?

A. Yes

B. No

C. More work is required

Remark 3.5.7 It turns out $V = \{(x, y) \,|\, y = 2^x\}$ with operations $\oplus, \odot$ defined by

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

satisifes all eight properties from Definition 3.5.4.

Thus, V is a vector space.

Activity 3.5.7 Let $V = \{(x, y) \,|\, x, y \in \mathbb{R}\}$ have operations defined by

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

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

(a) Show that 1 is the scalar multiplication identity element by simplifying $1 \odot (x, y)$ to (x, y).

(b) Show that V does not have an additive identity element $\vec{z} = (z, w)$ by showing that $(0, -1) \oplus (z, w) \neq (0, -1)$ no matter what the values of z, w are.

(c) Is V a vector space?

A. Yes

B. No

C. More work is required

Activity 3.5.8 Let $V = \{(x, y) \,|\, x, y \in \mathbb{R}\}$ have operations defined by

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

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

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

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

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

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

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

(c) Is V a vector space?

A. Yes

B. No

C. More work is required

3.5.2 Videos

Figure 37 Video: Verifying that a vector space property holds

Figure 38 Video: Showing something is not a vector space

3.5.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/AT5.slides.html.

3.5.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/AT5/.

3.5.5 Mathematical Writing Explorations

Exploration 3.5.9

- Show that $\mathbb{R}^+$, the set of positive real numbers, is a vector space, but where $x \oplus y$ really means the product (so $2 \oplus 3 = 6$), and where scalar multiplication $\alpha \odot x$ really means x^α. Yes, you really do need to check all of the properties, but this is the only time I'll make you do so. Remember, examples aren't proofs, so you should start with arbitrary elements of $\mathbb{R}^+$ for your vectors. Make sure you're careful about telling the reader what α means.

- Prove that the additive identity $\vec{z}$ in an arbitrary vector space is unique.

- Prove that additive inverses are unique. Assume you have a vector space V and some $\vec{v} \in V$. Further, assume $\vec{w_1}, \vec{w_2} \in V$ with $\vec{v} \oplus \vec{w_1} = \vec{v} \oplus \vec{w_2} = \vec{z}$. Prove that $\vec{w_1} = \vec{w_2}$.

Exploration 3.5.10 Consider the vector space of polynomials, $\mathcal{P}_n$. Suppose further that $n = ab$, where a and b are each positive integers. Conjecture a relationship between $M_{a,b}$ and $\mathcal{P}_n$. We will investigate this further in section Section 3.6

3.5.6 Sample Problem and Solution

Sample problem Example B.1.16.

3.6 Polynomial and Matrix Spaces (AT6)

Learning Outcomes

- Answer questions about vector spaces of polynomials or matrices.

3.6.1 Class Activities

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

- Definition 2.1.2
- Definition 2.1.3
- Definition 2.3.1
- Definition 2.4.1
- Definition 2.5.1
- Definition 3.1.1
- Definition 3.1.2
- Definition 3.3.1
- Definition 3.3.2
- Definition 3.4.1
- Definition 3.4.2
- Definition 3.4.5

Activity 3.6.1 Let V be a vector space with the basis $\{\vec{v}_1, \vec{v}_2, \vec{v}_3\}$. Which of these completes the following definition for a bijective linear map $T : V \to \mathbb{R}^3$?

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

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

Fact 3.6.2 *Every vector space with finite dimension, that is, every vector space V with a basis of the form $\{\vec{v}_1, \vec{v}_2, \dots, \vec{v}_n\}$ has a linear bijection T with Euclidean space $\mathbb{R}^n$ that simply swaps its basis with the standard basis $\{\vec{e}_1, \vec{e}_2, \dots, \vec{e}_n\}$ for $\mathbb{R}^n$:*

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

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

Activity 3.6.2 The matrix space $M_{2,2} = \left\{ \begin{bmatrix} a & b \\ c & d \end{bmatrix} \middle| a, b, c, d \in \mathbb{R} \right\}$ has the basis

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

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

A. $\mathbb{R}^2$

B. $\mathbb{R}^3$

C. $\mathbb{R}^4$

D. $\mathbb{R}^5$

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

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

Activity 3.6.3 The polynomial space $\mathcal{P}^4 = \left\{ a + bx + cx^2 + dx^3 + ex^4 \middle| a, b, c, d, e \in \mathbb{R} \right\}$ has the basis

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

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

A. $\mathbb{R}^2$

B. $\mathbb{R}^3$

C. $\mathbb{R}^4$

D. $\mathbb{R}^5$

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

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

Remark 3.6.3 Since any finite-dimensional vector space is isomorphic to a Euclidean space $\mathbb{R}^n$, one approach to answering questions about such spaces is to answer the corresponding question about $\mathbb{R}^n$.

Activity 3.6.4 Consider how to construct the polynomial $x^3 + x^2 + 5x + 1$ as a linear combination of polynomials from the set

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

(a) Describe the vector space involved in this problem, and an isomorphic Euclidean space and relevant Eucldean vectors that can be used to solve this problem.

(b) Show how to construct an appropriate Euclidean vector from an appropriate set of Euclidean vectors.

(c) Use this result to answer the original question.

Observation 3.6.4 The space of polynomials $\mathcal{P}$ (of *any* degree) has the basis $\{1, x, x^2, x^3, \ldots\}$, so it is a natural example of an infinite-dimensional vector space.

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

3.6.2 Videos

Figure 39 Video: Polynomial and matrix calculations

3.6.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/AT6.slides.html.

3.6.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/AT6/.

3.6.5 Mathematical Writing Explorations

Exploration 3.6.5 Given a matrix M

- the span of the set of all columns is the **column space**
- the span of the set of all rows is the **row space**
- the **rank**of a matrix is the dimension of the column space.

Calculate the rank of these matrices.

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

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

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

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

Exploration 3.6.6 Calculate a basis for the row space and a basis for the column space of the matrix $\begin{bmatrix} 2 & 0 & 3 & 4 \\ 0 & 1 & 1 & -1 \\ 3 & 1 & 0 & 2 \\ 10 & -4 & -1 & -1 \end{bmatrix}$.

Exploration 3.6.7 If you are given the values of a, b, and c, what value of d will cause the matrix $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$ to have rank 1?

3.6.6 Sample Problem and Solution

Sample problem Example B.1.17.

Chapter 4

Matrices (MX)

Learning Outcomes

What algebraic structure do matrices have?

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

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

Readiness Assurance. Before beginning this chapter, you should be able to...

1. Compose functions of real numbers.
   - Review: Khan Academy[1]
2. Identify the domain and codomain of linear transformations.
   - Review: YouTube[2]
3. Find the matrix corresponding to a linear transformation and compute the image of a vector given a standard matrix.
   - Review: Section 3.2
4. Determine if a linear transformation is injective and/or surjective.
   - Review: Section 3.4
5. Interpret the ideas of injectivity and surjectivity in multiple ways.
   - Review: YouTube[3]

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[1] www.khanacademy.org/math/precalculus/composite/composing/v/function-composition

[2] www.youtube.com/watch?v=BQMyeQOLvpg

[3] www.youtube.com/watch?v=WpUv72Y6Dl0

4.1 Matrices and Multiplication (MX1)

Learning Outcomes

- Multiply matrices.

4.1.1 Class Activities

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

$$\begin{tikzcd} \mathbb{R}^n \arrow[r, "T"] \arrow[rr, bend right, "S \circ T"'] & \mathbb{R}^m \arrow[r, "S"] & \mathbb{R}^k \end{tikzcd}$$

Figure 40 The composition of two linear maps.

Activity 4.1.1 Let $T : \mathbb{R}^3 \to \mathbb{R}^2$ be defined by the 2×3 starndard matrix B and $S : \mathbb{R}^2 \to \mathbb{R}^4$ be defined by the 4×2 standard matrix A:

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

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

A. The domain is $\mathbb{R}^3$ and the codomain is $\mathbb{R}^2$

B. The domain is $\mathbb{R}^2$ and the codomain is $\mathbb{R}^4$

C. The domain is $\mathbb{R}^3$ and the codomain is $\mathbb{R}^4$

D. The domain is $\mathbb{R}^4$ and the codomain is $\mathbb{R}^3$

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

A. 4 (rows) $\times$ 3 (columns)

B. 3 (rows) $\times$ 4 (columns)

C. 3 (rows) $\times$ 2 (columns)

D. 2 (rows) $\times$ 4 (columns)

(c) Compute

$$(S \circ T)(\vec{e}_1) = S(T(\vec{e}_1)) = S\left(\begin{bmatrix} 2 \\ 5 \end{bmatrix}\right) = \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix}.$$

(d) Compute $(S \circ T)(\vec{e}_2)$.

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

(f) Use $(S \circ T)(\vec{e}_1), (S \circ T)(\vec{e}_2), (S \circ T)(\vec{e}_3)$ to write the standard matrix for $S \circ T$.

Definition 4.1.2 We define the **product** AB of a $m \times n$ matrix A and a $n \times k$ matrix B to be the $m \times k$ standard matrix of the composition map of the two corresponding linear functions.

For the previous activity, T was a map $\mathbb{R}^3 \to \mathbb{R}^2$, and S was a map $\mathbb{R}^2 \to \mathbb{R}^4$, so $S \circ T$ gave a map $\mathbb{R}^3 \to \mathbb{R}^4$ with a 4×3 standard matrix:

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

$$= [(S \circ T)(\vec{e}_1) \quad (S \circ T)(\vec{e}_2) \quad (S \circ T)(\vec{e}_3)] = \begin{bmatrix} 12 & -5 & 5 \\ 5 & -3 & 4 \\ 31 & -12 & 11 \\ -12 & 5 & -5 \end{bmatrix}.$$

◊

Activity 4.1.2 Let $S : \mathbb{R}^3 \to \mathbb{R}^2$ be given by the matrix $A = \begin{bmatrix} -4 & -2 & 3 \\ 0 & 1 & 1 \end{bmatrix}$ and $T : \mathbb{R}^2 \to \mathbb{R}^3$ be given by the matrix $B = \begin{bmatrix} 2 & 3 \\ 1 & -1 \\ 0 & -1 \end{bmatrix}$.

(a) Write the dimensions (rows $\times$ columns) for A, B, AB, and BA.

(b) Find the standard matrix AB of $S \circ T$.

(c) Find the standard matrix BA of $T \circ S$.

Activity 4.1.3 Consider the following three matrices.

$$A = \begin{bmatrix} 1 & 0 & -3 \\ 3 & 2 & 1 \end{bmatrix} \qquad B = \begin{bmatrix} 2 & 2 & 1 & 0 & 1 \\ 1 & 1 & 1 & -1 & 0 \\ 0 & 0 & 3 & 2 & 1 \\ -1 & 5 & 7 & 2 & 1 \end{bmatrix} \qquad C = \begin{bmatrix} 2 & 2 \\ 0 & -1 \\ 3 & 1 \\ 4 & 0 \end{bmatrix}$$

(a) Find the domain and codomain of each of the three linear maps corresponding to A, B, and C.

(b) Only one of the matrix products AB, AC, BA, BC, CA, CB can actually be computed. Compute it.

Activity 4.1.4 Let $B = \begin{bmatrix} 3 & -4 & 0 \\ 2 & 0 & -1 \\ 0 & -3 & 3 \end{bmatrix}$, and let $A = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$.

(a) Compute the product BA by hand.

(b) Check your work using technology. Using Octave:

```
B = [3 -4 0 ; 2 0 -1 ; 0 -3 3]
A = [2 7 -1 ; 0 3 2  ; 1 1 -1]
B*A
```

```
B = [3 -4 0 ; 2 0 -1 ; 0 -3 3]
A = [2 7 -1 ; 0 3 2  ; 1 1 -1]
```

```
B*A
```

Activity 4.1.5 Of the following three matrices, only two may be multiplied.

$$A=\begin{bmatrix}-1 & 3 & -2 & -3\\ 1 & -4 & 2 & 3\end{bmatrix} \quad B=\begin{bmatrix}1 & -6 & -1\\ 0 & 1 & 0\end{bmatrix} \quad C=\begin{bmatrix}1 & -1 & -1\\ 0 & 1 & -2\\ -2 & 4 & -1\\ -2 & 3 & -1\end{bmatrix}$$

Explain which two can be multiplied and why. Then show how to find their product.

4.1.2 Videos

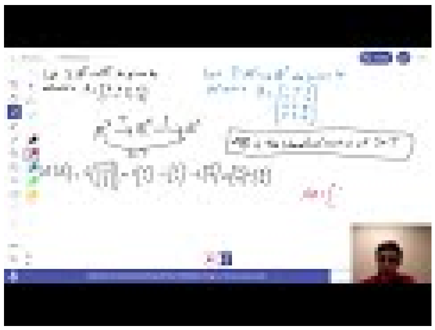


Figure 41 Video: Multiplying matrices

4.1.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/MX1.slides.html.

4.1.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/MX1/.

4.1.5 Mathematical Writing Explorations

Exploration 4.1.6 Construct 3 matrices, $A, B,$ and C, such that

- $AB : \mathbb{R}^4 \to \mathbb{R}^2$
- $BC : \mathbb{R}^2 \to \mathbb{R}^3$
- $CA : \mathbb{R}^3 \to \mathbb{R}^4$.
- $ABC : \mathbb{R}^2 \to \mathbb{R}^2$

Exploration 4.1.7 Construct 3 examples of matrix multiplication, with all matrix dimensions at least 2.

- Where A and B are not square, but AB is square.
- Where $AB = BA$.
- Where $AB \neq BA$.

Exploration 4.1.8 Use the included map in this problem.

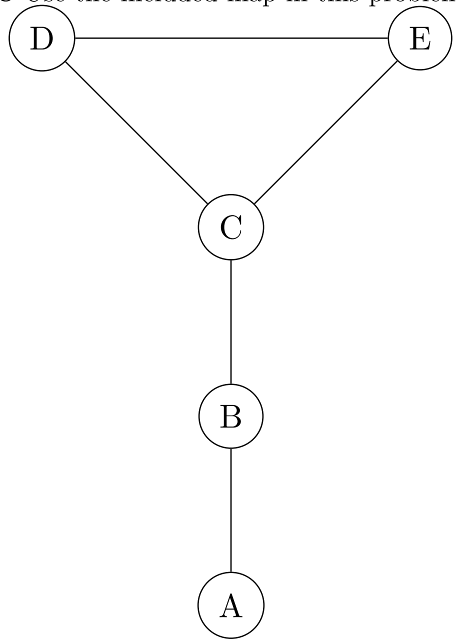


Figure 42 Adjacency map, showing roads between 5 cities

- An *adjacency matrix* for this map is a matrix that has the number of roads from city i to city j in the (i,j) entry of the matrix. A road is a path of length exactly 1. All (i,i)entries are 0. Write the adjacency matrix for this map, with the cities in alphabetical order.
- What does the square of this matrix tell you about the map? The cube? The n-th power?

4.1.6 Sample Problem and Solution

Sample problem Example B.1.18.

4.2 The Inverse of a Matrix (MX2)

Learning Outcomes

- Determine if a matrix is invertible, and if so, compute its inverse.

4.2.1 Class Activities

Activity 4.2.1 Let $A = \begin{bmatrix} 2 & 7 & -1 \\ 0 & 3 & 2 \\ 1 & 1 & -1 \end{bmatrix}$. Find a 3×3 matrix B such that $BA = A$, that is,

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

Check your guess using technology.

Definition 4.2.1 The identity matrix I_n (or just I when n is obvious from context) is the $n \times n$ matrix

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

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

Fact 4.2.2 *For any square matrix A, $IA = AI = A$:*

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

Activity 4.2.2 Let $T : \mathbb{R}^n \to \mathbb{R}^m$ be a linear map with standard matrix A. Sort the following items into three groups of statements: a group that means T is *injective*, a group that means T is *surjective*, and a group that means T is *bijective*.

A. $A\vec{x} = \vec{b}$ has a solution for all $\vec{b} \in \mathbb{R}^m$

B. $A\vec{x} = \vec{b}$ has a unique solution for all $\vec{b} \in \mathbb{R}^m$

C. $A\vec{x} = \vec{0}$ has a unique solution.

D. The columns of A span $\mathbb{R}^m$

E. The columns of A are linearly independent

F. The columns of A are a basis of $\mathbb{R}^m$

G. Every column of $\mathrm{RREF}(A)$ has a pivot

H. Every row of $\mathrm{RREF}(A)$ has a pivot

I. $m = n$ and $\mathrm{RREF}(A) = I$

Activity 4.2.3 Let $T : \mathbb{R}^3 \to \mathbb{R}^3$ be the linear transformation given by the standard matrix $A = \begin{bmatrix} 2 & -1 & 0 \\ 2 & 1 & 4 \\ 1 & 1 & 3 \end{bmatrix}$.

Write an augmented matrix representing the system of equations given by $T(\vec{x}) = \vec{0}$, that is, $A\vec{x} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$. Then solve $T(\vec{x}) = \vec{0}$ to find the kernel of T.

Definition 4.2.3 Let $T : \mathbb{R}^n \to \mathbb{R}^n$ be a linear map with standard matrix A.

- If T is a bijection and $\vec{b}$ is any $\mathbb{R}^n$ vector, then $T(\vec{x}) = A\vec{x} = \vec{b}$ has a unique solution.
- So we may define an **inverse map** $T^{-1} : \mathbb{R}^n \to \mathbb{R}^n$ by setting $T^{-1}(\vec{b})$ to be this unique solution.
- Let A^{-1} be the standard matrix for T^{-1}. We call A^{-1} the **inverse matrix** of A, so we also say that A is **invertible**.

$\Diamond$

Activity 4.2.4 Let $T : \mathbb{R}^3 \to \mathbb{R}^3$ be the linear transformation given by the standard matrix $A = \begin{bmatrix} 2 & -1 & -6 \\ 2 & 1 & 3 \\ 1 & 1 & 4 \end{bmatrix}$.

(a) Write an augmented matrix representing the system of equations given by $T(\vec{x}) = \vec{e}_1$, that is, $A\vec{x} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$. Then solve $T(\vec{x}) = \vec{e}_1$ to find $T^{-1}(\vec{e}_1)$.

(b) Solve $T(\vec{x}) = \vec{e}_2$ to find $T^{-1}(\vec{e}_2)$.

(c) Solve $T(\vec{x}) = \vec{e}_3$ to find $T^{-1}(\vec{e}_3)$.

(d) Write A^{-1}, the standard matrix for T^{-1}.

Observation 4.2.4 We could have solved these three systems simultaneously by row reducing the matrix $[A \,|\, I]$ at once.

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

Activity 4.2.5 Find the inverse A^{-1} of the matrix $A = \begin{bmatrix} 1 & 3 \\ 0 & -2 \end{bmatrix}$ by row-reducing $[A \,|\, I]$.

Activity 4.2.6 Is the matrix $\begin{bmatrix} 2 & 3 & 1 \\ -1 & -4 & 2 \\ 0 & -5 & 5 \end{bmatrix}$ invertible? Give a reason for your answer.

Observation 4.2.5 An $n \times n$ matrix A is invertible if and only if $\mathrm{RREF}(A) = I_n$.

Activity 4.2.7 Let $T : \mathbb{R}^2 \to \mathbb{R}^2$ be the bijective linear map defined by $T\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} 2x - 3y \\ -3x + 5y \end{bmatrix}$, with the inverse map $T^{-1}\left(\begin{bmatrix} x \\ y \end{bmatrix}\right) = \begin{bmatrix} 5x + 3y \\ 3x + 2y \end{bmatrix}$.

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

(b) If A is the standard matrix for T and A^{-1} is the standard matrix for T^{-1}, find the 2×2 matrix

$$A^{-1}A = \begin{bmatrix} ? & ? \\ ? & ? \end{bmatrix}.$$

Observation 4.2.6 $T^{-1} \circ T = T \circ T^{-1}$ is the identity map for any bijective linear transformation T. Therefore $A^{-1}A = AA^{-1}$ equals the identity matrix I for any invertible matrix A.

4.2.2 Videos

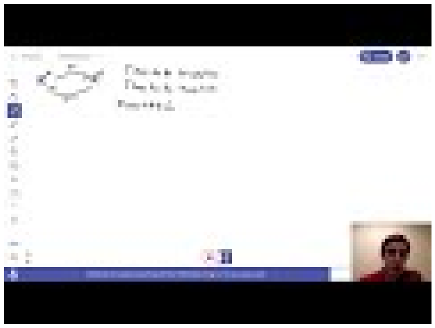


Figure 43 Video: Invertible matrices

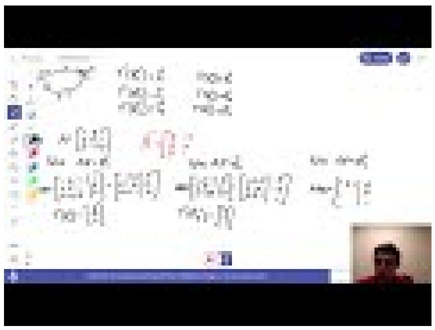


Figure 44 Video: Finding the inverse of a matrix

4.2.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/MX2.slides.html.

4.2.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/MX2/.

4.2.5 Mathematical Writing Explorations

Exploration 4.2.8 Assume A is an $n \times n$ matrix. Prove the following are equivalent. Some of these results you have proven previously.

- A is non-singular.
- A row reduces to the identity matrix.
- For any choice of $\vec{b} \in \mathbb{R}^n$, the system of equations represented by the augmented matrix $[A|\vec{b}]$ has a unique solution.
- The columns of A are a linearly independent set.
- The columns of A form a basis for $\mathbb{R}^n$.
- The rank of A is n.
- The nullity of A is 0.
- A is invertible.

- The linear transformation T with standard matrix A is injective and surjective. Such a map is called an *isomorphism*.

Exploration 4.2.9

- Assume T is a square matrix, and T^4 is the zero matrix. Prove that $(I - T)^{-1} = I + T + T^2 + T^3$. You will need to first prove a lemma that matrix multiplication distributes over matrix addition.

- Generalize your result to the case where T^n is the zero matrix.

4.2.6 Sample Problem and Solution

Sample problem Example B.1.19.

4.3 Solving Systems with Matrix Inverses (MX3)

Learning Outcomes

- Invert an appropriate matrix to solve a system of linear equations.

4.3.1 Class Activities

Activity 4.3.1 Consider the following linear system with a unique solution:

$$\begin{array}{rcrcrcrcr} 3x_1 & - & 2x_2 & - & 2x_3 & - & 4x_4 & = & -7 \\ 2x_1 & - & x_2 & - & x_3 & - & x_4 & = & -1 \\ -x_1 & & & + & x_3 & & & = & -1 \\ & - & x_2 & & & - & 2x_4 & = & -5 \end{array}$$

(a) Define

$$T\left(\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix}\right) = \begin{bmatrix} ? \\ ? \\ ? \\ ? \end{bmatrix}$$

so that $T(\vec{x}) = \begin{bmatrix} -7 \\ -1 \\ -1 \\ -5 \end{bmatrix}$ has the same solution set as this system.

(b) Define

$$A = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix}$$

so that $A\vec{x} = \begin{bmatrix} -7 \\ -1 \\ -1 \\ -5 \end{bmatrix}$ has the same solution set as this system.

(c) Find

$$B = \begin{bmatrix} ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \\ ? & ? & ? & ? \end{bmatrix}$$

so that $BA\vec{x} = \vec{x}$.

(d) Find $\vec{x} = BA\vec{x} = B \begin{bmatrix} -7 \\ -1 \\ -1 \\ -5 \end{bmatrix}$ to solve the system.

Remark 4.3.1 The linear system described by the augmented matrix $[A \mid \vec{w}]$ has exactly the same solution set as the matrix equation $A\vec{x} = \vec{w}$.

Activity 4.3.2 Let $A\vec{x} = \vec{w}$ describe a linear system. When will this linear system have exactly one solution?

A. When A is invertible.

B. When A is not invertible.

C. When RREF A has a non-pivot column.

D. When RREF A has a non-pivot row.

Fact 4.3.2 *When $A\vec{x} = \vec{w}$ has exactly one solution, this solution is given by $\vec{x} = A^{-1}\vec{w}$.*

Activity 4.3.3 Consider the vector equation

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

with a unique solution.

(a) Explain and demonstrate how this problem can be restated using matrix multiplication.

(b) Use the properties of matrix multiplication to find the unique solution.

4.3.2 Videos

Video coming soon to this YouTube playlist[1].

4.3.3 Exercises

Exercises available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/MX3/`.

4.3.4 Mathematical Writing Explorations

Exploration 4.3.4 Use row reduction to find the inverse of the following general matrix. Give conditions on which this inverse exists.

$$\begin{bmatrix} 1 & b & c \\ d & e & f \\ g & h & i \end{bmatrix}$$

Exploration 4.3.5 Assume that H is invertible, and that HG is the zero matrix. Prove that G must be the zero matrix. Would this still be true if H were not invertible?

Exploration 4.3.6 If H is invertible and $r \in \mathbb{R}$, what is the inverse of rH?

Exploration 4.3.7 If H and G are invertible, is $H^{-1} + G^{-1} = (H + G)^{-1}$?

[1] `www.youtube.com/watch?v=kpOK7RhFEiQ&list=PLwXCBkIf7xBMo3zMnD7WVt39rANLlSdmj`

Exploration 4.3.8 If A is nonsingular and square, and both P and Q are nonsingular, with $PAQ = I$, prove that $A^{-1} = QP$.

4.3.5 Sample Problem and Solution

Sample problem Example B.1.20.

4.4 Row Operations as Matrix Multiplication (MX4)

Learning Outcomes

- Express row operations through matrix multiplication.

4.4.1 Class Activities

Activity 4.4.1 Tweaking the identity matrix slightly allows us to write row operations in terms of matrix multiplication.

(a) Create a matrix that doubles the third row of A:

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

(b) Create a matrix that swaps the second and third rows of A:

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

(c) Create a matrix that adds 5 times the third row of A to the first row:

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

Fact 4.4.1 *If R is the result of applying a row operation to I, then RA is the result of applying the same row operation to A.*

- *Scaling a row:* $R = \begin{bmatrix} c & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$
- *Swapping rows:* $R = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$
- *Adding a row multiple to another row:* $R = \begin{bmatrix} 1 & 0 & c \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

Such matrices can be chained together to emulate multiple row operations. In particular,

$$\mathrm{RREF}(A) = R_k \dots R_2 R_1 A$$

for some sequence of matrices $R_1, R_2, \dots, R_k$.

Activity 4.4.2 Consider the two row operations $R_2 \leftrightarrow R_3$ and $R_1 + R_2 \to R_1$ applied as follows to show $A \sim B$:

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

$$\sim \begin{bmatrix} -1+1 & 4+2 & 5+3 \\ 1 & 2 & 3 \\ 0 & 3 & -1 \end{bmatrix} = \begin{bmatrix} 0 & 6 & 8 \\ 1 & 2 & 3 \\ 0 & 3 & -1 \end{bmatrix} = B$$

Express these row operations as matrix multiplication by expressing B as the product of two matrices and A:

$$B = \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix} A$$

Check your work using technology.

4.4.2 Videos

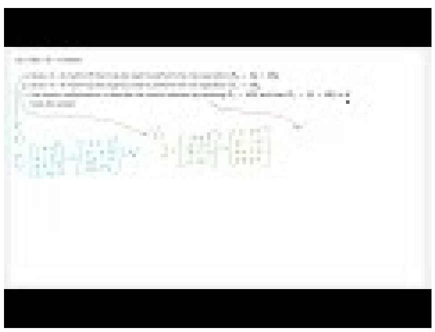


Figure 45 Video: Row operations as matrix multiplication

4.4.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/MX4.slides.html.

4.4.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/MX4/.

4.4.5 Sample Problem and Solution

Sample problem Example B.1.21.

Chapter 5

Geometric Properties of Linear Maps (GT)

Learning Outcomes

How do we understand linear maps geometrically?

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

1. Describe how a row operation affects the determinant of a matrix.
2. Compute the determinant of a 4×4 matrix.
3. Find the eigenvalues of a 2×2 matrix.
4. Find a basis for the eigenspace of a 4×4 matrix associated with a given eigenvalue.

Readiness Assurance. Before beginning this chapter, you should be able to...

1. Calculate the area of a parallelogram.
   - Review: Khan Academy[1]
2. Recall and use the definition of a linear transformation.
   - Review: Section 3.1
3. Find the matrix corresponding to a linear transformation of Euclidean spaces.
   - Review: Section 3.2
4. Find all roots of quadratic polynomials (including complex ones).
   - Review: Khan Academy[2], YouTube (1)[3], YouTube (2)[4]
5. Interpret the statement "A is an invertible matrix" in many equivalent ways in different contexts.

[1] www.khanacademy.org/math/cc-sixth-grade-math/cc-6th-geometry-topic/cc-6th-parallelogram-area/v/intuition-for-area-of-a-parallelogram

[2] www.khanacademy.org/math/algebra-home/alg-polynomials/alg-factoring-polynomials-quadratic-forms/v/factoring-trinomials-by-grouping-5

[3] youtu.be/Aa-v1EK7DR4

[4] www.youtube.com/watch?v=2yBhDsNE0w

- Review: Section 4.3

5.1 Row Operations and Determinants (GT1)

Learning Outcomes

- Describe how a row operation affects the determinant of a matrix.

5.1.1 Class Activities

Activity 5.1.1 The image in Figure 46 illustrates how the linear transformation $T : \mathbb{R}^2 \to \mathbb{R}^2$ given by the standard matrix $A = \begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}$ transforms the unit square.

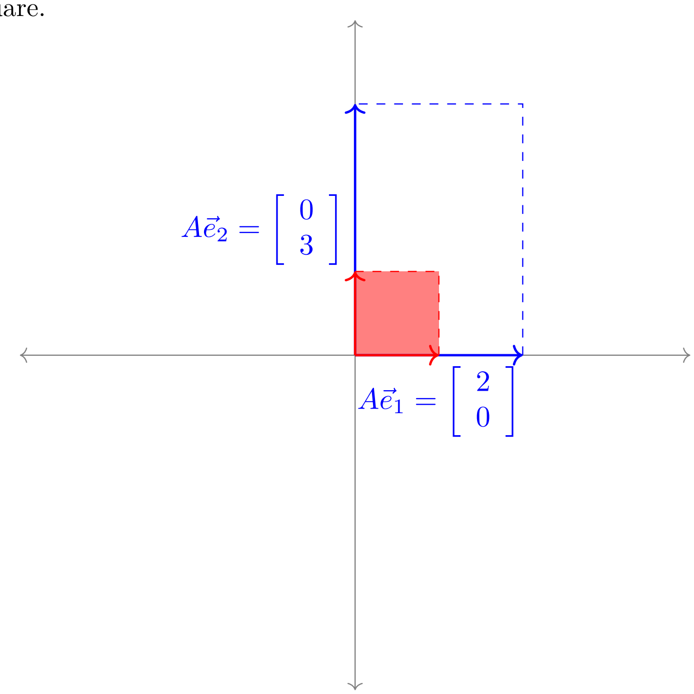


Figure 46 Transformation of the unit square by the matrix A.

(a) What are the lengths of $A\vec{e}_1$ and $A\vec{e}_2$?

(b) What is the area of the transformed unit square?

Activity 5.1.2 The image below illustrates how the linear transformation $S : \mathbb{R}^2 \to \mathbb{R}^2$ given by the standard matrix $B = \begin{bmatrix} 2 & 3 \\ 0 & 4 \end{bmatrix}$ transforms the unit square.

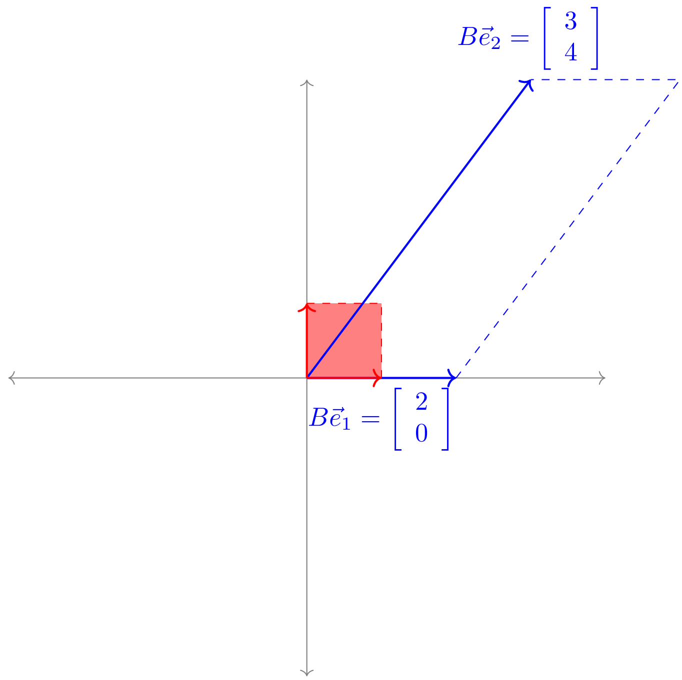


Figure 47 Transformation of the unit square by the matrix B

(a) What are the lengths of $B\vec{e}_1$ and $B\vec{e}_2$?

(b) What is the area of the transformed unit square?

Observation 5.1.1 It is possible to find two nonparallel vectors that are scaled but not rotated by the linear map given by B.

$$B\vec{e}_1 = \left[\begin{array}{cc} 2 & 3 \\ 0 & 4 \end{array}\right]\left[\begin{array}{c} 1 \\ 0 \end{array}\right] = \left[\begin{array}{c} 2 \\ 0 \end{array}\right] = 2\vec{e}_1$$

$$B\left[\begin{array}{c} \frac{3}{4} \\ \frac{1}{2} \end{array}\right] = \left[\begin{array}{cc} 2 & 3 \\ 0 & 4 \end{array}\right]\left[\begin{array}{c} \frac{3}{4} \\ \frac{1}{2} \end{array}\right] = \left[\begin{array}{c} 3 \\ 2 \end{array}\right] = 4\left[\begin{array}{c} \frac{3}{4} \\ \frac{1}{2} \end{array}\right]$$

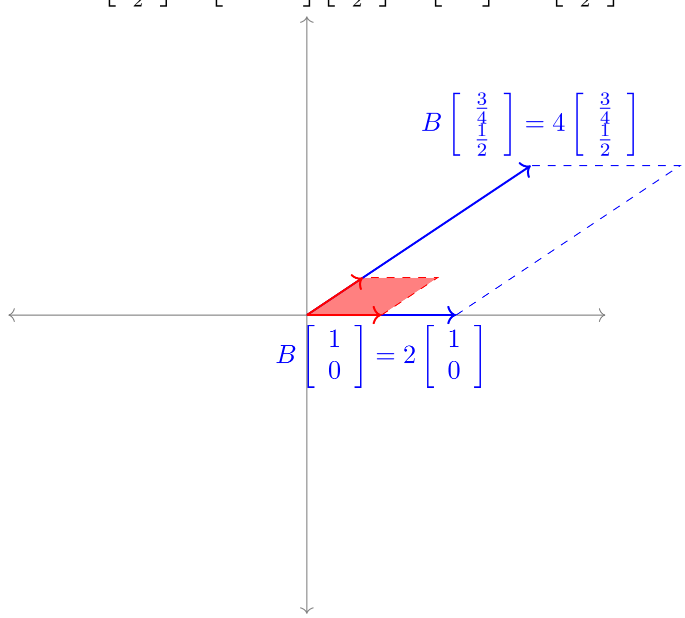


Figure 48 Certain vectors are stretched out without being rotated.

The process for finding such vectors will be covered later in this chapter.

Observation 5.1.2 Notice that while a linear map can transform vectors in various ways, linear maps always transform parallelograms into parallelograms, and these areas are always transformed by the same factor: in the case of $B = \begin{bmatrix} 2 & 3 \\ 0 & 4 \end{bmatrix}$, this factor is 8.

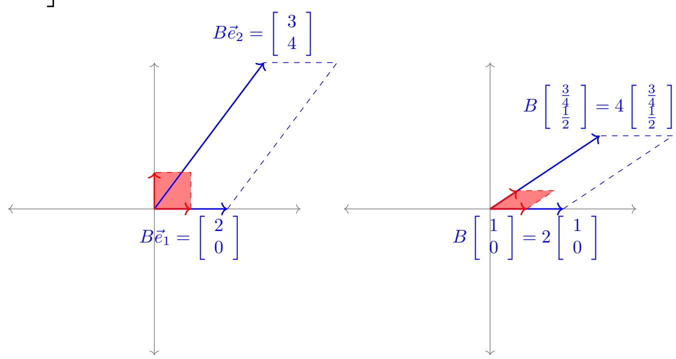


Figure 49 A linear map transforming parallelograms into parallelograms.

Since this change in area is always the same for a given linear map, it will be equal to the value of the transformed unit square (which begins with area 1).

Remark 5.1.3 We will define the **determinant** of a square matrix B, or $\det(B)$ for short, to be the factor by which B scales areas. In order to figure out how to compute it, we first figure out the properties it must satisfy.

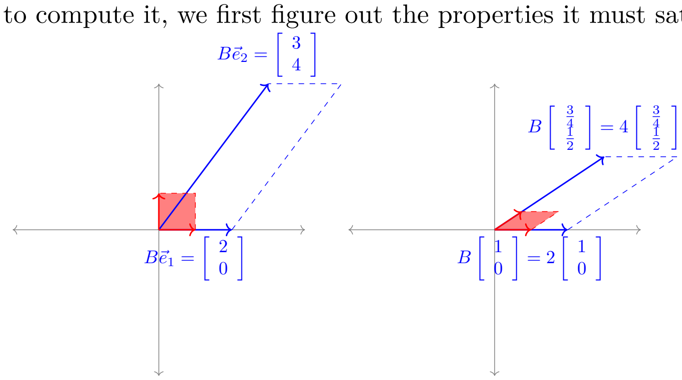


Figure 50 The linear transformation B scaling areas by a constant factor, which we call the **determinant**

Activity 5.1.3 The transformation of the unit square by the standard matrix $[\vec{e}_1 \ \ \vec{e}_2] = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = I$ is illustrated below. If $\det([\vec{e}_1 \ \ \vec{e}_2]) = \det(I)$ is the area of resulting parallelogram, what is the value of $\det([\vec{e}_1 \ \ \vec{e}_2]) = \det(I)$?

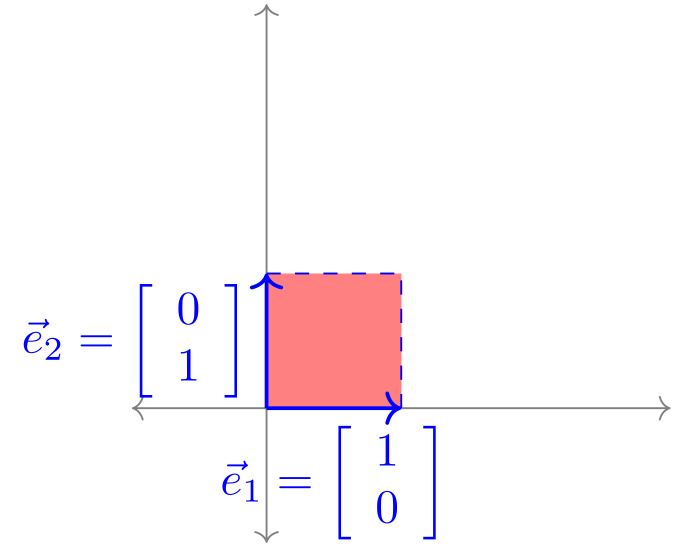


Figure 51 The transformation of the unit square by the identity matrix.

The value for $\det([\vec{e}_1 \;\; \vec{e}_2]) = \det(I)$ is:

A. 0

B. 1

C. 2

D. 4

Activity 5.1.4 The transformation of the unit square by the standard matrix $[\vec{v} \;\; \vec{v}]$ is illustrated below: both $T(\vec{e}_1) = T(\vec{e}_2) = \vec{v}$. If $\det([\vec{v} \;\; \vec{v}])$ is the area of the generated parallelogram, what is the value of $\det([\vec{v} \;\; \vec{v}])$?

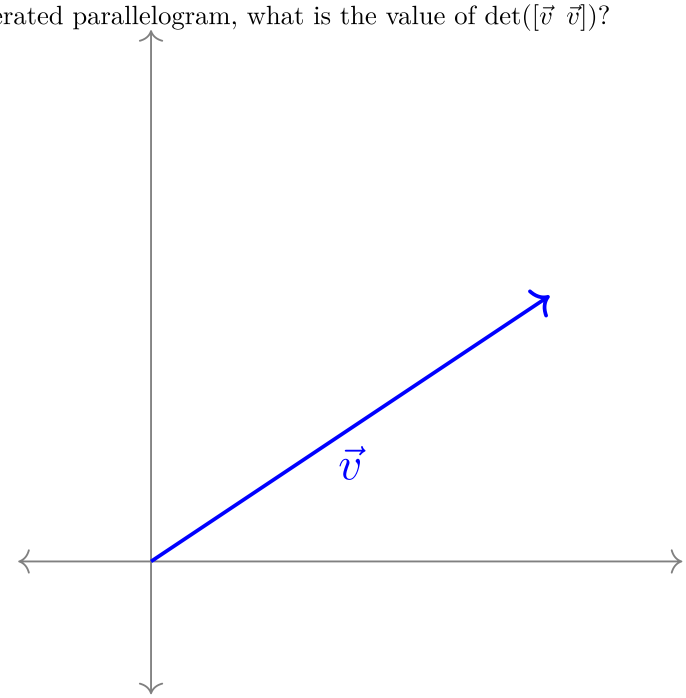


Figure 52 Transformation of the unit square by a matrix with identical columns.

The value of $\det([\vec{v} \;\; \vec{v}])$ is:

A. 0

B. 1

C. 2

D. 4

Activity 5.1.5 The transformations of the unit square by the standard matrices $[\vec{v}\ \ \vec{w}]$ and $[c\vec{v}\ \ \vec{w}]$ are illustrated below. Describe the value of $\det([c\vec{v}\ \ \vec{w}])$.

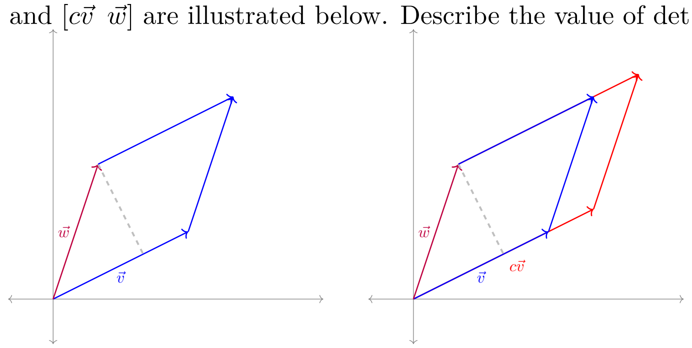


Figure 53 The parallelograms generated by $\vec{v}$ and $\vec{w}/c\vec{w}$

Describe the value of $\det([c\vec{v}\ \ \vec{w}])$:

A. $\det([\vec{v}\ \ \vec{w}])$

B. $c\det([\vec{v}\ \ \vec{w}])$

C. $c^2\det([\vec{v}\ \ \vec{w}])$

D. Cannot be determined from this information.

Remark 5.1.4 Consider the vectors $\vec{u}$, $\vec{v}$, $\vec{u}+\vec{v}$, and $\vec{w}$ displayed below. Each pair of vectors generates a parallelogram, and the area of each parallelogram can be described in terms of determinants.

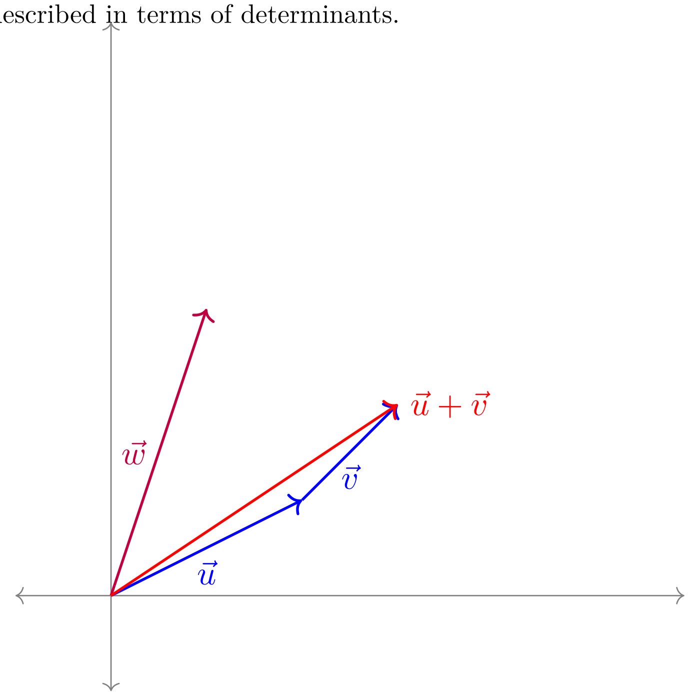


Figure 54 The vectors $\vec{u}$, $\vec{v}$, $\vec{u}+\vec{v}$ and $\vec{w}$

Remark 5.1.5 For example, $\det([\vec{u}\ \ \vec{w}])$ represents the shaded area shown below.

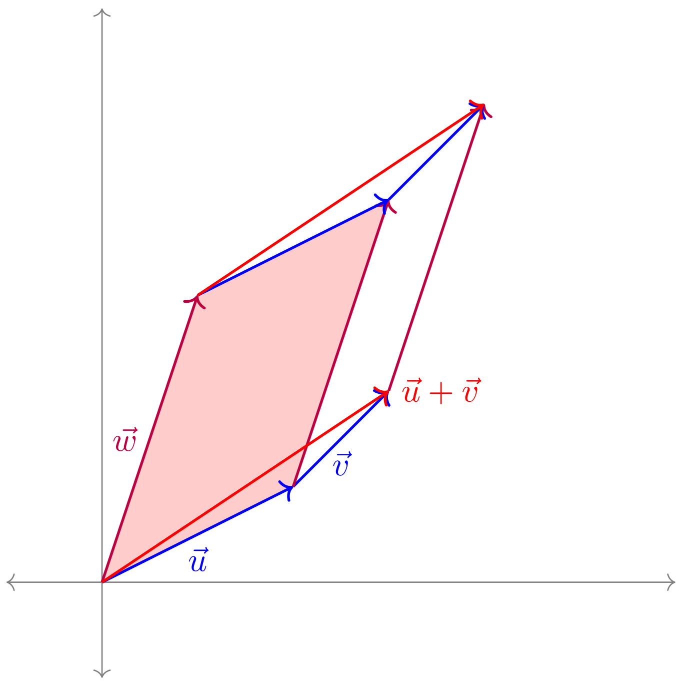


Figure 55 Parallelogram generated by $\vec{u}$ and $\vec{w}$

Remark 5.1.6 Similarly, $\det([\vec{v}\ \ \vec{w}])$ represents the shaded area shown below.

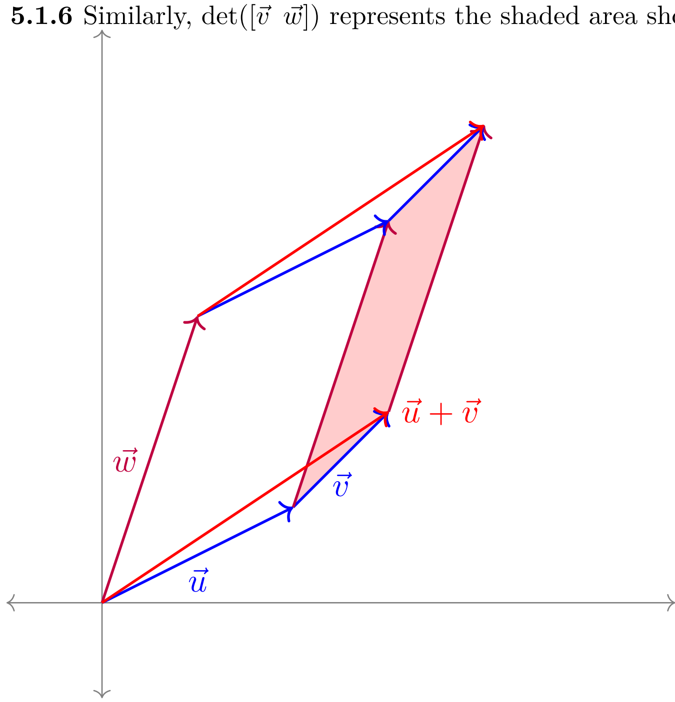


Figure 56 Parallelogram generated by $\vec{v}$ and $\vec{w}$

Activity 5.1.6 The paralellograms generated by the standard matrices $[\vec{u}\ \ \vec{w}]$, $[\vec{v}\ \ \vec{w}]$ and $[\vec{u}+\vec{v}\ \ \vec{w}]$ are illustrated below.

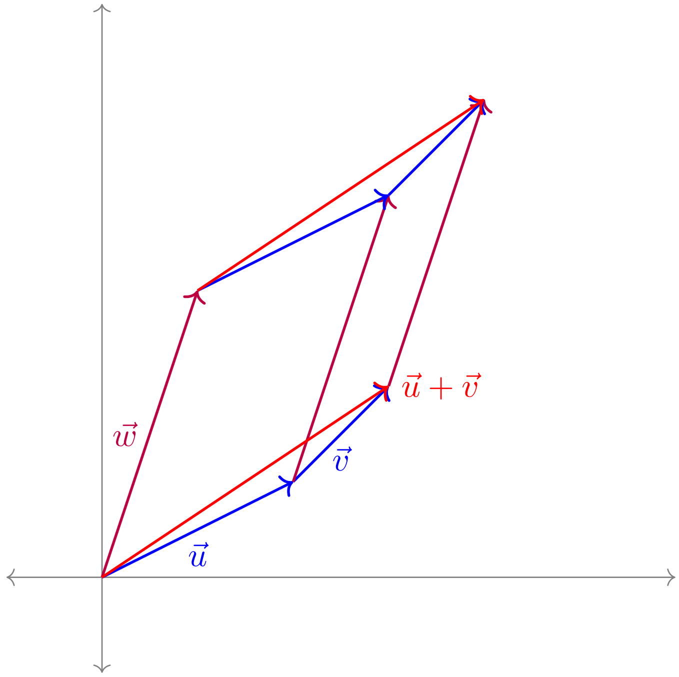


Figure 57 Parallelogram generated by $\vec{u}+\vec{v}$ and $\vec{w}$

Describe the value of $\det([\vec{u}+\vec{v}\ \ \vec{w}])$.

A. $\det([\vec{u}\ \ \vec{w}]) = \det([\vec{v}\ \ \vec{w}])$

B. $\det([\vec{u}\ \ \vec{w}]) + \det([\vec{v}\ \ \vec{w}])$

C. $\det([\vec{u}\ \ \vec{w}])\det([\vec{v}\ \ \vec{w}])$

D. Cannot be determined from this information.

Definition 5.1.7 The **determinant** is the unique function $\det : M_{n,n} \to \mathbb{R}$ satisfying these properties:

1. $\det(I) = 1$
2. $\det(A) = 0$ whenever two columns of the matrix are identical.
3. $\det[\cdots\ \ c\vec{v}\ \ \cdots] = c\det[\cdots\ \ \vec{v}\ \ \cdots]$, assuming no other columns change.
4. $\det[\cdots\ \ \vec{v}+\vec{w}\ \ \cdots] = \det[\cdots\ \ \vec{v}\ \ \cdots]+\det[\cdots\ \ \vec{w}\ \ \cdots]$, assuming no other columns change.

Note that these last two properties together can be phrased as “The determinant is linear in each column.” $\Diamond$

Observation 5.1.8 The determinant must also satisfy other properties. Consider $\det([\vec{v}\quad \vec{w}+c\vec{v}])$ and $\det([\vec{v}\quad \vec{w}])$.

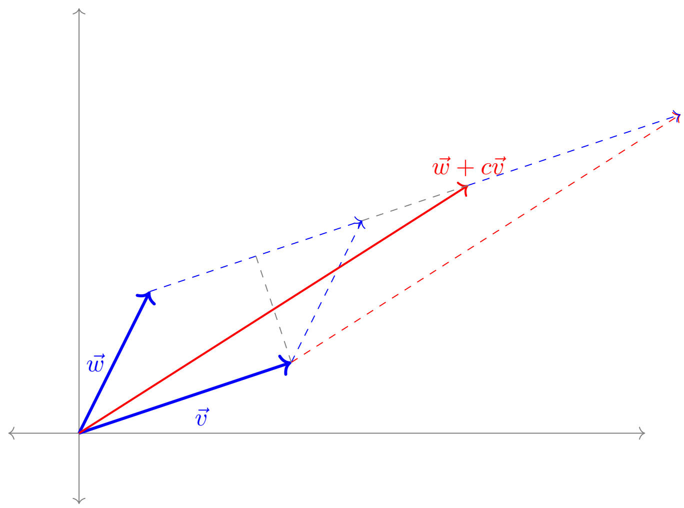


Figure 58 Parallelogram built by $\vec{w}+c\vec{v}$ and $\vec{w}$

The base of both parallelograms is $\vec{v}$, while the height has not changed, so the determinant does not change either. This can also be proven using the other properties of the determinant:

$$\begin{aligned}\det([\vec{v}+c\vec{w} \quad \vec{w}]) &= \det([\vec{v} \quad \vec{w}]) + \det([c\vec{w} \quad \vec{w}])\\ &= \det([\vec{v} \quad \vec{w}]) + c\det([\vec{w} \quad \vec{w}])\\ &= \det([\vec{v} \quad \vec{w}]) + c\cdot 0\\ &= \det([\vec{v} \quad \vec{w}])\end{aligned}$$

Remark 5.1.9 Swapping columns may be thought of as a reflection, which is represented by a negative determinant. For example, the following matrices transform the unit square into the same parallelogram, but the second matrix reflects its orientation.

$$A = \begin{bmatrix} 2 & 3 \\ 0 & 4 \end{bmatrix} \quad \det A = 8 \qquad B = \begin{bmatrix} 3 & 2 \\ 4 & 0 \end{bmatrix} \quad \det B = -8$$

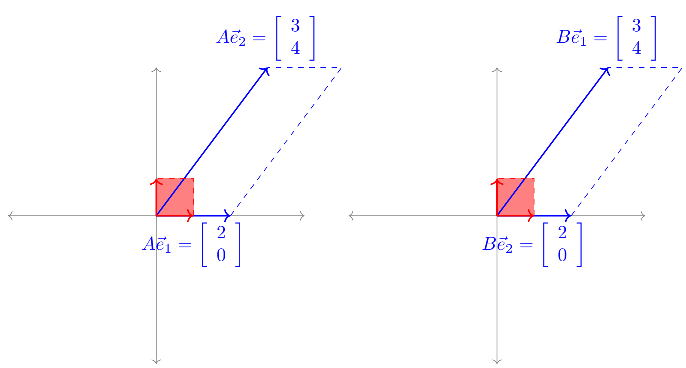


Figure 59 Reflection of a parallelogram as a result of swapping columns.

Observation 5.1.10 The fact that swapping columns multiplies determinants by a negative may be verified by adding and subtracting columns.

$$\begin{aligned}\det([\vec{v} \quad \vec{w}]) &= \det([\vec{v}+\vec{w} \quad \vec{w}])\\ &= \det([\vec{v}+\vec{w} \quad \vec{w}-(\vec{v}+\vec{w})])\\ &= \det([\vec{v}+\vec{w} \quad -\vec{v}])\end{aligned}$$

$$\begin{aligned}&= \det([\vec{v}+\vec{w}-\vec{v} \quad -\vec{v}])\\ &= \det([\vec{w} \quad -\vec{v}])\\ &= -\det([\vec{w} \quad \vec{v}])\end{aligned}$$

Fact 5.1.11 *To summarize, we've shown that the column versions of the three row-reducing operations a matrix may be used to simplify a determinant in the following way:*

1. *Multiplying a column by a scalar multiplies the determinant by that scalar:*

$$c\det([\cdots \quad \vec{v} \quad \cdots]) = \det([\cdots \quad c\vec{v} \quad \cdots])$$

2. *Swapping two columns changes the sign of the determinant:*

$$\det([\cdots \quad \vec{v} \quad \cdots \quad \vec{w} \quad \cdots]) = -\det([\cdots \quad \vec{w} \quad \cdots \quad \vec{v} \quad \cdots])$$

3. *Adding a multiple of a column to another column does not change the determinant:*

$$\det([\cdots \quad \vec{v} \quad \cdots \quad \vec{w} \quad \cdots]) = \det([\cdots \quad \vec{v}+c\vec{w} \quad \cdots \quad \vec{w} \quad \cdots])$$

Activity 5.1.7 The transformation given by the standard matrix A scales areas by 4, and the transformation given by the standard matrix B scales areas by 3. By what factor does the transformation given by the standard matrix AB scale areas?

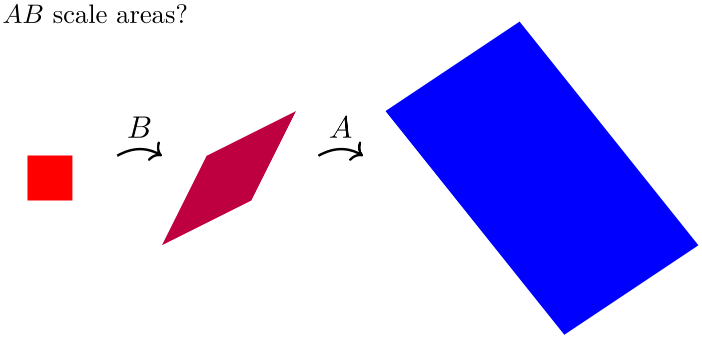


Figure 60 Area changing under the composition of two linear maps

A. 1

B. 7

C. 12

D. Cannot be determined

Fact 5.1.12 *Since the transformation given by the standard matrix AB is obtained by applying the transformations given by A and B, it follows that*

$$\det(AB) = \det(A)\det(B) = \det(B)\det(A) = \det(BA).$$

Remark 5.1.13 Recall that row operations may be produced by matrix multiplication.

- Multiply the first row of A by c: $\begin{bmatrix} c & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} A$

- Swap the first and second row of A: $\begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} A$

- Add c times the third row to the first row of A: $\begin{bmatrix} 1 & 0 & c & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} A$

Fact 5.1.14 *The determinants of row operation matrices may be computed by manipulating columns to reduce each matrix to the identity:*

- *Scaling a row:* $\det \begin{bmatrix} c & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = c \det \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = c$

- *Swapping rows:* $\det \begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = -1 \det \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = -1$

- *Adding a row multiple to another row:* $\det \begin{bmatrix} 1 & 0 & c & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \det \begin{bmatrix} 1 & 0 & c-1c & 0 \\ 0 & 1 & 0-0c & 0 \\ 0 & 0 & 1-0c & 0 \\ 0 & 0 & 0-0c & 1 \end{bmatrix} =$ $\det(I) = 1$

Activity 5.1.8 Consider the row operation $R_1 + 4R_3 \to R_1$ applied as follows to show $A \sim B$:

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} \sim \begin{bmatrix} 1+4(9) & 2+4(10) & 3+4(11) & 4+4(12) \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} = B$$

(a) Find a matrix R such that $B = RA$, by applying the same row operation to $I = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$.

(b) Find $\det R$ by comparing with the previous slide.

(c) If $C \in M_{4,4}$ is a matrix with $\det(C) = -3$, find

$$\det(RC) = \det(R)\det(C).$$

Activity 5.1.9 Consider the row operation $R_1 \leftrightarrow R_3$ applied as follows to show $A \sim B$:

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} \sim \begin{bmatrix} 9 & 10 & 11 & 12 \\ 5 & 6 & 7 & 8 \\ 1 & 2 & 3 & 4 \\ 13 & 14 & 15 & 16 \end{bmatrix} = B$$

(a) Find a matrix R such that $B = RA$, by applying the same row operation to I.

(b) If $C \in M_{4,4}$ is a matrix with $\det(C) = 5$, find $\det(RC)$.

Activity 5.1.10 Consider the row operation $3R_2 \to R_2$ applied as follows to show $A \sim B$:

$$A = \begin{bmatrix} 1 & 2 & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} \sim \begin{bmatrix} 1 & 2 & 3 & 4 \\ 3(5) & 3(6) & 3(7) & 3(8) \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{bmatrix} = B$$

(a) Find a matrix R such that $B = RA$.

(b) If $C \in M_{4,4}$ is a matrix with $\det(C) = -7$, find $\det(RC)$.

Activity 5.1.11 Let A be *any* 4×4 matrix with determinant 2.

(a) Let B be the matrix obtained from A by applying the row operation $R_1 - 5R_3 \to R_1$. What is $\det B$?

A -4 B -2 C 2 D 10

(b) Let M be the matrix obtained from A by applying the row operation $R_3 \leftrightarrow R_1$. What is $\det M$?

A -4 B -2 C 2 D 10

(c) Let P be the matrix obtained from A by applying the row operation $2R_4 \to R_4$. What is $\det P$?

A -4 B -2 C 2 D 10

Remark 5.1.15 Recall that the column versions of the three row-reducing operations a matrix may be used to simplify a determinant:

1. Multiplying columns by scalars:

$$\det([\cdots \; c\vec{v} \; \cdots]) = c\det([\cdots \; \vec{v} \; \cdots])$$

2. Swapping two columns:

$$\det([\cdots \; \vec{v} \; \cdots \; \vec{w} \; \cdots]) = -\det([\cdots \; \vec{w} \; \cdots \; \vec{v} \; \cdots])$$

3. Adding a multiple of a column to another column:

$$\det([\cdots \; \vec{v} \; \cdots \; \vec{w} \; \cdots]) = \det([\cdots \; \vec{v}+c\vec{w} \; \cdots \; \vec{w} \; \cdots])$$

Remark 5.1.16 The determinants of row operation matrices may be computed by manipulating columns to reduce each matrix to the identity:

- Scaling a row: $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & c & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$
- Swapping rows: $\begin{bmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$

- Adding a row multiple to another row: $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & c & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

Fact 5.1.17 *Thus we can also use both row operations to simplify determinants:*

- *Multiplying rows by scalars:*

$$\det \begin{bmatrix} \vdots \\ cR \\ \vdots \end{bmatrix} = c \det \begin{bmatrix} \vdots \\ R \\ \vdots \end{bmatrix}$$

- *Swapping two rows:*

$$\det \begin{bmatrix} \vdots \\ R \\ \vdots \\ S \\ \vdots \end{bmatrix} = -\det \begin{bmatrix} \vdots \\ S \\ \vdots \\ R \\ \vdots \end{bmatrix}$$

- *Adding multiples of rows/columns to other rows:*

$$\det \begin{bmatrix} \vdots \\ R \\ \vdots \\ S \\ \vdots \end{bmatrix} = \det \begin{bmatrix} \vdots \\ R + cS \\ \vdots \\ S \\ \vdots \end{bmatrix}$$

Activity 5.1.12 Complete the following derivation for a formula calculating 2×2 determinants:

$$\begin{aligned} \det \begin{bmatrix} a & b \\ c & d \end{bmatrix} &= \ ?\ \det \begin{bmatrix} 1 & b/a \\ c & d \end{bmatrix} \\ &= \ ?\ \det \begin{bmatrix} 1 & b/a \\ c - c & d - bc/a \end{bmatrix} \\ &= \ ?\ \det \begin{bmatrix} 1 & b/a \\ 0 & d - bc/a \end{bmatrix} \\ &= \ ?\ \det \begin{bmatrix} 1 & b/a \\ 0 & 1 \end{bmatrix} \\ &= \ ?\ \det \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &= \ ?\ \det I \\ &= \ ? \end{aligned}$$

Observation 5.1.18 So we may compute the determinant of $\begin{bmatrix} 2 & 4 \\ 2 & 3 \end{bmatrix}$ by using determinant properties to manipulate its rows/columns to reduce the matrix to I:

$$\begin{aligned}\det\begin{bmatrix} 2 & 4 \\ 2 & 3 \end{bmatrix} &= 2\det\begin{bmatrix} 1 & 2 \\ 2 & 3 \end{bmatrix} \\ &= 2\det\begin{bmatrix} 1 & 2 \\ 0 & -1 \end{bmatrix} \\ &= -2\det\begin{bmatrix} 1 & -2 \\ 0 & 1 \end{bmatrix} \\ &= -2\det\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \\ &= -2\end{aligned}$$

Or we may use a formula:

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

5.1.2 Videos

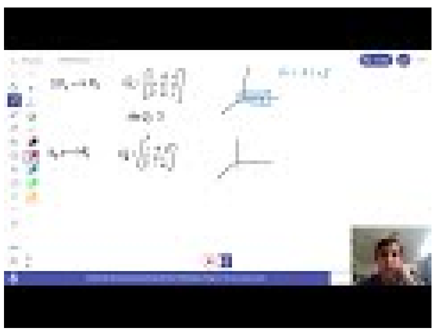


Figure 61 Video: Row operations, matrix multiplication, and determinants

5.1.3 Slideshow

Slideshow of activities available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/GT1.slides.html`.

5.1.4 Exercises

Exercises available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/GT1/`.

5.1.5 Mathematical Writing Explorations

Exploration 5.1.13

- Prove or disprove. The determinant is a linear operator on the vector space of $n \times n$ matrices.
- Find a matrix that will double the area of a region in $\mathbb{R}^2$.
- Find a matrix that will triple the area of a region in $\mathbb{R}^2$.
- Find a matrix that will halve the area of a region in $\mathbb{R}^2$.

5.1.6 Sample Problem and Solution

Sample problem Example B.1.22.

5.2 Computing Determinants (GT2)

Learning Outcomes

- Compute the determinant of a 4×4 matrix.

5.2.1 Class Activities

Remark 5.2.1 We've seen that row reducing all the way into RREF gives us a method of computing determinants.

However, we learned in Chapter 1 that this can be tedious for large matrices. Thus, we will try to figure out how to turn the determinant of a larger matrix into the determinant of a smaller matrix.

Activity 5.2.1 The following image illustrates the transformation of the unit cube by the matrix $\begin{bmatrix} 1 & 1 & 0 \\ 1 & 3 & 1 \\ 0 & 0 & 1 \end{bmatrix}$.

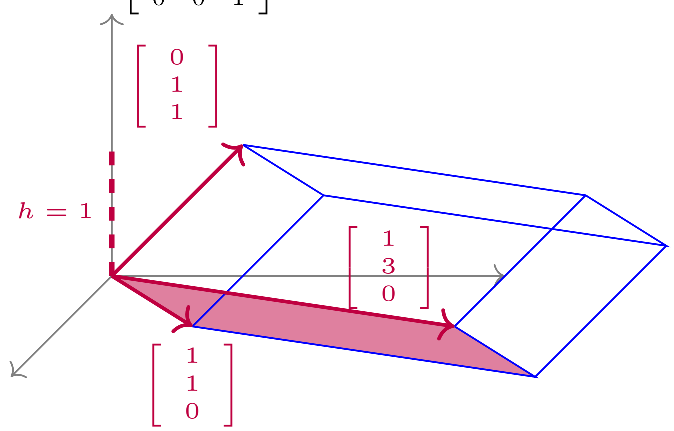


Figure 62 Transformation of the unit cube by the linear transformation.

Recall that for this solid $V = Bh$, where h is the height of the solid and B is the area of its parallelogram base. So what must its volume be?

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

B. $\det \begin{bmatrix} 1 & 0 \\ 3 & 1 \end{bmatrix}$

C. $\det \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix}$

D. $\det \begin{bmatrix} 1 & 3 \\ 0 & 0 \end{bmatrix}$

Fact 5.2.2 *If row i contains all zeros except for a 1 on the main (upper-left to lower-right) diagonal, then both column and row i may be removed without changing the value of the determinant.*

$$\det \begin{bmatrix} 3 & 2 & -1 & 3 \\ 0 & 1 & 0 & 0 \\ -1 & 4 & 1 & 0 \\ 5 & 0 & 11 & 1 \end{bmatrix} = \det \begin{bmatrix} 3 & -1 & 3 \\ -1 & 1 & 0 \\ 5 & 11 & 1 \end{bmatrix}$$

Since row and column operations affect the determinants in the same way, the same technique works for a column of all zeros except for a 1 on the main *diagonal.*

$$\det\begin{bmatrix} 3 & 0 & -1 & 5 \\ 2 & 1 & 4 & 0 \\ -1 & 0 & 1 & 11 \\ 3 & 0 & 0 & 1 \end{bmatrix} = \det\begin{bmatrix} 3 & -1 & 5 \\ -1 & 1 & 11 \\ 3 & 0 & 1 \end{bmatrix}$$

Put another way, if you have either a column or row from the identity matrix, you can cancel both the column and row containing the 1.

Warning 5.2.3 If the 1 is not on the main diagonal, you'll need to use row or column swaps in order to cancel.

$$\det\begin{bmatrix} 3 & 0 & -1 & 5 \\ -1 & 0 & 1 & 11 \\ 2 & 1 & 4 & 0 \\ 3 & 0 & 0 & 1 \end{bmatrix} = -\det\begin{bmatrix} 3 & 0 & -1 & 5 \\ 2 & 1 & 4 & 0 \\ -1 & 0 & 1 & 11 \\ 3 & 0 & 0 & 1 \end{bmatrix} = -\det\begin{bmatrix} 3 & -1 & 5 \\ -1 & 1 & 11 \\ 3 & 0 & 1 \end{bmatrix}$$

Activity 5.2.2 Remove an appropriate row and column of $\det\begin{bmatrix} 1 & 0 & 0 \\ 1 & 5 & 12 \\ 3 & 2 & -1 \end{bmatrix}$ to simplify the determinant to a 2×2 determinant.

Activity 5.2.3 Simplify $\det\begin{bmatrix} 0 & 3 & -2 \\ 2 & 5 & 12 \\ 0 & 2 & -1 \end{bmatrix}$ to a multiple of a 2×2 determinant by first doing the following:

(a) Factor out a 2 from a column.

(b) Swap rows or columns to put a 1 on the main diagonal.

Activity 5.2.4 Simplify $\det\begin{bmatrix} 4 & -2 & 2 \\ 3 & 1 & 4 \\ 1 & -1 & 3 \end{bmatrix}$ to a multiple of a 2×2 determinant by first doing the following:

(a) Use row/column operations to create two zeroes in the same row or column.

(b) Factor/swap as needed to get a row/column of all zeroes except a 1 on the main diagonal.

Observation 5.2.4 Using row/column operations, you can introduce zeros and reduce dimension to whittle down the determinant of a large matrix to a determinant of a smaller matrix.

$$\begin{aligned}
\det\begin{bmatrix} 4 & 3 & 0 & 1 \\ 2 & -2 & 4 & 0 \\ -1 & 4 & 1 & 5 \\ 2 & 8 & 0 & 3 \end{bmatrix} &= \det\begin{bmatrix} 4 & 3 & 0 & 1 \\ 6 & -18 & 0 & -20 \\ -1 & 4 & 1 & 5 \\ 2 & 8 & 0 & 3 \end{bmatrix} = \det\begin{bmatrix} 4 & 3 & 1 \\ 6 & -18 & -20 \\ 2 & 8 & 3 \end{bmatrix} \\
&= \cdots = -2\det\begin{bmatrix} 1 & 3 & 4 \\ 0 & 21 & 43 \\ 0 & -1 & -10 \end{bmatrix} = -2\det\begin{bmatrix} 21 & 43 \\ -1 & -10 \end{bmatrix} \\
&= \cdots = -2\det\begin{bmatrix} -167 & 21 \\ 0 & 1 \end{bmatrix} = -2\det[-167] \\
&= -2(-167)\det(I) = 334
\end{aligned}$$

Activity 5.2.5 Rewrite

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

as a multiple of a determinant of a 3×3 matrix.

Activity 5.2.6 Compute $\det\begin{bmatrix} 2 & 3 & 5 & 0 \\ 0 & 3 & 2 & 0 \\ 1 & 2 & 0 & 3 \\ -1 & -1 & 2 & 2 \end{bmatrix}$ by using any combination of row/column operations.

Observation 5.2.5 Another option is to take advantage of the fact that the determinant is linear in each row or column. This approach is called **Laplace expansion** or **cofactor expansion**.

For example, since $\begin{bmatrix} 1 & 2 & 4 \end{bmatrix} = 1\begin{bmatrix} 1 & 0 & 0 \end{bmatrix} + 2\begin{bmatrix} 0 & 1 & 0 \end{bmatrix} + 4\begin{bmatrix} 0 & 0 & 1 \end{bmatrix}$,

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

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

$$= -\det\begin{bmatrix} 5 & 3 \\ 5 & 3 \end{bmatrix} - 2\det\begin{bmatrix} 2 & 5 \\ -1 & 5 \end{bmatrix} + 4\det\begin{bmatrix} 2 & 3 \\ -1 & 3 \end{bmatrix}$$

Observation 5.2.6 Recall the formula for a 2×2 determinant found in Observation 5.1.18:

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

There are formulas and algorithms for the determinants of larger matrices, but they can be pretty tedious to use. For example, writing out a formula for a 4×4 determinant would require 24 different terms!

$$\det\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} = a_{11}(a_{22}(a_{33}a_{44}-a_{43}a_{34})-a_{23}(a_{32}a_{44}-a_{42}a_{34})+\dots)+\dots$$

Activity 5.2.7 Based on the previous activities, which technique is easier for computing determinants?

A. Memorizing formulas.

B. Using row/column operations.

C. Laplace expansion.

D. Some other technique.

Activity 5.2.8 Use your preferred technique to compute $\det\begin{bmatrix} 4 & -3 & 0 & 0 \\ 1 & -3 & 2 & -1 \\ 3 & 2 & 0 & 3 \\ 0 & -3 & 2 & -2 \end{bmatrix}$.

Insight 5.2.7 You can check your answers using technology.

```
det([4,-3,0,0; 1,-3,2,-1; 3,2,0,3; 0,-3,2,-2])
```

5.2.2 Videos

Figure 63 Video: Simplifying a determinant using row operations

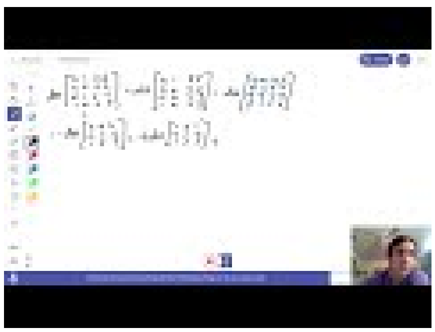


Figure 64 Video: Computing a determinant

5.2.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/GT2.slides.html.

5.2.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/GT2/.

5.2.5 Mathematical Writing Explorations

Exploration 5.2.9 Prove that the equation of a line in the plane, through points $(x_1, y_1), (x_2, y_2)$, when $x_1 \neq x_2$ is given by the equation $\det \begin{pmatrix} x & y & 1 \\ x_1 & y_1 & 1 \\ x_2 & y_2 & 1 \end{pmatrix} = 0$.

Exploration 5.2.10 Prove that the determinant of any diagonal matrix, upper triangular matrix, or lower triangular matrix, is the product of it's diagonal entries.

Exploration 5.2.11 Show that, if an $n \times n$ matrix M has a non-zero determinant, then any $\vec{v} \in \mathbb{R}^n$ can be represented as a linear combination of the columns of M.

Exploration 5.2.12 What is the smallest number of zeros necessary to place in a 4×4 matrix, and the placement of those zeros, such that the matrix has a zero determinant?

5.2.6 Sample Problem and Solution

Sample problem Example B.1.23.

5.3 Eigenvalues and Characteristic Polynomials (GT3)

Learning Outcomes

- Find the eigenvalues of a 2×2 matrix.

5.3.1 Class Activities

Activity 5.3.1 An invertible matrix M and its inverse M^{-1} are given below:

$$M = \begin{bmatrix} 1 & 2 \\ 3 & 4 \end{bmatrix} \qquad M^{-1} = \begin{bmatrix} -2 & 1 \\ 3/2 & -1/2 \end{bmatrix}$$

Which of the following is equal to $\det(M)\det(M^{-1})$?

A. -1

B. 0

C. 1

D. 4

Fact 5.3.1 *For every invertible matrix M,*

$$\det(M)\det(M^{-1}) = \det(I) = 1$$

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

Furthermore, a square matrix M is invertible if and only if $\det(M) \neq 0$.

Observation 5.3.2 Consider the linear transformation $A : \mathbb{R}^2 \to \mathbb{R}^2$ given by the matrix $A = \begin{bmatrix} 2 & 2 \\ 0 & 3 \end{bmatrix}$.

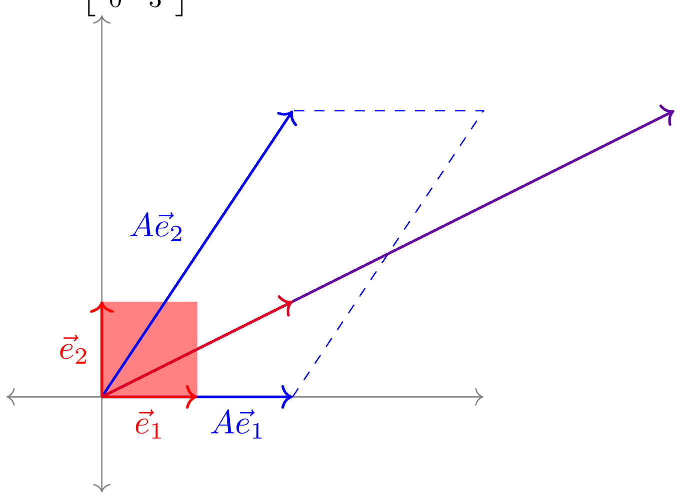


Figure 65 Transformation of the unit square by the linear transformation A

It is easy to see geometrically that

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

It is less obvious (but easily checked once you find it) that

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

Definition 5.3.3 Let $A \in M_{n,n}$. An **eigenvector** for A is a vector $\vec{x} \in \mathbb{R}^n$ such that $A\vec{x}$ is parallel to $\vec{x}$.

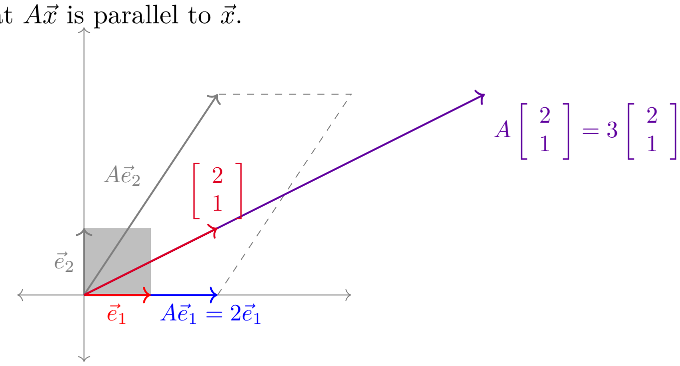


Figure 66 The map A stretches out the eigenvector $\begin{bmatrix}2\\1\end{bmatrix}$ by a factor of 3 (the corresponding eigenvalue).

In other words, $A\vec{x} = \lambda\vec{x}$ for some scalar λ. If $\vec{x} \neq \vec{0}$, then we say $\vec{x}$ is a **nontrivial eigenvector** and we call this λ an **eigenvalue** of A. ♢

Activity 5.3.2 Finding the eigenvalues λ that satisfy

$$A\vec{x} = \lambda\vec{x} = \lambda(I\vec{x}) = (\lambda I)\vec{x}$$

for some nontrivial eigenvector $\vec{x}$ is equivalent to finding nonzero solutions for the matrix equation

$$(A - \lambda I)\vec{x} = \vec{0}.$$

(a) If λ is an eigenvalue, and T is the transformation with standard matrix $A - \lambda I$, which of these must contain a non-zero vector?

A. The kernel of T

B. The image of T

C. The domain of T

D. The codomain of T

(b) Therefore, what can we conclude?

A. A is invertible

B. A is not invertible

C. $A - \lambda I$ is invertible

D. $A - \lambda I$ is not invertible

(c) And what else?

A. $\det A = 0$

B. $\det A = 1$

C. $\det(A - \lambda I) = 0$

D. $\det(A - \lambda I) = 1$

Fact 5.3.4 *The eigenvalues λ for a matrix A are exactly the values that make $A - \lambda I$ non-invertible.*

Thus the eigenvalues λ for a matrix A are the solutions to the equation

$$\det(A - \lambda I) = 0.$$

Definition 5.3.5 The expression $\det(A - \lambda I)$ is called **characteristic polynomial** of A.

For example, when $A = \begin{bmatrix} 1 & 2 \\ 5 & 4 \end{bmatrix}$, we have

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

Thus the characteristic polynomial of A is

$$\det \begin{bmatrix} 1-\lambda & 2 \\ 5 & 4-\lambda \end{bmatrix} = (1-\lambda)(4-\lambda) - (2)(5) = \lambda^2 - 5\lambda - 6$$

and its eigenvalues are the solutions $-1, 6$ to $\lambda^2 - 5\lambda - 6 = 0$. ◊

Activity 5.3.3 Let $A = \begin{bmatrix} 5 & 2 \\ -3 & -2 \end{bmatrix}$.

(a) Compute $\det(A - \lambda I)$ to determine the characteristic polynomial of A.

(b) Set this characteristic polynomial equal to zero and factor to determine the eigenvalues of A.

Activity 5.3.4 Find all the eigenvalues for the matrix $A = \begin{bmatrix} 3 & -3 \\ 2 & -4 \end{bmatrix}$.

Activity 5.3.5 Find all the eigenvalues for the matrix $A = \begin{bmatrix} 1 & -4 \\ 0 & 5 \end{bmatrix}$.

Activity 5.3.6 Find all the eigenvalues for the matrix $A = \begin{bmatrix} 3 & -3 & 1 \\ 0 & -4 & 2 \\ 0 & 0 & 7 \end{bmatrix}$.

5.3.2 Videos

Figure 67 Video: Finding eigenvalues

5.3.3 Slideshow

Slideshow of activities available at `https://teambasedinquirylearning.github.io/linear-algebra/2023/GT3.slides.html`.

5.3.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/GT3/.

5.3.5 Mathematical Writing Explorations

Exploration 5.3.7 What are the maximum and minimum number of eigenvalues associated with an $n \times n$ matrix? Write small examples to convince yourself you are correct, and then prove this in generality.

5.3.6 Sample Problem and Solution

Sample problem Example B.1.24.

5.4 Eigenvectors and Eigenspaces (GT4)

Learning Outcomes

- Find a basis for the eigenspace of a 4×4 matrix associated with a given eigenvalue.

5.4.1 Class Activities

Activity 5.4.1 It's possible to show that -2 is an eigenvalue for $\begin{bmatrix} -1 & 4 & -2 \\ 2 & -7 & 9 \\ 3 & 0 & 4 \end{bmatrix}$.

Compute the kernel of the transformation with standard matrix

$$A - (-2)I = \begin{bmatrix} ? & 4 & -2 \\ 2 & ? & 9 \\ 3 & 0 & ? \end{bmatrix}$$

to find all the eigenvectors $\vec{x}$ such that $A\vec{x} = -2\vec{x}$.

Definition 5.4.1 Since the kernel of a linear map is a subspace of $\mathbb{R}^n$, and the kernel obtained from $A - \lambda I$ contains all the eigenvectors associated with λ, we call this kernel the **eigenspace** of A associated with λ. $\Diamond$

Activity 5.4.2 Find a basis for the eigenspace for the matrix $\begin{bmatrix} 0 & 0 & 3 \\ 1 & 0 & -1 \\ 0 & 1 & 3 \end{bmatrix}$ associated with the eigenvalue 3.

Activity 5.4.3 Find a basis for the eigenspace for the matrix $\begin{bmatrix} 5 & -2 & 0 & 4 \\ 6 & -2 & 1 & 5 \\ -2 & 1 & 2 & -3 \\ 4 & 5 & -3 & 6 \end{bmatrix}$ associated with the eigenvalue 1.

Activity 5.4.4 Find a basis for the eigenspace for the matrix $\begin{bmatrix} 4 & 3 & 0 & 0 \\ 3 & 3 & 0 & 0 \\ 0 & 0 & 2 & 5 \\ 0 & 0 & 0 & 2 \end{bmatrix}$ associated with the eigenvalue 2.

5.4.2 Videos

Figure 68 Video: Finding eigenvectors

5.4.3 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/GT4.slides.html.

5.4.4 Exercises

Exercises available at https://teambasedinquirylearning.github.io/linear-algebra/2023/exercises/#/bank/GT4/.

5.4.5 Mathematical Writing Explorations

Exploration 5.4.5 Given a matrix A, let $\{\vec{v_1}, \vec{v_2}, \ldots, \vec{v_n}\}$ be the eigenvectors with associated distinct eigenvalues $\{\lambda_1, \lambda_2, \ldots, \lambda_n\}$. Prove the set of eigenvectors is linearly independent.

5.4.6 Sample Problem and Solution

Sample problem Example B.1.25.

Appendix A

Applications

A.1 Civil Engineering: Trusses and Struts

A.1.1 Activities

Definition A.1.1 In engineering, a **truss** is a structure designed from several beams of material called **struts**, assembled to behave as a single object.

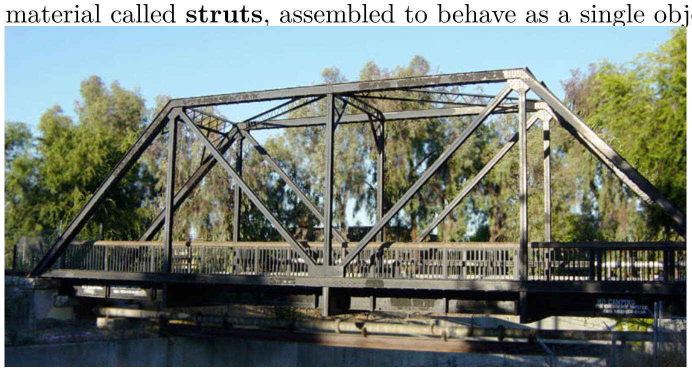


Figure 69 A simple truss

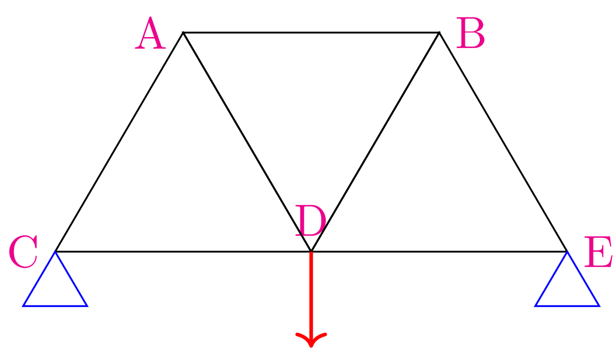


Figure 70 A simple truss

◊

Activity A.1.1 Consider the representation of a simple truss pictured below. All of the seven struts are of equal length, affixed to two anchor points applying a normal force to nodes C and E, and with a $10000N$ load applied to the node given by D.

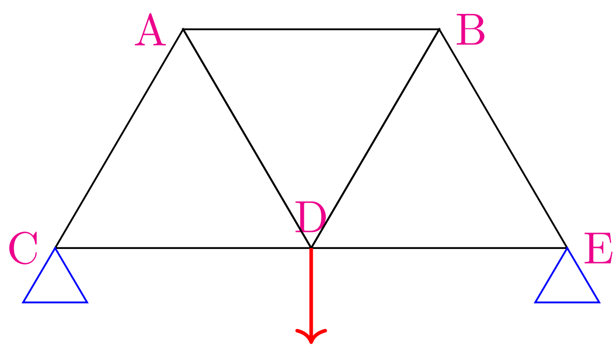


Figure 71 A simple truss

Which of the following must hold for the truss to be stable?

1. All of the struts will experience compression.
2. All of the struts will experience tension.
3. Some of the struts will be compressed, but others will be tensioned.

Observation A.1.2 Since the forces must balance at each node for the truss to be stable, some of the struts will be compressed, while others will be tensioned.

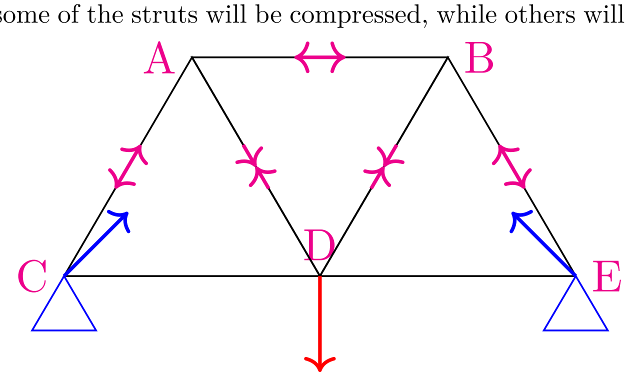


Figure 72 Completed truss

By finding vector equations that must hold at each node, we may determine many of the forces at play.

Remark A.1.3 For example, at the bottom left node there are 3 forces acting.

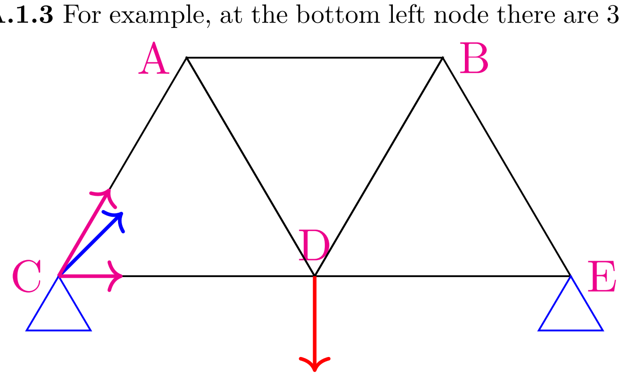


Figure 73 Truss with forces

Let $\vec{F}_{CA}$ be the force on C given by the compression/tension of the strut CA, let $\vec{F}_{CD}$ be defined similarly, and let $\vec{N}_C$ be the normal force of the anchor point on C.

For the truss to be stable, we must have:

$$\vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$

Activity A.1.2 Using the conventions of the previous remark, and where $\vec{L}$ represents the load vector on node D, find four more vector equations that must be satisfied for each of the other four nodes of the truss.

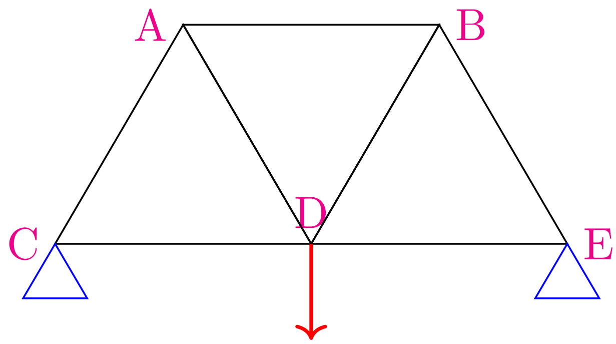


Figure 74 A simple truss

$$A : ?$$

$$B : ?$$

$$C : \vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$

$$D : ?$$

$$E : ?$$

Remark A.1.4 The five vector equations may be written as follows.

$$A : \vec{F}_{AC} + \vec{F}_{AD} + \vec{F}_{AB} = \vec{0}$$

$$B : \vec{F}_{BA} + \vec{F}_{BD} + \vec{F}_{BE} = \vec{0}$$

$$C : \vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$

$$D : \vec{F}_{DC} + \vec{F}_{DA} + \vec{F}_{DB} + \vec{F}_{DE} + \vec{L} = \vec{0}$$

$$E : \vec{F}_{EB} + \vec{F}_{ED} + \vec{N}_E = \vec{0}$$

Observation A.1.5 Each vector has a vertical and horizontal component, so it may be treated as a vector in $\mathbb{R}^2$. Note that $\vec{F}_{CA}$ must have the same magnitude (but opposite direction) as $\vec{F}_{AC}$.

$$\vec{F}_{CA} = x \begin{bmatrix} \cos(60°) \\ \sin(60°) \end{bmatrix} = x \begin{bmatrix} 1/2 \\ \sqrt{3}/2 \end{bmatrix}$$

$$\vec{F}_{AC} = x \begin{bmatrix} \cos(-120°) \\ \sin(-120°) \end{bmatrix} = x \begin{bmatrix} -1/2 \\ -\sqrt{3}/2 \end{bmatrix}$$

Activity A.1.3 To write a linear system that models the truss under consideration with constant load 10000 newtons, how many scalar variables will be required?

- 7: 5 from the nodes, 2 from the anchors
- 9: 7 from the struts, 2 from the anchors
- 11: 7 from the struts, 4 from the anchors

- 12: 7 from the struts, 4 from the anchors, 1 from the load
- 13: 5 from the nodes, 7 from the struts, 1 from the load

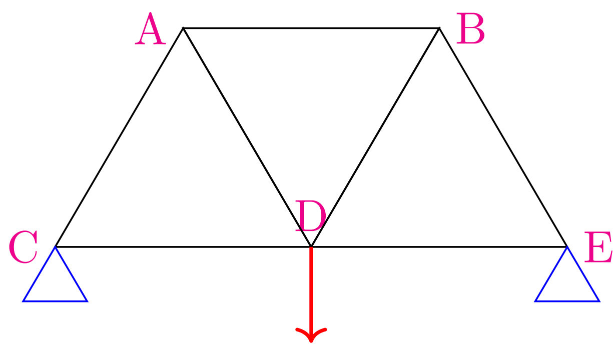


Figure 75 A simple truss

Observation A.1.6 Since the angles for each strut are known, one variable may be used to represent each.

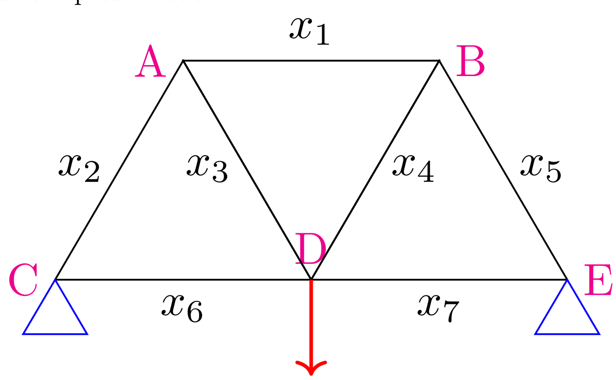


Figure 76 Variables for the truss

For example:

$$\vec{F}_{AB} = -\vec{F}_{BA} = x_1 \begin{bmatrix}\cos(0)\\ \sin(0)\end{bmatrix} = x_1 \begin{bmatrix}1\\ 0\end{bmatrix}$$

$$\vec{F}_{BE} = -\vec{F}_{EB} = x_5 \begin{bmatrix}\cos(-60°)\\ \sin(-60°)\end{bmatrix} = x_5 \begin{bmatrix}1/2\\ -\sqrt{3}/2\end{bmatrix}$$

Observation A.1.7 Since the angle of the normal forces for each anchor point are unknown, two variables may be used to represent each.

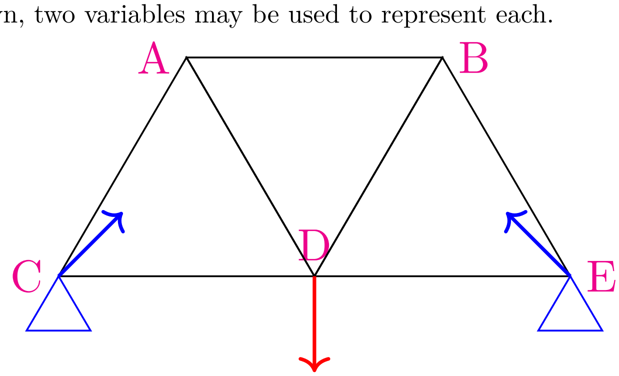


Figure 77 Truss with normal forces

$$\vec{N}_C = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} \qquad \vec{N}_D = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}$$

The load vector is constant.

$$\vec{L} = \begin{bmatrix} 0 \\ -10000 \end{bmatrix}$$

Remark A.1.8 Each of the five vector equations found previously represent two linear equations: one for the horizontal component and one for the vertical.

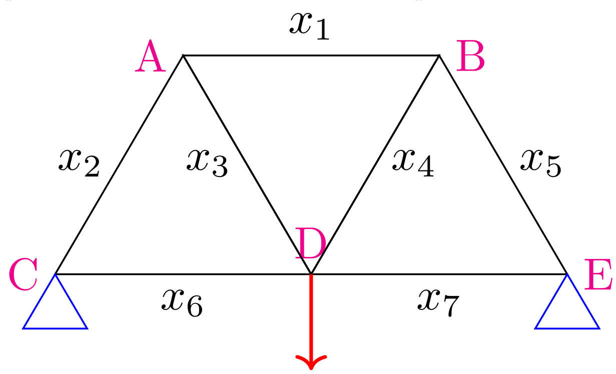


Figure 78 Variables for the truss

$$C : \vec{F}_{CA} + \vec{F}_{CD} + \vec{N}_C = \vec{0}$$
$$\Leftrightarrow x_2 \begin{bmatrix} \cos(60°) \\ \sin(60°) \end{bmatrix} + x_6 \begin{bmatrix} \cos(0°) \\ \sin(0°) \end{bmatrix} + \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Using the approximation $\sqrt{3}/2 \approx 0.866$, we have

$$\Leftrightarrow x_2 \begin{bmatrix} 0.5 \\ 0.866 \end{bmatrix} + x_6 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + y_1 \begin{bmatrix} 1 \\ 0 \end{bmatrix} + y_2 \begin{bmatrix} 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Activity A.1.4 Expand the vector equation given below using sine and cosine of appropriate angles, then compute each component (approximating $\sqrt{3}/2 \approx 0.866$).

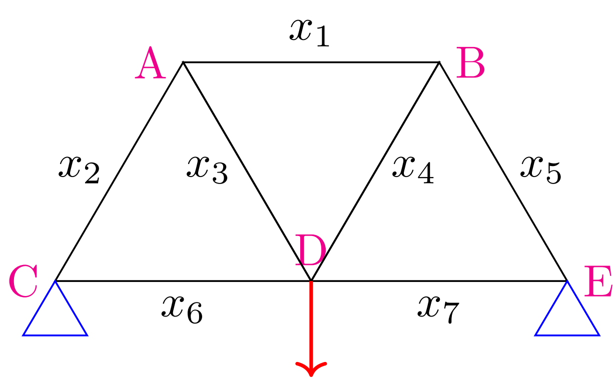


Figure 79 Variables for the truss

$$D : \vec{F}_{DA} + \vec{F}_{DB} + \vec{F}_{DC} + \vec{F}_{DE} = -\vec{L}$$
$$\Leftrightarrow x_3 \begin{bmatrix} \cos(\ ?\ ) \\ \sin(\ ?\ ) \end{bmatrix} + x_4 \begin{bmatrix} \cos(\ ?\ ) \\ \sin(\ ?\ ) \end{bmatrix} + x_6 \begin{bmatrix} \cos(\ ?\ ) \\ \sin(\ ?\ ) \end{bmatrix} + x_7 \begin{bmatrix} \cos(\ ?\ ) \\ \sin(\ ?\ ) \end{bmatrix} = \begin{bmatrix} ? \\ ? \end{bmatrix}$$

$$\Leftrightarrow x_3 \begin{bmatrix} ? \\ ? \end{bmatrix} + x_4 \begin{bmatrix} ? \\ ? \end{bmatrix} + x_6 \begin{bmatrix} ? \\ ? \end{bmatrix} + x_7 \begin{bmatrix} ? \\ ? \end{bmatrix} = \begin{bmatrix} ? \\ ? \end{bmatrix}$$

Observation A.1.9 The full augmented matrix given by the ten equations in this linear system is given below, where the elevent columns correspond to $x_1, \ldots, x_7, y_1, y_2, z_1, z_2$, and the ten rows correspond to the horizontal and vertical components of the forces acting at $A, \ldots, E$.

$$\left[\begin{array}{ccccccccccc|c}
1 & -0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -0.866 & -0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
-1 & 0 & 0 & -0.5 & 0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & -0.866 & -0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.5 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & -0.5 & 0.5 & 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.866 & 0.866 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 10000 \\
0 & 0 & 0 & 0 & -0.5 & 0 & -1 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.866 & 0 & 0 & 0 & 0 & 0 & 1 & 0
\end{array}\right]$$

Observation A.1.10 This matrix row-reduces to the following.

$$\sim \left[\begin{array}{ccccccccccc|c}
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5773.7 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -5773.7 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5773.7 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5773.7 \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & -5773.7 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & -1 & 0 & 2886.8 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 & 0 & 2886.8 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 5000 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 5000
\end{array}\right]$$

Observation A.1.11 Thus we know the truss must satisfy the following conditions.

$$\begin{aligned}
x_1 = x_2 = x_5 &= -5882.4 \\
x_3 = x_4 &= 5882.4 \\
x_6 = x_7 &= 2886.8 + z_1 \\
y_1 &= -z_1 \\
y_2 = z_2 &= 5000
\end{aligned}$$

In particular, the negative x_1, x_2, x_5 represent tension (forces pointing into the nodes), and the postive x_3, x_4 represent compression (forces pointing out of the nodes). The vertical normal forces $y_2 + z_2$ counteract the 10000 load.

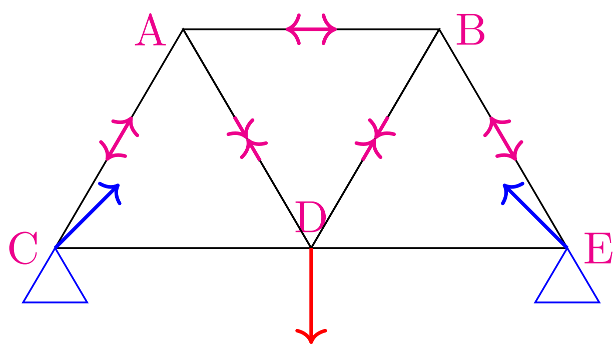


Figure 80 Completed truss

A.1.2 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/truss.slides.html.

A.2 Computer Science: PageRank

A.2.1 Activities

Activity A.2.1 The $978,000,000,000 Problem.
In the picture below, each circle represents a webpage, and each arrow represents a link from one page to another.

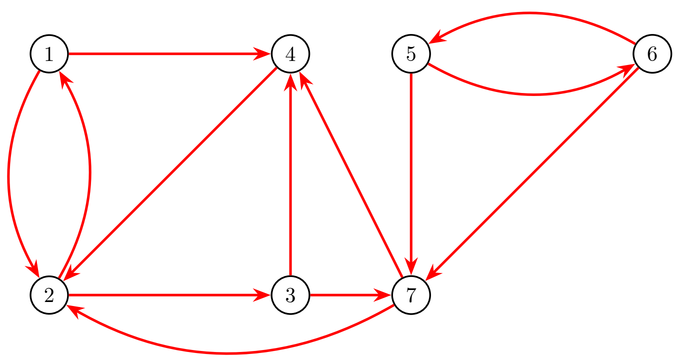


Figure 81 A seven-webpage network

Based on how these pages link to each other, write a list of the 7 webpages in order from most important to least important.

Observation A.2.1 The $978,000,000,000 Idea. Links are endorsements. That is:

1. A webpage is important if it is linked to (endorsed) by important pages.

2. A webpage distributes its importance equally among all the pages it links to (endorses).

Example A.2.2 Consider this small network with only three pages. Let x_1, x_2, x_3 be the importance of the three pages respectively.

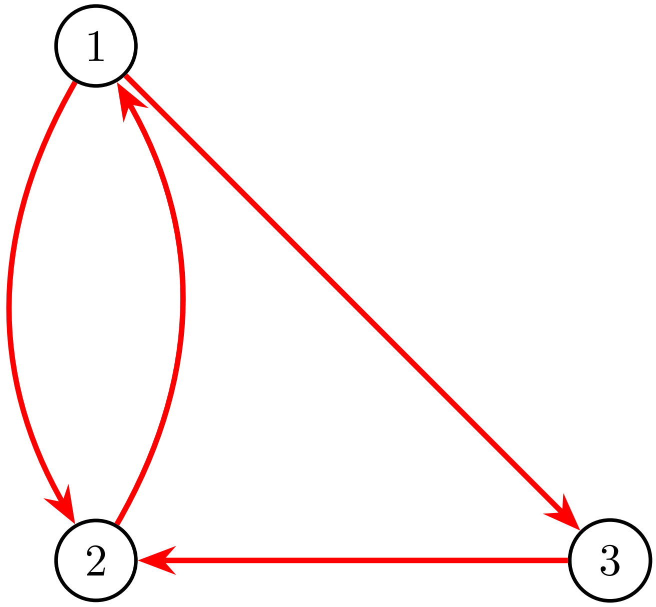


Figure 82 A three-webpage network

1. x_1 splits its endorsement in half between x_2 and x_3
2. x_2 sends all of its endorsement to x_1
3. x_3 sends all of its endorsement to x_2.

This corresponds to the **page rank system**:

$$\begin{aligned} x_2 \qquad &= x_1 \\ \frac{1}{2}x_1 \qquad + x_3 &= x_2 \\ \frac{1}{2}x_1 \qquad &= x_3 \end{aligned}$$

□

Observation A.2.3

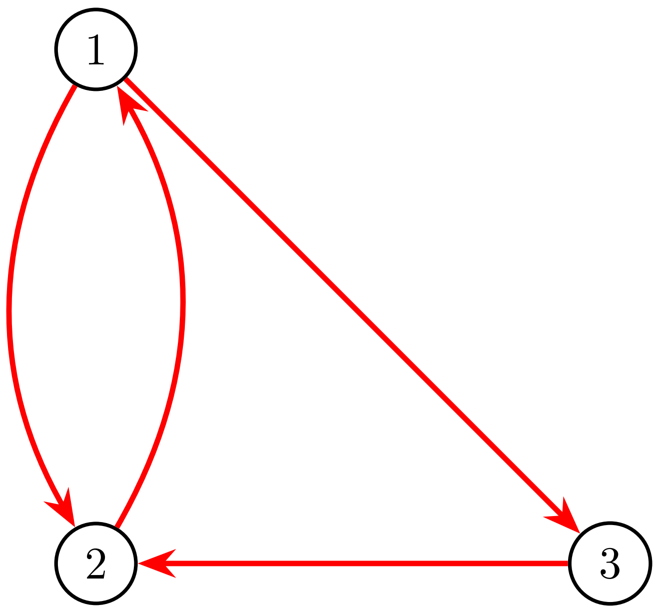


Figure 83 A three-webpage network

$$\begin{aligned} x_2 &= x_1 \\ \frac{1}{2}x_1 + x_3 &= x_2 \\ \frac{1}{2}x_1 &= x_3 \end{aligned} \qquad \begin{bmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & 1 \\ \frac{1}{2} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

By writing this linear system in terms of matrix multiplication, we obtain the **page rank matrix** $A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & 1 \\ \frac{1}{2} & 0 & 0 \end{bmatrix}$ and page rank vector $\vec{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$.

Thus, computing the importance of pages on a network is equivalent to solving the matrix equation $A\vec{x} = 1\vec{x}$.

Activity A.2.2 Thus, our \$978,000,000,000 problem is what kind of problem?

$$\begin{bmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & \frac{1}{2} \\ \frac{1}{2} & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = 1 \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

A. An antiderivative problem

B. A bijection problem

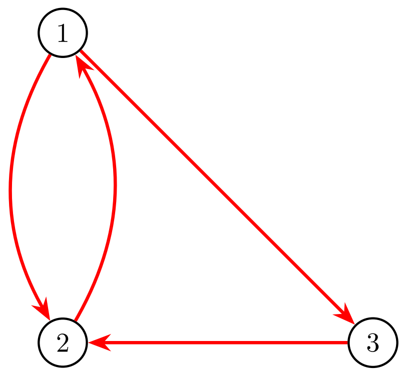
C. A cofactoring problem

D. A determinant problem

E. An eigenvector problem

Activity A.2.3 Find a page rank vector $\vec{x}$ satisfying $A\vec{x} = 1\vec{x}$ for the following network's page rank matrix A.

That is, find the eigenspace associated with $\lambda = 1$ for the matrix A, and choose a vector from that eigenspace.



$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{1}{2} & 0 & 1 \\ \frac{1}{2} & 0 & 0 \end{bmatrix}$$

Figure 84 A three-webpage network

Observation A.2.4 Row-reducing $A-I = \begin{bmatrix} -1 & 1 & 0 \\ \frac{1}{2} & -1 & 1 \\ \frac{1}{2} & 0 & -1 \end{bmatrix} \sim \begin{bmatrix} 1 & 0 & -2 \\ 0 & 1 & -2 \\ 0 & 0 & 0 \end{bmatrix}$ yields the basic eigenvector $\begin{bmatrix} 2 \\ 2 \\ 1 \end{bmatrix}$.

Therefore, we may conclude that pages 1 and 2 are equally important, and both pages are twice as important as page 3.

Activity A.2.4 Compute the 7×7 page rank matrix for the following network.

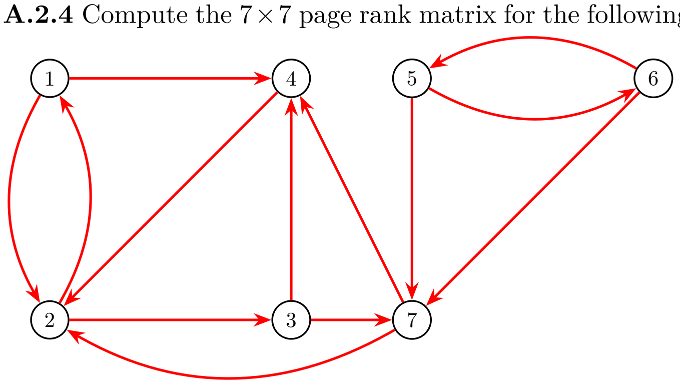


Figure 85 A seven-webpage network

For example, since website 1 distributes its endorsement equally between 2 and 4, the first column is $\begin{bmatrix} 0 \\ \frac{1}{2} \\ 0 \\ \frac{1}{2} \\ 0 \\ 0 \\ 0 \end{bmatrix}$.

Activity A.2.5 Find a page rank vector for the given page rank matrix.

$$A = \begin{bmatrix} 0 & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & 0 & 1 & 0 & 0 & \frac{1}{2} \\ 0 & \frac{1}{2} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{2} & 0 & \frac{1}{2} & 0 & 0 & 0 & \frac{1}{2} \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2} & 0 & 0 \\ 0 & 0 & \frac{1}{2} & 0 & \frac{1}{2} & \frac{1}{2} & 0 \end{bmatrix}$$

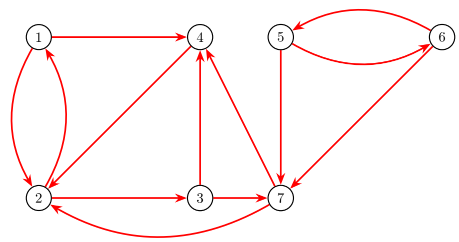


Figure 86 A seven-webpage network

Which webpage is most important?

Observation A.2.5 Since a page rank vector for the network is given by $\vec{x}$, it's reasonable to consider page 2 as the most important page.

$$\vec{x} = \begin{bmatrix} 2 \\ 4 \\ 2 \\ 2.5 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

Based upon this page rank vector, here is a complete ranking of all seven pages from most important to least important:

$$2, 4, 1, 3, 7, 5, 6$$

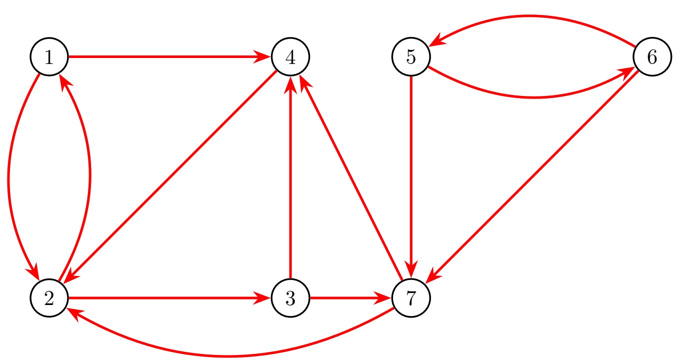


Figure 87 A seven-webpage network

Activity A.2.6 Given the following diagram, use a page rank vector to rank the pages 1 through 7 in order from most important to least important.

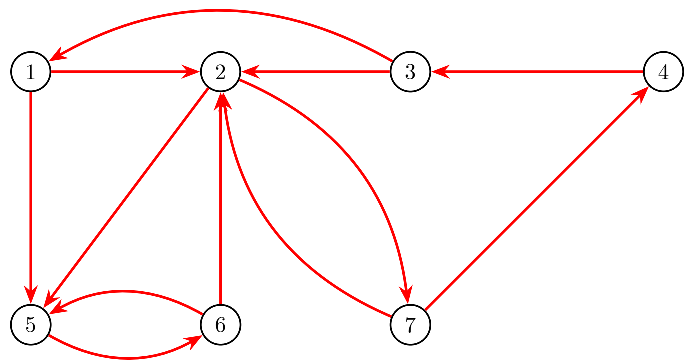


Figure 88 Another seven-webpage network

A.2.2 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/pagerank.slides.html.

A.3 Geology: Phases and Components

A.3.1 Activities

Definition A.3.1 In geology, a **phase** is any physically separable material in the system, such as various minerals or liquids.

A **component** is a chemical compound necessary to make up the phases; these are usually oxides such as Calcium Oxide (CaO) or Silicon Dioxide (SiO_2).

In a typical application, a geologist knows how to build each phase from the components, and is interested in determining reactions among the different phases. ◊

Observation A.3.2 Consider the 3 components

$$\vec{c}_1 = \mathrm{CaO} \quad \vec{c}_2 = \mathrm{MgO} \quad \text{and } \vec{c}_3 = \mathrm{SiO}_2$$

and the 5 phases:

$$\begin{array}{lll} \vec{p}_1 = \mathrm{Ca_3MgSi_2O_8} & \vec{p}_2 = \mathrm{CaMgSiO_4} & \vec{p}_3 = \mathrm{CaSiO_3} \\ \vec{p}_4 = \mathrm{CaMgSi_2O_6} & \vec{p}_5 = \mathrm{Ca_2MgSi_2O_7} & \end{array}$$

Geologists already know (or can easily deduce) that

$$\begin{array}{lll} \vec{p}_1 = 3\vec{c}_1 + \vec{c}_2 + 2\vec{c}_3 & \vec{p}_2 = \vec{c}_1 + \vec{c}_2 + \vec{c}_3 & \vec{p}_3 = \vec{c}_1 + 0\vec{c}_2 + \vec{c}_3 \\ \vec{p}_4 = \vec{c}_1 + \vec{c}_2 + 2\vec{c}_3 & \vec{p}_5 = 2\vec{c}_1 + \vec{c}_2 + 2\vec{c}_3 & \end{array}$$

since, for example:

$$\vec{c}_1 + \vec{c}_3 = \mathrm{CaO} + \mathrm{SiO_2} = \mathrm{CaSiO_3} = \vec{p}_3$$

Activity A.3.1 To study this vector space, each of the three components $\vec{c}_1, \vec{c}_2, \vec{c}_3$ may be considered as the three components of a Euclidean vector.

$$\vec{p}_1 = \begin{bmatrix} 3 \\ 1 \\ 2 \end{bmatrix}, \vec{p}_2 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \vec{p}_3 = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \vec{p}_4 = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}, \vec{p}_5 = \begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix}.$$

Determine if the set of phases is linearly dependent or linearly independent.

Activity A.3.2 Geologists are interested in knowing all the possible chemical reactions among the 5 phases:

$$\vec{p}_1 = \mathrm{Ca_3MgSi_2O_8} = \begin{bmatrix} 3 \\ 1 \\ 2 \end{bmatrix} \quad \vec{p}_2 = \mathrm{CaMgSiO_4} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad \vec{p}_3 = \mathrm{CaSiO_3} = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$$

$$\vec{p}_4 = \mathrm{CaMgSi_2O_6} = \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix} \quad \vec{p}_5 = \mathrm{Ca_2MgSi_2O_7} = \begin{bmatrix} 2 \\ 1 \\ 2 \end{bmatrix}.$$

That is, they want to find numbers x_1, x_2, x_3, x_4, x_5 such that

$$x_1\vec{p}_1 + x_2\vec{p}_2 + x_3\vec{p}_3 + x_4\vec{p}_4 + x_5\vec{p}_5 = 0.$$

(a) Set up a system of equations equivalent to this vector equation.

(b) Find a basis for its solution space.

(c) Interpret each basis vector as a vector equation and a chemical equation.

Activity A.3.3 We found two basis vectors $\begin{bmatrix} 1 \\ -2 \\ -2 \\ 1 \\ 0 \end{bmatrix}$ and $\begin{bmatrix} 0 \\ -1 \\ -1 \\ 0 \\ 1 \end{bmatrix}$, corresponding to the vector and chemical equations

$$\begin{array}{ll} 2\vec{p}_2 + 2\vec{p}_3 = \vec{p}_1 + \vec{p}_4 & 2\mathrm{CaMgSiO_4} + 2\mathrm{CaSiO_3} = \mathrm{Ca_3MgSi_2O_8} + \mathrm{CaMgSi_2O_6} \\ \vec{p}_2 + \vec{p}_3 = \vec{p}_5 & \mathrm{CaMgSiO_4} + \mathrm{CaSiO_3} = \mathrm{Ca_2MgSi_2O_7} \end{array}$$

Combine the basis vectors to produce a chemical equation among the five phases that does not involve $\vec{p}_2 = \mathrm{CaMgSiO_4}$.

A.3.2 Slideshow

Slideshow of activities available at https://teambasedinquirylearning.github.io/linear-algebra/2023/geology.slides.html.

Appendix B

Appendix

B.1 Sample Exercises with Solutions

Here we model one exercise and solution for each learning objective. Your solutions should not look identical to those shown below, but these solutions can give you an idea of the level of detail required for a complete solution.

Example B.1.1 LE1. Consider the scalar system of equations

$$\begin{aligned} 3x_1 + 2x_2 \phantom{{}+x_3} + x_4 &= 1 \\ -x_1 - 4x_2 + x_3 - 7x_4 &= 0 \\ x_2 - x_3 \phantom{{}-7x_4} &= -2 \end{aligned}$$

1. Rewrite this system as a vector equation.

2. Write an augmented matrix corresponding to this system.

Solution.

1.

$$x_1 \begin{bmatrix} 3 \\ -1 \\ 0 \end{bmatrix} + x_2 \begin{bmatrix} 2 \\ -4 \\ 1 \end{bmatrix} + x_3 \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix} + x_4 \begin{bmatrix} 1 \\ -7 \\ 0 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ -2 \end{bmatrix}$$

2.

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

□

Example B.1.2 LE2.

1. For each of the following matrices, explain why it is not in reduced row echelon form.

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

2. Show step-by-step why

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

Solution.

1.
   - $A = \begin{bmatrix} -4 & 0 & 4 \\ 0 & 1 & -2 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ is not in reduced row echelon form because the pivots are not all 1.
   - $B = \begin{bmatrix} 0 & 1 & 2 \\ 1 & 0 & -3 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ is not in reduced row echelon form because the pivots are not descending to the right.
   - $C = \begin{bmatrix} 1 & -4 & 4 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ is not in reduced row echelon form because not every entry above and below each pivot is zero.

2.

$$\begin{bmatrix} 0 & 3 & 1 & 2 \\ 1 & 2 & -1 & -3 \\ 2 & 4 & -1 & -1 \end{bmatrix} \sim \begin{bmatrix} \boxed{1} & 2 & -1 & -3 \\ 0 & 3 & 1 & 2 \\ 2 & 4 & -1 & -1 \end{bmatrix} \quad \text{Swap Rows 1 and 2}$$

$$\sim \begin{bmatrix} \boxed{1} & 2 & -1 & -3 \\ 0 & 3 & 1 & 2 \\ 0 & 0 & 1 & 5 \end{bmatrix} \quad \text{Add } -2 \text{ Row 1 to Row 3}$$

$$\sim \begin{bmatrix} \boxed{1} & 2 & -1 & -3 \\ 0 & \boxed{1} & \frac{1}{3} & \frac{2}{3} \\ 0 & 0 & 1 & 5 \end{bmatrix} \quad \text{Multiply Row 3 by } \frac{1}{3}$$

$$\sim \begin{bmatrix} \boxed{1} & 0 & -\frac{5}{3} & -\frac{13}{3} \\ 0 & \boxed{1} & \frac{1}{3} & \frac{2}{3} \\ 0 & 0 & \boxed{1} & 5 \end{bmatrix} \quad \text{Add } -2 \text{ Row 2 to Row 1}$$

$$\sim \begin{bmatrix} \boxed{1} & 0 & -\frac{5}{3} & -\frac{13}{3} \\ 0 & \boxed{1} & 0 & -1 \\ 0 & 0 & \boxed{1} & 5 \end{bmatrix} \quad \text{Add } -\frac{1}{3} \text{ Row 3 to Row 2}$$

$$\sim \begin{bmatrix} \boxed{1} & 0 & 0 & 4 \\ 0 & \boxed{1} & 0 & -1 \\ 0 & 0 & \boxed{1} & 5 \end{bmatrix} \quad \text{Add } \frac{5}{3} \text{ Row 3 to Row 1}$$

□

Example B.1.3 LE3. Consider each of the following systems of linear equations or vector equations.

1.
$$\begin{array}{rcrcrcr} -2\,x_1 & + & x_2 & + & x_3 & = & -2 \\ -2\,x_1 & - & 3\,x_2 & - & 3\,x_3 & = & 0 \\ 3\,x_1 & + & x_2 & + & x_3 & = & 3 \end{array}$$

2.
$$x_1 \left[\begin{array}{c} -5 \\ 3 \\ -1 \end{array}\right] + x_2 \left[\begin{array}{c} 3 \\ -2 \\ 2 \end{array}\right] + x_3 \left[\begin{array}{c} 14 \\ -9 \\ 7 \end{array}\right] = \left[\begin{array}{c} 1 \\ 0 \\ -4 \end{array}\right]$$

3.
$$x_1 \left[\begin{array}{c} 0 \\ -1 \\ -1 \end{array}\right] + x_2 \left[\begin{array}{c} 1 \\ -4 \\ -4 \end{array}\right] + x_3 \left[\begin{array}{c} 2 \\ -4 \\ -3 \end{array}\right] = \left[\begin{array}{c} -5 \\ 11 \\ 8 \end{array}\right]$$

- Explain how to find a simpler system or vector equation that has the same solution set for each.
- Explain whether each solution set has no solutions, one solution, or infinitely-many solutions. If the set is finite, describe it using set notation.

Solution.

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

This matrix corresponds to the simpler system

$$\begin{array}{rcrcrcr} x_1 & & & & & = & 0 \\ & & x_2 & + & x_3 & = & 0 \\ & & & & 0 & = & 1 \end{array}$$

The third equation $0 = 1$ indicates that the system has no solutions. The solution set is $\emptyset$.

2.
$$\text{RREF} \left[\begin{array}{ccc|c} -5 & 3 & 14 & 1 \\ 3 & -2 & -9 & 0 \\ -1 & 2 & 7 & -4 \end{array}\right] = \left[\begin{array}{ccc|c} 1 & 0 & -1 & -2 \\ 0 & 1 & 3 & -3 \\ 0 & 0 & 0 & 0 \end{array}\right]$$

This matrix corresponds to the simpler system

$$\begin{array}{rcrcrcr} x_1 & & & - & x_3 & = & -2 \\ & & x_2 & + & 3\,x_3 & = & -3. \\ & & & & 0 & = & 0 \end{array}$$

Since there are three variables and two nontrivial equations, the solution set has infinitely-many solutions.

3.
$$\text{RREF} \left[\begin{array}{ccc|c} 0 & 1 & 2 & -5 \\ -1 & -4 & -4 & 11 \\ -1 & -4 & -3 & 8 \end{array}\right] = \left[\begin{array}{ccc|c} 1 & 0 & 0 & -3 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & -3 \end{array}\right]$$

This matrix corresponds to the simpler system

$$\begin{array}{rcrcrcr} x_1 & & & & & = & -3 \\ & & x_2 & & & = & 1 \\ & & & & x_3 & = & -3 \end{array}.$$

This system has one solution. The solution set is $\left\{ \begin{bmatrix} -3 \\ 1 \\ -3 \end{bmatrix} \right\}$.

□

Example B.1.4 LE4. Consider the following vector equation.

$$x_1 \begin{bmatrix} -3 \\ 0 \\ 4 \end{bmatrix} + x_2 \begin{bmatrix} -3 \\ 0 \\ 4 \end{bmatrix} + x_3 \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} + x_4 \begin{bmatrix} -4 \\ -5 \\ 5 \end{bmatrix} = \begin{bmatrix} -11 \\ -9 \\ 14 \end{bmatrix}$$

1. Explain how to find a simpler system or vector equation that has the same solution set.
2. Explain how to describe this solution set using set notation.

Solution. First, we compute

$$\text{RREF} \left[\begin{array}{cccc|c} -3 & -3 & 0 & -4 & -11 \\ 0 & 0 & 1 & -5 & -9 \\ 4 & 4 & 0 & 5 & 14 \end{array} \right] = \left[\begin{array}{cccc|c} 1 & 1 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 \\ 0 & 0 & 0 & 1 & 2 \end{array} \right].$$

This corresponds to the simpler system

$$\begin{array}{rcrcrcrcr} x_1 & + & x_2 & & & & & = & 1 \\ & & & & x_3 & & & = & 1. \\ & & & & & & x_4 & = & 2 \end{array}$$

Since the second column is a non-pivot column, we let $x_2 = a$. Making this substitution and then solving for x_1, x_3, and x_4 produces the system

$$\begin{array}{rcl} x_1 & = & 1 - a \\ x_2 & = & a \\ x_3 & = & 1 \\ x_4 & = & 2 \end{array}$$

Thus, the solution set is $\left\{ \begin{bmatrix} -a+1 \\ a \\ 1 \\ 2 \end{bmatrix} \middle| a \in \mathbb{R} \right\}$. □

Example B.1.5 EV1.

1. Write a statement involving the solutions of a vector equation that's equivalent to each claim below.
   - $\begin{bmatrix} -13 \\ 3 \\ -13 \end{bmatrix}$ is a linear combination of the vectors $\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$, $\begin{bmatrix} 2 \\ 0 \\ 2 \end{bmatrix}$, $\begin{bmatrix} 3 \\ 0 \\ 3 \end{bmatrix}$, and $\begin{bmatrix} -5 \\ 1 \\ -5 \end{bmatrix}$.

- $\begin{bmatrix} -13 \\ 3 \\ -15 \end{bmatrix}$ is a linear combination of the vectors $\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$, $\begin{bmatrix} 2 \\ 0 \\ 2 \end{bmatrix}$, $\begin{bmatrix} 3 \\ 0 \\ 3 \end{bmatrix}$, and $\begin{bmatrix} -5 \\ 1 \\ -5 \end{bmatrix}$.

2. Use these statements to determine if each vector is or is not a linear combination. If it is, give an example of such a linear combination.

Solution.

- $\begin{bmatrix} -13 \\ 3 \\ -13 \end{bmatrix}$ is a linear combination of the vectors $\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$, $\begin{bmatrix} 2 \\ 0 \\ 2 \end{bmatrix}$, $\begin{bmatrix} 3 \\ 0 \\ 3 \end{bmatrix}$, and $\begin{bmatrix} -5 \\ 1 \\ -5 \end{bmatrix}$ exactly when the vector equation

$$x_1 \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} + x_2 \begin{bmatrix} 2 \\ 0 \\ 2 \end{bmatrix} + x_3 \begin{bmatrix} 3 \\ 0 \\ 3 \end{bmatrix} + x_4 \begin{bmatrix} -5 \\ 1 \\ -5 \end{bmatrix} = \begin{bmatrix} -13 \\ 3 \\ -13 \end{bmatrix}$$

has a solution. To solve this vector equation, we compute

$$\mathrm{RREF} \left[\begin{array}{cccc|c} 1 & 2 & 3 & -5 & -13 \\ 0 & 0 & 0 & 1 & 3 \\ 1 & 2 & 3 & -5 & -13 \end{array}\right] = \left[\begin{array}{cccc|c} 1 & 2 & 3 & 0 & 2 \\ 0 & 0 & 0 & 1 & 3 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right].$$

We see that this vector equation has solution set $\left\{ \begin{bmatrix} 2-2a-3b \\ a \\ b \\ 3 \end{bmatrix} \middle| \, a, b \in \mathbb{R} \right\}$, so $\begin{bmatrix} -13 \\ 3 \\ -13 \end{bmatrix}$ is a linear combination; for example, $2 \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} + 3 \begin{bmatrix} -5 \\ 1 \\ -5 \end{bmatrix} = \begin{bmatrix} -13 \\ 3 \\ -13 \end{bmatrix}$

- $\begin{bmatrix} -13 \\ 3 \\ -15 \end{bmatrix}$ is a linear combination of the vectors $\begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}$, $\begin{bmatrix} 2 \\ 0 \\ 2 \end{bmatrix}$, $\begin{bmatrix} 3 \\ 0 \\ 3 \end{bmatrix}$, and $\begin{bmatrix} -5 \\ 1 \\ -5 \end{bmatrix}$ exactly when the vector equation

$$x_1 \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix} + x_2 \begin{bmatrix} 2 \\ 0 \\ 2 \end{bmatrix} + x_3 \begin{bmatrix} 3 \\ 0 \\ 3 \end{bmatrix} + x_4 \begin{bmatrix} -5 \\ 1 \\ -5 \end{bmatrix} = \begin{bmatrix} -13 \\ 3 \\ -15 \end{bmatrix}$$

has a solution. To solve this vector equation, we compute

$$\mathrm{RREF} \left[\begin{array}{cccc|c} 1 & 2 & 3 & -5 & -13 \\ 0 & 0 & 0 & 1 & 3 \\ 1 & 2 & 3 & -5 & -15 \end{array}\right] = \left[\begin{array}{cccc|c} 1 & 2 & 3 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{array}\right].$$

This vector equation has no solution, so $\begin{bmatrix} -13 \\ 3 \\ -15 \end{bmatrix}$ is not a linear combination.

□

Example B.1.6 EV2.

1. Write a statement involving the solutions of a vector equation that's equivalent to each claim below.
   - The set of vectors $\left\{\begin{bmatrix}1\\-1\\2\\0\end{bmatrix},\begin{bmatrix}3\\-2\\3\\3\end{bmatrix},\begin{bmatrix}10\\-7\\11\\9\end{bmatrix},\begin{bmatrix}-6\\3\\-3\\-9\end{bmatrix}\right\}$ *spans* $\mathbb{R}^4$.
   - The set of vectors $\left\{\begin{bmatrix}1\\-1\\2\\0\end{bmatrix},\begin{bmatrix}3\\-2\\3\\3\end{bmatrix},\begin{bmatrix}10\\-7\\11\\9\end{bmatrix},\begin{bmatrix}-6\\3\\-3\\-9\end{bmatrix}\right\}$ does *not* span $\mathbb{R}^4$.
2. Explain how to determine which of these statements is true.

Solution. The set of vectors $\left\{\begin{bmatrix}1\\-1\\2\\0\end{bmatrix},\begin{bmatrix}3\\-2\\3\\3\end{bmatrix},\begin{bmatrix}10\\-7\\11\\9\end{bmatrix},\begin{bmatrix}-6\\3\\-3\\-9\end{bmatrix}\right\}$ spans $\mathbb{R}^4$ exactly when the vector equation

$$x_1\begin{bmatrix}1\\-1\\2\\0\end{bmatrix}+x_2\begin{bmatrix}3\\-2\\3\\3\end{bmatrix}+x_3\begin{bmatrix}10\\-7\\11\\9\end{bmatrix}+x_4\begin{bmatrix}-6\\3\\-3\\-9\end{bmatrix}=\vec{v}$$

has a solution *for all* $\vec{v}\in\mathbb{R}^4$. If there is *some* vector $\vec{v}\in\mathbb{R}^4$ for which this vector equation has no solution, then the set does not span $\mathbb{R}^4$. To answer this, we compute

$$\mathrm{RREF}\begin{bmatrix}1&3&10&-6\\-1&-2&-7&3\\2&3&11&-3\\0&3&9&-9\end{bmatrix}=\begin{bmatrix}1&0&1&3\\0&1&3&-3\\0&0&0&0\\0&0&0&0\end{bmatrix}.$$

We see that for some $\vec{v}\in\mathbb{R}^4$, this vector equation will not have a solution, so the set of vectors $\left\{\begin{bmatrix}1\\-1\\2\\0\end{bmatrix},\begin{bmatrix}3\\-2\\3\\3\end{bmatrix},\begin{bmatrix}10\\-7\\11\\9\end{bmatrix},\begin{bmatrix}-6\\3\\-3\\-9\end{bmatrix}\right\}$ does *not* span $\mathbb{R}^4$.

□

Example B.1.7 EV3. Consider the following two sets of Euclidean vectors.

$$W=\left\{\begin{bmatrix}x\\y\\z\\w\end{bmatrix}\middle|\,x+y=3z+2w\right\}\qquad U=\left\{\begin{bmatrix}x\\y\\z\\w\end{bmatrix}\middle|\,x+y=3z+w^2\right\}$$

Explain why one of these sets is a subspace of $\mathbb{R}^3$, and why the other is not.

Solution. To show that W is a subspace, let $\vec{v}=\begin{bmatrix}x_1\\y_1\\z_1\\w_1\end{bmatrix}\in W$ and $\vec{w}=$

$\begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ w_2 \end{bmatrix} \in W$, so we know that $x_1 + y_1 = 3z_1 + 2w_1$ and $x_2 + y_2 = 3z_2 + 2w_2$.

Consider

$$\begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ w_1 \end{bmatrix} + \begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ w_2 \end{bmatrix} = \begin{bmatrix} x_1 + x_2 \\ y_1 + y_2 \\ z_1 + z_2 \\ w_1 + w_2 \end{bmatrix}.$$

To see if $\vec{v} + \vec{w} \in W$, we need to check if $(x_1 + x_2) + (y_1 + y_2) = 3(z_1 + z_2) + 2(w_1 + w_2)$. We compute

$$\begin{aligned} (x_1 + x_2) + (y_1 + y_2) &= (x_1 + y_1) + (x_2 + y_2) && \text{by regrouping} \\ &= (3z_1 + 2w_1) + (3z_2 + 2w_2) && \text{since} \\ &= 3(z_1 + z_2) + 2(w_1 + w_2) && \text{by regrouping.} \end{aligned}$$

Thus $\vec{v} + \vec{w} \in W$, so W is closed under vector addition.

Now consider

$$c\vec{v} = \begin{bmatrix} cx_1 \\ cy_1 \\ cz_1 \\ cw_1 \end{bmatrix}.$$

Similarly, to check that $c\vec{v} \in W$, we need to check if $cx_1 + cy_1 = 3(cz_1) + 2(cw_1)$, so we compute

$$\begin{aligned} cx_1 + cy_1 &= c(x_1 + y_1) && \text{by factoring} \\ &= c(3z_1 + 2w_1) && \text{since} \\ &= 3(cz_1) + 2(cw_1) && \text{by regrouping} \end{aligned}$$

and we see that $c\vec{v} \in W$, so W is closed under scalar multiplication. Therefore W is a subspace of $\mathbb{R}^3$.

Now, to show U is not a subspace, we will show that it is not closed under vector addition.

- (Solution Method 1) Now let $\vec{v} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ w_1 \end{bmatrix} \in U$ and $\vec{w} = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ w_2 \end{bmatrix} \in U$, so we know that $x_1 + y_1 = 3z_1 + w_1^2$ and $x_2 + y_2 = 3z_2 + w_2^2$.

  Consider

  $$\vec{v} + \vec{w} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ w_1 \end{bmatrix} + \begin{bmatrix} x_2 \\ y_2 \\ z_2 \\ w_2 \end{bmatrix} = \begin{bmatrix} x_1 + x_2 \\ y_1 + y_2 \\ z_1 + z_2 \\ w_1 + w_2 \end{bmatrix}.$$

  To see if $\vec{v} + \vec{w} \in U$, we need to check if $(x_1 + x_2) + (y_1 + y_2) = 3(z_1 + z_2) + (w_1 + w_2)^2$. We compute

  $$\begin{aligned} (x_1 + x_2) + (y_1 + y_2) &= (x_1 + y_1) + (x_2 + y_2) && \text{by regrouping} \\ &= (3z_1 + w_1^2) + (3z_2 + w_2^2) && \text{since} \\ &= 3(z_1 + z_2) + (w_1^2 + w_2^2) && \text{by regrouping} \end{aligned}$$

  and thus $\vec{v} + \vec{w} \in U$ \textbf{only when} $w_1^2 + w_2^2 = (w_1 + w_2)^2$. Since this is not true in general, U is not closed under vector addition, and thus cannot be a subspace.

- (Solution Method 2) Note that the vector $\vec{v} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 1 \end{bmatrix}$ belongs to U since $0 + 1 = 3(0) + 1^2$. However, the vector $2\vec{v} = \begin{bmatrix} 0 \\ 2 \\ 0 \\ 2 \end{bmatrix}$ does not belong to U since $0 + 2 \neq 3(0) + 2^2$. Therefore U is not closed under scalar multiplication, and thus is not a subspace.

□

Example B.1.8 EV4.

1. Write a statement involving the solutions of a vector equation that's equivalent to each claim below.
   - The set of vectors $\left\{ \begin{bmatrix} 1 \\ 3 \\ 4 \\ -4 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ -4 \\ 4 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 3 \\ -3 \end{bmatrix} \right\}$ is linearly *independent*.
   - The set of vectors $\left\{ \begin{bmatrix} 1 \\ 3 \\ 4 \\ -4 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ -4 \\ 4 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 3 \\ -3 \end{bmatrix} \right\}$ is linearly *dependent*.
2. Explain how to determine which of these statements is true.

Solution. The set of vectors $\left\{ \begin{bmatrix} 1 \\ 3 \\ 4 \\ -4 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ -4 \\ 4 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 3 \\ -3 \end{bmatrix} \right\}$ is linearly independent exactly when the vector equation

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

has no non-trivial (i.e. nonzero) solutions. The set is linearly *dependent* when there exists a nontrivial (i.e. nonzero) solution. We compute

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

Thus, this vector equation has a solution set $\left\{ \begin{bmatrix} a \\ a \\ 0 \end{bmatrix} \middle|\, a \in \mathbb{R} \right\}$. Since there are nontrivial solutions, we conclude that the set of vectors $\left\{ \begin{bmatrix} 1 \\ 3 \\ 4 \\ -4 \end{bmatrix}, \begin{bmatrix} -1 \\ -3 \\ -4 \\ 4 \end{bmatrix}, \begin{bmatrix} 0 \\ 1 \\ 3 \\ -3 \end{bmatrix} \right\}$ is linearly *dependent*. □

Example B.1.9 EV5.

1. Write a statement involving spanning and independence properties that's equivalent to each claim below.

   - The set of vectors $\left\{\begin{bmatrix}1\\3\\4\\-4\end{bmatrix},\begin{bmatrix}0\\1\\3\\-3\end{bmatrix},\begin{bmatrix}3\\11\\18\\-18\end{bmatrix},\begin{bmatrix}-2\\-7\\-11\\11\end{bmatrix}\right\}$ is a *basis* of $\mathbb{R}^4$.
   - The set of vectors $\left\{\begin{bmatrix}1\\3\\4\\-4\end{bmatrix},\begin{bmatrix}0\\1\\3\\-3\end{bmatrix},\begin{bmatrix}3\\11\\18\\-18\end{bmatrix},\begin{bmatrix}-2\\-7\\-11\\11\end{bmatrix}\right\}$ is *not* a basis of $\mathbb{R}^4$.

2. Explain how to determine which of these statements is true.

Solution. The set of vectors $\left\{\begin{bmatrix}1\\3\\4\\-4\end{bmatrix},\begin{bmatrix}0\\1\\3\\-3\end{bmatrix},\begin{bmatrix}3\\11\\18\\-18\end{bmatrix},\begin{bmatrix}-2\\-7\\-11\\11\end{bmatrix}\right\}$ is a basis of $\mathbb{R}^4$ exactly when it is linearly independent *and* the set spans $\mathbb{R}^4$. If it is either linearly dependent, *or* the set does not span $\mathbb{R}^4$, then the set is not a basis.

To answer this, we compute

$$\operatorname{RREF}\begin{bmatrix}1&0&3&-2\\3&1&11&-7\\4&3&18&-11\\-4&-3&-18&11\end{bmatrix}=\begin{bmatrix}1&0&3&-2\\0&1&2&-1\\0&0&0&0\\0&0&0&0\end{bmatrix}.$$

We see that this set of vectors is linearly dependent, so therefore the set of vectors $\left\{\begin{bmatrix}1\\3\\4\\-4\end{bmatrix},\begin{bmatrix}0\\1\\3\\-3\end{bmatrix},\begin{bmatrix}3\\11\\18\\-18\end{bmatrix},\begin{bmatrix}-2\\-7\\-11\\11\end{bmatrix}\right\}$ is *not* a basis. □

Example B.1.10 EV6. Consider the subspace

$$W=\operatorname{span}\left\{\begin{bmatrix}1\\-3\\-1\\2\end{bmatrix},\begin{bmatrix}1\\0\\1\\-2\end{bmatrix},\begin{bmatrix}3\\-6\\-1\\2\end{bmatrix},\begin{bmatrix}1\\6\\1\\-1\end{bmatrix},\begin{bmatrix}2\\3\\0\\1\end{bmatrix}\right\}.$$

1. Explain how to find a basis of W.

2. Explain how to find the dimension of W.

Solution.

1. Observe that

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

If we remove the vectors yielding non-pivot columns, the resulting set will span the same vectors while being linearly independent. Therefore

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

is a basis of W.

2. Since this (and thus every other) basis has three vectors in it, the dimension of W is 3.

□

Example B.1.11 EV7. Consider the homogeneous system of equations

$$\begin{aligned} x_1 + x_2 + 3x_3 + x_4 + 2x_5 &= 0 \\ -3x_1 - 6x_3 + 6x_4 + 3x_5 &= 0 \\ -x_1 + x_2 - x_3 + x_4 &= 0 \\ 2x_1 - 2x_2 + 2x_3 - x_4 + x_5 &= 0 \end{aligned}$$

1. Find the solution space of the system.
2. Find a basis of the solution space.

Solution.

1. Observe that

$$\mathrm{RREF}\left[\begin{array}{ccccc|c} 1 & 1 & 3 & 1 & 2 & 0 \\ -3 & 0 & -6 & 6 & 3 & 0 \\ -1 & 1 & -1 & 1 & 0 & 0 \\ 2 & -2 & 2 & -1 & 1 & 0 \end{array}\right] = \left[\begin{array}{ccccc|c} 1 & 0 & 2 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

Letting $x_3 = a$ and $x_5 = b$ (since those correspond to the non-pivot columns), this is equivalent to the system

$$\begin{aligned} x_1 + 2x_3 + x_5 &= 0 \\ x_2 + x_3 &= 0 \\ x_3 &= a \\ x_4 + x_5 &= 0 \\ x_5 &= b \end{aligned}$$

Thus, the solution set is

$$\left\{ \begin{bmatrix} -2a - b \\ -a \\ a \\ -b \\ b \end{bmatrix} \middle| \, a, b \in \mathbb{R} \right\}.$$

2. Since we can write

$$\begin{bmatrix} -2a - b \\ -a \\ a \\ -b \\ b \end{bmatrix} = a \begin{bmatrix} -2 \\ -1 \\ 1 \\ 0 \\ 0 \end{bmatrix} + b \begin{bmatrix} -1 \\ 0 \\ 0 \\ -1 \\ 1 \end{bmatrix},$$

a basis for the solution space is

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

□

Example B.1.12 AT1. Consider the following maps of polynomials $S : \mathcal{P} \to \mathcal{P}$ and $T : \mathcal{P} \to \mathcal{P}$ defined by

$$S(f(x)) = 3xf(x) \text{ and } T(f(x)) = 3f'(x)f(x).$$

Explain why one of these maps is a linear transformation, and why the other map is not.

Solution. To show S is a linear transformation, we must show two things:

$$S\left(f(x) + g(x)\right) = S(f(x)) + s(g(x))$$

$$S(cf(x)) = cS(f(x))$$

To show S respects addition, we compute

$$\begin{aligned} S\left(f(x) + g(x)\right) &= 3x\left(f(x) + g(x)\right) && \text{by definition of} \\ &= 3xf(x) + 3xg(x) && \text{by distributing} \end{aligned}$$

But note that $S(f(x)) = 3xf(x)$ and $S(g(x)) = 3xg(x)$, so we have $S(f(x) + g(x)) = S(f(x)) + S(g(x))$.

For the second part, we compute

$$\begin{aligned} S\left(cf(x)\right) &= 3x\left(cf(x)\right) && \text{by definition of} \\ &= 3cxf(x) && \text{rewriting the multiplication.} \end{aligned}$$

But note that $cS(f(x)) = c(3xf(x)) = 3cxf(x)$ as well, so we have $S(cf(x)) = cS(f(x))$. Now, since S respects both addition and scalar multiplication, we can conclude S is a linear transformation.

- (Solution method 1) As for T, we compute

  $$\begin{aligned} T(f(x) + g(x)) &= 3(f(x) + g(x))'(f(x) + g(x)) && \text{by definition of} \\ &= 3(f'(x) + g'(x))(f(x) + g(x)) && \text{since the derivative is linear} \\ &= 3f(x)f'(x) + 3f(x)g'(x) + 3f'(x)g(x) + 3g(x)g'(x) && \text{by distributing} \end{aligned}$$

  However, note that $T(f(x)) + T(g(x)) = 3f'(x)f(x) + 3g'(x)g(x)$, which is not always the same polynomial (for example, when $f(x) = g(x) = x$). So we see that $T(f(x)+g(x)) \neq T(f(x))+T(g(x))$, so T does not respect addition and is therefore not a linear transformation.

- (Solution method 2) As for T, we may choose the polynomial $f(x) = x$ and scalar $c = 2$. Then

  $$T(cf(x)) = T(2x) = 3(2x)'(2x) = 3(2)(2x) = 12x.$$

But on the other hand,

$$cT(f(x)) = 2T(x) = 2(3)(x)'(x) = 2(3)(1)(x) = 6x.$$

Since this isn't the same polynomial, T does not preserve multiplication and is therefore not a linear transformation.

$\square$

Example B.1.13 AT2.

1. Find the standard matrix for the linear transformation $T : \mathbb{R}^3 \to \mathbb{R}^4$ given by
$$T\left(\begin{bmatrix} x \\ y \\ z \end{bmatrix}\right) = \begin{bmatrix} -x+y \\ -x+3y-z \\ 7x+y+3z \\ 0 \end{bmatrix}.$$

2. Let $S : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by the standard matrix
$$\begin{bmatrix} 2 & 3 & 4 & 1 \\ 0 & 1 & -1 & -1 \\ 3 & -2 & -2 & 4 \end{bmatrix}.$$
Compute $S\left(\begin{bmatrix} -2 \\ 1 \\ 3 \\ 2 \end{bmatrix}\right)$.

Solution.

1. Since
$$T\left(\begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} -1 \\ -1 \\ 7 \\ 0 \end{bmatrix}$$
$$T\left(\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}\right) = \begin{bmatrix} 1 \\ 3 \\ 1 \\ 0 \end{bmatrix}$$
$$T\left(\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\right) = \begin{bmatrix} 0 \\ -1 \\ 3 \\ 0 \end{bmatrix},$$
the standard matrix for T is $\begin{bmatrix} -1 & 1 & 0 \\ -1 & 3 & -1 \\ 7 & 1 & 3 \\ 0 & 0 & 0 \end{bmatrix}$.

2. $$S\left(\begin{bmatrix} -2 \\ 1 \\ 3 \\ 2 \end{bmatrix}\right) = -2S(\vec{e}_1) + S(\vec{e}_2) + 3S(\vec{e}_3) + 2S(\vec{e}_4)$$
$$= -2\begin{bmatrix} 2 \\ 0 \\ 3 \end{bmatrix} + \begin{bmatrix} 3 \\ 1 \\ -2 \end{bmatrix} + 3\begin{bmatrix} 4 \\ -1 \\ -2 \end{bmatrix} + 2\begin{bmatrix} 1 \\ -1 \\ 4 \end{bmatrix} = \begin{bmatrix} 13 \\ -4 \\ -6 \end{bmatrix}.$$

$\square$

Example B.1.14 AT3. Let $T : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by

$$T\left(\begin{bmatrix} x \\ y \\ z \\ w \end{bmatrix}\right) = \begin{bmatrix} x+3y+2z-3w \\ 2x+4y+6z-10w \\ x+6y-z+3w \end{bmatrix}$$

1. Explain how to find the image of T and the kernel of T.
2. Explain how to find a basis of the image of T and a basis of the kernel of T.
3. Explain how to find the rank and nullity of T, and why the rank-nullity theorem holds for T.

Solution.

1. To find the image we compute

$$\begin{aligned} \mathrm{Im}(T) &= T\left(\mathrm{span}\left\{\vec{e}_1, \vec{e}_2, \vec{e}_3, \vec{e}_4\right\}\right) \\ &= \mathrm{span}\left\{T(\vec{e}_1), T(\vec{e}_2), T(\vec{e}_3), T(\vec{e}_4)\right\} \\ &= \mathrm{span}\left\{\begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}, \begin{bmatrix} 3 \\ 4 \\ 6 \end{bmatrix}, \begin{bmatrix} 2 \\ 6 \\ -1 \end{bmatrix}, \begin{bmatrix} -3 \\ -10 \\ 3 \end{bmatrix}\right\}. \end{aligned}$$

2. The kernel is the solution set of the corresponding homogeneous system of equations, i.e.

$$\begin{aligned} x+3y+2z-\ 3w &= 0 \\ 2x+4y+6z-10w &= 0 \\ x+6y-\ z+\ 3w &= 0. \end{aligned}$$

So we compute

$$\mathrm{RREF}\left[\begin{array}{cccc|c} 1 & 3 & 2 & -3 & 0 \\ 2 & 4 & 6 & -10 & 0 \\ 1 & 6 & -1 & 3 & 0 \end{array}\right] = \left[\begin{array}{cccc|c} 1 & 0 & 5 & -9 & 0 \\ 0 & 1 & -1 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right].$$

Then, letting $z = a$ and $w = b$ we have

$$\ker T = \left\{\begin{bmatrix} -5a+9b \\ a-2b \\ a \\ b \end{bmatrix} \middle| a, b \in \mathbb{R}\right\}.$$

3. Since $\mathrm{Im}(T) = \mathrm{span}\left\{\begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}, \begin{bmatrix} 3 \\ 4 \\ 6 \end{bmatrix}, \begin{bmatrix} 2 \\ 6 \\ -1 \end{bmatrix}, \begin{bmatrix} -3 \\ -10 \\ 3 \end{bmatrix}\right\}$, we simply need to find a linearly independent subset of these four spanning vectors. So we compute

$$\mathrm{RREF}\begin{bmatrix} 1 & 3 & 2 & -3 \\ 2 & 4 & 6 & -10 \\ 1 & 6 & -1 & 3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 5 & -9 \\ 0 & 1 & -1 & 2 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

Since the first two columns are pivot columns, they form a linearly independent spanning set, so a basis for $\operatorname{Im} T$ is $\left\{ \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}, \begin{bmatrix} 3 \\ 4 \\ 6 \end{bmatrix} \right\}$.

To find a basis for the kernel, note that

$$\begin{aligned} \ker T &= \left\{ \begin{bmatrix} -5a+9b \\ a-2b \\ a \\ b \end{bmatrix} \middle|\, a,b \in \mathbb{R} \right\} \\ &= \left\{ a \begin{bmatrix} -5 \\ 1 \\ 1 \\ 0 \end{bmatrix} + b \begin{bmatrix} 9 \\ -2 \\ 0 \\ 1 \end{bmatrix} \middle|\, a,b \in \mathbb{R} \right\} \\ &= \operatorname{span} \left\{ \begin{bmatrix} -5 \\ 1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 9 \\ -2 \\ 0 \\ 1 \end{bmatrix} \right\}. \end{aligned}$$

so a basis for the kernel is

$$\left\{ \begin{bmatrix} -5 \\ 1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 9 \\ -2 \\ 0 \\ 1 \end{bmatrix} \right\}.$$

4. The dimension of the image (the rank) is 2, the dimension of the kernel (the nullity) is 2, and the dimension of the domain of T is 4, so we see $2+2=4$, which verifies that the sum of the rank and nullity of T is the dimension of the domain of T.

□

Example B.1.15 AT4. Let $T : \mathbb{R}^4 \to \mathbb{R}^3$ be the linear transformation given by the standard matrix $\begin{bmatrix} 1 & 3 & 2 & -3 \\ 2 & 4 & 6 & -10 \\ 1 & 6 & -1 & 3 \end{bmatrix}$.

1. Explain why T is or is not injective.

2. Explain why T is or is not surjective.

Solution. Compute

$$\operatorname{RREF} \begin{bmatrix} 1 & 3 & 2 & -3 \\ 2 & 4 & 6 & -10 \\ 1 & 6 & -1 & 3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 5 & -9 \\ 0 & 1 & -1 & 2 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

1. Note that the third and fourth columns are non-pivot columns, which means $\ker T$ contains infinitely many vectors, so T is not injective.

2. Since there are only two pivots, the image (i.e. the span of the columns) is a 2-dimensional subspace (and thus does not equal $\mathbb{R}^3$), so T is not surjective.

□

Example B.1.16 AT5. Let V be the set of all pairs of numbers (x, y) of real numbers together with the following operations:

$$\begin{aligned}(x_1, y_1) \oplus (x_2, y_2) &= (2x_1 + 2x_2, 2y_1 + 2y_2)\\ c \odot (x, y) &= (cx, c^2 y)\end{aligned}$$

1. Show that scalar multiplication distributes over vector addition:
$$c \odot ((x_1, y_1) \oplus (x_2, y_2)) = c \odot (x_1, y_1) \oplus c \odot (x_2, y_2)$$
2. Explain why V nonetheless is not a vector space.

Solution.

1. We compute both sides:
$$\begin{aligned}c \odot ((x_1, y_1) \oplus (x_2, y_2)) &= c \odot (2x_1 + 2x_2, 2y_1 + 2y_2)\\ &= (c(2x_1 + 2x_2), c^2(2y_1 + 2y_2))\\ &= (2cx_1 + 2cx_2, 2c^2 y_1 + 2c^2 y_2)\end{aligned}$$
and
$$\begin{aligned}c \odot (x_1, y_1) \oplus c \odot (x_2, y_2) &= (cx_1, c^2 y_1) \oplus (cx_2, c^2 y_2)\\ &= (2cx_1 + 2cx_2, 2c^2 y_1 + 2c^2 y_2)\end{aligned}$$
Since these are the same, we have shown that the property holds.
2. To show V is not a vector space, we must show that it fails one of the 8 defining properties of vector spaces. We will show that scalar multiplication does not distribute over scalar addition, i.e., there are values such that
$$(c + d) \odot (x, y) \neq c \odot (x, y) \oplus d \odot (x, y)$$
   - (Solution method 1) First, we compute
$$\begin{aligned}(c + d) \odot (x, y) &= ((c + d)x, (c + d)^2 y)\\ &= ((c + d)x, (c^2 + 2cd + d^2)y).\end{aligned}$$
Then we compute
$$\begin{aligned}c \odot (x, y) \oplus d \odot (x, y) &= (cx, c^2 y) \oplus (dx, d^2 y)\\ &= (2cx + 2dx, 2c^2 y + 2d^2 y).\end{aligned}$$
Since $(c + d)x \neq 2cx + 2dy$ when $c, d, x, y = 1$, the property fails to hold.
   - (Solution method 2) When we let $c, d, x, y = 1$, we may simplify both sides as follows.
$$\begin{aligned}(c + d) \odot (x, y) &= 2 \odot (1, 1)\\ &= (2 \cdot 1, 2^2 \cdot 1)\\ &= (2, 4)\end{aligned}$$
$$\begin{aligned}c \odot (x, y) \oplus d \odot (x, y) &= 1 \odot (1, 1) \oplus 1 \odot (1, 1)\\ &= (1 \cdot 1, 1^2 \cdot 1) \oplus (1 \cdot 1, 1^2 \cdot 1)\\ &= (1, 1) \oplus (1, 1)\\ &= (2 \cdot 1 + 2 \cdot 1, 2 \cdot 1 + 2 \cdot 1)\\ &= (4, 4)\end{aligned}$$
Since these ordered pairs are different, the property fails to hold.

□

Example B.1.17 AT6.

1. Given the set

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

   write a statement involving the solutions to a polynomial equation that's equivalent to each claim below.

   - The set of polynomials is linearly *independent*.
   - The set of polynomials is linearly *dependent*.

2. Explain how to determine which of these statements is true.

Solution. The set of polynomials

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

is linearly *independent* exactly when the polynomial equation

$$y_1\left(x^3 - 2\,x^2 + x + 2\right) + y_2\left(2\,x^2 - 1\right) + y_3\left(-x^3 + 3\,x^2 + 3\,x - 2\right) + y_4\left(x^3 - 6\,x^2 + 9\,x + 5\right) = 0$$

has no nontrivial (i.e. nonzero) solutions. The set is linearly *dependent* when this equation has a nontrivial (i.e. nonzero) solution.

To solve this equation, we distribute and then collect coefficients to obtain

$$(y_1 - y_3 + y_4)\,x^3 + (-2y_1 + 2y_2 + 3y_3 - 6y_4)\,x^2 + (y_1 + 3y_3 + 9y_4)\,x + (2y_1 - y_2 - 2y_3 + 5y_4) = 0.$$

These polynomials are equal precisely when their coefficients are equal, leading to the system

$$\begin{alignedat}{5} y_1 & & & - & y_3 & + & y_4 & = & 0 \\ -2y_1 & + & 2y_2 & + & 3y_3 & - & 6y_4 & = & 0 \\ y_1 & + & & + & 3y_3 & + & 9y_4 & = & 0 \\ 2y_1 & - & y_2 & - & 2y_3 & + & 5y_4 & = & 0 \end{alignedat}.$$

To solve this, we compute

$$\mathrm{RREF}\left[\begin{array}{cccc|c} 1 & 0 & -1 & 1 & 0 \\ -2 & 2 & 3 & -6 & 0 \\ 1 & 0 & 3 & 9 & 0 \\ 2 & -1 & -2 & 5 & 0 \end{array}\right] = \left[\begin{array}{cccc|c} 1 & 0 & 0 & 3 & 0 \\ 0 & 1 & 0 & -3 & 0 \\ 0 & 0 & 1 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right]$$

The system has (infintely many) nontrivial solutions, so we that the set of polynomials is linearly *dependent*. □

Example B.1.18 MX1. Of the following three matrices, only two may be multiplied.

$$A = \left[\begin{array}{cc} 1 & -3 \\ 0 & 1 \end{array}\right] \qquad B = \left[\begin{array}{ccc} 4 & 1 & 2 \end{array}\right] \qquad C = \left[\begin{array}{ccc} 0 & 1 & 3 \\ 1 & -2 & 5 \end{array}\right]$$

Explain which two may be multiplied and why. Then show how to find their product.

Solution. AC is the only one that can be computed, since C corresponds to a linear transformation $\mathbb{R}^3 \to \mathbb{R}^2$ and A corresponds to a linear transfromation $\mathbb{R}^2 \to \mathbb{R}^2$. Thus the composition AC corresponds to a linear transformation

$\mathbb{R}^3 \to \mathbb{R}^2$ with a 2×3 standard matrix. We compute

$$AC(\vec{e}_1) = A\left(\begin{bmatrix} 0 \\ 1 \end{bmatrix}\right) = 0\begin{bmatrix} 1 \\ 0 \end{bmatrix} + 1\begin{bmatrix} -3 \\ 1 \end{bmatrix} = \begin{bmatrix} -3 \\ 1 \end{bmatrix}$$

$$AC(\vec{e}_2) = A\left(\begin{bmatrix} 1 \\ -2 \end{bmatrix}\right) = 1\begin{bmatrix} 1 \\ 0 \end{bmatrix} - 2\begin{bmatrix} -3 \\ 1 \end{bmatrix} = \begin{bmatrix} 7 \\ -2 \end{bmatrix}$$

$$AC(\vec{e}_3) = A\left(\begin{bmatrix} 3 \\ 5 \end{bmatrix}\right) = 3\begin{bmatrix} 1 \\ 0 \end{bmatrix} + 5\begin{bmatrix} -3 \\ 1 \end{bmatrix} = \begin{bmatrix} -12 \\ 5 \end{bmatrix}$$

.

Thus

$$AC = \begin{bmatrix} -3 & 7 & -12 \\ 1 & -2 & 5 \end{bmatrix}.$$

□

Example B.1.19 MX2. Explain why each of the following matrices is or is not invertible by disussing its corresponding linear transformation. If the matrix is invertible, explain how to find its inverse.

$$D = \begin{bmatrix} -1 & 1 & 0 & 2 \\ -2 & 5 & 5 & -4 \\ 2 & -3 & -2 & 0 \\ 4 & -4 & -3 & 5 \end{bmatrix} \qquad N = \begin{bmatrix} -3 & 9 & 1 & -11 \\ 3 & -9 & -2 & 13 \\ 3 & -9 & -3 & 15 \\ -4 & 12 & 2 & -16 \end{bmatrix}$$

Solution. We compute

$$\mathrm{RREF}(D) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

We see D is bijective, and therefore invertible. To compute the inverse, we solve $D\vec{x} = \vec{e}_1$ by computing

$$\mathrm{RREF}\left[\begin{array}{cccc|c} -1 & 1 & 0 & 2 & 1 \\ -2 & 5 & 5 & -4 & 0 \\ 2 & -3 & -2 & 0 & 0 \\ 4 & -4 & -3 & 5 & 0 \end{array}\right] = \left[\begin{array}{cccc|c} 1 & 0 & 0 & 0 & 21 \\ 0 & 1 & 0 & 0 & 38 \\ 0 & 0 & 1 & 0 & -36 \\ 0 & 0 & 0 & 1 & -8 \end{array}\right].$$

Similarly, we solve $D\vec{x} = \vec{e}_2$ by computing

$$\mathrm{RREF}\left[\begin{array}{cccc|c} -1 & 1 & 0 & 2 & 0 \\ -2 & 5 & 5 & -4 & 1 \\ 2 & -3 & -2 & 0 & 0 \\ 4 & -4 & -3 & 5 & 0 \end{array}\right] = \left[\begin{array}{cccc|c} 1 & 0 & 0 & 0 & 8 \\ 0 & 1 & 0 & 0 & 14 \\ 0 & 0 & 1 & 0 & -13 \\ 0 & 0 & 0 & 1 & -3 \end{array}\right].$$

Similarly, we solve $D\vec{x} = \vec{e}_3$ by computing

$$\mathrm{RREF}\left[\begin{array}{cccc|c} -1 & 1 & 0 & 2 & 0 \\ -2 & 5 & 5 & -4 & 0 \\ 2 & -3 & -2 & 0 & 1 \\ 4 & -4 & -3 & 5 & 0 \end{array}\right] = \left[\begin{array}{cccc|c} 1 & 0 & 0 & 0 & 23 \\ 0 & 1 & 0 & 0 & 41 \\ 0 & 0 & 1 & 0 & -39 \\ 0 & 0 & 0 & 1 & -9 \end{array}\right].$$

Similarly, we solve $D\vec{x} = \vec{e}_4$ by computing

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

Combining these, we obtain

$$D^{-1} = \begin{bmatrix} 21 & 8 & 23 & -2 \\ 38 & 14 & 41 & -4 \\ -36 & -13 & -39 & 4 \\ -8 & -3 & -9 & 1 \end{bmatrix}.$$

We compute

$$\text{RREF}\,(N) = \begin{bmatrix} 1 & -3 & 0 & 3 \\ 0 & 0 & 1 & -2 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}.$$

We see N is not bijective and thus is *not* invertible. □

Example B.1.20 MX3. Use a matrix inverse to solve the following matrix-vector equation.

$$\begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 2 \\ 1 & 1 & 1 \end{bmatrix} \vec{v} = \begin{bmatrix} 4 \\ -2 \\ 2 \end{bmatrix}$$

Solution. Using the techniques from section Section 4.3, and letting $M = \begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 2 \\ 1 & 1 & 1 \end{bmatrix}$, we find $M^{-1} = \begin{bmatrix} -1 & -1/2 & 2 \\ 1 & 0 & -1 \\ 0 & 1/2 & 0 \end{bmatrix}$. Our equation can be written as $M\vec{v} = \begin{bmatrix} 4 \\ -2 \\ 2 \end{bmatrix}$, and may therefore be solved via

$$\vec{v} = I\vec{v} = M^{-1}M\vec{v} = M^{-1}\begin{bmatrix} 4 \\ -2 \\ 2 \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ -1 \end{bmatrix}$$

□

Example B.1.21 MX4. Let A be a 4×4 matrix.

1. Give a 4×4 matrix P that may be used to perform the row operation $R_3 \to R_3 + 4\,R_1$.

2. Give a 4×4 matrix Q that may be used to perform the row operation $R_1 \to -4\,R_1$.

3. Use matrix multiplication to describe the matrix obtained by applying $R_3 \to 4\,R_1 + R_3$ and then $R_1 \to -4\,R_1$ to A (note the order).

Solution.

1. $P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 4 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

2. $Q = \begin{bmatrix} -4 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$

3. QPA

□

Example B.1.22 GT1. Let A be a 4×4 matrix with determinant -7.

1. Let B be the matrix obtained from A by applying the row operation $R_3 \to R_3 + 3R_4$. What is $\det(B)$?

2. Let C be the matrix obtained from A by applying the row operation $R_2 \to -3R_2$. What is $\det(C)$?

3. Let D be the matrix obtained from A by applying the row operation $R_3 \leftrightarrow R_4$. What is $\det(D)$?

Solution.

1. Adding a multiple of one row to another row does not change the determinant, so $\det(B) = \det(A) = -7$.

2. Scaling a row scales the determinant by the same factor, so so $\det(B) = -3\det(A) = -3(-7) = 21$.

3. Swaping rows changes the sign of the determinant, so $\det(B) = -\det(A) = 7$.

□

Example B.1.23 GT2. Show how to compute the determinant of the matrix

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

Solution. Here is one possible solution, first applying a single row operation, and then performing Laplace/cofactor expansions to reduce the determinant to a linear combination of 2×2 determinants:

$$\begin{aligned} \det \begin{bmatrix} 1 & 3 & 0 & -1 \\ 1 & 1 & 2 & 4 \\ 1 & 1 & 1 & 3 \\ -3 & 1 & 2 & -5 \end{bmatrix} &= \det \begin{bmatrix} 1 & 3 & 0 & -1 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 3 \\ -3 & 1 & 2 & -5 \end{bmatrix} = (-1)\det \begin{bmatrix} 1 & 3 & -1 \\ 1 & 1 & 3 \\ -3 & 1 & -5 \end{bmatrix} + (1)\det \begin{bmatrix} 1 & 3 & 0 \\ 1 & 1 & 1 \\ -3 & 1 & 2 \end{bmatrix} \\ &= (-1)\left((1)\det \begin{bmatrix} 1 & 3 \\ 1 & -5 \end{bmatrix} - (1)\det \begin{bmatrix} 3 & -1 \\ 1 & -5 \end{bmatrix} + (-3)\det \begin{bmatrix} 3 & -1 \\ 1 & 3 \end{bmatrix}\right) + \\ &\quad (1)\left((1)\det \begin{bmatrix} 1 & 1 \\ 1 & 2 \end{bmatrix} - (3)\det \begin{bmatrix} 1 & 1 \\ -3 & 2 \end{bmatrix}\right) \\ &= (-1)(-8 + 14 - 30) + (1)(1 - 15) \\ &= 10 \end{aligned}$$

Here is another possible solution, using row and column operations to first reduce the determinant to a 3×3 matrix and then applying a formula:

$$\det\begin{bmatrix} 1 & 3 & 0 & -1 \\ 1 & 1 & 2 & 4 \\ 1 & 1 & 1 & 3 \\ -3 & 1 & 2 & -5 \end{bmatrix} = \det\begin{bmatrix} 1 & 3 & 0 & -1 \\ 0 & 0 & 1 & 1 \\ 1 & 1 & 1 & 3 \\ -3 & 1 & 2 & -5 \end{bmatrix} = \det\begin{bmatrix} 1 & 3 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 1 & 1 & 2 \\ -3 & 1 & 2 & -7 \end{bmatrix}$$
$$= -\det\begin{bmatrix} 1 & 3 & 0 & -1 \\ 1 & 1 & 1 & 2 \\ 0 & 0 & 1 & 0 \\ -3 & 1 & 2 & -7 \end{bmatrix} = -\det\begin{bmatrix} 1 & 3 & -1 \\ 1 & 1 & 2 \\ -3 & 1 & -7 \end{bmatrix}$$
$$= -((-7-18-1)-(3+2-21))$$
$$= 10$$

□

Example B.1.24 GT3. Explain how to find the eigenvalues of the matrix $\begin{bmatrix} -2 & -2 \\ 10 & 7 \end{bmatrix}$.

Solution. Compute the characteristic polynomial:

$$\det(A-\lambda I) = \det\begin{bmatrix} -2-\lambda & -2 \\ 10 & 7-\lambda \end{bmatrix}$$

$$= (-2-\lambda)(7-\lambda)+20 = \lambda^2-5\lambda+6 = (\lambda-2)(\lambda-3)$$

The eigenvalues are the roots of the characteristic polynomial, namely 2 and 3.
□

Example B.1.25 GT4. Explain how to find a basis for the eigenspace associated to the eigenvalue 3 in the matrix

$$\begin{bmatrix} -7 & -8 & 2 \\ 8 & 9 & -1 \\ \frac{13}{2} & 5 & 2 \end{bmatrix}.$$

Solution. The eigenspace associated to 3 is the kernel of $A-3I$, so we compute

$$\mathrm{RREF}(A-3I) = \mathrm{RREF}\begin{bmatrix} -7-3 & -8 & 2 \\ 8 & 9-3 & -1 \\ \frac{13}{2} & 5 & 2-3 \end{bmatrix} =$$

$$\mathrm{RREF}\begin{bmatrix} -10 & -8 & 2 \\ 8 & 6 & -1 \\ \frac{13}{2} & 5 & -1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ 0 & 1 & -\frac{3}{2} \\ 0 & 0 & 0 \end{bmatrix}.$$

Thus we see the kernel is

$$\left\{ \begin{bmatrix} -a \\ \frac{3}{2}a \\ a \end{bmatrix} \middle| a \in \mathbb{R} \right\}$$

which has a basis of $\left\{ \begin{bmatrix} -1 \\ \frac{3}{2} \\ 1 \end{bmatrix} \right\}$. □

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