



## Section 2.3 : Invertible Matrices

Chapter 2 : Matrix Algebra

Math 1554 Linear Algebra

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- Baltasar Gracián

The theorem we introduce in this section of the course gives us many ways of saying the same thing. Depending on the context, some will be more convenient than others.

## Topics and Objectives

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We will cover these topics in this section.

1. The invertible matrix theorem, which is a review/synthesis of many of the concepts we have introduced.

### Objectives

For the topics covered in this section, students are expected to be able to do the following.

1. Characterize the invertibility of a matrix using the Invertible Matrix Theorem.
2. Construct and give examples of matrices that are/are not invertible.

### Motivating Question

When is a square matrix invertible? Let me count the ways!

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Course Schedule						
Cancellations due to inclement weather will likely result in cancelling review lectures and possibly moving through course material more quickly.						
Week	Dates	Mon Lecture	Tue Studio	Wed Lecture	Thu Studio	Fri Lecture
1	8/21 - 8/25	1.1	WS1.1	1.2	WS1.2	1.3
2	8/28 - 9/1	1.4	WS1.3,1.4	1.5	WS1.5	1.7
3	9/4 - 9/8	Break	WS1.7	1.8	WS1.8	1.9
4	9/11 - 9/15	2.1	WS1.9,2.1	Exam 1, Review	Cancelled	2.2
5	9/18 - 9/22	2.3,2.4	WS2.2,2.3	2.5	WS2.4,2.5	2.8
6	9/25 - 9/29	2.9	WS2.8,2.9	3.1,3.2	WS3.1,3.2	3.3
7	10/2 - 10/6	4.9	WS3.4,4.9	5.1,5.2	WS5.1,5.2	5.2
8	10/9 - 10/13	Break	Break	Exam 2, Review	Cancelled	5.3
9	10/16 - 10/20	5.3	WS5.3	5.5	WS5.5	6.1
10	10/23 - 10/27	6.1,6.2	WS6.1	6.2	WS6.2	6.3
11	10/30 - 11/3	6.4	WS6.3,6.4	6.4,6.5	WS6.4,6.5	6.5
12	11/6 - 11/10	6.6	WS6.5,6.6	Exam 3, Review	Cancelled	PageRank
13	11/13 - 11/17	7.1	WSPageRank	7.2	WS7.1,7.2	7.3
14	11/20 - 11/24	7.3,7.4	WS7.2,7.3	Break	Break	Break
15	11/27 - 12/1	7.4	WS7.3,7.4	7.4	WS7.4	7.4
16	12/4 - 12/8	Last lecture	Last Studio	Reading Period		
17	12/11 - 12/15	Final Exam: MATH 1554 Common Final Exam Tuesday, December 12th at 6pm				

The Invertible Matrix Theorem

Invertible matrices enjoy a rich set of equivalent descriptions.

- Theorem**  
Let  $A$  be an  $n \times n$  matrix. These statements are all equivalent.
- $A$  is invertible.
  - $A$  is row equivalent to  $I_n$ .
  - $A$  has  $n$  pivotal columns. (All columns are pivotal.)
  - $A\vec{x} = \vec{0}$  has only the trivial solution.
  - The columns of  $A$  are linearly independent.
  - The linear transformation  $\vec{x} \mapsto A\vec{x}$  is one-to-one.
  - The equation  $A\vec{x} = \vec{b}$  has a solution for all  $\vec{b} \in \mathbb{R}^n$ .
  - The columns of  $A$  span  $\mathbb{R}^n$ .
  - The linear transformation  $\vec{x} \mapsto A\vec{x}$  is onto.
  - There is a  $n \times n$  matrix  $C$  so that  $CA = I_n$ . ( $A$  has a left inverse.)
  - There is a  $n \times n$  matrix  $D$  so that  $AD = I_n$ . ( $A$  has a right inverse.)
  - $A^T$  is invertible.

Invertibility and Composition

The diagram below gives us another perspective on the role of  $A^{-1}$ .



The matrix inverse  $A^{-1}$  transforms  $Ax$  back to  $\vec{x}$ . This is because:

$$A^{-1}(A\vec{x}) = (A^{-1}A)\vec{x} = \vec{x}$$

- Items j and k of the invertible matrix theorem (IMT) lead us directly to the following theorem.

Theorem

If  $A$  and  $B$  are  $n \times n$  matrices and  $AB = I$ , then  $A$  and  $B$  are invertible, and  $B = A^{-1}$  and  $A = B^{-1}$ .

- The IMT is a set of equivalent statements. They divide the set of all square matrices into two separate classes: invertible, and non-invertible.
- As we progress through this course, we will be able to add additional equivalent statements to the IMT (that deal with determinants, eigenvalues, etc).

Is this matrix invertible?

$$\begin{bmatrix} 1 & 0 & -2 \\ 3 & 1 & -2 \\ -5 & -1 & 9 \end{bmatrix}$$

Example 2

If possible, fill in the missing elements of the matrices below with numbers so that each of the matrices are singular. If it is not possible to do so, state why.

$$\begin{pmatrix} 1 & 0 & 1 \\ 1 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & & 1 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & & 1 \end{pmatrix}$$

Matrix Completion Problems

- The previous example is an example of a matrix completion problem (MCP).
- MCPs are great questions for recitations, midterms, exams.
- the **Netflix Problem** is another example of an MCP.

Given a **ratings matrix** in which each entry  $(i,j)$  represents the rating of movie  $j$  by customer  $i$  if customer  $i$  has watched movie  $j$ , and is otherwise missing, predict the remaining matrix entries in order to make recommendations to customers on what to watch next.

Students aren't expected to be familiar with this material. It's presented to motivate matrix completion.



## 2.3 EXERCISES

Unless otherwise specified, assume that all matrices in these exercises are  $n \times n$ . Determine which of the matrices in Exercises 1–10 are invertible. Use as few calculations as possible. Justify your answers.

1.  $\begin{bmatrix} 5 & 7 \\ -3 & -6 \end{bmatrix}$
2.  $\begin{bmatrix} -4 & 6 \\ 6 & -9 \end{bmatrix}$
3.  $\begin{bmatrix} 5 & 0 & 0 \\ -3 & -7 & 0 \\ 8 & 5 & -1 \end{bmatrix}$
4.  $\begin{bmatrix} -7 & 0 & 4 \\ 3 & 0 & -1 \\ 2 & 0 & 9 \end{bmatrix}$
5.  $\begin{bmatrix} 0 & 3 & -5 \\ 1 & 0 & 2 \\ -4 & -9 & 7 \end{bmatrix}$
6.  $\begin{bmatrix} 1 & -5 & -4 \\ 0 & 3 & 4 \\ -3 & 6 & 0 \end{bmatrix}$
7.  $\begin{bmatrix} -1 & -3 & 0 & 1 \\ 3 & 5 & 8 & -3 \\ -2 & -6 & 3 & 2 \\ 0 & -1 & 2 & 1 \end{bmatrix}$
8.  $\begin{bmatrix} 1 & 3 & 7 & 4 \\ 0 & 5 & 9 & 6 \\ 0 & 0 & 2 & 8 \\ 0 & 0 & 0 & 10 \end{bmatrix}$
9. [M]  $\begin{bmatrix} 4 & 0 & -7 & -7 \\ -6 & 1 & 11 & 9 \\ 7 & -5 & 10 & 19 \\ -1 & 2 & 3 & -1 \end{bmatrix}$
10. [M]  $\begin{bmatrix} 5 & 3 & 1 & 7 & 9 \\ 6 & 4 & 2 & 8 & -8 \\ 7 & 5 & 3 & 10 & 9 \\ 9 & 6 & 4 & -9 & -5 \\ 8 & 5 & 2 & 11 & 4 \end{bmatrix}$

In Exercises 11 and 12, the matrices are all  $n \times n$ . Each part of the exercises is an *implication* of the form “If ‘statement 1’, then ‘statement 2’.” Mark an implication as True if the truth of “statement 2” *always* follows whenever “statement 1” happens to be true. An implication is False if there is an instance in which “statement 2” is false but “statement 1” is true. Justify each answer.

11. a. If the equation  $A\mathbf{x} = \mathbf{0}$  has only the trivial solution, then  $A$  is row equivalent to the  $n \times n$  identity matrix.  
b. If the columns of  $A$  span  $\mathbb{R}^n$ , then the columns are linearly independent.  
c. If  $A$  is an  $n \times n$  matrix, then the equation  $A\mathbf{x} = \mathbf{b}$  has at least one solution for each  $\mathbf{b}$  in  $\mathbb{R}^n$ .  
d. If the equation  $A\mathbf{x} = \mathbf{0}$  has a nontrivial solution, then  $A$  has fewer than  $n$  pivot positions.  
e. If  $A^T$  is not invertible, then  $A$  is not invertible.
12. a. If there is an  $n \times n$  matrix  $D$  such that  $AD = I$ , then there is also an  $n \times n$  matrix  $C$  such that  $CA = I$ .  
b. If the columns of  $A$  are linearly independent, then the

columns of  $A$  span  $\mathbb{R}^n$ .

30. If  $A$  is an  $n \times n$  matrix and the transformation  $\mathbf{x} \mapsto A\mathbf{x}$  is one-to-one, what else can you say about this transformation? Justify your answer.
31. Suppose  $A$  is an  $n \times n$  matrix with the property that the equation  $A\mathbf{x} = \mathbf{b}$  has at least one solution for each  $\mathbf{b}$  in  $\mathbb{R}^n$ . Without using Theorems 5 or 8, explain why each equation  $A\mathbf{x} = \mathbf{b}$  has in fact exactly one solution.
32. Suppose  $A$  is an  $n \times n$  matrix with the property that the equation  $A\mathbf{x} = \mathbf{0}$  has only the trivial solution. Without using the Invertible Matrix Theorem, explain directly why the equation  $A\mathbf{x} = \mathbf{b}$  must have a solution for each  $\mathbf{b}$  in  $\mathbb{R}^n$ .

In Exercises 33 and 34,  $T$  is a linear transformation from  $\mathbb{R}^2$  into  $\mathbb{R}^2$ . Show that  $T$  is invertible and find a formula for  $T^{-1}$ .

33.  $T(x_1, x_2) = (-5x_1 + 9x_2, 4x_1 - 7x_2)$
34.  $T(x_1, x_2) = (6x_1 - 8x_2, -5x_1 + 7x_2)$

35. Let  $T: \mathbb{R}^n \rightarrow \mathbb{R}^n$  be an invertible linear transformation. Explain why  $T$  is both one-to-one and onto  $\mathbb{R}^n$ . Use equations (1) and (2). Then give a second explanation using one or more theorems.
36. Let  $T$  be a linear transformation that maps  $\mathbb{R}^n$  onto  $\mathbb{R}^n$ . Show that  $T^{-1}$  exists and maps  $\mathbb{R}^n$  onto  $\mathbb{R}^n$ . Is  $T^{-1}$  also one-to-one?
37. Suppose  $T$  and  $U$  are linear transformations from  $\mathbb{R}^n$  to  $\mathbb{R}^n$  such that  $T(U\mathbf{x}) = \mathbf{x}$  for all  $\mathbf{x}$  in  $\mathbb{R}^n$ . Is it true that  $U(T\mathbf{x}) = \mathbf{x}$  for all  $\mathbf{x}$  in  $\mathbb{R}^n$ ? Why or why not?

- d. If the linear transformation  $(\mathbf{x}) \mapsto A\mathbf{x}$  maps  $\mathbb{R}^n$  into  $\mathbb{R}^n$ , then  $A$  has  $n$  pivot positions.
- e. If there is a  $\mathbf{b}$  in  $\mathbb{R}^n$  such that the equation  $A\mathbf{x} = \mathbf{b}$  is inconsistent, then the transformation  $\mathbf{x} \mapsto A\mathbf{x}$  is not one-to-one.
13. An  $m \times n$  **upper triangular matrix** is one whose entries *below* the main diagonal are 0's (as in Exercise 8). When is a square upper triangular matrix invertible? Justify your answer.
14. An  $m \times n$  **lower triangular matrix** is one whose entries *above* the main diagonal are 0's (as in Exercise 3). When is a square lower triangular matrix invertible? Justify your answer.
15. Can a square matrix with two identical columns be invertible? Why or why not?
16. Is it possible for a  $5 \times 5$  matrix to be invertible when its columns do not span  $\mathbb{R}^5$ ? Why or why not?
17. If  $A$  is invertible, then the columns of  $A^{-1}$  are linearly independent. Explain why.
18. If  $C$  is  $6 \times 6$  and the equation  $C\mathbf{x} = \mathbf{v}$  is consistent for every  $\mathbf{v}$  in  $\mathbb{R}^6$ , is it possible that for some  $\mathbf{v}$ , the equation  $C\mathbf{x} = \mathbf{v}$  has more than one solution? Why or why not?
19. If the columns of a  $7 \times 7$  matrix  $D$  are linearly independent, what can you say about solutions of  $D\mathbf{x} = \mathbf{b}$ ? Why?
20. If  $n \times n$  matrices  $E$  and  $F$  have the property that  $EF = I$ , then  $E$  and  $F$  commute. Explain why.
21. If the equation  $G\mathbf{x} = \mathbf{y}$  has more than one solution for some  $\mathbf{y}$  in  $\mathbb{R}^n$ , can the columns of  $G$  span  $\mathbb{R}^n$ ? Why or why not?
22. If the equation  $H\mathbf{x} = \mathbf{c}$  is inconsistent for some  $\mathbf{c}$  in  $\mathbb{R}^n$ , what can you say about the equation  $H\mathbf{x} = \mathbf{0}$ ? Why?
23. If an  $n \times n$  matrix  $K$  cannot be row reduced to  $I_n$ , what can you say about the columns of  $K$ ? Why?
24. If  $L$  is  $n \times n$  and the equation  $L\mathbf{x} = \mathbf{0}$  has the trivial solution, do the columns of  $L$  span  $\mathbb{R}^n$ ? Why?
25. Verify the boxed statement preceding Example 1.
26. Explain why the columns of  $A^2$  span  $\mathbb{R}^n$  whenever the columns of  $A$  are linearly independent.
27. Show that if  $AB$  is invertible, so is  $A$ . You cannot use Theorem 6(b), because you cannot *assume* that  $A$  and  $B$  are invertible. [Hint: There is a matrix  $W$  such that  $ABW = I$ . Why?]
28. Show that if  $AB$  is invertible, so is  $B$ .
29. If  $A$  is an  $n \times n$  matrix and the equation  $A\mathbf{x} = \mathbf{b}$  has more than

## Section 2.4 : Partitioned Matrices

Chapter 2 : Matrix Algebra

Math 1554 Linear Algebra

## Topics and Objectives

### Topics

We will cover these topics in this section.

1. Partitioned matrices (or block matrices)

### Objectives

For the topics covered in this section, students are expected to be able to do the following.

1. Apply partitioned matrices to solve problems regarding matrix invertibility and matrix multiplication.

Topics and Objectives

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Chapter 2 : Matrix Algebra  
Math 1554 Linear Algebra

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6	9/25 - 9/29	2.9	WS2.8.2.9	3.1.3.2	WS3.1.3.2	3.3
7	10/2 - 10/6	4.9	WS3.3.4.9	5.1.5.2	WS5.1.5.2	5.2
8	10/9 - 10/13	Break	Break	Exam 2, Review	Cancelled	5.3

What is a Partitioned Matrix?

**Example**  
This matrix:  
$$\begin{bmatrix} 3 & 1 & 4 & 1 & 0 \\ 1 & 6 & 1 & 0 & 1 \\ 0 & 0 & 0 & 4 & 2 \end{bmatrix}$$

can also be written as:

$$\left[ \begin{bmatrix} 3 & 1 & 4 \\ 1 & 6 & 1 \\ 0 & 0 & 0 \end{bmatrix} \quad \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 4 & 2 \end{bmatrix} \right] = \begin{bmatrix} A_{1,1} & A_{1,2} \\ A_{2,1} & A_{2,2} \end{bmatrix}$$

We partitioned our matrix into four **blocks**, each of which has different dimensions.

Another Example of a Partitioned Matrix

**Example:** The reduced echelon form of a matrix. We can use a partitioned matrix to

$$\begin{bmatrix} 1 & 0 & 0 & 0 & * & \cdots & * \\ 0 & 1 & 0 & 0 & * & \cdots & * \\ 0 & 0 & 1 & 0 & * & \cdots & * \\ 0 & 0 & 0 & 1 & * & \cdots & * \\ 0 & 0 & 0 & 0 & \cdots & 0 & \\ 0 & 0 & 0 & 0 & \cdots & 0 & \end{bmatrix} = \begin{bmatrix} I_n & F \\ 0 & 0 \end{bmatrix}$$

This is useful when studying the **null space** of  $A$ , as we will see later in this course.

Row Column Method

Recall that a row vector times a column vector (of the right dimensions) is a scalar. For example,

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

This is the **row column** matrix multiplication method from Section 2.1.

Theorem

Let  $A$  be  $m \times n$  and  $B$  be  $n \times p$  matrix. Then, the  $(i, j)$  entry of  $AB$  is

$$\text{row}_i A \cdot \text{col}_j B.$$

This is the **Row Column Method** for matrix multiplication.

Partitioned matrices can be multiplied using this method, as if each block were a scalar (provided each block has appropriate dimensions).

Example of Row Column Method

Recall, using our formula for a  $2 \times 2$  matrix,  $\begin{bmatrix} a & b \\ 0 & c \end{bmatrix}^{-1} = \frac{1}{ac} \begin{bmatrix} c & -b \\ 0 & a \end{bmatrix}$ .

**Example:** Suppose  $A \in \mathbb{R}^{n \times n}$ ,  $B \in \mathbb{R}^{n \times n}$ , and  $C \in \mathbb{R}^{n \times n}$  are invertible matrices. Construct the inverse of  $\begin{bmatrix} A & B \\ 0 & C \end{bmatrix}$ .

21. a. Verify that  $A^2 = I$  when  $A = \begin{bmatrix} 1 & 0 \\ 3 & -1 \end{bmatrix}$ .  
b. Use partitioned matrices to show that  $M^2 = I$  when

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

$$6. \begin{bmatrix} X & 0 \\ Y & Z \end{bmatrix} \begin{bmatrix} A & 0 \\ B & C \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix}$$

## The Column Row Method (if time permits)

A column vector times a row vector is a matrix. For example,

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

### Theorem

Let  $A$  be  $m \times n$  and  $B$  be  $n \times p$  matrix. Then,

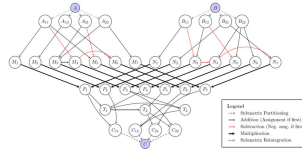
$$AB = \begin{bmatrix} \text{col}_1 A & \cdots & \text{col}_n A \end{bmatrix} \begin{bmatrix} \text{row}_1 B \\ \vdots \\ \text{row}_n B \end{bmatrix} \\ = \underbrace{\text{col}_1 A \text{row}_1 B + \cdots + \text{col}_n A \text{row}_n B}_{m \times p \text{ matrices}}$$

This is the **Column Row Method** for matrix multiplication.

Section 2.4 Slide 127

## The Strassen Algorithm: An impressive use of partitioned matrices

Naive Multiplication of two  $n \times n$  matrices  $A$  and  $B$  requires  $n^3$  arithmetic steps. Strassen's algorithm **partitions** the matrices, makes a very clever sequence of multiplications, additions, to reduce the computation to  $n^{2.803...}$  steps.



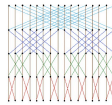
Students aren't expected to be familiar with this material. It's presented to motivate matrix partitioning.

Section 2.4 Slide 128

## The Fast Fourier Transform (FFT)

The FFT is an essential algorithm of modern technology that uses partitioned matrices recursively.

$$G_0 = \begin{bmatrix} 1 \end{bmatrix}, \quad G_{n+1} = \begin{bmatrix} G_n & -G_n \\ G_n & G_n \end{bmatrix}$$



The recursive structure of the matrix means that it can be computed in nearly **linear** time. This is an incredible saving over the general complexity of  $n^3$ . It means that we can compute  $G_n x$ , and  $G_n^{-1}$  very quickly.

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Section 2.4 Slide 129

## 2.4 EXERCISES

In Exercises 1–9, assume that the matrices are partitioned conformably for block multiplication. Compute the products shown in Exercises 1–4.

$$\begin{array}{ll} 1. \begin{bmatrix} I & 0 \\ E & I \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} & 2. \begin{bmatrix} E & 0 \\ 0 & F \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \\ 3. \begin{bmatrix} 0 & I \\ I & 0 \end{bmatrix} \begin{bmatrix} W & X \\ Y & Z \end{bmatrix} & 4. \begin{bmatrix} I & 0 \\ -X & I \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \end{array}$$

In Exercises 5–8, find formulas for  $X$ ,  $Y$ , and  $Z$  in terms of  $A$ ,  $B$ , and  $C$ , and justify your calculations. In some cases, you may need to make assumptions about the size of a matrix in order to produce a formula. [Hint: Compute the product on the left, and set it equal to the right side.]

$$\begin{array}{ll} 5. \begin{bmatrix} A & B \\ C & 0 \end{bmatrix} \begin{bmatrix} I & 0 \\ X & Y \end{bmatrix} = \begin{bmatrix} 0 & I \\ Z & 0 \end{bmatrix} & 6. \begin{bmatrix} X & 0 \\ Y & Z \end{bmatrix} \begin{bmatrix} A & 0 \\ B & C \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} \\ 7. \begin{bmatrix} X & 0 & 0 \\ Y & 0 & I \end{bmatrix} \begin{bmatrix} A & Z \\ 0 & 0 \\ B & I \end{bmatrix} = \begin{bmatrix} I & 0 \\ 0 & I \end{bmatrix} & 8. \begin{bmatrix} A & B \\ 0 & I \end{bmatrix} \begin{bmatrix} X & Y & Z \\ 0 & 0 & I \end{bmatrix} = \begin{bmatrix} I & 0 & 0 \\ 0 & 0 & I \end{bmatrix} \end{array}$$

9. Suppose  $A_{11}$  is an invertible matrix. Find matrices  $X$  and  $Y$  such that the product below has the form indicated. Also, compute  $B_{22}$ . [Hint: Compute the product on the left, and set it equal to the right side.]

$$\begin{bmatrix} I & 0 & 0 \\ X & I & 0 \\ Y & 0 & I \end{bmatrix} \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \\ A_{31} & A_{32} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} \\ 0 & B_{22} \\ 0 & B_{32} \end{bmatrix}$$

10. The inverse of  $\begin{bmatrix} I & 0 & 0 \\ C & I & 0 \\ A & B & I \end{bmatrix}$  is  $\begin{bmatrix} I & 0 & 0 \\ Z & I & 0 \\ X & Y & I \end{bmatrix}$ . Find  $X$ ,  $Y$ , and  $Z$ .

In Exercises 11 and 12, mark each statement True or False. Justify each answer.

11. a. If  $A = \begin{bmatrix} A_1 & A_2 \end{bmatrix}$  and  $B = \begin{bmatrix} B_1 & B_2 \end{bmatrix}$ , with  $A_1$  and  $A_2$  the same sizes as  $B_1$  and  $B_2$ , respectively, then  $A + B = \begin{bmatrix} A_1 + B_1 & A_2 + B_2 \end{bmatrix}$ .

b. If  $A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}$  and  $B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix}$ , then the partitions of  $A$  and  $B$  are conformable for block multiplication.

12. a. The definition of the matrix–vector product  $Ax$  is a special case of block multiplication.

b. If  $A_1$ ,  $A_2$ ,  $B_1$ , and  $B_2$  are  $n \times n$  matrices,  $A = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix}$ , and  $B = \begin{bmatrix} B_1 & B_2 \end{bmatrix}$ , then the product  $BA$  is defined, but  $AB$  is not.

13. Let  $A = \begin{bmatrix} B & 0 \\ 0 & C \end{bmatrix}$ , where  $B$  and  $C$  are square. Show that  $A$  is invertible if and only if both  $B$  and  $C$  are invertible.

14. Show that the block upper triangular matrix  $A$  in Example 5 is invertible if and only if both  $A_{11}$  and  $A_{22}$  are invertible. [Hint: If  $A_{11}$  and  $A_{22}$  are invertible, the formula for  $A^{-1}$  given in Example 5 actually works as the inverse of  $A$ .] This fact about  $A$  is an important part of several computer algorithms that estimate eigenvalues of matrices. Eigenvalues are discussed in Chapter 5.

15. Suppose  $A_{11}$  is invertible. Find  $X$  and  $Y$  such that

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} = \begin{bmatrix} I & 0 \\ X & I \end{bmatrix} \begin{bmatrix} A_{11} & 0 \\ 0 & S \end{bmatrix} \begin{bmatrix} I & Y \\ 0 & I \end{bmatrix} \quad (7)$$

where  $S = A_{22} - A_{21}A_{11}^{-1}A_{12}$ . The matrix  $S$  is called the **Schur complement** of  $A_{11}$ . Likewise, if  $A_{22}$  is invertible, the matrix  $A_{11} - A_{12}A_{22}^{-1}A_{21}$  is called the Schur complement of  $A_{22}$ . Such expressions occur frequently in the theory of systems engineering, and elsewhere.

16. Suppose the block matrix  $A$  on the left side of (7) is invertible and  $A_{11}$  is invertible. Show that the Schur complement  $S$  of  $A_{11}$  is invertible. [Hint: The outside factors on the right side of (7) are always invertible. Verify this.] When  $A$  and  $A_{11}$  are both invertible, (7) leads to a formula for  $A^{-1}$ , using  $S^{-1}$ ,  $A_{11}^{-1}$ , and the other entries in  $A$ .

## Section 2.5 : Matrix Factorizations

Chapter 2 : Matrix Algebra

Math 1554 Linear Algebra

*"Mathematical reasoning may be regarded rather schematically as the exercise of a combination of two facilities, which we may call intuition and ingenuity." - Alan Turing*

The use of the LU Decomposition to solve linear systems was one of the areas of mathematics that Turing helped develop.

## Topics and Objectives

### Topics

We will cover these topics in this section.

1. The  $LU$  factorization of a matrix
2. Using the  $LU$  factorization to solve a system
3. Why the  $LU$  factorization works

### Objectives

For the topics covered in this section, students are expected to be able to do the following.

1. Compute an  $LU$  factorization of a matrix.
2. Apply the  $LU$  factorization to solve systems of equations.
3. Determine whether a matrix has an  $LU$  factorization.

## Section 2.5 : Matrix Factorizations

Chapter 2 : Matrix Algebra  
Math 1554 Linear Algebra

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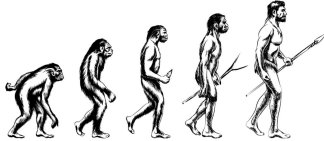
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For the topics covered in this section, students are expected to be able to do the following.

1. Compute an  $LU$  factorization of a matrix.
2. Apply the  $LU$  factorization to solve systems of equations.
3. Determine whether a matrix has an  $LU$  factorization.

Section 2.5 Slide 100

Section 2.5 Slide 131



In the beginning, ...

with **integers** there were \*prime\* factorizations...

then came the \***polynomial**\* factorizations...

until finally, ...

**\*\*matrix\*\*** factorizations appeared!

### Motivation

- Recall that we could solve  $A\vec{x} = \vec{b}$  by using  $\vec{x} = A^{-1}\vec{b}$
- This requires computation of the inverse of an  $n \times n$  matrix, which is especially difficult for large  $n$ .
- Instead we could solve  $A\vec{x} = \vec{b}$  with Gaussian Elimination, but this is not efficient for large  $n$ .
- There are more efficient and accurate methods for solving linear systems that rely on matrix factorizations.

Section 2.5 Slide 132

### Matrix Factorizations

- A **matrix factorization**, or **matrix decomposition** is a factorization of a matrix into a product of matrices.
- Factorizations can be useful for solving  $A\vec{x} = \vec{b}$ , or understanding the properties of a matrix.
- We explore a few matrix factorizations throughout this course.
- In this section, we factor a matrix into **lower** and into **upper** triangular matrices.

Section 2.5 Slide 133



Triangular Matrices

- A rectangular matrix  $A$  is **upper triangular** if  $a_{i,j} = 0$  for  $i > j$ .  
Examples:

$$\begin{pmatrix} 1 & 5 & 0 \\ 0 & 2 & 4 \end{pmatrix}, \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 2 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 2 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

- A rectangular matrix  $A$  is **lower triangular** if  $a_{i,j} = 0$  for  $i < j$ .  
Examples:

$$\begin{pmatrix} 1 & 0 & 0 \\ 3 & 2 & 0 \end{pmatrix}, \begin{pmatrix} 3 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 2 & 0 & 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 2 \\ 1 \\ 2 \end{pmatrix}$$

Ask: Can you name a matrix that is both upper and lower triangular?

The LU Factorization

Theorem

If  $A$  is an  $m \times n$  matrix that can be row reduced to echelon form without row exchanges, then  $A = LU$ .  $L$  is a lower triangular  $m \times m$  matrix with 1's on the diagonal,  $U$  is an echelon form of  $A$ .

Example: If  $A \in \mathbb{R}^{3 \times 2}$ , the LU factorization has the form:

$$A = LU = \begin{pmatrix} 1 & 0 & 0 \\ * & 1 & 0 \\ * & * & 1 \end{pmatrix} \begin{pmatrix} * & * \\ 0 & * \\ 0 & 0 \end{pmatrix}$$

Why We Can Compute the LU Factorization

Suppose  $A$  can be row reduced to echelon form  $U$  without interchanging rows. Then,

$$E_p \cdots E_1 A = U$$

where the  $E_j$  are matrices that perform elementary row operations. They happen to be lower triangular and invertible, e.g.

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

Therefore,

$$A = \underbrace{E_1^{-1} \cdots E_p^{-1}}_{=L} U = LU.$$

Using the LU Decomposition

Goal: given  $A$  and  $\vec{b}$ , solve  $A\vec{x} = \vec{b}$  for  $\vec{x}$ .

Algorithm: construct  $A = LU$ , solve  $A\vec{x} = LU\vec{x} = \vec{b}$  by:

- Forward solve for  $\vec{y}$  in  $L\vec{y} = \vec{b}$ .
- Backwards solve for  $\vec{x}$  in  $U\vec{x} = \vec{y}$ .

Example: Solve the linear system whose LU decomposition is given.

$$A = LU = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 2 & 1 & 0 \\ 0 & -1 & -1 & 1 \end{pmatrix} \begin{pmatrix} 1 & 1 & 0 \\ 0 & -1 & -1 \\ 0 & 0 & 2 \\ 0 & 0 & 0 \end{pmatrix}, \quad \vec{b} = \begin{pmatrix} 16 \\ 2 \\ -4 \\ 6 \end{pmatrix}$$

## An Algorithm for Computing LU

To compute the LU decomposition:

1. Reduce  $A$  to an echelon form  $U$  by a sequence of row replacement operations, if possible.
2. Place entries in  $L$  such that the same sequence of row operations reduces  $L$  to  $I$ .

Note that

- In MATH 1554, the only row replacement operation we can use is to *replace a row with a multiple of a row above it*.
- More advanced linear algebra courses address this limitation.

**Example:** Compute the  $LU$  factorization of  $A$ .

$$A = \begin{pmatrix} 4 & -3 & -1 & 5 \\ -16 & 12 & 2 & -17 \\ 8 & -6 & -12 & 22 \end{pmatrix}$$

## Another Explanation for How to Construct L

First compute the echelon form  $U$  of  $A$ . Highlight the entries that determine the sequence of row operations used to arrive at  $U$ .

$$A = \begin{bmatrix} 4 & -3 & -1 & 5 \\ -16 & 12 & 2 & -17 \\ 8 & -6 & -12 & 22 \end{bmatrix} \sim \begin{bmatrix} 4 & -3 & -1 & 5 \\ 0 & 12 & -12 & -5 \\ 0 & 12 & -12 & -5 \end{bmatrix} = A_1$$

$$\sim A_2 = \begin{bmatrix} 4 & -3 & -1 & 5 \\ 0 & 12 & -12 & -5 \\ 0 & 0 & 0 & 0 \end{bmatrix} \sim \begin{bmatrix} 4 & -3 & -1 & 5 \\ 0 & 12 & -12 & -5 \\ 0 & 0 & 0 & 0 \end{bmatrix} = U$$

The highlighted entries describe the row reduction of  $A$ . For each highlighted pivot column, divide entries by the pivot and place the result into  $L$ .

$$\begin{bmatrix} 4 & -3 & -1 & 5 \\ -16 & 12 & 2 & -17 \\ 8 & -6 & -12 & 22 \end{bmatrix} \sim \begin{bmatrix} 1 & -3/4 & -1/4 & 5/4 \\ 0 & 12 & -12 & -5 \\ 0 & 12 & -12 & -5 \end{bmatrix} \sim \begin{bmatrix} 1 & -3/4 & -1/4 & 5/4 \\ 0 & 1 & -1 & -5/12 \\ 0 & 1 & -1 & -5/12 \end{bmatrix}$$

$$\text{and } L = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -1/4 & 1 & 0 & 0 \\ -1/2 & -1 & 1 & 0 \end{bmatrix}$$

## Summary

- To solve  $A\vec{x} = LU\vec{x} = \vec{b}$ ,
  1. Forward solve for  $\vec{y}$  in  $L\vec{y} = \vec{b}$ .
  2. Backwards solve for  $\vec{x}$  in  $U\vec{x} = \vec{y}$ .
- To compute the LU decomposition:
  1. Reduce  $A$  to an echelon form  $U$  by a sequence of row replacement operations, if possible.
  2. Place entries in  $L$  such that the same sequence of row operations reduces  $L$  to  $I$ .
- The textbook offers a different explanation of how to construct the LU decomposition that students may find helpful.
- Another explanation on how to calculate the LU decomposition that students may find helpful is available from MIT OpenCourseWare: [www.youtube.com/watch?v=rhNKncraJMK](http://www.youtube.com/watch?v=rhNKncraJMK)

## Additional Example (if time permits)

Construct the LU decomposition of  $A$ .

$$A = \begin{pmatrix} 3 & -1 & 4 \\ 9 & -5 & 15 \\ 15 & -1 & 10 \\ -6 & 2 & -4 \end{pmatrix}$$

## 2.5 EXERCISES

In Exercises 1–6, solve the equation  $Ax = b$  by using the LU factorization given for  $A$ . In Exercises 1 and 2, also solve  $Ax = b$  by ordinary row reduction.

$$1. A = \begin{bmatrix} 3 & -7 & -2 \\ -3 & 5 & 1 \\ 6 & -4 & 0 \end{bmatrix}, b = \begin{bmatrix} -7 \\ 5 \\ 2 \end{bmatrix}$$

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

$$2. A = \begin{bmatrix} 4 & 3 & -5 \\ -4 & -5 & 7 \\ 8 & 6 & -8 \end{bmatrix}, b = \begin{bmatrix} 2 \\ -4 \\ 6 \end{bmatrix}$$

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

$$3. A = \begin{bmatrix} 2 & -1 & 2 \\ -6 & 0 & -2 \\ 8 & -1 & 5 \end{bmatrix}, b = \begin{bmatrix} 1 \\ 0 \\ 4 \end{bmatrix}$$

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

$$4. A = \begin{bmatrix} 2 & -2 & 4 \\ 1 & -3 & 1 \\ 3 & 7 & 5 \end{bmatrix}, b = \begin{bmatrix} 0 \\ -5 \\ 7 \end{bmatrix}$$

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 1/2 & 1 & 0 \\ 3/2 & -5 & 1 \end{bmatrix} \begin{bmatrix} 2 & -2 & 4 \\ 0 & -2 & -1 \\ 0 & 0 & -6 \end{bmatrix}$$

$$5. A = \begin{bmatrix} 1 & -2 & -4 & -3 \\ 2 & -7 & -7 & -6 \\ -1 & 2 & 6 & 4 \\ -4 & -1 & 9 & 8 \end{bmatrix}, b = \begin{bmatrix} 1 \\ 7 \\ 0 \\ 3 \end{bmatrix}$$

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

$$6. A = \begin{bmatrix} 1 & 3 & 4 & 0 \\ -3 & -6 & -7 & 2 \\ 3 & 3 & 0 & -4 \\ -5 & -3 & 2 & 9 \end{bmatrix}, b = \begin{bmatrix} 1 \\ -2 \\ -1 \\ 2 \end{bmatrix}$$

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

Find an LU factorization of the matrices in Exercises 7–16 (with  $L$  unit lower triangular). Note that MATLAB will usually produce a permuted LU factorization because it uses partial pivoting for numerical accuracy.

$$7. \begin{bmatrix} 2 & 5 \\ -3 & -4 \end{bmatrix}$$

$$8. \begin{bmatrix} 6 & 9 \\ 4 & 5 \end{bmatrix}$$

$$9. \begin{bmatrix} 3 & -1 & 2 \\ -3 & -2 & 10 \\ 9 & -5 & 6 \end{bmatrix}$$

$$10. \begin{bmatrix} -5 & 3 & 4 \\ 10 & -8 & -9 \\ 15 & 1 & 2 \end{bmatrix}$$

$$11. \begin{bmatrix} 3 & -6 & 3 \\ 6 & -7 & 2 \\ -1 & 7 & 0 \end{bmatrix}$$

$$12. \begin{bmatrix} 2 & -4 & 2 \\ 1 & 5 & -4 \\ -6 & -2 & 4 \end{bmatrix}$$

$$13. \begin{bmatrix} 1 & 3 & -5 & -3 \\ -1 & -5 & 8 & 4 \\ 4 & 2 & -5 & -7 \\ -2 & -4 & 7 & 5 \end{bmatrix}$$

$$14. \begin{bmatrix} 1 & 4 & -1 & 5 \\ 3 & 7 & -2 & 9 \\ -2 & -3 & 1 & -4 \\ -1 & 6 & -1 & 7 \end{bmatrix}$$

$$15. \begin{bmatrix} 2 & -4 & 4 & -2 \\ 6 & -9 & 7 & -3 \\ -1 & -4 & 8 & 0 \end{bmatrix}$$

$$16. \begin{bmatrix} 2 & -6 & 6 \\ -4 & 5 & -7 \\ 3 & 5 & -1 \\ -6 & 4 & -8 \\ 8 & -3 & 9 \end{bmatrix}$$

17. When  $A$  is invertible, MATLAB finds  $A^{-1}$  by factoring  $A = LU$  (where  $L$  may be permuted lower triangular), inverting  $L$  and  $U$ , and then computing  $U^{-1}L^{-1}$ . Use this method to compute the inverse of  $A$  in Exercise 2. (Apply the algorithm of Section 2.2 to  $L$  and to  $U$ .)

18. Find  $A^{-1}$  as in Exercise 17, using  $A$  from Exercise 3.

## Section 2.8 : Subspaces of $\mathbb{R}^n$

Chapter 2 : Matrix Algebra

Math 1554 Linear Algebra

## Topics and Objectives

### Topics

We will cover these topics in this section.

1. Subspaces, Column space, and Null spaces
2. A basis for a subspace.

### Objectives

For the topics covered in this section, students are expected to be able to do the following.

1. Determine whether a set is a subspace.
2. Determine whether a vector is in a particular subspace, or find a vector in that subspace.
3. Construct a basis for a subspace (for example, a basis for  $\text{Col}(A)$ )

### Motivating Question

Given a matrix  $A$ , what is the set of vectors  $\vec{b}$  for which we can solve  $A\vec{x} = \vec{b}$ ?

5	9/18 - 9/22	2.3,2.4	WS2.2.2.3	2.5	WS2.4.2.5	2.8
6	9/25 - 9/29	2.9	WS2.8.2.9	3.1.3.2	WS3.1.3.2	3.3
7	10/2 - 10/6	4.9	WS3.3.4.9	5.1.5.2	WS5.1.5.2	5.2
8	10/9 - 10/13	Break	Break	Exam 2, Review	Cancelled	5.3

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## Section 2.8 : Subspaces of $\mathbb{R}^n$

Chapter 2 : Matrix Algebra

Math 1554 Linear Algebra

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## Subsets of $\mathbb{R}^n$

### Definition

A subset of  $\mathbb{R}^n$  is any collection of vectors that are in  $\mathbb{R}^n$ .

Section 2.8 Page 101

## Subspaces in $\mathbb{R}^n$

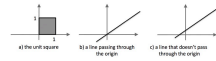
### Definition

A subset  $H$  of  $\mathbb{R}^n$  is a subspace if it is closed under scalar multiples and vector addition. That is: for any  $c \in \mathbb{R}$  and for  $\vec{u}, \vec{v} \in H$ ,

1.  $c\vec{u} \in H$
2.  $\vec{u} + \vec{v} \in H$

Note that condition 1 implies that the zero vector must be in  $H$ .

**Example 1.** Which of the following subsets could be a subspace of  $\mathbb{R}^2$ ?



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## Definition

A subset of  $\mathbb{R}^n$  is any collection of vectors that are in  $\mathbb{R}^n$ .

e.g.,

\*three vectors

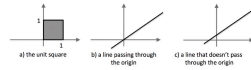
## Definition

A subset  $H$  of  $\mathbb{R}^n$  is a **subspace** if it is closed under scalar multiples and vector addition. That is: for any  $c \in \mathbb{R}$  and for  $\vec{u}, \vec{v} \in H$ ,

1.  $c\vec{u} \in H$
2.  $\vec{u} + \vec{v} \in H$

Note that condition 1 implies that the zero vector must be in  $H$ .

**Example 1:** Which of the following subsets could be a subspace of  $\mathbb{R}^2$ ?



\*the span of three vectors

\*the set containing only  
the zero vector

\*all vectors in  $\mathbb{R}^2$  that  
are either on the x-axis or  
on the y-axis

The Column Space and the Null Space of a Matrix

Recall: for  $\vec{v}_1, \dots, \vec{v}_p \in \mathbb{R}^n$ , that  $\text{Span}\{\vec{v}_1, \dots, \vec{v}_p\}$  is:

This is a **subspace**, spanned by  $\vec{v}_1, \dots, \vec{v}_p$ .

Definition

Given an  $m \times n$  matrix  $A = [\vec{a}_1 \ \cdots \ \vec{a}_n]$

- 1. The **column space of  $A$** ,  $\text{Col } A$ , is the subspace of  $\mathbb{R}^m$  spanned by  $\vec{a}_1, \dots, \vec{a}_n$ .
- 2. The **null space of  $A$** ,  $\text{Null } A$ , is the subspace of  $\mathbb{R}^n$  spanned by the set of all vectors  $\vec{x}$  that solve  $A\vec{x} = \vec{0}$ .

Example

Is  $\vec{v}$  in the column space of  $A$ ?

$$A = \begin{bmatrix} 1 & -3 & -4 \\ -4 & 6 & -2 \\ -3 & 7 & 6 \end{bmatrix} \sim \begin{bmatrix} 1 & -3 & -4 \\ 0 & -6 & -18 \\ 0 & 0 & 0 \end{bmatrix}, \quad \vec{b} = \begin{pmatrix} 3 \\ 3 \\ -4 \end{pmatrix}$$

Example 2 (continued)

Using the matrix on the previous slide: is  $\vec{v}$  in the null space of  $A$ ?

$$\vec{v} = \begin{pmatrix} -3\lambda \\ -3\lambda \\ \lambda \end{pmatrix}, \quad \lambda \in \mathbb{R}$$



Definition

A **basis** for a subspace  $H$  is a set of linearly independent vectors in  $H$  that span  $H$ .

Example

The set  $H = \left\{ \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} \in \mathbb{R}^4 \mid x_1 + 2x_2 + x_3 + 5x_4 = 0 \right\}$  is a subspace.

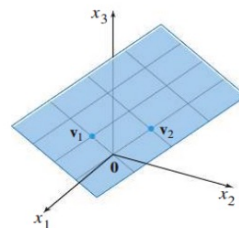
- a)  $H$  is a null space for what matrix  $A$ ?
- b) Construct a basis for  $H$ .

Construct a basis for  $\text{Null}A$  and a basis for  $\text{Col}A$ .

$$A = \begin{bmatrix} -3 & 6 & -1 & 1 & -7 \\ 1 & -2 & 2 & 3 & -1 \\ 2 & -4 & 5 & 8 & -4 \end{bmatrix} \sim \begin{bmatrix} 1 & -2 & 0 & -1 & 3 \\ 0 & 0 & 1 & 2 & -2 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

A **subspace** of  $\mathbb{R}^n$  is any set  $H$  in  $\mathbb{R}^n$  that has three properties:

- The zero vector is in  $H$ .
- For each  $\mathbf{u}$  and  $\mathbf{v}$  in  $H$ , the sum  $\mathbf{u} + \mathbf{v}$  is in  $H$ .
- For each  $\mathbf{u}$  in  $H$  and each scalar  $c$ , the vector  $c\mathbf{u}$  is in  $H$ .



**FIGURE 1**  
Span  $\{\mathbf{v}_1, \mathbf{v}_2\}$  as a plane through the origin.

**Theorem**

The pivotal columns of a matrix  $A$  form a basis for the Column space of  $A$ .

Use the pivotal columns of  $A$ , not the pivotal columns of the Echelon form.

**Theorem**

Suppose that the matrix  $A$  has reduced echelon form  $\begin{bmatrix} I & F \\ 0 & 0 \end{bmatrix}$ , in block matrix form. Then a basis of the Null space of  $A$  is given by the columns of  $\begin{bmatrix} F \\ -I \end{bmatrix}$ .

The assumption says that the first few columns are pivotal, and the last few are all free. This can be assumed, after the exchange of columns.

**Additional Example (if time permits)**

Let  $V = \left\{ \begin{pmatrix} a \\ b \end{pmatrix} \in \mathbb{R}^2 \mid ab = 0 \right\}$ . Is  $V$  a subspace?

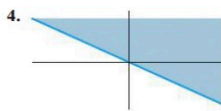
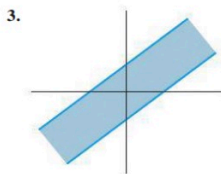
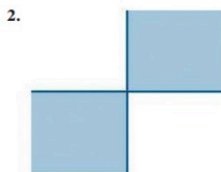
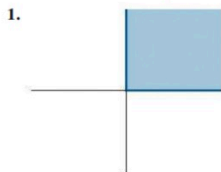
**EXAMPLE 6** Find a basis for the null space of the matrix

$$A = \begin{bmatrix} -3 & 6 & -1 & 1 & -7 \\ 1 & -2 & 2 & 3 & -1 \\ 2 & -4 & 5 & 8 & -4 \end{bmatrix}$$

$$[A \ 0] \sim \begin{bmatrix} 0 & 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 2 & -2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad \begin{aligned} x_4 + 2x_5 &= 0 \\ x_3 - 2x_5 &= 0 \\ 0 &= 0 \end{aligned}$$

## 2.8 EXERCISES

Exercises 1–4 display sets in  $\mathbb{R}^2$ . Assume the sets include the bounding lines. In each case, give a specific reason why the set  $H$  is *not* a subspace of  $\mathbb{R}^2$ . (For instance, find two vectors in  $H$  whose sum is *not* in  $H$ , or find a vector in  $H$  with a scalar multiple that is *not* in  $H$ . Draw a picture.)



5. Let  $\mathbf{v}_1 = \begin{bmatrix} 2 \\ 3 \\ -5 \end{bmatrix}$ ,  $\mathbf{v}_2 = \begin{bmatrix} -4 \\ -5 \\ 8 \end{bmatrix}$ , and  $\mathbf{w} = \begin{bmatrix} 8 \\ 2 \\ -9 \end{bmatrix}$ . Determine if  $\mathbf{w}$  is in the subspace of  $\mathbb{R}^3$  generated by  $\mathbf{v}_1$  and  $\mathbf{v}_2$ .

6. Let  $\mathbf{v}_1 = \begin{bmatrix} 1 \\ -2 \\ 4 \\ 3 \end{bmatrix}$ ,  $\mathbf{v}_2 = \begin{bmatrix} 4 \\ -7 \\ 9 \\ 7 \end{bmatrix}$ ,  $\mathbf{v}_3 = \begin{bmatrix} 5 \\ -8 \\ 6 \\ 5 \end{bmatrix}$ , and  $\mathbf{u} = \begin{bmatrix} -4 \\ 10 \\ -7 \\ -5 \end{bmatrix}$ . Determine if  $\mathbf{u}$  is in the subspace of  $\mathbb{R}^4$  generated by  $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3\}$ .

7. Let  $\mathbf{v}_1 = \begin{bmatrix} 2 \\ -8 \\ 6 \end{bmatrix}$ ,  $\mathbf{v}_2 = \begin{bmatrix} -3 \\ 8 \\ -7 \end{bmatrix}$ ,  $\mathbf{v}_3 = \begin{bmatrix} -4 \\ 6 \\ -7 \end{bmatrix}$ ,

$\mathbf{p} = \begin{bmatrix} 6 \\ -10 \\ 11 \end{bmatrix}$ , and  $A = [\mathbf{v}_1 \ \mathbf{v}_2 \ \mathbf{v}_3]$ .

- How many vectors are in  $\{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3\}$ ?
- How many vectors are in  $\text{Col } A$ ?
- Is  $\mathbf{p}$  in  $\text{Col } A$ ? Why or why not?

8. Let  $\mathbf{v}_1 = \begin{bmatrix} -3 \\ 0 \\ 6 \end{bmatrix}$ ,  $\mathbf{v}_2 = \begin{bmatrix} -2 \\ 2 \\ 3 \end{bmatrix}$ ,  $\mathbf{v}_3 = \begin{bmatrix} 0 \\ -6 \\ 3 \end{bmatrix}$ , and  $\mathbf{p} = \begin{bmatrix} 1 \\ 14 \\ -9 \end{bmatrix}$ . Determine if  $\mathbf{p}$  is in  $\text{Col } A$ , where  $A = [\mathbf{v}_1 \ \mathbf{v}_2 \ \mathbf{v}_3]$ .

9. With  $A$  and  $\mathbf{p}$  as in Exercise 7, determine if  $\mathbf{p}$  is in  $\text{Nul } A$ .
10. With  $\mathbf{u} = (-2, 3, 1)$  and  $A$  as in Exercise 8, determine if  $\mathbf{u}$  is in  $\text{Nul } A$ .

In Exercises 11 and 12, give integers  $p$  and  $q$  such that  $\text{Nul } A$  is a subspace of  $\mathbb{R}^p$  and  $\text{Col } A$  is a subspace of  $\mathbb{R}^q$ .

11.  $A = \begin{bmatrix} 3 & 2 & 1 & -5 \\ -9 & -4 & 1 & 7 \\ 9 & 2 & -5 & 1 \end{bmatrix}$

12.  $A = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 7 \\ -5 & -1 & 0 \\ 2 & 7 & 11 \end{bmatrix}$

13. For  $A$  as in Exercise 11, find a nonzero vector in  $\text{Nul } A$  and a nonzero vector in  $\text{Col } A$ .
14. For  $A$  as in Exercise 12, find a nonzero vector in  $\text{Nul } A$  and a nonzero vector in  $\text{Col } A$ .

Determine which sets in Exercises 15–20 are bases for  $\mathbb{R}^2$  or  $\mathbb{R}^3$ . Justify each answer.

15.  $\begin{bmatrix} 5 \\ -2 \end{bmatrix}, \begin{bmatrix} 10 \\ -3 \end{bmatrix}$

16.  $\begin{bmatrix} -4 \\ 6 \end{bmatrix}, \begin{bmatrix} 2 \\ -3 \end{bmatrix}$

17.  $\begin{bmatrix} 0 \\ 1 \\ -2 \end{bmatrix}, \begin{bmatrix} 5 \\ -7 \\ 4 \end{bmatrix}, \begin{bmatrix} 6 \\ 3 \\ 5 \end{bmatrix}$

18.  $\begin{bmatrix} 1 \\ 1 \\ -2 \end{bmatrix}, \begin{bmatrix} -5 \\ -1 \\ 2 \end{bmatrix}, \begin{bmatrix} 7 \\ 0 \\ -5 \end{bmatrix}$

19.  $\begin{bmatrix} 3 \\ -8 \\ 1 \end{bmatrix}, \begin{bmatrix} 6 \\ 2 \\ -5 \end{bmatrix}$

20.  $\begin{bmatrix} 1 \\ -6 \\ -7 \end{bmatrix}, \begin{bmatrix} 3 \\ -4 \\ 7 \end{bmatrix}, \begin{bmatrix} -2 \\ 7 \\ 5 \end{bmatrix}, \begin{bmatrix} 0 \\ 8 \\ 9 \end{bmatrix}$

In Exercises 21 and 22, mark each statement True or False. Justify each answer.

21. a. A subspace of  $\mathbb{R}^n$  is any set  $H$  such that (i) the zero vector is in  $H$ , (ii)  $u, v$ , and  $u + v$  are in  $H$ , and (iii)  $c$  is a scalar and  $cu$  is in  $H$ .  
 b. If  $v_1, \dots, v_p$  are in  $\mathbb{R}^n$ , then  $\text{Span}\{v_1, \dots, v_p\}$  is the same as the column space of the matrix  $[v_1 \ \dots \ v_p]$ .  
 c. The set of all solutions of a system of  $m$  homogeneous equations in  $n$  unknowns is a subspace of  $\mathbb{R}^n$ .  
 d. The columns of an invertible  $n \times n$  matrix form a basis for  $\mathbb{R}^n$ .  
 e. Row operations do not affect linear dependence relations among the columns of a matrix.
22. a. A subset  $H$  of  $\mathbb{R}^n$  is a subspace if the zero vector is in  $H$ .  
 b. Given vectors  $v_1, \dots, v_p$  in  $\mathbb{R}^n$ , the set of all linear combinations of these vectors is a subspace of  $\mathbb{R}^n$ .  
 c. The null space of an  $m \times n$  matrix is a subspace of  $\mathbb{R}^n$ .  
 d. The column space of a matrix  $A$  is the set of solutions of  $Ax = b$ .  
 e. If  $B$  is an echelon form of a matrix  $A$ , then the pivot columns of  $B$  form a basis for  $\text{Col } A$ .

Exercises 23–26 display a matrix  $A$  and an echelon form of  $A$ . Find a basis for  $\text{Col } A$  and a basis for  $\text{Nul } A$ .

$$23. A = \begin{bmatrix} 4 & 5 & 9 & -2 \\ 6 & 5 & 1 & 12 \\ 3 & 4 & 8 & -3 \end{bmatrix} \sim \begin{bmatrix} 1 & 2 & 6 & -5 \\ 0 & 1 & 5 & -6 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$24. A = \begin{bmatrix} -3 & 9 & -2 & -7 \\ 2 & -6 & 4 & 8 \\ 3 & -9 & -2 & 2 \end{bmatrix} \sim \begin{bmatrix} 1 & -3 & 6 & 9 \\ 0 & 0 & 4 & 5 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$25. A = \begin{bmatrix} 1 & 4 & 8 & -3 & -7 \\ -1 & 2 & 7 & 3 & 4 \\ -2 & 2 & 9 & 5 & 5 \\ 3 & 6 & 9 & -5 & -2 \end{bmatrix} \sim \begin{bmatrix} 1 & 4 & 8 & 0 & 5 \\ 0 & 2 & 5 & 0 & -1 \\ 0 & 0 & 0 & 1 & 4 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$26. A = \begin{bmatrix} 3 & -1 & 7 & 3 & 9 \\ -2 & 2 & -2 & 7 & 5 \\ -5 & 9 & 3 & 3 & 4 \\ -2 & 6 & 6 & 3 & 7 \end{bmatrix} \sim \begin{bmatrix} 3 & -1 & 7 & 0 & 6 \\ 0 & 2 & 4 & 0 & 3 \\ 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

27. Construct a nonzero  $3 \times 3$  matrix  $A$  and a nonzero vector  $b$  such that  $b$  is in  $\text{Col } A$ , but  $b$  is not the same as any one of the columns of  $A$ .  
 28. Construct a nonzero  $3 \times 3$  matrix  $A$  and a vector  $b$  such that  $b$  is not in  $\text{Col } A$ .  
 29. Construct a nonzero  $3 \times 3$  matrix  $A$  and a nonzero vector  $b$  such that  $b$  is in  $\text{Nul } A$ .  
 30. Suppose the columns of a matrix  $A = [a_1 \ \dots \ a_p]$  are linearly independent. Explain why  $\{a_1, \dots, a_p\}$  is a basis for  $\text{Col } A$ .

In Exercises 31–36, respond as comprehensively as possible, and justify your answer.

31. Suppose  $F$  is a  $5 \times 5$  matrix whose column space is not equal to  $\mathbb{R}^5$ . What can you say about  $\text{Nul } F$ ?  
 32. If  $R$  is a  $6 \times 6$  matrix and  $\text{Nul } R$  is not the zero subspace, what can you say about  $\text{Col } R$ ?  
 33. If  $Q$  is a  $4 \times 4$  matrix and  $\text{Col } Q = \mathbb{R}^4$ , what can you say about solutions of equations of the form  $Qx = b$  for  $b$  in  $\mathbb{R}^4$ ?  
 34. If  $P$  is a  $5 \times 5$  matrix and  $\text{Nul } P$  is the zero subspace, what can you say about solutions of equations of the form  $Px = b$  for  $b$  in  $\mathbb{R}^5$ ?  
 35. What can you say about  $\text{Nul } B$  when  $B$  is a  $5 \times 4$  matrix with linearly independent columns?  
 36. What can you say about the shape of an  $m \times n$  matrix  $A$  when the columns of  $A$  form a basis for  $\mathbb{R}^m$ ?

[M] In Exercises 37 and 38, construct bases for the column space and the null space of the given matrix  $A$ . Justify your work.

$$37. A = \begin{bmatrix} 3 & -5 & 0 & -1 & 3 \\ -7 & 9 & -4 & 9 & -11 \\ -5 & 7 & -2 & 5 & -7 \\ 3 & -7 & -3 & 4 & 0 \end{bmatrix}$$

$$38. A = \begin{bmatrix} 5 & 2 & 0 & -8 & -8 \\ 4 & 1 & 2 & -8 & -9 \\ 5 & 1 & 3 & 5 & 19 \\ -8 & -5 & 6 & 8 & 5 \end{bmatrix}$$

**WEB** Column Space and Null Space

**WEB** A Basis for  $\text{Col } A$