Gwinnett School of Math, Science, and Technology

Multivariable Calculus Yearlong Notes

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1st Period

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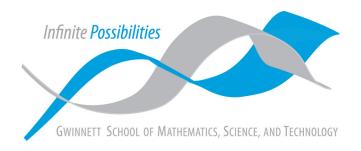## 2023-2024

Infinite Possibilities

GWINNETT SCHOOL OF MATHEMATICS, SCIENCE, AND TECHNOLOGY

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1 Chapter 1: Systems of Linear Equations and Matrices

1.1 Matrix Operations

- Matrix operations are given as: rows x columns
- Two matrices are equal $\iff$ they have the same dimensions and values

1.1.1 Addition & Subtraction

Two matrices can be added/subtracted $\iff$ they have the same dimensions.

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

1.1.2 Scalar Multiplication

- Scalar multiplication is defined as multiplying each element of a matrix by a number

$$3 \begin{bmatrix} 2 & 1 \\ 5 & 2 \end{bmatrix} = \begin{bmatrix} 6 & 3 \\ 15 & 6 \end{bmatrix}$$

1.1.3 Matrix Multiplication

- We can **only** multiply an (m x n) by (n x p) matrix.
- The resulting matrix will be (m x p)

1.1.4 Properties of Matrix Arithmetic

(a) $A + B = B + A$ **(Commutative law for addition)**
(b) $A + (B + C) = (A + B) + C$ **(Associative law for addition)**
(c) $A(BC) = (AB)C$ **(Associative law for multiplication)**
(d) $A(B + C) = AB + AC$ **(Left distributive law)**
(e) $(B + C)A = BA + CA$ **(Right distributive law)**
(f) $A(B - C) = AB - AC$
(g) $(B - C)A = BA - CA$
(h) $a(B+C) = aB + aC$
(i) $a(B-C) = aB - aC$
(j) $(a+b)C = aC + bC$
(k) $(a-b)C = aC - bC$
(l) $a(bC) = (ab)C$
(m) $a(BC) = (aB)C = B(aC)$

1.1.5 Examples

1.

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

$$= \begin{bmatrix} 1\cdot 1 + 2\cdot 3 & 1\cdot 2 + 2\cdot 4 \\ 3\cdot 1 + 4\cdot 3 & 3\cdot 2 + 4\cdot 4 \end{bmatrix}$$

$$= \begin{bmatrix} 7 & 10 \\ 15 & 22 \end{bmatrix}$$

2.

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

$$= \begin{bmatrix} 2\cdot(-1) + (-3)\cdot 3 \\ 5\cdot(-1) + 0\cdot 3 \\ -2\cdot(-1) + 4\cdot 3 \\ 1\cdot(-1) + 2\cdot 3 \end{bmatrix}$$

$$= \begin{bmatrix} -11 \\ -5 \\ 14 \\ 5 \end{bmatrix}$$

3.

$$\begin{bmatrix} 4 & 5 & -1 \end{bmatrix} \begin{bmatrix} 8 \\ 0 \\ 2 \end{bmatrix}$$

$$= \begin{bmatrix} 4 \cdot 8 + 5 \cdot 0 + (-1) \cdot 2 \end{bmatrix}$$

$$= \begin{bmatrix} 30 \end{bmatrix}$$

1.2 Transpose of a Matrix

The transpose of an (m x n) matrix is the (n x m) matrix where the rows and columns are swapped.

If $B = \begin{bmatrix} 4 & 2 \\ -1 & 0 \\ 3 & 5 \end{bmatrix}, B^T = \begin{bmatrix} 4 & -1 & 3 \\ 2 & 0 & 5 \end{bmatrix}$

$$B \cdot B^T = \begin{bmatrix} 4 & 2 \\ -1 & 0 \\ 3 & 5 \end{bmatrix} \begin{bmatrix} 4 & -1 & 3 \\ 2 & 0 & 5 \end{bmatrix}$$

$$= \begin{bmatrix} 4 \cdot 4 + 2 \cdot 2 & 4 \cdot (-1) + 2 \cdot 0 & 4 \cdot 3 + 2 \cdot 5 \\ (-1) \cdot 4 + 0 \cdot 2 & (-1) \cdot (-1) + 0 \cdot 0 & (-1) \cdot 3 + 0 \cdot 5 \\ 3 \cdot 4 + 5 \cdot 2 & 3 \cdot (-1) + 5 \cdot 0 & 3 \cdot 3 + 5 \cdot 5 \end{bmatrix}$$

$$= \begin{bmatrix} 20 & -4 & 22 \\ -4 & 1 & -3 \\ 22 & -3 & 34 \end{bmatrix}$$

- The transpose of a matrix is **always** multiplicative with the original.
- There is also a **main diagonal** that is the diagonal from the top left to the bottom right, but only square matrices have these.
- The **trace** of a square matrix A is equal to the sum of all the elements on the main diagonal: tr(A)

1.2.1 Transpose Matrix Properties

- $(A^T)^T = A$
- $(A + B)^T = A^T + B^T$
- $(A - B)^T = A^T - B^T$
- $(kA)^T = kA^T$
- $(AB)^T = B^T A^T$

1.3 Homework — "Matrix Stuff" (08/03/2023)

1.3.1 Suppose that A, B, C, D and E are matrices with the following sizes:

A	B	C	D	E
(3×2)	(2×3)	(3×3)	(3×2)	(2×3)

For each matrix operation, sort them into undefined if the operation can't be done, or defined if it can along with the correct dimensions of the outcome.

Undefined	Defined; (4×2)	Defined; (5×5)	Defined; (5×2)
BA	$AC + D$	$E(A + B)$	$(A^T + E)D$
$AB + B$			$E(AC)$
$E^T A$			
$AE + B$			

1.3.2 Consider the matrices

$$A = \begin{bmatrix} 3 & 0 \\ -1 & 2 \\ 1 & 1 \end{bmatrix}, B = \begin{bmatrix} 4 & -1 \\ 0 & 2 \end{bmatrix}, C = \begin{bmatrix} 1 & 4 & 2 \\ 3 & 1 & 5 \end{bmatrix}, D = \begin{bmatrix} 1 & 5 & 2 \\ -1 & 0 & 1 \\ 3 & 2 & 4 \end{bmatrix}, E = \begin{bmatrix} 6 & 1 & 3 \\ -1 & 1 & 2 \\ 4 & 1 & 3 \end{bmatrix}$$

In each part, compute the given expression (where possible).

2. **$2A^T + C$**

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

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

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

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

3. $\mathbf{B^T + 5C^T}$

$$B^T + 5C^T = \begin{bmatrix} 4 & -1 \\ 0 & 2 \end{bmatrix}^T + 5\begin{bmatrix} 1 & 4 & 2 \\ 3 & 1 & 5 \end{bmatrix}^T$$

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

$$= \begin{bmatrix} 4 & 0 \\ -1 & 2 \end{bmatrix} + \begin{bmatrix} 5 & 15 \\ 20 & 5 \\ 10 & 25 \end{bmatrix}$$

$$= \text{Undefined}$$

4. $\mathbf{2E^T - 3D^T}$

$$2E^T - 3D^T = 2\begin{bmatrix} 6 & 1 & 3 \\ -1 & 1 & 2 \\ 4 & 1 & 3 \end{bmatrix}^T - 3\begin{bmatrix} 1 & 5 & 2 \\ -1 & 0 & 1 \\ 3 & 2 & 4 \end{bmatrix}^T$$

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

$$= \begin{bmatrix} 12 & -2 & 8 \\ 2 & 2 & 2 \\ 6 & 4 & 6 \end{bmatrix} - \begin{bmatrix} 3 & -3 & 9 \\ 15 & 0 & 6 \\ 6 & 3 & 12 \end{bmatrix}$$

$$= \begin{bmatrix} 9 & -5 & -1 \\ -13 & 2 & -4 \\ 0 & 1 & -6 \end{bmatrix}$$

5. tr($\mathbf{DE}$)

$$\text{tr}(DE) = \text{tr}\left(\begin{bmatrix} 1 & 5 & 2 \\ -1 & 0 & 1 \\ 3 & 2 & 4 \end{bmatrix}\begin{bmatrix} 6 & 1 & 3 \\ -1 & 1 & 2 \\ 4 & 1 & 3 \end{bmatrix}\right)$$

$$= \text{tr}\left(\begin{bmatrix} 1\cdot6+5\cdot(-1)+2\cdot4 & 1\cdot1+5\cdot1+2\cdot1 & 1\cdot3+5\cdot2+2\cdot3 \\ (-1)\cdot6+0\cdot(-1)+1\cdot4 & (-1)\cdot1+0\cdot1+1\cdot1 & (-1)\cdot3+0\cdot2+1\cdot3 \\ 3\cdot6+2\cdot(-1)+4\cdot4 & 3\cdot1+2\cdot1+4\cdot1 & 3\cdot3+2\cdot2+4\cdot3 \end{bmatrix}\right)$$

$$= \text{tr}\left(\begin{bmatrix} 9 & 8 & 19 \\ -2 & 0 & 0 \\ 32 & 9 & 25 \end{bmatrix}\right)$$

$$= 34$$

2 Intro to Systems

What are we looking for?

Lines: How many possible solutions?

- Infinite solutions
- One solution
- No solutions

Planes: How many possible solutions?

- Infinite solutions
- No solutions

What does linear actually mean?

- The word linear *really* means that you've got equations with variables and **all** of the variables are degree one.
- This means that there is no limit to the number of dimensions in a linear system.

Linear Systems in Three Unknowns

No solutions
(three parallel planes;
no common intersection)

No solutions
(two parallel planes;
no common intersection)

No solutions
(no common intersection)

No solutions
(two coincident planes
parallel to the third;
no common intersection)

One solution
(intersection is a point)

Infinitely many solutions
(intersection is a line)

Infinitely many solutions
(planes are all coincident;
intersection is a plane)

Infinitely many solutions
(two coincident planes;
intersection is a line)

2.1 Review: Solve the following systems

1. $\begin{cases} 2x + y = 10 \\ 3x - y = 5 \end{cases}$

$$5x = 15$$
$$x = 3$$
$$2(3) + y = 10$$
$$6 + y = 10$$
$$y = 4$$

2. $\begin{cases} 2x + \ y = 10 \\ 6x + 3y = 10 \end{cases}$

$$y = 10 - 2x$$
$$6x + 3(10 - 2x) = 10$$
$$6x + 30 - 6x = 10$$
$$30 = 10 \therefore \text{ no solution}$$

3. $\begin{cases} 5x - 2y = 4 \\ 15x - 6y = 12 \end{cases}$

$$0 = 0$$
$$12 = 12 \therefore \text{ infinite solutions}$$

2.1.1 Consistent

- A system of equations is **consistent** if it has at least one solution.

2.1.2 Inconsistent

- A system of equations is **inconsistent** if it has no solutions.

2.2 The Augmented Matrix

$$\begin{cases} x - y + 2z = 5 \\ 2x - 2y + 4z = 10 \\ 3x - 3y + 6z = 15 \end{cases} \longrightarrow \left[\begin{array}{ccc|c} 1 & -1 & 2 & 5 \\ 2 & -2 & 4 & 10 \\ 3 & -3 & 6 & 15 \end{array}\right]$$

2.3 Elementary Row Operations

1. Interchange 2 rows
2. Multiply a row by a non-zero constant
3. Add/substract a multiple of one row to/from another row

Doing these things changes the matrix, but it's the same system!

2.3.1 Example 1... again

$$\begin{cases} 2x + y = 10 \\ 3x - y = 5 \end{cases}$$

$$\left[\begin{array}{cc|c} 2 & 1 & 10 \\ 3 & -1 & 5 \end{array}\right] \xrightarrow{\frac{1}{2}R_1} \left[\begin{array}{cc|c} 1 & \frac{1}{2} & 5 \\ 3 & -1 & 5 \end{array}\right] \xrightarrow{R_2 - 3R_1} \left[\begin{array}{cc|c} 1 & \frac{1}{2} & 5 \\ 0 & -\frac{5}{2} & -10 \end{array}\right]$$

$$\xrightarrow{-\frac{2}{5}R_2} \left[\begin{array}{cc|c} 1 & \frac{1}{2} & 5 \\ 0 & 1 & 4 \end{array}\right] \xrightarrow{R1 - \frac{1}{2}R_2} \left[\begin{array}{cc|c} 1 & 0 & 3 \\ 0 & 1 & 4 \end{array}\right]$$

And so... $x = 3$ and $y = 4$!

2.4 Connection to Matrices

If we can make a system's matrix look like

$$\left[\begin{array}{ccc|c} 1 & 0 & 0 & c_1 \\ 0 & 1 & 0 & c_2 \\ 0 & 0 & 1 & c_3 \end{array}\right],$$

then the solution to the system will be the ordered triple (c_1, c_2, c_3).

2.4.1 Example 2: again

$$\begin{cases} 2x + y = 10 \\ 6x + 3y = 10 \end{cases}$$

$$\left[\begin{array}{cc|c} 2 & 1 & 10 \\ 6 & 3 & 10 \end{array}\right] \xrightarrow{\frac{1}{2}R1} \left[\begin{array}{cc|c} 1 & \frac{1}{2} & 5 \\ 6 & 3 & 10 \end{array}\right] \xrightarrow{R2-6R1} \left[\begin{array}{cc|c} 1 & \frac{1}{2} & 5 \\ 0 & 0 & -20 \end{array}\right]$$

This is inconsistent, so there is no solution.

2.4.2 Example 3: again

$$\begin{cases} 5x - 2y = 4 \\ 15x - 6y = 12 \end{cases}$$

$$\left[\begin{array}{cc|c} 5 & -2 & 4 \\ 15 & -6 & 12 \end{array}\right] \xrightarrow{\frac{1}{5}R1} \left[\begin{array}{cc|c} 1 & -\frac{2}{5} & \frac{4}{5} \\ 15 & -6 & 12 \end{array}\right] \xrightarrow{R2-15R1} \left[\begin{array}{cc|c} 1 & -\frac{2}{5} & \frac{4}{5} \\ 0 & 0 & 0 \end{array}\right]$$

Since 0 = 0, there are infinitely many solutions.

2.4.3 Example 4: Solve the following system

$$\begin{cases} x_1 - 2x_2 + x_3 = 0 \\ 2x_2 - 8x_3 = 8 \\ -4x_1 + 5x_2 + 9x_3 = -9 \end{cases}$$

$$\left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ -4 & 5 & 9 & -9 \end{array}\right] \xrightarrow{R3+4R1} \left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 0 & -3 & 13 & -9 \end{array}\right] \xrightarrow{R3+\frac{3}{2}R2} \left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ 0 & 0 & -1 & 3 \end{array}\right]$$

$$\xrightarrow{\frac{1}{2}R2} \left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & -3 & 13 & -9 \end{array}\right] \begin{array}{c} \xrightarrow{R_1+2R_2} \\ \xrightarrow{R_3+3R_2} \end{array} \left[\begin{array}{ccc|c} 1 & 0 & -7 & 8 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 1 & 3 \end{array}\right] \begin{array}{c} \xrightarrow{R1+7R_3} \\ \xrightarrow{R_2+4R_3} \end{array} \left[\begin{array}{ccc|c} 1 & 0 & 0 & 29 \\ 0 & 1 & 0 & 16 \\ 0 & 0 & 1 & 3 \end{array}\right]$$

Therefore the solution to (x_1, x_2, x_3) is $(29, 16, 3)$.

2.4.4 Elementary Row Operations & REF Homework Problem (08/08/2023)

$$\begin{cases} x + y + 2z = 8 \\ -x - 2y + 3z = 1 \\ 3x - 7y + 4z = 10 \end{cases}$$

$$
\begin{bmatrix} 1 & 1 & 2 & 8 \\ -1 & -2 & 3 & 1 \\ 3 & -7 & 4 & 10 \end{bmatrix}
\xrightarrow[R_3-3R_1]{R_2+R_1}
\begin{bmatrix} 1 & 1 & 2 & 8 \\ 0 & -1 & 5 & 9 \\ 0 & -10 & -2 & -14 \end{bmatrix}
\xrightarrow[-R_3]{-R_2}
\begin{bmatrix} 1 & 1 & 2 & 8 \\ 0 & 1 & -5 & -9 \\ 0 & 10 & 2 & 14 \end{bmatrix}
$$

$$
\xrightarrow[R_3-10R_2]{R_1-R_2}
\begin{bmatrix} 1 & 0 & 7 & 17 \\ 0 & 1 & -5 & -9 \\ 0 & 0 & 52 & 104 \end{bmatrix}
\xrightarrow{\frac{1}{52}R_3}
\begin{bmatrix} 1 & 0 & 7 & 17 \\ 0 & 1 & -5 & -9 \\ 0 & 0 & 1 & 2 \end{bmatrix}
\xrightarrow[R_2+5R_3]{R_1-7R_3}
\begin{bmatrix} 1 & 0 & 0 & 3 \\ 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 2 \end{bmatrix}
$$

Therefore, the solution to (x, y, z) is $(3, 1, 2)$.

2.5 Gaussian Elimination

Vocabulary: A matrix is in Row Echelon Form (REF) if:

(a) Any rows of all zeroes are placed at the bottom of the matrix
(b) All other rows have a leading 1 ("pivot")
(c) As we move down the matrix, each leading 1 is further to the right than the 1 above it

A matrix is in Row Reduced Echelon Form if the three above conditions are met in adition to:

(d) Each column with a leading 1 has all other entries in the column as a 0. ("pivot column")

2.5.1 Examples

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 8 \\ 0 & 1 & 0 & 6 & -3 \\ 0 & 0 & 1 & 7 & 10 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$
REF? ✓
RREF? ✓

$$\begin{bmatrix} 1 & 1 & 1 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
REF? ✓
RREF? ×

$$\begin{bmatrix} 1 & 2 & -3 & 4 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 2 & -4 \end{bmatrix}$$
REF? ×
RREF? ×

2.6 Gaussian Elimination With Back-Substitution

2.6.1 Goal:

To get the augmented matrix in REF

Solve: $\begin{cases} x_1 - 2x_2 + 3x_3 = 9 \\ -x_1 + 3x_2 \quad\quad = -4 \\ 2x_1 - 5x_2 + 5x_3 = 17 \end{cases}$

$$\left[\begin{array}{ccc|c} 1 & -2 & 3 & 9 \\ -1 & 3 & 0 & -4 \\ 2 & -5 & 5 & 17 \end{array}\right] \xrightarrow[R_3-2R_1]{R_2+R_1} \left[\begin{array}{ccc|c} 1 & -2 & 3 & 9 \\ 0 & 1 & 3 & 5 \\ 0 & -1 & -1 & -1 \end{array}\right] \xrightarrow[R_3+R_2]{R_1+2R_2} \left[\begin{array}{ccc|c} 1 & 0 & 9 & 19 \\ 0 & 1 & 3 & 5 \\ 0 & 0 & 2 & 4 \end{array}\right]$$

$$\xrightarrow{\frac{1}{2}R_3} \left[\begin{array}{ccc|c} 1 & 0 & 9 & 19 \\ 0 & 1 & 3 & 5 \\ 0 & 0 & 1 & 2 \end{array}\right]$$

$$x + 9z = 19$$
$$y + 3z = 5$$
$$z = 2$$
$$\therefore z = 2, y = 5 - 3z, x = 19 - 9z$$
$$z = 2, y = 5 - 3(2), x = 19 - 9(2)$$
$$z = 2, y = -1, x = 1$$

Therefore, the solution (x_1, x_2, x_3) is $(1, -1, 2)$.

2.6.2 Gaussian Elimination Homework Problem (08/09/2023)

$$\begin{cases} -2w \quad\;\; + \;\; y + \;\; z = -3 \\ \qquad x + 2y - \;\; z = 2 \\ -3w + 2x + 4y + \;\; z = -2 \\ \;\, -w + \;\; x - 4y - 7z = -19 \end{cases}$$

$$\left[\begin{array}{cccc|c} -2 & 0 & 1 & 1 & -3 \\ 0 & 1 & 2 & -1 & 2 \\ -3 & 2 & 4 & 1 & -2 \\ -1 & 1 & -4 & -7 & -19 \end{array}\right] \begin{array}{c} \xrightarrow{R_4} \\ \\ \xrightarrow{R_1} \end{array} \left[\begin{array}{cccc|c} -1 & 1 & -4 & -7 & -19 \\ 0 & 1 & 2 & -1 & 2 \\ -3 & 2 & 4 & 1 & -2 \\ -2 & 0 & 1 & 1 & -3 \end{array}\right] \xrightarrow{-R_1}$$

$$\left[\begin{array}{cccc|c} 1 & -1 & 4 & 7 & 19 \\ 0 & 1 & 2 & -1 & 2 \\ -3 & 2 & 4 & 1 & -2 \\ -2 & 0 & 1 & 1 & -3 \end{array}\right] \begin{array}{c} \xrightarrow{R_3+3R_1} \\ \xrightarrow{R_4+2R_1} \end{array} \left[\begin{array}{cccc|c} 1 & -1 & 4 & 7 & 19 \\ 0 & 1 & 2 & -1 & 2 \\ 0 & -1 & 16 & 22 & 55 \\ 0 & -2 & 9 & 15 & 35 \end{array}\right] \begin{array}{c} \xrightarrow{R_1+R_2} \\ \xrightarrow{R_3+R_2} \\ \xrightarrow{R_4+2R_2} \end{array}$$

$$\left[\begin{array}{cccc|c} 1 & 0 & 6 & 6 & 21 \\ 0 & 1 & 2 & -1 & 2 \\ 0 & 0 & 18 & 21 & 57 \\ 0 & 0 & 13 & 13 & 39 \end{array}\right] \xrightarrow{\frac{1}{18}R_3} \left[\begin{array}{cccc|c} 1 & 0 & 6 & 6 & 21 \\ 0 & 1 & 2 & -1 & 2 \\ 0 & 0 & 1 & \frac{7}{6} & \frac{19}{6} \\ 0 & 0 & 13 & 13 & 39 \end{array}\right] \begin{array}{c} \xrightarrow{R_1-6R_3} \\ \xrightarrow{R_2-2R_3} \\ \xrightarrow{R_4-13R_3} \end{array}$$

$$\left[\begin{array}{cccc|c} 1 & 0 & 0 & -1 & 2 \\ 0 & 1 & 0 & -\frac{10}{3} & -\frac{13}{3} \\ 0 & 0 & 1 & \frac{7}{6} & \frac{19}{6} \\ 0 & 0 & 0 & -\frac{13}{6} & -\frac{13}{6} \end{array}\right] \xrightarrow{\frac{-6}{13}R_4} \left[\begin{array}{cccc|c} 1 & 0 & 0 & -1 & 2 \\ 0 & 1 & 0 & -\frac{10}{3} & -\frac{13}{3} \\ 0 & 0 & 1 & \frac{7}{6} & \frac{19}{6} \\ 0 & 0 & 0 & 1 & 1 \end{array}\right] \begin{array}{c} \xrightarrow{R_1+R_4} \\ \xrightarrow{R_2+\frac{10}{3}R_4} \\ \xrightarrow{R_3-\frac{7}{6}R_4} \end{array}$$

$$\left[\begin{array}{cccc|c} 1 & 0 & 0 & 0 & 3 \\ 0 & 1 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 & 2 \\ 0 & 0 & 0 & 1 & 1 \end{array}\right] \implies \begin{cases} w = 3 \\ x = -1 \\ y = 2 \\ z = 1 \end{cases}$$

2.7 Gauss-Jordan Elimination

2.7.1 Goal:

To get the matrix into RREF

Solve: $\begin{cases} x_1 \quad\quad - 3x_3 = -2 \\ 3x_1 + \ x_2 - 2x_3 = 5 \\ 2x_1 + 2x_2 + \ x_3 = 4 \end{cases}$

$$\left[\begin{array}{ccc|c} 1 & 0 & -3 & -2 \\ 3 & 1 & -2 & 5 \\ 2 & 2 & 1 & 4 \end{array}\right] \xrightarrow[R_3-2R_1]{R_2-3R_1} \left[\begin{array}{ccc|c} 1 & 0 & -3 & -2 \\ 0 & 1 & 7 & 11 \\ 0 & 2 & 7 & 8 \end{array}\right] \xrightarrow{R_3-2R_2} \left[\begin{array}{ccc|c} 1 & 0 & -3 & -2 \\ 0 & 1 & 7 & 11 \\ 0 & 0 & -7 & -14 \end{array}\right]$$

$$\xrightarrow{\frac{-1}{7}R_3} \left[\begin{array}{ccc|c} 1 & 0 & -3 & -2 \\ 0 & 1 & 7 & 11 \\ 0 & 0 & 1 & 2 \end{array}\right] \xrightarrow[R_2-7R_3]{R_1+3R_3} \left[\begin{array}{ccc|c} 1 & 0 & 0 & 4 \\ 0 & 1 & 0 & -3 \\ 0 & 0 & 1 & 2 \end{array}\right] \implies \begin{cases} x_1 = 4 \\ x_2 = -3 \\ x_3 = 2 \end{cases}$$

2.8 Matrix Properties, Equations, and Inverses

2.8.1 With Real Numbers

- If $ab = bc$, then $a = c$, if $b \neq 0$
- If $ab = 0$, then $a = 0$ or $b = 0$, or both

2.8.2 With Matrices

- If $AB = AC$, then $B = C$, if A is invertible
- If $AB = [0]$, then $A = [0]$ or $B = [0]$, or both

2.8.2.1 Multiply:

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

2.8.3 Matrix Inverses

- If a matrix has an inverse, it is said to be invertible or non-singular.

- If a matrix does not have an inverse, it is said to be singular.

- Every square matrix has a "special number" associated with it called the **determinant**.

- For the 2 × 2 matrix $A = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$, the determinant is $ad - bc$

- $A^{-1} = \frac{1}{\det A} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$

- When $\det A = 0$, the matrix is singular and has no inverse (since you cannot divide by zero)

Find the inverse of $A = \begin{bmatrix} 4 & 3 \\ 1 & 2 \end{bmatrix}$

$$\begin{bmatrix} 4 & 3 \\ 1 & 2 \end{bmatrix}^{-1} \qquad\qquad = \frac{1}{\det A} \begin{bmatrix} 2 & -3 \\ -1 & 4 \end{bmatrix}$$

$$= \frac{1}{(4)(2) - (3)(1)} \begin{bmatrix} 2 & -3 \\ -1 & 4 \end{bmatrix}$$

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

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

3 Chapter 2: Determinants

3.1 Prior Knowledge:

$$\begin{bmatrix} 10 & -4 \\ -3 & -5 \end{bmatrix} = -50 - = -62$$

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

$= ((2 \cdot 2 \cdot -2) + (4 \cdot 3 \cdot 3) + (3 \cdot -1 \cdot 0)) - ((3 \cdot 2 \cdot 3) + (0 \cdot 3 \cdot 2) + (-2 \cdot -1 \cdot 4))$

$= (-8 + 36 + 0) - (18 + 0 + 8)$

$= 28 - 26$

$= 2$

3.2 Minors & Cofactors

Given a square matrix A, the <u>minor</u> of matrix element a_{ij}, (M_{ij}) is the determinant of the matrix formed by removing the ith row and j^{th} column from matrix A.

The <u>cofactor</u> of matrix element a_{ij}, $C_{ij} = (-1)^{i+j} \cdot M_{ij}$

3.2.1 Example

Let $\det \begin{bmatrix} 2 & 4 & 3 \\ -1 & 2 & 3 \\ 3 & 0 & -2 \end{bmatrix}$. What is the cofactor of element (1, 1)?

Cofactor checkerboard:

$$\begin{bmatrix} + & - & + \\ - & + & - \\ + & - & + \end{bmatrix}$$

$M_{11} = \begin{vmatrix} 2 & 3 \\ 0 & -2 \end{vmatrix} = -4$

$C_{11} = 1 \cdot -4 = -4$

Find the minor and cofactor of: \ a) a_{21} = −1

$$M_{21} = \begin{vmatrix} 4 & 3 \\ 0 & -2 \end{vmatrix} = -8$$

$$C_{21} = 8$$

b) a_{33} = −2

$$M_{33} = \begin{vmatrix} 2 & 4 \\ -1 & 2 \end{vmatrix} = 8$$

$$C_{33} = 8$$

3.3 Cofactor Expansion

1) Pick a row or column
2) Multiply every entry in that row or column by it's corresponding cofactor
3) Add those together. That's it

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

$$\det(A) = 6\left(\begin{vmatrix} 4 & 1 \\ 5 & -3 \end{vmatrix}\right) + 7\left(-\begin{vmatrix} 0 & 1 \\ 2 & -3 \end{vmatrix}\right) + -1\left(\begin{vmatrix} 0 & 4 \\ 2 & 5 \end{vmatrix}\right)$$
$$= 6(-17) + 7(2) + (-1(-8))$$
$$= -102 + 14 + 8$$
$$= -80$$

3.3.1 Example

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

$$6\begin{vmatrix} -6 & 1 \\ 3 & 0 \end{vmatrix} + 4\left(-\begin{vmatrix} 5 & 1 \\ 0 & 0 \end{vmatrix}\right) + 2\begin{vmatrix} 5 & -6 \\ 0 & 3 \end{vmatrix}$$
$$= 6(-3) + 0 + 2(15)$$
$$= -18 + 30$$
$$= 12$$

3.3.2 Does the method generalize to 2×2 matrices?

$$\begin{vmatrix} 3 & 5 \\ 7 & 2 \end{vmatrix}$$
$$= 3|2| - 5|7|$$
$$= 6 - 35$$
$$= -29$$

The determinant of a 1×1 matrix is... **itself!**

3.3.3 Find the determinant of a 4×4

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

$$= 0 + 0 + \begin{vmatrix} -3 & 2 & 8 \\ 2 & 1 & -4 \\ 2 & 3 & 6 \end{vmatrix} + 0$$

$$= -2 \begin{vmatrix} 2 & 8 \\ 3 & 6 \end{vmatrix} + \begin{vmatrix} -3 & 8 \\ 2 & 6 \end{vmatrix} - \left(-4 \begin{vmatrix} -3 & 2 \\ 2 & 3 \end{vmatrix} \right)$$

$$= 24 - 34 - 52$$

$$= -62$$

3.4 Theorem

If *A* is an *n* × *n* matrix, then regardless of which row or column of *A* is chosen, the number obtained by multiplying the elements in that row or column by their corresponding cofactors is **always the same** and is called the determinant of *A*.

3.4.1 Example

Find the determinant of $A = \begin{bmatrix} 1 & 0 & 0 & -1 \\ 3 & 1 & 2 & 2 \\ 1 & 0 & -2 & 1 \\ 2 & 0 & 0 & 1 \end{bmatrix}$

$$1 \cdot \begin{vmatrix} 1 & 0 & -1 \\ 1 & -2 & 1 \\ 2 & 0 & 1 \end{vmatrix}$$

$$= \left(-2 \begin{vmatrix} 1 & -1 \\ 2 & 1 \end{vmatrix} \right)$$

$$= -6$$

3.5 Triangular Matrices

Find the determinant of $A = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 0 & 2 & 2 & 2 \\ 0 & 0 & 3 & 3 \\ 0 & 0 & 0 & 4 \end{bmatrix}$

$$\begin{vmatrix} 2 & 2 & 2 \\ 0 & 3 & 3 \\ 0 & 0 & 4 \end{vmatrix}$$

$$= 2 \begin{vmatrix} 3 & 3 \\ 0 & 4 \end{vmatrix}$$

$$= 2(3 \cdot 4)$$

$$= 2 \cdot 12$$

$$= 24$$

If A is an $n \times n$ triangular matrix, then det(A) is equal to the product of the elements along the main diagonal.

3.6 An Important Definition

Elementary Matrix a matrix that can be obtanied from the $n \times n$ identity matrix by performing a single row operation. \

Are the following matrices elementary? 1) $\begin{bmatrix} 1 & 0 \\ -5 & 1 \end{bmatrix} + (R_3 + 5R_1)$ yes 2) $\begin{bmatrix} -5 & 1 \\ 1 & 0 \end{bmatrix} + (R_1 + 5R_2)$... no

3.7 A Pair of Theorems

3.7.1 Theorem: If a square matrix A **has a row of column of zeros, then** $\det(A) = 0$

3.7.2 Theorem: If A **is a square matrix, then** $\det(A) = \det(A^T)$

3.8 Unit 1 & 2 Homework Problems

3.8.1 "Gaussian Elimination" (08/11/2023)

3.8.1.1 Solve this system using Gaussian Elimination

$$\begin{cases} x_1 + x_2 + 2x_3 = 8 \\ -x_1 - 2x_2 + 3x_3 = 1 \\ 3x_1 - 7x_2 + 4x_3 = 10 \end{cases}$$

$$\Rightarrow \left[\begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ -1 & -2 & 3 & 1 \\ 3 & -7 & 4 & 10 \end{array}\right] \xrightarrow[R_3-3R_1]{R_2+R_1} \left[\begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ 0 & -1 & 5 & 9 \\ 0 & -10 & -2 & -14 \end{array}\right] \xrightarrow{-R_2} \left[\begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ 0 & 1 & -5 & -9 \\ 0 & -10 & -2 & -14 \end{array}\right]$$

$$\xrightarrow{R_3+10R_2} \left[\begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ 0 & 1 & -5 & -9 \\ 0 & 0 & -52 & -104 \end{array}\right] \xrightarrow{-\frac{1}{52}R_3} \left[\begin{array}{ccc|c} 1 & 1 & 2 & 8 \\ 0 & 1 & -5 & -9 \\ 0 & 0 & 1 & 2 \end{array}\right]$$

$$\therefore \begin{cases} x_1 + x_2 + 2x_3 = 8 \\ \quad x_2 - 5x_3 = -9 \\ \qquad\quad x_3 = 2 \end{cases} \Rightarrow \begin{cases} x_1 = 3 \\ x_2 = 1 \\ x_3 = 2 \end{cases}$$

3.8.1.2 Solve this system using Gaussian Elimination

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

$$\Rightarrow \left[\begin{array}{ccc|c} 1 & -2 & 3 & 0 \\ -2 & -3 & -4 & 0 \\ 2 & -4 & 4 & 0 \end{array}\right] \xrightarrow[R_3-2R_1]{R_2+2R_1} \left[\begin{array}{ccc|c} 1 & -2 & 3 & 0 \\ 0 & -7 & 2 & 0 \\ 0 & 0 & -2 & 0 \end{array}\right] \xrightarrow[-\frac{1}{2}R_3]{-\frac{1}{7}R_2} \left[\begin{array}{ccc|c} 1 & -2 & 3 & 0 \\ 0 & 1 & \frac{2}{7} & 0 \\ 0 & 0 & 1 & 0 \end{array}\right]$$

$$\therefore \begin{cases} x_1 - 2x_2 + 3x_3 = 0 \\ \quad x_2 + \frac{2}{7}x_3 = 0 \\ \qquad\quad x_3 = 0 \end{cases} \Rightarrow 1 \neq 0 \therefore \text{ no solution}$$

3.8.2 "Inverses and Determinants" (08/14)

3.8.2.1 Find the determinants of the following:

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

$\begin{vmatrix} 2 & -3 \\ 4 & 4 \end{vmatrix} = 2(4) - (-3)(4) = 8 + 12 = 20$

2) $\begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}$

$\begin{vmatrix} 2 & 0 \\ 0 & 3 \end{vmatrix} = 2(3) - 0(0) = 6$

3) $\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$

$\begin{vmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{vmatrix} = \cos^2\theta + \sin^2\theta = 1$

3.8.2.2 Find the INVERSES of those matrices:

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

$\begin{bmatrix} 2 & -3 \\ 4 & 4 \end{bmatrix}^{-1} = \frac{1}{20}\begin{bmatrix} 4 & 3 \\ -4 & 2 \end{bmatrix} = \begin{bmatrix} \frac{1}{5} & \frac{3}{20} \\ -\frac{1}{5} & \frac{1}{10} \end{bmatrix}$

2) $\begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}$

$\begin{bmatrix} 2 & 0 \\ 0 & 3 \end{bmatrix}^{-1} = \frac{1}{6}\begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{3} \end{bmatrix}$

3) $\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$

$\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}^{-1} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$

3.8.3 Inverses and Determinants (08/15)

3.8.3.1 Use a matrix equation to solve the following problems:

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

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

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

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \frac{1}{23} \begin{bmatrix} 5 & 2 \\ -4 & 3 \end{bmatrix} \begin{bmatrix} -1 \\ 3 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \frac{1}{23} \begin{bmatrix} -1 \\ 9 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{23} \\ \frac{9}{23} \end{bmatrix}$$

2) $\begin{cases} 6x_1 + x_2 = 0 \\ 4x_1 - 3x_2 = -2 \end{cases}$

$$\Rightarrow \begin{bmatrix} 6 & 1 \\ 4 & -3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 0 \\ -2 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} 6 & 1 \\ 4 & -3 \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ -2 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \frac{1}{-22} \begin{bmatrix} -3 & -1 \\ -4 & 6 \end{bmatrix} \begin{bmatrix} 0 \\ -2 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \frac{1}{-22} \begin{bmatrix} 2 \\ 8 \end{bmatrix}$$

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} -\frac{1}{11} \\ -\frac{4}{11} \end{bmatrix}$$

3.8.4 Consistent Systems (08/21)

3.8.4.1 Solve the linear systems together by reducing the appropriate augmented matrix.

$$\begin{cases} x_1 - 5x_2 = b_1 \\ 3x_1 + 2x_2 = b_2 \end{cases}$$

   1) $b_1 = 1, \; b_2 = 4$
   2) $b_1 = -2, \; b_2 = 5$

First, let's solve it for the general case:

$$\left[\begin{array}{cc|c} 1 & -5 & b_1 \\ 3 & 2 & b_2 \end{array}\right] \xrightarrow{R_2 - 3R_1} \left[\begin{array}{cc|c} 1 & -5 & b_1 \\ 0 & 17 & b_2 - 3b_1 \end{array}\right] \xrightarrow{\frac{1}{17}R_2} \left[\begin{array}{cc|c} 1 & -5 & b_1 \\ 0 & 1 & \frac{b_2 - 3b_1}{17} \end{array}\right] \xrightarrow{R_1 + 5R_2} \left[\begin{array}{cc|c} 1 & 0 & \frac{2b_1 + 5b_2}{17} \\ 0 & 1 & \frac{-3b_1 + b_2}{17} \end{array}\right]$$

Therefore, the solution to the general case is $(x_1, x_2) = \left(\frac{2b_1 + 5b_2}{17}, \frac{-3b_1 + b_2}{17}\right)$

And so, for the specific cases:

   1) $(x_1, x_2) = \left(\frac{2(1) + 5(4)}{17}, \frac{-3(1) + 4}{17}\right) = \left(\frac{13}{17}, \frac{1}{17}\right)$
   2) $(x_1, x_2) = \left(\frac{2(-2) + 5(5)}{17}, \frac{-3(-2) + 5}{17}\right) = \left(\frac{16}{17}, \frac{11}{17}\right)$

3.8.4.2 Determine the conditions on b, if any, in order to guarantee that the linear system is consistent.

$$\begin{cases} x_1 + 3x_2 = b_1 \\ -2x_1 + x_2 = b_2 \end{cases}$$

$$\left[\begin{array}{cc|c} 1 & 3 & b_1 \\ -2 & 1 & b_2 \end{array}\right] \xrightarrow{R_2 + 2R_1} \left[\begin{array}{cc|c} 1 & 3 & b_1 \\ 0 & 7 & b_2 + 2b_1 \end{array}\right] \xrightarrow{\frac{1}{7}R_2} \left[\begin{array}{cc|c} 1 & 3 & b_1 \\ 0 & 1 & \frac{b_2 + 2b_1}{7} \end{array}\right] \xrightarrow{R_1 - 3R_2} \left[\begin{array}{cc|c} 1 & 0 & \frac{b_1 - 3b_2}{7} \\ 0 & 1 & \frac{b_2 + 2b_1}{7} \end{array}\right]$$

There are no conditions. The system is consistent for all values of b_1 and b_2.

3.8.5 Another "determining the conditions" problem:

$$\begin{cases} x_1 - 2x_2 - x_3 = b_1 \\ -4x_1 + 5x_2 + 2x_3 = b_2 \\ -4x_1 + 7x_2 + 4x_3 = b_3 \end{cases}$$

$$\left[\begin{array}{ccc|c} 1 & -2 & -1 & b_1 \\ -4 & 5 & 2 & b_2 \\ -4 & 7 & 4 & b_3 \end{array}\right] \xrightarrow[R_3 + 4R_1]{R_2 + 4R_1} \left[\begin{array}{ccc|c} 1 & -2 & -1 & b_1 \\ 0 & -3 & -2 & b_2 + 4b_1 \\ 0 & -1 & 0 & b_3 + 4b_1 \end{array}\right] \xrightarrow{-\frac{1}{3}R_2} \left[\begin{array}{ccc|c} 1 & -2 & -1 & b_1 \\ 0 & 1 & \frac{2}{3} & \frac{-b_2 - 4b_1}{3} \\ 0 & 0 & -\frac{2}{3} & \frac{b_3 + 4b_1}{3} \end{array}\right]$$

$$\xrightarrow{-\frac{3}{2}R_3} \left[\begin{array}{ccc|c} 1 & -2 & -1 & b_1 \\ 0 & 1 & \frac{2}{3} & \frac{-b_2 - 4b_1}{3} \\ 0 & 0 & 1 & \frac{-b_3 - 4b_1}{2} \end{array}\right]$$

Therefore, the system is consistent for all values of b_1, b_2, and b_3.

3.8.6 Triangular and Diagonal Matrices

3.8.6.1 Find A^2

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

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

$$= \begin{bmatrix} 1(1) + 0(0) & 1(0) + 0(-2) \\ 0(1) + (-2)(0) & 0(0) + (-2)(-2) \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 \\ 0 & 4 \end{bmatrix}$$

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

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

$$= \begin{bmatrix} (-6)(-6) + (0)(0) + (0)(0) & (-6)(0) + (0)(3) + (0)(0) & (-6)(0) + (0)(0) + (0)(5) \\ (0)(-6) + (3)(0) + (0)(0) & (0)(0) + (3)(3) + (0)(0) & (0)(0) + (3)(0) + (0)(5) \\ (0)(-6) + (0)(0) + (5)(0) & (0)(0) + (0)(3) + (5)(0) & (0)(0) + (0)(0) + (5)(5) \end{bmatrix}$$

$$= \begin{bmatrix} 36 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 0 & 25 \end{bmatrix}$$

3.8.6.2 Find A^{-k}, such that k is some nonzero constant

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

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

$$= \begin{bmatrix} 2^{-k} & 0 & 0 & 0 \\ 0 & (-4)^{-k} & 0 & 0 \\ 0 & 0 & (-3)^{-k} & 0 \\ 0 & 0 & 0 & 2^{-k} \end{bmatrix}$$

4. Determine whether each matrix is symmetric or not.

$$\begin{bmatrix} -8 & -8 \\ 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 2 & -1 \\ 1 & 2 \end{bmatrix}$$

$$\begin{bmatrix} 0 & -7 \\ -7 & 7 \end{bmatrix}$$

$$\begin{bmatrix} 3 & 4 \\ 4 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 1 & 2 \\ 1 & 5 & -6 \\ 2 & 6 & 6 \end{bmatrix}$$

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

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

Symmetric

$$\begin{bmatrix} 0 & -7 \\ -7 & 7 \end{bmatrix}$$

$$\begin{bmatrix} 3 & 4 \\ 4 & 0 \end{bmatrix}$$

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

Not symmetric

$$\begin{bmatrix} 2 & -1 \\ 1 & 2 \end{bmatrix}$$

$$\begin{bmatrix} -8 & -8 \\ 0 & 0 \end{bmatrix}$$

$$\begin{bmatrix} 0 & 1 & 2 \\ 1 & 5 & -6 \\ 2 & 6 & 6 \end{bmatrix}$$

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

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3.8.6.3 Find a diagonal matrix A that satisfies the given condition

1) $A^5 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}^{\frac{1}{5}}$$

$$= \begin{bmatrix} 1^{\frac{1}{5}} & 0 & 0 \\ 0 & (-1)^{\frac{1}{5}} & 0 \\ 0 & 0 & (-1)^{\frac{1}{5}} \end{bmatrix}$$

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

2) $A^{-2} = \begin{bmatrix} 9 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

$$A = \begin{bmatrix} 9 & 0 & 0 \\ 0 & 4 & 0 \\ 0 & 0 & 1 \end{bmatrix}^{-\frac{1}{2}}$$

$$= \begin{bmatrix} 9^{-\frac{1}{2}} & 0 & 0 \\ 0 & 4^{-\frac{1}{2}} & 0 \\ 0 & 0 & 1^{-\frac{1}{2}} \end{bmatrix}$$

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

3.8.7 Determinants and Triangular Matrices (08/29)

3.8.7.1 What is C_{32}

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

$$C_{32} = (-1)^{3+2} \begin{vmatrix} 2 & -1 & 1 \\ -3 & 0 & 3 \\ 3 & 1 & 0 \end{vmatrix}$$

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

$$= - \left(2 \begin{vmatrix} 0 & 3 \\ 1 & 0 \end{vmatrix} - (-1) \begin{vmatrix} -3 & 3 \\ 3 & 0 \end{vmatrix} + 1 \begin{vmatrix} -3 & 0 \\ 3 & 1 \end{vmatrix} \right)$$

$$= - (2(-3) - (-1)(-9) + 1(-3))$$

$$= -(-6 + 9 - 3)$$

$$= 0$$

3.8.7.2 Find all values of λ such that $|A| = 0$

$$A = \begin{bmatrix} \lambda - 2 & 1 \\ -5 & \lambda + 4 \end{bmatrix}$$

$$\det(A) = (\lambda - 2)(\lambda + 4) - (-5)(1)$$

$$= \lambda^2 + 2\lambda - 8 + 5$$

$$= \lambda^2 + 2\lambda - 3$$

$$= (\lambda + 3)(\lambda - 1)$$

$$= 0$$

Therefore, $\lambda = -3, 1$

3.8.7.3 For the matrix $\begin{bmatrix} 3 & 0 & 0 \\ 2 & -1 & 5 \\ 1 & 9 & -4 \end{bmatrix}$ find the determinant 3 different ways with cofactor expansion. Pick different rows and columns each time.

$$\det(A) = 3 \begin{vmatrix} -1 & 5 \\ 9 & -4 \end{vmatrix} - 0 \begin{vmatrix} 2 & 5 \\ 1 & -4 \end{vmatrix} + 0 \begin{vmatrix} 2 & -1 \\ 1 & 9 \end{vmatrix}$$

$$= 3(-1(-4) - 5(9)) - 0(2(-4) - 5(1)) + 0(2(9) - (-1)(1))$$

$$= 3(4 - 45) - 0(-8 - 5) + 0(18 + 1)$$

$$= 3(-41) - 0(-13) + 0(19)$$

$$= 36$$

$$\det(A) = 0 \begin{vmatrix} 2 & 5 \\ 9 & -4 \end{vmatrix} - 3 \begin{vmatrix} 3 & 0 \\ 1 & -4 \end{vmatrix} + 0 \begin{vmatrix} 3 & 0 \\ 2 & 5 \end{vmatrix}$$

$$= 0(2(-4) - 5(9)) - 3(3(-4) - 0(1)) + 0(3(5) - 0(2))$$

$$= 0(-8 - 45) - 3(-12 - 0) + 0(15 - 0)$$

$$= 0(-53) - 3(-12)$$

$$= 36$$

$$\det(A) = 0 \begin{vmatrix} 2 & -1 \\ 9 & -4 \end{vmatrix} - 0 \begin{vmatrix} 3 & 0 \\ 1 & -4 \end{vmatrix} + 3 \begin{vmatrix} 3 & 0 \\ 2 & -1 \end{vmatrix}$$

$$= 0(2(-4) - (-1)(9)) - 0(3(-4) - 0(1)) + 3(3(-1) - 0(2))$$

$$= 0(-8 + 9) - 0(-12 - 0) + 3(-3 - 0)$$

$$= 0(1) - 0(-12) + 3(-3)$$

$$= 0 + 0 - 9$$

$$= 36$$

3.8.7.4 Evaluate $\det(A)$ **by a cofactor expansion along a row or column of your choice**

$$A = \begin{bmatrix} 1 & k & k^2 \\ 1 & k & k^2 \\ 1 & k & k^2 \end{bmatrix}$$

$$\det(A) = 1 \begin{vmatrix} k & k^2 \\ k & k^2 \end{vmatrix} - k \begin{vmatrix} 1 & k^2 \\ 1 & k^2 \end{vmatrix} + k^2 \begin{vmatrix} 1 & k \\ 1 & k \end{vmatrix}$$

$$= 1(k^2 - k^2) - k(1(k^2) - k^2(1)) + k^2(1(k) - k(1))$$

$$= 0$$

3.8.7.5 Evaluate the determinant of the following matrices by just looking at them.

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

$$\det(A) = 1(-1)(1) = -1$$

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

$$\det(A) = 1(1)(2)(3) = 6$$

3.8.7.6 Show that the value of the determinant is independent of θ

$$A = \begin{vmatrix} \sin\theta & \cos\theta & 0 \\ -\cos\theta & \sin\theta & 0 \\ \sin\theta - \cos\theta & \sin\theta + \cos\theta & 1 \end{vmatrix}$$

$$\det(A) = \sin\theta \begin{vmatrix} \sin\theta & 0 \\ \sin\theta + \cos\theta & 1 \end{vmatrix} - \cos\theta \begin{vmatrix} \cos\theta & 0 \\ \sin\theta + \cos\theta & 1 \end{vmatrix}$$

$$+0 \begin{vmatrix} \cos\theta & \sin\theta \\ \sin\theta + \cos\theta & \sin\theta \end{vmatrix}$$

$$= \sin\theta \left(\sin\theta(1) - 0(\sin\theta + \cos\theta)\right) - \cos\theta \left(\cos\theta(1) - 0(\sin\theta + \cos\theta)\right)$$

$$+0 \left(\cos\theta(\sin\theta) - \sin\theta(\sin\theta + \cos\theta)\right)$$

$$= \sin^2\theta - \cos^2\theta$$

$$= 1$$

3.8.8 Row operations and Determinants (08/31)

3.8.8.1 Find the determinant of $\begin{bmatrix} 1 & -3 & 0 \\ -2 & 4 & 1 \\ 5 & -2 & 2 \end{bmatrix}$ **WITHOUT using cofactor expansion**

$$\det(A) = \begin{vmatrix} 1 & -3 & 0 \\ -2 & 4 & 1 \\ 5 & -2 & 2 \end{vmatrix}$$

$$= \begin{vmatrix} 1 & -3 & 0 \\ 0 & -2 & 1 \\ 0 & 13 & 2 \end{vmatrix}$$

$$= \begin{vmatrix} 1 & -3 & 0 \\ 0 & -2 & 1 \\ 0 & 0 & \frac{28}{2} \end{vmatrix}$$

$$= 1(-2)\left(\frac{28}{2}\right)$$

$$= -28$$

3.8.8.2 Find the determinant of $\begin{bmatrix} 2 & 1 & 3 & 1 \\ 1 & 0 & 1 & 1 \\ 0 & 2 & 1 & 0 \\ 0 & 1 & 2 & 3 \end{bmatrix}$

$$\det(A) = \begin{vmatrix} 2 & 1 & 3 & 1 \\ 1 & 0 & 1 & 1 \\ 0 & 2 & 1 & 0 \\ 0 & 1 & 2 & 3 \end{vmatrix}$$

$$= \begin{vmatrix} 2 & 1 & 3 & 1 \\ 0 & -2 & -5 & -1 \\ 0 & 2 & 1 & 0 \\ 0 & 1 & 2 & 3 \end{vmatrix}$$

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

$$= 2(-2)(-4)(2)$$

$$= 64$$

3.8.9 Adjoints and Cramer's Rule (09/05)

3.8.9.1 Find the inverse of $A = \begin{bmatrix} 2 & 5 & 5 \\ -1 & -1 & 0 \\ 2 & 4 & 3 \end{bmatrix}$ **using the adjoint method**

$$\det(A) = 2 \begin{vmatrix} -1 & 0 \\ 4 & 3 \end{vmatrix} - 5 \begin{vmatrix} -1 & 0 \\ 2 & 3 \end{vmatrix} + 5 \begin{vmatrix} -1 & -1 \\ 2 & 4 \end{vmatrix}$$

$$= 2(-3) - 5(-3) + 5(-2)$$

$$= -6 + 15 - 10$$

$$= -1$$

$$\text{adj}(A) = \begin{bmatrix} (-1)^{1+1}\begin{vmatrix} -1 & 0 \\ 4 & 3 \end{vmatrix} & (-1)^{1+2}\begin{vmatrix} -1 & 0 \\ 2 & 3 \end{vmatrix} & (-1)^{1+3}\begin{vmatrix} -1 & -1 \\ 2 & 4 \end{vmatrix} \\ (-1)^{2+1}\begin{vmatrix} 5 & 5 \\ 4 & 3 \end{vmatrix} & (-1)^{2+2}\begin{vmatrix} 2 & 5 \\ 2 & 3 \end{vmatrix} & (-1)^{2+3}\begin{vmatrix} 2 & 5 \\ 2 & 4 \end{vmatrix} \\ (-1)^{3+1}\begin{vmatrix} 5 & 5 \\ -1 & 0 \end{vmatrix} & (-1)^{3+2}\begin{vmatrix} 2 & 5 \\ -1 & 0 \end{vmatrix} & (-1)^{3+3}\begin{vmatrix} 2 & 5 \\ -1 & -1 \end{vmatrix} \end{bmatrix}$$

$$= \begin{bmatrix} (-1)(3) & -(-1)(3) & -4+2 \\ -(15-20) & 6-10 & -(8-10) \\ 5 & -5 & -2+5 \end{bmatrix}^T$$

$$= \begin{bmatrix} -3 & 3 & -2 \\ 5 & -4 & 2 \\ 5 & -5 & 3 \end{bmatrix}^T$$

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

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

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

3.8.9.2 Solve the following system of equations using Cramer's Rule

$$\begin{cases} 4x + 5y \quad\;\; = 2 \\ 11x + \;\; y + 2z = 3 \\ \;\; x + 5y + 2z = 1 \end{cases} \longrightarrow \begin{vmatrix} 4 & 5 & 0 \\ 11 & 1 & 2 \\ 1 & 5 & 2 \end{vmatrix} \longrightarrow 4\begin{vmatrix} 1 & 2 \\ 5 & 2 \end{vmatrix} - 5\begin{vmatrix} 11 & 2 \\ 1 & 2 \end{vmatrix} = -132$$

$$\det(x) = \begin{vmatrix} 2 & 5 & 0 \\ 3 & 1 & 2 \\ 1 & 5 & 2 \end{vmatrix}$$

$$= 2\begin{vmatrix} 1 & 2 \\ 5 & 2 \end{vmatrix} - 5\begin{vmatrix} 3 & 2 \\ 1 & 2 \end{vmatrix}$$

$$= 2(2 - 10) - 5(6 - 2)$$

$$= -16 - 20$$

$$= -36$$

$$\det(y) = \begin{vmatrix} 4 & 2 & 0 \\ 11 & 3 & 2 \\ 1 & 1 & 2 \end{vmatrix}$$

$$= 4\begin{vmatrix} 3 & 2 \\ 1 & 2 \end{vmatrix} - 2\begin{vmatrix} 11 & 2 \\ 1 & 2 \end{vmatrix}$$

$$= 4(6 - 2) - 2(22 - 2)$$

$$= 16 - 40$$

$$= -24$$

$$\det(z) = \begin{vmatrix} 4 & 5 & 2 \\ 11 & 1 & 3 \\ 1 & 5 & 1 \end{vmatrix}$$

$$= 4\begin{vmatrix} 1 & 3 \\ 5 & 1 \end{vmatrix} - 5\begin{vmatrix} 11 & 3 \\ 1 & 3 \end{vmatrix} + 2\begin{vmatrix} 11 & 1 \\ 1 & 5 \end{vmatrix}$$

$$= 4(1 - 15) - 5(33 - 3) + 2(55 - 1)$$

$$= -56 - 150 + 108$$

$$= -98$$

Therefore, the solution $(x, y, z) = \left(\frac{3}{11}, \frac{2}{11}, -\frac{49}{66}\right)$

4 Chapter 5: Eigenvectors and Eigenvalues

4.1 Eigenvalues and Eigenvectors (11/06)

If A is an $n \times n$ matrix, then a non-zero vector **x**, in R^n, is called an eigenvector of A if A**x** is a scalar multiple of **x**; that is A**x** = λ**x** for some scalar λ. This scalar λ is called an eigenvalue of A and **x** is said to be an eigenvector corresponding to λ.

See, normally, multiplying a vector by a square matrix changes both the magnitude and the direction of the vector. Really screws it up.

Some examples:

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

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

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

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

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

$$\begin{bmatrix} 7 & 8 \\ -2 & 3 \end{bmatrix}\begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 23 \\ 4 \end{bmatrix}$$

However, there are some ways to get consistent results.

4.1.1 Examples

4.1.1.1 $\vec{x} = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$ **is an eigenvector of** $A = \begin{bmatrix} 3 & -2 \\ 1 & 0 \end{bmatrix}$ **because**

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

4.1.1.2 Let $A = \begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix}, \vec{u} = \begin{bmatrix} 6 \\ -5 \end{bmatrix}, \vec{v} = \begin{bmatrix} 3 \\ -2 \end{bmatrix}.$ **Are** $\vec{u}$ **and** $\vec{v}$ **eigenvectors of** A**?**

$$A\vec{u} = \begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix}\begin{bmatrix} 6 \\ -5 \end{bmatrix} = \begin{bmatrix} 1(6) + 6(-5) \\ 5(6) + 2(-5) \end{bmatrix} = \begin{bmatrix} -24 \\ 20 \end{bmatrix} = -4\begin{bmatrix} 6 \\ -5 \end{bmatrix} \therefore \lambda = -4$$

$$A\vec{v} = \begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix}\begin{bmatrix} 3 \\ -2 \end{bmatrix} = \begin{bmatrix} 1(3) + 6(-2) \\ 5(3) + 2(-2) \end{bmatrix} = \begin{bmatrix} -9 \\ 11 \end{bmatrix} \neq \lambda\vec{v}$$

4.2 Eigenvector Homework Problem (11/06)

Confirm by multiplication that x is an eigenvector of A, and find the corresponding eigenvalue.

4.2.1 $A = \begin{bmatrix} 4 & 0 & 1 \\ 2 & 3 & 2 \\ 1 & 0 & 4 \end{bmatrix}; \mathbf{x} = \begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix}$

$$A\mathbf{x} = \begin{bmatrix} 4 & 0 & 1 \\ 2 & 3 & 2 \\ 1 & 0 & 4 \end{bmatrix}\begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} = \begin{bmatrix} 4(1) + 0(2) + 1(1) \\ 2(1) + 3(2) + 2(1) \\ 1(1) + 0(2) + 4(1) \end{bmatrix} = \begin{bmatrix} 5 \\ 10 \\ 5 \end{bmatrix} = 5\begin{bmatrix} 1 \\ 2 \\ 1 \end{bmatrix} \therefore \lambda = 5$$

4.3 Finding Eigenvalues and Eigenvectors (11/07)

Essential question:

If we know an n × n matrix A, can we find its λ?

If $A\vec{x} = \lambda\vec{x}$, then:

$$A\vec{x} = \lambda\vec{x}$$
$$A\vec{x} - \lambda\vec{x} = \vec{0}$$
$$(A - \lambda I)\vec{x} = \vec{0}$$

This equation is familiar. It's the homogeneous system of equations $A\vec{x} = \vec{0}$, the solution of which is the nullspace of $A - \lambda I$. Therefore, $\vec{x}$ is an eigenvector of $A \iff \vec{x}$ is in the nullspace of $A - \lambda I$.

In this situation, what do we know about that matrix?

Everything in the equivalent statements is false because $\vec{x}$ cannot be the zero vector. Therefore, we can see that det($A - \lambda I$) OR det($\lambda I - A$) MUST be 0.

Big Idea: If A is an $n \times n$ matrix, then λ is an eigenvalue of A $\iff$ $\det(\lambda I - A) = 0$. This is called the <u>characteristic equation</u> of A.

4.3.1 Find the characteristic equation and the eigenvalues of $A = \begin{bmatrix} 3 & 0 & 5 \\ \frac{1}{5} & -1 & 0 \\ 1 & 1 & -2 \end{bmatrix}$

$$\det(\lambda I - A) = 0$$

$$\begin{vmatrix} \lambda - 3 & 0 & 5 \\ -\frac{1}{5} & \lambda + 1 & 0 \\ -1 & -1 & \lambda + 2 \end{vmatrix} = 0$$

$$0 = (\lambda - 3)((\lambda + 1)(\lambda + 2)) + 5(\frac{1}{5} + \lambda + 1)$$

$$0 = (\lambda - 3)(\lambda^2 + 3\lambda + 2)$$

$$0 = \lambda^3 - 2\lambda$$

$$0 = \lambda(\lambda^2 - 2)\lambda \qquad\qquad = 0, \pm\sqrt{2}$$

4.3.2 Find the characteristic equation and the eigenvalues of $A = \begin{bmatrix} -1 & 0 & 1 \\ -1 & 3 & 0 \\ -4 & 13 & -1 \end{bmatrix}$

$$\begin{vmatrix} -1 - \lambda & 0 & 1 \\ -1 & 3 - \lambda & 0 \\ -4 & 13 & -\lambda \end{vmatrix} = 0$$

$$(-1 - \lambda)((3 - \lambda)(-\lambda) - 0(13)) + (-1(13) - (3 - \lambda)(-4)) = 0$$

$$(-1 - \lambda)(\lambda^2 - 3\lambda) + (-13 - 4\lambda + 12) = 0$$

$$(-1 - \lambda)(\lambda^2 - 3\lambda) + (-4\lambda - 1) = 0$$

$$-\lambda^3 + 3\lambda^2 + 2 = 0$$

$$(-\lambda + 2)(-\lambda^2 - \lambda - 1) = 0$$

$$(-\lambda + 2)(-\lambda - 1)(-\lambda + 1) = 0$$

$$\lambda = 2$$

4.3.3 Find the eigenvalues of $A = \begin{bmatrix} 2 & 0 & 0 \\ 6 & 3 & 0 \\ 1 & 4 & 5 \end{bmatrix}$

$$\begin{vmatrix} \lambda - 2 & 0 & 0 \\ 6 & \lambda - 3 & 0 \\ 1 & 4 & \lambda - 5 \end{vmatrix} = 0$$

$$(\lambda - 2)(\lambda - 3)(\lambda - 5) = 0$$

$$\lambda = 2, 3, 5$$

Theorem 1: For a triangular matrix, the eigenvalues are the elements on the main diagonal.

4.3.4 Find the eigenvalues of A^3 **if** $A = \begin{bmatrix} \frac{1}{2} & 4 & 5 & -2 \\ 0 & -1 & 3 & -8 \\ 0 & 0 & 2 & 6 \\ 0 & 0 & 0 & 4 \end{bmatrix}$

$$\lambda_A = \frac{1}{2}, -1, 2, 4$$

$$\lambda_{A^3} = \frac{1}{8}, -1, 8, 64$$

Theorem 2: The eigenvalues of A^k are $\lambda_1^k, \lambda_2^k, \ldots$

4.3.5 Give me a matrix with eigenvalues $\lambda = 0, 2, 5$

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

Theorem 3: A square matrix A is invertible $\iff \lambda \neq 0$ (which also means its determinant is 0).

4.3.6 Finding eigenvectors!

Find the nontrivial eigenvectors of:

$A = \begin{bmatrix} 1 & 6 \\ 5 & 2 \end{bmatrix}$

$$\begin{vmatrix} \lambda - 1 & -6 \\ -5 & \lambda - 2 \end{vmatrix} = 0$$

$$(\lambda - 1)(\lambda - 2) - (-6)(-5) = 0$$

$$\lambda^2 - 3\lambda - 28 = 0$$

$$(\lambda - 7)(\lambda + 4) = 0$$

$$\lambda = 7, -4$$

Substitute each λ, one at a time into the $\lambda I - A$ matrix and find the null space.

For $\lambda = -4$:

$$\begin{pmatrix} -5 & -6 & | & 0 \\ -5 & -6 & | & 0 \end{pmatrix}$$

$$\begin{pmatrix} -5 & -6 & | & 0 \\ 0 & 0 & | & 0 \end{pmatrix}$$

$$\langle -\frac{6}{5}t, t \rangle$$

$$\vec{x} = \{\langle -6, 5 \rangle\}$$

For $\lambda = 7$:

$$\begin{pmatrix} 6 & -6 & | & 0 \\ -5 & 5 & | & 0 \end{pmatrix}$$

$$\begin{pmatrix} 6 & -6 & | & 0 \\ 0 & 0 & | & 0 \end{pmatrix}$$

$$\langle t, t \rangle$$

$$\vec{x} = \{\langle 6, 6 \rangle\}$$

Therefore, the eigen space is: $\{\langle -6, 5 \rangle, \langle 6, 6 \rangle\}$

4.4 Diagonalization and Similar Triangles

Similar matrices: If A and D are square matrices, we say that A and D are "similar" if there exists an invertible matrix P such that:

$D = P^{-1}AP$.

4.4.1 Properties of Similar Matricces

- They have the same determinant
- If one is invertible, so is the other
- They have the same trace
- They have the same characteristic polynomial
- They have the same eigenvalues

4.4.2 Procedure

1. Find the eigenvectors for the $n \times n$ matrix A.

- Theorem: If an $n \times n$ matrix A has n distinct eigenvalues, then A is **for sure** diagonalizable.

2. Make matrix P out of the eigenveectors (P is the matrix that diagonalizes A)
3. Check your work to find matrix D if reasonable

4.4.3 Example: Find a matrix P that diagonalizes A and compute $P^{-1}AP$

1. $A = \begin{bmatrix} 3 & 7 \\ 5 & 5 \end{bmatrix}$

Find the eigenvalues:

$$\begin{bmatrix} \lambda - 3 & -7 \\ -5 & \lambda - 5 \end{bmatrix} = 0$$
$$(\lambda - 3)(\lambda - 5) - (-7)(-5) = 0$$
$$\lambda^2 - 5\lambda - 3\lambda + 15 - 35 = 0$$
$$\lambda^2 - 8\lambda - 20 = 0$$
$$\lambda = -2, 10$$

Find the eigenvectors:

$$\lambda = -2 : \begin{bmatrix} -5 & -7 & | & 0 \\ -5 & -7 & | & 0 \end{bmatrix} \vec{x} = \{\langle -7, 5 \rangle\}$$
$$\lambda = 10 : \begin{bmatrix} -7 & -7 & | & 0 \\ -5 & 5 & | & 0 \end{bmatrix} \vec{x} = \{\langle 1, 1 \rangle\}$$

Create the matrix P:

$$P = \begin{bmatrix} -7 & 1 \\ 5 & 1 \end{bmatrix}$$

Find matrix D:

$$D = P^{-1}AP$$

$$= \begin{bmatrix} 7 & 1 \\ 5 & -1 \end{bmatrix}^{-1} \begin{bmatrix} 3 & 7 \\ 5 & 5 \end{bmatrix} \begin{bmatrix} 7 & 1 \\ 5 & -1 \end{bmatrix}$$

$$= \begin{bmatrix} -2 & 0 \\ 0 & 10 \end{bmatrix}$$

4.4.4 Conclusion

- If D has the same eigenvalues of A and if D must be diagonal, then D is **THE** diagonal matrix with eigenvalues of A on the diagonal.

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

First, find D:

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

Then, find P:

$$\lambda = 2 : \left[\begin{array}{ccc|c} 0 & 0 & 2 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array} \right] \vec{x} = \langle 1, 0, 0 \rangle$$

$$\lambda = 3 : \left[\begin{array}{ccc|c} 1 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 \end{array} \right] \vec{x} = \langle 0, 1, 0 \rangle$$

$$\lambda = 1 : \left[\begin{array}{ccc|c} -1 & 0 & 2 & 0 \\ 0 & -2 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{array} \right] \vec{x} = \langle 2, 0, 1 \rangle$$

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

4.5 More on Similar Matrices

There are a few more properties of similar matrices:

- They have the same rank (non-zero eigenvalues)
- They have the same nullity
- They have the same column space
- They have the same row space

4.5.1 Example

**Matrix A is similar to the following matrix:

$$D = \begin{bmatrix} 3 & -1 & 1 & 4 & 5 & 2 \\ 0 & -3 & 5 & -10 & -16 & 1 \\ 0 & 0 & 5 & 7 & -8 & 2 \\ 0 & 0 & 0 & 2 & 2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Rank of A: 4

Nullity of A: 2

Eigenvalues: 3, -3, 5, 2, 0, 0

Characteristic Polynomial:

$$\det(\lambda I - A) = 0$$

$$\begin{vmatrix} \lambda - 3 & 1 & -1 & -4 & -5 & -2 \\ 0 & \lambda + 3 & -5 & 10 & 16 & -1 \\ 0 & 0 & \lambda - 5 & -7 & 8 & -2 \\ 0 & 0 & 0 & \lambda - 2 & -2 & 0 \\ 0 & 0 & 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda \end{vmatrix} = 0$$

$$(\lambda - 3)(\lambda + 3)(\lambda - 5)(\lambda - 2)\lambda^2 = 0$$

4.5.2 Some review

- Eigenspace of λ: The nullspace of $\lambda I - A$. Each eigenvalue will have its own eigenspace.
- Algebraic multiplicty: The number of times a given λ appears as a root of the characteristic equation.
- Geometric multiplicity: The number of eigenvectors it maps to.

4.5.2.1 Theorem: Geometric and Algebraic Multiplicity

If A is a square matrix, then: a. For every eigenvalue of A, the geometric multiplicity is less than or equal to the algebraic multiplicity. b. A is diagonalizable $\iff$ the geometric multiplicity of each eigenvalue is equal to the algebraic multiplicity.

4.6 Similar Matrices Continued (11/13/2023)

4.6.1 Warm-Up

Can you write a new statement involving eigenvalues to add to the list of equivalent statements?

$\lambda = 0$ is not an eigenvalue of A

4.6.2 Homework Review

$$A = \begin{bmatrix} 19 & -9 & -6 \\ 25 & -11 & -9 \\ 17 & -9 & -4 \end{bmatrix}$$

$$\begin{bmatrix} \lambda - 19 & 9 & 6 \\ -25 & \lambda + 11 & 9 \\ 17 & 9 & \lambda + 4 \end{bmatrix} = (\lambda - 19)((\lambda + 11)(\lambda + 4) - 81) + 25(9\lambda + 36 - 54) - 17(81 - 6\lambda - 66)$$

$$= (\lambda - 1)^2(\lambda - 2)$$

$\lambda = 1$ has an algebraic multiplicity of 2 and $\lambda = 2$ has an algebraic multiplicity of 1.

4.6.3 Suppose that a characteristic polynomial of some matrix _A_ is found to be:

$p(\lambda) = (\lambda - 1)(\lambda - 3)^2(\lambda = 4)^3$

    a. What are the dimensions of _A_?

6×6

    b. What are the algebraic multiplicities of each eigenvalue?

$\lambda = 1 : 1, \lambda = 3 : 2, \lambda = 4 : 3$

    c. What are the possible dimensions of the eigenspace associated with each of the eigenvalues?

$\lambda = 1 : 1, \lambda = 3 : 1$ or $2, \lambda = 4 : 1$ or 2 or 3

    d. If $\{v_1, v_2\}$ is a linearly independent set of eigenvectors of _A_, all of which correspond to the same eigenvalue of _A_, what can you say about the eigenvalue?

The eigenvalue must be 3 or 4.

5 Semester II

5.1 Introduction to Multivariable functions (01/04)

5.1.1 Definition of a Multivariable Function

Suppose _D_ is a set of _n_-tuples of real numbers $(x_1, x_2, ..., x_n)$. A function _f_ on _D_ is a rule that assigns a real number

$w = f(x_1, x_2, ..., x_n)$

to each element in _D_. The set _D_ is the function's **domain**. The set of _w_-values taken on by _f_ is the function's **range**. The symbol _w_ is the **dependent variable** of _f_, and _f_ is a function of the _n_ **independent variables** x_1 to x_n. The _x_'s are the function's **input variables**; _w_ is the function's **output variable**.

5.2 Limits and Continuity (01/05)

5.2.1 Level Curve, Graph, Surface

The set of points in the plane where a function $f(x,y)$ has a constant value k is called a **level curve** of f. The graph of f is the set of all points (x,y,z) in space, where $z = f(x,y)$. The graph of f is a surface in space.

5.2.2 Limits With Multivariable Functions

Limits: Let f be a function of two variables defined on an open region, except possibly at (x_0, y_0).

In 2-D:

$\lim_{x \to c} f(x)$ exists iff $\lim_{x \to c^-} f(x) = \lim_{x \to c^+} f(x) = L \in \mathbb{R}$

In 3-D:

$\lim_{(x,y) \to (x_0,y_0)} f(x,y)$ exists iff $\lim_{(x,y) \to (x_0,y_0)^-} f(x,y) = L \in \mathbb{R}$ from <u>all</u> directions.

5.2.3 Examples

1. $\lim_{(x,y) \to (1,2)} \dfrac{5x^2 y}{x^2 + y^2} = \dfrac{5 \cdot 1 \cdot 2}{1 + 4} = \dfrac{10}{5} = 2$

2. $\lim_{(x,y) \to (1,1)} \dfrac{x - y}{x^2 - y^2} = \dfrac{0}{0}$

Since this is indeterminate, you need to switch to traditional limit solving methods. There is no *L'Hopital's Rule* for multivariable functions. Instead, factor the numerator and denominator and cancel out common factors.

$\lim_{(x,y) \to (1,1)} \dfrac{x - y}{(x - y)(x + y)} = \dfrac{1}{2}$

3. $\lim_{(x,y) \to (4,3)} \dfrac{\sqrt{x} - \sqrt{y + 1}}{x - y - 1}$

5.2.4 Homework

5.2.4.1 Evaluate the limit $\lim_{(x,y)\to(0,0)} \dfrac{3x^2 - y^2 + 5}{x^2 + y^2 + 2}$

$$\lim_{(x,y)\to(0,0)} \frac{3x^2 - y^2 + 5}{x^2 + y^2 + 2}\bigg|_{(0,0)} = \frac{5}{2}$$

5.2.4.2 Evaluate the limit $\lim_{(x,y)\to(1,1)} \cos\sqrt[3]{|xy| - 1}$

$$\lim_{(x,y)\to(1,1)} \cos\sqrt[3]{|xy| - 1}\bigg|_{(1,1)} = \cos 0 = 1$$

5.2.4.3 Evaluate the limit $\lim_{(x,y)\to(1,1)} \dfrac{xy - y - 2x + 2}{x - 1}$

$$\lim_{(x,y)\to(1,1)} \frac{xy - y - 2x + 2}{x - 1} = \frac{(x-1)(y-2)}{x-1} = y - 2\big|_{(1,1)} = -1$$

5.2.4.4 On what interval is the function $f(x, y) = \sin(x + y)$ **continuous?**

The sin function is continuous everywhere, so $(x, y) \in \mathbb{R}^2$

5.2.4.5 On what interval is the function $f(x, y, z) = x^2 + y^2 - 2z^2$ **continuous?**

$(x, y, z) \in \mathbb{R}^3$

5.2.4.6 On what interval is the function $f(x, y, z) = xy\sin\left(\frac{1}{z}\right)$ **continuous?**

Can't divide by zero, so $(x, y, z) \in \mathbb{R}^3 | z \neq 0$

5.3 Limits that DO NOT EXIST in 3-Space (01/08)

5.3.1 Question: Does the function $f(x, y) = \dfrac{2x^2 y}{x^4 + y^2}$ **have a limit as (x,y) approaches (0,0)?**

Nope, it approaches the point differently.

5.3.2 Find $f(x, y)|_{y=x^2}$ **and compute** $\lim_{(x,y)\to(0,0)} f(x, y)$ **along** $y = x^2$

$$f(x, y) = \frac{2x^2y}{x^4 + y^2}\bigg|_{y=x^2} = \frac{2x^4}{2x^4} = 1$$

5.3.3 Find $f(x, y)|_{y=-x^2}$ **and compute** $\lim_{(x,y)\to(0,0)} f(x, y)$ **along** $y = -x^2$

$$f(x, y) = \frac{2x^2y}{x^4 + y^2}\bigg|_{y=x^2} = \frac{-2x^4}{2x^4} = 1$$

5.3.4 Explain why we can conclude that $\lim_{(x,y)\to(0,0)} f(x, y)$ **does not exist**

$\lim_{(x,y)\to(0,0)} f(x, y)$ along $y = x^2 \neq \lim_{(x,y)\to(0,0)} f(x, y)$ along $y = -x^2$

5.3.5 How did we know to choose $y = x^2$ **and** $y = -x^2$ **to evaluate the limit?**

You want to try to choose things that, as you plug them in, you get a nice expression that you can simplify. For this prblem in particular, we chose paths towards $(0, 0)$ that, when substituted, would be easy to solve and yield different answers upon simplification. We could've also used the equation of the x-axis ($y = 0$).

5.3.6 Show that these functions have no limit as (x, y) **approaches** $(0, 0)$ **by considering different paths of approach.**

5.3.6.1 $f(x, y) = \dfrac{x^4}{x^4 + y^2}$

$\lim_{(x,y)\to(0,0)} f(x, y)$ along $y = 2x^2 = \dfrac{x^4}{5x^4} = \dfrac{1}{5} \neq \lim_{(x,y)\to(0,0)} f(x, y)$ along $y = x^2 = \dfrac{x^4}{2x^4} = \dfrac{1}{2}$

5.3.6.2 $f(x, y) = \dfrac{x^2 + y}{y}$

$\lim_{(x,y)\to(0,0)} f(x, y)$ along $y = x^2 = \dfrac{2y}{y} = 2 \neq \lim_{(x,y)\to(0,0)} f(x, y)$ along $y = 2x^2 = \dfrac{3x^2}{2x^2} = \dfrac{3}{2}$