

Cheatography

Penn State: Math 220 Cheat Sheet

by luckystarr via cheatography.com/59106/cs/15528/

1.1

A Matrix	row, columns
Coefficients Matrix	Just Left Hand Side
Augmented Matrix	Left and Right Hand Side
Solving Linear Systems	(1) Augmented Matrix (2) Row Operations (3) Solution to Linear System The RHS is the solution
One Solution	Upper triangle with Augmented Matrix
No Solution	Last row is all zeros = RHS number
Infinitely Many Solutions	Last row (including RHS) is all zeros
Inconsistent	Has No Solution

1.1 Example(1)

Example - Use matrices to solve the following system of equations:

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

$$\left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 2 & -8 & 8 \\ -4 & 5 & 9 & -9 \end{array} \right] \xrightarrow{\begin{array}{l} R1+R3 \\ R2/2 \end{array}} \left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & -3 & 13 & -9 \end{array} \right] \xrightarrow{\begin{array}{l} 3R2+R3 \\ -R3+R1 \end{array}} \left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 10 & -13 \end{array} \right] \xrightarrow{\begin{array}{l} R3+R2 \\ R2+R1 \end{array}} \left[\begin{array}{ccc|c} 1 & -2 & 1 & 0 \\ 0 & 1 & -4 & 4 \\ 0 & 0 & 1 & -1.3 \end{array} \right]$$

work down and to the right ↓ →
then up and to the left ← ↑

$$\left[\begin{array}{ccc|c} 1 & 0 & 0 & 0.99 \\ 0 & 1 & 0 & 1.6 \\ 0 & 0 & 1 & 3 \end{array} \right]$$

$x_1 = 0.99$
 $x_2 = 1.6$
 $x_3 = 3$

1.2

Echelon Matrix	(1) Zero Rows at the bottom (2) Leading Entries are down and to the right (3) Zeros are below each leading entry
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1.2 (cont)

Reduced Echelon Matrix	(1) The leading entry of each nonzero row is 1 (2) Zeros are below AND above each 1
Pivot Position	Location of Matrix that Corresponds to a leading 1 in REF
Pivot Column	Column in Matrix that contains a pivot
To get to EF	down and right
To get to REF	up and left
Free Variables	Variables that don't correspond to pivot columns
Consistent System	Pivot in every Column

1.2 Example (1)

- Example 1 - Determine the value(s) of h such that the following matrix is the augmented matrix of a consistent linear system.

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

Reduce the augmented matrix to echelon form

$$\left[\begin{array}{ccc|c} 1 & -3 & 1 & 1 \\ 0 & 6 & -2 & h-2 \end{array} \right] \xrightarrow{-R1+R2}$$

A consistent system cannot contain an equation of the form $0 = \frac{h}{6}$ but it can contain an equation of the form $0 = 0$.

Set $6+3h=0$ and check the value of $-h+2$

$$6+3h=0 \quad \rightarrow \quad h=-2$$

The last row is $0=0$ if $h=-2$, and $\frac{h}{6}=\frac{-2}{6}=-\frac{1}{3}$ is consistent for all h .

1.3

\mathbb{R}^2 Set of all vectors with 2 rows

1.3 Example (1)

Example

$$\mathbf{a}_1 = \begin{bmatrix} 1 \\ 3 \end{bmatrix}, \quad \mathbf{a}_2 = \begin{bmatrix} 4 \\ 2 \end{bmatrix}, \quad \mathbf{a}_3 = \begin{bmatrix} 3 \\ 10 \end{bmatrix}, \quad \text{and let } \mathbf{b} = \begin{bmatrix} -1 \\ 8 \end{bmatrix}$$

Determine if \mathbf{b} is a linear combination of $\mathbf{a}_1, \mathbf{a}_2$, and \mathbf{a}_3 .

→ See if $x_1\mathbf{a}_1 + x_2\mathbf{a}_2 + x_3\mathbf{a}_3 = \mathbf{b}$ has a solution by reducing $\left[\begin{array}{ccc|c} \mathbf{a}_1 & \mathbf{a}_2 & \mathbf{a}_3 & \mathbf{b} \end{array} \right]$ to echelon form and checking if it is consistent.

$$\left[\begin{array}{ccc|c} 1 & 4 & 3 & -1 \\ 0 & 2 & 2 & 4 \\ 3 & 14 & 10 & -5 \end{array} \right] \xrightarrow{\begin{array}{l} R2/2 \\ -3R1+R3 \end{array}} \left[\begin{array}{ccc|c} 1 & 4 & 3 & -1 \\ 0 & 1 & 1 & 2 \\ 0 & 14 & 10 & -5 \end{array} \right] \xrightarrow{\begin{array}{l} R3-14R2 \\ -3R1+R3 \end{array}} \left[\begin{array}{ccc|c} 1 & 4 & 3 & -1 \\ 0 & 1 & 1 & 2 \\ 0 & 0 & -4 & -29 \end{array} \right]$$

pivot in each column
System is consistent
yes, \mathbf{b} can be written as a linear combination of $\mathbf{a}_1, \mathbf{a}_2$, and \mathbf{a}_3 .

1.3 Example (2)

Example 1
Let $\mathbf{a}_1 = \begin{bmatrix} 1 \\ 0 \\ -2 \end{bmatrix}$, $\mathbf{a}_2 = \begin{bmatrix} -2 \\ 1 \\ 7 \end{bmatrix}$ and $\mathbf{b} = \begin{bmatrix} h \\ 3 \\ 7 \end{bmatrix}$

For what value(s) of h is \mathbf{b} in the plane spanned by \mathbf{a}_1 and \mathbf{a}_2 ?
 \mathbf{b} will be in the plane spanned by \mathbf{a}_1 and \mathbf{a}_2 if \mathbf{b} can be written as a linear combination of \mathbf{a}_1 and \mathbf{a}_2 .

Reduce $\left[\begin{array}{cc|c} \mathbf{a}_1 & \mathbf{a}_2 & \mathbf{b} \end{array} \right]$ to echelon form to determine what values of h will make the system consistent.

$$\left[\begin{array}{cc|c} 1 & -2 & h \\ 0 & 1 & 3 \\ 0 & 7 & 7 \end{array} \right] \xrightarrow{\begin{array}{l} R1+2R2 \\ -7R1+R3 \end{array}} \left[\begin{array}{cc|c} 1 & -2 & h \\ 0 & 1 & 3 \\ 0 & 0 & 7-h+4 \end{array} \right] \xrightarrow{\begin{array}{l} R2+R1 \\ -7R1+R3 \end{array}} \left[\begin{array}{cc|c} 1 & -2 & h \\ 0 & 0 & 7-h+4 \end{array} \right]$$

will be consistent if $7-h+4=0$

when $h=-2$, \mathbf{b} is in the plane spanned by \mathbf{a}_1 and \mathbf{a}_2 .

1.4

Vector Equation $\mathbf{x}_1\mathbf{a}_1 + \mathbf{x}_2\mathbf{a}_2 + \mathbf{x}_3\mathbf{a}_3 = \mathbf{b}$

Matrix Equation $\mathbf{A}\mathbf{x} = \mathbf{b}$

If \mathbf{A} is an $m \times n$ matrix the following are all true or all false

$\mathbf{Ax} = \mathbf{b}$ has a solution for every \mathbf{b} in \mathbb{R}^m

Every \mathbf{b} in \mathbb{R}^m is a lin. combo of columns in \mathbf{A}

Columns of \mathbf{A} span \mathbb{R}^m

Matrix \mathbf{A} has a pivot in every row (i.e. no row of zeros)

Anything in **Bold** means it is a vector.

1.4 Example (1)

Example 2 - Show that the matrix equation $\mathbf{Ax} = \mathbf{b}$ does not have a solution for all possible \mathbf{b} , and describe the set of all \mathbf{b} for which $\mathbf{Ax} = \mathbf{b}$ does have a solution.

Reduce $\left[\begin{array}{ccc|c} \mathbf{a}_1 & \mathbf{a}_2 & \mathbf{a}_3 & \mathbf{b} \end{array} \right]$ to echelon form to determine the restrictions on \mathbf{b} for the system to be consistent.

$$\left[\begin{array}{ccc|c} 1 & -2 & -1 & b_1 \\ -2 & 2 & 0 & b_2 \\ 4 & -1 & 3 & b_3 \end{array} \right] \xrightarrow{\begin{array}{l} R1+R2 \\ R2+R1 \end{array}} \left[\begin{array}{ccc|c} 1 & -2 & -1 & b_1 \\ 0 & 0 & -1 & b_1+b_2 \\ 0 & -3 & 2 & b_3-b_1 \end{array} \right] \xrightarrow{\begin{array}{l} R3+3R2 \\ R2+R1 \end{array}} \left[\begin{array}{ccc|c} 1 & -2 & -1 & b_1 \\ 0 & 0 & -1 & b_1+b_2 \\ 0 & 0 & 1 & b_3-2b_1-3b_2 \end{array} \right]$$

A restriction on \mathbf{b} will occur when the last row does not have a pivot.

This system will only have a solution when $b_3 - 2b_1 + \frac{1}{2}b_2 + 7b_3 = 0 \Rightarrow 3b_1 + \frac{1}{2}b_2 + b_3 = 0$

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1.4 Example (2)

• Example - Determine if the columns of matrix A span \mathbb{R}^3 .

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

$\begin{bmatrix} 0 & 0 & 4 & | & b_1 \\ 0 & -3 & -2 & | & b_2 \\ -3 & 9 & -6 & | & b_3 \end{bmatrix} \rightarrow \begin{bmatrix} 0 & 0 & 4 & | & b_1 \\ 0 & -3 & -2 & | & b_2 \\ 0 & 0 & 4 & | & b_3 \end{bmatrix}$

Every row has a pivot so there will be no restrictions on b and there will be a solution for every b . This means that the columns of A span \mathbb{R}^3 because there are 3 rows in A .

1.5

Homogeneous $\mathbf{Ax = 0}$

Trivial Solution $\mathbf{Ax = 0}$ if at least one column is missing a pivot

Determine if homogenous Linear System has a non trivial solution

- (1) Write as Augmented Matrix
- (2) Reduce to EF
- (3) Determine if there are any free variables(column w/o pivot)
- (4) If any free variables, than a non-trivial solution exists
- (5) Non-Trivial Solution can be found by further reducing to REF and solving for x

If $\mathbf{Ax = 0}$ has one free variable

Than x is a line that passes through the origin

If $\mathbf{Ax = 0}$ has two free variables

Than x has a plane that passes through the origin

1.5 Example (1)

• Example 1 - Determine if the following linear system has a nontrivial solution and then describe the solution set.

$$\begin{array}{l} x_1 - 2x_2 + 3x_3 = 0 \\ -2x_1 - 3x_2 - 4x_3 = 0 \\ 2x_1 - 4x_2 + 9x_3 = 0 \end{array}$$

Reduce the augmented matrix to echelon form and check if there are free variables

$\begin{bmatrix} 1 & -2 & 3 & | & 0 \\ -2 & -3 & -4 & | & 0 \\ 2 & -4 & 9 & | & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & -2 & 3 & | & 0 \\ 0 & -7 & 2 & | & 0 \\ 0 & 0 & 3 & | & 0 \end{bmatrix}$

Every column has a pivot so there are no free variables

$\boxed{\vec{x} = \vec{0}}$ (the trivial solution) is the only solution

No nontrivial solution

1.5 Example (2)

• Example 2 - Determine if the following linear system has a nontrivial solution and then describe the solution set.

$$\begin{array}{l} 2x_1 + 4x_2 - 6x_3 = 0 \\ 4x_1 + 8x_2 - 10x_3 = 0 \end{array}$$

Repeat the same procedure as in Example 1.

$\begin{bmatrix} 2 & 4 & -6 & | & 0 \\ 4 & 8 & -10 & | & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 2 & 4 & -6 & | & 0 \\ 0 & 0 & 2 & | & 0 \end{bmatrix}$

Column 2 is missing a pivot $\Rightarrow x_2$ is free variable and \vec{x} has a nontrivial solution

Reduce $[A|b]$ to reduced echelon form to solve for \vec{x}

$\rightarrow \begin{bmatrix} 2 & 4 & -6 & | & 0 \\ 0 & 0 & 1 & | & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 0 & 4 & 0 & | & 0 \\ 0 & 0 & 1 & | & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 0 & 0 & | & 0 \\ 0 & 0 & 1 & | & 0 \end{bmatrix}$

$\vec{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} -2x_2 \\ x_2 \\ 0 \end{bmatrix}$

1.7

Linear Independent No free Variables, none of the vectors are multiples of each other

To check ind/dep reduce augmented matrix to EF and see if there are free variables(i.e. every column must have a pivot to be linearly independent)

To check if multiples $\mathbf{u} = c * \mathbf{v}$ find value of c , then it is a multiple therefore linearly dependent

Linearly Dependent If there are more columns than rows

1.7 Example (1)

• Example 4 - Determine the values of h that make the following vectors linearly dependent.

$$\mathbf{v}_1 = \begin{bmatrix} 3 \\ -6 \\ 1 \end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix} -6 \\ 4 \\ -3 \end{bmatrix}, \mathbf{v}_3 = \begin{bmatrix} 9 \\ h \\ 3 \end{bmatrix}$$

Reduce $[\vec{v}_1 \vec{v}_2 \vec{v}_3 | 0]$ to echelon form and choose h so that there is a free variable

$$\begin{bmatrix} 3 & -6 & 9 & | & 0 \\ -6 & 4 & h & | & 0 \\ -3 & 1 & 3 & | & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & -2 & 3 & | & 0 \\ -6 & 4 & h+18 & | & 0 \\ -1 & 0 & 0 & | & 0 \end{bmatrix}$$

$$\rightarrow \begin{bmatrix} 1 & -2 & 3 & | & 0 \\ 0 & -8 & h+18 & | & 0 \\ 0 & 0 & 0 & | & 0 \end{bmatrix} \quad \text{For there to be a free variable, } -(h+18) = 0 \rightarrow \boxed{h = -18}$$

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1.8

Every Matrix Transformation is a: Linear Transformation

$T(\mathbf{x}) = A(\mathbf{x})$

If A is $m \times n$ Matrix, then the properties are

$$(1) T(\mathbf{u} + \mathbf{v}) = T(\mathbf{u}) + T(\mathbf{v})$$

$$(2) T(c\mathbf{u}) = cT(\mathbf{u})$$

$$(3) T(\mathbf{0}) = \mathbf{0}$$

$$(4) T(\mathbf{cu} + \mathbf{dv}) = cT(\mathbf{u}) + dT(\mathbf{v})$$

1.8 Example (1)

• Example 5 - Suppose $T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ be a linear transformation such that $T \left(\begin{bmatrix} 1 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} 2 \\ 3 \end{bmatrix}$ and $T \left(\begin{bmatrix} 1 \\ -1 \end{bmatrix} \right) = \begin{bmatrix} 1 \\ -2 \end{bmatrix}$. Find $T \left(\begin{bmatrix} 4 \\ 0 \end{bmatrix} \right)$. Let $\vec{x} = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$

$$\begin{aligned} \textcircled{1} \quad \text{write } \vec{x} \text{ as a linear combination of } \begin{bmatrix} 1 \\ 1 \end{bmatrix} \text{ and } \begin{bmatrix} 1 \\ -1 \end{bmatrix}. \\ \begin{bmatrix} 4 \\ 0 \end{bmatrix} = c_1 \begin{bmatrix} 1 \\ 1 \end{bmatrix} + c_2 \begin{bmatrix} 1 \\ -1 \end{bmatrix} \\ 4 = c_1 + c_2 \\ 0 = c_1 - c_2 \\ \hline 4 = 2c_1 \Rightarrow c_1 = 2 \text{ & } c_2 = 2 \end{aligned}$$

$$\begin{aligned} \textcircled{2} \quad \text{Find the transformation of } \vec{x} \\ T \left(\begin{bmatrix} 4 \\ 0 \end{bmatrix} \right) = T \left(2 \begin{bmatrix} 1 \\ 1 \end{bmatrix} + 2 \begin{bmatrix} 1 \\ -1 \end{bmatrix} \right) \\ = 2T \left(\begin{bmatrix} 1 \\ 1 \end{bmatrix} \right) + 2T \left(\begin{bmatrix} 1 \\ -1 \end{bmatrix} \right) \\ = 2 \begin{bmatrix} 2 \\ 3 \end{bmatrix} + 2 \begin{bmatrix} 1 \\ -2 \end{bmatrix} = \begin{bmatrix} 6 \\ 2 \end{bmatrix} \end{aligned}$$

given in the original problem.

1.8 Example (2)

• Example 5 - Suppose $T : \mathbb{R}^2 \rightarrow \mathbb{R}^2$ be a linear transformation such that $T \left(\begin{bmatrix} 1 \\ 1 \end{bmatrix} \right) = \begin{bmatrix} 2 \\ 3 \end{bmatrix}$ and $T \left(\begin{bmatrix} 1 \\ -1 \end{bmatrix} \right) = \begin{bmatrix} 1 \\ -2 \end{bmatrix}$. Find $T \left(\begin{bmatrix} 4 \\ 0 \end{bmatrix} \right)$. Let $\vec{x} = \begin{bmatrix} 4 \\ 0 \end{bmatrix}$

$$\begin{aligned} \textcircled{1} \quad \text{write } \vec{x} \text{ as a linear combination of } \begin{bmatrix} 1 \\ 1 \end{bmatrix} \text{ and } \begin{bmatrix} 1 \\ -1 \end{bmatrix}. \\ \begin{bmatrix} 4 \\ 0 \end{bmatrix} = c_1 \begin{bmatrix} 1 \\ 1 \end{bmatrix} + c_2 \begin{bmatrix} 1 \\ -1 \end{bmatrix} \\ 4 = c_1 + c_2 \\ 0 = c_1 - c_2 \\ \hline 4 = 2c_1 \Rightarrow c_1 = 2 \text{ & } c_2 = 2 \end{aligned}$$

$$\begin{aligned} \textcircled{2} \quad \text{Find the transformation of } \vec{x} \\ T \left(\begin{bmatrix} 4 \\ 0 \end{bmatrix} \right) = T \left(2 \begin{bmatrix} 1 \\ 1 \end{bmatrix} + 2 \begin{bmatrix} 1 \\ -1 \end{bmatrix} \right) \\ = 2T \left(\begin{bmatrix} 1 \\ 1 \end{bmatrix} \right) + 2T \left(\begin{bmatrix} 1 \\ -1 \end{bmatrix} \right) \\ = 2 \begin{bmatrix} 2 \\ 3 \end{bmatrix} + 2 \begin{bmatrix} 1 \\ -2 \end{bmatrix} = \begin{bmatrix} 6 \\ 2 \end{bmatrix} \end{aligned}$$

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1.9

$RR^n \rightarrow RR^m$ is said to be 'onto' Equation $T(x) = Ax = b$ has a unique solution or more than one solution each row has a pivot

$RR^n \rightarrow RR^m$ is said to be one-to-one Equation $T(x) = Ax = b$ has a unique solution or no solution each row has a pivot

2.1

Addition of Matrices Can Add matrices if they have same # of rows and columns (ie $A(3x4)$ and $B(3x4)$ so you can add them)

Multiply by Scalar Multiply each entry by scalar

Matrix Multiplication on $(A \times B)$ Must each row of A by each column of B

Powers of a Matrix Can compute powers by if the matrix has the same number of columns as rows

Transpose of Matrix row 1 of A becomes column 1 of A
row 2 of A becomes column 2 of A

2.1 (cont)

Properties of Transpose (1) if A is $m \times n$, then A^T is $n \times m$
 (2) $(A^T)^T = A$
 (3) $(A + B)^T = A^T + B^T$
 (4) $(tA)^T = tA^T$
 (5) $(AB)^T = B^T A^T$

2.2

Singular matrix A matrix that is NOT invertable

Determinate of A (2 x 2) $\det A = ad - bc$

Matrix If A is invertable & (nxn) There will never be no solution or infinitely many solutions to $Ax = b$

Properties of Invertable Matrices $(A^{-1})^{-1} = A$
 (assuming A & B are invertable) $(AB)^{-1} = B^{-1} A^{-1}$
 $(A^T)^{-1} = (A^{-1})^T$

Finding Inverse Matrix $[A | I] \rightarrow [I | A^{-1}]$ Use row operations
 STOP when you get a row of Zeros, it cannot be reduced

2.3 Invertable Matrix Theorem

- The Invertible Matrix Theorem - Let A be a square $n \times n$ matrix. Then all of the following statements are equivalent:
 - (a) A is an invertible matrix
 - (b) A is row equivalent to the $n \times n$ identity matrix I .
 - (c) A has n pivots.
 - (d) The equation $Ax = 0$ has only the trivial solution.
 - (e) The columns of A form a linearly independent set.
 - (f) The linear transformation $T(x) = Ax$ is one-to-one.
 - (g) The equation $Ax = b$ has a unique solution for each b in \mathbb{R}^n .
 - (h) The columns of A span \mathbb{R}^n .
 - (i) The linear transformation $T(x) = Ax$ is onto.
 - (j) There is an $n \times n$ matrix C such that $CA = I$.
 - (k) There is an $n \times n$ matrix D such that $AD = I$.
 - (l) A^T is invertible.

The above theorem states that if one of these is false, they all must be false. If one is true, then they are all true.

2.8

A subspace S of RR^n is a subspace if S satisfies:

- (1) S contains zero vector
- (2) If \mathbf{u} & \mathbf{v} are in S , then $\mathbf{u} + \mathbf{v}$ is also in S
- (3) If r is a real # & \mathbf{u} is in S , then $r\mathbf{u}$ is also in S

Subspace RR^3 Any Plane that Passes through the origin forms a subspace RR^3
 Any set that contains nonlinear terms will NOT form a subspace RR^3

Null Space (Nul A) To determine if \mathbf{u} is in the Nul(A), check if: $A\mathbf{u} = \mathbf{0}$
 If yes --> then \mathbf{u} is in the Nullspace

2.2 Example (1)

- Example 2 - Let A , B , C and X be $n \times n$ invertible matrices. Solve $B(X + A)^{-1} = C$ for the matrix X .

<p><u>Method 1</u> Get $(X + A)^{-1}$ by itself 1st. $B(X + A)^{-1} = C$ $B^{-1}B(X + A)^{-1} = B^{-1}C$ <small>Note: If you multiply on the left for one side, you must multiply on the left on the other side!</small> $\Rightarrow X(X + A)^{-1} = B^{-1}C$ $(X + A)^{-1} = B^{-1}C$ $((X + A)^{-1})^{-1} = (B^{-1}C)^{-1}$ $X + A = C^{-1}(B^{-1})^{-1}$ $X = C^{-1}B - A$</p>	<p><u>Method 2</u> $B(X + A)^{-1} = C$ $(B(X + A)^{-1})^T = C^T$ $((X + A)^{-1})^T B^T = C^T$ $(X + A)(B^T) = C^T$ $X B^T + A B^T = C^T$ $X B^T = C^T - A B^T$ $X = C^T B^{-1} - A B^T$ $X = C^{-1}B - A$</p>
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2.8 Example (1)

- Example 1 - Given the following matrix A and an echelon form of A , find a basis for $\text{Col } A$.

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

↑ echelon form of A .
 pivot columns = columns 1 and 3.
 basis for $\text{Col } A$ = pivot columns of A (not pivot columns of \tilde{A})
 basis for $\text{Col } A = \left\{ \begin{bmatrix} 3 \\ 2 \\ 3 \end{bmatrix}, \begin{bmatrix} 9 \\ 0 \\ 6 \end{bmatrix} \right\}$
 $\text{Col } A = c_1 \begin{bmatrix} 3 \\ 2 \\ 3 \end{bmatrix} + c_2 \begin{bmatrix} 9 \\ 0 \\ 6 \end{bmatrix}$

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2.8 Example (2)

- Example 2 - Given the following matrix A and an echelon form of A , find a basis for $\text{Nul } A$.

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

Reduce $[A | \vec{0}]$ to reduced echelon form to solve for \vec{x}

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

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

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

Basis for $\text{Nul } A = \left\{ \begin{bmatrix} 2 \\ 1 \\ -1 \\ 1 \end{bmatrix}, \begin{bmatrix} 6 \\ 0 \\ -1 \\ 1 \end{bmatrix} \right\}$ * vectors in basis for $\text{Nul } A = \neq$ free variables.

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2.9

Dimension of a non-zero Subspace # of vectors in any basis; it is the # of linearly independent vectors

Dimension of a zero Subspace is Zero

Dimension of a Column Space # of pivot columns

Dimension of a Null Space # of free variables in the solution $\text{Ax}=\vec{0}$

Rank of a Matrix # of pivot columns

The Rank Theorem Matrix A has n columns: rank A (# pivots) + dim $\text{Nul } A$ (# free var.) = n

dim = dimension; var. = variable

2.9 Reference

- The Invertible Matrix Theorem Continued- Let A be a square $n \times n$ matrix. Then all of the following statements are equivalent to the statement that A is an invertible matrix. (see Section 2.3)

- (m) The columns of A form a basis of \mathbb{R}^n (because they are linearly independent)
- (n) $\text{Col } A = \mathbb{R}^n$
- (o) $\dim \text{Col } A = n$ (because n pivots)
- (p) $\text{rank } A = n$ (because n pivots)
- (q) $\text{Nul } A = \{\vec{0}\}$ (because no free variables)
- (r) $\dim \text{Nul } A = 0$ (because no free variables)

Because every vector in \mathbb{R}^n can be written as a linear combination of the columns of A .

rank A + dim $\text{Nul } A = n$

3.1

Calculating Determinant of Matrix A is another way to tell if a linear system of equations has a solution

- (1) $\text{Det}(A) \neq 0$, then $\text{Ax}=\vec{b}$ has a unique solution
- (2) $\text{Det}(A) = 0$, then $\text{Ax}=\vec{b}$ has no solutions or infinitely many

If $\text{Ax} \neq \vec{0}$

A^{-1} exist

If $\text{Ax} = \vec{0}$

A^{-1} Does NOT exist

Cofactor Expansion

Use row/column w/ most zeros

If Matrix A has an upper or lower triangle of zeros

The $\text{det}(A)$ is the multiplication down the diagonals

3.1 Reference (1)

2. Determinant of a 3×3 Matrix

- Let A be an $n \times n$ matrix (or here a 3×3 matrix)

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

- The determinant of matrix A is given as follows:

$$\begin{aligned} \det A &= a_{11} \det A_{11} - a_{12} \det A_{12} + a_{13} \det A_{13} \\ \det A_{11} &= a_{22}a_{33} - a_{23}a_{32} = \begin{vmatrix} a_{22} & a_{23} \\ a_{32} & a_{33} \end{vmatrix} \\ \det A_{12} &= a_{21}a_{33} - a_{23}a_{31} = \begin{vmatrix} a_{21} & a_{23} \\ a_{31} & a_{33} \end{vmatrix} \\ \det A_{13} &= a_{21}a_{32} - a_{22}a_{31} = \begin{vmatrix} a_{21} & a_{22} \\ a_{31} & a_{32} \end{vmatrix} \end{aligned}$$

- This formula utilizes a cofactor expansion across the first row

3.1 Example (1)

- Example - Compute the determinate of

$$\begin{aligned} A &= \begin{bmatrix} -3 & 1 & 2 \\ 5 & 5 & -8 \\ 4 & 2 & -5 \end{bmatrix} \\ \det A &= \begin{vmatrix} -3 & 1 & 2 \\ 5 & 5 & -8 \\ 4 & 2 & -5 \end{vmatrix} = +(-3) \begin{vmatrix} 5 & -8 \\ 4 & -5 \end{vmatrix} + 2 \begin{vmatrix} 5 & 5 \\ 4 & 2 \end{vmatrix} \\ &= -3(-25+40) - 1(-25+32) + 2(10-20) \\ &= -3(-15) - 1(7) + 2(-10) \\ &= 27 - 7 - 20 \\ &= \boxed{0} \end{aligned}$$

← This means A^{-1} does not exist and $A\vec{x} = \vec{b}$ has no solution or infinitely many solutions

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3.1 Reference (2)

- Shortcut Method for a 3×3 matrix

$$\begin{aligned} \text{det } A &= a_{11}a_{22}a_{33} + a_{12}a_{23}a_{31} + a_{13}a_{21}a_{32} - a_{11}a_{23}a_{32} - a_{12}a_{21}a_{33} - a_{13}a_{22}a_{31} \\ &\quad \text{add column 1 \# 2 to the right of the matrix} \\ &\quad \text{do not memorize this, learn the method!} \end{aligned}$$

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3.1 Example (2)

- Example 2 - Use a cofactor expansion to compute the determinate of

$$\begin{aligned} A &= \begin{bmatrix} 1 & -2 & 5 & 2 \\ 0 & 0 & 3 & 0 \\ 2 & -6 & -7 & 5 \\ 5 & 0 & 4 & 4 \end{bmatrix} \\ &\quad \text{choose the row or column with the most zeros} \Rightarrow \text{choose row 2.} \\ \det A &= -3 \begin{vmatrix} 5 & -2 & 2 & | & 0 & 1 & 2 \\ 0 & -6 & 5 & | & -6 & 5 & -2 \\ 0 & 0 & 0 & | & 4 & 1 & -6 \end{vmatrix} \\ &= -3 \begin{vmatrix} 5 & -2 & 2 & | & 0 & 1 & 2 \\ 0 & -6 & 5 & | & -6 & 5 & -2 \\ 0 & 0 & 0 & | & 4 & 1 & -6 \end{vmatrix} \\ &= -3 \begin{vmatrix} 5 & (-10+12) & 0 & | & 0 & 1 & 2 \\ 0 & 4 & 4 & | & -6 & 5 & -2 \\ 0 & 0 & 0 & | & 4 & 1 & -6 \end{vmatrix} \\ &= -3 (10-8) = \boxed{-6} \end{aligned}$$

You can also use the shortcut 3x3 method to evaluate this.

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3.2

Determine if a multiple of 1 row of A is added to another row to produce Matrix B , then $\det(B) = \det(A)$

1

Determine if 2 rows of A are interchanged to produce B , then $\det(B) = -\det(A)$

2

Determine if one row of A is multiplied to produce B , then $\det(B) = k \cdot \det(A)$

3

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3.2 (cont)

Assuming both A & B are n x n Matrices	(1) $\det(A^T) = \det(A)$
	(2) $\det(AB) = \det(A)\det(B)$
	(3) $\det(A^{-1}) = 1/\det(A)$
	(4) $\det(cA) = c^n \det(A)$
	(5) $\det(A^T) = (\det A)^T$

3.3 AKA Cramer's Rule

Cramer's Rule	Can be used to find the solution to a linear system of equations $Ax=b$ when A is an invertible square matrix
Def. of Cramer's Rule	Let A be an n x n invertible matrix. For any b in \mathbb{R}^n , the unique solution x of $Ax=b$ has entries given by $x_i = \det(A_i)/\det(A)$ $i = 1, 2, \dots, n$

$A_i(b)$ is the matrix A w/ column i replaced w/ vector b

3.3 Example (1)

• Example 2 - Use Cramer's Rule to compute the solution to the system for 3x3's.

$$\begin{aligned} 3x_1 + x_2 &= 5 \\ -x_1 + 2x_2 + x_3 &= -2 \\ -x_2 + 2x_3 &= -1 \end{aligned}$$

$$x_1 = \frac{\begin{vmatrix} 5 & 1 & 0 \\ -1 & 2 & 1 \\ 0 & -1 & 2 \end{vmatrix}}{\begin{vmatrix} 3 & 1 & 0 \\ -1 & 2 & 1 \\ 0 & -1 & 2 \end{vmatrix}} = \frac{20-1+0+4+5-0}{12+0+0+2+3-0} = \frac{28}{17}$$

$$x_2 = \frac{\begin{vmatrix} 3 & 5 & 0 \\ -1 & -2 & 1 \\ 0 & 1 & 2 \end{vmatrix}}{\begin{vmatrix} 3 & 1 & 0 \\ -1 & 2 & 1 \\ 0 & -1 & 2 \end{vmatrix}} = \frac{-6+0+5-(-6)-0}{17} = \frac{-8}{17}$$

$$x_3 = \frac{\begin{vmatrix} 3 & 1 & 5 \\ -1 & 2 & -1 \\ 0 & -1 & 1 \end{vmatrix}}{\begin{vmatrix} 3 & 1 & 0 \\ -1 & 2 & 1 \\ 0 & -1 & 2 \end{vmatrix}} = \frac{-1+0+5-(-1)-0}{17} = \frac{1}{17}$$

5.1

$Au = \lambda u$	A is an nxn matrix. A nonzero vector u is an eigenvector of A if there exists such a scalar λ
To determine if λ is an eigenvalue	reduce $[(A-\lambda I) 0]$ to echelon form and see if it has any free variables. yes $\rightarrow \lambda$ is Eigenvalue no $\rightarrow \lambda$ is not eigenvalue

To determine if given vector is an eigenvector

Eigenspace of A = Nullspace of $(A-\lambda I)$

Eigenvalues of triangular Matrix entries along diagonal *you CANNOT row reduce a matrix to find its eigenvalues

5.1 Example (1)

• Example 2 (3x3 Example)
Is $\lambda = 1$ an eigenvalue of $A = \begin{bmatrix} 4 & -2 & 3 \\ 0 & -1 & 3 \\ -1 & 2 & -2 \end{bmatrix}$? Why or why not?
Also, find the corresponding eigenvector.

Check if $[(A-\lambda I)|0]$ has a nontrivial solution (free variable).
 $[(A-\lambda I)|0] = \left[\begin{array}{ccc|c} 4-1 & -2 & 3 & 0 \\ 0 & -1 & 3 & 0 \\ -1 & 2 & -2 & 0 \end{array} \right] \xrightarrow{\substack{R1-R2 \\ R3+R2}} \left[\begin{array}{ccc|c} 3 & -2 & 3 & 0 \\ 0 & -1 & 3 & 0 \\ 1 & 0 & 1 & 0 \end{array} \right] \xrightarrow{\substack{R2 \cdot -1 \\ R3-R2}} \left[\begin{array}{ccc|c} 3 & -2 & 3 & 0 \\ 0 & 1 & -3 & 0 \\ 1 & 0 & 1 & 0 \end{array} \right] \xrightarrow{\substack{R1+R3 \\ R2+R3}} \left[\begin{array}{ccc|c} 4 & -2 & 3 & 0 \\ 0 & 2 & -2 & 0 \\ 1 & 0 & 1 & 0 \end{array} \right] \xrightarrow{\substack{R1-R2 \\ R2 \cdot -1}} \left[\begin{array}{ccc|c} 4 & -2 & 3 & 0 \\ 0 & 2 & 2 & 0 \\ 1 & 0 & 1 & 0 \end{array} \right] \xrightarrow{\substack{R1-R2 \\ R2 \cdot \frac{1}{2}}} \left[\begin{array}{ccc|c} 4 & -2 & 3 & 0 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 1 & 0 \end{array} \right] \xrightarrow{\substack{R1-4R3 \\ R2-R3}} \left[\begin{array}{ccc|c} 0 & -2 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 \end{array} \right] \xrightarrow{\substack{R1 \cdot -1 \\ R3-R1}} \left[\begin{array}{ccc|c} 0 & 2 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array} \right] \xrightarrow{\substack{R1 \cdot \frac{1}{2} \\ R3-R1}} \left[\begin{array}{ccc|c} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array} \right] \xrightarrow{\substack{R1 \rightarrow 0 \\ R3-R1}} \left[\begin{array}{ccc|c} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{array} \right]$

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5.1 Example (2)

• Example 2
Is $\begin{bmatrix} 1 \\ 2 \\ 2 \end{bmatrix}$ an eigenvector of $\begin{bmatrix} 3 & 6 & 7 \\ 3 & 2 & 7 \\ 5 & 6 & 4 \end{bmatrix}$? If so, find the eigenvalue.

Check if $A\vec{x} = \lambda\vec{x}$
 $A\vec{x} = \begin{bmatrix} 3 & 6 & 7 \\ 3 & 2 & 7 \\ 5 & 6 & 4 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \\ 2 \end{bmatrix} = \begin{bmatrix} 5 \\ 13 \\ 1 \end{bmatrix} \stackrel{?}{=} \lambda \begin{bmatrix} 1 \\ 2 \\ 2 \end{bmatrix}$

No value of λ will make this true.
 \vec{x} is not an eigenvector.

5.1 Example (3)

matrix A and eigenvalue λ .

Reduce $[(A-\lambda I)|0]$ to reduced echelon form and solve for λ .
 $[(A-\lambda I)|0] = \left[\begin{array}{ccc|c} 4-\lambda & 4 & -2 & 0 \\ 1 & 4 & -1 & 0 \\ 3 & 6 & -1 & 0 \end{array} \right]$
 $\xrightarrow{\substack{R1-R2 \\ R3-3R2}} \left[\begin{array}{ccc|c} 3-\lambda & 0 & -2 & 0 \\ 1 & 4 & -1 & 0 \\ 0 & 6 & -4 & 0 \end{array} \right] \xrightarrow{\substack{R3-R1 \\ R3 \cdot \frac{1}{6}}} \left[\begin{array}{ccc|c} 3-\lambda & 0 & -2 & 0 \\ 1 & 4 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{array} \right] \xrightarrow{\substack{R1-R2 \\ R2 \cdot -1}} \left[\begin{array}{ccc|c} 2-\lambda & 0 & -2 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{array} \right] \xrightarrow{\substack{R1 \cdot \frac{1}{2} \\ R1+R2}} \left[\begin{array}{ccc|c} 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{array} \right]$

$\lambda_1 = -2, \lambda_2 = 1, \lambda_3 = 2$

geometric description is a plane

5.2

If λ is an eigenvalue of A then $(A-\lambda I)x=0$ will have a nontrivial solution of a Matrix A

A nontrivial solution will exist if $\det(A-\lambda I)=0$ (Characteristic Equation)

A is nxn
(1) The # 0 is NOT an λ of A
(2) The $\det(A)$ is not zero
is invertible if and only if

Similar Matrices
If nxn Matrices A and B are similar, then they have the same characteristic polynomial (same λ) with same multiplicities

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6.2 Example (3)

• Example 1 - Compute the orthogonal projection of $\begin{bmatrix} 1 \\ -1 \end{bmatrix}$ onto the line through $\begin{bmatrix} -1 \\ 3 \end{bmatrix}$ and the origin.

$\vec{y} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$ = vector being projected
 $\vec{u} = \begin{bmatrix} -1 \\ 3 \end{bmatrix}$ = vector that the line passes through

orthogonal projection = $\hat{y} = \left(\frac{\vec{u} \cdot \vec{u}}{\vec{u} \cdot \vec{u}} \right) \vec{u}$
 $= \frac{-1+9}{(-1)^2+3^2} \vec{u}$
 $= \frac{8}{10} \vec{u} = \frac{4}{5} \vec{u} = \begin{bmatrix} \frac{4}{5} \\ \frac{12}{5} \end{bmatrix}$

6.2 Example (4)

• Example 2 - Let $y = \begin{bmatrix} 2 \\ 6 \end{bmatrix}$ and $u = \begin{bmatrix} 7 \\ 1 \end{bmatrix}$. Write y as the sum of a vector in $\text{Span}\{u\}$ and a vector orthogonal to u .

$= \alpha \vec{u} = \vec{y}$
 $\vec{y} = \vec{y} + \vec{z}$
 $\vec{y} = \left(\frac{\vec{y} \cdot \vec{u}}{\vec{u} \cdot \vec{u}} \right) \vec{u} = \left(\frac{14+6}{49+1} \right) \vec{u} = \frac{20}{50} \vec{u} = \begin{bmatrix} 14/5 \\ 2/5 \end{bmatrix}$
 $\vec{z} = \vec{y} - \vec{y} = \begin{bmatrix} 2 \\ 6 \end{bmatrix} - \begin{bmatrix} 14/5 \\ 2/5 \end{bmatrix} = \begin{bmatrix} -4/5 \\ 28/5 \end{bmatrix}$
 $\vec{y} = \begin{bmatrix} 14/5 \\ 2/5 \end{bmatrix} + \begin{bmatrix} -4/5 \\ 28/5 \end{bmatrix}$

6.2 Example (5)

• Example 3 - Let $y = \begin{bmatrix} -3 \\ 9 \end{bmatrix}$ and $u = \begin{bmatrix} 1 \\ 2 \end{bmatrix}$. Compute the distance from y to the line through u and the origin.

distance = $\|\vec{y} - \hat{y}\|$

① Find \hat{y}
 $\hat{y} = \left(\frac{\vec{y} \cdot \vec{u}}{\vec{u} \cdot \vec{u}} \right) \vec{u} = \left(\frac{-3+18}{1+4} \right) \vec{u} = 3 \vec{u} = \begin{bmatrix} 3 \\ 6 \end{bmatrix}$

② Find $\vec{y} - \hat{y}$
 $\vec{y} - \hat{y} = \begin{bmatrix} -3 \\ 9 \end{bmatrix} - \begin{bmatrix} 3 \\ 6 \end{bmatrix} = \begin{bmatrix} -6 \\ 3 \end{bmatrix}$

③ Find $\|\vec{y} - \hat{y}\|$
 $\|\vec{y} - \hat{y}\| = \sqrt{(-6)^2 + 3^2} = \sqrt{36+9} = \sqrt{45} = \boxed{3\sqrt{5}}$

6.2 Example (6)

• Example 1 - Determine if the following set of vectors is orthonormal. If it is only orthogonal, normalize the vectors to produce an orthonormal set.

$\begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} 0 \\ -1 \\ 0 \end{bmatrix}$ orthogonal and normalized
 $\vec{v}_1, \vec{v}_2 = 0+1+0 \neq 0 \Rightarrow$ not orthogonal
 \Rightarrow not orthonormal

② No need to check if they are normalized since they are not orthogonal

6.2 Example (7)

• Example 2 - Determine if the following set of vectors is orthonormal. If it is only orthogonal, normalize the vectors to produce an orthonormal set.

① Check if they are orthogonal
 $\vec{v}_1, \vec{v}_2 = -\frac{2}{3} + \frac{2}{3} + 0 = 0 \neq 1$
 $\vec{v}_1, \vec{v}_3 = -\frac{2}{3} + 0 + 0 = 0 \neq 1$
 $\vec{v}_2, \vec{v}_3 = \frac{2}{3} + 0 + 0 = 0 \neq 1$

② Check if they are normalized
 $\|\vec{v}_1\| = \sqrt{(-\frac{2}{3})^2 + (\frac{1}{3})^2} = 1$
 $\|\vec{v}_2\| = \sqrt{(\frac{2}{3})^2 + (\frac{1}{3})^2} = 1$
 $\|\vec{v}_3\| = \sqrt{(\frac{2}{3})^2 + 0^2} = 1$

$\vec{v}_1 = \begin{bmatrix} -2/3 \\ 1/3 \\ 0 \end{bmatrix}, \vec{v}_2 = \begin{bmatrix} 2/3 \\ 1/3 \\ 0 \end{bmatrix}, \vec{v}_3 = \begin{bmatrix} 2/3 \\ 0 \\ 0 \end{bmatrix}$ orthonormal set

6.3 Example (2)

• Example 1 - Verify that $\{u_1, u_2\}$ is an orthogonal set, and then find the orthogonal projection of y onto $\text{Span}\{u_1, u_2\}$.

$\vec{u}_1 = \begin{bmatrix} 6 \\ 3 \\ -2 \end{bmatrix}, \vec{u}_2 = \begin{bmatrix} 3 \\ 4 \\ 0 \end{bmatrix}, \vec{u}_3 = \begin{bmatrix} -4 \\ 3 \\ 0 \end{bmatrix}$
 $\vec{u}_1 \cdot \vec{u}_2 = -12+12+0 = 0 \Rightarrow \vec{u}_1 \perp \vec{u}_2$

Orthogonal projection of \vec{y} onto $\text{Span}\{\vec{u}_1, \vec{u}_2\}$
 $= \hat{y} = \left(\frac{\vec{y} \cdot \vec{u}_1}{\vec{u}_1 \cdot \vec{u}_1} \right) \vec{u}_1 + \left(\frac{\vec{y} \cdot \vec{u}_2}{\vec{u}_2 \cdot \vec{u}_2} \right) \vec{u}_2 = \begin{bmatrix} 6 \\ 3 \\ -2 \end{bmatrix} - \frac{4}{5} \begin{bmatrix} 3 \\ 4 \\ 0 \end{bmatrix}$
 $= \begin{bmatrix} 18+12+8 \\ 9+16+0 \\ -16+0+0 \end{bmatrix} = \begin{bmatrix} 38 \\ 25 \\ 0 \end{bmatrix} = \frac{38}{25} \vec{u}_1 - \frac{16}{25} \vec{u}_2 = \begin{bmatrix} \frac{38}{25} \\ \frac{12}{5} \\ 0 \end{bmatrix}$

6.3 Example (3)

• Example 3 - Let W be a subspace spanned by the u 's, and write y as the sum of a vector in W and a vector orthogonal to W .

$\vec{y} = \begin{bmatrix} -1 \\ 4 \\ 3 \end{bmatrix}, \vec{u}_1 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \vec{u}_2 = \begin{bmatrix} -1 \\ 2 \\ -2 \end{bmatrix}$
 $\vec{z} = \vec{y} + \vec{w}$
 $\vec{w} = \left(\frac{\vec{y} \cdot \vec{u}_1}{\vec{u}_1 \cdot \vec{u}_1} \right) \vec{u}_1 + \left(\frac{\vec{y} \cdot \vec{u}_2}{\vec{u}_2 \cdot \vec{u}_2} \right) \vec{u}_2$
 $\vec{y} = \left(\frac{-1+4+3}{1+1+1} \right) \vec{u}_1 + \left(\frac{-1+8-6}{1+4+4} \right) \vec{u}_2$
 $\vec{y} = 2\vec{u}_1 + \frac{1}{2}\vec{u}_2 = 2 \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} + \frac{1}{2} \begin{bmatrix} -1 \\ 2 \\ -2 \end{bmatrix} = \begin{bmatrix} 3/2 \\ 3/2 \\ -1/2 \end{bmatrix}$

6.3 Example (4)

• Example 2 - Find the best approximation to z by vectors of the form $c_1 v_1 + c_2 v_2$. $\hat{z} = \hat{z}$ = closest point to \hat{z}

Same as vectors in $\text{Span}\{\vec{v}_1, \vec{v}_2\}$
 $\vec{z} = \begin{bmatrix} 2 \\ 4 \\ 0 \\ -1 \end{bmatrix}, \vec{v}_1 = \begin{bmatrix} 2 \\ 0 \\ -1 \\ -3 \end{bmatrix}, \vec{v}_2 = \begin{bmatrix} 5 \\ 4 \\ 2 \\ 2 \end{bmatrix}$
 $\hat{z} = \left(\frac{\vec{z} \cdot \vec{v}_1}{\vec{v}_1 \cdot \vec{v}_1} \right) \vec{v}_1 + \left(\frac{\vec{z} \cdot \vec{v}_2}{\vec{v}_2 \cdot \vec{v}_2} \right) \vec{v}_2$
 $\hat{z} = \left(\frac{4+0+0+3}{4+0+1+9} \right) \vec{v}_1 + \left(\frac{10-8+0-2}{25+4+16+4} \right) \vec{v}_2$
 $\hat{z} = \frac{1}{2} \vec{v}_1 + 0 \vec{v}_2 = \begin{bmatrix} 1 \\ 0 \\ -\frac{1}{2} \\ 0 \end{bmatrix}$

6.4

Gram-Schmidt Process Overview	take a given set of vectors & transform them into a set of orthogonal or orthonormal vectors
Given x_1 & x_2 , produce v_1 & v_2 where the v 's are perp. to each other	(1) Let $v_1 = x_1$ (2) Find $v_2 = x_2 - \text{proj}_{v_1} x_2$
$x_2 \hat{}$	$(x_2 \cdot v_1) / (v_1 \cdot v_1) \cdot v_1$

6.3 Example (1.1)

• Example - Assume that $\{u_1, \dots, u_4\}$ is an orthogonal basis for \mathbb{R}^4 . Write x as the sum of two vectors, one in $\text{Span}\{u_1, u_2, u_3\}$ and one in $\text{Span}\{u_4\}$.

$\vec{v}_1 = \begin{bmatrix} 4 \\ -3 \\ 3 \end{bmatrix}, \vec{u}_1 = \begin{bmatrix} -1 \\ 1 \\ -2 \end{bmatrix}, \vec{u}_2 = \begin{bmatrix} -2 \\ 1 \\ 1 \end{bmatrix}, \vec{u}_3 = \begin{bmatrix} 1 \\ -2 \\ -1 \end{bmatrix}, \vec{u}_4 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$

$\vec{x} = \vec{v}_1 + \vec{v}_2$
 \vec{v}_1 = vector in $\text{Span}\{\vec{v}_1, \vec{v}_2, \vec{v}_3\} = \vec{v}_1 + \vec{v}_2 + \vec{v}_3$
 \vec{v}_2 = vector in $\text{Span}\{\vec{v}_4\} = c_4 \vec{v}_4$
Find c_1, c_2, c_3 and c_4 by using the fact that the v 's are orthogonal.

6.3 Example (1.2)

Find c_4 1st (because it's easier!)

$\vec{x} = \vec{v}_1 + \vec{v}_2 = c_1 \vec{u}_1 + c_2 \vec{u}_2 + c_3 \vec{u}_3 + c_4 \vec{u}_4$
 $\vec{x} \cdot \vec{v}_4 = c_1 \vec{u}_1 \cdot \vec{v}_4 + c_2 \vec{u}_2 \cdot \vec{v}_4 + c_3 \vec{u}_3 \cdot \vec{v}_4 + c_4 \vec{u}_4 \cdot \vec{v}_4$
 $c_4 = \frac{\vec{x} \cdot \vec{v}_4}{\vec{v}_4 \cdot \vec{v}_4} = \frac{4+10-3+3}{1+4+1+1} = \frac{14}{7} = 2 \Rightarrow \vec{v}_2 = c_4 \vec{v}_4$

To find \vec{v}_1 , use the fact that
 $\vec{x} = \vec{v}_1 + \vec{v}_2$
 $\vec{v}_1 = \vec{x} - \vec{v}_2 = \begin{bmatrix} 4 \\ 5 \\ 3 \\ 3 \end{bmatrix} - \begin{bmatrix} 2 \\ 2 \\ 2 \\ 2 \end{bmatrix} = \begin{bmatrix} 2 \\ 3 \\ 1 \\ 1 \end{bmatrix}$

$\vec{x} = \vec{v}_1 + \vec{v}_2 = \begin{bmatrix} 2 \\ 1 \\ -5 \\ 1 \end{bmatrix} + \begin{bmatrix} 2 \\ 2 \\ 2 \\ 2 \end{bmatrix}$

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6.4 (cont)

Orthogonal {v1,v2,...,vn}

Basis

Orthonormal {v1/||v1||, v2/ ||v2||,...,
Basis vn/||vn||}

6.4 Reference (1)

Given $\vec{v}_1, \vec{v}_2, \vec{v}_3$, produce $\vec{v}_1, \vec{v}_2, \vec{v}_3$

$\vec{v}_2 \perp \vec{v}_1$
 $\vec{v}_3 \perp$ to the plane formed by \vec{v}_1 and \vec{v}_2

$\vec{v}_1 = \vec{v}_1$
 $\vec{v}_2 = \vec{v}_2 - (\frac{\vec{v}_2 \cdot \vec{v}_1}{\vec{v}_1 \cdot \vec{v}_1}) \vec{v}_1$ → orthogonal projection of \vec{v}_2 onto \vec{v}_1
 $\vec{v}_3 = \vec{v}_3 - (\vec{v}_3 \cdot \vec{v}_1) \vec{v}_1 - (\vec{v}_3 \cdot \vec{v}_2) \vec{v}_2$ → orthogonal projection of \vec{v}_3 onto \vec{v}_1 and \vec{v}_2

6.4 Example (1)

- Example - Use the Gram-Schmidt process to produce an orthogonal basis for the given subspace W:

$$\begin{aligned} \vec{v}_1 &= \vec{v}_1 \\ \vec{v}_2 &= \vec{v}_2 - \left(\frac{\vec{v}_2 \cdot \vec{v}_1}{\vec{v}_1 \cdot \vec{v}_1} \right) \vec{v}_1 \\ \vec{v}_2 &= \vec{v}_2 - \left(\frac{1+4+8}{1+4+4} \right) \vec{v}_1 = \vec{v}_2 - \vec{v}_1 = \begin{bmatrix} 0 \\ -2 \\ 2 \end{bmatrix} \\ \vec{v}_3 &= \vec{v}_3 - \left(\frac{\vec{v}_3 \cdot \vec{v}_1}{\vec{v}_1 \cdot \vec{v}_1} \right) \vec{v}_1 - \left(\frac{\vec{v}_3 \cdot \vec{v}_2}{\vec{v}_2 \cdot \vec{v}_2} \right) \vec{v}_2 = \vec{v}_3 - \left(\frac{5+4+0}{1+4+4} \right) \vec{v}_1 - \left(\frac{0+4+0}{4+4} \right) \vec{v}_2 \\ \text{Orthogonal basis} &= 3\vec{v}_1, \vec{v}_2, \vec{v}_3 \\ &= \left\{ \begin{bmatrix} 1 \\ 2 \\ -2 \end{bmatrix}, \begin{bmatrix} 0 \\ -2 \\ 2 \end{bmatrix}, \begin{bmatrix} 4 \\ 1 \\ 1 \end{bmatrix} \right\} \end{aligned}$$

7.1

Symmetric A square matrix where $A^T=A$
Matrix

If A is a symmetric then eigenvectors associated w/
symmetric distinct eigenvalues are Matrix orthogonal

If a matrix is symmetrical, it has an orthogonal & orthonormal basis of vectors

7.1 (cont)

Orthogonal matrix is a square matrix w/
orthonormal columns

- Matrix is square
- Columns are orthogonal
- Columns are unit vectors

If Matrix P has orthonormal columns

If P is a nxn orthogonal matrix

$A = PDPT$

- (1) Matrix is
- (2) Columns are
- (3) Columns are

$PTP = I$

A must be symmetric, P must be normalized

7.1 Example (2.2)

$$\begin{aligned} \lambda &= 25 \\ [(A-\lambda I)]\vec{v} &= \begin{bmatrix} -26 & -36 & 0 \\ 0 & -18 & 0 \\ 0 & 0 & -22 \end{bmatrix} \rightarrow \begin{bmatrix} 3 & 4 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ R1/-9 & \quad x_1 = -4x_2 \\ R2/-12 & \quad x_2 = 0 \\ R3/-22 & \quad x_3 = 0 \\ \vec{x} &= \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad \text{c eigenvector} \\ & \quad \text{normalized eigenvector} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \\ \lambda &= 3 \\ [(A-\lambda I)]\vec{v} &= \begin{bmatrix} -6 & -36 & 0 \\ -36 & -22 & 0 \\ 0 & 0 & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 24/15 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ R1/-6 & \quad x_1 = 0 \\ R2/-24 & \quad x_2 = 0 \\ R3/-22 & \quad x_3 = 0 \\ \vec{x} &= \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \quad \text{normalized eigenvector} \\ & \quad \text{normalized eigenvector} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \\ \vec{v} &= \begin{bmatrix} 3/5 & -4/5 & 0 \\ 4/5 & 3/5 & 0 \\ 0 & 0 & 0 \end{bmatrix} \end{aligned}$$

7.1 Reference (1)

4. The Spectral Theorem

- A set of eigenvalues of a matrix is called the "spectrum" of A.
- The spectral theorem for symmetric matrices - An $n \times n$ symmetric matrix A has the following properties:
 - A has n real eigenvalues, counting multiplicities
 - The dimension of the eigenspace for each eigenvalue λ equals the multiplicity of λ
 - The eigenspaces are mutually orthogonal - eigenvectors corresponding to different eigenvalues are orthogonal
 - A is orthogonally diagonalizable

Note: A symmetric matrix is always orthogonally diagonalizable but an orthogonal matrix is not necessarily orthogonally diagonalizable.

7.1 Example (1)

- Example 2 - Determine if the following matrix is orthogonal. If it is orthogonal, find its inverse.

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

NOT orthogonal because the columns are not normalized

$\Rightarrow \|\vec{v}_i\| = \sqrt{1+4+4} = 3 \neq 1$.

7.1 Example (2.1)

- Example 2 - Orthogonally diagonalize the following matrix, giving an orthogonal matrix P and a diagonal matrix D. Note: The eigenvalues for this matrix are 25, 3 and -50.

3x3 example

① Find D

$\lambda = 25, 3, -50$ (given)

$D = \begin{bmatrix} 25 & 0 & 0 \\ 0 & 3 & 0 \\ 0 & 0 & -50 \end{bmatrix}$

② Find P

$\lambda = 25$

$[(A-\lambda I)]\vec{v} + \begin{bmatrix} -2 & -36 & 0 \\ -36 & -23 & 0 \\ 0 & 0 & 3 \end{bmatrix} \rightarrow \begin{bmatrix} 4 & -3 & 0 \\ 4 & -3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \rightarrow \begin{bmatrix} 1 & -3/4 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$

$R1/2, R2/4, R3/3$

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