
9

Section 5.3 : Diagonalization

Chapter 5 : Eigenvalues and Eigenvectors

Math 1554 Linear Algebra

Motivation: it can be useful to take large powers of matrices, for example A^k, for large k.

But: multiplying two $n \times n$ matrices requires roughly n^3 computations. Is there a more efficient way to compute A^k?

Topics and Objectives

Topics

1. Diagonal, similar, and diagonalizable matrices
2. Diagonalizing matrices

Learning Objectives

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

1. Determine whether a matrix can be diagonalized, and if possible diagonalize a square matrix.
2. Apply diagonalization to compute matrix powers.

Section 5.3 : Diagonalization

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Course Schedule

Cancellations due to inclement weather will likely result in cancelling review lectures and possibly moving through course ma

Week	Dates	Mon Lecture	Tue Studio	Wed Lecture	Thu Studio	Fri Lecture
1	8/21 – 8/25	1.1	WS1.1	1.2	WS1.2	1.3
2	8/28 – 9/1	1.4	WS1.3,1.4	1.5	WS1.5	1.7
3	9/4 – 9/8	Break	WS1.7	1.8	WS1.8	1.9
4	9/11 – 9/15	2.1	WS1.9,2.1	**Exam 1**, Review	Cancelled	2.2
5	9/18 – 9/22	2.3,2.4	WS2.2,2.3	2.5	WS2.4,2.5	2.8
6	9/25 – 9/29	2.9	WS2.8,2.9	3.1,3.2	WS3.1,3.2	3.3
7	10/2 – 10/6	4.9	WS3.3,4.9	5.1,5.2	WS5.1,5.2	5.2
8	10/9 – 10/13	Break	Break	**Exam 2**, Review	Cancelled	5.3
9	10/16 – 10/20	5.3	WS5.3	5.5	WS5.5	6.1
10	10/23 – 10/27	6.1,6.2	WS6.1	6.2	WS6.2	6.3
11	10/30 – 11/3	6.4	WS6.3,6.4	6.4,6.5	WS6.4,6.5	6.5
12	11/6 – 11/10	6.6	WS6.5,6.6	**Exam 3**, Review	Cancelled	PageRank
13	11/13 – 11/17	7.1	WSPageRank	7.2	WS7.1,7.2	7.3
14	11/20 – 11/24	7.3,7.4	WS7.2,7.3	Break	Break	Break
15	11/27 – 12/1	7.4	WS7.3,7.4	7.4	WS7.4	7.4
16	12/4 – 12/8	Last lecture	Last Studio	Reading Period		
17	12/11 – 12/15	Final Exams: **MATH 1554 Common Final Exam Tuesday, December 12th at 6pm**				

Diagonal Matrices

A matrix is **diagonal** if the only non-zero elements, if any, are on the main diagonal.

The following are all diagonal matrices.

$$\begin{bmatrix} 2 & 0 \\ 0 & 2 \end{bmatrix}, \quad [2], \quad I_n, \quad \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

We'll only be working with diagonal square matrices in this course.

Powers of Diagonal Matrices

If A is diagonal, then A^k is easy to compute. For example,

$$A = \begin{pmatrix} 3 & 0 \\ 0 & 0.5 \end{pmatrix}$$

$A^2 =$

$A^k =$

But what if A is not diagonal?

Diagonalization

Suppose $A \in \mathbb{R}^{n\times n}$. We say that A is **diagonalizable** if it is similar to a diagonal matrix, D. That is, we can write

$$A = PDP^{-1}$$

Diagonalization

Theorem

If A is diagonalizable $\Leftrightarrow$ A has n linearly independent eigenvectors.

Note: the symbol $\Leftrightarrow$ means " if and only if ".

Also note that $A = PDP^{-1}$ if and only if

$$A = [\vec{v}_1 \; \vec{v}_2 \cdots \vec{v}_n] \begin{bmatrix} \lambda_1 & & & \\ & \lambda_2 & & \\ & & \ddots & \\ & & & \lambda_n \end{bmatrix} [\vec{v}_1 \; \vec{v}_2 \cdots \vec{v}_n]^{-1}$$

where $\vec{v}_1, \ldots, \vec{v}_n$ are linearly independent eigenvectors, and $\lambda_1, \ldots, \lambda_n$ are the corresponding eigenvalues (**in order**).

Distinct Eigenvalues

Theorem

If A is $n \times n$ and has n distinct eigenvalues, then A is diagonalizable.

Why does this theorem hold?

Is it necessary for an $n \times n$ matrix to have n distinct eigenvalues for it to be diagonalizable?

Non-Distinct Eigenvalues

Theorem. Suppose

- A is $n \times n$
- A has distinct eigenvalues $\lambda_1, \ldots, \lambda_k$, $k \le n$
- a_i = algebraic multiplicity of λ_i
- d_i = dimension of λ_i eigenspace ("geometric multiplicity")

Then

1. $d_i \le a_i$ for all i
2. A is diagonalizable $\Leftrightarrow$ $\Sigma d_i = n \Leftrightarrow d_i = a_i$ for all i
3. A is diagonalizable $\Leftrightarrow$ the eigenvectors, for all eigenvalues, together form a basis for $\mathbb{R}^n$.

Example 1

Diagonalize if possible.

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

Example 2

Diagonalize if possible.

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

Example 3

The eigenvalues of A are $\lambda = 3, 1$. If possible, construct P and D such that $AP = PD$.

$$A = \begin{pmatrix} 7 & 4 & 16 \\ 2 & 5 & 8 \\ -2 & -2 & -5 \end{pmatrix}$$

Additional Example (if time permits)

Note that

$$\vec{x}_k = \begin{bmatrix} 0 & 1 \\ 1 & 1 \end{bmatrix} \vec{x}_{k-1}, \quad \vec{x}_0 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad k = 1, 2, 3, \ldots$$

generates a well-known sequence of numbers.

Use a diagonalization to find a matrix equation that gives the n^{th} number in this sequence.

Additional Example (if time permits)

Note that

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Use a diagonalization to find a matrix equation that gives the n^{th} number in this sequence.

THEOREM 5 **The Diagonalization Theorem**

An $n \times n$ matrix A is diagonalizable if and only if A has n linearly independent eigenvectors.

In fact, $\boxed{A} = PDP^{-1}$, with D a diagonal matrix, if and only if the columns of P are n linearly independent eigenvectors of A. In this case, the diagonal entries of D are eigenvalues of A that correspond, respectively, to the eigenvectors in P.

key idea
alg = geo

$P = [\vec{v}_1\ \vec{v}_2\ \vec{v}_3]$ and $D = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$

EXAMPLE 4 Diagonalize the following matrix, if possible.

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

ans: NP

$\lambda_1 = 1 \quad \lambda_2 = -2$

write $A = PDP^{-1}$ where D diagonal, P invertible
(aka A similar to diagonal matrix D).

Soln. $\lambda_1 = 1$

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

Check $\lambda_1 = 1$

$$A * \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix}$$

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

geo=1

$$\sim \begin{bmatrix} 1 & 0 & -1 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{bmatrix} \qquad \vec{x} = r \begin{bmatrix} 1 \\ -1 \\ 1 \end{bmatrix}$$

$\lambda_2 = -2$

$$A + 2I = \begin{bmatrix} 4 & 4 & 3 \\ -4 & -4 & -3 \\ 3 & 3 & 3 \end{bmatrix} \sim \begin{bmatrix} 4 & 4 & 3 \\ 0 & 0 & 0 \\ 0 & 0 & 3/4 \end{bmatrix} \sim \begin{bmatrix} 4 & 4 & 3 \\ 0 & 0 & 3/4 \\ 0 & 0 & 0 \end{bmatrix}$$

r

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

$3 - \frac{3}{4} 3$

one free var
So $\boxed{\text{geo} = 1}$

THEOREM 6 An $n \times n$ matrix with n distinct eigenvalues is diagonalizable.

If λ's all distinct $\Longrightarrow$ A diag'ble.

otherwise

THEOREM 7 Let A be an $n \times n$ matrix whose distinct eigenvalues are $\lambda_1, \ldots, \lambda_p$.

a. For $1 \le k \le p$, the dimension of the eigenspace for λ_k is less than or equal to the multiplicity of the eigenvalue λ_k. geo ≤ alg

b. The matrix A is diagonalizable if and only if the sum of the dimensions of the eigenspaces equals n, and this happens if and only if *(i)* the characteristic polynomial factors completely into linear factors and *(ii)* the dimension of the eigenspace for each λ_k equals the multiplicity of λ_k. geo = alg

c. If A is diagonalizable and $\mathcal{B}_k$ is a basis for the eigenspace corresponding to λ_k for each k, then the total collection of vectors in the sets $\mathcal{B}_1, \ldots, \mathcal{B}_p$ forms an eigenvector basis for $\mathbb{R}^n$.

Basis of Eigenvectors

Express the vector $\vec{x}_0 = \begin{bmatrix}4\\5\end{bmatrix}$ as a linear combination of the vectors $\vec{v}_1 = \begin{bmatrix}1\\1\end{bmatrix}$ and $\vec{v}_2 = \begin{bmatrix}1\\-1\end{bmatrix}$ and find the coordinates of $\vec{x}_0$ in the basis $\mathcal{B} = \{\vec{v}_1, \vec{v}_0\}$.

$[\vec{x}_0]_{\mathcal{B}} =$

Let $P = [\vec{v}_1\ \vec{v}_2]$ and $D = \begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$, and find $[A^k\vec{x}_0]_{\mathcal{B}}$ where $A = PDP^{-1}$, for $k = 1, 2, \ldots$.

$[A^k\vec{x}_0]_{\mathcal{B}} =$

$$[x_0]_B = \begin{bmatrix}4\\5\end{bmatrix}_B = \begin{bmatrix}9/2\\-1/2\end{bmatrix} = \boxed{\begin{bmatrix}4.5\\-.5\end{bmatrix}}$$

Find $[A x_0]_B \overset{?}{=} \begin{bmatrix}c_1\\c_2\end{bmatrix}$? $= \boxed{\begin{bmatrix}4.5\\.5\end{bmatrix}}$

$$A*\begin{bmatrix}4\\5\end{bmatrix} = c_1\begin{bmatrix}1\\1\end{bmatrix} + c_2\begin{bmatrix}1\\-1\end{bmatrix}$$

```
clc
P=[1 1 ; 1 -1]
% first example
%D=[1 0 ; 0 -1]
% part 2
%D=[1 0 ; 0 -1/2]
% part 3
D=[2 0 ; 0 3/2]
A=P*D*inv(P)
x0=[4;5];
s=10
format bank
for k=0:s
   % convert current index to string and
create xk and coordk strings
   index=string(k);
   s=strcat('x',index,'=');
   c=strcat('[x',index,']_B=');
   % compute xk value
   xk=A^k*x0;
   coordk=inv(P)*xk;
   % display each xk=A^k*x0
   disp(s)
   disp(xk)
   disp(c)
   disp(coordk)
end
```

Step1 write

$$\begin{bmatrix}4\\5\end{bmatrix} = 4.5\begin{bmatrix}1\\1\end{bmatrix} - 0.5\begin{bmatrix}1\\-1\end{bmatrix}$$

$$A\begin{bmatrix}1\\1\end{bmatrix} = 1\begin{bmatrix}1\\1\end{bmatrix}$$

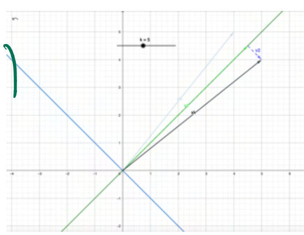
$$A\begin{bmatrix}1\\-1\end{bmatrix} = (-1)\begin{bmatrix}1\\-1\end{bmatrix}$$

Step2 apply A to both sides

$$A*\begin{bmatrix}4\\5\end{bmatrix} = A\left(4.5\begin{bmatrix}1\\1\end{bmatrix} - 0.5\begin{bmatrix}1\\-1\end{bmatrix}\right)$$

$$= 4.5*\boxed{A\begin{bmatrix}1\\1\end{bmatrix}} - 0.5\, A\begin{bmatrix}1\\-1\end{bmatrix}$$

$$= 4.5\begin{bmatrix}1\\1\end{bmatrix} + 0.5\begin{bmatrix}1\\-1\end{bmatrix}$$



$$[A^2 x_0]_B = \begin{bmatrix}4.5\\-.5\end{bmatrix}$$

$$\boxed{[A^k x_0]_B = \begin{bmatrix}4.5\\(-1)^{k+1}(.5)\end{bmatrix}}$$

https://www.geogebra.org/calculator/bcahjxed

Basis of Eigenvectors - part 2

Let $\vec{x}_0 = \begin{bmatrix}4\\5\end{bmatrix}$, $\vec{v}_1 = \begin{bmatrix}1\\1\end{bmatrix}$ and $\vec{v}_2 = \begin{bmatrix}1\\-1\end{bmatrix}$ as before.

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

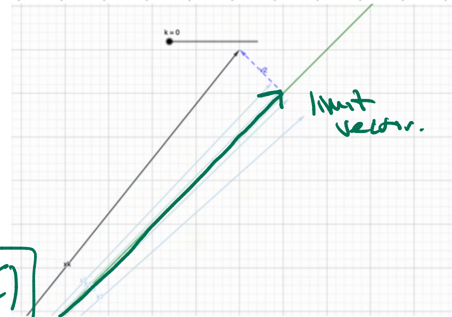
$A = PDP^{-1}$

Again define $P = [\vec{v}_1\ \vec{v}_2]$ but this time let $D = \begin{bmatrix}1 & 0\\ 0 & -1/2\end{bmatrix}$, and now find $[A^k\vec{x}_0]_\mathcal{B}$ where $A = PDP^{-1}$, for $k = 1, 2, \ldots$.

$[A^k\vec{x}_0]_\mathcal{B} = \begin{bmatrix}9/2\\ (-1/2)^{k+1}\end{bmatrix}$

if $k >> 0$ then $[A^k x_0]_B = \begin{bmatrix}9/2\\ 0\end{bmatrix}$

https://www.geogebra.org/calculator/czdnmrgc



long run

$\boxed{\frac{9}{2}\begin{bmatrix}1\\1\end{bmatrix} = \begin{bmatrix}4.5\\4.5\end{bmatrix}}$

$\vec{x}_0 = \begin{bmatrix}4\\5\end{bmatrix} \stackrel{?}{=} \frac{9}{2}\begin{bmatrix}1\\1\end{bmatrix} + \frac{-1}{2}\begin{bmatrix}1\\-1\end{bmatrix}$

$\left[\begin{array}{cc|c}1 & 1 & 4\\ 1 & -1 & 5\end{array}\right] \sim \left[\begin{array}{cc|c}1 & 1 & 4\\ 0 & -2 & 1\end{array}\right] \sim \left[\begin{array}{cc|c}1 & 0 & 9/2\\ 0 & 1 & -1/2\end{array}\right]$

$\boxed{\begin{bmatrix}4\\5\end{bmatrix}_B = \begin{bmatrix}9/2\\ -1/2\end{bmatrix}}$

?? BAD IDEA

$A\vec{x}_0 = \begin{bmatrix}.25 & .75\\ .75 & .25\end{bmatrix}\begin{bmatrix}4\\5\end{bmatrix}$

$A\vec{x}_0 = A\left(\frac{9}{2}\begin{bmatrix}1\\1\end{bmatrix} - \frac{1}{2}\begin{bmatrix}1\\-1\end{bmatrix}\right)$

$= \frac{9}{2}A\begin{bmatrix}1\\1\end{bmatrix} - \frac{1}{2}A\begin{bmatrix}1\\-1\end{bmatrix}$

v_1 w/ $\lambda_1 = 1$ $\quad$ v_2 w/ $\lambda_2 = -1/2$

$\boxed{\begin{array}{l}Av_1 = v_1\\ Av_2 = -\frac{1}{2}v_1\end{array}}$

$= \frac{9}{2}\begin{bmatrix}1\\1\end{bmatrix} - \frac{1}{2}\left(-\frac{1}{2}\right)\begin{bmatrix}1\\-1\end{bmatrix}$

$\boxed{[Ax_0]_B = [\vec{x}_1]_B = \begin{bmatrix}9/2\\ 1/4\end{bmatrix}}$

$\boxed{[A^2 x_0]_B = \begin{bmatrix}9/2\\ -1/8\end{bmatrix}}$

$A^2 x_0 = A\vec{x}_1 = A\left(\frac{9}{2}\begin{bmatrix}1\\1\end{bmatrix} + \frac{1}{4}\begin{bmatrix}1\\-1\end{bmatrix}\right) = \frac{9}{2}A\begin{bmatrix}1\\1\end{bmatrix} + \frac{1}{4}A\begin{bmatrix}1\\-1\end{bmatrix}$

$= \frac{9}{2}\begin{bmatrix}1\\1\end{bmatrix} + \frac{1}{4}\left(-\frac{1}{2}\right)\begin{bmatrix}1\\-1\end{bmatrix}$

Basis of Eigenvectors - part 3

FYI $A = \begin{bmatrix} 1.75 & .25 \\ .25 & 1.75 \end{bmatrix}$

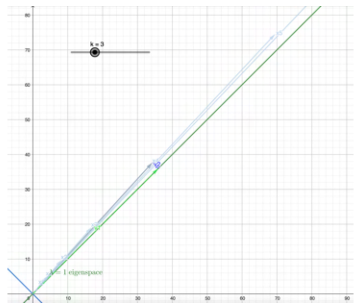
Let $\vec{x}_0 = \begin{bmatrix} 4 \\ 5 \end{bmatrix}$, $\vec{v}_1 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}$ and $\vec{v}_2 = \begin{bmatrix} 1 \\ -1 \end{bmatrix}$ as before.

Again define $P = [\vec{v}_1 \; \vec{v}_2]$ but this time let $D = \begin{bmatrix} 2 & 0 \\ 0 & 3/2 \end{bmatrix}$, and now find $[A^k \vec{x}_0]_{\mathcal{B}}$ where $A = PDP^{-1}$, for $k = 1, 2, \ldots$.

$[A^k \vec{x}_0]_{\mathcal{B}} =$

Section 5.3 Slide 15

https://www.geogebra.org/calculator/ddcanyxh



Step 1 write $\vec{x}_0$ as lin comb of $\vec{v}_1, \vec{v}_2$ eigenvectors

$A\vec{v}_1 = 2\vec{v}_1 \quad \lambda_1 = 2$

$A\vec{v}_2 = \frac{3}{2}\vec{v}_2 \quad \lambda_2 = 3/2 = 1.5$

$$\begin{bmatrix} 4 \\ 5 \end{bmatrix} = 4.5 \begin{bmatrix} 1 \\ 1 \end{bmatrix} - 0.5 \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$[x_0]_B = \begin{bmatrix} 4.5 \\ -0.5 \end{bmatrix}$

$[Ax_0]_B = \begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} 9 \\ .75 \end{bmatrix}$

Step 2: apply A & simplify $A v_i = \lambda_i v_i$

$$A\begin{bmatrix} 4 \\ 5 \end{bmatrix} = 4.5\, A\begin{bmatrix} 1 \\ 1 \end{bmatrix} - 0.5\, A\begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$= 4.5 * 2 \begin{bmatrix} 1 \\ 1 \end{bmatrix} - 0.5 * (1.5) \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$(A^k x_0)_B = \begin{pmatrix} 4.5(2)^k \\ -0.5(1.5)^k \end{pmatrix}$

repeat

$$A^k \begin{bmatrix} 4 \\ 5 \end{bmatrix} = 4.5 * 2 * A^k \begin{bmatrix} 1 \\ 1 \end{bmatrix} - 0.5(1.5) A^k \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$= 4.5 (2)^k \begin{bmatrix} 1 \\ 1 \end{bmatrix} - 0.5 (1.5)^k \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

$$\boxed{A\vec{x} = \lambda\vec{x}}$$ ✓

5.3 EXERCISES

In Exercises 1 and 2, let $A = PDP^{-1}$ and compute A^4.

1. $P = \begin{bmatrix} 5 & 7 \\ 2 & 3 \end{bmatrix}, D = \begin{bmatrix} 2 & 0 \\ 0 & 1 \end{bmatrix}$

2. $P = \begin{bmatrix} 2 & -3 \\ -3 & 5 \end{bmatrix}, D = \begin{bmatrix} 1 & 0 \\ 0 & 1/2 \end{bmatrix}$

In Exercises 3 and 4, use the factorization $A = PDP^{-1}$ to compute A^k, where k represents an arbitrary positive integer.

3. $\begin{bmatrix} a & 0 \\ 3(a-b) & b \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 3 & 1 \end{bmatrix}\begin{bmatrix} a & 0 \\ 0 & b \end{bmatrix}\begin{bmatrix} 1 & 0 \\ -3 & 1 \end{bmatrix}$

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

In Exercises 5 and 6, the matrix A is factored in the form PDP^{-1}. Use the Diagonalization Theorem to find the eigenvalues of A and a basis for each eigenspace.

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

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

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

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

Diagonalize the matrices in Exercises 7–20, if possible. The eigenvalues for Exercises 11–16 are as follows: (11) $\lambda = 1, 2, 3$; (12) $\lambda = 2, 8$; (13) $\lambda = 5, 1$; (14) $\lambda = 5, 4$; (15) $\lambda = 3, 1$; (16) $\lambda = 2, 1$. For Exercise 18, one eigenvalue is $\lambda = 5$ and one eigenvector is $(-2, 1, 2)$.

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

8. $\begin{bmatrix} 5 & 1 \\ 0 & 5 \end{bmatrix}$

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

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

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

12. $\begin{bmatrix} 4 & 2 & 2 \\ 2 & 4 & 2 \\ 2 & 2 & 4 \end{bmatrix}$

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

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

15. $\begin{bmatrix} 7 & 4 & 16 \\ 2 & 5 & 8 \\ -2 & -2 & -5 \end{bmatrix}$

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

17. $\begin{bmatrix} 4 & 0 & 0 \\ 1 & 4 & 0 \\ 0 & 0 & 5 \end{bmatrix}$

18. $\begin{bmatrix} -7 & -16 & 4 \\ 6 & 13 & -2 \\ 12 & 16 & 1 \end{bmatrix}$

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

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

In Exercises 21 and 22, A, B, P, and D are $n \times n$ matrices. Mark each statement True or False. Justify each answer. (Study Theorems 5 and 6 and the examples in this section carefully before you try these exercises.)

21. a. A is diagonalizable if $A = PDP^{-1}$ for some matrix D and some invertible matrix P.

    b. If $\mathbb{R}^n$ has a basis of eigenvectors of A, then A is diagonalizable.

    c. A is diagonalizable if and only if A has n eigenvalues, counting multiplicities.

    d. If A is diagonalizable, then A is invertible.

22. a. A is diagonalizable if A has n eigenvectors.

    b. If A is diagonalizable, then A has n distinct eigenvalues.

    c. If $AP = PD$, with D diagonal, then the nonzero columns of P must be eigenvectors of A.

    d. If A is invertible, then A is diagonalizable.

23. A is a 5×5 matrix with two eigenvalues. One eigenspace is three-dimensional, and the other eigenspace is two-dimensional. Is A diagonalizable? Why?

24. A is a 3×3 matrix with two eigenvalues. Each eigenspace is one-dimensional. Is A diagonalizable? Why?

25. A is a 4×4 matrix with three eigenvalues. One eigenspace is one-dimensional, and one of the other eigenspaces is two-dimensional. Is it possible that A is *not* diagonalizable? Justify your answer.

26. A is a 7×7 matrix with three eigenvalues. One eigenspace is two-dimensional, and one of the other eigenspaces is three-dimensional. Is it possible that A is *not* diagonalizable? Justify your answer.

27. Show that if A is both diagonalizable and invertible, then so is A^{-1}.

28. Show that if A has n linearly independent eigenvectors, then so does A^T. [*Hint:* Use the Diagonalization Theorem.]

29. A factorization $A = PDP^{-1}$ is not unique. Demonstrate this for the matrix A in Example 2. With $D_1 = \begin{bmatrix} 3 & 0 \\ 0 & 5 \end{bmatrix}$, use the information in Example 2 to find a matrix P_1 such that $A = P_1 D_1 P_1^{-1}$.

30. With A and D as in Example 2, find an invertible P_2 unequal to the P in Example 2, such that $A = P_2 D P_2^{-1}$.

31. Construct a nonzero 2×2 matrix that is invertible but not diagonalizable.

32. Construct a nondiagonal 2×2 matrix that is diagonalizable but not invertible.

[M] Diagonalize the matrices in Exercises 33–36. Use your matrix program's eigenvalue command to find the eigenvalues, and then compute bases for the eigenspaces as in Section 5.1.

33. $\begin{bmatrix} -6 & 4 & 0 & 9 \\ -3 & 0 & 1 & 6 \\ -1 & -2 & 1 & 0 \\ -4 & 4 & 0 & 7 \end{bmatrix}$ **34.** $\begin{bmatrix} 0 & 13 & 8 & 4 \\ 4 & 9 & 8 & 4 \\ 8 & 6 & 12 & 8 \\ 0 & 5 & 0 & -4 \end{bmatrix}$

35. $\begin{bmatrix} 11 & -6 & 4 & -10 & -4 \\ -3 & 5 & -2 & 4 & 1 \\ -8 & 12 & -3 & 12 & 4 \\ 1 & 6 & -2 & 3 & -1 \\ 8 & -18 & 8 & -14 & -1 \end{bmatrix}$

Chapter 5 : Eigenvalues and Eigenvectors

5.5 : Complex Eigenvalues

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9	10/16 – 10/20	5.3	WS5.3	5.5	WS5.5	6.1
10	10/23 – 10/27	6.1,6.2	WS6.1	6.2	WS6.2	6.3
11	10/30 – 11/3	6.4	WS6.3,6.4	6.4,6.5	WS6.4,6.5	6.5
12	11/6 – 11/10	6.6	WS6.5,6.6	**Exam 3**, Review	Cancelled	PageRank

Chapter 5 : Eigenvalues and Eigenvectors

5.5 : Complex Eigenvalues

Topics and Objectives

Topics

1. Complex numbers: addition, multiplication, complex conjugate
2. Diagonalizing matrices with complex eigenvalues
3. Eigenvalue theorems

Learning Objectives

1. Diagonalize 2×2 matrices that have complex eigenvalues.
2. Use eigenvalues to determine identify the rotation and dilation of a linear transform.
3. Apply theorems to characterize matrices with complex eigenvalues.

Motivating Question
What are the eigenvalues of a rotation matrix?

Imaginary Numbers $\mathbb{C} \simeq \mathbb{R}^2$

Recall: When calculating roots of polynomials, we can encounter square roots of negative numbers. For example:

$$x^2 + 1 = 0$$

The roots of this equation are:

We usually write $\sqrt{-1}$ as i (for "imaginary").

ex. $A = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ $T: \mathbb{R}^2 \to \mathbb{R}^2$, $T(\vec{x}) = A\vec{x}$

rotation by $90°$ CCW.

$p(\lambda) = \det\begin{pmatrix} -\lambda & -1 \\ 1 & -\lambda \end{pmatrix} = \lambda^2 + 1 = 0$

irreducible poly of deg 2 over $\mathbb{R}$ $\to$ $\mathbb{C}$

$= (\lambda - i)(\lambda + i) = 0$

reduces into linear factors over $\mathbb{C}$.

eigenvalues

$\lambda_1 = i, \lambda_2 = -i$

Find $\vec{v}_1, \vec{v}_2$ e-vectors

$\lambda_1 = i$. $A - \lambda I = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} - i\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

$= \begin{bmatrix} -i & -1 \\ 1 & -i \end{bmatrix} \sim^{iR_1} \begin{bmatrix} 1 & -i \\ 1 & -i \end{bmatrix} \sim \begin{bmatrix} 1 & -i \\ 0 & 0 \end{bmatrix}$

$i(-i) = -i^2 = -(-1) = 1$

$x_1 - ix_2 = 0$

$x_2 = r$ (free)

$\begin{cases} x_1 = ir \\ x_2 = r \end{cases}$

in $\mathbb{C}^2$ ~~$\mathbb{R}^2$~~

$\boxed{x = r\begin{bmatrix} i \\ 1 \end{bmatrix}}$

$v_2 = \begin{bmatrix} -i \\ 1 \end{bmatrix}$

$= \overline{v_1}$

Addition and Multiplication $a + bi \in \mathbb{C}$ ($a, b \in \mathbb{R}$)

$\begin{bmatrix} a \\ b \end{bmatrix} = a+bi$ (Im, Re)

The imaginary (or complex) numbers are denoted by $\mathbb{C}$, where

$$\mathbb{C} = \{a + bi \mid a, b \text{ in } \mathbb{R}\}$$

We can identify $\mathbb{C}$ with $\mathbb{R}^2$: $a + bi \leftrightarrow (a, b)$

$\varphi: \mathbb{C} \to \mathbb{R}^2$

$\varphi(a+bi) = \begin{bmatrix} a \\ b \end{bmatrix}$

φ is linear, 1-1, onto. } isomorphism.

We can add and multiply complex numbers as follows:

$(2 - 3i) + (-1 + i) = (2 + (-1)) + (-3+1)i = \boxed{1 - 2i}$

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

$= -2 - 3i^2 + 5i =$

$= -2 + 3(-1) + 5i = \boxed{-5 + 5i}$

def. $\boxed{i^2 = -1}$

Complex Conjugate, Absolute Value, Polar Form

We can **conjugate** complex numbers: $\overline{a + bi} =$ $a - bi$

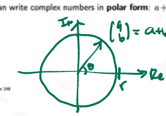
$\overline{2+3i} = 2 - 3i$ $\overline{3} = 3$ ✓

$\overline{3-5i} = 3 + 5i$ $\overline{i} = -i$ ✓

The ~~absolute~~ norm **value** of a complex number: $|a + bi| =$ $\sqrt{a^2+b^2}$

$|2+3i| = \sqrt{2^2+3^2} = \sqrt{13}$

We can write complex numbers in **polar form**: $a + ib = r(\cos\phi + i\sin\phi)$ $= re^{i\theta}$



$\begin{bmatrix} a \\ b \end{bmatrix} = a+bi = r\cos\theta + ir\sin\theta$

$\theta = \tan^{-1}(b/a)$

$r = \sqrt{a^2+b^2}$

Complex Conjugate Properties $z = a+bi$

$\text{Re}(z) = a$ "real part"
$\text{Im}(z) = b$ "imaginary part"

If x and y are complex numbers, $\vec{v} \in \mathbb{C}^n$, it can be shown that:

- $\overline{(x+y)} = \bar{x} + \bar{y}$
- $\overline{A\vec{v}} = A\bar{\vec{v}}$
- $\text{Im}(x\bar{x}) = 0$.

$(a+bi)(a-bi) = a^2+b^2 \in \mathbb{R}$

Example True or false: if x and y are complex numbers, then

$$\overline{(xy)} = \bar{x}\,\bar{y}$$

$\overline{(a+bi)(c+di)} = (a-bi)(c-di)$ ✓

$$\overline{(1+i)(2+3i)} = \overline{2+3i+2i+3i^2} = \overline{2+5i-3} = \overline{-1+5i} = \boxed{-1-5i}$$

Vs.

$$\overline{(1+i)} * \overline{(2+3i)} = (1-i)(2-3i) = 2-3i-2i+3i^2 = 2-3-5i = \boxed{-1-5i}$$

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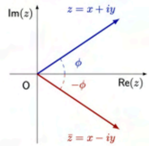
Polar Form and the Complex Conjugate

Conjugation reflects points across the real axis.



"z bar" z conjugate.

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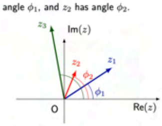
$$z = re^{i\theta}$$

$$\boxed{z^k = r^k e^{ik\theta}}$$

$$e^{i\theta} := \cos\theta + i\sin\theta$$

Euler's Formula

Suppose z_1 has angle ϕ_1, and z_2 has angle ϕ_2.



The product z_1z_2 has angle $\phi_1+\phi_2$ and modulus $|z|\,|w|$. Easy to remember using Euler's formula.

$$\boxed{z = |z|e^{i\phi}}$$

The product z_1z_2 is:

$$z_3 = z_1z_2 = (|z_1|e^{i\phi_1})(|z_2|e^{i\phi_2}) = |z_1|\,|z_2|\,e^{i(\phi_1+\phi_2)}$$

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Complex Numbers and Polynomials

How $\mathbb{C}$ w/ linear alg?

Theorem: Fundamental Theorem of Algebra
Every polynomial of degree n has exactly n complex roots, counting multiplicity.

(deg n
$p(\lambda) = \det(A-\lambda I)$ $A \in \mathbb{R}^{n\times n}$

Theorem
1. If $\lambda \in \mathbb{C}$ is a root of a real polynomial $p(x)$, then the conjugate $\bar{\lambda}$ is also a root of $p(x)$.
2. If λ is an eigenvalue of real matrix A with eigenvector $\vec{v}$, then $\bar{\lambda}$ is an eigenvalue of A with eigenvector $\bar{\vec{v}}$.

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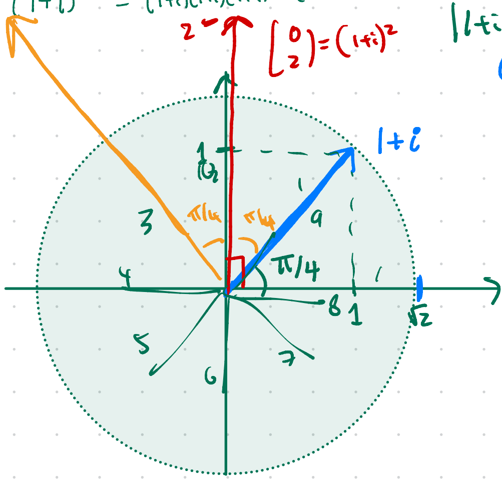
$$(1+i)^{10} \overset{?}{=} (1+i)(1+i)(1+i)\cdots(1+i)$$



$|1+i| = \sqrt{1^2+1^2} = \sqrt{2}$

$(1+i)$ $\theta = 45°$ $r = \sqrt{2}$

$(1+i)^2$ $\theta = 90°$ $r = 2$

$(1+i)^3$ $\theta = 135° = 3*45°$ $r = 2\sqrt{2} = (\sqrt{2})^3$

⋮

$(1+i)^k$ $\theta = k*45°$ $r = (\sqrt{2})^k$

$(1+i)^{10}$ $\theta = \pi/2$ $r = (\sqrt{2})^{10} = 2^5 = 32$

$$\boxed{(1+i)^{10} = 32i}$$

Example

$\mathbb{R}$ $\lambda_1 = 2$, $\lambda_2 = 4+i$, $\lambda_3 = -4-i$, $\lambda_4 = i$ $\mathbb{C}$

Four of the eigenvalues of a 7×7 matrix are $-2, 4+i, -4-i$, and i. What are the other eigenvalues?

$A \in \mathbb{R}^{7\times 7}$

$\lambda_5 = \overline{\lambda_2} = 4-i$

$\lambda_6 = \overline{\lambda_3} = -4+i$

$\lambda_7 = \overline{\lambda_4} = -i$

irreducible over $\mathbb{R}$ deg 2

$$p(\lambda) = (-1)(\lambda-2)(\lambda-(4+i))(\lambda-(-4-i))(\lambda-i)(\lambda-(4-i))$$

$$(\lambda-(-4+i))(\lambda+i)$$

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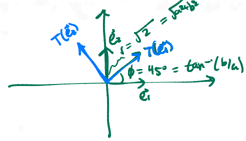
Example Rotation - dilation.

The matrix that rotates vectors by $\phi = \pi/4$ radians about the origin, and then scales (or dilates) vectors by $r = \sqrt{2}$, is

$$A = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix} \begin{bmatrix} \cos\phi & -\sin\phi \\ \sin\phi & \cos\phi \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} = \begin{bmatrix} a & -b \\ b & a \end{bmatrix}$$

What are the eigenvalues of A? Express them in polar form.



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$$\begin{bmatrix} a+bi \\ c+di \end{bmatrix} \in \mathbb{C}^2 \cong \mathbb{R}^4 \quad \longleftrightarrow \quad \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix}$$

P/I A 3x3, real matrix w/ no real eigenvalues

$\lambda_1, \lambda_2, \lambda_3$

$\not\exists$ conjugate

Rotation-dilation λ's.

Example

The matrix in the previous example is a special case of this matrix:

$$C = \begin{pmatrix} a & -b \\ b & a \end{pmatrix} = \begin{bmatrix} r & 0 \\ 0 & r \end{bmatrix}\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

Calculate the eigenvalues of C and express them in polar form.

$$p(\lambda) = \lambda^2 - \underbrace{(2a)}_{\text{tr} C}\lambda + \underbrace{(a^2+b^2)}_{\det C}$$

$$\lambda = \frac{2a \pm \sqrt{(2a)^2 - 4(a^2+b^2)}}{2}$$

$$= a \pm \frac{\sqrt{\cancel{4a^2} - \cancel{4a^2} - 4b^2}}{2}$$

$$= a \pm \frac{\sqrt{4}\sqrt{b^2}\sqrt{-1}}{2}$$

$$= a \pm \frac{2bi}{2} = \boxed{a \pm bi} = r\cos\theta \pm ri\sin\theta$$

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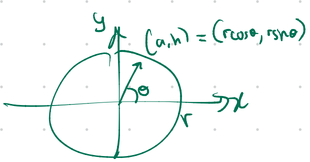

$a = r\cos\theta$

$b = r\sin\theta$

$r = \sqrt{a^2+b^2}$

$\theta = \tan^{-1}(b/a)$

$$\boxed{A = PDP^{-1}}$$

diag.

when A diag'ble: $\lambda_i \in \mathbb{R}$ all geo=alg.

Diagonalization

Theorem

Let A be a real 2 × 2 matrix with a complex eigenvalue $\lambda = a - bi$ (where $b \neq 0$) and associated eigenvector $\vec{v}$. Then we may construct a diagonalization

$$\boxed{A = PCP^{-1}}$$

where

$$P = (\mathrm{Re}\,\vec{v} \quad \mathrm{Im}\,\vec{v}) \quad \text{and} \quad C = \begin{pmatrix} a & -b \\ b & a \end{pmatrix}$$

Note the following.

- C is referred to as a **rotation dilation** matrix, because it is the composition of a rotation by ϕ and dilation by r.
- The proof for why the columns of P are always linearly independent is a bit long and goes beyond the scope of this course.

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??

$$A = \begin{pmatrix} D_1 & 0 & 0 & 0 \\ 0 & D_2 & 0 & 0 \\ 0 & 0 & C_1 & 0 \\ 0 & 0 & 0 & C_2 \end{pmatrix}$$

Example

Find the complex eigenvalues and an associated complex eigenvector for each eigenvalue for the matrix.

$$A = \begin{pmatrix} 1 & -2 \\ 1 & 3 \end{pmatrix} = \overset{P}{\begin{bmatrix} * & * \\ * & * \end{bmatrix}} \overset{C}{\begin{bmatrix} a & -b \\ b & a \end{bmatrix}} \overset{P^{-1}}{\begin{bmatrix} * & * \\ * & * \end{bmatrix}^{-1}}$$

Theory: $\overline{\lambda_1} = \lambda_2$, $\overline{v_1} = v_2$ } λ_i's, $\vec{v}_i$'s are conjugates

$$p(\lambda) = \lambda^2 - 4\lambda + 5 = 0$$

$$\lambda = \frac{4 \pm \sqrt{16-20}}{2} = \frac{4}{2} \pm \frac{\sqrt{-4}}{2} = 2 \pm \frac{\sqrt{4(-1)}}{2} = 2 \pm \frac{\sqrt{4}\sqrt{-1}}{2}$$

$$= 2 \pm \frac{2i}{2}$$

$$= \boxed{2 \pm i}$$

$\lambda_1 = 2 - i$

$$A - \lambda I_2 = \begin{bmatrix} 1 & -2 \\ 1 & 3 \end{bmatrix} - \begin{bmatrix} 2-i & 0 \\ 0 & 2-i \end{bmatrix} = \begin{pmatrix} 1-(2-i) & -2 \\ 1 & 3-(2-i) \end{pmatrix}$$

$$= \begin{bmatrix} -1+i & -2 \\ 1 & 1+i \end{bmatrix} \sim \begin{bmatrix} 1 & 1+i \\ -1+i & -2 \end{bmatrix}$$

$$\vec{x} = r\begin{pmatrix} -(1+i) \\ 1 \end{pmatrix}$$

$$\sim_{-(-1+i)R_1+R_2} \begin{bmatrix} 1 & 1+i \\ 0 & 0 \end{bmatrix}$$

$(i-1)(i+1)$

$$-(-1+i)(1+i) - 2 = -(i^2-1) - 2 = -(-1-1) - 2 = -(-2) - 2 = 2 - 2 = 0 \checkmark$$

$$\boxed{v_1 = \begin{bmatrix} -1-i \\ 1 \end{bmatrix}}$$

??

$$v_1 = \begin{bmatrix} 2/(-1+i) \\ 1 \end{bmatrix}$$

$$\begin{bmatrix} -1+i & -2 \\ 0 & 0 \end{bmatrix}$$

$(-1+i)x_1 - 2x_2 = 0$

$x_2 = x_2$ free

$\lambda_2 = 2 + i$

$$\boxed{v_2 = \begin{bmatrix} -1+i \\ 1 \end{bmatrix}}$$

5.5 EXERCISES

Let each matrix in Exercises 1–6 act on $\mathbb{C}^2$. Find the eigenvalues and a basis for each eigenspace in $\mathbb{C}^2$.

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

In Exercises 7–12, use Example 6 to list the eigenvalues of A. In each case, the transformation $\mathbf{x} \mapsto A\mathbf{x}$ is the composition of a rotation and a scaling. Give the angle φ of the rotation, where $-\pi < \varphi \le \pi$, and give the scale factor r.

7. $\begin{bmatrix} \sqrt{3} & -1 \\ 1 & \sqrt{3} \end{bmatrix}$
8. $\begin{bmatrix} \sqrt{3} & 3 \\ -3 & \sqrt{3} \end{bmatrix}$
9. $\begin{bmatrix} -\sqrt{3}/2 & 1/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}$
10. $\begin{bmatrix} -5 & -5 \\ 5 & -5 \end{bmatrix}$
11. $\begin{bmatrix} .1 & .1 \\ -.1 & .1 \end{bmatrix}$
12. $\begin{bmatrix} 0 & .3 \\ -.3 & 0 \end{bmatrix}$

In Exercises 13–20, find an invertible matrix P and a matrix C of the form $\begin{bmatrix} a & -b \\ b & a \end{bmatrix}$ such that the given matrix has the form $A = PCP^{-1}$. For Exercises 13–16, use information from Exercises 1–4.

13. $\begin{bmatrix} 1 & -2 \\ 1 & 3 \end{bmatrix}$
14. $\begin{bmatrix} 5 & -5 \\ 1 & 1 \end{bmatrix}$
15. $\begin{bmatrix} 1 & 5 \\ -2 & 3 \end{bmatrix}$
16. $\begin{bmatrix} 5 & -2 \\ 1 & 3 \end{bmatrix}$
17. $\begin{bmatrix} 1 & -.8 \\ 4 & -2.2 \end{bmatrix}$
18. $\begin{bmatrix} 1 & -1 \\ .4 & .6 \end{bmatrix}$
19. $\begin{bmatrix} 1.52 & -.7 \\ .56 & .4 \end{bmatrix}$
20. $\begin{bmatrix} -1.64 & -2.4 \\ 1.92 & 2.2 \end{bmatrix}$

21. In Example 2, solve the first equation in (2) for x_2 in terms of x_1, and from that produce the eigenvector $\mathbf{y} = \begin{bmatrix} 2 \\ -1+2i \end{bmatrix}$ for the matrix A. Show that this $\mathbf{y}$ is a (complex) multiple of the vector $\mathbf{v}_1$ used in Example 2.

22. Let A be a complex (or real) $n \times n$ matrix, and let $\mathbf{x}$ in $\mathbb{C}^n$ be an eigenvector corresponding to an eigenvalue λ in $\mathbb{C}$. Show that for each nonzero complex scalar μ, the vector $\mu\mathbf{x}$ is an eigenvector of A.

Chapter 7 will focus on matrices A with the property that $A^T = A$. Exercises 23 and 24 show that every eigenvalue of such a matrix is necessarily real.

23. Let A be an $n \times n$ real matrix with the property that $A^T = A$, let $\mathbf{x}$ be any vector in $\mathbb{C}^n$, and let $q = \bar{\mathbf{x}}^T A\mathbf{x}$. The equalities below show that q is a real number by verifying that $\bar{q} = q$. Give a reason for each step.

$$\bar{q} = \overline{\bar{\mathbf{x}}^T A\mathbf{x}} \underset{(a)}{=} \mathbf{x}^T \overline{A\mathbf{x}} \underset{(b)}{=} \mathbf{x}^T A\bar{\mathbf{x}} \underset{(c)}{=} (\mathbf{x}^T A\bar{\mathbf{x}})^T \underset{(d)}{=} \bar{\mathbf{x}}^T A^T \mathbf{x} \underset{(e)}{=} q$$

Section 6.1 : Inner Product, Length, and Orthogonality

Chapter 6: Orthogonality and Least Squares

Math 1554 Linear Algebra

Section 6.1 : Inner Product, Length, and Orthogonality

dot product

Chapter 6: Orthogonality and Least Squares

Math 1554 Linear Algebra

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9	10/16 - 10/20	5.3	WS5.3	5.5	WS5.5	6.1
10	10/23 - 10/27	6.1,6.2	WS6.1	6.2	WS6.2	6.3
11	10/30 - 11/3	6.4	WS6.3,6.4	6.4,6.5	WS6.4,6.5	6.5
12	11/6 - 11/10	6.6	WS6.5,6.6	**Exam 3**, Review	Cancelled	PageRank

Topics and Objectives

Topics

1. Dot product of vectors
2. Magnitude of vectors, and distances in $\mathbb{R}^n$
3. Orthogonal vectors and complements
4. Angles between vectors

Learning Objectives

1. Compute (a) dot product of two vectors, (b) length (or magnitude) of a vector, (c) distance between two points in $\mathbb{R}^n$, and (d) angles between vectors.
2. Apply theorems related to orthogonal complements, and their relationships to Row and Null space, to characterize vectors and linear systems.

Motivating Question
For a matrix A, which vectors are orthogonal to all the rows of A? To the columns of A?

The Dot Product

$$\vec{u}\cdot\vec{v} = \vec{u}^T * \vec{v}$$

$$\vec{u}\cdot\vec{v} = \begin{bmatrix} u_1 & u_2 & \cdots & u_n \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_n \end{bmatrix} = u_1v_1 + u_2v_2 + \cdots + u_nv_n.$$

Example 1: For what values of k is $\vec{u}\cdot\vec{v} = 0$?

$$\vec{u} = \begin{pmatrix} -1 \\ 3 \\ k \\ 2 \end{pmatrix} \qquad \vec{v} = \begin{pmatrix} 4 \\ 2 \\ 1 \\ -3 \end{pmatrix}$$

$$\vec{u}\cdot\vec{v} = (-1)(4) + (3)(2) + (k)(1) + (2)(-3)$$

$$= -4 \cancel{+6} + k \cancel{-6} = -4 + k$$

if $k=4$, then $\boxed{\vec{u}\cdot\vec{v} = 0}$ so $\vec{u} \perp \vec{v}$ "$\vec{u}$ and $\vec{v}$ are orthogonal"

Properties of the Dot Product

The dot product is a special form of matrix multiplication, so it inherits linear properties.

Theorem (Basic Identities of Dot Product)

Let $\vec{u}, \vec{v}, \vec{w}$ be three vectors in $\mathbb{R}^n$, and $c \in \mathbb{R}$.

1. (Symmetry) $\vec{u}\cdot\vec{w} =$ $\vec{w}\cdot\vec{u}$
2. (Linear in each vector) $(\vec{v}+\vec{w})\cdot\vec{u} =$ $\vec{v}\cdot\vec{u} + \vec{w}\cdot\vec{u}$
3. (Scalars) $(c\vec{u})\cdot\vec{w} =$ $c(\vec{u}\cdot\vec{w})$
4. (Positivity) $\vec{u}\cdot\vec{u} \geq 0$, and the dot product equals $\|\vec{u}\|^2$

$$\begin{pmatrix} a \\ b \\ c \end{pmatrix} \cdot \begin{pmatrix} a \\ b \\ c \end{pmatrix} = \underbrace{a^2+b^2+c^2}_{} = \left\|\begin{pmatrix} a \\ b \\ c \end{pmatrix}\right\|^2$$

If This is zero then a, b, c are all zero.

THEOREM 1 Let $\mathbf{u}$, $\mathbf{v}$, and $\mathbf{w}$ be vectors in $\mathbb{R}^n$, and let c be a scalar. Then

a. $\mathbf{u}\cdot\mathbf{v} = \mathbf{v}\cdot\mathbf{u}$
b. $(\mathbf{u}+\mathbf{v})\cdot\mathbf{w} = \mathbf{u}\cdot\mathbf{w} + \mathbf{v}\cdot\mathbf{w}$
c. $(c\mathbf{u})\cdot\mathbf{v} = c(\mathbf{u}\cdot\mathbf{v}) = \mathbf{u}\cdot(c\mathbf{v})$
d. $\mathbf{u}\cdot\mathbf{u} \geq 0$, and $\mathbf{u}\cdot\mathbf{u} = 0$ if and only if $\mathbf{u} = \mathbf{0}$

The Length of a Vector

Norm $\|\vec{u}\|$ BAD

$\|\vec{u}\|^2$ GOOD!

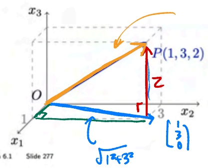
Definition

The **length** of a vector $\vec{u} \in \mathbb{R}^n$ is ✓ $\qquad \|u\|^2 = u \cdot u$

$$\boxed{\|\vec{u}\| = \sqrt{\vec{u} \cdot \vec{u}} = \sqrt{u_1^2 + u_2^2 + \cdots + u_n^2}}$$

Example: the length of the vector $\overrightarrow{OP}$ is

$$\sqrt{1^2 + 3^2 + 2^2} = \sqrt{14} \approx 3.5$$



$$\sqrt{\left(\sqrt{1^2+3^2}\right)^2 + z^2} = \sqrt{1^2+3^2+2^2} = \sqrt{14}$$

Example

$\|u\|^2 = u \cdot u = 25$ $\qquad \|v\|^2 = v \cdot v = 3$

Let $\vec{u}, \vec{v}$ be two vectors in $\mathbb{R}^n$ with $\|\vec{u}\| = 5$, $\|\vec{v}\| = \sqrt{3}$, and $\underline{\vec{u} \cdot \vec{v} = -1}$.
Compute the value of $\|\vec{u} + \vec{v}\|$.

hint $\cancel{\|\vec{u}+\vec{v}\|}$

$$\checkmark \quad \|\vec{u}+\vec{v}\|^2 = (\vec{u}+\vec{v})\cdot(\vec{u}+\vec{v})$$
$$= (\vec{u}+\vec{v})\cdot\vec{u} + (\vec{u}+\vec{v})\cdot\vec{v}$$
$$= \vec{u}\cdot\vec{u} + \vec{v}\cdot\vec{u} + \vec{u}\cdot\vec{v} + \vec{v}\cdot\vec{v}$$
$$= \vec{u}\cdot\vec{u} + 2\,\vec{u}\cdot\vec{v} + \vec{v}\cdot\vec{v} \qquad ??$$
$$= 25 + 2(-1) + 3 = \boxed{26}$$

$$\boxed{\|u+v\| = \sqrt{26}}$$

DEFINITION

The **length** (or **norm**) of $\mathbf{v}$ is the nonnegative scalar $\|\mathbf{v}\|$ defined by

$$\|\mathbf{v}\| = \sqrt{\mathbf{v}\cdot\mathbf{v}} = \sqrt{v_1^2 + v_2^2 + \cdots + v_n^2}, \quad \text{and} \quad \|\mathbf{v}\|^2 = \mathbf{v}\cdot\mathbf{v}$$

Length of Vectors and Unit Vectors

Note: for any vector $\vec{v}$ and scalar c, the length of $c\vec{v}$ is

$$\|c\vec{v}\| = |c|\,\|v\|$$

Definition

If $\vec{v} \in \mathbb{R}^n$ has length one, we say that it is a **unit vector.**

Example: Let W be a subspace of $\mathbb{R}^4$ spanned by

$$\vec{v} = \begin{bmatrix} -1 \\ -3 \\ -2 \\ 1 \end{bmatrix}$$

want $\vec{u} = c\vec{v}$ but $\|\vec{u}\| = 1$

$\boxed{\vec{u} = \underbrace{\frac{1}{\|\vec{v}\|}}_{\text{scalar}}\vec{v}}$ vector

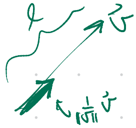
a) Construct a unit vector $\vec{u}$ in the same direction as $\vec{v}$.

b) Construct a basis for W using unit vectors.

$\|\vec{v}\| = \sqrt{1+9+4+1} = \sqrt{15}$

$\{\vec{u}\}$

$$\vec{u} = \begin{bmatrix} -1/\sqrt{15} \\ -3/\sqrt{15} \\ -2/\sqrt{15} \\ 1/\sqrt{15} \end{bmatrix}$$



One more Give the unit vector in direction of $\vec{v} = \begin{pmatrix} 1 \\ 2 \\ 2 \end{pmatrix}$?

$$\vec{u} = \begin{bmatrix} 1/3 \\ 2/3 \\ 2/3 \end{bmatrix} \checkmark$$

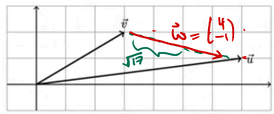
Distance in $\mathbb{R}^n$

Definition

For $\vec{u}, \vec{v} \in \mathbb{R}^n$, the **distance** between $\vec{u}$ and $\vec{v}$ is given by the formula

$$\boxed{\|u - v\|}$$

Example: Compute the distance from $\vec{u} = \begin{pmatrix} 7 \\ 1 \end{pmatrix}$ and $\vec{v} = \begin{pmatrix} 3 \\ 2 \end{pmatrix}$.



$\|\vec{w}\| = \sqrt{16+1} = \sqrt{17}$

$\vec{v} + \vec{w} = \vec{u}$

$\vec{w} = \vec{u} - \vec{v}$

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

$= \begin{bmatrix} 4 \\ -1 \end{bmatrix}$

DEFINITION For $\mathbf{u}$ and $\mathbf{v}$ in $\mathbb{R}^n$, the **distance between u and v**, written as dist$(\mathbf{u}, \mathbf{v})$, is the length of the vector $\mathbf{u} - \mathbf{v}$. That is,

$$\text{dist}(\mathbf{u}, \mathbf{v}) = \|\mathbf{u} - \mathbf{v}\|$$

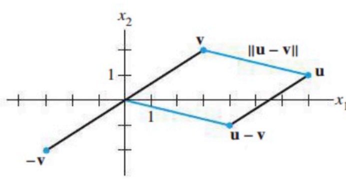


FIGURE 4 The distance between $\mathbf{u}$ and $\mathbf{v}$ is the length of $\mathbf{u} - \mathbf{v}$.

Orthogonality

Definition (Orthogonal Vectors)

Two vectors $\vec{u}$ and $\vec{w}$ are **orthogonal** if $\boxed{\vec{u}\cdot\vec{w} = 0}$. This is equivalent to:

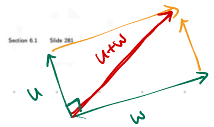
$$\|\vec{u}+\vec{w}\|^2 = \|\vec{u}\|^2 + \|\vec{w}\|^2$$

Note: The zero vector is orthogonal to every vector. But we usually only mean non-zero vectors.

Proof. $\|\vec{u}+\vec{w}\|^2 = (u+w)\cdot(u+w)$

$= u\cdot u + 2u\cdot w + w\cdot w$

$= \|u\|^2 + \|w\|^2$

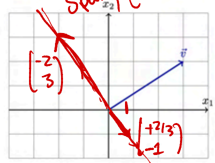


So orthogonal (alg) $\Leftrightarrow$ perpendicular (geometric)

Example

Sketch the subspace spanned by the set of all vectors $\vec{u}$ that are orthogonal to $\vec{v} = \begin{pmatrix}3\\2\end{pmatrix}$.

$\text{Span}\left\{\begin{bmatrix}+2/3\\-1\end{bmatrix}\right\} = \text{Span}\left\{\begin{bmatrix}-2\\3\end{bmatrix}\right\}$



Want $\begin{bmatrix}a\\b\end{bmatrix}$ s.t. $\begin{bmatrix}3\\2\end{bmatrix}\cdot\begin{bmatrix}a\\b\end{bmatrix} = 0$

Solve $\{3a+2b=0$

Compute null. $\begin{bmatrix}3 & 2\end{bmatrix}\begin{bmatrix}a\\b\end{bmatrix} = 0$

$V^T \sim \begin{bmatrix}1 & 2/3\end{bmatrix}$ $\vec{x} = r\begin{bmatrix}-2/3\\1\end{bmatrix}$

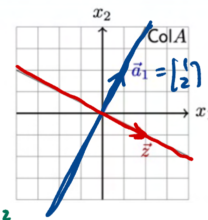
So far

* dot product $\vec{u}\cdot\vec{v} = \vec{u}^T * \vec{v}$
* $\|\vec{u}\| = \sqrt{\vec{u}\cdot\vec{u}}$
* $dist(\vec{u},\vec{v}) = \|u-v\|$
* unit vectors.

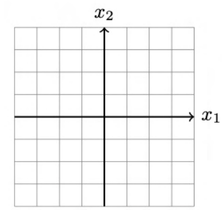
Example

Example: suppose $A = \begin{pmatrix}1 & 3\\2 & 6\end{pmatrix}$.

- Col$A$ is the span of $\vec{a}_1 = \begin{pmatrix}1\\2\end{pmatrix}$
- Col$A^\perp$ (perp) is the span of $\vec{z} = \begin{pmatrix}2\\-1\end{pmatrix}$



Sketch Null$A$ and Null$A^\perp$ on the grid below.



$(\text{Col}A)^\perp$ is the subspace of $\mathbb{R}^2$ consisting of all the vectors orthogonal to Col$A$.

$(\text{Col}A)^\perp = \text{Nul}\,A^T$

how to get vectors in $(\text{Col}A)^\perp$?

want $\begin{bmatrix}a\\b\end{bmatrix}$ s.t. $\begin{bmatrix}1\\2\end{bmatrix}\cdot\begin{bmatrix}a\\b\end{bmatrix} = 0$ $\begin{bmatrix}3\\6\end{bmatrix}\cdot\begin{bmatrix}a\\b\end{bmatrix} = 0$

$\begin{cases}a+2b=0\\3a+6b=0\end{cases}$

$B = \begin{bmatrix}1 & 2\\3 & 6\end{bmatrix} = A^T$

Orthogonal Compliments

Definitions

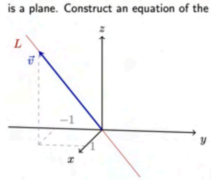
Let W be a subspace of $\mathbb{R}^n$. A vector $\vec{z} \in \mathbb{R}^n$ is said to be **orthogonal** to W if $\vec{z}$ is orthogonal to each vector in W.

The set of all vectors orthogonal to W is a subspace, the **orthogonal compliment** of W, or $W^\perp$ or 'W perp.'

$$W^\perp = \{\vec{z} \in \mathbb{R}^n \ : \ \vec{z}\cdot \qquad \}$$

Example

Line L is a subspace of $\mathbb{R}^3$ spanned by $\vec{v} = \begin{pmatrix}1\\-1\\2\end{pmatrix}$. Then the space $L^\perp$ is a plane. Construct an equation of the plane $L^\perp$.

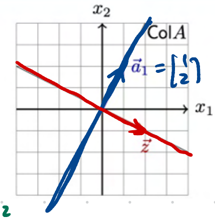


Can also visualise line and plane with CalcPlot3D: web.monroecc.edu/calcNSF

Example

Example: suppose $A = \begin{pmatrix} 1 & 3 \\ 2 & 6 \end{pmatrix}$.

- Col$A$ is the span of $\vec{a}_1 = \begin{pmatrix} 1 \\ 2 \end{pmatrix}$
- perp Col$A^\perp$ is the span of $\vec{z} = \begin{pmatrix} 2 \\ -1 \end{pmatrix}$



how to get vectors in $(\mathrm{Col}\,A)^\perp$?

want $\begin{bmatrix} a \\ b \end{bmatrix}$ s.t. $\begin{bmatrix} 1 \\ 2 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} = 0$ $\begin{bmatrix} 3 \\ 6 \end{bmatrix} \cdot \begin{bmatrix} a \\ b \end{bmatrix} = 0$

$\begin{cases} a + 2b = 0 \\ 3a + 6b = 0 \end{cases}$

$B = \begin{bmatrix} 1 & 2 \\ 3 & 6 \end{bmatrix} = A^T$

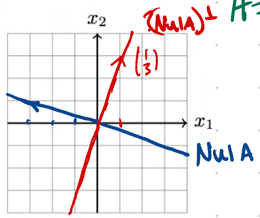
$(\mathrm{Col}\,A)^\perp$ is the subspace of $\mathbb{R}^2$ consisting of all the vectors orthogonal to Col$A$.

So. $(\mathrm{Col}\,A)^\perp = \mathrm{Nul}\,A^T$

Sketch Null$A$ and Null$A^\perp$ on the grid below.

$(\mathrm{Nul}A)^\perp$ $A = \begin{bmatrix} 1 & 3 \\ 2 & 6 \end{bmatrix}$

Nul A = span$\left\{\begin{bmatrix} -3 \\ 1 \end{bmatrix}\right\}$



$(\mathrm{Nul}\,A)^\perp = \mathrm{Span}\left\{\begin{bmatrix} 1 \\ 3 \end{bmatrix}\right\}$

If you want to find $(\mathrm{Nul}A)^\perp$ then you are looking for $\begin{bmatrix} a \\ b \end{bmatrix}$

$\boxed{\text{Row } A = \mathrm{span}\left\{\begin{bmatrix} 1 \\ 3 \end{bmatrix}, \begin{bmatrix} 2 \\ 6 \end{bmatrix}\right\} = (\mathrm{Nul}\,A)^\perp.}$

s.t. $\begin{bmatrix} a \\ b \end{bmatrix} \cdot \begin{bmatrix} -3 \\ 1 \end{bmatrix} = 0$

$(r=3)$ $\begin{bmatrix} 1 \\ 3 \end{bmatrix}$

$\Leftrightarrow$ $-3a + b = 0$

$\Leftrightarrow$ $\begin{bmatrix} -3 & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = 0$ Nul of $\begin{bmatrix} -3 & 1 \end{bmatrix}$ $\vec{x} = r\begin{bmatrix} 1/3 \\ 1 \end{bmatrix}$

$\sim \begin{bmatrix} 1 & -1/3 \end{bmatrix}$

when is $\vec{z}$ orthogonal to subspace W?

Orthogonal Compliments

$\vec{z} \in W^\perp \Leftrightarrow \vec{z} \cdot \vec{w} = 0$ for every $\vec{w} \in W$

Definitions

Let W be a subspace of $\mathbb{R}^n$. A vector $\vec{z} \in \mathbb{R}^n$ is said to be **orthogonal** to W if $\vec{z}$ is orthogonal to each vector in W.

The set of all vectors orthogonal to W is a subspace, the **orthogonal compliment** of W, or $\boxed{W^\perp}$ or 'W perp.'

$$W^\perp = \{\vec{z} \in \mathbb{R}^n \;:\; \vec{z} \cdot \vec{w} \text{ for every } \vec{w} \in W \quad \}$$

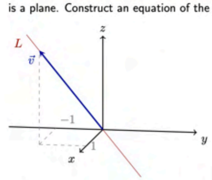
W subspace only.

warning $A^\perp$ not meaningful.

"matrix" not subspace.

Example

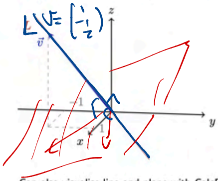
Line L is a subspace of $\mathbb{R}^3$ spanned by $\vec{v} = \begin{pmatrix} 1 \\ -1 \\ 2 \end{pmatrix}$. Then the space $L^\perp$ is a plane. Construct an equation of the plane $L^\perp$.



Can also visualise line and plane with CalcPlot3D: web.monroecc.edu/calcNSF

Example

Line L is a subspace of $\mathbb{R}^3$ spanned by $\vec{v} = \begin{pmatrix}1\\-1\\2\end{pmatrix}$. Then the space $L^\perp$ is a plane. Construct an equation of the plane $L^\perp$.



Can also visualise line and plane with CalcPlot3D: web.monroecc.edu/calcNSF

$L^\perp$ = all the vectors orthogonal to the line L.

$$L^\perp = \text{span}\left\{ \begin{bmatrix}1\\1\\0\end{bmatrix}, \begin{bmatrix}-2\\0\\1\end{bmatrix} \right\}$$

Note

$$\boxed{\dim L + \dim L^\perp = n}$$

Want $\begin{bmatrix}a\\b\\c\end{bmatrix}$ s.t.

$$\begin{bmatrix}a\\b\\c\end{bmatrix} \cdot \begin{bmatrix}1\\-1\\2\end{bmatrix} = 0$$

$$\iff a - b + 2c = 0$$

$$\iff \begin{array}{ccc} & r & s \\ \Big[1 & -1 & 2\Big] \end{array} \begin{bmatrix}a\\b\\c\end{bmatrix} = 0$$

$$\iff \vec{x} = r\begin{bmatrix}1\\1\\0\end{bmatrix} + s\begin{bmatrix}-2\\0\\1\end{bmatrix}$$

$\begin{bmatrix}a\\b\\c\end{bmatrix}$ vectors of this form

If
$x \cdot v = 0$
then
$x \cdot (sv) = 0$ ✓

Row$A$ vs. $\text{Col}A = \text{Span}\{\text{cols of } A\}$

Definition

Row$A$ is the space spanned by the rows of matrix A.

We can show that

- $\dim(\text{Row}(A)) = \dim(\text{Col}(A))$
- a basis for Row$A$ is the pivot rows of A

Example $\text{Nul}\,A = (\text{Row}\,A)^\perp$ & $\text{Row}\,A = (\text{Nul}\,A)^\perp$

Describe the Null(A) in terms of an orthogonal subspace.

A vector $\vec{x}$ is in Null A if and only if

1. $A\vec{x} = \vec{0}$
2. This means that $\vec{x}$ is $\boxed{\text{orthogonal}}$ to each row of A.
3. Row A is $\boxed{\text{orthogonal complement}}$ to Null A.
4. The $\underbrace{\text{dimension of Row } A}_{\text{rank } A}$ plus the $\underbrace{\text{dimension of Null } A}_{\#\text{ free}}$ equals $\boxed{n}$ ← # cols.

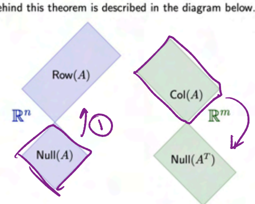
$$A\vec{x} = \vec{0} \iff \begin{bmatrix} \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \end{bmatrix}\begin{bmatrix} | \end{bmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\begin{bmatrix} 1 & 3 \\ 2 & 6 \end{bmatrix}\begin{bmatrix} -3 \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \iff \begin{cases} \begin{bmatrix} 1 & 3 \end{bmatrix}\begin{bmatrix} -3 \\ 1 \end{bmatrix} = 0 \\ \begin{bmatrix} 2 & 6 \end{bmatrix}\begin{bmatrix} -3 \\ 1 \end{bmatrix} = 0 \end{cases} \iff \begin{cases} \begin{bmatrix} 1 \\ 3 \end{bmatrix} \cdot \begin{bmatrix} -3 \\ 1 \end{bmatrix} = 0 \\ \begin{bmatrix} 2 \\ 6 \end{bmatrix} \cdot \begin{pmatrix} -3 \\ 1 \end{pmatrix} = 0 \end{cases}$$

Theorem (The Four Subspaces)

For any $A \in \mathbb{R}^{m\times n}$, the orthogonal complement of Row A is Null A, and the orthogonal complement of Col A is Null A^T.

The idea behind this theorem is described in the diagram below.



$$(\text{Col}\,A)^\perp = (\text{Row}\,A^T)^\perp \overset{①}{=} \text{Nul}\,A^T$$

Additional Example (if time permits)

A has the LU factorization:

$$A = LU = \begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 4 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 & 2 & 0 \\ 0 & 1 & -1 & 2 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

a) Construct a basis for $(\text{Row}A)^\perp$

b) Construct a basis for $(\text{Col}A)^\perp$

Hint: it is not necessary to compute A. Recall that $A^T = U^TL^T$, matrix L^T is invertible, and U^T has a non-empty nullspace.

THEOREM 3 Let A be an $m \times n$ matrix. The orthogonal complement of the row space of A is the null space of A, and the orthogonal complement of the column space of A is the null space of A^T:

$$(\text{Row}\,A)^\perp = \text{Nul}\,A \quad \text{and} \quad (\text{Col}\,A)^\perp = \text{Nul}\,A^T$$

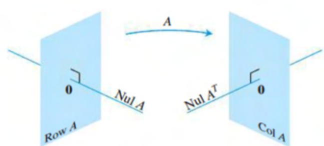


FIGURE 8 The fundamental subspaces determined by an $m \times n$ matrix A.

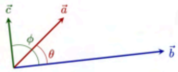
Angles

Theorem

$\vec{a}\cdot\vec{b} = |\vec{a}|\,|\vec{b}|\cos\theta$. Thus, if $\vec{a}\cdot\vec{b} = 0$, then:

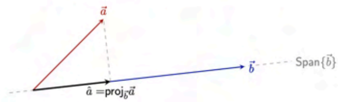
- $\vec{a}$ and/or $\vec{b}$ are zero vectors, or
- $\vec{a}$ and $\vec{b}$ are perpendicular.

For example, consider the vectors below.



Looking Ahead - Projections

Suppose we want to find the closed vector in Span$\{\vec{b}\}$ to $\vec{a}$.



- Later in this Chapter, we will make connections between dot products and **projections**.
- Projections are also used throughout multivariable calculus courses.

6.1 EXERCISES

Compute the quantities in Exercises 1–8 using the vectors

$\mathbf{u} = \begin{bmatrix} -1 \\ 2 \end{bmatrix}$, $\mathbf{v} = \begin{bmatrix} 4 \\ 6 \end{bmatrix}$, $\mathbf{w} = \begin{bmatrix} 3 \\ -1 \\ -5 \end{bmatrix}$, $\mathbf{x} = \begin{bmatrix} 6 \\ -2 \\ 3 \end{bmatrix}$

1. $\mathbf{u}\cdot\mathbf{u}$, $\mathbf{v}\cdot\mathbf{u}$, and $\dfrac{\mathbf{v}\cdot\mathbf{u}}{\mathbf{u}\cdot\mathbf{u}}$

2. $\mathbf{w}\cdot\mathbf{w}$, $\mathbf{x}\cdot\mathbf{w}$, and $\dfrac{\mathbf{x}\cdot\mathbf{w}}{\mathbf{w}\cdot\mathbf{w}}$

3. $\dfrac{1}{\mathbf{w}\cdot\mathbf{w}}\mathbf{w}$

4. $\dfrac{1}{\mathbf{u}\cdot\mathbf{u}}\mathbf{u}$

5. $\left(\dfrac{\mathbf{u}\cdot\mathbf{v}}{\mathbf{v}\cdot\mathbf{v}}\right)\mathbf{v}$

6. $\left(\dfrac{\mathbf{x}\cdot\mathbf{w}}{\mathbf{x}\cdot\mathbf{x}}\right)\mathbf{x}$

7. $\|\mathbf{w}\|$

8. $\|\mathbf{x}\|$

In Exercises 9–12, find a unit vector in the direction of the given vector.

9. $\begin{bmatrix} -30 \\ 40 \end{bmatrix}$

10. $\begin{bmatrix} -6 \\ 4 \\ -3 \end{bmatrix}$

11. $\begin{bmatrix} 7/4 \\ 1/2 \\ 1 \end{bmatrix}$

12. $\begin{bmatrix} 8/3 \\ 2 \end{bmatrix}$

13. Find the distance between $\mathbf{x} = \begin{bmatrix} 10 \\ -3 \end{bmatrix}$ and $\mathbf{y} = \begin{bmatrix} -1 \\ -5 \end{bmatrix}$.

14. Find the distance between $\mathbf{u} = \begin{bmatrix} 0 \\ -5 \\ 2 \end{bmatrix}$ and $\mathbf{z} = \begin{bmatrix} -4 \\ -1 \\ 8 \end{bmatrix}$.

Determine which pairs of vectors in Exercises 15–18 are orthogonal.

15. $\mathbf{a} = \begin{bmatrix} 8 \\ -5 \end{bmatrix}$, $\mathbf{b} = \begin{bmatrix} -2 \\ -3 \end{bmatrix}$

16. $\mathbf{u} = \begin{bmatrix} 12 \\ 3 \\ -5 \end{bmatrix}$, $\mathbf{v} = \begin{bmatrix} 2 \\ -3 \\ 3 \end{bmatrix}$

17. $\mathbf{u} = \begin{bmatrix} 3 \\ 2 \\ -5 \\ 0 \end{bmatrix}$, $\mathbf{v} = \begin{bmatrix} -4 \\ 1 \\ -2 \\ 6 \end{bmatrix}$

18. $\mathbf{y} = \begin{bmatrix} -3 \\ 7 \\ 4 \\ 0 \end{bmatrix}$, $\mathbf{z} = \begin{bmatrix} 1 \\ -8 \\ 15 \\ -7 \end{bmatrix}$

In Exercises 19 and 20, all vectors are in $\mathbb{R}^n$. Mark each statement True or False. Justify each answer.

19. a. $\mathbf{v}\cdot\mathbf{v} = \|\mathbf{v}\|^2$.

b. For any scalar c, $\mathbf{u}\cdot(c\mathbf{v}) = c(\mathbf{u}\cdot\mathbf{v})$.

c. If the distance from $\mathbf{u}$ to $\mathbf{v}$ equals the distance from $\mathbf{u}$ to $-\mathbf{v}$, then $\mathbf{u}$ and $\mathbf{v}$ are orthogonal.

d. For a square matrix A, vectors in Col A are orthogonal to vectors in Nul A.

e. If vectors $\mathbf{v}_1, \dots, \mathbf{v}_p$ span a subspace W and if $\mathbf{x}$ is orthogonal to each $\mathbf{v}_j$ for $j = 1, \dots, p$, then $\mathbf{x}$ is in $W^\perp$.

20. a. $\mathbf{u}\cdot\mathbf{v} - \mathbf{v}\cdot\mathbf{u} = 0$.

b. For any scalar c, $\|c\mathbf{v}\| = c\|\mathbf{v}\|$.

c. If $\mathbf{x}$ is orthogonal to every vector in a subspace W, then $\mathbf{x}$ is in $W^\perp$.

d. If $\|\mathbf{u}\|^2 + \|\mathbf{v}\|^2 = \|\mathbf{u} + \mathbf{v}\|^2$, then $\mathbf{u}$ and $\mathbf{v}$ are orthogonal.

e. For an $m \times n$ matrix A, vectors in the null space of A are orthogonal to vectors in the row space of A.

21. Use the transpose definition of the inner product to verify parts (b) and (c) of Theorem 1. Mention the appropriate facts from Chapter 2.

22. Let $\mathbf{u} = (u_1, u_2, u_3)$. Explain why $\mathbf{u}\cdot\mathbf{u} \geq 0$. When is $\mathbf{u}\cdot\mathbf{u} = 0$?

23. Let $\mathbf{u} = \begin{bmatrix} 2 \\ -5 \\ -1 \end{bmatrix}$ and $\mathbf{v} = \begin{bmatrix} -7 \\ -4 \\ 6 \end{bmatrix}$. Compute and compare $\mathbf{u}\cdot\mathbf{v}$, $\|\mathbf{u}\|^2$, $\|\mathbf{v}\|^2$, and $\|\mathbf{u} + \mathbf{v}\|^2$. Do not use the Pythagorean Theorem.

24. Verify the *parallelogram law* for vectors $\mathbf{u}$ and $\mathbf{v}$ in $\mathbb{R}^n$:

$$\|\mathbf{u} + \mathbf{v}\|^2 + \|\mathbf{u} - \mathbf{v}\|^2 = 2\|\mathbf{u}\|^2 + 2\|\mathbf{v}\|^2$$

25. Let $\mathbf{v} = \begin{bmatrix} a \\ b \end{bmatrix}$. Describe the set H of vectors $\begin{bmatrix} x \\ y \end{bmatrix}$ that are orthogonal to $\mathbf{v}$. [*Hint:* Consider $\mathbf{v} = \mathbf{0}$ and $\mathbf{v} \neq \mathbf{0}$.]

26. Let $\mathbf{u} = \begin{bmatrix} 5 \\ -6 \\ 7 \end{bmatrix}$, and let W be the set of all $\mathbf{x}$ in $\mathbb{R}^3$ such that $\mathbf{u}\cdot\mathbf{x} = 0$. What theorem in Chapter 4 can be used to show that W is a subspace of $\mathbb{R}^3$? Describe W in geometric language.

27. Suppose a vector $\mathbf{y}$ is orthogonal to vectors $\mathbf{u}$ and $\mathbf{v}$. Show that $\mathbf{y}$ is orthogonal to the vector $\mathbf{u} + \mathbf{v}$.

28. Suppose $\mathbf{y}$ is orthogonal to $\mathbf{u}$ and $\mathbf{v}$. Show that $\mathbf{y}$ is orthogonal to every $\mathbf{w}$ in Span $\{\mathbf{u}, \mathbf{v}\}$. [*Hint:* An arbitrary $\mathbf{w}$ in Span $\{\mathbf{u}, \mathbf{v}\}$ has the form $\mathbf{w} = c_1\mathbf{u} + c_2\mathbf{v}$. Show that $\mathbf{y}$ is orthogonal to such a vector $\mathbf{w}$.]

29. Let $W = \text{Span}\,\{\mathbf{v}_1, \dots, \mathbf{v}_p\}$. Show that if $\mathbf{x}$ is orthogonal to each $\mathbf{v}_j$, for $1 \leq j \leq p$, then $\mathbf{x}$ is orthogonal to every vector in W.