LINEAR ALGEBRA

Week 10

Section 6.2 : Orthogonal Sets

Chapter 6 : Orthogonality and Least Squares

Math 1554 Linear Algebra

Section 6.2 : Orthogonal Sets

Chapter 6 : Orthogonality and Least Squares

Math 1554 Linear Algebra

Topics and Objectives

Topics

1. Orthogonal Sets of Vectors
2. Orthogonal Bases and Projections.

Learning Objectives

1. Apply the concepts of orthogonality to
   a) compute orthogonal projections and distances,
   b) express a vector as a linear combination of orthogonal vectors,
   c) characterize bases for subspaces of $\mathbb{R}^n$, and
   d) construct orthonormal bases.

Motivating Question
What are the special properties of this basis for $\mathbb{R}^3$?

$$\begin{bmatrix}3\\1\\1\end{bmatrix}/\sqrt{11},\quad \begin{bmatrix}-1\\2\\1\end{bmatrix}/\sqrt{6},\quad \begin{bmatrix}-1\\-4\\7\end{bmatrix}/\sqrt{66}$$

Course Schedule

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

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**				

Orthogonal Vector Sets

e.g. $\left\{\begin{bmatrix}0\\0\end{bmatrix}, \begin{bmatrix}-1\\1\end{bmatrix}, \begin{bmatrix}1\\1\end{bmatrix}\right\}$

Definition

A set of vectors $\{\vec{u}_1, \dots, \vec{u}_p\}$ are an **orthogonal set** of vectors if for each $j \neq k$, $\underbrace{\vec{u}_j \perp \vec{u}_k}$.

$U_j \cdot U_k = 0$ "orthogonal"

Example: Fill in the missing entries to make $\{\vec{u}_1, \vec{u}_2, \vec{u}_3\}$ an orthogonal set of vectors.

$$\vec{u}_1 = \begin{bmatrix}4\\1\\1\end{bmatrix}, \quad \vec{u}_2 = \begin{bmatrix}-2\\1\\7\end{bmatrix}, \quad \vec{u}_3 = \begin{bmatrix}1\\-5\\1\end{bmatrix}$$

$$\begin{cases} U_3 \cdot U_1 = 0 \\ U_3 \cdot U_2 = 0 \end{cases}$$

$$U_1 \cdot U_2 = \begin{bmatrix}4\\1\\1\end{bmatrix} \cdot \begin{bmatrix}-2\\1\\7\end{bmatrix} = -8 + 1 + 7 = 0$$

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

solve for a.

$$\begin{bmatrix}4 & 1 & 1\\-2 & 1 & 7\end{bmatrix}\begin{bmatrix}a\\b\\c\end{bmatrix} = \begin{bmatrix}0\\0\end{bmatrix}$$

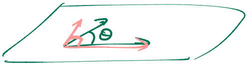
Linear Independence

Theorem (Linear Independence for Orthogonal Sets)

Let $\{\vec{u}_1, \dots, \vec{u}_p\}$ be an orthogonal set of vectors. Then, for scalars $c_1, \dots, c_p$,

$$\|c_1\vec{u}_1 + \cdots + c_p\vec{u}_p\|^2 = c_1^2\|\vec{u}_1\|^2 + \cdots + c_p^2\|\vec{u}_p\|^2.$$

In particular, if all the vectors $\vec{u}_r$ are non-zero, the set of vectors $\{\vec{u}_1, \dots, \vec{u}_p\}$ are linearly independent.



$$\begin{bmatrix}-2 & 1 & 7\\4 & 1 & 1\end{bmatrix} \sim \begin{bmatrix}-2 & 1 & 7\\0 & 3 & 15\end{bmatrix} \sim \begin{bmatrix}-2 & 1 & 7\\0 & 1 & 5\end{bmatrix}$$

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

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

$$X = s\begin{bmatrix}1\\-5\\1\end{bmatrix}$$

✓ $U_1 \cdot U_2 = -8 + 1 + 7 = 0$

✓ $U_1 \cdot U_3 = 4 - 5 + 1 = 0$

✓ $U_2 \cdot U_3 = -2 - 5 + 7 = 0$

EXAMPLE 1 Show that $\{\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3\}$ is an orthogonal set, where

$$\mathbf{u}_1 = \begin{bmatrix}3\\1\\1\end{bmatrix}, \quad \mathbf{u}_2 = \begin{bmatrix}-1\\2\\1\end{bmatrix}, \quad \mathbf{u}_3 = \begin{bmatrix}-1/2\\-2\\7/2\end{bmatrix}$$

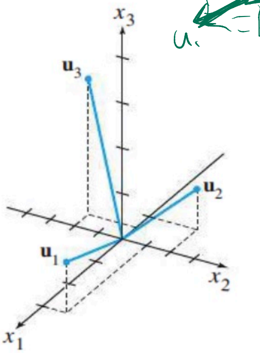
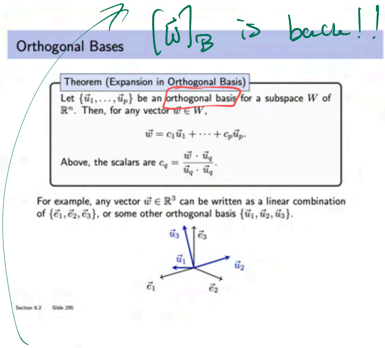


FIGURE 1

$[\vec{w}]_B$ is back!!



Orthogonal Bases

Theorem (Expansion in Orthogonal Basis)

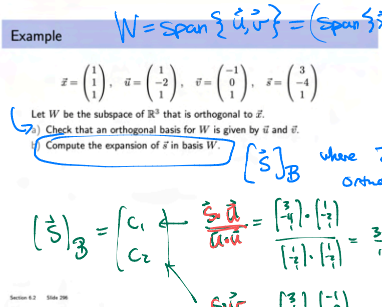
Let $\{\vec{u}_1, \dots, \vec{u}_p\}$ be an orthogonal basis for a subspace W of $\mathbb{R}^n$. Then, for any vector $\vec{w} \in W$,

$$\vec{w} = c_1\vec{u}_1 + \cdots + c_p\vec{u}_p.$$

Above, the scalars are $c_q = \dfrac{\vec{w} \cdot \vec{u}_q}{\vec{u}_q \cdot \vec{u}_q}$.

For example, any vector $\vec{w} \in \mathbb{R}^3$ can be written as a linear combination of $\{\vec{e}_1, \vec{e}_2, \vec{e}_3\}$, or some other orthogonal basis $\{\vec{u}_1, \vec{u}_2, \vec{u}_3\}$.

$W = \text{span}\{\vec{u}, \vec{v}\} = (\text{span}\{\vec{x}\})^{\perp}$



Example

$$\vec{x} = \begin{pmatrix}1\\1\\1\end{pmatrix}, \quad \vec{u} = \begin{pmatrix}1\\-2\\1\end{pmatrix}, \quad \vec{v} = \begin{pmatrix}-1\\0\\1\end{pmatrix}, \quad \vec{s} = \begin{pmatrix}3\\-4\\1\end{pmatrix}$$

Let W be the subspace of $\mathbb{R}^3$ that is orthogonal to $\vec{x}$.

a) Check that an orthogonal basis for W is given by $\vec{u}$ and $\vec{v}$.

b) Compute the expansion of $\vec{s}$ in basis W.

$[\vec{s}]_B$ where $B = \{\vec{u}, \vec{v}\}$ orthogonal basis for W.

$$[\vec{s}]_B = \begin{bmatrix}c_1\\c_2\end{bmatrix}$$

$$\frac{\vec{s}\cdot\vec{u}}{\vec{u}\cdot\vec{u}} = \frac{\begin{bmatrix}3\\-4\\1\end{bmatrix}\cdot\begin{bmatrix}1\\-2\\1\end{bmatrix}}{\begin{bmatrix}1\\-2\\1\end{bmatrix}\cdot\begin{bmatrix}1\\-2\\1\end{bmatrix}} = \frac{3+8+1}{1+4+1} = \frac{12}{6} = \boxed{2}$$

$$\frac{\vec{s}\cdot\vec{v}}{\vec{v}\cdot\vec{v}} = \frac{\begin{bmatrix}3\\-4\\1\end{bmatrix}\cdot\begin{bmatrix}-1\\0\\1\end{bmatrix}}{\begin{bmatrix}-1\\0\\1\end{bmatrix}\cdot\begin{bmatrix}-1\\0\\1\end{bmatrix}} = \frac{-3+0+1}{1+1} = \frac{-2}{2} = \boxed{-1}$$

Check.

$$\begin{bmatrix}3\\-4\\1\end{bmatrix} \overset{?}{=} 2\begin{bmatrix}1\\-2\\1\end{bmatrix} - 1\begin{bmatrix}-1\\0\\1\end{bmatrix}$$

$[\vec{w}]_B$ = "the coords of $\vec{w}$ in the basis B"

$B = \{\vec{u}_1, \vec{u}_2, \dots, \vec{u}_p\}$ basis for W.

$$c_1\vec{u}_1 + c_2\vec{u}_2 + \dots + c_p\vec{u}_p = \vec{w}$$

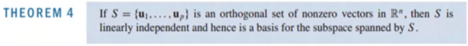
$$\begin{bmatrix}\vec{u}_1 \cdots \vec{u}_p\end{bmatrix}\begin{bmatrix}c_1\\ \vdots \\ c_p\end{bmatrix} = \vec{w}$$

solve for weights.

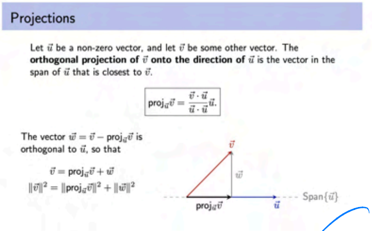
$$\left[u_1 \cdots u_p \mid \vec{w}\right]$$

get $[w]_B$

$$[u_1 \cdots u_p]^{-1} * \vec{w} = \vec{c}.$$



THEOREM 4 If $S = \{\mathbf{u}_1, \dots, \mathbf{u}_p\}$ is an orthogonal set of nonzero vectors in $\mathbb{R}^n$, then S is linearly independent and hence is a basis for the subspace spanned by S.



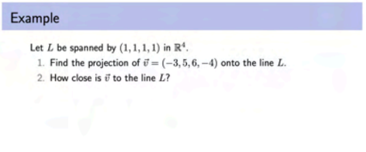
Projections

Let $\vec{u}$ be a non-zero vector, and let $\vec{v}$ be some other vector. The **orthogonal projection of $\vec{v}$ onto the direction of $\vec{u}$** is the vector in the span of $\vec{u}$ that is closest to $\vec{v}$.

$$\boxed{\text{proj}_{\vec{u}}\vec{v} = \frac{\vec{v}\cdot\vec{u}}{\vec{u}\cdot\vec{u}}\vec{u}.}$$

The vector $\vec{w} = \vec{v} - \text{proj}_{\vec{u}}\vec{v}$ is orthogonal to $\vec{u}$, so that

$$\vec{v} = \text{proj}_{\vec{u}}\vec{v} + \vec{w}$$
$$\|\vec{v}\|^2 = \|\text{proj}_{\vec{u}}\vec{v}\|^2 + \|\vec{w}\|^2$$



Example

Let L be spanned by $(1,1,1,1)$ in $\mathbb{R}^4$.

1. Find the projection of $\vec{v} = (-3, 5, 6, -4)$ onto the line L.
2. How close is $\vec{v}$ to the line L?

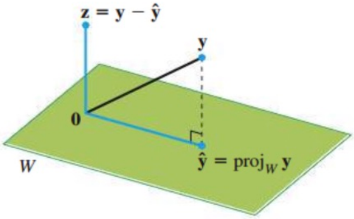
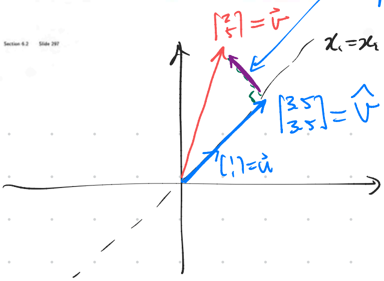


FIGURE 2 Finding α to make $\mathbf{y} - \hat{\mathbf{y}}$ orthogonal to $\mathbf{u}$.

$$\|\vec{v} - \hat{v}\| = \left\|\begin{bmatrix}2\\5\end{bmatrix} - \begin{bmatrix}3.5\\3.5\end{bmatrix}\right\| = \left\|\begin{bmatrix}-1.5\\1.5\end{bmatrix}\right\|$$

$$= \sqrt{(1.5)^2 + (1.5)^2}$$

$$= \sqrt{4.5}$$

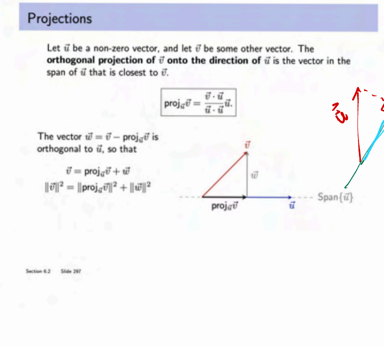


$$\text{proj}_{\vec{u}}(\vec{v}) = \frac{\vec{v}\cdot\vec{u}}{\vec{u}\cdot\vec{u}}\vec{u}$$

$$= \frac{\begin{bmatrix}2\\5\end{bmatrix}\cdot\begin{bmatrix}1\\1\end{bmatrix}}{\begin{bmatrix}1\\1\end{bmatrix}\cdot\begin{bmatrix}1\\1\end{bmatrix}}\begin{pmatrix}1\\1\end{pmatrix}$$

$$= \frac{7}{2}\begin{pmatrix}1\\1\end{pmatrix}$$

$$= \begin{bmatrix}3.5\\3.5\end{bmatrix}$$



Projections

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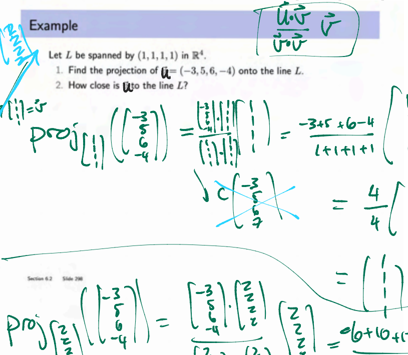
$$\boxed{\text{proj}_{\vec{u}}\vec{v} = \frac{\vec{v}\cdot\vec{u}}{\vec{u}\cdot\vec{u}}\vec{u}.}$$

The vector $\vec{w} = \vec{v} - \text{proj}_{\vec{u}}\vec{v}$ is orthogonal to $\vec{u}$, so that

$$\vec{v} = \text{proj}_{\vec{u}}\vec{v} + \vec{w}$$
$$\|\vec{v}\|^2 = \|\text{proj}_{\vec{u}}\vec{v}\|^2 + \|\vec{w}\|^2$$

$\vec{u}$

$\begin{bmatrix}2\\2\\2\\2\end{bmatrix}$



Example

$$\boxed{\frac{\vec{u}\cdot\vec{v}}{\vec{v}\cdot\vec{v}}\vec{v}}$$

Let L be spanned by $(1,1,1,1)$ in $\mathbb{R}^4$.

1. Find the projection of $\vec{v}$ u $= (-3,5,6,-4)$ onto the line L.
2. How close is $\vec{v}$ u to the line L?

$\begin{bmatrix}1\\1\\1\\1\end{bmatrix}=\vec{v}$

$$\text{proj}_{\begin{bmatrix}1\\1\\1\\1\end{bmatrix}}\left(\begin{pmatrix}-3\\5\\6\\-4\end{pmatrix}\right) = \frac{\begin{bmatrix}-3\\5\\6\\-4\end{bmatrix}\cdot\begin{bmatrix}1\\1\\1\\1\end{bmatrix}}{\begin{bmatrix}1\\1\\1\\1\end{bmatrix}\cdot\begin{bmatrix}1\\1\\1\\1\end{bmatrix}}\begin{bmatrix}1\\1\\1\\1\end{bmatrix} = \frac{-3+5+6-4}{1+1+1+1}\begin{pmatrix}1\\1\\1\\1\end{pmatrix}$$

$$c\cancel{\begin{pmatrix}-3\\5\\6\\7\end{pmatrix}}$$

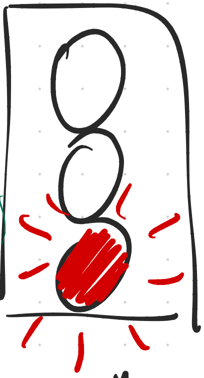
$$= \frac{4}{4}\begin{pmatrix}1\\1\\1\\1\end{pmatrix}$$

$$= \begin{pmatrix}1\\1\\1\\1\end{pmatrix}$$

$$\text{proj}_{\begin{bmatrix}2\\2\\2\\2\end{bmatrix}}\left(\begin{pmatrix}-3\\5\\6\\-4\end{pmatrix}\right) = \frac{\begin{bmatrix}-3\\5\\6\\-4\end{bmatrix}\cdot\begin{bmatrix}2\\2\\2\\2\end{bmatrix}}{\begin{bmatrix}2\\2\\2\\2\end{bmatrix}\cdot\begin{bmatrix}2\\2\\2\\2\end{bmatrix}}\begin{bmatrix}2\\2\\2\\2\end{bmatrix} = \frac{-6+10+12-8}{4+4+4+4}\begin{bmatrix}2\\2\\2\\2\end{bmatrix}$$

$$= \frac{8}{16}\begin{bmatrix}2\\2\\2\\2\end{bmatrix} = \frac{1}{2}\begin{bmatrix}2\\2\\2\\2\end{bmatrix}$$

$$= \begin{pmatrix}1\\1\\1\\1\end{pmatrix}.$$



stop talking please

EXAMPLE 3 Let $\mathbf{y} = \begin{bmatrix}7\\6\end{bmatrix}$ and $\mathbf{u} = \begin{bmatrix}4\\2\end{bmatrix}$. Find the orthogonal projection of $\mathbf{y}$ onto $\mathbf{u}$. Then write $\mathbf{y}$ as the sum of two orthogonal vectors, one in Span $\{\mathbf{u}\}$ and one orthogonal to $\mathbf{u}$.

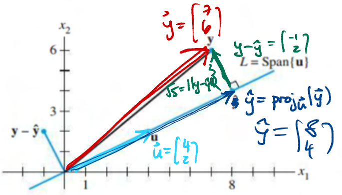


FIGURE 3 The orthogonal projection of $\mathbf{y}$ onto a line L through the origin.

$$\hat y = \text{proj}_{\vec u}(\vec y) = \frac{\vec y \cdot \vec u}{\vec u \cdot \vec u}\vec u = \frac{\begin{bmatrix}7\\6\end{bmatrix}\cdot\begin{bmatrix}4\\2\end{bmatrix}}{\begin{bmatrix}4\\2\end{bmatrix}\cdot\begin{bmatrix}4\\2\end{bmatrix}}\begin{bmatrix}4\\2\end{bmatrix} = \frac{40}{20}\begin{bmatrix}4\\2\end{bmatrix} = 2\begin{bmatrix}4\\2\end{bmatrix}$$

$$= \begin{bmatrix}8\\4\end{bmatrix}$$

$$y - \hat y = \begin{bmatrix}7\\6\end{bmatrix} - \begin{bmatrix}8\\4\end{bmatrix} = \begin{bmatrix}-1\\2\end{bmatrix}$$

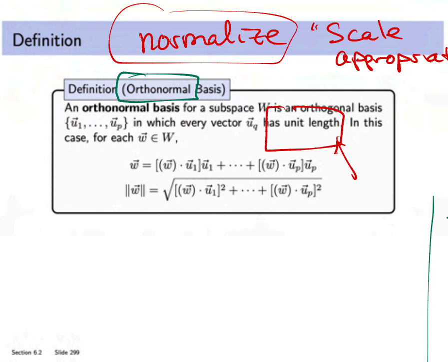
$$\vec y = \hat y + (\vec y - \hat y) = \begin{bmatrix}8\\4\end{bmatrix} + \begin{bmatrix}-1\\2\end{bmatrix}$$

& $$\text{dist}(\vec y, L) = \|\vec y - \hat y\| = \left\|\begin{bmatrix}-1\\2\end{bmatrix}\right\| = \sqrt{1^2+2^2} = \sqrt5$$

Defn: An orthogonal basis for W is a set of vectors $\{v_1, \dots, v_p\}$ st.

① $\{v_1, \dots, v_p\}$ basis for W

② $\{v_1, \dots, v_p\}$ orthogonal set of vectors.



Definition normalize "Scale appropriately"

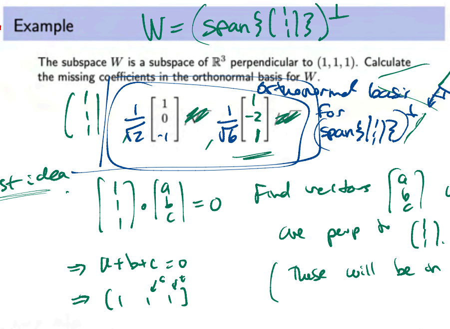
Definition (Orthonormal Basis)

An **orthonormal basis** for a subspace W ~~is an orthogonal basis~~ $\{\vec u_1, \dots, \vec u_p\}$ in which every vector $\vec u_q$ has unit length. In this case, for each $\vec w \in W$,

$$\vec w = [(\vec w)\cdot \vec u_1]\vec u_1 + \cdots + [(\vec w)\cdot\vec u_p]\vec u_p$$

$$\|\vec w\| = \sqrt{[(\vec w)\cdot\vec u_1]^2 + \cdots + [(\vec w)\cdot\vec u_p]^2}$$

Section 6.2 Slide 299



Example $W = \left(\text{span}\left\{\begin{bmatrix}1\\1\\1\end{bmatrix}\right\}\right)^\perp$

The subspace W is a subspace of $\mathbb{R}^3$ perpendicular to $(1,1,1)$. Calculate the missing ~~coefficients in the orthonormal basis for~~ W.

$$\begin{bmatrix}1\\1\\1\end{bmatrix} \quad \frac{1}{\sqrt2}\begin{bmatrix}1\\0\\-1\end{bmatrix}, \frac{1}{\sqrt6}\begin{bmatrix}1\\-2\\1\end{bmatrix}$$

orthonormal basis for $\left(\text{span}\left\{\begin{bmatrix}1\\1\\1\end{bmatrix}\right\}\right)^\perp$

Section 6.2 Slide 300

$\text{span}\left\{\begin{bmatrix}1\\1\\1\end{bmatrix}\right\}$

W

§6.4

Gram-Schmidt

First idea: $\begin{bmatrix}1\\1\\1\end{bmatrix}\cdot\begin{bmatrix}a\\b\\c\end{bmatrix} = 0$ Find vectors $\begin{bmatrix}a\\b\\c\end{bmatrix}$ which are perp to $\begin{bmatrix}1\\1\\1\end{bmatrix}$.

(These will be in W)

$\Rightarrow a+b+c=0$

$\Rightarrow [1 \ \ 1 \ \ 1]$

$$\vec x = s\begin{bmatrix}-1\\1\\0\end{bmatrix} + t\begin{bmatrix}-1\\0\\1\end{bmatrix}$$

So a basis for $W = \left(\text{span}\left\{\begin{bmatrix}1\\1\\1\end{bmatrix}\right\}\right)^\perp$ is $\left\{\begin{bmatrix}-1\\1\\0\end{bmatrix}, \begin{bmatrix}-1\\0\\1\end{bmatrix}\right\}$

↑ ↑ are they orthogonal?

$$\begin{bmatrix}-1\\1\\0\end{bmatrix}\cdot\begin{bmatrix}-1\\0\\1\end{bmatrix} = (-1)^2+0+0 = 1 \neq 0$$

Second idea

$$\begin{bmatrix}1\\1\\1\end{bmatrix}\cdot\begin{bmatrix}a\\b\\c\end{bmatrix} = 0 \qquad a+b+c=0$$

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

$$-R_2+R_1 \quad \begin{bmatrix}1 & 1 & 1\\1 & 0 & -1\end{bmatrix} \sim \begin{bmatrix}1 & 0 & -1\\0 & 1 & 2\end{bmatrix} \qquad \boxed{x = s\begin{bmatrix}1\\-2\\1\end{bmatrix}}$$

Orthogonal Matrices

I'm Sorry!

An **orthogonal matrix** is a square matrix whose columns are orthonormal.

Theorem

An $m \times n$ matrix U has orthonormal columns if and only if $U^T U = I_n$.

Note that this theorem does not apply when $n > m$. Why?

Theorem

Theorem (Mapping Properties of Orthogonal Matrices)

Assume $m \times m$ matrix U has orthonormal columns. Then

1. (Preserves length) $\|U\vec{x}\| = \boxed{}$
2. (Preserves angles) $(U\vec{x}) \cdot (U\vec{y}) = \boxed{}$
3. (Preserves orthogonality)

$$\underset{3\times m}{U^T}\ \underset{m\times 3}{U} \qquad 3\times 3$$

$$\begin{bmatrix} - u_1^T - \\ - u_2^T - \\ - u_3^T - \end{bmatrix}\begin{bmatrix} | & | & | \\ u_1 & u_2 & u_3 \\ | & | & | \end{bmatrix} = \begin{bmatrix} u_1^T u_1 & u_1^T u_2 & u_1^T u_3 \\ u_2^T u_1 & u_2^T u_2 & u_2^T u_3 \\ u_3^T u_1 & u_3^T u_2 & u_3^T u_3 \end{bmatrix}$$

$$= \begin{bmatrix} u_1 \cdot u_1 & u_1 \cdot u_2 & u_1 \cdot u_3 \\ u_2 \cdot u_1 & u_2 \cdot u_2 & u_2 \cdot u_3 \\ u_3 \cdot u_1 & u_3 \cdot u_2 & u_3 \cdot u_3 \end{bmatrix}$$

$(i \neq j)\ u_i \cdot u_j = 0$

$(\text{any } i)\ u_i \cdot u_i = 1$

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

$$\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = I \quad \text{orthogonal!}$$

$$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = E \quad ✓$$

$$\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} = P \quad \boxed{\text{no}}$$

$$P' = \begin{bmatrix} \overset{\vec{u}_1}{1/\sqrt{2}} & \overset{\vec{u}_2}{-1/\sqrt{2}} \\ 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \leftarrow \text{orthogonal? } \boxed{\text{yes}}$$

transpose P' itself

$$(P')^T P' = \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} \\ -1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}\begin{bmatrix} 1/\sqrt{2} & -1/\sqrt{2} \\ 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix}$$

$u_i \cdot u_j = 0$

$$= \begin{bmatrix} \vec{u}_1 \cdot \vec{u}_1 & \boxed{\vec{u}_1 \cdot \vec{u}_2} \\ \vec{u}_2 \cdot \vec{u}_1 & \vec{u}_2 \cdot \vec{u}_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

$$\begin{bmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{bmatrix} \cdot \begin{bmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{bmatrix} = \left(\frac{1}{\sqrt{2}}\right)^2 + \left(\frac{1}{\sqrt{2}}\right)^2 = 1$$

$$\|u_i\|^2 = u_i \cdot u_i = 1.$$

$$\begin{array}{cc} \vec{u}_1 & \vec{u}_2 \\ \downarrow & \downarrow \end{array}\ \begin{bmatrix} a & -b \\ b & a \end{bmatrix} \ ✗$$

$$u_1 \cdot u_2 = \begin{bmatrix} a \\ b \end{bmatrix} \cdot \begin{bmatrix} -b \\ a \end{bmatrix} = -ab + ab = 0$$

$$\frac{1}{\sqrt{a^2+b^2}}\begin{bmatrix} a & -b \\ b & a \end{bmatrix} \quad \text{orthogonal.}$$

$$\begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \quad \text{orthogonal matrix?} \quad \boxed{\text{yes}} \ ✓$$

Example

Compute the length of the vector below.

$$\left\| \begin{bmatrix} 1/2 & 2/\sqrt{14} \\ 1/2 & 1/\sqrt{14} \\ 1/2 & -3/\sqrt{14} \\ 1/2 & 0 \end{bmatrix} \begin{bmatrix} \sqrt{2} \\ -3 \end{bmatrix} \right\|$$

$$\left\| \begin{bmatrix} \sqrt{2} \\ -3 \end{bmatrix} \right\| = \left\| \begin{bmatrix} 1/2 & 2/\sqrt{14} \\ 1/2 & 1/\sqrt{14} \\ 1/2 & -3/\sqrt{14} \\ 1/2 & 0 \end{bmatrix} \begin{bmatrix} \sqrt{2} \\ -3 \end{bmatrix} \right\| = \left\| \sqrt{2}\begin{bmatrix} 1/2 \\ 1/2 \\ 1/2 \\ 1/2 \end{bmatrix} + (-3)\begin{bmatrix} 2/\sqrt{14} \\ 1/\sqrt{14} \\ -3/\sqrt{14} \\ 0 \end{bmatrix} \right\|$$

wrong way

since has orthonormal cols.

$$\left\| \begin{bmatrix} \sqrt{2} \\ -3 \end{bmatrix} \right\| = \sqrt{(\sqrt{2})^2 + 3^2} = \sqrt{2+9} = \boxed{\sqrt{11}}$$

Additional Example (if time permits)

A 4×4 orthonormal matrix is below. It's columns are orthonormal.

$$A = \begin{bmatrix} 1/2 & 2/\sqrt{10} & 1/2 & 1/\sqrt{10} \\ 1/2 & 1/\sqrt{10} & -1/2 & -2/\sqrt{10} \\ 1/2 & -1/\sqrt{10} & -1/2 & 2/\sqrt{10} \\ 1/2 & -2/\sqrt{10} & 1/2 & -1/\sqrt{10} \end{bmatrix}$$

Verify that the rows also form an orthonormal basis.

$$\left\| \begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} \right\| = \sqrt{1+1+1+1} = \sqrt{4} = 2$$

$$\mathbb{1} \ \perp ?$$

$$\left\| \begin{bmatrix} 2 \\ 1 \\ -3 \\ 0 \end{bmatrix} \right\| = \sqrt{4+1+9} = \sqrt{14}$$

Orthogonal Matrices

An **orthogonal matrix** is a square matrix whose columns are orthonormal.

Theorem

An $m \times n$ matrix U has orthonormal columns if and only if $U^T U = I_n$.

Note that this theorem does not apply when $n > m$. Why?

Theorem

Theorem (Mapping Properties of Orthogonal Matrices)

Assume $m \times m$ matrix U has orthonormal columns. Then

1. (Preserves length) $\|U\vec{x}\| = \boxed{\|x\|}$
2. (Preserves angles) $(U\vec{x}) \cdot (U\vec{y}) = \boxed{\vec{x} \cdot \vec{y}}$
3. (Preserves orthogonality) If $x \cdot y = 0$ then $Ux \cdot Uy$ also orthogonal.

$(AB)^T = B^T A^T$

$$\|u_1\|^2 = \begin{bmatrix} 1/\sqrt{2} \\ 0 \\ 1/\sqrt{2} \end{bmatrix} \cdot \begin{pmatrix} 1/\sqrt{2} \\ 0 \\ 1/\sqrt{2} \end{pmatrix} = \frac{1}{2} + 0 + \frac{1}{2} = 1$$

$$U = [\vec{u}_1 \; \vec{u}_2] = \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{6} \\ 0 & 2/\sqrt{6} \\ 1/\sqrt{2} & -1/\sqrt{6} \end{bmatrix}$$

$$u_1 \cdot u_2 = \begin{bmatrix} 1/\sqrt{2} \\ 0 \\ 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} 1/\sqrt{6} \\ 2/\sqrt{6} \\ -1/\sqrt{6} \end{bmatrix} = \frac{1}{\sqrt{12}} + 0 - \frac{1}{\sqrt{12}} = 0$$

$$\|\vec{u}_2\|^2 = \frac{1}{6} + \frac{4}{6} + \frac{1}{6} = \frac{6}{6} = 1.$$

① $\|U\vec{x}\|^2 = (Ux) \cdot (Ux)$

$= (U\vec{x})^T U\vec{x}$

$= x^T U^T U \vec{x} = x^T x = x \cdot x = \|x\|^2$

② $(Ux) \cdot (Uy) = (Ux)^T Uy$

$= x^T U^T U y = x^T y$

$= x \cdot y$

$$U^T U = \overset{2 \times 3}{\begin{pmatrix} 1/\sqrt{2} & 0 & 1/\sqrt{2} \\ 1/\sqrt{6} & 2/\sqrt{6} & -1/\sqrt{6} \end{pmatrix}} \overset{3 \times 2}{\begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{6} \\ 0 & 2/\sqrt{6} \\ 1/\sqrt{2} & -1/\sqrt{6} \end{pmatrix}} = \overset{2 \times 2}{\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}}$$

$u_i \cdot u_i = 1$

$$= \begin{bmatrix} u_1 \cdot u_1 & u_1 \cdot u_2 \\ u_2 \cdot u_1 & u_2 \cdot u_2 \end{bmatrix}$$

$u_i \cdot u_j = 0$

$\{u_1, u_2\}$ orthonormal cols.

$$UU^T = \begin{bmatrix} 2/3 & -1/3 & 1/3 \\ -1/3 & 2/3 & 1/3 \\ 1/3 & 1/3 & 2/3 \end{bmatrix}$$

Standard matrix of $\text{proj}_{\text{Col}(U)}(\vec{x})$

$\text{proj}_{\text{Col}\,U} : \mathbb{R}^3 \to \mathbb{R}^3$ is a linear transformation

6.2 EXERCISES

In Exercises 1–6, determine which sets of vectors are orthogonal.

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

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

3. $\begin{bmatrix} 2 \\ -7 \\ -1 \end{bmatrix}, \begin{bmatrix} -6 \\ -3 \\ 9 \end{bmatrix}, \begin{bmatrix} 3 \\ 1 \\ -1 \end{bmatrix}$

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

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

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

In Exercises 7–10, show that $\{\mathbf{u}_1, \mathbf{u}_2\}$ or $\{\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3\}$ is an orthogonal basis for $\mathbb{R}^2$ or $\mathbb{R}^3$, respectively. Then express $\mathbf{x}$ as a linear combination of the $\mathbf{u}$'s.

7. $\mathbf{u}_1 = \begin{bmatrix} 2 \\ -3 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} 6 \\ 4 \end{bmatrix}$, and $\mathbf{x} = \begin{bmatrix} 9 \\ -7 \end{bmatrix}$

8. $\mathbf{u}_1 = \begin{bmatrix} 3 \\ 1 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -2 \\ 6 \end{bmatrix}$, and $\mathbf{x} = \begin{bmatrix} -6 \\ 3 \end{bmatrix}$

9. $\mathbf{u}_1 = \begin{bmatrix} 1 \\ 0 \\ 1 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -1 \\ 4 \\ 1 \end{bmatrix}, \mathbf{u}_3 = \begin{bmatrix} 2 \\ 1 \\ -2 \end{bmatrix}$, and $\mathbf{x} = \begin{bmatrix} 8 \\ -4 \\ -3 \end{bmatrix}$

10. $\mathbf{u}_1 = \begin{bmatrix} 3 \\ -3 \\ 0 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} 2 \\ 2 \\ -1 \end{bmatrix}, \mathbf{u}_3 = \begin{bmatrix} 1 \\ 1 \\ 4 \end{bmatrix}$, and $\mathbf{x} = \begin{bmatrix} 5 \\ -3 \\ 1 \end{bmatrix}$

11. Compute the orthogonal projection of $\begin{bmatrix} 1 \\ 7 \end{bmatrix}$ onto the line through $\begin{bmatrix} -4 \\ 2 \end{bmatrix}$ and the origin.

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

13. Let $\mathbf{y} = \begin{bmatrix} 2 \\ 3 \end{bmatrix}$ and $\mathbf{u} = \begin{bmatrix} 4 \\ -7 \end{bmatrix}$. Write $\mathbf{y}$ as the sum of two orthogonal vectors, one in Span $\{\mathbf{u}\}$ and one orthogonal to $\mathbf{u}$.

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

15. Let $\mathbf{y} = \begin{bmatrix} 3 \\ 1 \end{bmatrix}$ and $\mathbf{u} = \begin{bmatrix} 8 \\ 6 \end{bmatrix}$. Compute the distance from $\mathbf{y}$ to the line through $\mathbf{u}$ and the origin.

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

In Exercises 17–22, determine which sets of vectors are orthonormal. If a set is only orthogonal, normalize the vectors to produce an orthonormal set.

17. $\begin{bmatrix} 1/3 \\ 1/3 \\ 1/3 \end{bmatrix}, \begin{bmatrix} -1/2 \\ 0 \\ 1/2 \end{bmatrix}$

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

19. $\begin{bmatrix} -.6 \\ .8 \end{bmatrix}, \begin{bmatrix} .8 \\ .6 \end{bmatrix}$

20. $\begin{bmatrix} -2/3 \\ 1/3 \\ 2/3 \end{bmatrix}, \begin{bmatrix} 1/3 \\ 2/3 \\ 0 \end{bmatrix}$

21. $\begin{bmatrix} 1/\sqrt{10} \\ 3/\sqrt{20} \\ 3/\sqrt{20} \end{bmatrix}, \begin{bmatrix} 3/\sqrt{10} \\ -1/\sqrt{20} \\ -1/\sqrt{20} \end{bmatrix}, \begin{bmatrix} 0 \\ -1/\sqrt{2} \\ 1/\sqrt{2} \end{bmatrix}$

22. $\begin{bmatrix} 1/\sqrt{18} \\ 4/\sqrt{18} \\ 1/\sqrt{18} \end{bmatrix}, \begin{bmatrix} 1/\sqrt{2} \\ 0 \\ -1/\sqrt{2} \end{bmatrix}, \begin{bmatrix} -2/3 \\ 1/3 \\ -2/3 \end{bmatrix}$

In Exercises 23 and 24, all vectors are in $\mathbb{R}^n$. Mark each statement True or False. Justify each answer.

b. If $\mathbf{y}$ is a linear combination of nonzero vectors from an orthogonal set, then the weights in the linear combination can be computed without row operations on a matrix.

c. If the vectors in an orthogonal set of nonzero vectors are normalized, then some of the new vectors may not be orthogonal.

d. A matrix with orthonormal columns is an orthogonal matrix.

e. If L is a line through $\mathbf{0}$ and if $\hat{\mathbf{y}}$ is the orthogonal projection of $\mathbf{y}$ onto L, then $\|\hat{\mathbf{y}}\|$ gives the distance from $\mathbf{y}$ to L.

24. a. Not every orthogonal set in $\mathbb{R}^n$ is linearly independent.

b. If a set $S = \{\mathbf{u}_1, \dots, \mathbf{u}_p\}$ has the property that $\mathbf{u}_i \cdot \mathbf{u}_j = 0$ whenever $i \neq j$, then S is an orthonormal set.

c. If the columns of an $m \times n$ matrix A are orthonormal, then the linear mapping $\mathbf{x} \mapsto A\mathbf{x}$ preserves lengths.

d. The orthogonal projection of $\mathbf{y}$ onto $\mathbf{v}$ is the same as the orthogonal projection of $\mathbf{y}$ onto $c\mathbf{v}$ whenever $c \neq 0$.

e. An orthogonal matrix is invertible.

---

[1] A better name might be *orthonormal matrix*, and this term is found in some statistics texts. However, *orthogonal matrix* is the standard term in linear algebra.

24. a. Not every orthogonal set in $\mathbb{R}^n$ is linearly independent.

b. If a set $S = \{\mathbf{u}_1, \dots, \mathbf{u}_p\}$ has the property that $\mathbf{u}_i \cdot \mathbf{u}_j = 0$ whenever $i \neq j$, then S is an orthonormal set.

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e. An orthogonal matrix is invertible.

25. Prove Theorem 7. [*Hint:* For (a), compute $\|U\mathbf{x}\|^2$, or prove (b) first.]

26. Suppose W is a subspace of $\mathbb{R}^n$ spanned by n nonzero orthogonal vectors. Explain why $W = \mathbb{R}^n$.

27. Let U be a square matrix with orthonormal columns. Explain why U is invertible. (Mention the theorems you use.)

28. Let U be an $n \times n$ orthogonal matrix. Show that the rows of U form an orthonormal basis of $\mathbb{R}^n$.

29. Let U and V be $n \times n$ orthogonal matrices. Explain why UV is an orthogonal matrix. [That is, explain why UV is invertible and its inverse is $(UV)^T$.]

30. Let U be an orthogonal matrix, and construct V by interchanging some of the columns of U. Explain why V is an orthogonal matrix.

31. Show that the orthogonal projection of a vector $\mathbf{y}$ onto a line L through the origin in $\mathbb{R}^2$ does not depend on the choice of the nonzero $\mathbf{u}$ in L used in the formula for $\hat{\mathbf{y}}$. To do this, suppose $\mathbf{y}$ and $\mathbf{u}$ are given and $\hat{\mathbf{y}}$ has been computed by formula (2) in this section. Replace $\mathbf{u}$ in that formula by $c\mathbf{u}$, where c is an unspecified nonzero scalar. Show that the new formula gives the same $\hat{\mathbf{y}}$.

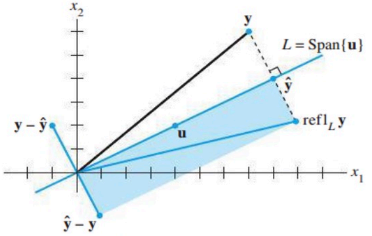
32. Let $\{\mathbf{v}_1, \mathbf{v}_2\}$ be an orthogonal set of nonzero vectors, and let c_1, c_2 be any nonzero scalars. Show that $\{c_1\mathbf{v}_1, c_2\mathbf{v}_2\}$ is also an orthogonal set. Since orthogonality of a set is defined in terms of pairs of vectors, this shows that if the vectors in an orthogonal set are normalized, the new set will still be orthogonal.

33. Given $\mathbf{u} \neq \mathbf{0}$ in $\mathbb{R}^n$, let $L = \text{Span}\,\{\mathbf{u}\}$. Show that the mapping $\mathbf{x} \mapsto \text{proj}_L\,\mathbf{x}$ is a linear transformation.

34. Given $\mathbf{u} \neq \mathbf{0}$ in $\mathbb{R}^n$, let $L = \text{Span}\,\{\mathbf{u}\}$. For $\mathbf{y}$ in $\mathbb{R}^n$, the **reflection of y in** L is the point $\text{refl}_L\,\mathbf{y}$ defined by

$$\text{refl}_L\,\mathbf{y} = 2 \cdot \text{proj}_L\,\mathbf{y} - \mathbf{y}$$

See the figure, which shows that $\text{refl}_L\,\mathbf{y}$ is the sum of $\hat{\mathbf{y}} = \text{proj}_L\,\mathbf{y}$ and $\hat{\mathbf{y}} - \mathbf{y}$. Show that the mapping $\mathbf{y} \mapsto \text{refl}_L\,\mathbf{y}$ is a linear transformation.



The reflection of $\mathbf{y}$ in a line through the origin.

35. **[M]** Show that the columns of the matrix A are orthogonal by making an appropriate matrix calculation. State the calculation you use.

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

36. **[M]** In parts (a)–(d), let U be the matrix formed by normalizing each column of the matrix A in Exercise 35.

a. Compute U^TU and UU^T. How do they differ?

b. Generate a random vector $\mathbf{y}$ in $\mathbb{R}^8$, and compute $\mathbf{p} = UU^T\mathbf{y}$ and $\mathbf{z} = \mathbf{y} - \mathbf{p}$. Explain why $\mathbf{p}$ is in Col A. Verify that $\mathbf{z}$ is orthogonal to $\mathbf{p}$.

c. Verify that $\mathbf{z}$ is orthogonal to each column of U.

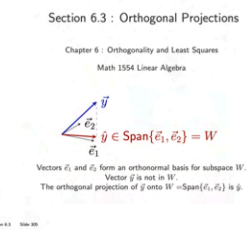
d. Notice that $\mathbf{y} = \mathbf{p} + \mathbf{z}$, with $\mathbf{p}$ in Col A. Explain why $\mathbf{z}$ is in $(\text{Col}\,A)^{\perp}$. (The significance of this decomposition of $\mathbf{y}$ will be explained in the next section.)

Section 6.3 : Orthogonal Projections

Chapter 6 : Orthogonality and Least Squares

Math 1554 Linear Algebra

Vectors $\vec{e}_1$ and $\vec{e}_2$ form an orthonormal basis for subspace W.
Vector $\vec{y}$ is not in W.
The orthogonal projection of $\vec{y}$ onto $W =$Span$\{\vec{e}_1, \vec{e}_2\}$ is $\hat{y}$.



Section 6.3 : Orthogonal Projections

Chapter 6 : Orthogonality and Least Squares

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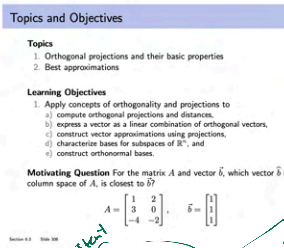


Topics and Objectives

Topics

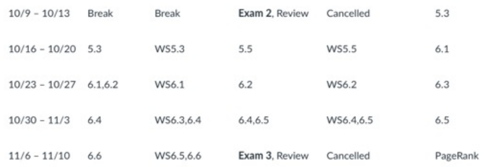
1. Orthogonal projections and their basic properties
2. Best approximations

Learning Objectives

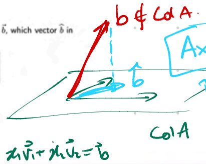
1. Apply concepts of orthogonality and projections to
   a) compute orthogonal projections and distances,
   b) express a vector as a linear combination of orthogonal vectors,
   c) construct vector approximations using projections,
   d) characterize bases for subspaces of $\mathbb{R}^n$, and
   e) construct orthonormal bases.

Motivating Question For the matrix A and vector $\vec{b}$, which vector $\hat{b}$ in column space of A, is closest to $\vec{b}$?

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



10/9 – 10/13	Break	Break	**Exam 2**, Review	Cancelled	5.3
10/16 – 10/20	5.3	WS5.3	5.5	WS5.5	6.1
10/23 – 10/27	6.1,6.2	WS6.1	6.2	WS6.2	6.3
10/30 – 11/3	6.4	WS6.3,6.4	6.4,6.5	WS6.4,6.5	6.5
11/6 – 11/10	6.6	WS6.5,6.6	**Exam 3**, Review	Cancelled	PageRank



$$\boxed{Ax = \hat{b}}$$

$$\hat{b} = \text{proj}_{\text{Col}A}(b)$$

inconsistent

$$\boxed{A\vec{x} = \vec{b}} \leftarrow x_1\vec{v}_1 + x_2\vec{v}_2 = \vec{b}$$

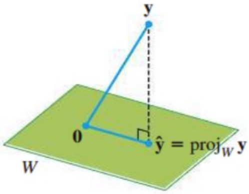


FIGURE 1

THEOREM 8

The Orthogonal Decomposition Theorem

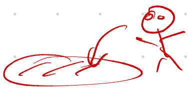
Let W be a subspace of $\mathbb{R}^n$. Then each $\mathbf{y}$ in $\mathbb{R}^n$ can be written uniquely in the form

$$\mathbf{y} = \hat{\mathbf{y}} + \mathbf{z} \tag{1}$$

where $\hat{\mathbf{y}}$ is in W and $\mathbf{z}$ is in $W^{\perp}$. In fact, if $\{\mathbf{u}_1, \ldots, \mathbf{u}_p\}$ is any orthogonal basis of W, then

$$\hat{\mathbf{y}} = \frac{\mathbf{y} \cdot \mathbf{u}_1}{\mathbf{u}_1 \cdot \mathbf{u}_1}\mathbf{u}_1 + \cdots + \frac{\mathbf{y} \cdot \mathbf{u}_p}{\mathbf{u}_p \cdot \mathbf{u}_p}\mathbf{u}_p \tag{2}$$

and $\mathbf{z} = \mathbf{y} - \hat{\mathbf{y}}$.



$$\mathbf{y} = \begin{bmatrix} -1 \\ 4 \\ 3 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}$$

$\mathbb{R}^n$ orthogonal basis for $\mathbb{R}^n$

$$\mathcal{B} = \{u_1, \ldots, u_n\}$$

$y \in \mathbb{R}^n$

coords for y in basis B

$$y = \underbrace{\frac{y \cdot u_1}{u_1 \cdot u_1}u_1 + \frac{y \cdot u_2}{u_2 \cdot u_1}u_2}_{W} \Big/ + \underbrace{\ldots + \frac{y \cdot u_n}{u_n \cdot u_n}u_n}_{W^{\perp}}$$

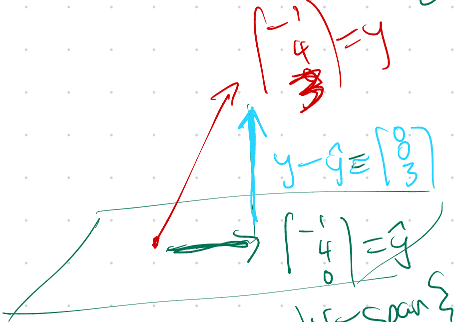
$$W = \text{Span}\{\vec{u}_1, \vec{u}_2\} \qquad y \in \mathbb{R}^3$$

compute $\boxed{\text{proj}_W(\vec{y}) = \hat{y}}$

$$\hat{y} = \text{proj}_W(\vec{y}) = \frac{y \cdot u_1}{u_1 \cdot u_1}u_1 + \frac{y \cdot u_2}{u_2 \cdot u_2}u_2 \leftarrow$$

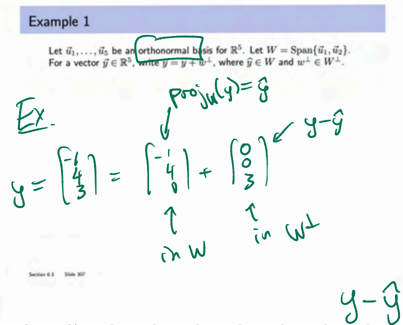
WARNING (Formula only when $u_1 \cdot u_2 = 0$)

$$\hat{y} = \frac{\begin{bmatrix} -1 \\ 4 \\ 3 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}}{\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}}\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix} + \frac{\begin{bmatrix} -1 \\ 4 \\ 3 \end{bmatrix} \cdot \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}}{\begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix} \cdot \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}}\begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}$$



$$W = \text{span}\left\{\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}\right\}$$

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

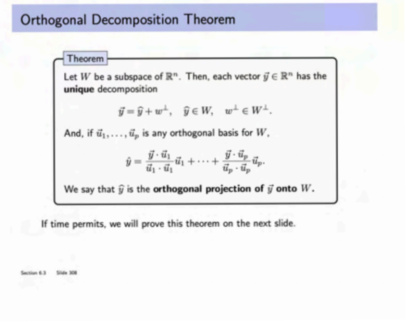


Example 1

Let $\vec{u}_1, \ldots, \vec{u}_5$ be an orthonormal basis for $\mathbb{R}^5$. Let $W = \mathrm{Span}\{\vec{u}_1, \vec{u}_2\}$. For a vector $\vec{y} \in \mathbb{R}^5$, write $\vec{y} = \hat{y} + w^\perp$, where $\hat{y} \in W$ and $w^\perp \in W^\perp$.

Ex.

$$y = \begin{bmatrix} -6 \\ 4 \\ 3 \end{bmatrix} = \underbrace{\begin{bmatrix} -1 \\ 4 \\ 0 \end{bmatrix}}_{\text{in } W}^{\mathrm{proj}_W(y) = \hat{y}} + \underbrace{\begin{bmatrix} 0 \\ 0 \\ 3 \end{bmatrix}}_{\text{in } W^\perp}^{y - \hat{y}}$$



Orthogonal Decomposition Theorem

Theorem

Let W be a subspace of $\mathbb{R}^n$. Then, each vector $\vec{y} \in \mathbb{R}^n$ has the **unique** decomposition

$$\vec{y} = \hat{y} + w^\perp, \quad \hat{y} \in W, \quad w^\perp \in W^\perp.$$

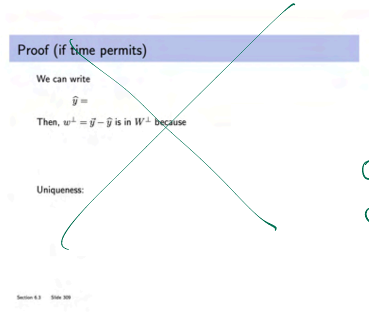
And, if $\vec{u}_1, \ldots, \vec{u}_p$ is any orthogonal basis for W,

$$\hat{y} = \frac{\vec{y} \cdot \vec{u}_1}{\vec{u}_1 \cdot \vec{u}_1} \vec{u}_1 + \cdots + \frac{\vec{y} \cdot \vec{u}_p}{\vec{u}_p \cdot \vec{u}_p} \vec{u}_p.$$

We say that $\hat{y}$ is the **orthogonal projection of $\vec{y}$ onto W.**

If time permits, we will prove this theorem on the next slide.

$$y = \underbrace{(y \cdot u_1) u_1 + (y \cdot u_2) u_2}_{\mathrm{proj}_W(\vec{y}) = \hat{y}} + \overbrace{\underbrace{(y \cdot u_3) u_3 + (y \cdot u_4) u_4 + (y \cdot u_5) u_5}_{\mathrm{proj}_{W^\perp}(\vec{y})}}^{y - \hat{y}}$$



~~Proof (if time permits)~~

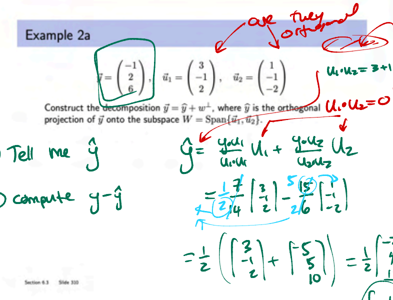
~~We can write~~

~~$\hat{y} =$~~

~~Then, $w^\perp = \vec{y} - \hat{y}$ is in $W^\perp$ because~~

~~Uniqueness:~~

$$y = \overset{\swarrow \text{in } W}{y} + \overset{\swarrow \text{in } W^\perp}{0}$$



Example 2a

$$\boxed{\vec{y} = \begin{pmatrix} -1 \\ 2 \\ 6 \end{pmatrix}}, \quad \vec{u}_1 = \begin{pmatrix} 3 \\ -1 \\ 2 \end{pmatrix}, \quad \vec{u}_2 = \begin{pmatrix} 1 \\ -1 \\ -2 \end{pmatrix}$$

Construct the decomposition $\vec{y} = \hat{y} + w^\perp$, where $\hat{y}$ is the orthogonal projection of $\vec{y}$ onto the subspace $W = \mathrm{Span}\{\vec{u}_1, \vec{u}_2\}$.

are they orthogonal

$u_1 \cdot u_2 = 3 + 1 - 4 = 0$ ✓

$u_1 \cdot u_2 = 0$??

① Tell me $\hat{y}$

② compute $y - \hat{y}$

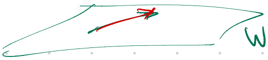
$$\hat{y} = \frac{y \cdot u_1}{u_1 \cdot u_1} u_1 + \frac{y \cdot u_2}{u_2 \cdot u_2} u_2$$

$$= \frac{1}{2}\frac{7}{14}\begin{bmatrix} 3 \\ -1 \\ 2 \end{bmatrix} - \frac{5}{2}\frac{15}{6}\begin{bmatrix} 1 \\ -1 \\ -2 \end{bmatrix}$$

$$= \frac{1}{2}\left(\begin{bmatrix} 3 \\ -1 \\ 2 \end{bmatrix} + \begin{bmatrix} -5 \\ 5 \\ 10 \end{bmatrix}\right) = \frac{1}{2}\begin{bmatrix} -2 \\ 4 \\ 12 \end{bmatrix}$$

$$= \boxed{\begin{bmatrix} -1 \\ 2 \\ 6 \end{bmatrix}} = \boxed{\hat{y} = y}$$

!!



$\hat{y} = \text{proj}_W(\vec{y})$

$\text{proj}_W : \mathbb{R}^n \to \mathbb{R}^n$

$\text{proj}_W(\vec{x}) = \boxed{}$

$U = [u_1 \;\; u_2]$

$\underbrace{u_1 \;\; u_2}_{\text{orthonormal basis for } W}$

$\boxed{UU^T}$ Standard matrix

Best Approximation Theorem

Theorem

Let W be a subspace of $\mathbb{R}^n$, $\vec{y} \in \mathbb{R}^n$, and $\hat{y}$ is the orthogonal projection of $\vec{y}$ onto W. Then for **any** $\vec{w} \neq \hat{y} \in W$, we have

$$\|\vec{y} - \hat{y}\| < \|\vec{y} - \vec{w}\|$$

That is, $\hat{y}$ is the unique vector in W that is closest to $\vec{y}$.

Example 2b

$$\vec{y} = \begin{pmatrix} -1 \\ 2 \\ 6 \end{pmatrix}, \quad \vec{u}_1 = \begin{pmatrix} 3 \\ -1 \\ 2 \end{pmatrix}, \quad \vec{u}_2 = \begin{pmatrix} 1 \\ -1 \\ -2 \end{pmatrix}$$

What is the distance between $\vec{y}$ and subspace $W = \text{Span}\{\vec{u}_1, \vec{u}_2\}$? Note that these vectors are the same vectors that we used in Example 2a.

$\text{dist}(y, W) = \|y - \hat{y}\|$

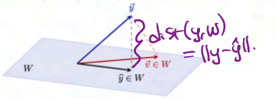
$$\begin{bmatrix} -1 \\ 4 \\ 3 \end{bmatrix} = \begin{bmatrix} -1 \\ 4 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 3 \end{bmatrix}$$

$\hat{y}$

$y - \hat{y} = \begin{bmatrix} 0 \\ 0 \\ 3 \end{bmatrix}$

Proof (if time permits)

The orthogonal projection of $\vec{y}$ onto W is the closest point in W to $\vec{y}$.



$\text{dist}(y,W) = \|y - \hat{y}\|.$

if $x \cdot \vec{v} = 0$ and $x \cdot \vec{w} = 0$ then $x \cdot \vec{z} = 0$ for any $z \in \text{span}\{\vec{v}, \vec{w}\}$

Additional Example (if time permits)

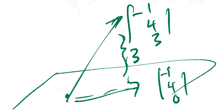
Indicate whether each statement is true or false. If true, explain why in one or two sentences. If false, give a counter example or explain why in one or two sentences.

a) If $\vec{x}$ is orthogonal to $\vec{v}$ and $\vec{w}$, then $\vec{x}$ is also orthogonal to $\vec{v} - \vec{w}$.

b) If $\text{proj}_W \vec{y} = \vec{y}$, then $\vec{y} \in W$.

c) If $\vec{y} = \vec{u}_1 + \vec{v}_1$, where $\vec{u}_1 \in W$ and $\vec{v}_1 \in W^\perp$, then $\vec{u}_1$ is the orthogonal projection of $\vec{y}$ onto W.

$$\boxed{\begin{aligned} &\vec{x} \cdot (\vec{v} - \vec{w}) \\ &= \vec{x} \cdot \vec{v} - \vec{x} \cdot \vec{w} \\ &= 0 - 0 \end{aligned}}$$



$y = \hat{y} + \underbrace{(y - \hat{y})}_{y^\perp}$

$\boxed{y = \hat{y} + y^\perp}$

in W in $W^\perp$

$\|y - \hat{y}\| = \left\| \begin{pmatrix} 0 \\ 0 \\ 3 \end{pmatrix} \right\| = \sqrt{0^2 + 0^2 + 3^2}$

$= \sqrt{9} = \boxed{3}$

6.3 EXERCISES

In Exercises 1 and 2, you may assume that $\{\mathbf{u}_1, \dots, \mathbf{u}_4\}$ is an orthogonal basis for $\mathbb{R}^4$.

1. $\mathbf{u}_1 = \begin{bmatrix} 0 \\ 1 \\ -4 \\ -1 \end{bmatrix}$, $\mathbf{u}_2 = \begin{bmatrix} 3 \\ 5 \\ 1 \\ 1 \end{bmatrix}$, $\mathbf{u}_3 = \begin{bmatrix} 1 \\ 0 \\ 1 \\ -4 \end{bmatrix}$, $\mathbf{u}_4 = \begin{bmatrix} 5 \\ -3 \\ -1 \\ 1 \end{bmatrix}$,
$\mathbf{x} = \begin{bmatrix} 10 \\ -8 \\ 2 \\ 0 \end{bmatrix}$. Write $\mathbf{x}$ as the sum of two vectors, one in Span $\{\mathbf{u}_1, \mathbf{u}_2, \mathbf{u}_3\}$ and the other in Span $\{\mathbf{u}_4\}$.

2. $\mathbf{u}_1 = \begin{bmatrix} 1 \\ 2 \\ 1 \\ 1 \end{bmatrix}$, $\mathbf{u}_2 = \begin{bmatrix} -2 \\ 1 \\ -1 \\ 1 \end{bmatrix}$, $\mathbf{u}_3 = \begin{bmatrix} 1 \\ 1 \\ -2 \\ -1 \end{bmatrix}$, $\mathbf{u}_4 = \begin{bmatrix} -1 \\ 1 \\ 1 \\ -2 \end{bmatrix}$,
$\mathbf{v} = \begin{bmatrix} 4 \\ 5 \\ -3 \\ 3 \end{bmatrix}$. Write $\mathbf{v}$ as the sum of two vectors, one in Span $\{\mathbf{u}_1\}$ and the other in Span $\{\mathbf{u}_2, \mathbf{u}_3, \mathbf{u}_4\}$.

In Exercises 3–6, verify that $\{\mathbf{u}_1, \mathbf{u}_2\}$ is an orthogonal set, and then find the orthogonal projection of $\mathbf{y}$ onto Span $\{\mathbf{u}_1, \mathbf{u}_2\}$.

3. $\mathbf{y} = \begin{bmatrix} -1 \\ 4 \\ 3 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -1 \\ 1 \\ 0 \end{bmatrix}$

4. $\mathbf{y} = \begin{bmatrix} 6 \\ 3 \\ -2 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 3 \\ 4 \\ 0 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -4 \\ 3 \\ 0 \end{bmatrix}$

5. $\mathbf{y} = \begin{bmatrix} -1 \\ 2 \\ 6 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 3 \\ -1 \\ 2 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} 1 \\ -1 \\ -2 \end{bmatrix}$

6. $\mathbf{y} = \begin{bmatrix} 6 \\ 4 \\ 1 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} -4 \\ -1 \\ 1 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$

In Exercises 7–10, let W be the subspace spanned by the $\mathbf{u}$'s, and write $\mathbf{y}$ as the sum of a vector in W and a vector orthogonal to W.

7. $\mathbf{y} = \begin{bmatrix} 1 \\ 3 \\ 5 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 1 \\ 3 \\ -2 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} 5 \\ 1 \\ 4 \end{bmatrix}$

8. $\mathbf{y} = \begin{bmatrix} -1 \\ 4 \\ 3 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -1 \\ 3 \\ -2 \end{bmatrix}$

9. $\mathbf{y} = \begin{bmatrix} 4 \\ 3 \\ 3 \\ -1 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 1 \\ 1 \\ 0 \\ 1 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -1 \\ 3 \\ 1 \\ -2 \end{bmatrix}, \mathbf{u}_3 = \begin{bmatrix} -1 \\ 0 \\ 1 \\ 1 \end{bmatrix}$

10. $\mathbf{y} = \begin{bmatrix} 3 \\ 4 \\ 5 \\ 6 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 1 \\ 1 \\ 0 \\ -1 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} 1 \\ 0 \\ 1 \\ 1 \end{bmatrix}, \mathbf{u}_3 = \begin{bmatrix} 0 \\ -1 \\ 1 \\ -1 \end{bmatrix}$

In Exercises 11 and 12, find the closest point to $\mathbf{y}$ in the subspace W spanned by $\mathbf{v}_1$ and $\mathbf{v}_2$.

11. $\mathbf{y} = \begin{bmatrix} 3 \\ 1 \\ 5 \\ 1 \end{bmatrix}, \mathbf{v}_1 = \begin{bmatrix} 3 \\ 1 \\ -1 \\ 1 \end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix} 1 \\ -1 \\ 1 \\ -1 \end{bmatrix}$

12. $\mathbf{y} = \begin{bmatrix} 3 \\ -1 \\ 1 \\ 13 \end{bmatrix}, \mathbf{v}_1 = \begin{bmatrix} 1 \\ -2 \\ -1 \\ 2 \end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix} -4 \\ 1 \\ 0 \\ 3 \end{bmatrix}$

In Exercises 13 and 14, find the best approximation to $\mathbf{z}$ by vectors of the form $c_1\mathbf{v}_1 + c_2\mathbf{v}_2$.

13. $\mathbf{z} = \begin{bmatrix} 3 \\ -7 \\ 2 \\ 3 \end{bmatrix}, \mathbf{v}_1 = \begin{bmatrix} 2 \\ -1 \\ -3 \\ 1 \end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix} 1 \\ 1 \\ 0 \\ -1 \end{bmatrix}$

14. $\mathbf{z} = \begin{bmatrix} 2 \\ 4 \\ 0 \\ -1 \end{bmatrix}, \mathbf{v}_1 = \begin{bmatrix} 2 \\ 0 \\ -1 \\ -3 \end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix} 5 \\ -2 \\ 4 \\ 2 \end{bmatrix}$

15. Let $\mathbf{y} = \begin{bmatrix} 5 \\ -9 \\ 5 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} -3 \\ -5 \\ 1 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} -3 \\ 2 \\ 1 \end{bmatrix}$. Find the distance from $\mathbf{y}$ to the plane in $\mathbb{R}^3$ spanned by $\mathbf{u}_1$ and $\mathbf{u}_2$.

16. Let $\mathbf{y}, \mathbf{v}_1$, and $\mathbf{v}_2$ be as in Exercise 12. Find the distance from $\mathbf{y}$ to the subspace of $\mathbb{R}^4$ spanned by $\mathbf{v}_1$ and $\mathbf{v}_2$.

17. Let $\mathbf{y} = \begin{bmatrix} 4 \\ 8 \\ 1 \end{bmatrix}$, $\mathbf{u}_1 = \begin{bmatrix} 2/3 \\ 1/3 \\ 2/3 \end{bmatrix}$, $\mathbf{u}_2 = \begin{bmatrix} -2/3 \\ 2/3 \\ 1/3 \end{bmatrix}$, and $W = \text{Span}\{\mathbf{u}_1, \mathbf{u}_2\}$.

a. Let $U = [\,\mathbf{u}_1 \;\; \mathbf{u}_2\,]$. Compute U^TU and UU^T.

b. Compute $\text{proj}_W\, \mathbf{y}$ and $(UU^T)\mathbf{y}$.

18. Let $\mathbf{y} = \begin{bmatrix} 7 \\ 9 \end{bmatrix}, \mathbf{u}_1 = \begin{bmatrix} 1/\sqrt{10} \\ -3/\sqrt{10} \end{bmatrix}$, and $W = \text{Span}\{\mathbf{u}_1\}$.

a. Let U be the 2×1 matrix whose only column is $\mathbf{u}_1$. Compute U^TU and UU^T.

b. Compute $\text{proj}_W\, \mathbf{y}$ and $(UU^T)\mathbf{y}$.

19. Let $\mathbf{u}_1 = \begin{bmatrix} 1 \\ 1 \\ -2 \end{bmatrix}, \mathbf{u}_2 = \begin{bmatrix} 5 \\ -1 \\ 2 \end{bmatrix}$, and $\mathbf{u}_3 = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$. Note that $\mathbf{u}_1$ and $\mathbf{u}_2$ are orthogonal but that $\mathbf{u}_3$ is not orthogonal to $\mathbf{u}_1$ or $\mathbf{u}_2$. It can be shown that $\mathbf{u}_3$ is not in the subspace W spanned by $\mathbf{u}_1$ and $\mathbf{u}_2$. Use this fact to construct a nonzero vector $\mathbf{v}$ in $\mathbb{R}^3$ that is orthogonal to $\mathbf{u}_1$ and $\mathbf{u}_2$.

20. Let $\mathbf{u}_1$ and $\mathbf{u}_2$ be as in Exercise 19, and let $\mathbf{u}_4 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$. It can be shown that $\mathbf{u}_4$ is not in the subspace W spanned by $\mathbf{u}_1$ and $\mathbf{u}_2$. Use this fact to construct a nonzero vector $\mathbf{v}$ in $\mathbb{R}^3$ that is orthogonal to $\mathbf{u}_1$ and $\mathbf{u}_2$.

In Exercises 21 and 22, all vectors and subspaces are in $\mathbb{R}^n$. Mark each statement True or False. Justify each answer.

21. a. If $\mathbf{z}$ is orthogonal to $\mathbf{u}_1$ and to $\mathbf{u}_2$ and if $W = \text{Span}\{\mathbf{u}_1, \mathbf{u}_2\}$, then $\mathbf{z}$ must be in $W^\perp$.

b. For each $\mathbf{y}$ and each subspace W, the vector $\mathbf{y} - \text{proj}_W\, \mathbf{y}$ is orthogonal to W.

c. The orthogonal projection $\hat{\mathbf{y}}$ of $\mathbf{y}$ onto a subspace W can sometimes depend on the orthogonal basis for W used to compute $\hat{\mathbf{y}}$.

d. If $\mathbf{y}$ is in a subspace W, then the orthogonal projection of $\mathbf{y}$ onto W is $\mathbf{y}$ itself.

e. If the columns of an $n \times p$ matrix U are orthonormal, then $UU^T\mathbf{y}$ is the orthogonal projection of $\mathbf{y}$ onto the column space of U.

22. a. If W is a subspace of $\mathbb{R}^n$ and if $\mathbf{v}$ is in both W and $W^\perp$, then $\mathbf{v}$ must be the zero vector.

b. In the Orthogonal Decomposition Theorem, each term in formula (2) for $\hat{\mathbf{y}}$ is itself an orthogonal projection of $\mathbf{y}$ onto a subspace of W.

c. If $\mathbf{y} = \mathbf{z}_1 + \mathbf{z}_2$, where $\mathbf{z}_1$ is in a subspace W and $\mathbf{z}_2$ is in $W^\perp$, then $\mathbf{z}_1$ must be the orthogonal projection of $\mathbf{y}$ onto W.

d. The best approximation to $\mathbf{y}$ by elements of a subspace W is given by the vector $\mathbf{y} - \text{proj}_W\, \mathbf{y}$.

e. If an $n \times p$ matrix U has orthonormal columns, then $UU^T\mathbf{x} = \mathbf{x}$ for all $\mathbf{x}$ in $\mathbb{R}^n$.

23. Let A be an $m \times n$ matrix. Prove that every vector $\mathbf{x}$ in $\mathbb{R}^n$ can be written in the form $\mathbf{x} = \mathbf{p} + \mathbf{u}$, where $\mathbf{p}$ is in Row A and $\mathbf{u}$ is in Nul A. Also, show that if the equation $A\mathbf{x} = \mathbf{b}$ is consistent, then there is a unique $\mathbf{p}$ in Row A such that $A\mathbf{p} = \mathbf{b}$.

24. Let W be a subspace of $\mathbb{R}^n$ with an orthogonal basis $\{\mathbf{w}_1, \dots, \mathbf{w}_p\}$, and let $\{\mathbf{v}_1, \dots, \mathbf{v}_q\}$ be an orthogonal basis for $W^\perp$.

a. Explain why $\{\mathbf{w}_1, \dots, \mathbf{w}_p, \mathbf{v}_1, \dots, \mathbf{v}_q\}$ is an orthogonal set.

b. Explain why the set in part (a) spans $\mathbb{R}^n$.

c. Show that $\dim W + \dim W^\perp = n$.

25. [M] Let U be the 8×4 matrix in Exercise 36 in Section 6.2. Find the closest point to $\mathbf{y} = (1, 1, 1, 1, 1, 1, 1, 1)$ in Col U. Write the keystrokes or commands you use to solve this problem.

26. [M] Let U be the matrix in Exercise 25. Find the distance from $\mathbf{b} = (1, 1, 1, 1, -1, -1, -1, -1)$ to Col U.