Orthogonal Vector

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Orthogonal Set

- A set of vectors is called an orthogonal set if every pair of distinct vectors in the set is orthogonal.

$$\mathcal{S} = \left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 5 \\ -4 \\ 1 \end{bmatrix} \right\}$$ An orthogonal set?

By definition, a set with only one vector is an orthogonal set.

Is orthogonal set independent?

- Reference: Chapter 7.2

Independent?

- Any orthogonal set of nonzero vectors is linearly independent.

Let $\mathcal{S} = \{\mathbf{v}_1, \mathbf{v}_2, \ldots, \mathbf{v}_k\}$ be an orthogonal set $\mathbf{v}_i \neq \mathbf{0}$ for $i = 1, 2, \ldots, k$.

Assume $c_1, c_2, \ldots, c_k$ make $c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \cdots + c_k\mathbf{v}_k = \mathbf{0}$

$$(c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + \cdots + c_i\mathbf{v}_i + \cdots + c_k\mathbf{v}_k) \cdot \mathbf{v}_i = \mathbf{0} \cdot \mathbf{v}_i = \mathbf{0}$$

$$= c_1\mathbf{v}_1 \cdot \mathbf{v}_i + c_2\mathbf{v}_2 \cdot \mathbf{v}_i + \cdots + c_i\mathbf{v}_i \cdot \mathbf{v}_i + \cdots + c_k\mathbf{v}_k \cdot \mathbf{v}_i$$

$$= c_i(\mathbf{v}_i \cdot \mathbf{v}_i) = c_i \underbrace{||\mathbf{v}_i||^2}_{\neq 0} \Rightarrow c_i = 0$$

$$\Rightarrow c_1 = c_2 = \cdots = c_k = 0$$

Orthonormal Set

- A set of vectors is called an orthonormal set if it is an orthogonal set, and the norm of all the vectors is 1

$$\mathcal{S} = \left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}, \begin{bmatrix} 5 \\ -4 \\ 1 \end{bmatrix} \right\}$$

$$\frac{1}{\sqrt{14}}\begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \quad \frac{1}{\sqrt{3}}\begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix} \quad \frac{1}{\sqrt{42}}\begin{bmatrix} 5 \\ -4 \\ 1 \end{bmatrix}$$

Is orthonormal set independent?

Yes

A vector that has norm equal to 1 is called a unit vector.

Orthogonal Basis

- A basis that is an orthogonal (orthonormal) set is called an orthogonal (orthonormal) basis

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

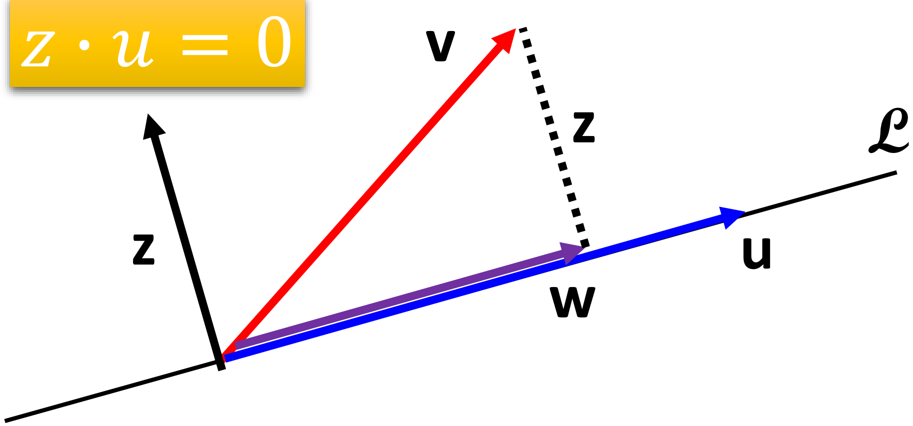
Orthogonal basis of R^3

Orthonormal basis of R^3

Orthogonal Projection

- Orthogonal projection of a vector onto a line

$z \cdot u = 0$



v: any vector
u: any nonzero vector on $\mathcal{L}$
w: orthogonal projection of **v** onto $\mathcal{L}$, **w** = c**u**
z: **v** − **w**

$$(v-w)\cdot u \;=(v-cu)\cdot u \;=v\cdot u-cu\cdot u \;=v\cdot u-c\|u\|^2$$

=0

$$c=\frac{v\cdot u}{\|u\|^2} \qquad w=cu=\frac{v\cdot u}{\|u\|^2}u$$

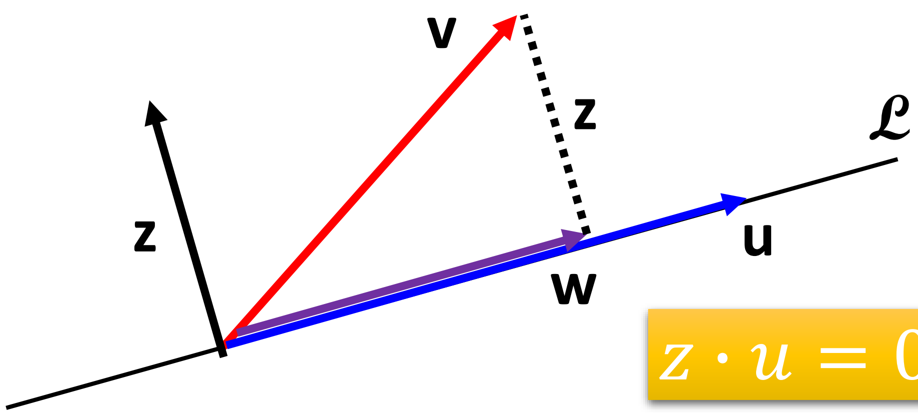
Distance from tip of **v** to $\mathcal{L}$: $\|z\|=\|v-w\| \;=\left\|v-\frac{v\cdot u}{\|u\|^2}u\right\|$

Orthogonal Projection

$$c = \frac{v \cdot u}{\|u\|^2}$$

$$w = cu = \frac{v \cdot u}{\|u\|^2} u$$

- Example:



$z \cdot u = 0$

$\mathcal{L}$ is $y = (1/2)x$

$$v = \begin{bmatrix} 4 \\ 1 \end{bmatrix} \quad u = \begin{bmatrix} 2 \\ 1 \end{bmatrix}$$

Orthogonal Basis

$$c = \frac{v \cdot u}{\|u\|^2} \qquad w = cu = \frac{v \cdot u}{\|u\|^2} u$$

- Let $S = \{v_1, v_2, \cdots, v_k\}$ be an orthogonal basis for a subspace V, and let u be a vector in V.

$$u = c_1 v_1 + c_2 v_2 + \cdots + c_k v_k$$

$$\frac{u \cdot v_1}{\|v_1\|^2} \qquad \frac{u \cdot v_2}{\|v_2\|^2} \qquad \frac{u \cdot v_k}{\|v_k\|^2}$$

Proof

To find c_i

$$u \cdot v_i = (c_1 v_1 + c_2 v_2 + \cdots + c_i v_i + \cdots + c_k v_k) \cdot v_i$$

$$= c_1 v_1 \cdot v_i + c_2 v_2 \cdot v_i + \cdots + c_i v_i \cdot v_i + \cdots + c_k v_k \cdot v_i$$

$$= c_i (v_i \cdot v_i) = c_i \|v_i\|^2 \quad \Rightarrow \quad c_i = \frac{u \cdot v_i}{\|v_i\|^2}$$

Example

- Example: $\mathcal{S}$ = {$\mathbf{v}_1$, $\mathbf{v}_2$, $\mathbf{v}_3$} is an orthogonal basis for $\mathcal{R}^3$

$$\mathbf{v}_1 = \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, \mathbf{v}_2 = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}, \mathbf{v}_3 = \begin{bmatrix} 5 \\ -4 \\ 1 \end{bmatrix}$$

$$\text{Let } \mathbf{u} = \begin{bmatrix} 3 \\ 2 \\ 1 \end{bmatrix} \text{ and } \mathbf{u} = c_1\mathbf{v}_1 + c_2\mathbf{v}_2 + c_3\mathbf{v}_3.$$

c_1 c_2 c_3

Orthogonal Basis

Let $\{u_1, u_2, \cdots, u_k\}$ be a basis of a subspace V. How to transform $\{u_1, u_2, \cdots, u_k\}$ into an orthogonal basis $\{v_1, v_2, \cdots, v_k\}$?

Let $\{\mathbf{u}_1, \mathbf{u}_2, \cdots, \mathbf{u}_k\}$ be a basis for a subspace W of $\mathcal{R}^n$. Define

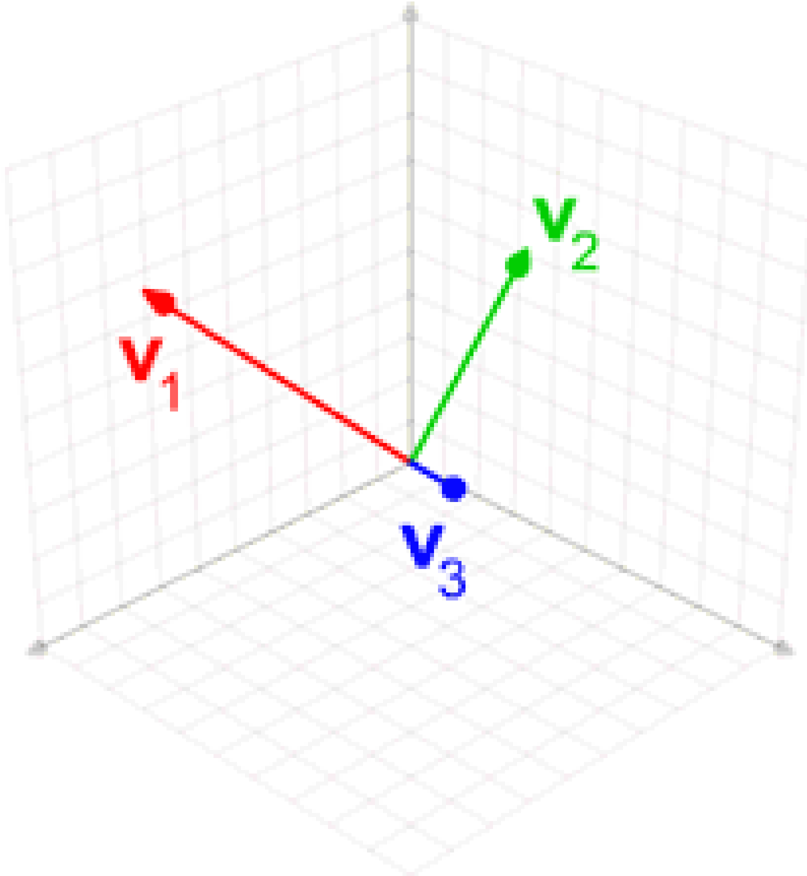
$$\begin{aligned}
\mathbf{v}_1 &= \mathbf{u}_1, \\
\mathbf{v}_2 &= \mathbf{u}_2 - \frac{\mathbf{u}_2 \cdot \mathbf{v}_1}{||\mathbf{v}_1||^2}\mathbf{v}_1, \\
\mathbf{v}_3 &= \mathbf{u}_3 - \frac{\mathbf{u}_3 \cdot \mathbf{v}_1}{||\mathbf{v}_1||^2}\mathbf{v}_1 - \frac{\mathbf{u}_3 \cdot \mathbf{v}_2}{||\mathbf{v}_2||^2}\mathbf{v}_2, \\
&\vdots \\
\mathbf{v}_k &= \mathbf{u}_k - \frac{\mathbf{u}_k \cdot \mathbf{v}_1}{||\mathbf{v}_1||^2}\mathbf{v}_1 - \frac{\mathbf{u}_k \cdot \mathbf{v}_2}{||\mathbf{v}_2||^2}\mathbf{v}_2 - \cdots - \frac{\mathbf{u}_k \cdot \mathbf{v}_{k-1}}{||\mathbf{v}_{k-1}||^2}\mathbf{v}_{k-1}.
\end{aligned}$$

Then $\{\mathbf{v}_1, \mathbf{v}_2, \cdots, \mathbf{v}_i\}$ is an orthogonal set of nonzero vectors such that

$$\text{Span}\ \{\mathbf{v}_1, \mathbf{v}_2, \cdots, \mathbf{v}_i\} = \text{Span}\ \{\mathbf{u}_1, \mathbf{u}_2, \cdots, \mathbf{u}_i\}$$

for each i. So $\{\mathbf{v}_1, \mathbf{v}_2, \cdots, \mathbf{v}_k\}$ is an **orthogonal basis** for W.

Visualization



https://www.youtube.com/watch?v=Ys28-Yq21B8