Definition

A set of vectors $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ in $\mathbb{R}^n$ is an *orthogonal set* if each pair each pair of vectors in this set is orthogonal, i.e.

$$\mathbf{v}_i \cdot \mathbf{v}_j = 0$$

for all $i \neq j$.

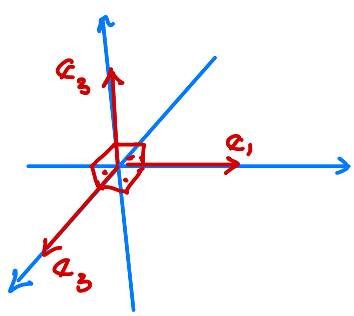
Example.

$$\left\{ \begin{array}{c} e_1 \\ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \end{array}, \begin{array}{c} e_2 \\ \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix} \end{array}, \begin{array}{c} e_3 \\ \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \end{array} \right\}$$ is an orthogonal set in $\mathbb{R}^3$.

<u>Check:</u> $e_1 \cdot e_2 = 0$

$e_1 \cdot e_3 = 0$

$e_2 \cdot e_3 = 0$



Example.

$$\left\{ \begin{array}{c} v_1 \\ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix} \end{array}, \begin{array}{c} v_2 \\ \begin{bmatrix} -3 \\ 0 \\ 1 \end{bmatrix} \end{array}, \begin{array}{c} v_3 \\ \begin{bmatrix} 1 \\ -5 \\ 3 \end{bmatrix} \end{array} \right\}$$ is another orthogonal set in $\mathbb{R}^3$.

<u>Check:</u> $v_1 \cdot v_2 = 1 \cdot (-3) + 2 \cdot 0 + 3 \cdot 1 = 0$

$v_1 \cdot v_3 = \ldots = 0$

$v_2 \cdot v_3 = \ldots = 0$

Proposition

If $\{\mathbf{v}_1, \ldots, \mathbf{v}_k\}$ is an orthogonal set of non-zero vectors in $\mathbb{R}^n$ then this set is linearly independent.

Proof: Assume that

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

We need to show that $c_1 = c_2 = \ldots = c_k = 0$.

We have:

$$\underbrace{\mathbf{v}_1 \cdot (c_1 \mathbf{v}_1 + c_2 \mathbf{v}_2 + \ldots + c_k \mathbf{v}_k)}_{\|} = \mathbf{v}_1 \cdot \mathbf{0} = 0$$

$$c_1 (\mathbf{v}_1 \cdot \mathbf{v}_1) + c_2 \underbrace{(\mathbf{v}_1 \cdot \mathbf{v}_2)}_{= 0} + \ldots + c_k \underbrace{(\mathbf{v}_1 \cdot \mathbf{v}_k)}_{= 0}$$

This gives: $c_1 (\mathbf{v}_1 \cdot \mathbf{v}_1) = 0$.

Since $\mathbf{v}_1 \neq \mathbf{0}$, we have $\mathbf{v}_1 \cdot \mathbf{v}_1 \neq 0$ so $c_1 = 0$.

In the same way we get $c_2 = 0, c_3 = 0, \ldots, c_k = 0$.

Recall: Any linearly independent set of n vectors in $\mathbb{R}^n$ is a basis of $\mathbb{R}^n$.

Corollary

If $\{\mathbf{v}_1, \ldots, \mathbf{v}_n\}$ is an orthogonal set of n non-zero vectors in $\mathbb{R}^n$ then this set is a basis of $\mathbb{R}^n$.

Definition

If V is a subspace of $\mathbb{R}^n$ then we say that a set $\{\mathbf{v}_1, \dots \mathbf{v}_k\}$ is an *orthogonal basis* of V if

1) $\{\mathbf{v}_1, \dots \mathbf{v}_k\}$ is a basis of V and
2) $\{\mathbf{v}_1, \dots \mathbf{v}_k\}$ is an orthogonal set.

Recall. If $\mathcal{B} = \{\mathbf{v}_1, \dots \mathbf{v}_k\}$ is a basis of a vector space V and $\mathbf{w} \in V$ then the coordinate vector of $\mathbf{w}$ relative to $\mathcal{B}$ is the vector

$$[\ \mathbf{w}\ ]_{\mathcal{B}} = \begin{bmatrix} c_1 \\ \vdots \\ c_k \end{bmatrix}$$

where $c_1, \dots, c_k$ are scalars such that $c_1\mathbf{v}_1 + \dots + c_k\mathbf{v}_k = \mathbf{w}$.

Propostion

If $\mathcal{B} = \{\mathbf{v}_1, \dots \mathbf{v}_k\}$ is an orthogonal basis of V and $\mathbf{w} \in V$ then

$$[\ \mathbf{w}\ ]_{\mathcal{B}} = \begin{bmatrix} c_1 \\ \vdots \\ c_k \end{bmatrix}$$

where $c_i = \dfrac{\mathbf{w} \cdot \mathbf{v}_i}{\mathbf{v}_i \cdot \mathbf{v}_i} = \dfrac{\mathbf{w} \cdot \mathbf{v}_i}{||\mathbf{v}_i||^2}$

Proof: If $[w]_{\mathcal{B}} = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_k \end{bmatrix}$ then $w = c_1v_1 + c_2v_2 + \dots + c_kv_k$

We have: $w \cdot v_1 = (c_1v_1 + c_2v_2 + \dots + c_kv_k) \cdot v_1$

$$= c_1(v_1 \cdot v_1) + c_2\underbrace{(v_2 \cdot v_1)}_{=0} + \dots + c_k\underbrace{(v_k \cdot v_1)}_{=0}$$

So: $w \cdot v_1 = c_1(v_1 \cdot v_1)$

$$\boxed{c_1 = \frac{w \cdot v_1}{v_1 \cdot v_1}}$$

In the same way $c_i = \dfrac{w \cdot v_i}{v_i \cdot v_i}$ for $i = 1, 2, \dots, k$.

Example. Let

$$\mathcal{B} = \left\{ \begin{bmatrix} 1 \\ 2 \\ 3 \end{bmatrix}, \begin{bmatrix} -3 \\ 0 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ -5 \\ 3 \end{bmatrix} \right\}, \qquad \mathbf{w} = \begin{bmatrix} 3 \\ 2 \\ 1 \end{bmatrix}$$

The set $\mathcal{B}$ is an orthogonal basis of $\mathbb{R}^3$. Compute $[\,\mathbf{w}\,]_{\mathcal{B}}$.

Solution:

$$[w]_{\mathcal{B}} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix}$$

$$c_1 = \frac{w \cdot v_1}{v_1 \cdot v_1} = \frac{3\cdot 1 + 2\cdot 2 + 1\cdot 3}{1^2 + 2^2 + 3^2} = \frac{10}{14} = \frac{5}{7}$$

$$c_2 = \frac{w \cdot v_2}{v_2 \cdot v_2} = \frac{3\cdot(-3) + 2\cdot 0 + 1\cdot 1}{(-3)^2 + 0^2 + 1^2} = \frac{-8}{10} = -\frac{4}{5}$$

$$c_3 = \frac{w \cdot v_3}{v_3 \cdot v_3} = \frac{3\cdot 1 + 2\cdot(-5) + 1\cdot 3}{1^2 + (-5)^2 + 3^2} = \frac{-4}{35}$$

We get:

$$[w]_{\mathcal{B}} = \begin{bmatrix} 5/7 \\ -4/5 \\ -4/35 \end{bmatrix}$$

Check: $\quad w = \frac{5}{7} v_1 - \frac{4}{5} v_2 - \frac{4}{35} v_3$

Theorem (Gram-Schmidt Process)

Let $\{\mathbf{v}_1, \dots, \mathbf{v}_k\}$ be a basis of V. Define vectors $\{\mathbf{w}_1, \dots, \mathbf{w}_k\}$ as follows:

$$\mathbf{w}_1 = \mathbf{v}_1$$

$$\mathbf{w}_2 = \mathbf{v}_2 - \left(\frac{\mathbf{w}_1 \cdot \mathbf{v}_2}{\mathbf{w}_1 \cdot \mathbf{w}_1}\right)\mathbf{w}_1$$

$$\mathbf{w}_3 = \mathbf{v}_3 - \left(\frac{\mathbf{w}_1 \cdot \mathbf{v}_3}{\mathbf{w}_1 \cdot \mathbf{w}_1}\right)\mathbf{w}_1 - \left(\frac{\mathbf{w}_2 \cdot \mathbf{v}_3}{\mathbf{w}_2 \cdot \mathbf{w}_2}\right)\mathbf{w}_2$$

$$\dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots \quad \dots$$

$$\mathbf{w}_k = \mathbf{v}_k - \left(\frac{\mathbf{w}_1 \cdot \mathbf{v}_k}{\mathbf{w}_1 \cdot \mathbf{w}_1}\right)\mathbf{w}_1 - \left(\frac{\mathbf{w}_2 \cdot \mathbf{v}_k}{\mathbf{w}_2 \cdot \mathbf{w}_2}\right)\mathbf{w}_2 - \dots - \left(\frac{\mathbf{w}_{k-1} \cdot \mathbf{v}_k}{\mathbf{w}_{k-1} \cdot \mathbf{w}_{k-1}}\right)\mathbf{w}_{k-1}$$

Then the set $\{\mathbf{w}_1, \dots, \mathbf{w}_k\}$ is an orthogonal basis of V.

<u>E.g. check $w_1 \cdot w_2$</u>:

$$w_1 \cdot w_2 = w_1 \cdot \left(v_2 - \left(\frac{w_1 \cdot v_2}{w_1 \cdot w_1}\right) w_1\right)$$

$$= w_1 \cdot v_2 - \left(\frac{w_1 \cdot v_2}{\cancel{w_1 \cdot w_1}}\right)\cancel{(w_1 \cdot w_1)}$$

$$= w_1 \cdot v_2 - w_1 \cdot v_2 = 0$$

Example. In $\mathbb{R}^4$ take

$$\mathbf{v}_1 = \begin{bmatrix} 2 \\ 1 \\ 3 \\ -1 \end{bmatrix}, \quad \mathbf{v}_2 = \begin{bmatrix} 7 \\ 4 \\ 3 \\ -3 \end{bmatrix}, \quad \mathbf{v}_3 = \begin{bmatrix} 5 \\ 7 \\ 7 \\ 8 \end{bmatrix}$$

The set $\mathcal{B} = \{\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3\}$ is a basis of some subspace $V \subseteq \mathbb{R}^4$. Find an orthogonal basis of V.

Solution: Apply the Gram - Schmidt process:

$$w_1 = v_1 = \begin{bmatrix} 2 \\ 1 \\ 3 \\ -1 \end{bmatrix}$$

$$w_2 = v_2 - \left(\frac{w_1 \cdot v_2}{w_1 \cdot w_1}\right) w_1$$

$$w_1 \cdot w_1 = 2^2 + 1^2 + 3^2 + (-1)^2 = 15$$

$$w_1 \cdot v_2 = 2 \cdot 7 + 1 \cdot 4 + 3 \cdot 3 + (-1) \cdot (-3) = 30$$

$$= v_2 - \frac{30}{15} w_1 = v_2 - 2w_1 = \begin{bmatrix} 7 \\ 4 \\ 3 \\ -3 \end{bmatrix} - 2 \cdot \begin{bmatrix} 2 \\ 1 \\ 3 \\ -1 \end{bmatrix} = \begin{bmatrix} 3 \\ 2 \\ -3 \\ -1 \end{bmatrix}$$

$$w_3 = v_3 - \left(\frac{w_1 \cdot v_3}{w_1 \cdot w_1}\right) w_1 - \left(\frac{w_2 \cdot v_3}{w_2 \cdot w_2}\right) w_2$$

$$w_1 \cdot w_1 = 15$$

$$w_1 \cdot v_3 = 2 \cdot 5 + 1 \cdot 7 + 3 \cdot 7 + (-1) \cdot 8 = 30$$

$$w_2 \cdot w_2 = 3^2 + 2^2 + (-3)^2 + (-1)^2 = 23$$

$$w_2 \cdot v_3 = 3 \cdot 5 + 2 \cdot 7 + (-3) \cdot 7 + (-1) \cdot 8 = 0$$

$$= v_3 - \frac{30}{15} w_1 - \frac{0}{23} w_2$$

$$= v_3 - 2w_1 = \begin{bmatrix} 5 \\ 7 \\ 7 \\ 8 \end{bmatrix} - 2 \cdot \begin{bmatrix} 2 \\ 1 \\ 3 \\ -1 \end{bmatrix} = \begin{bmatrix} 1 \\ 5 \\ 1 \\ 10 \end{bmatrix}$$

We obtain an orthogonal basis of V:

$$\{w_1, w_2, w_3\} = \left\{ \begin{bmatrix} 2 \\ 1 \\ 3 \\ -1 \end{bmatrix}, \begin{bmatrix} 3 \\ 2 \\ -3 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ 1 \\ 10 \end{bmatrix} \right\}$$

Definition

An orthogonal basis $\mathcal{B} = \{\mathbf{w}_1, \ldots, \mathbf{w}_k\}$ of V is called an *orthonormal basis* if $||\mathbf{w}_i|| = 1$ for $i = 1, \ldots, k$.

Propostion

If $\mathcal{B} = \{\mathbf{v}_1, \ldots \mathbf{v}_k\}$ is an orthonormal basis of V and $\mathbf{w} \in V$ then

$$[\ \mathbf{w}\ ]_{\mathcal{B}} = \begin{bmatrix} c_1 \\ \vdots \\ c_k \end{bmatrix}$$

where $c_i = \mathbf{w} \cdot \mathbf{v}_i$.

Note. If $\mathcal{B} = \{\mathbf{v}_1, \ldots \mathbf{v}_k\}$ is an orthogonal basis of V then

$$\mathcal{C} = \left\{ \frac{\mathbf{v}_1}{||\mathbf{v}_1||}, \ldots, \frac{\mathbf{v}_k}{||\mathbf{v}_k||} \right\}$$

is an orthonormal basis of V.

Example:

In the last example we had:

$$\{w_1, w_2, w_3\} = \left\{ \begin{bmatrix} 2 \\ 1 \\ 3 \\ -1 \end{bmatrix}, \begin{bmatrix} 3 \\ 2 \\ -3 \\ -1 \end{bmatrix}, \begin{bmatrix} 1 \\ 5 \\ 1 \\ 10 \end{bmatrix} \right\} \leftarrow$$ an orthogonal basis of some subspace $V \subseteq \mathbb{R}^4$

We can obtain an orthonormal basis of V as follows:

$$\left\{ \frac{w_1}{\|w_1\|}, \frac{w_2}{\|w_2\|}, \frac{w_3}{\|w_3\|} \right\} = \left\{ \frac{1}{\sqrt{15}} \begin{bmatrix} 2 \\ 1 \\ 3 \\ -1 \end{bmatrix}, \frac{1}{\sqrt{23}} \begin{bmatrix} 3 \\ 2 \\ -3 \\ -1 \end{bmatrix}, \frac{1}{\sqrt{127}} \begin{bmatrix} 1 \\ 5 \\ 1 \\ 10 \end{bmatrix} \right\}$$

$$\|w_1\| = \sqrt{2^2+1^2+3^2+(-1)^2} = \sqrt{15}$$

$$\|w_2\| = \sqrt{3^2+2^2+(-3)^2+(-1)^2} = \sqrt{23}$$

$$\|w_3\| = \sqrt{1^2+5^2+1^2+10^2} = \sqrt{127}$$