

Inner Product Spaces and Orthogonality

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Definition

Let V be a vector space on \mathbb{R} .

We say that a function $\langle \cdot, \cdot \rangle: V \times V \rightarrow \mathbb{R}$ is an inner product on V if it satisfies the following:

For all $u, v, w \in V, \alpha \in \mathbb{R}$.

- 1 $\langle u, v \rangle = \langle v, u \rangle$
- 2 $\langle u + v, w \rangle = \langle u, w \rangle + \langle v, w \rangle$
- 3 $\langle \alpha u, v \rangle = \alpha \langle u, v \rangle$
- 4 $\langle u, u \rangle \geq 0$
- 5 $\langle u, u \rangle = 0 \iff u = 0$

- 1 The Euclidean inner product on \mathbb{R}^n defined by:

$$\langle u, v \rangle = \sum_{j=1}^n x_j y_j = x_1 y_1 + \dots + x_n y_n,$$

where $u, v \in \mathbb{R}^n$, $u = (x_1, \dots, x_n)$ and $v = (y_1, \dots, y_n)$.

- 2 If $E = \mathcal{C}([0, 1])$ the vector space of continuous functions on $[0, 1]$. For all $f, g \in E$, we define the inner product of f and g by:

$$\langle f, g \rangle = \int_0^1 f(t)g(t)dt.$$

If $(E, \langle \cdot, \cdot \rangle)$ is an inner product space and $u, v, w, x \in E$, $a, b, c, d \in \mathbb{R}$, we have:

$$\langle u + v, w + x \rangle = \langle u, w \rangle + \langle u, x \rangle + \langle v, w \rangle + \langle v, x \rangle.$$

$$\begin{aligned} \langle au + bv, cw + dx \rangle &= ac\langle u, w \rangle + ad\langle u, x \rangle \\ &\quad + bc\langle v, w \rangle + bd\langle v, x \rangle. \end{aligned}$$

Example

Let $u = (x, y)$ and $v = (a, b)$, we define

$$\langle u, v \rangle = 2ax + by - bx - ay$$

$\langle \cdot, \cdot \rangle$ is an inner product on \mathbb{R}^2 .

It is enough to prove that $\langle u, u \rangle \geq 0$ and $\langle u, u \rangle = 0 \iff u = 0$.

$$\langle u, u \rangle = 2x^2 + y^2 - 2xy = (x - y)^2 + x^2 \geq 0$$

and $\langle u, u \rangle = 0 \iff u = 0$.

Example

Let $u = (x, y, z)$ and $v = (a, b, c)$, we define

$$\langle u, v \rangle = 2ax + by + 3cz - bx - ay + cy + bz$$

$\langle \cdot, \cdot \rangle$ is an inner product on \mathbb{R}^3 .

It is enough to prove that $\langle u, u \rangle \geq 0$ and $\langle u, u \rangle = 0 \iff u = 0$.

$$\begin{aligned}\langle u, u \rangle &= (y + z - x)^2 - (z - x)^2 + 2x^2 + 3z^2 \\ &= (y + z - x)^2 + (x + z)^2 + z^2 \geq 0\end{aligned}$$

$$\langle u, u \rangle = 0 \iff z = x = y = 0 \iff u = 0.$$

Example

Let $u = (x, y, z)$ and $v = (a, b, c)$, we define

$$\langle u, v \rangle = 2ax + by + cz - bx - ay + cy + bz$$

\langle , \rangle is not an inner product on \mathbb{R}^3 .

$$\begin{aligned}\langle u, u \rangle &= (y + z - x)^2 - (z - x)^2 + 2x^2 + z^2 \\ &= (y + z - x)^2 + x^2 + 2xz \\ &= (y + z - x)^2 + (x + z)^2 - z^2.\end{aligned}$$

Example

If $A = (a_{j,k}) \in M_n(\mathbb{R})$, we define the trace of the matrix A by:

$$\operatorname{tr}(A) = \sum_{j=1}^n a_{j,j}$$

and

$$\langle A, B \rangle = \operatorname{tr}(AB^T)$$

for all $A, B \in M_n(\mathbb{R})$.

$\langle A, B \rangle$ is an inner product on the vector space $M_n(\mathbb{R})$.

Exercise

If $u = (x_1, x_2, x_3)$, $v = (y_1, y_2, y_3)$, we define the following functions: $f, g, h, k: \mathbb{R}^2 \times \mathbb{R}^3 \rightarrow \mathbb{R}$.

- 1 $f(u, v) = x_1y_1 + x_2y_2 + 2x_3y_3 + x_2y_1 + 2x_1y_2 + x_2y_3 + y_2x_3$.
- 2 $g(u, v) = x_1y_2 + x_2y_1 + x_2y_3 + x_3y_2 + 3x_1y_3 + 3x_3y_1$.
- 3 $h(u, v) =$
 $x_1y_1 + x_2y_2 + x_3y_3 + x_2y_1 + x_1y_2 + x_2y_3 + y_2x_3 + x_3y_1 + x_1y_3$.
- 4 $k(u, v) = x_1y_1 + x_2y_2 + x_3y_3x_2y_3x_3y_2 + x_1y_3 + y_1x_3$.

Select from which the functions f, g, h, k is an inner product on \mathbb{R}^3 .

① $f(u, v) - f(v, u) = x_1y_2 - x_2y_1$. Then f is not an inner product on \mathbb{R}^3 .

② $g(u, u) = 2x_1x_2 + 2x_2x_3 + 6x_1x_3 = 2(x_1 + x_3)(x_2 + 3x_3) - 6x_3^2 = (x_1 + x_2 + 4x_3)^2 - (x_1 - x_2 - 2x_3)^2 - 6x_3^2$.
Then g is not an inner product on \mathbb{R}^3 .

③

$$\begin{aligned}h(u, u) &= x_1^2 + x_2^2 + x_3^2 + 2x_1x_2 + 2x_2x_3 + 2x_1x_3 \\ &= (x_1 + x_2 + x_3)^2\end{aligned}$$

Then h is not an inner product on \mathbb{R}^3 because

$$h(u, u) = 0 \not\Rightarrow u = 0.$$

④

$$\begin{aligned}k(u, u) &= x_1^2 + x_2^2 + x_3^2 - 2x_2x_3 + 2x_1x_3 \\&= (x_1 + x_3)^2 + x_2^2 - 2x_2x_3 \\&= (x_1 + x_3)^2 + (x_2 - x_3)^2 - x_3^2\end{aligned}$$

Then k is not an inner product on \mathbb{R}^3 because

$$k(u, u) = 0 \not\Rightarrow u = 0.$$

Example

Find the values of a, b such that

$$\langle (x_1, x_2), (y_1, y_2) \rangle = x_1y_1 + x_2y_2 + ax_1y_2 + bx_2y_1$$

is an inner product on \mathbb{R}^2 .

$\langle (x_1, x_2), (y_1, y_2) \rangle = \langle (y_1, y_2), (x_1, x_2) \rangle$ if $a = b$.

$$\begin{aligned}\langle (x_1, x_2), (x_1, x_2) \rangle &= x_1^2 + x_2^2 + 2ax_1x_2 \\ &= (x_1 + ax_2)^2 + x_2^2(1 - a^2).\end{aligned}$$

Then $\langle \cdot, \cdot \rangle$ is an inner product on \mathbb{R}^2 if and only if $|a| < 1$.

Definition

Let $(E, \langle \cdot, \cdot \rangle)$ be an inner product space.

- 1 If $u \in E$, we define the norm of the vector u by:

$$\|u\| = \sqrt{\langle u, u \rangle}.$$

- 2 If $u, v \in E$, we define distance between u and v by:

$$d(u, v) = \|u - v\|.$$

- 3 We define the angle $0 \leq \theta \leq \pi$ between the vectors $u, v \in E$ by:

$$\cos \theta = \frac{\langle u, v \rangle}{\|u\| \cdot \|v\|}$$

Let the inner product space $M_2(\mathbb{R}), \langle \cdot, \cdot \rangle$ defined by:

$$\langle A, B \rangle = \text{tr}(AB^T).$$

Find $\cos \theta$ If θ is the angle between the matrices

$$A = \begin{pmatrix} 1 & -1 \\ 2 & 3 \end{pmatrix} \text{ and } B = \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}.$$

$$AB^T = \begin{pmatrix} 1 & 0 \\ 7 & 5 \end{pmatrix}, \quad \|A\|^2 = 15, \quad \|B\|^2 = 7.$$

Then

$$\cos \theta = \frac{2\sqrt{3}}{\sqrt{35}}.$$

Theorem (Cauchy-Schwarz Inequality)

If $(E, \langle \cdot, \cdot \rangle)$ is an inner product space and $u, v \in E$, then

$$|\langle u, v \rangle| \leq \|u\| \|v\|. \quad (1)$$

We have the equality in (??) if the vectors u, v are linearly dependent.

Let $Q(t)$ be the polynomial

$$Q(t) = \|u + tv\|^2 = \|u\|^2 + 2t\langle u, v \rangle + t^2\|v\|^2.$$

Since $Q(t) \geq 0$ for all $t \in \mathbb{R}$, then the discriminant of $Q(t)$ is non positive. Then

$$\langle u, v \rangle^2 \leq \|u\|^2\|v\|^2.$$

If $|\langle u, v \rangle| = \|u\|\|v\|$, this mean that the discriminant of $Q(t)$ is zero. Then the equation $Q(t) = 0$ has a solution. This means that the vectors u, v are linearly dependent.

Theorem

If $(E, \langle \cdot, \cdot \rangle)$ is an inner product space and $u, v \in E$, then

$$\|u + v\| \leq \|u\| + \|v\|.$$

Proof

$$\begin{aligned}\|u + v\|^2 &= \|u\|^2 + \|v\|^2 + 2\langle u, v \rangle \\ &\leq \|u\|^2 + \|v\|^2 + 2\|u\| \|v\| = (\|u\| + \|v\|)^2.\end{aligned}$$

Definition

If $(E, \langle \cdot, \cdot \rangle)$ is an inner product space. We say that the vectors $u, v \in E$ are orthogonal and we denote $u \perp v$ if $\langle u, v \rangle = 0$.

Theorem (Pythagor's Theorem)

If $u \perp v$ if and only if

$$\|u + v\|^2 = \|u\|^2 + \|v\|^2.$$

Proof

$$\|u + v\|^2 = \|u\|^2 + \|v\|^2 + 2\langle u, v \rangle = \|u\|^2 + \|v\|^2.$$

Definition

If $(E, \langle \cdot, \cdot \rangle)$ is an inner product space. We say that set $S = \{e_1, \dots, e_n\}$ of non zeros vectors is orthogonal if

$$\langle e_j, e_k \rangle = 0, \quad \forall 1 \leq j \neq k \leq n.$$

and we say that S is normal if

$$\|e_j\| = 1, \quad \forall 1 \leq j \leq n.$$

and we say that it is orthonormal if

$$\langle e_j, e_k \rangle = \delta_{j,k}, \quad \forall 1 \leq j, k \leq n.$$

($\delta_{j,k} = 0$ If $j \neq k$ and $\delta_{j,j} = 1$.)

Theorem

Any set of non zero orthogonal vectors is linearly independent .

Theorem

If $(E, \langle \cdot, \cdot \rangle)$ is an inner product space and if $S = \{e_1, \dots, e_n\}$ is an orthonormal basis of E , then for all $u \in E$

$$u = \langle u, e_1 \rangle e_1 + \dots + \langle u, e_n \rangle e_n.$$

$$\text{If } u = \sum_{j=1}^n a_j e_j, \text{ then } \langle u, e_k \rangle = \sum_{j=1}^n a_j \langle e_j, e_k \rangle = a_k.$$

Theorem

(Gramm-Schmidt Algorithm) If $(E, \langle \cdot, \cdot \rangle)$ is an inner product space and (v_1, \dots, v_n) a set of linearly independent vectors in E , there is a unique orthonormal set (e_1, \dots, e_n) such that

- 1 for all $k \in \{1, \dots, n\}$,

$$\text{Vect}(e_1, \dots, e_k) = \text{Vect}(v_1, \dots, v_k),$$

- 2 for all $k \in \{1, \dots, n\}$,

$$\langle e_k, v_k \rangle > 0.$$

Proof

We construct in the first time an orthogonal set (u_1, \dots, u_n) such that:

$$\begin{cases} u_1 = v_1 \\ u_2 = v_2 - \frac{\langle u_1, v_2 \rangle}{\|u_1\|^2} u_1 \\ \vdots \\ u_n = v_n - \sum_{i=1}^{n-1} \frac{\langle u_i, v_n \rangle}{\|u_i\|^2} u_i. \end{cases}$$

We construct the set (e_1, \dots, e_n) from (u_1, \dots, u_n) as follows:

$$e_k = \frac{u_k}{\|u_k\|}, \quad k \in \{1, \dots, n\}.$$

Example

Let F be the vector sub-space of \mathbb{R}^4 spanned by the vectors $S = \{u = (1, 1, 0, 0), v = (1, 0, -1, 0), w = (0, 0, 1, 1)\}$.

- 1 Prove that S is a basis of the sub-space F .
- 2 In use of Gram-Schmidt Algorithm, find an orthonormal basis of F . (with respect to the Euclidean inner product).

- ① Let $A = \begin{pmatrix} 1 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & -1 & 1 \\ 0 & 0 & 1 \end{pmatrix}$ with columns the vectors u, v, w .

The matrix $A = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$ is a row reduced form of the matrix A . This proves that S is a basis of the sub-space F .

- ② $u_1 = \frac{1}{\sqrt{2}}(1, 1, 0, 0)$, $u_2 = \frac{1}{\sqrt{6}}(1, -1, -2, 0)$,
 $u_3 = \frac{1}{\sqrt{12}}(1, -1, 1, 3)$.

$\{u_1, u_2, u_3\}$ is an orthonormal basis of the sub-space F .

- 1 Prove that $\langle (a, b), (x, y) \rangle = ax + ay + bx + 2by$ is an inner product in \mathbb{R}^2 .
- 2 Use Gram-Schmidt algorithm to construct an orthonormal basis of \mathbb{R}^2 from the basis $\{u_1 = (1, -1), u_2 = (1, 2)\}$.

- ① • $\langle (a, b) + (c, d), (x, y) \rangle = (a + c)x + (a + c)y + (b + d)x + 2(b + d)y = \langle (a, b), (x, y) \rangle + \langle (c, d), (x, y) \rangle$

 - $\langle (a, b), (x, y) \rangle = ax + ay + bx + 2by = \langle (x, y), (a, b) \rangle$
 - $\langle \lambda(a, b), (x, y) \rangle = \lambda ax + \lambda ay + \lambda bx + 2\lambda by = \lambda \langle (a, b), (x, y) \rangle$
 - $\langle (a, b), (a, b) \rangle = a^2 + 2ab + 2b^2 = (a + b)^2 + b^2 \geq 0$
 - $\langle (a, b), (a, b) \rangle = 0 \iff a + b = 0 = b \iff a = b = 0$
- ② The vector u_1 is unitary and the second vector is $v_2 = (1, 0)$. Then $\{v_1 = (1, -1), v_2 = (1, 0)\}$ is an orthonormal basis.

Example

Let $S = \{u_1, u_2, u_3, u_4\}$ is a basis of the space $M_2(\mathbb{R})$ such that

$$u_1 = \begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix}, u_2 = \begin{pmatrix} 1 & 0 \\ 1 & 1 \end{pmatrix}, u_3 = \begin{pmatrix} 1 & 0 \\ 0 & 2 \end{pmatrix}, u_4 = \begin{pmatrix} 0 & 1 \\ 1 & 1 \end{pmatrix}$$

We use the Gram-Schmidt algorithm to construct an orthonormal basis from the basis S .

$$v_1 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix}.$$

$$\langle u_2, v_1 \rangle = \frac{2}{\sqrt{3}},$$

$$u_2 - \langle u_2, v_1 \rangle v_1 = \frac{1}{3} \begin{pmatrix} 1 & 2 \\ 3 & 1 \end{pmatrix}.$$

$$v_2 = \frac{1}{\sqrt{15}} \begin{pmatrix} 1 & 2 \\ 3 & 1 \end{pmatrix}.$$

$$\langle u_3, v_1 \rangle = \sqrt{3}, \quad \langle u_3, v_2 \rangle = \frac{3}{\sqrt{15}}$$

$$u_3 - \langle u_3, v_1 \rangle v_1 - \langle u_3, v_2 \rangle v_2 = \frac{1}{5} \begin{pmatrix} -1 & 3 \\ -3 & 4 \end{pmatrix}.$$

$$v_3 = \frac{1}{\sqrt{35}} \begin{pmatrix} -1 & 3 \\ -3 & 4 \end{pmatrix}.$$

$$\langle u_4, v_1 \rangle = 0, \quad \langle u_4, v_2 \rangle = \frac{6}{\sqrt{15}}, \quad \langle u_4, v_3 \rangle = \frac{4}{\sqrt{35}}$$

$$u_4 - \langle u_4, v_1 \rangle v_1 - \langle u_4, v_2 \rangle v_2 - \langle u_4, v_3 \rangle v_3 = \frac{1}{35} \begin{pmatrix} -10 & -39 \\ -29 & -29 \end{pmatrix}.$$

$$v_4 = \frac{1}{\sqrt{7}} \begin{pmatrix} 2 & 1 \\ -1 & -1 \end{pmatrix}.$$

Exercise

Let F be the vector sub-space of the Euclidean space \mathbb{R}^4 spanned by the following vectors

$$u_1 = (1, 2, 0, 2), \quad u_2 = (-1, 1, 1, 1).$$

- 1 Use Gram-Schmidt algorithm to construct an orthonormal basis of the vector sub-space F
- 2 Prove that the set $F^\perp = \{u \in \mathbb{R}^4 : \langle u, v \rangle = 0, \forall v \in F\}$ is a vector sub-space of \mathbb{R}^4 .
- 3 Find an orthonormal basis of the vector sub-space F^\perp .

① $v_1 = \frac{1}{3}u_1, \langle u_2, v_1 \rangle = 1,$

$$u_2 - \langle u_2, v_1 \rangle v_1 = (0, 3, 1, 1) - \frac{1}{3}(-1, 1, 1, 1) = \frac{1}{3}(-4, 1, 3, 1).$$

Then $v_2 = \frac{1}{3\sqrt{3}}(-4, 1, 3, 1).$

(v_1, v_2) is an orthonormal basis of the vector sub-space F .

② If $v_1, v_2 \in F^\perp, \alpha, \beta \in \mathbb{R}$ and $u \in F$, then

$$\langle \alpha v_1 + \beta v_2, u \rangle = \alpha \langle v_1, u \rangle + \beta \langle v_2, u \rangle = 0.$$

Then F^\perp is a vector sub-space of \mathbb{R}^4 .

③ Let $u = (x, y, z, t) \in \mathbb{R}^4$.

$$u \in F^\perp \iff \begin{cases} \langle u, u_1 \rangle = 0 \\ \langle u, u_2 \rangle = 0 \end{cases} \iff \begin{cases} x + 2y + 2t = 0 \\ -x + y + z + t = 0 \end{cases}$$

$$\begin{cases} x + 2y + 2t = 0 \\ -x + y + z + t = 0 \end{cases} \iff \begin{cases} x = \frac{2}{3}z \\ y = -\frac{z}{3} - t \end{cases}$$

Then $u \in F^\perp \iff u = -\frac{z}{3}(-2, 1, -3, 0) + t(0, -1, 0, 1)$.

The vectors $e_1 = (-2, 1, -3, 0)$, $e_2 = (0, -1, 0, 1)$ is an orthogonal basis of the vector sub-space F^\perp .

$$w_1 = \frac{1}{\sqrt{14}}e_1, \langle w_1, e_2 \rangle = -\frac{1}{\sqrt{14}},$$

$$e_2 - \langle e_2, w_1 \rangle w_1 = \frac{1}{14}(2, 13, 3, 14).$$

Then $(\frac{1}{\sqrt{14}}(-2, 1, -3, 0), \frac{1}{3\sqrt{42}}(2, 13, 3, 14))$ is an orthonormal basis of the vector sub-space F^\perp .