

MATH 311

Topics in Applied Mathematics I

**Lecture 25:**

**Orthogonal projection (continued).**

**Least squares problems.**

## Orthogonal complement

*Definition.* Let  $S \subset \mathbb{R}^n$ . The **orthogonal complement** of  $S$ , denoted  $S^\perp$ , is the set of all vectors  $\mathbf{x} \in \mathbb{R}^n$  that are orthogonal to  $S$ .

**Theorem 1 (i)**  $S^\perp$  is a subspace of  $\mathbb{R}^n$ .

**(ii)**  $(S^\perp)^\perp = \text{Span}(S)$ .

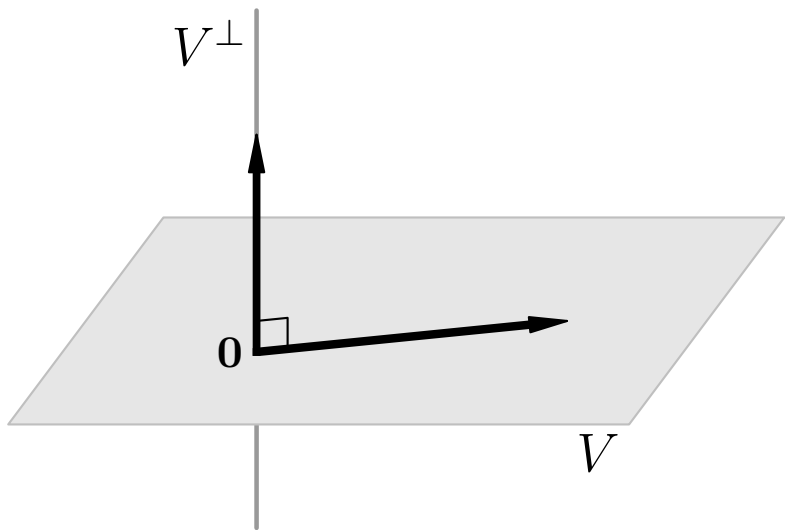
**Theorem 2** If  $V$  is a subspace of  $\mathbb{R}^n$ , then

**(i)**  $(V^\perp)^\perp = V$ ,

**(ii)**  $V \cap V^\perp = \{\mathbf{0}\}$ ,

**(iii)**  $\dim V + \dim V^\perp = n$ .

**Theorem 3** If  $V$  is the row space of a matrix, then  $V^\perp$  is the nullspace of the same matrix.



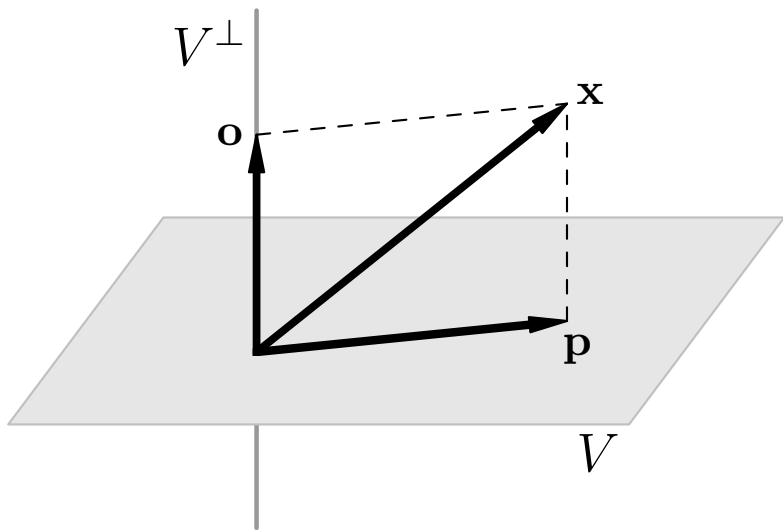
## Orthogonal projection

**Theorem 1** Let  $V$  be a subspace of  $\mathbb{R}^n$ . Then any vector  $\mathbf{x} \in \mathbb{R}^n$  is uniquely represented as  $\mathbf{x} = \mathbf{p} + \mathbf{o}$ , where  $\mathbf{p} \in V$  and  $\mathbf{o} \in V^\perp$ .

In the above expansion,  $\mathbf{p}$  is called the **orthogonal projection** of the vector  $\mathbf{x}$  onto the subspace  $V$ .

**Theorem 2**  $\|\mathbf{x} - \mathbf{v}\| > \|\mathbf{x} - \mathbf{p}\|$  for any  $\mathbf{v} \neq \mathbf{p}$  in  $V$ .

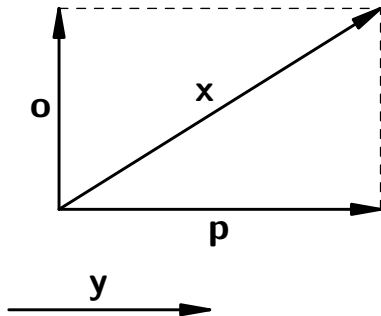
Thus  $\|\mathbf{o}\| = \|\mathbf{x} - \mathbf{p}\| = \min_{\mathbf{v} \in V} \|\mathbf{x} - \mathbf{v}\|$  is the **distance** from the vector  $\mathbf{x}$  to the subspace  $V$ .



## Orthogonal projection onto a vector

Let  $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$ , with  $\mathbf{y} \neq \mathbf{0}$ .

Then there exists a unique decomposition  $\mathbf{x} = \mathbf{p} + \mathbf{o}$  such that  $\mathbf{p}$  is parallel to  $\mathbf{y}$  and  $\mathbf{o}$  is orthogonal to  $\mathbf{y}$ .



$\mathbf{p}$  = orthogonal projection of  $\mathbf{x}$  onto  $\mathbf{y}$

## Orthogonal projection onto a vector

Let  $\mathbf{x}, \mathbf{y} \in \mathbb{R}^n$ , with  $\mathbf{y} \neq \mathbf{0}$ .

Then there exists a unique decomposition  $\mathbf{x} = \mathbf{p} + \mathbf{o}$  such that  $\mathbf{p}$  is parallel to  $\mathbf{y}$  and  $\mathbf{o}$  is orthogonal to  $\mathbf{y}$ .

We have  $\mathbf{p} = \alpha \mathbf{y}$  for some  $\alpha \in \mathbb{R}$ . Then

$$0 = \mathbf{o} \cdot \mathbf{y} = (\mathbf{x} - \alpha \mathbf{y}) \cdot \mathbf{y} = \mathbf{x} \cdot \mathbf{y} - \alpha \mathbf{y} \cdot \mathbf{y}.$$

$$\implies \alpha = \frac{\mathbf{x} \cdot \mathbf{y}}{\mathbf{y} \cdot \mathbf{y}} \implies \boxed{\mathbf{p} = \frac{\mathbf{x} \cdot \mathbf{y}}{\mathbf{y} \cdot \mathbf{y}} \mathbf{y}}$$

**Problem.** Find the distance from the point  $\mathbf{x} = (3, 1)$  to the line spanned by  $\mathbf{y} = (2, -1)$ .

Consider the decomposition  $\mathbf{x} = \mathbf{p} + \mathbf{o}$ , where  $\mathbf{p}$  is parallel to  $\mathbf{y}$  while  $\mathbf{o} \perp \mathbf{y}$ . The required distance is the length of the orthogonal component  $\mathbf{o}$ .

$$\mathbf{p} = \frac{\mathbf{x} \cdot \mathbf{y}}{\mathbf{y} \cdot \mathbf{y}} \mathbf{y} = \frac{5}{5} (2, -1) = (2, -1),$$

$$\mathbf{o} = \mathbf{x} - \mathbf{p} = (3, 1) - (2, -1) = (1, 2), \quad \|\mathbf{o}\| = \sqrt{5}.$$

**Problem.** Find the point on the line  $y = -x$  that is closest to the point  $(3, 4)$ .

The required point is the projection  $\mathbf{p}$  of  $\mathbf{v} = (3, 4)$  on the vector  $\mathbf{w} = (1, -1)$  spanning the line  $y = -x$ .

$$\mathbf{p} = \frac{\mathbf{v} \cdot \mathbf{w}}{\mathbf{w} \cdot \mathbf{w}} \mathbf{w} = \frac{-1}{2} (1, -1) = \left(-\frac{1}{2}, \frac{1}{2}\right).$$



**Problem.** Let  $\Pi$  be the plane spanned by vectors  $\mathbf{v}_1 = (1, 1, 0)$  and  $\mathbf{v}_2 = (0, 1, 1)$ .

(i) Find the orthogonal projection of the vector  $\mathbf{x} = (4, 0, -1)$  onto the plane  $\Pi$ .

(ii) Find the distance from  $\mathbf{x}$  to  $\Pi$ .

We have  $\mathbf{x} = \mathbf{p} + \mathbf{o}$ , where  $\mathbf{p} \in \Pi$  and  $\mathbf{o} \perp \Pi$ .

Then the orthogonal projection of  $\mathbf{x}$  onto  $\Pi$  is  $\mathbf{p}$  and the distance from  $\mathbf{x}$  to  $\Pi$  is  $\|\mathbf{o}\|$ .

We have  $\mathbf{p} = \alpha\mathbf{v}_1 + \beta\mathbf{v}_2$  for some  $\alpha, \beta \in \mathbb{R}$ .

Then  $\mathbf{o} = \mathbf{x} - \mathbf{p} = \mathbf{x} - \alpha\mathbf{v}_1 - \beta\mathbf{v}_2$ .

$$\begin{cases} \mathbf{o} \cdot \mathbf{v}_1 = 0 \\ \mathbf{o} \cdot \mathbf{v}_2 = 0 \end{cases} \iff \begin{cases} \alpha(\mathbf{v}_1 \cdot \mathbf{v}_1) + \beta(\mathbf{v}_2 \cdot \mathbf{v}_1) = \mathbf{x} \cdot \mathbf{v}_1 \\ \alpha(\mathbf{v}_1 \cdot \mathbf{v}_2) + \beta(\mathbf{v}_2 \cdot \mathbf{v}_2) = \mathbf{x} \cdot \mathbf{v}_2 \end{cases}$$

$$\mathbf{x} = (4, 0, -1), \quad \mathbf{v}_1 = (1, 1, 0), \quad \mathbf{v}_2 = (0, 1, 1)$$

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$$\begin{cases} \alpha(\mathbf{v}_1 \cdot \mathbf{v}_1) + \beta(\mathbf{v}_2 \cdot \mathbf{v}_1) = \mathbf{x} \cdot \mathbf{v}_1 \\ \alpha(\mathbf{v}_1 \cdot \mathbf{v}_2) + \beta(\mathbf{v}_2 \cdot \mathbf{v}_2) = \mathbf{x} \cdot \mathbf{v}_2 \end{cases}$$

$$\Leftrightarrow \begin{cases} 2\alpha + \beta = 4 \\ \alpha + 2\beta = -1 \end{cases} \Leftrightarrow \begin{cases} \alpha = 3 \\ \beta = -2 \end{cases}$$

$$\mathbf{p} = 3\mathbf{v}_1 - 2\mathbf{v}_2 = (3, 1, -2)$$

$$\mathbf{o} = \mathbf{x} - \mathbf{p} = (1, -1, 1)$$

$$\|\mathbf{o}\| = \sqrt{3}$$

**Problem.** Let  $\Pi$  be the plane spanned by vectors  $\mathbf{v}_1 = (1, 1, 0)$  and  $\mathbf{v}_2 = (0, 1, 1)$ .

(i) Find the orthogonal projection of the vector  $\mathbf{x} = (4, 0, -1)$  onto the plane  $\Pi$ .

(ii) Find the distance from  $\mathbf{x}$  to  $\Pi$ .

*Alternative solution:* We have  $\mathbf{x} = \mathbf{p} + \mathbf{o}$ , where  $\mathbf{p} \in \Pi$  and  $\mathbf{o} \perp \Pi$ . Then the orthogonal projection of  $\mathbf{x}$  onto  $\Pi$  is  $\mathbf{p}$  and the distance from  $\mathbf{x}$  to  $\Pi$  is  $\|\mathbf{o}\|$ .

Notice that  $\mathbf{o}$  is the orthogonal projection of  $\mathbf{x}$  onto the orthogonal complement  $\Pi^\perp$ . In the previous lecture, we found that  $\Pi^\perp$  is the line spanned by the vector  $\mathbf{y} = (1, -1, 1)$ . It follows that

$$\mathbf{o} = \frac{\mathbf{x} \cdot \mathbf{y}}{\mathbf{y} \cdot \mathbf{y}} \mathbf{y} = \frac{3}{3} (1, -1, 1) = (1, -1, 1).$$

Then  $\mathbf{p} = \mathbf{x} - \mathbf{o} = (4, 0, -1) - (1, -1, 1) = (3, 1, -2)$  and  $\|\mathbf{o}\| = \sqrt{3}$ .

Overdetermined system of linear equations:

$$\begin{cases} x + 2y = 3 \\ 3x + 2y = 5 \\ x + y = 2.09 \end{cases} \iff \begin{cases} x + 2y = 3 \\ -4y = -4 \\ -y = -0.91 \end{cases}$$

No solution: inconsistent system

Assume that a solution  $(x_0, y_0)$  does exist but the system is not quite accurate, namely, there may be some errors in the right-hand sides.

**Problem.** Find a good approximation of  $(x_0, y_0)$ .

One approach is the **least squares fit**. Namely, we look for a pair  $(x, y)$  that minimizes the sum  $(x + 2y - 3)^2 + (3x + 2y - 5)^2 + (x + y - 2.09)^2$ .

## Least squares solution

System of linear equations:

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \cdots + a_{1n}x_n = b_1 \\ a_{21}x_1 + a_{22}x_2 + \cdots + a_{2n}x_n = b_2 \\ \dots\dots\dots \\ a_{m1}x_1 + a_{m2}x_2 + \cdots + a_{mn}x_n = b_m \end{cases} \iff \mathbf{Ax} = \mathbf{b}$$

For any  $\mathbf{x} \in \mathbb{R}^n$  define a **residual**  $r(\mathbf{x}) = \mathbf{b} - \mathbf{Ax}$ .

The **least squares solution**  $\mathbf{x}$  to the system is the one that minimizes  $\|r(\mathbf{x})\|$  (or, equivalently,  $\|r(\mathbf{x})\|^2$ ).

$$\|r(\mathbf{x})\|^2 = \sum_{i=1}^m (a_{i1}x_1 + a_{i2}x_2 + \cdots + a_{in}x_n - b_i)^2$$

Let  $A$  be an  $m \times n$  matrix and let  $\mathbf{b} \in \mathbb{R}^m$ .

**Theorem** A vector  $\hat{\mathbf{x}}$  is a least squares solution of the system  $A\mathbf{x} = \mathbf{b}$  if and only if it is a solution of the associated **normal system**  $A^T A\mathbf{x} = A^T \mathbf{b}$ .

*Proof:*  $A\mathbf{x}$  is an arbitrary vector in the column space of  $A$ . Hence the length of  $r(\mathbf{x}) = \mathbf{b} - A\mathbf{x}$  is minimal if  $A\mathbf{x}$  is the orthogonal projection of  $\mathbf{b}$  onto the column space. That is, if  $r(\mathbf{x})$  is orthogonal to the column space of  $A$ .

We know that  $\{\text{row space}\}^\perp = \{\text{nullspace}\}$  for any matrix. It follows that  $\{\text{column space of } A\}^\perp = \{\text{nullspace of } A^T\}$ . Thus  $\hat{\mathbf{x}}$  is a least squares solution if and only if

$$A^T r(\hat{\mathbf{x}}) = \mathbf{0} \iff A^T(\mathbf{b} - A\hat{\mathbf{x}}) = \mathbf{0} \iff A^T A\hat{\mathbf{x}} = A^T \mathbf{b}.$$

**Corollary** The normal system  $A^T A\mathbf{x} = A^T \mathbf{b}$  is always consistent.

**Problem.** Find the least squares solution to

$$\begin{cases} x + 2y = 3 \\ 3x + 2y = 5 \\ x + y = 2.09 \end{cases}$$

$$\begin{pmatrix} 1 & 2 \\ 3 & 2 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 3 \\ 5 \\ 2.09 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 3 & 1 \\ 2 & 2 & 1 \end{pmatrix} \begin{pmatrix} 1 & 2 \\ 3 & 2 \\ 1 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 1 & 3 & 1 \\ 2 & 2 & 1 \end{pmatrix} \begin{pmatrix} 3 \\ 5 \\ 2.09 \end{pmatrix}$$

$$\begin{pmatrix} 11 & 9 \\ 9 & 9 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} 20.09 \\ 18.09 \end{pmatrix} \iff \begin{cases} x = 1 \\ y = 1.01 \end{cases}$$

**Problem.** Find the constant function that is the least squares fit to the following data

$x$	0	1	2	3
$f(x)$	1	0	1	2

$$f(x) = c \implies \begin{cases} c = 1 \\ c = 0 \\ c = 1 \\ c = 2 \end{cases} \implies \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} (c) = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 2 \end{pmatrix}$$

$$(1, 1, 1, 1) \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} (c) = (1, 1, 1, 1) \begin{pmatrix} 1 \\ 0 \\ 1 \\ 2 \end{pmatrix}$$

$$c = \frac{1}{4}(1 + 0 + 1 + 2) = 1 \quad (\text{mean arithmetic value})$$



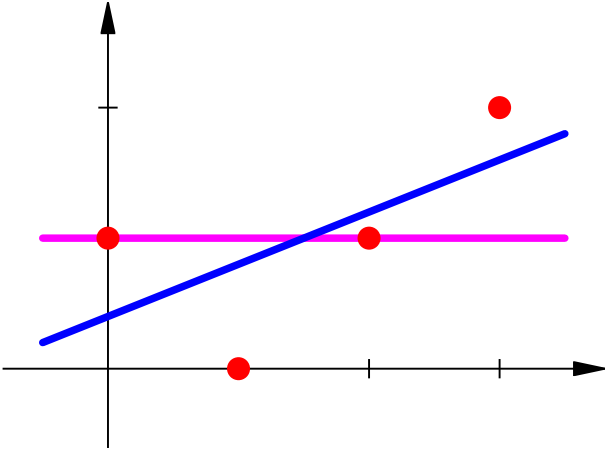
**Problem.** Find the linear polynomial that is the least squares fit to the following data

$x$	0	1	2	3
$f(x)$	1	0	1	2

$$f(x) = c_1 + c_2x \implies \begin{cases} c_1 = 1 \\ c_1 + c_2 = 0 \\ c_1 + 2c_2 = 1 \\ c_1 + 3c_2 = 2 \end{cases} \implies \begin{pmatrix} 1 & 0 \\ 1 & 1 \\ 1 & 2 \\ 1 & 3 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 2 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 2 & 3 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 1 & 1 \\ 1 & 2 \\ 1 & 3 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 2 & 3 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 2 \end{pmatrix}$$

$$\begin{pmatrix} 4 & 6 \\ 6 & 14 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \end{pmatrix} = \begin{pmatrix} 4 \\ 8 \end{pmatrix} \iff \begin{cases} c_1 = 0.4 \\ c_2 = 0.4 \end{cases}$$



**Problem.** Find the quadratic polynomial that is the least squares fit to the following data

$x$	0	1	2	3
$f(x)$	1	0	1	2

$$f(x) = c_1 + c_2x + c_3x^2$$

$$\Rightarrow \begin{cases} c_1 = 1 \\ c_1 + c_2 + c_3 = 0 \\ c_1 + 2c_2 + 4c_3 = 1 \\ c_1 + 3c_2 + 9c_3 = 2 \end{cases} \Rightarrow \begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 2 & 4 \\ 1 & 3 & 9 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 1 \\ 2 \end{pmatrix}$$

$$\begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 2 & 3 \\ 0 & 1 & 4 & 9 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & 2 & 4 \\ 1 & 3 & 9 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 0 & 1 & 2 & 3 \\ 0 & 1 & 4 & 9 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ 1 \\ 2 \end{pmatrix}$$

$$\begin{pmatrix} 4 & 6 & 14 \\ 6 & 14 & 36 \\ 14 & 36 & 98 \end{pmatrix} \begin{pmatrix} c_1 \\ c_2 \\ c_3 \end{pmatrix} = \begin{pmatrix} 4 \\ 8 \\ 22 \end{pmatrix} \iff \begin{cases} c_1 = 0.9 \\ c_2 = -1.1 \\ c_3 = 0.5 \end{cases}$$

