Math 221: LINEAR ALGEBRA

Chapter 4. Vector Geometry
§4-2. Projections and Planes

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Emory University, 2021 Spring

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[1] Slides are adapted from those by Karen Seyffarth from University of Calgary.

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The Dot Product and Angles

Projections

Planes

Cross Product

Shortest Distances

Linear Algebra with Applications

Lecture Notes

Current Lecture Notes Revision: Version 2018 — Revision B

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- **Ilijas Farah, York University**

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NOTE: Much of this chapter is what you would learn in Multivariable Calculus.

You might find it interesting/useful to read.

But I will only cover the material important to this course.

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The Dot Product and Angles

The Dot Product and Angles

Definition

Let $\vec{u} = \begin{bmatrix} x_1 \\ y_1 \\ z_1 \end{bmatrix}$ and $\vec{v} = \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix}$ be vectors in $\mathbb{R}^3$. The dot product of $\vec{u}$ and $\vec{v}$ is

$$\vec{u} \cdot \vec{v} = x_1 x_2 + y_1 y_2 + z_1 z_2,$$

i.e., $\vec{u} \cdot \vec{v}$ is a scalar.

The Dot Product and Angles

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Remark

Another way to think about the dot product is as the 1×1 matrix

$$\vec{u}^T\vec{v} = \begin{bmatrix} x_1 & y_1 & z_1 \end{bmatrix} \begin{bmatrix} x_2 \\ y_2 \\ z_2 \end{bmatrix} = \begin{bmatrix} x_1x_2 + y_1y_2 + z_1z_2 \end{bmatrix}.$$

Theorem (Properties of the Dot Product)

Let $\vec{u}, \vec{v}, \vec{w}$ be vectors in $\mathbb{R}^3$ (or $\mathbb{R}^2$) and let $k \in \mathbb{R}$.

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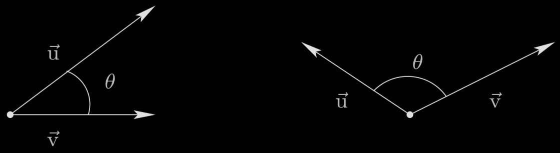
5. $(k\vec{u}) \cdot \vec{v} = k(\vec{u} \cdot \vec{v}) = \vec{u} \cdot (k\vec{v})$. (associative property)
6. $\vec{u} \cdot (\vec{v} + \vec{w}) = \vec{u} \cdot \vec{v} + \vec{u} \cdot \vec{w}$. (distributive properties)
   $\vec{u} \cdot (\vec{v} - \vec{w}) = \vec{u} \cdot \vec{v} - \vec{u} \cdot \vec{w}$.

Let $\vec{u}$ and $\vec{v}$ be two vectors in $\mathbb{R}^3$ (or $\mathbb{R}^2$). There is a unique angle θ between $\vec{u}$ and $\vec{v}$ with $0 \leq \theta \leq \pi$.



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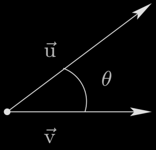

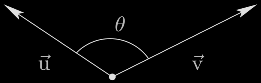

Theorem

Let $\vec{u}$ and $\vec{v}$ be nonzero vectors, and let θ denote the angle between $\vec{u}$ and $\vec{v}$. Then

$$\vec{u} \cdot \vec{v} = ||\vec{u}|| \; ||\vec{v}|| \cos\theta.$$

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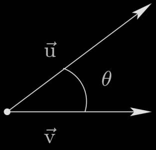

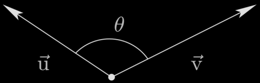

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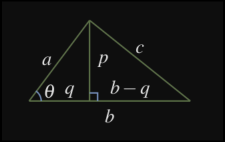
Proof.

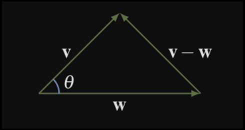
We first prove the Law of Cosines – a generalization of the Pythagorean theorem:



$$\begin{aligned} c^2 = p^2 + (b-q)^2 &= a^2 \sin^2\theta + (b - a\cos\theta)^2 \\ &= a^2\left(\sin^2\theta + \cos^2\theta\right) + b^2 - 2ab\cos\theta \\ &= a^2 + b^2 - 2ab\cos\theta. \end{aligned}$$

Proof. (continued)

In terms of vectors, we see that



$$||\vec{v} - \vec{w}||^2 = ||\vec{v}||^2 + ||\vec{w}||^2 - 2||\vec{v}||\,||\vec{w}||\cos\theta$$

Proof. (continued)

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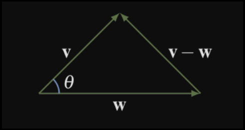

$$\begin{array}{c} ||\vec{\mathrm{v}} - \vec{\mathrm{w}}||^2 = ||\vec{\mathrm{v}}||^2 + ||\vec{\mathrm{w}}||^2 - 2||\vec{\mathrm{v}}||\,||\vec{\mathrm{w}}||\cos\theta \\ || \\ (\vec{\mathrm{v}} - \vec{\mathrm{w}}) \cdot (\vec{\mathrm{v}} - \vec{\mathrm{w}}) = ||\vec{\mathrm{v}}||^2 - 2\vec{\mathrm{v}} \cdot \vec{\mathrm{w}} + ||\vec{\mathrm{w}}||^2 \end{array}$$

Proof. (continued)

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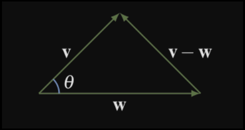

$$
\begin{array}{c}
||\vec{v} - \vec{w}||^2 = ||\vec{v}||^2 + ||\vec{w}||^2 - 2||\vec{v}||\,||\vec{w}||\cos\theta \\
|| \\
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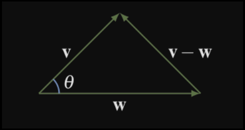

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$\blacksquare$

$$\vec{u} \cdot \vec{v} = ||\vec{u}||\ ||\vec{v}|| \cos\theta.$$

$$\vec{\mathrm{u}} \cdot \vec{\mathrm{v}} = ||\vec{\mathrm{u}}|| \; ||\vec{\mathrm{v}}|| \cos\theta.$$

- If $0 \leq \theta < \frac{\pi}{2}$, then $\cos\theta > 0$.

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Therefore, for nonzero vectors $\vec{u}$ and $\vec{v}$,

- $\vec{u} \cdot \vec{v} > 0$ if and only if $0 \leq \theta \ < \frac{\pi}{2}$.

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- $\vec{u} \cdot \vec{v} < 0$ if and only if $\frac{\pi}{2} < \theta \leq \pi$.

Definition

Vectors $\vec{u}$ and $\vec{v}$ are orthogonal if and only if $\vec{u} = \vec{0}$ or $\vec{v} = \vec{0}$ or $\theta = \frac{\pi}{2}$.

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Theorem

Vectors $\vec{u}$ and $\vec{v}$ are orthogonal if and only if $\vec{u} \cdot \vec{v} = 0$.

Problem

Find the angle between $\vec{u} = \begin{bmatrix} 1 \\ 0 \\ -1 \end{bmatrix}$ and $\vec{v} = \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$.

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Solution

$\vec{u} \cdot \vec{v} = 1$, $||\vec{u}|| = \sqrt{2}$ and $||\vec{v}|| = \sqrt{2}$.
Therefore,

$$\cos\theta = \frac{\vec{u} \cdot \vec{v}}{||\vec{u}||\ ||\vec{v}||} = \frac{1}{\sqrt{2}\sqrt{2}} = \frac{1}{2}.$$

Since $0 \leq \theta \leq \pi$, $\theta = \frac{\pi}{3}$.

Therefore, the angle between $\vec{u}$ and $\vec{v}$ is $\frac{\pi}{3}$.

Problem

Find the angle between $\vec{u} = \begin{bmatrix} 7 \\ -1 \\ 3 \end{bmatrix}$ and $\vec{v} = \begin{bmatrix} 1 \\ 4 \\ -1 \end{bmatrix}$.

Solution

$\vec{u} \cdot \vec{v} = 0$, and therefore the angle between the vectors is $\frac{\pi}{2}$.

Problem

Find all vectors $\vec{v} = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$ orthogonal to both $\vec{u} = \begin{bmatrix} -1 \\ -3 \\ 2 \end{bmatrix}$ and $\vec{w} = \begin{bmatrix} 0 \\ 1 \\ 1 \end{bmatrix}$.

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Solution

There are infinitely many such vectors. Since $\vec{v}$ is orthogonal to both $\vec{u}$ and $\vec{w}$,

$$\begin{aligned} \vec{v} \cdot \vec{u} &= -x - 3y + 2z = 0 \\ \vec{v} \cdot \vec{w} &= y + z = 0 \end{aligned}$$

Solution (continued)

This is a homogeneous system of two linear equation in three variables.

$$\left[\begin{array}{rrr|r} -1 & -3 & 2 & 0 \\ 0 & 1 & 1 & 0 \end{array}\right] \rightarrow \cdots \rightarrow \left[\begin{array}{rrr|r} 1 & 0 & -5 & 0 \\ 0 & 1 & 1 & 0 \end{array}\right]$$

Therefore, $\vec{v} = t \left[\begin{array}{r} 5 \\ -1 \\ 1 \end{array}\right]$ for all $t \in \mathbb{R}$.

Problem

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Solution

$$\overrightarrow{AB} = \begin{bmatrix} 2 \\ 11 \\ -5 \end{bmatrix}, \quad \overrightarrow{AC} = \begin{bmatrix} 3 \\ 17 \\ -15 \end{bmatrix}, \quad \overrightarrow{BC} = \begin{bmatrix} 1 \\ 6 \\ -10 \end{bmatrix}$$

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Because none of the angles is $\frac{\pi}{2}$, the triangle is not a right angle triangle.

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A rhombus is a parallelogram with sides of equal length. Prove that the diagonals of a rhombus are perpendicular.

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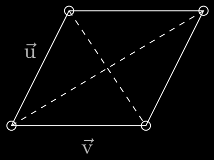
Solution



Define the parallelogram (rhombus) by vectors $\vec{u}$ and $\vec{v}$.

Then the diagonals are $\vec{u} + \vec{v}$ and $\vec{u} - \vec{v}$.

Show that $\vec{u} + \vec{v}$ and $\vec{u} - \vec{v}$ are perpendicular.

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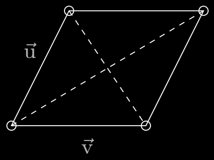

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Show that $\vec{u}+\vec{v}$ and $\vec{u}-\vec{v}$ are perpendicular.

$$\begin{aligned}
(\vec{u}+\vec{v})\cdot(\vec{u}-\vec{v}) &= \vec{u}\cdot\vec{u}-\vec{u}\cdot\vec{v}+\vec{v}\cdot\vec{u}-\vec{v}\cdot\vec{v} \\
&= ||\vec{u}||^2-\vec{u}\cdot\vec{v}+\vec{u}\cdot\vec{v}-||\vec{v}||^2 \\
&= ||\vec{u}||^2-||\vec{v}||^2 \\
&= 0, \qquad \text{since } ||\vec{u}|| = ||\vec{v}||.
\end{aligned}$$

Therefore, the diagonals are perpendicular.

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Given two nonzero vectors $\vec{u}$ and $\vec{d}$, one can always express $\vec{u}$ as a sum $\vec{u} = \vec{u}_1 + \vec{u}_2$, where $\vec{u}_1$ is parallel to $\vec{d}$ and $\vec{u}_2$ is orthogonal to $\vec{d}$.

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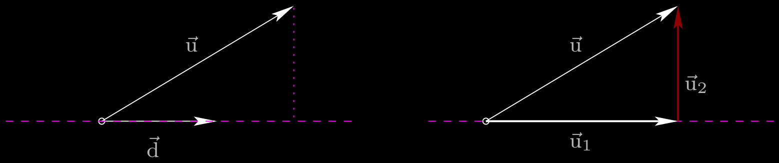

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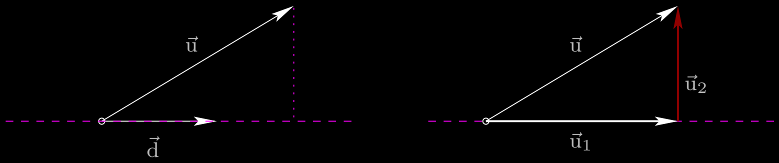

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Projections

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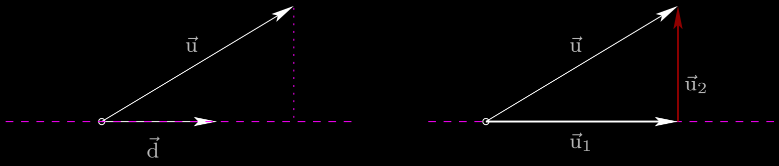
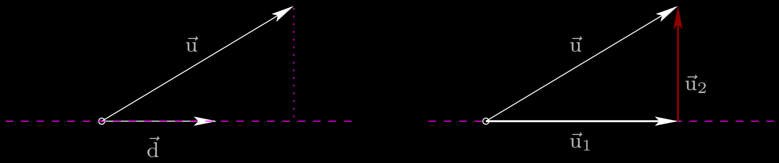
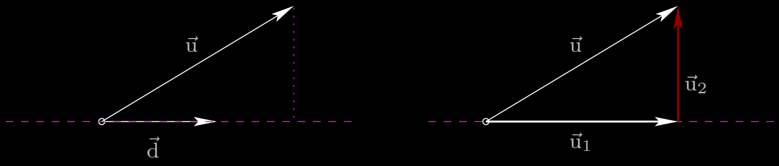


$\vec{u}_1$ is the projection of $\vec{u}$ onto $\vec{d}$, written $\vec{u}_1 = \mathrm{proj}_{\vec{d}}\vec{u}$.

How to find $\vec{u}_1 = \mathrm{proj}_{\vec{d}}\vec{u}$?

$$\begin{aligned}
\vec{u}_2 \cdot \vec{u}_1 &= 0 && (\vec{u}_1 \perp \vec{u}_2) \\
\vec{u}_2 \cdot (t\vec{d}) &= 0 && (\vec{u}_1 = t\vec{d}) \\
t(\vec{u}_2 \cdot \vec{d}) &= 0 && \\
\vec{u}_2 \cdot \vec{d} &= 0 && (t \neq 0 \text{ b.c. } \vec{u} \neq \vec{0}) \\
(\vec{u} - \vec{u_1}) \cdot \vec{d} &= 0 && (\vec{u}_1 + \vec{u}_2 = \vec{u}) \\
\vec{u} \cdot \vec{d} - \vec{u_1} \cdot \vec{d} &= 0 && \\
\vec{u} \cdot \vec{d} - (t\vec{d}) \cdot \vec{d} &= 0 && (\vec{u}_1 = t\vec{d}) \\
\vec{u} \cdot \vec{d} - t(\vec{d} \cdot \vec{d}) &= 0 && \\
\vec{u} \cdot \vec{d} - t||\vec{d}||^2 &= 0 && \\
\vec{u} \cdot \vec{d} &= t||\vec{d}||^2 && \\
t &= \frac{\vec{u} \cdot \vec{d}}{||\vec{d}||^2} && (\vec{d} \neq \vec{0}) \\
\vec{u}_1 &= \frac{\vec{u} \cdot \vec{d}}{||\vec{d}||^2}\vec{d} && (\vec{u}_1 = t\vec{d})
\end{aligned}$$


$\vec{u}$
$\vec{d}$
$\vec{u}$
$\vec{u}_2$
$\vec{u}_1$

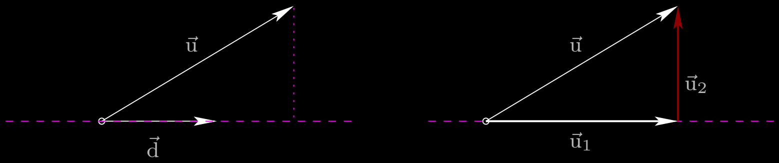


Theorem

Let $\vec{u}$ and $\vec{d}$ be vectors with $\vec{d} \neq \vec{0}$.

1. The projection of $\vec{u}$ onto $\vec{d}$ is

$$\vec{u}_1 = \mathrm{proj}_{\vec{d}}\vec{u} = \frac{\vec{u} \cdot \vec{d}}{||\vec{d}||^2}\vec{d}.$$



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2.

$$\vec{u}_2 = \vec{u} - \frac{\vec{u} \cdot \vec{d}}{||\vec{d}||^2}\vec{d}$$

is orthogonal to $\vec{d}$.

$$\vec{u}_1 = \text{proj}_{\vec{d}}\vec{u} = \left(\vec{u} \cdot \frac{\vec{d}}{||\vec{d}||}\right) \frac{\vec{d}}{||\vec{d}||} = \frac{\vec{u} \cdot \vec{d}}{||\vec{d}||^2}\vec{d}$$

unit vector

$$\vec{u}_1 = \mathrm{proj}_{\vec{d}}\vec{u} = \left(\vec{u} \cdot \frac{\vec{d}}{||\vec{d}||}\right)\frac{\vec{d}}{||\vec{d}||} = \frac{\vec{u}\cdot\vec{d}}{||\vec{d}||^2}\vec{d}$$

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$$\vec{u}_1 = \text{proj}_{\vec{d}}\vec{u} = \underbrace{\left(\vec{u} \cdot \frac{\vec{d}}{||\vec{d}||}\right)}_{\text{length}} \frac{\vec{d}}{||\vec{d}||} = \frac{\vec{u}\cdot\vec{d}}{||\vec{d}||^2}\vec{d}$$

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direction

Problem

Let $\vec{u} = \begin{bmatrix} 2 \\ -1 \\ 0 \end{bmatrix}$ and $\vec{v} = \begin{bmatrix} 3 \\ 1 \\ -1 \end{bmatrix}$. Find vectors $\vec{u}_1$ and $\vec{u}_2$ so that $\vec{u} = \vec{u}_1 + \vec{u}_2$, with $\vec{u}_1$ parallel to $\vec{v}$ and $\vec{u}_2$ orthogonal to $\vec{v}$.

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Solution

$$\vec{u}_1 = \mathrm{proj}_{\vec{v}}\vec{u} = \frac{\vec{u}\cdot\vec{v}}{||\vec{v}||^2}\vec{v} = \frac{5}{11}\begin{bmatrix} 3 \\ 1 \\ -1 \end{bmatrix} = \begin{bmatrix} 15/11 \\ 5/11 \\ -5/11 \end{bmatrix}.$$

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Let $\vec{u} = \begin{bmatrix} 2 \\ -1 \\ 0 \end{bmatrix}$ and $\vec{v} = \begin{bmatrix} 3 \\ 1 \\ -1 \end{bmatrix}$. Find vectors $\vec{u}_1$ and $\vec{u}_2$ so that $\vec{u} = \vec{u}_1 + \vec{u}_2$, with $\vec{u}_1$ parallel to $\vec{v}$ and $\vec{u}_2$ orthogonal to $\vec{v}$.

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$$\vec{u}_2 = \vec{u} - \vec{u}_1 = \begin{bmatrix} 2 \\ -1 \\ 0 \end{bmatrix} - \frac{5}{11}\begin{bmatrix} 3 \\ 1 \\ -1 \end{bmatrix} = \frac{1}{11}\begin{bmatrix} 7 \\ -16 \\ 5 \end{bmatrix} = \begin{bmatrix} 7/11 \\ -16/11 \\ 5/11 \end{bmatrix}.$$

Problem

Let $P(3, 2, -1)$ be a point in $\mathbb{R}^3$ and L a line with equation

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix} + t \begin{bmatrix} 3 \\ -1 \\ -2 \end{bmatrix}.$$

Find the shortest distance from P to L, and find the point Q on L that is closest to P.

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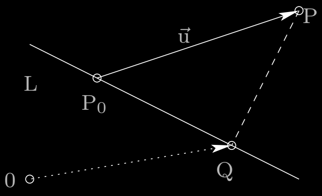
Find the shortest distance from P to L, and find the point Q on L that is closest to P.

Solution



Let $P_0 = P_0(2,1,3)$ be a point on L, and let $\vec{d} = \begin{bmatrix} 3 & -1 & -2 \end{bmatrix}^T$. Then $\overrightarrow{P_0Q} = \text{proj}_{\vec{d}}\overrightarrow{P_0P}$, $\overrightarrow{0Q} = \overrightarrow{0P_0} + \overrightarrow{P_0Q}$, and the shortest distance from P to L is the length of $\overrightarrow{QP}$, where $\overrightarrow{QP} = \overrightarrow{P_0P} - \overrightarrow{P_0Q}$.

Solution (continued)

$\overrightarrow{P_0P} = \begin{bmatrix} 1 & 1 & -4 \end{bmatrix}^T$, $\vec{d} = \begin{bmatrix} 3 & -1 & -2 \end{bmatrix}^T$.

$$\overrightarrow{P_0Q} = \mathrm{proj}_{\vec{d}}\overrightarrow{P_0P} = \frac{\overrightarrow{P_0P} \cdot \vec{d}}{||\vec{d}||^2}\vec{d} = \frac{10}{14}\begin{bmatrix} 3 \\ -1 \\ -2 \end{bmatrix} = \frac{1}{7}\begin{bmatrix} 15 \\ -5 \\ -10 \end{bmatrix}.$$

Solution (continued)

$\overrightarrow{P_0P} = \begin{bmatrix} 1 & 1 & -4 \end{bmatrix}^T$, $\vec{d} = \begin{bmatrix} 3 & -1 & -2 \end{bmatrix}^T$.

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Therefore,

$$\overrightarrow{0Q} = \overrightarrow{0P_0} + \overrightarrow{P_0Q} = \begin{bmatrix} 2 \\ 1 \\ 3 \end{bmatrix} + \frac{1}{7}\begin{bmatrix} 15 \\ -5 \\ -10 \end{bmatrix} = \frac{1}{7}\begin{bmatrix} 29 \\ 2 \\ 11 \end{bmatrix},$$

so $Q = Q\left(\frac{29}{7}, \frac{2}{7}, \frac{11}{7}\right)$.

Solution (continued)

Finally, the shortest distance from $P(3, 2, -1)$ to L is the length of $\overrightarrow{QP}$, where

$$\overrightarrow{QP} = \overrightarrow{P_0P} - \overrightarrow{P_0Q} = \begin{bmatrix} 1 \\ 1 \\ -4 \end{bmatrix} - \frac{1}{7}\begin{bmatrix} 15 \\ -5 \\ -10 \end{bmatrix} = \frac{2}{7}\begin{bmatrix} -4 \\ 6 \\ -9 \end{bmatrix}.$$

Solution (continued)

Finally, the shortest distance from $P(3, 2, -1)$ to L is the length of $\overrightarrow{QP}$, where

$$\overrightarrow{QP} = \overrightarrow{P_0P} - \overrightarrow{P_0Q} = \begin{bmatrix} 1 \\ 1 \\ -4 \end{bmatrix} - \frac{1}{7}\begin{bmatrix} 15 \\ -5 \\ -10 \end{bmatrix} = \frac{2}{7}\begin{bmatrix} -4 \\ 6 \\ -9 \end{bmatrix}.$$

Therefore the shortest distance from P to L is

$$||\overrightarrow{QP}|| = \frac{2}{7}\sqrt{(-4)^2 + 6^2 + (-9)^2} = \frac{2}{7}\sqrt{133}.$$

Copyright

The Dot Product and Angles

Projections

Planes

Cross Product

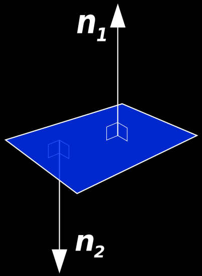
Shortest Distances

Planes

Planes

Definition

A nonzero vector $\vec{n}$ is a normal vector to a plane if and only if $\vec{n} \cdot \vec{v} = 0$ for every vector $\vec{v}$ in the plane.



Given a point P_0 and a nonzero vector $\vec{n}$, there is a unique plane containing P_0 and orthogonal to $\vec{n}$.

Consider a plane containing a point P_0 and orthogonal to vector $\vec{n}$, and let P be an arbitrary point on this plane.

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Then

$$\vec{n} \cdot \overrightarrow{P_0P} = 0,$$

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Then

$$\vec{n} \cdot \overrightarrow{\mathrm{P}_0\mathrm{P}} = 0,$$

or, equivalently,

$$\vec{n} \cdot (\overrightarrow{0\mathrm{P}} - \overrightarrow{0\mathrm{P}_0}) = 0,$$

and is a vector equation of the plane.

$$\vec{n} \cdot (\overrightarrow{0P} - \overrightarrow{0P_0}) = 0 \quad \Longleftrightarrow \quad \vec{n} \cdot \overrightarrow{0P} = \vec{n} \cdot \overrightarrow{0P_0}$$

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by setting $P_0 = P_0(x_0, y_0, z_0)$, $P = P(x, y, z)$, $\vec{n} = \begin{bmatrix} a & b & c \end{bmatrix}^T$

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$$\Longleftrightarrow \quad \begin{bmatrix} a \\ b \\ c \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} a \\ b \\ c \end{bmatrix} \cdot \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}$$

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$$\Longleftrightarrow \quad ax + by + cz = ax_0 + by_0 + cz_0,$$

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setting $d = ax_0 + by_0 + cz_0$ – a scalar

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$$\Longleftrightarrow \quad \boxed{ax + by + cz = d}, \text{ where } a, b, c, d \in \mathbb{R}.$$

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$$\Longleftrightarrow \quad \boxed{ax + by + cz = d}, \text{ where } a, b, c, d \in \mathbb{R}.$$

This is the scalar equation of the plane.

Problem

Find an equation of the plane containing $P_0(1, -1, 0)$ and orthogonal to $\vec{n} = \left[\begin{array}{ccc} -3 & 5 & 2 \end{array} \right]^T$.

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Solution

A vector equation of this plane is

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Solution

A vector equation of this plane is

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A scalar equation of this plane is

$$-3x + 5y + 2z = -3(1) + 5(-1) + 2(0) = -8,$$

i.e., the plane has scalar equation

$$-3x + 5y + 2z = -8.$$

Problem

Find the shortest distance from the point $P(2, 3, 0)$ to the plane with equation $5x + y + z = -1$, and find the point Q on the plane that is closest to P.

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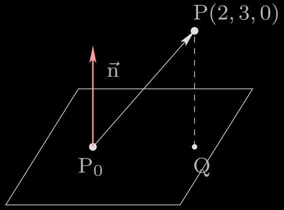

Pick an arbitrary point P_0 on the plane.

Then $\overrightarrow{QP} = \text{proj}_{\vec{n}} \overrightarrow{P_0P}$,

$||\overrightarrow{QP}||$ is the shortest distance,

and $\overrightarrow{0Q} = \overrightarrow{0P} - \overrightarrow{QP}$.

Problem

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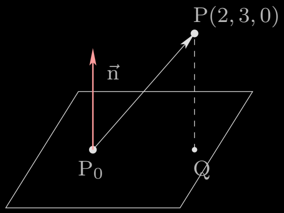

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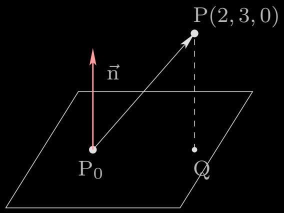
$\vec{n} = \begin{bmatrix} 5 & 1 & 1 \end{bmatrix}^T$.

Problem

Find the shortest distance from the point $P(2,3,0)$ to the plane with equation $5x+y+z=-1$, and find the point Q on the plane that is closest to P.

Solution



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$\vec{n} = \left[\begin{array}{ccc} 5 & 1 & 1 \end{array}\right]^T$. Choose $P_0 = P_0(0,0,-1)$.

Problem

Find the shortest distance from the point $P(2,3,0)$ to the plane with equation $5x+y+z=-1$, and find the point Q on the plane that is closest to P.

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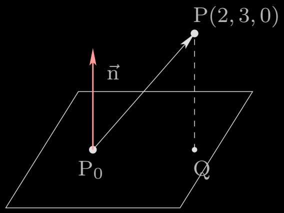

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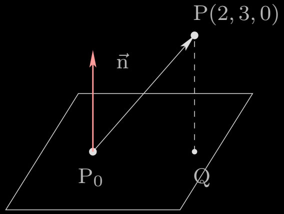
$\vec{n} = \left[\begin{array}{ccc} 5 & 1 & 1 \end{array}\right]^T$. Choose $P_0 = P_0(0,0,-1)$. Then

$$\overrightarrow{P_0P} = \left[\begin{array}{ccc} 2 & 3 & 1 \end{array}\right]^T$$

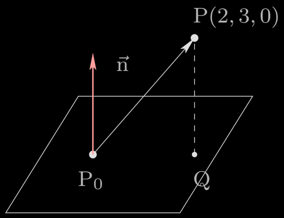
Solution (continued)



$$\overrightarrow{P_0P} = \left[\begin{array}{ccc} 2 & 3 & 1 \end{array}\right]^T.$$

$$\vec{n} = \left[\begin{array}{ccc} 5 & 1 & 1 \end{array}\right]^T.$$

Solution (continued)

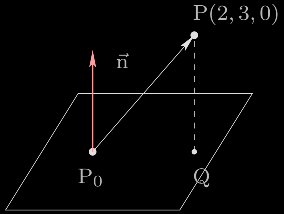


$$\overrightarrow{P_0P} = \begin{bmatrix} 2 & 3 & 1 \end{bmatrix}^T.$$

$$\vec{n} = \begin{bmatrix} 5 & 1 & 1 \end{bmatrix}^T.$$

$$\overrightarrow{QP} = \mathrm{proj}_{\vec{n}}\overrightarrow{P_0P} = \frac{\overrightarrow{P_0P} \cdot \vec{n}}{||\vec{n}||^2}\vec{n} = \frac{14}{27}\begin{bmatrix} 5 & 1 & 1 \end{bmatrix}^T.$$

Solution (continued)



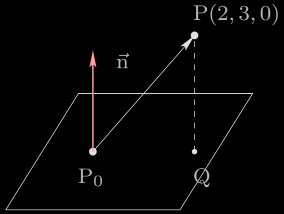
$$\overrightarrow{P_0P} = \left[\begin{array}{ccc} 2 & 3 & 1 \end{array}\right]^T.$$

$$\vec{n} = \left[\begin{array}{ccc} 5 & 1 & 1 \end{array}\right]^T.$$

$$\overrightarrow{QP} = \mathrm{proj}_{\vec{n}}\overrightarrow{P_0P} = \frac{\overrightarrow{P_0P}\cdot\vec{n}}{||\vec{n}||^2}\vec{n} = \frac{14}{27}\left[\begin{array}{ccc} 5 & 1 & 1 \end{array}\right]^T.$$

Since $||\overrightarrow{QP}|| = \frac{14}{27}\sqrt{27} = \frac{14\sqrt{3}}{9}$, the shortest distance from P to the plane is $\frac{14\sqrt{3}}{9}$.

Solution (continued)



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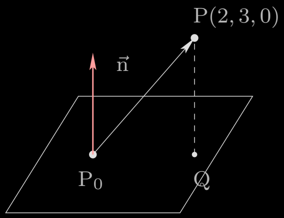
Since $||\overrightarrow{QP}|| = \frac{14}{27}\sqrt{27} = \frac{14\sqrt{3}}{9}$, the shortest distance from P to the plane is $\frac{14\sqrt{3}}{9}$.

To find Q, we have

$$\begin{aligned} \overrightarrow{0Q} = \overrightarrow{0P} - \overrightarrow{QP} &= \begin{bmatrix} 2 & 3 & 0 \end{bmatrix}^T - \frac{14}{27}\begin{bmatrix} 5 & 1 & 1 \end{bmatrix}^T \\ &= \frac{1}{27}\begin{bmatrix} -16 & 67 & -14 \end{bmatrix}^T. \end{aligned}$$

Solution (continued)



$$\overrightarrow{P_0P} = \begin{bmatrix} 2 & 3 & 1 \end{bmatrix}^T.$$

$$\vec{n} = \begin{bmatrix} 5 & 1 & 1 \end{bmatrix}^T.$$

$$\overrightarrow{QP} = \mathrm{proj}_{\vec{n}}\overrightarrow{P_0P} = \frac{\overrightarrow{P_0P} \cdot \vec{n}}{||\vec{n}||^2}\vec{n} = \frac{14}{27}\begin{bmatrix} 5 & 1 & 1 \end{bmatrix}^T.$$

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Therefore $Q = Q\left(-\frac{16}{27}, \frac{67}{27}, -\frac{14}{27}\right)$.

Remark

Here is a general answer: the distance from $P(x_0, y_0, z_0)$ to the plane $ax + by + cz = d$ is

$$\text{distance} = \frac{|ax_0 + by_0 + cz_0 - d|}{\sqrt{a^2 + b^2 + c^2}}$$

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The Dot Product and Angles

Projections

Planes

Cross Product

Shortest Distances

The Cross Product

The Cross Product

Definition

Let $\vec{u} = \left[\begin{array}{ccc} x_1 & y_1 & z_1 \end{array}\right]^T$ and $\vec{v} = \left[\begin{array}{ccc} x_2 & y_2 & z_2 \end{array}\right]^T$. Then

$$\vec{u} \times \vec{v} = \left[\begin{array}{c} y_1 z_2 - z_1 y_2 \\ -(x_1 z_2 - z_1 x_2) \\ x_1 y_2 - y_1 x_2 \end{array}\right].$$

The Cross Product

Definition

Let $\vec{u} = \begin{bmatrix} x_1 & y_1 & z_1 \end{bmatrix}^T$ and $\vec{v} = \begin{bmatrix} x_2 & y_2 & z_2 \end{bmatrix}^T$. Then

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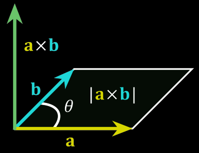

Remark

$\vec{u} \times \vec{v}$ is a vector:

- Direction: orthogonal to both $\vec{u}$ and $\vec{v}$.
- Size: the area of the corresponding parallelogram.

Remark

A mnemonic device:

$$\vec{u} \times \vec{v} = \begin{vmatrix} \vec{i} & x_1 & x_2 \\ \vec{j} & y_1 & y_2 \\ \vec{k} & z_1 & z_2 \end{vmatrix}, \text{ where } \vec{i} = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \vec{j} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \vec{k} = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}.$$

Or equivalently,

$$\vec{u} \times \vec{v} = \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \end{vmatrix}$$

Theorem

Let $\vec{v}, \vec{w} \in \mathbb{R}^3$.

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Theorem

Let $\vec{v}, \vec{w} \in \mathbb{R}^3$.

1. $\vec{v} \times \vec{w}$ is orthogonal to both $\vec{v}$ and $\vec{w}$.
2. If $\vec{v}$ and $\vec{w}$ are both nonzero, then $\vec{u} \times \vec{w} = \vec{0}$ if and only if $\vec{v}$ and $\vec{w}$ are parallel.

Problem

Find all vectors orthogonal to both $\vec{u} = \begin{bmatrix} -1 & -3 & 2 \end{bmatrix}^T$ and $\vec{v} = \begin{bmatrix} 0 & 1 & 1 \end{bmatrix}^T$. (We previously solved this using the dot product.)

Problem

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Solution

$$\vec{u} \times \vec{v} = \begin{vmatrix} \vec{i} & -1 & 0 \\ \vec{j} & -3 & 1 \\ \vec{k} & 2 & 1 \end{vmatrix} = -5\vec{i} + \vec{j} - \vec{k} = \begin{bmatrix} -5 \\ 1 \\ -1 \end{bmatrix}.$$

Any scalar multiple of $\vec{u} \times \vec{v}$ is also orthogonal to both $\vec{u}$ and $\vec{v}$, so

$$t \begin{bmatrix} -5 \\ 1 \\ -1 \end{bmatrix}, \quad \forall t \in \mathbb{R},$$

gives all vectors orthogonal to both $\vec{u}$ and $\vec{v}$.

(Compare this with our earlier answer.)

Problem

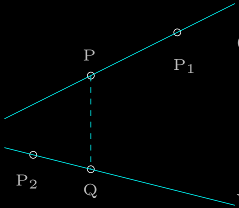
Given two lines

$$L_1 : \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 3 \\ 1 \\ -1 \end{bmatrix} + s \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix} \quad \text{and} \quad L_2 : \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 1 \\ 2 \\ 0 \end{bmatrix} + t \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix},$$

A. Find the shortest distance between L_1 and L_2.

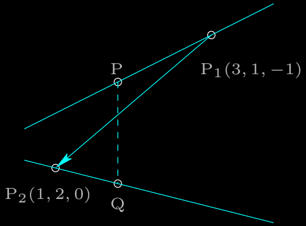
B. Find the points P on L_1 and Q on L_2 that are closest together.

Solution



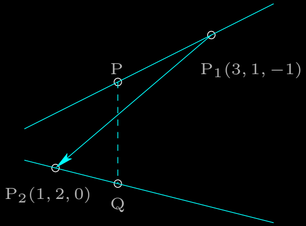
Choose $P_1(3,1,-1)$ on L_1 and $P_2(1,2,0)$ on L_2.

Let $\vec{d}_1 = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}$ and $\vec{d}_2 = \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix}$ denote direction vectors for L_1 and L_2, respectively.



$$\vec{d}_1 = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}, \vec{d}_2 = \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix}$$

The shortest distance between L_1 and L_2 is the length of the projection of $\overrightarrow{P_1P_2}$ onto $\vec{n} = \vec{d}_1 \times \vec{d}_2$.



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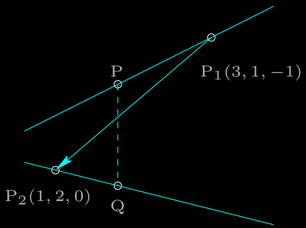
$$\overrightarrow{P_1P_2} = \begin{bmatrix} -2 \\ 1 \\ 1 \end{bmatrix} \quad \text{and} \quad \vec{n} = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix} \times \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix} = \begin{bmatrix} 2 \\ -3 \\ -1 \end{bmatrix}$$



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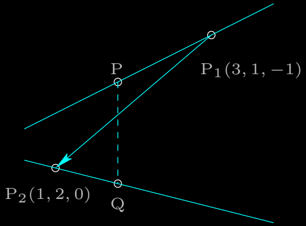
$$\text{proj}_{\vec{n}}\overrightarrow{P_1P_2} = \frac{\overrightarrow{P_1P_2} \cdot \vec{n}}{||\vec{n}||^2}\vec{n}, \quad \text{and} \quad ||\text{proj}_{\vec{n}}\overrightarrow{P_1P_2}|| = \frac{|\overrightarrow{P_1P_2} \cdot \vec{n}|}{||\vec{n}||}.$$



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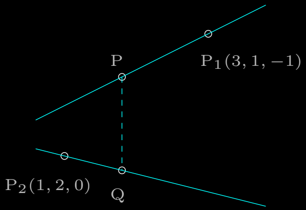
The shortest distance between L_1 and L_2 is the length of the projection of $\overrightarrow{P_1P_2}$ onto $\vec{n} = \vec{d}_1 \times \vec{d}_2$.

$$\overrightarrow{P_1P_2} = \begin{bmatrix} -2 \\ 1 \\ 1 \end{bmatrix} \quad \text{and} \quad \vec{n} = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix} \times \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix} = \begin{bmatrix} 2 \\ -3 \\ -1 \end{bmatrix}$$

$$\text{proj}_{\vec{n}}\overrightarrow{P_1P_2} = \frac{\overrightarrow{P_1P_2} \cdot \vec{n}}{||\vec{n}||^2}\vec{n}, \quad \text{and} \quad ||\text{proj}_{\vec{n}}\overrightarrow{P_1P_2}|| = \frac{|\overrightarrow{P_1P_2} \cdot \vec{n}|}{||\vec{n}||}.$$

Therefore, the shortest distance between L_1 and L_2 is $\frac{|-8|}{\sqrt{14}} = \frac{4}{7}\sqrt{14}$.

Solution B.

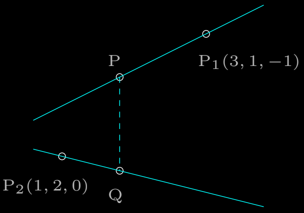


$$\vec{d}_1 = \begin{bmatrix} 1 \\ 1 \\ -1 \end{bmatrix}, \vec{d}_2 = \begin{bmatrix} 1 \\ 0 \\ 2 \end{bmatrix};$$

$$\overrightarrow{0P} = \begin{bmatrix} 3+s \\ 1+s \\ -1-s \end{bmatrix} \text{ for some } s \in \mathbb{R};$$

$$\overrightarrow{0Q} = \begin{bmatrix} 1+t \\ 2 \\ 2t \end{bmatrix} \text{ for some } t \in \mathbb{R}.$$

Solution B.



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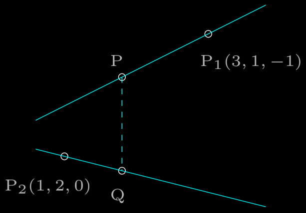
Now $\overrightarrow{PQ} = \begin{bmatrix} -2-s+t & 1-s & 1+s+2t \end{bmatrix}^T$ is orthogonal to both L_1 and L_2, so

$$\overrightarrow{PQ} \cdot \vec{d}_1 = 0 \quad \text{and} \quad \overrightarrow{PQ} \cdot \vec{d}_2 = 0,$$

Solution B.



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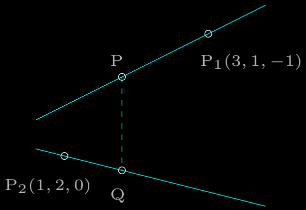
i.e.,

$$\begin{aligned} -2-3s-t &= 0 \\ s+5t &= 0. \end{aligned}$$

Solution B.



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This system has unique solution $s = -\frac{5}{7}$ and $t = \frac{1}{7}$.

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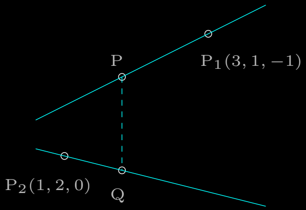

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$$\overrightarrow{PQ} \cdot \vec{d}_1 = 0 \quad \text{and} \quad \overrightarrow{PQ} \cdot \vec{d}_2 = 0,$$

i.e.,

$$\begin{aligned} -2-3s-t &= 0 \\ s+5t &= 0. \end{aligned}$$

This system has unique solution $s = -\frac{5}{7}$ and $t = \frac{1}{7}$. Therefore,

$$P = P\left(\frac{16}{7}, \frac{2}{7}, -\frac{2}{7}\right) \quad \text{and} \quad Q = Q\left(\frac{8}{7}, 2, \frac{2}{7}\right).$$

The shortest distance between L_1 and L_2 is $||\overrightarrow{\mathrm{PQ}}||$. Since

$$\mathrm{P} = \mathrm{P}\left(\frac{16}{7}, \frac{2}{7}, -\frac{2}{7}\right) \quad \text{and} \quad \mathrm{Q} = \mathrm{Q}\left(\frac{8}{7}, 2, \frac{2}{7}\right),$$

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$$\overrightarrow{\mathrm{PQ}} = \frac{1}{7}\begin{bmatrix} 8 \\ 14 \\ 2 \end{bmatrix} - \frac{1}{7}\begin{bmatrix} 16 \\ 2 \\ -2 \end{bmatrix} = \frac{1}{7}\begin{bmatrix} -8 \\ 12 \\ 4 \end{bmatrix},$$

The shortest distance between L_1 and L_2 is $||\overrightarrow{\mathrm{PQ}}||$. Since

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and

$$||\overrightarrow{\mathrm{PQ}}|| = \frac{1}{7}\sqrt{224} = \frac{4}{7}\sqrt{14}.$$

The shortest distance between L_1 and L_2 is $||\overrightarrow{\mathrm{PQ}}||$. Since

$$\mathrm{P} = \mathrm{P}\left(\frac{16}{7}, \frac{2}{7}, -\frac{2}{7}\right) \quad \text{and} \quad \mathrm{Q} = \mathrm{Q}\left(\frac{8}{7}, 2, \frac{2}{7}\right),$$

$$\overrightarrow{\mathrm{PQ}} = \frac{1}{7}\left[\begin{array}{r} 8 \\ 14 \\ 2 \end{array}\right] - \frac{1}{7}\left[\begin{array}{r} 16 \\ 2 \\ -2 \end{array}\right] = \frac{1}{7}\left[\begin{array}{r} -8 \\ 12 \\ 4 \end{array}\right],$$

and

$$||\overrightarrow{\mathrm{PQ}}|| = \frac{1}{7}\sqrt{224} = \frac{4}{7}\sqrt{14}.$$

Therefore the shortest distance between L_1 and L_2 is $\frac{4}{7}\sqrt{14}$.

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Shortest Distances

Shortest Distances

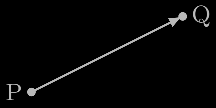
Problem (Challenge Problem)

Write yourself a plan to find the shortest distance in $\mathbb{R}^3$ between either a point, line or plane, to either a point, line or plane.

Point-point distance

Point-point distance

If P and Q are two points, then $\mathrm{d}\,(\mathrm{P},\mathrm{Q}) = |\overrightarrow{\mathrm{PQ}}|$.

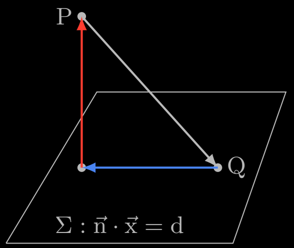


Point-plane distance

Point-plane distance

If P is a point and $\Sigma : \vec{\mathrm{n}} \cdot \vec{\mathrm{x}} = \mathrm{d}$ is a plane containing a point Q, then

$$\mathrm{d}\left(\mathrm{P}, \Sigma\right) = \frac{\left|\overrightarrow{\mathrm{PQ}} \cdot \vec{\mathrm{n}}\right|}{\left|\vec{\mathrm{n}}\right|}$$

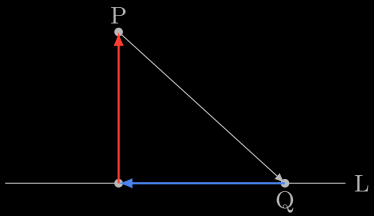


Point-line distance

Point-line distance

If P is a point and L is a line $\vec{r}(t) = Q + t\vec{u}$, then

$$d\left(P, L\right) = \frac{\left|\overrightarrow{PQ} \times \vec{u}\right|}{|\vec{u}|}$$

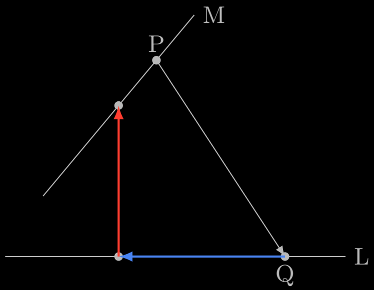


Line-line distance

Line-line distance

If L is a line $\vec{r}(t) = Q + t\vec{u}$ and M is another line $\vec{s} = P + t\vec{v}$, then

$$d\,(L, M) = \frac{\left|\overrightarrow{PQ} \cdot (\vec{u} \times \vec{v})\right|}{|\vec{u} \times \vec{v}|}$$



Plane-plane distance

Plane-plane distance

If $\Sigma : \vec{n} \cdot \vec{x} = d$ and $\Theta : \vec{n} \cdot \vec{x} = e$ are two parallel planes, then

$$d(\Sigma, \Theta) = \frac{|e - d|}{|\vec{n}|}$$