

Lecture 5

- 14. Lines
- 15. Planes
- 16. Projections

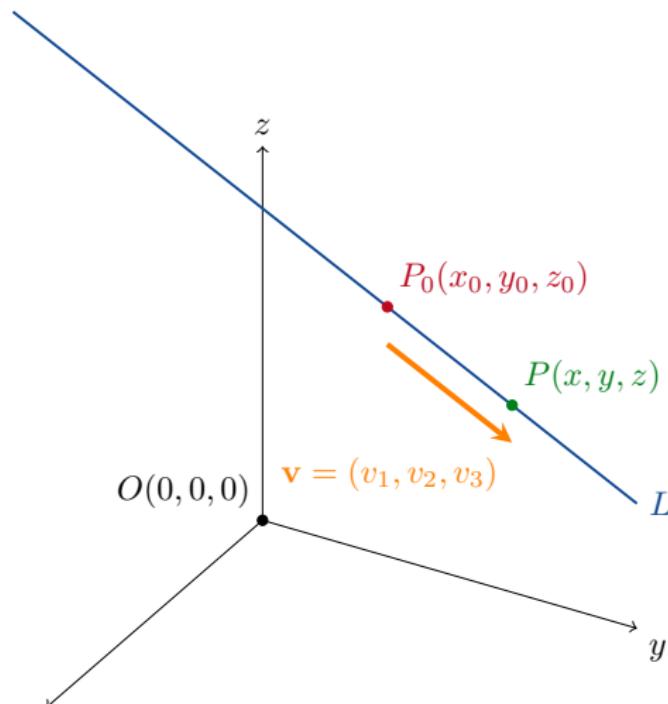


Lines

14. Lines

To describe a line in \mathbb{R}^3 , we need

- a point $P_0(x_0, y_0, z_0)$ which the line passes through; and
- a vector \mathbf{v} which gives the direction of the line.



14. Lines



Let $\mathbf{r}_0 = \overrightarrow{OP_0}$ and $\mathbf{r} = \overrightarrow{OP}$.

Definition

The *line L passing through $P_0(x_0, y_0, z_0)$ parallel to $\mathbf{v} = (v_1, v_2, v_3)$* has the vector equation

$$\mathbf{r} = \mathbf{r}_0 + t\mathbf{v}, \quad -\infty < t < \infty.$$

14. Lines



This equation is equivalent to

$$(x, y, z) = (x_0, y_0, z_0) + t(v_1, v_2, v_3)$$

or to the set of three equations

$$x = x_0 + tv_1, \quad y = y_0 + tv_2, \quad z = z_0 + tv_3.$$

14. Lines



Definition

The *parametric equations* for the line L passing through $P_0(x_0, y_0, z_0)$ parallel to $\mathbf{v} = (v_1, v_2, v_3)$ are

$$x = x_0 + tv_1, \quad y = y_0 + tv_2, \quad z = z_0 + tv_3.$$

14. Lines



Example

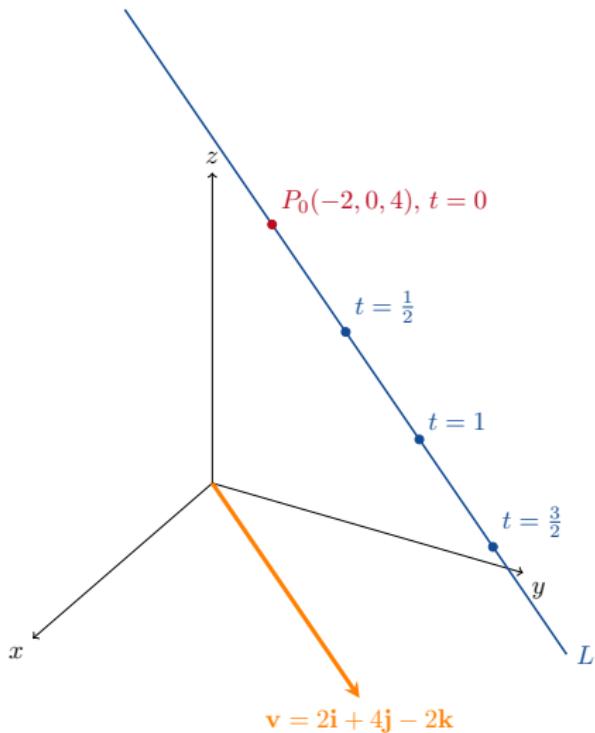
Find parametric equations for the line passing through $P_0(-2, 0, 4)$ parallel to $\mathbf{v} = 2\mathbf{i} + 4\mathbf{j} - 2\mathbf{k}$.

solution: We can write

$$x = -2 + 2t, \quad y = 4t, \quad z = 4 - 2t.$$

14. Lines

$$\begin{aligned}x &= -2 + 2t \\y &= 4t \\z &= 4 - 2t\end{aligned}$$



14. Lines

Example

Find parametric equations for the line passing through $P(-3, 2, -3)$ and $Q(1, -1, 4)$.

solution: Choose $P_0 = P$ and

$\mathbf{v} = \overrightarrow{PQ} = (4, -3, 7) = 4\mathbf{i} - 3\mathbf{j} + 7\mathbf{k}$. Then we can write

$$x = -3 + 4t, \quad y = 2 - 3t, \quad z = -3 + 7t.$$

14. Lines



Definition

The vector equation

$$\mathbf{r} = \mathbf{r}_0 + t\mathbf{v}, \quad a \leq t \leq b$$

denotes a *line segment*.

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Example

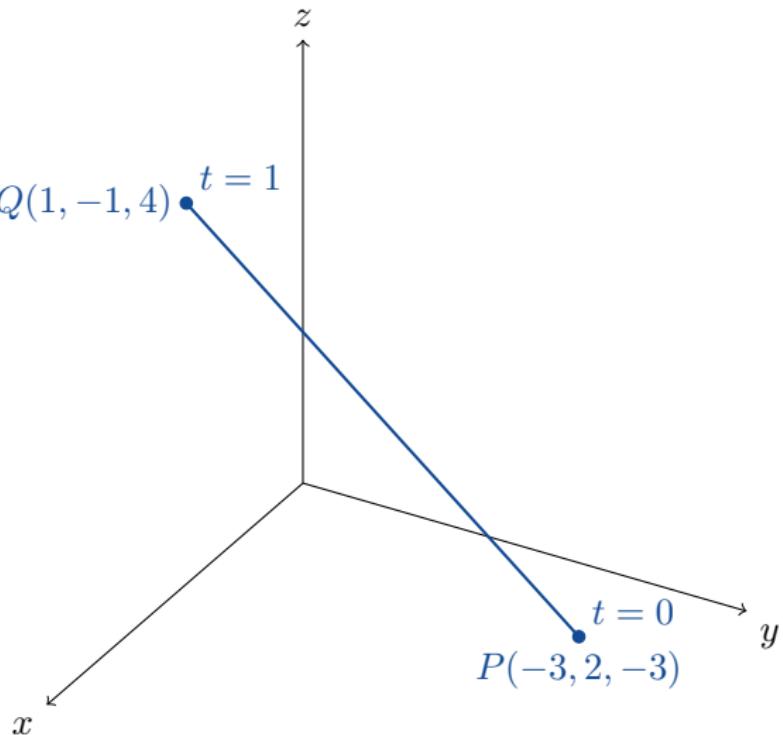
Parametrise the line segment joining $P(-3, 2, -3)$ and $Q(1, -1, 4)$.

solution: We know that $x = -3 + 4t$, $y = 2 - 3t$ and $z = -3 + 7t$. The line passes through P when $t = 0$ and passes through Q when $t = 1$. Therefore

$$x = -3 + 4t, \quad y = 2 - 3t, \quad z = -3 + 7t, \quad 0 \leq t \leq 1$$

denotes the line segment from P to Q .

14. Lines



EXAMPLE 4 A helicopter is to fly directly from a helipad at the origin in the direction of the point $(1, 1, 1)$ at a speed of 60 m/sec . What is the position of the helicopter after 10 sec ?

Solution We place the origin at the starting position (helipad) of the helicopter. Then the unit vector

$$\mathbf{u} = \frac{1}{\sqrt{3}}\mathbf{i} + \frac{1}{\sqrt{3}}\mathbf{j} + \frac{1}{\sqrt{3}}\mathbf{k}$$

gives the flight direction of the helicopter. From Equation (4), the position of the helicopter at any time t is

$$\begin{aligned}\mathbf{r}(t) &= \mathbf{r}_0 + t(\text{speed})\mathbf{u} \\ &= \mathbf{0} + t(60)\left(\frac{1}{\sqrt{3}}\mathbf{i} + \frac{1}{\sqrt{3}}\mathbf{j} + \frac{1}{\sqrt{3}}\mathbf{k}\right) \\ &= 20\sqrt{3}t(\mathbf{i} + \mathbf{j} + \mathbf{k}).\end{aligned}$$

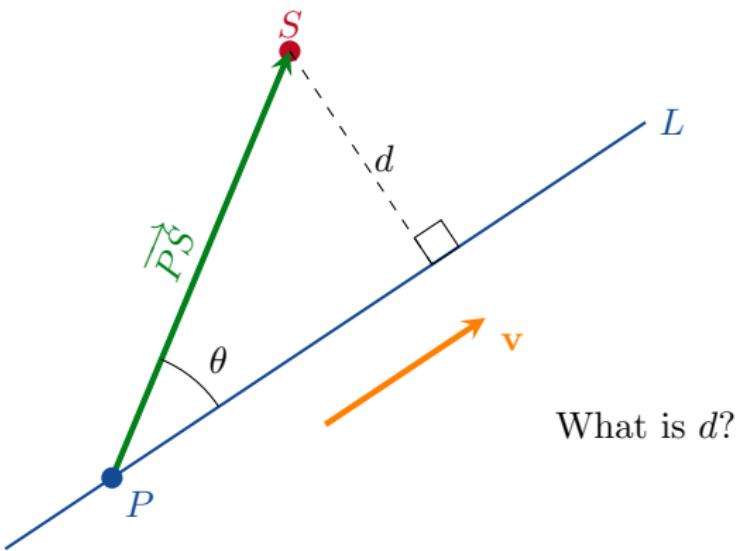
When $t = 10 \text{ sec}$,

$$\begin{aligned}\mathbf{r}(10) &= 200\sqrt{3}(\mathbf{i} + \mathbf{j} + \mathbf{k}) \\ &= \langle 200\sqrt{3}, 200\sqrt{3}, 200\sqrt{3} \rangle.\end{aligned}$$

After 10 sec of flight from the origin toward $(1, 1, 1)$, the helicopter is located at the point $(200\sqrt{3}, 200\sqrt{3}, 200\sqrt{3})$ in space. It has traveled a distance of $(60 \text{ m/sec})(10 \text{ sec}) = 600 \text{ m}$, which is the length of the vector $\mathbf{r}(10)$.



The Distance from a Point to a Line

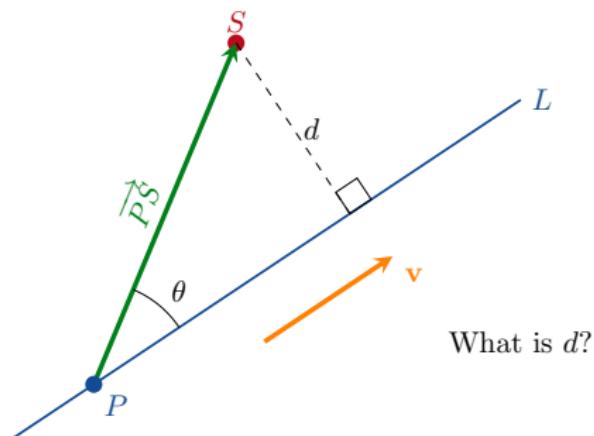


What is d ?

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Let d be the shortest distance from the point S to the line L .
 We can see from this diagram that

$$d = \|\overrightarrow{PS}\| \sin \theta.$$



14. Lines



Let d be the shortest distance from the point S to the line L . We can see from this diagram that

$$d = \|\overrightarrow{PS}\| \sin \theta.$$

But remember that $\overrightarrow{PS} \times \mathbf{v} = \|\overrightarrow{PS}\| \|\mathbf{v}\| \sin \theta \mathbf{n}$. Therefore

$$d = \frac{\|\overrightarrow{PS} \times \mathbf{v}\|}{\|\mathbf{v}\|}.$$

14.

$$d = \frac{\|\overrightarrow{PS} \times \mathbf{v}\|}{\|\mathbf{v}\|}$$



Example

Find the distance from the point $S(1, 1, 5)$ to the line

$$x = 1 + t, \quad y = 3 - t, \quad z = 2t.$$

14.

$$d = \frac{\|\overrightarrow{PS} \times \mathbf{v}\|}{\|\mathbf{v}\|}$$



Example

Find the distance from the point $S(1, 1, 5)$ to the line

$$x = 1 + t, \quad y = 3 - t, \quad z = 2t.$$

solution: The line passes through the point $P(1, 3, 0)$ in the direction $\mathbf{v} = \mathbf{i} - \mathbf{j} + 2\mathbf{k}$.

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$$d = \frac{\|\overrightarrow{PS} \times \mathbf{v}\|}{\|\mathbf{v}\|}$$



Example

Find the distance from the point $S(1, 1, 5)$ to the line

$$x = 1 + t, \quad y = 3 - t, \quad z = 2t.$$

solution: The line passes through the point $P(1, 3, 0)$ in the direction $\mathbf{v} = \mathbf{i} - \mathbf{j} + 2\mathbf{k}$. Thus

$$\overrightarrow{PS} = S - P = (1, 1, 5) - (1, 3, 0) = (0, -2, 5) = -2\mathbf{j} + 5\mathbf{k}$$

and

$$\overrightarrow{PS} \times \mathbf{v} = (-4 + 5)\mathbf{i} - (0 - 5)\mathbf{j} + (0 + 2)\mathbf{k} = \mathbf{i} + 5\mathbf{j} + 2\mathbf{k}.$$

14.

$$d = \frac{\|\overrightarrow{PS} \times \mathbf{v}\|}{\|\mathbf{v}\|}$$



Example

Find the distance from the point $S(1, 1, 5)$ to the line

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solution: The line passes through the point $P(1, 3, 0)$ in the direction $\mathbf{v} = \mathbf{i} - \mathbf{j} + 2\mathbf{k}$. Thus

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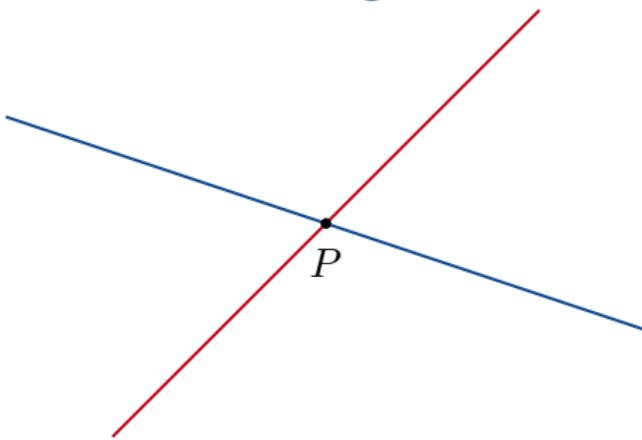
and

$$\overrightarrow{PS} \times \mathbf{v} = (-4 + 5)\mathbf{i} - (0 - 5)\mathbf{j} + (0 + 2)\mathbf{k} = \mathbf{i} + 5\mathbf{j} + 2\mathbf{k}.$$

Therefore

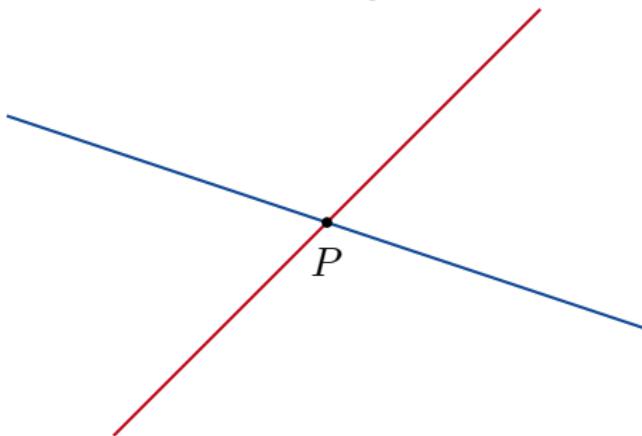
$$d = \frac{\|\overrightarrow{PS} \times \mathbf{v}\|}{\|\mathbf{v}\|} = \frac{\sqrt{1^2 + 5^2 + 2^2}}{\sqrt{1^2 + 1^2 + 2^2}} = \frac{\sqrt{30}}{\sqrt{6}} = \sqrt{5}.$$

Intersecting Lines¹



¹not in book

Intersecting Lines¹



Definition

Two lines intersect at a point P if and only if P lies on both lines.

¹not in book

14. Lines



Example

Do the following two lines intersect? If yes, where?

- 1 $x = 7 - t, y = 3 + 3t, z = 2t.$
- 2 $x = -1 + 2s, y = 3s, z = 1 + s.$

14. Lines

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Do the following two lines intersect? If yes, where?

- 1 $x = 7 - t, y = 3 + 3t, z = 2t.$
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solution: The two lines intersect if and only if there exist $s, t \in \mathbb{R}$ such that

$$7 - t = x = -1 + 2s$$

$$3 + 3t = y = 3s$$

$$2t = z = 1 + s$$

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Do the following two lines intersect? If yes, where?

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solution: The two lines intersect if and only if there exist $s, t \in \mathbb{R}$ such that

$$\begin{aligned} 7 - t &= x = -1 + 2s & \implies t &= 8 - 2s \\ 3 + 3t &= y = 3s \\ 2t &= z = 1 + s \end{aligned}$$

14. Lines



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The first equation tells us that $t = 8 - 2s$. Putting this into the second equation gives $s = t + 1 = (8 - 2s) + 1 = 9 - 2s$ which implies that $s = 3$ and $t = 2$.

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14. Lines

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Do the following two lines intersect? If yes, where?

- 1 $x = 7 - t, y = 3 + 3t, z = 2t.$
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solution: The two lines intersect if and only if there exist $s, t \in \mathbb{R}$ such that

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The first equation tells us that $t = 8 - 2s$. Putting this into the second equation gives $s = t + 1 = (8 - 2s) + 1 = 9 - 2s$ which implies that $s = 3$ and $t = 2$. We must check the third equation: $2t = 2 \times 2 = 4 = 1 + 3 = 1 + s$. Because the third equation is also true, we know that the two lines intersect at $P(5, 9, 4)$.

14. Lines

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Do the following two lines intersect? If yes, where?

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14. Lines



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Do the following two lines intersect? If yes, where?

- 1 $x = 1 + t, y = 3t, z = 3 + 3t.$
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solution: Can we find $s, t \in \mathbb{R}$ such that

$$1 + t = x = -1 + 2s$$

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are all true?

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$$1 + t = x = -1 + 2s \quad \Rightarrow \quad 2 + t = 2s \quad \Rightarrow \quad t = 2$$

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are all true?

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Do the following two lines intersect? If yes, where?

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solution: Can we find $s, t \in \mathbb{R}$ such that

$$1 + t = x = -1 + 2s \implies 2 + t = 2t \implies t = 2$$

$$3t = y = 3s \implies s = t$$

$$3 + 3t = z = 1 + s \implies 2 + 2t = 0 \implies t = -2 \neq 2$$

are all true?

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Do the following two lines intersect? If yes, where?

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$$3 + 3t = z = 1 + s \implies 2 + 2t = 0 \implies t = -2 \neq 2$$

are all true?

Therefore it is not possible to find an s and a t . Hence the lines do not intersect.

The Distance Between Two Lines²

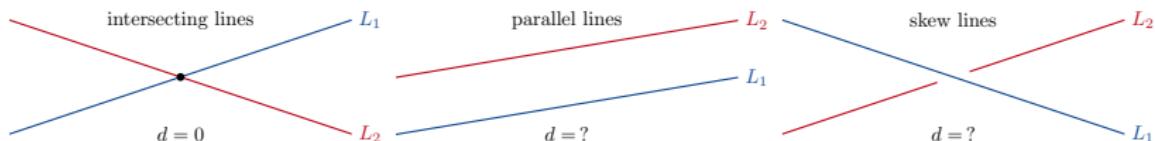
There are three cases to consider:

²not in book

The Distance Between Two Lines²

There are three cases to consider:

- the lines intersect;

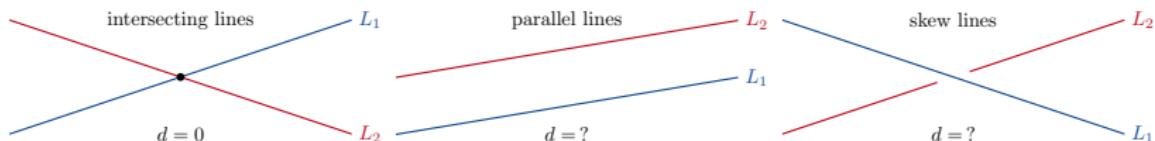


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The Distance Between Two Lines²

There are three cases to consider:

- the lines intersect;
- the lines do not intersect and are parallel ($\mathbf{v}_1 = k\mathbf{v}_2$ for some $k \in \mathbb{R}$); or

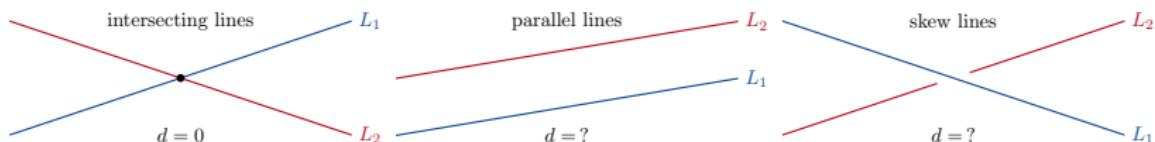


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The Distance Between Two Lines²

There are three cases to consider:

- the lines intersect;
- the lines do not intersect and are parallel ($\mathbf{v}_1 = k\mathbf{v}_2$ for some $k \in \mathbb{R}$); or
- the lines do not intersect and are skew ($\mathbf{v}_1 \neq k\mathbf{v}_2$ for all $k \in \mathbb{R}$).



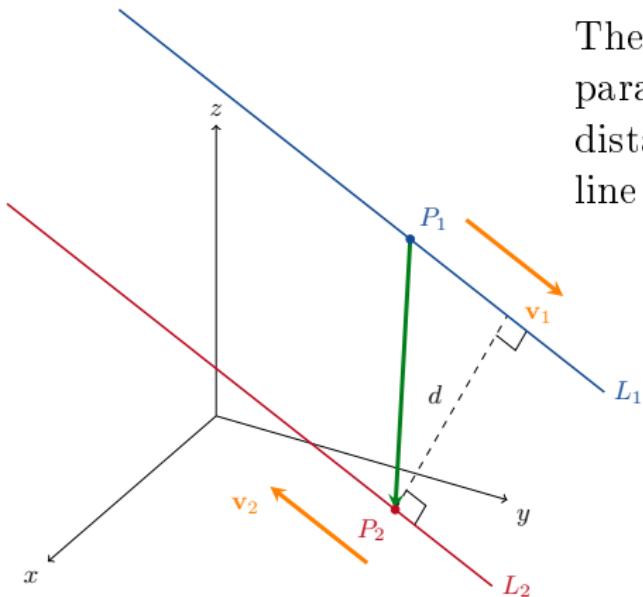
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Intersecting Lines

Clearly the distance between intersecting lines is zero. Hence

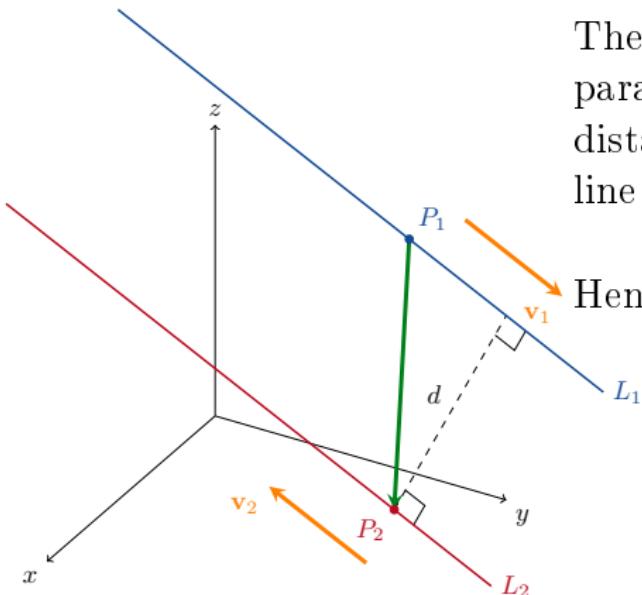
$$d = 0.$$

Parallel Lines ($\mathbf{v}_1 \times \mathbf{v}_2 = 0$)



The distance between the two parallel lines is the same as the distance between P_2 and the line L_1 .

Parallel Lines ($\mathbf{v}_1 \times \mathbf{v}_2 = 0$)



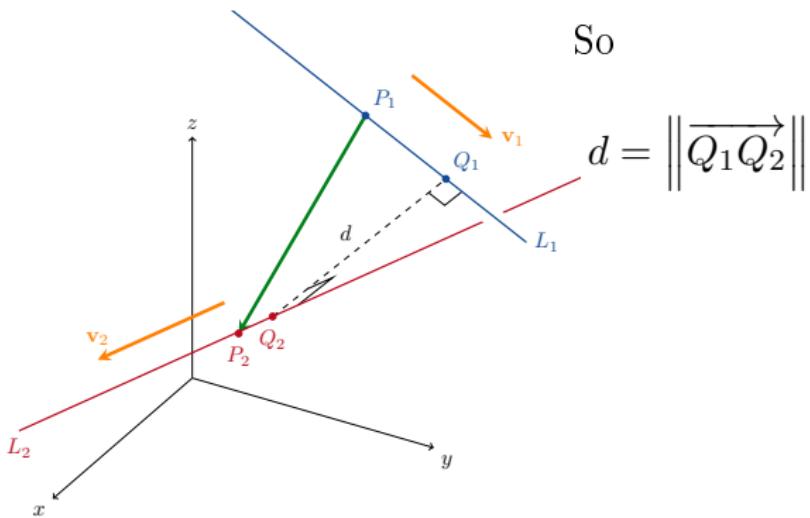
The distance between the two parallel lines is the same as the distance between P_2 and the line L_1 .

Hence

$$d = \frac{\|\overrightarrow{P_1P_2} \times \mathbf{v}_1\|}{\|\mathbf{v}_1\|}.$$

14. Lines

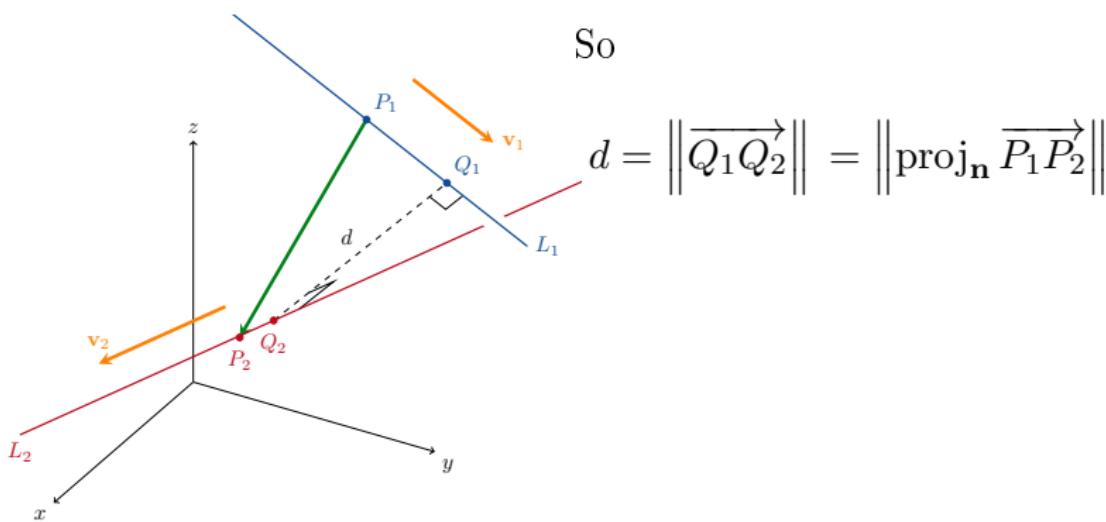
Skew Lines ($\mathbf{v}_1 \times \mathbf{v}_2 \neq 0$)



So

$$d = \|\overrightarrow{Q_1 Q_2}\|$$

Let $\mathbf{n} = \mathbf{v}_1 \times \mathbf{v}_2$. Then \mathbf{n} is orthogonal to both \mathbf{v}_1 and \mathbf{v}_2 .

Skew Lines ($\mathbf{v}_1 \times \mathbf{v}_2 \neq \mathbf{0}$)

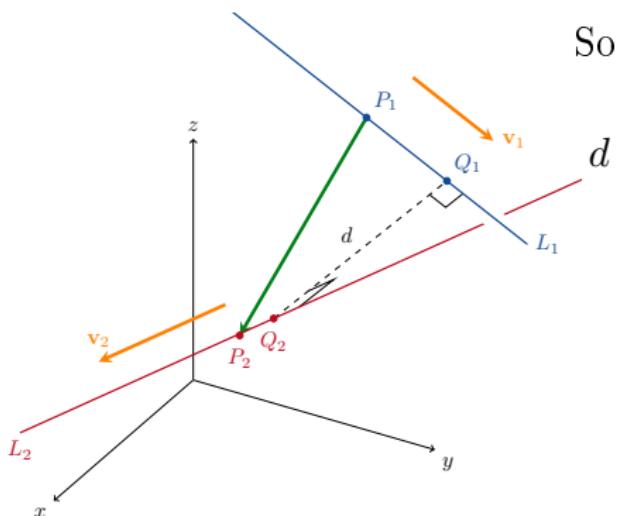
So

$$d = \|\overrightarrow{Q_1Q_2}\| = \|\text{proj}_{\mathbf{n}} \overrightarrow{P_1P_2}\|$$

Let $\mathbf{n} = \mathbf{v}_1 \times \mathbf{v}_2$. Then \mathbf{n} is orthogonal to both \mathbf{v}_1 and \mathbf{v}_2 .

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Skew Lines ($\mathbf{v}_1 \times \mathbf{v}_2 \neq \mathbf{0}$)

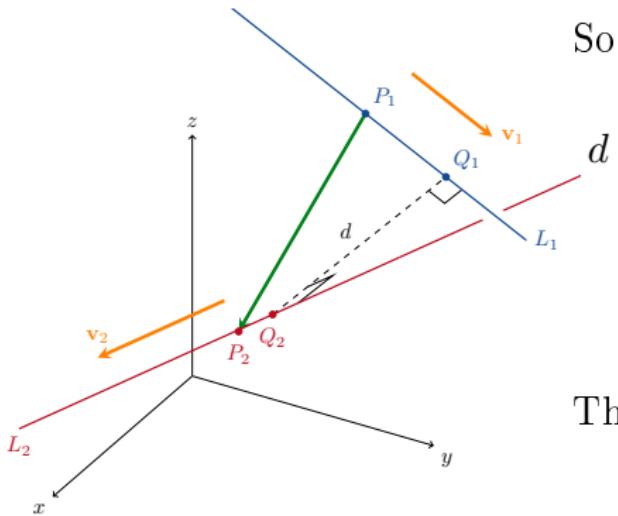


So

$$\begin{aligned} d &= \left\| \overrightarrow{Q_1 Q_2} \right\| = \left\| \text{proj}_{\mathbf{n}} \overrightarrow{P_1 P_2} \right\| \\ &= \frac{\left| \overrightarrow{P_1 P_2} \cdot \mathbf{n} \right|}{\left\| \mathbf{n} \right\|}. \end{aligned}$$

Let $\mathbf{n} = \mathbf{v}_1 \times \mathbf{v}_2$. Then \mathbf{n} is orthogonal to both \mathbf{v}_1 and \mathbf{v}_2 .

Skew Lines ($\mathbf{v}_1 \times \mathbf{v}_2 \neq \mathbf{0}$)



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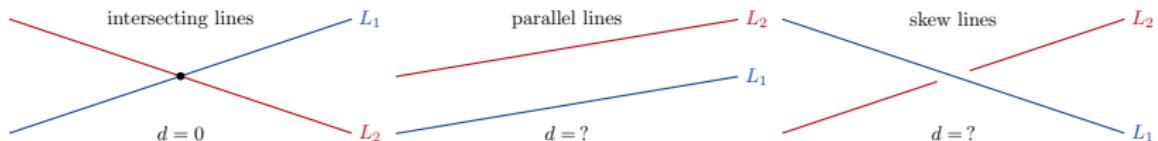
$$\begin{aligned} d &= \left\| \overrightarrow{Q_1 Q_2} \right\| = \left\| \text{proj}_{\mathbf{n}} \overrightarrow{P_1 P_2} \right\| \\ &= \frac{\left| \overrightarrow{P_1 P_2} \cdot \mathbf{n} \right|}{\| \mathbf{n} \|}. \end{aligned}$$

Thus

Let $\mathbf{n} = \mathbf{v}_1 \times \mathbf{v}_2$. Then \mathbf{n} is orthogonal to both \mathbf{v}_1 and \mathbf{v}_2 .

$$d = \frac{\left| \overrightarrow{P_1 P_2} \cdot (\mathbf{v}_1 \times \mathbf{v}_2) \right|}{\| \mathbf{v}_1 \times \mathbf{v}_2 \|}.$$

14. Lines



- Intersecting Lines: $d = 0$.

- Parallel Lines ($\mathbf{v}_1 \times \mathbf{v}_2 = \mathbf{0}$): $d = \frac{\left\| \overrightarrow{P_1 P_2} \times \mathbf{v}_1 \right\|}{\|\mathbf{v}_1\|}$.

- Skew Lines ($\mathbf{v}_1 \times \mathbf{v}_2 \neq \mathbf{0}$): $d = \frac{\left| \overrightarrow{P_1 P_2} \cdot (\mathbf{v}_1 \times \mathbf{v}_2) \right|}{\|\mathbf{v}_1 \times \mathbf{v}_2\|}$.

14. Lines



Example

Find the distance between the following two lines.

$$\text{line 1: } x = 0, y = -t, z = t,$$

$$\text{line 2: } x = 1 + 2s, y = s, z = -3s.$$

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Example

Find the distance between the following two lines.

$$\text{line 1: } x = 0, y = -t, z = t,$$

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solution: We have that $P_1(0, 0, 0)$, $\mathbf{v}_1 = -\mathbf{j} + \mathbf{k}$, $P_2(1, 0, 0)$ and $\mathbf{v}_2 = 2\mathbf{i} + \mathbf{j} - 3\mathbf{k}$. Since

$$\mathbf{v}_1 \times \mathbf{v}_2 = 2\mathbf{i} + 2\mathbf{j} + 2\mathbf{k} \neq \mathbf{0},$$

the lines are skew. (Recall that we have $\mathbf{v}_1 \times \mathbf{v}_2 = \mathbf{0}$ for parallel vectors.)

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Find the distance between the following two lines.

$$\text{line 1: } x = 0, y = -t, z = t,$$

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$$\mathbf{v}_1 \times \mathbf{v}_2 = 2\mathbf{i} + 2\mathbf{j} + 2\mathbf{k} \neq \mathbf{0},$$

the lines are skew. (Recall that we have $\mathbf{v}_1 \times \mathbf{v}_2 = \mathbf{0}$ for parallel vectors.) Moreover note that $\overrightarrow{P_1 P_2} = \mathbf{i}$. Then we calculate that

$$\begin{aligned} d &= \frac{\left| \overrightarrow{P_1 P_2} \cdot (\mathbf{v}_1 \times \mathbf{v}_2) \right|}{\|\mathbf{v}_1 \times \mathbf{v}_2\|} = \frac{|(\mathbf{i}) \cdot (2\mathbf{i} + 2\mathbf{j} + 2\mathbf{k})|}{\|2\mathbf{i} + 2\mathbf{j} + 2\mathbf{k}\|} \\ &= \frac{|2 + 0 + 0|}{\sqrt{2^2 + 2^2 + 2^2}} = \frac{1}{\sqrt{3}}. \end{aligned}$$

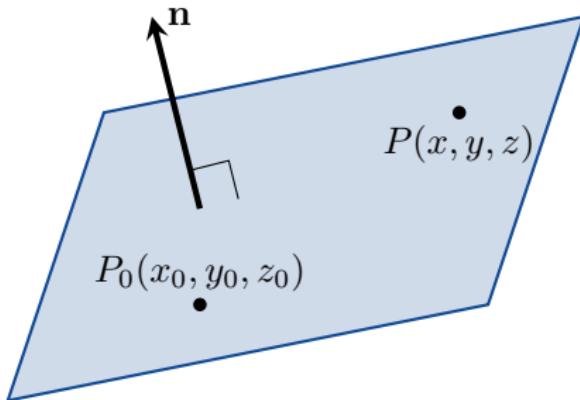
15 Planes

An Equation for a Plane in Space

To describe a plane, we need

- a point $P_0(x_0, y_0, z_0)$ which the plane passes through; and
- a vector $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ which is perpendicular to the plane.

The vector \mathbf{n} is said to be *normal* to the plane.



15. Planes



Definition

The plane passing through the point $P_0(x_0, y_0, z_0)$ with normal vector $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ has the vector equation

$$\mathbf{n} \cdot \overrightarrow{P_0P} = 0.$$

15. Planes

Definition

The plane passing through the point $P_0(x_0, y_0, z_0)$ with normal vector $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ has the vector equation

$$\mathbf{n} \cdot \overrightarrow{P_0P} = 0.$$

Writing this equation in coordinates, we have

$$A(x - x_0) + B(y - y_0) + C(z - z_0) = 0$$

or

$$Ax + By + Cz = D$$

where $D = Ax_0 + By_0 + Cz_0$ is a constant.

15. Planes



Example

Find an equation for the plane passing through $P_0(-3, 0, 7)$ normal to $\mathbf{n} = 5\mathbf{i} + 2\mathbf{j} - \mathbf{k}$.

15. Planes

Example

Find an equation for the plane passing through $P_0(-3, 0, 7)$ normal to $\mathbf{n} = 5\mathbf{i} + 2\mathbf{j} - \mathbf{k}$.

solution:

$$\begin{aligned}A(x - x_0) + B(y - y_0) + C(z - z_0) &= 0 \\5(x - (-3)) + 2(y - 0) + (-1)(z - 7) &= 0 \\5x - 15 + 2y - z + 7 &= 0 \\5x + 2y - z &= -22.\end{aligned}$$

15. Planes



Remark

The vector $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ is normal to the plane
 $Ax + By + Cz = D$.

15. Planes

Remark

The vector $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ is normal to the plane $Ax + By + Cz = D$.

Example

Find a vector normal to the plane $x + 2y + 3z = 4$.

15. Planes

Remark

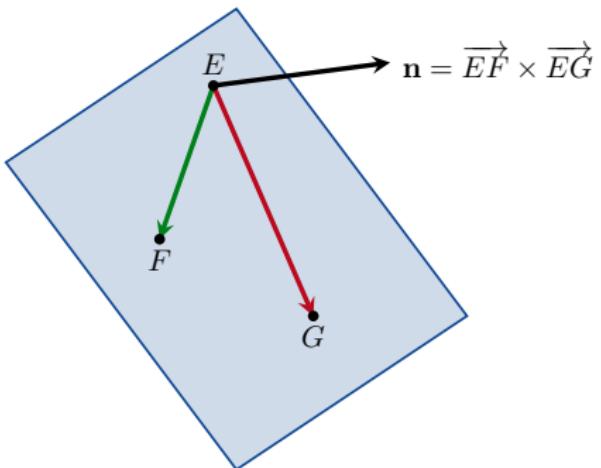
The vector $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ is normal to the plane $Ax + By + Cz = D$.

Example

Find a vector normal to the plane $x + 2y + 3z = 4$.

solution: We can immediately write down $\mathbf{n} = \mathbf{i} + 2\mathbf{j} + 3\mathbf{k}$.

15. Planes



Example

Find an equation for the plane containing the points $E(0, 0, 1)$, $F(2, 0, 0)$ and $G(0, 3, 0)$.

15. Planes



solution: First we need to find a vector normal to the plane. Since $\overrightarrow{EF} = 2\mathbf{i} - \mathbf{k}$ and $\overrightarrow{EG} = 3\mathbf{j} - \mathbf{k}$, we have that

$$\begin{aligned}\mathbf{n} &= \overrightarrow{EF} \times \overrightarrow{EG} = (0 - -3)\mathbf{i} - (-2 - 0)\mathbf{j} + (6 - 0)\mathbf{k} \\ &= 3\mathbf{i} + 2\mathbf{j} + 6\mathbf{k}\end{aligned}$$

is normal to the plane.

15. Planes

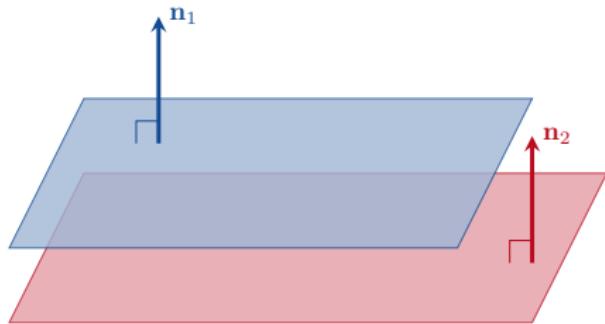
solution: First we need to find a vector normal to the plane. Since $\overrightarrow{EF} = 2\mathbf{i} - \mathbf{k}$ and $\overrightarrow{EG} = 3\mathbf{j} - \mathbf{k}$, we have that

$$\begin{aligned}\mathbf{n} &= \overrightarrow{EF} \times \overrightarrow{EG} = (0 - -3)\mathbf{i} - (-2 - 0)\mathbf{j} + (6 - 0)\mathbf{k} \\ &= 3\mathbf{i} + 2\mathbf{j} + 6\mathbf{k}\end{aligned}$$

is normal to the plane. Using $P_0 = E(0, 0, 1)$, the equation for the plane is

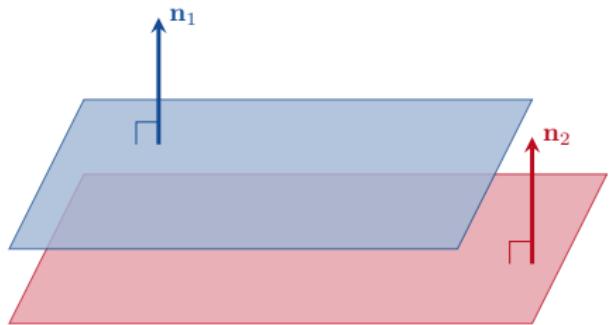
$$\begin{aligned}3(x - 0) + 2(y - 0) + 6(z - 1) &= 0 \\ 3x + 2y + 6z &= 6.\end{aligned}$$

Lines of Intersection

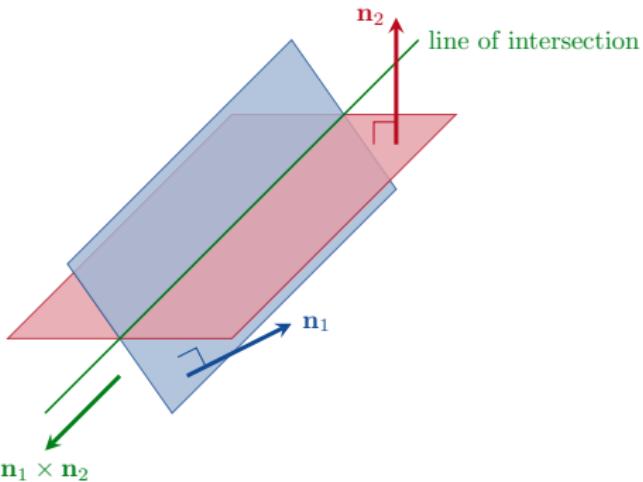


Two planes are parallel \iff
 $\mathbf{n}_1 = k\mathbf{n}_2$ for some $k \in \mathbb{R}$.

Lines of Intersection



Two planes are parallel \iff
 $\mathbf{n}_1 = k\mathbf{n}_2$ for some $k \in \mathbb{R}$.



Two planes intersect in a line
 $\iff \mathbf{n}_1 \neq k\mathbf{n}_2$ for all $k \in \mathbb{R}$.

15. Planes



Example

Find a vector parallel to the line of intersection of the planes

$$3x - 6y - 2z = 15 \text{ and } 2x + y - 2z = 5.$$

15. Planes



Example

Find a vector parallel to the line of intersection of the planes

$$3x - 6y - 2z = 15 \text{ and } 2x + y - 2z = 5.$$

solution: We can immediately write down $\mathbf{n}_1 = 3\mathbf{i} - 6\mathbf{j} - 2\mathbf{k}$ and $\mathbf{n}_2 = 2\mathbf{i} + \mathbf{j} - 2\mathbf{k}$.

15. Planes



Example

Find a vector parallel to the line of intersection of the planes
 $3x - 6y - 2z = 15$ and $2x + y - 2z = 5$.

solution: We can immediately write down $\mathbf{n}_1 = 3\mathbf{i} - 6\mathbf{j} - 2\mathbf{k}$ and $\mathbf{n}_2 = 2\mathbf{i} + \mathbf{j} - 2\mathbf{k}$. A vector parallel to the line of intersection is

$$\mathbf{n}_1 \times \mathbf{n}_2 = (12 + 2)\mathbf{i} - (-6 + 4)\mathbf{j} + (3 + 12)\mathbf{k} = 14\mathbf{i} + 2\mathbf{j} + 15\mathbf{k}.$$

15. Planes

Example

Find the point where the line $x = \frac{8}{3} + 2t$, $y = -2t$, $z = 1 + t$ intersects the plane $3x + 2y + 6z = 6$.

15. Planes

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Find the point where the line $x = \frac{8}{3} + 2t$, $y = -2t$, $z = 1 + t$ intersects the plane $3x + 2y + 6z = 6$.

solution: We calculate that

$$3x + 2y + 6z = 6$$

15. Planes

Example

Find the point where the line $x = \frac{8}{3} + 2t$, $y = -2t$, $z = 1 + t$ intersects the plane $3x + 2y + 6z = 6$.

solution: We calculate that

$$3x + 2y + 6z = 6$$

$$3\left(\frac{8}{3} + 2t\right) + 2(-2t) + 6(1 + t) = 6$$

15. Planes

Example

Find the point where the line $x = \frac{8}{3} + 2t$, $y = -2t$, $z = 1 + t$ intersects the plane $3x + 2y + 6z = 6$.

solution: We calculate that

$$3x + 2y + 6z = 6$$

$$3\left(\frac{8}{3} + 2t\right) + 2(-2t) + 6(1 + t) = 6$$

$$8 + 6t - 4t + 6 + 6t = 6$$

15. Planes

Example

Find the point where the line $x = \frac{8}{3} + 2t$, $y = -2t$, $z = 1 + t$ intersects the plane $3x + 2y + 6z = 6$.

solution: We calculate that

$$3x + 2y + 6z = 6$$

$$3\left(\frac{8}{3} + 2t\right) + 2(-2t) + 6(1 + t) = 6$$

$$8 + 6t - 4t + 6 + 6t = 6$$

$$8t = -8$$

$$t = -1.$$

15. Planes

Example

Find the point where the line $x = \frac{8}{3} + 2t$, $y = -2t$, $z = 1 + t$ intersects the plane $3x + 2y + 6z = 6$.

solution: We calculate that

$$\begin{aligned}3x + 2y + 6z &= 6 \\3\left(\frac{8}{3} + 2t\right) + 2(-2t) + 6(1 + t) &= 6 \\8 + 6t - 4t + 6 + 6t &= 6 \\8t &= -8 \\t &= -1.\end{aligned}$$

The point of intersection is

$$P(x, y, z)|_{t=-1} =$$

15. Planes

Example

Find the point where the line $x = \frac{8}{3} + 2t$, $y = -2t$, $z = 1 + t$ intersects the plane $3x + 2y + 6z = 6$.

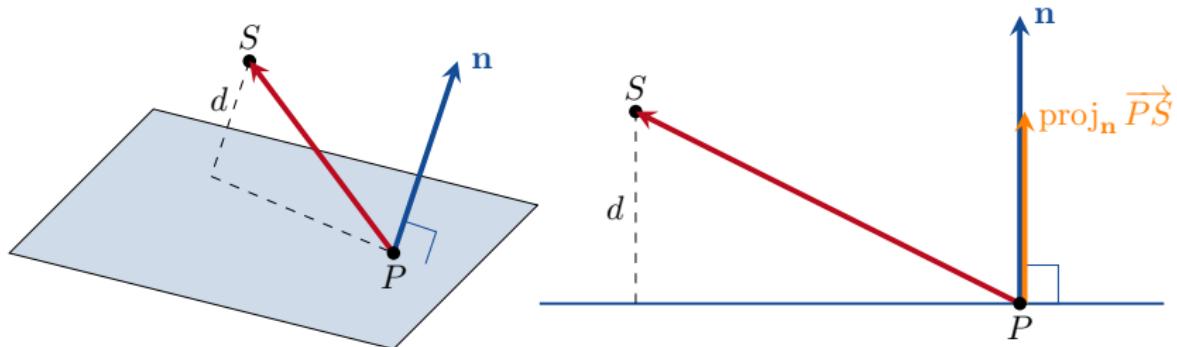
solution: We calculate that

$$\begin{aligned} 3x + 2y + 6z &= 6 \\ 3\left(\frac{8}{3} + 2t\right) + 2(-2t) + 6(1 + t) &= 6 \\ 8 + 6t - 4t + 6 + 6t &= 6 \\ 8t &= -8 \\ t &= -1. \end{aligned}$$

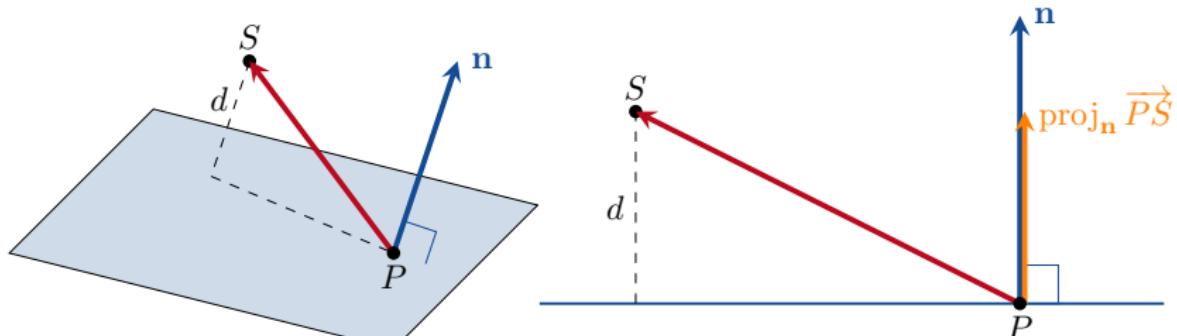
The point of intersection is

$$P(x, y, z)|_{t=-1} = P\left(\frac{8}{3} + 2t, -2t, 1 + t\right)\Big|_{t=-1} = P\left(\frac{2}{3}, 2, 0\right).$$

The Distance from a Point to a Plane

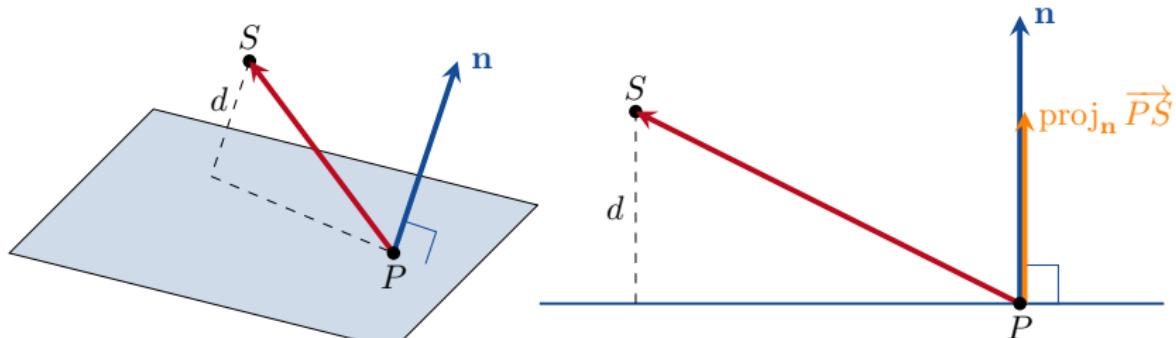


The Distance from a Point to a Plane



We can see that $d = \|\text{proj}_n \overrightarrow{PS}\|$.

The Distance from a Point to a Plane



We can see that $d = \|\text{proj}_n \overrightarrow{PS}\|$. Therefore the distance from a point S to a plane with normal \mathbf{n} containing the point P is

$$d = \frac{|\overrightarrow{PS} \cdot \mathbf{n}|}{\|\mathbf{n}\|}.$$

15.

$$d = \frac{|\overrightarrow{PS} \cdot \mathbf{n}|}{\|\mathbf{n}\|}$$



Example

Find the distance from the point $S(1, 2, 3)$ to the plane $x + 2y + 3z = 4$.

solution: First we need a point in the plane.

15.

$$d = \frac{|\overrightarrow{PS} \cdot \mathbf{n}|}{\|\mathbf{n}\|}$$



Example

Find the distance from the point $S(1, 2, 3)$ to the plane
 $x + 2y + 3z = 4$.

solution: First we need a point in the plane. Setting $y = 0$ and $z = 0$ we must have $x = 4 - 2y - 3z = 4$. Therefore $P(4, 0, 0)$ is in the plane.

15.

$$d = \frac{|\overrightarrow{PS} \cdot \mathbf{n}|}{\|\mathbf{n}\|}$$



Example

Find the distance from the point $S(1, 2, 3)$ to the plane
 $x + 2y + 3z = 4$.

solution: First we need a point in the plane. Setting $y = 0$ and $z = 0$ we must have $x = 4 - 2y - 3z = 4$. Therefore $P(4, 0, 0)$ is in the plane. Clearly $\mathbf{n} = \mathbf{i} + 2\mathbf{j} + 3\mathbf{k}$.

15.

$$d = \frac{|\overrightarrow{PS} \cdot \mathbf{n}|}{\|\mathbf{n}\|}$$



Example

Find the distance from the point $S(1, 2, 3)$ to the plane $x + 2y + 3z = 4$.

solution: First we need a point in the plane. Setting $y = 0$ and $z = 0$ we must have $x = 4 - 2y - 3z = 4$. Therefore $P(4, 0, 0)$ is in the plane. Clearly $\mathbf{n} = \mathbf{i} + 2\mathbf{j} + 3\mathbf{k}$.

Therefore the required distance is

$$\begin{aligned} d &= \frac{|\overrightarrow{PS} \cdot \mathbf{n}|}{\|\mathbf{n}\|} = \frac{|(-3\mathbf{i} + 2\mathbf{j} + 3\mathbf{k}) \cdot (\mathbf{i} + 2\mathbf{j} + 3\mathbf{k})|}{\|\mathbf{i} + 2\mathbf{j} + 3\mathbf{k}\|} \\ &= \frac{|-3 + 4 + 9|}{\sqrt{1^2 + 2^2 + 3^2}} = \frac{10}{\sqrt{14}}. \end{aligned}$$

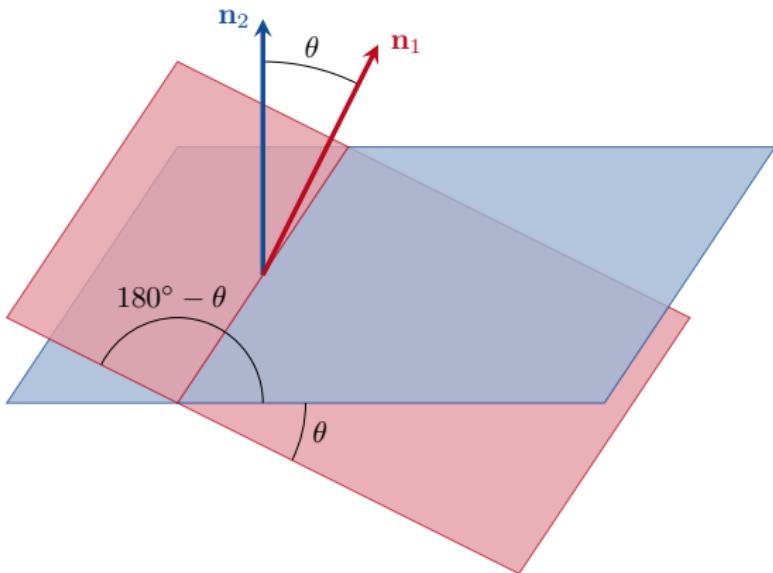
15. Planes



Please read Example 11 in the textbook.

Angles Between Planes

There are two possible angles that can be measured between planes. We are interested in the smaller angle.



15. Planes



Definition

The angle between two planes is defined to be equal to whichever of the following angles is smaller

- the angle between \mathbf{n}_1 and \mathbf{n}_2 ;
- 180° minus the angle between \mathbf{n}_1 and \mathbf{n}_2 .

The angle between two planes will always be between 0° and 90° .

15. Planes



Example

Find the angle between the planes $3x - 6y - 2z = 15$ and $-2x - y + 2z = 5$.

15. Planes

Example

Find the angle between the planes $3x - 6y - 2z = 15$ and $-2x - y + 2z = 5$.

solution: We have normal vectors $\mathbf{n}_1 = 3\mathbf{i} - 6\mathbf{j} - 2\mathbf{k}$ and $\mathbf{n}_2 = -2\mathbf{i} - \mathbf{j} + 2\mathbf{k}$. The angle between \mathbf{n}_1 and \mathbf{n}_2 is

$$\theta = \cos^{-1} \left(\frac{\mathbf{n}_1 \cdot \mathbf{n}_2}{\|\mathbf{n}_1\| \|\mathbf{n}_2\|} \right) = \cos^{-1} \left(\frac{-4}{21} \right) \approx 101^\circ.$$

15. Planes

Example

Find the angle between the planes $3x - 6y - 2z = 15$ and $-2x - y + 2z = 5$.

solution: We have normal vectors $\mathbf{n}_1 = 3\mathbf{i} - 6\mathbf{j} - 2\mathbf{k}$ and $\mathbf{n}_2 = -2\mathbf{i} - \mathbf{j} + 2\mathbf{k}$. The angle between \mathbf{n}_1 and \mathbf{n}_2 is

$$\theta = \cos^{-1} \left(\frac{\mathbf{n}_1 \cdot \mathbf{n}_2}{\|\mathbf{n}_1\| \|\mathbf{n}_2\|} \right) = \cos^{-1} \left(\frac{-4}{21} \right) \approx 101^\circ.$$

Because $101^\circ > 90^\circ$, the angle between the two planes is approximately $180^\circ - 101^\circ = 79^\circ$.



16 Projections

16. Projections



Recall that last week we defined the projection of a vector \mathbf{u} onto a vector \mathbf{v} to be

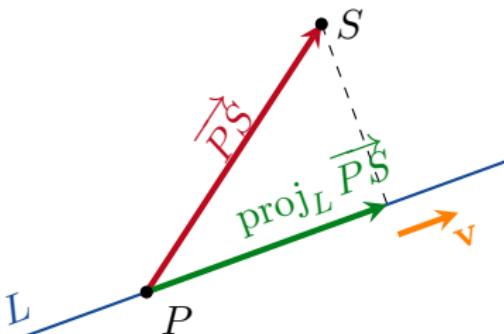
$$\text{proj}_{\mathbf{v}} \mathbf{u} = \left(\frac{\mathbf{u} \cdot \mathbf{v}}{\|\mathbf{v}\|^2} \right) \mathbf{v}.$$

Projection of a Vector onto a Line

Definition

Let L be the line passing through the point P in the direction \mathbf{v} . The projection of a vector \mathbf{u} onto the line L is

$$\text{proj}_L \mathbf{u} = \text{proj}_{\mathbf{v}} \mathbf{u}.$$



16. Projections

Example

Find the projection of the vector $\mathbf{u} = 2\mathbf{i} - \mathbf{j} + 3\mathbf{k}$ onto the line $x = 1 + 2t, y = 2 - t, z = 4 - 4t$.

solution: Clearly $\mathbf{v} = 2\mathbf{i} - \mathbf{j} - 4\mathbf{k}$ is parallel to the line. Thus

$$\begin{aligned}\text{proj}_L \mathbf{u} &= \text{proj}_{\mathbf{v}} \mathbf{u} = \left(\frac{\mathbf{u} \cdot \mathbf{v}}{\|\mathbf{v}\|^2} \right) \mathbf{v} \\&= \left(\frac{4 + 1 - 12}{2^2 + (-1)^2 + (-4)^2} \right) (2\mathbf{i} - \mathbf{j} - 4\mathbf{k}) \\&= \left(\frac{-7}{21} \right) (2\mathbf{i} - \mathbf{j} - 4\mathbf{k}) \\&= -\frac{1}{3} (2\mathbf{i} - \mathbf{j} - 4\mathbf{k}) \\&= -\frac{2}{3}\mathbf{i} + \frac{1}{3}\mathbf{j} + \frac{4}{3}\mathbf{k}.\end{aligned}$$

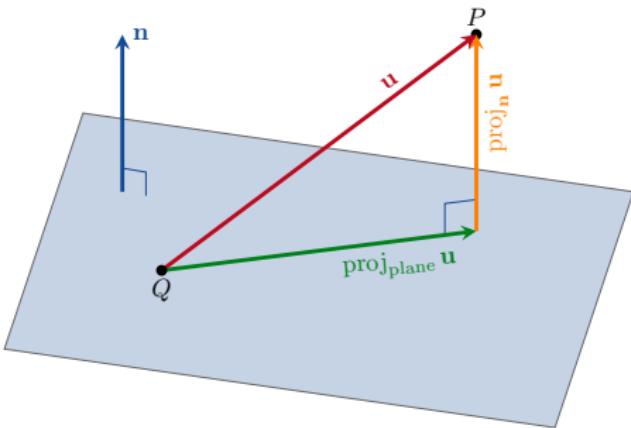
Projection of a Vector onto a Plane

Definition

The *projection* of a vector \mathbf{u} onto a plane with normal vector \mathbf{n} is

$$\text{proj}_{\text{plane}} \mathbf{u} = \mathbf{u} - \text{proj}_{\mathbf{n}} \mathbf{u} = \mathbf{u} - \left(\frac{\mathbf{u} \cdot \mathbf{n}}{\|\mathbf{n}\|^2} \right) \mathbf{n}.$$

16. Projections



16. Projections

Example

Find the projection of the vector $\mathbf{u} = \mathbf{i} + 2\mathbf{j} + 3\mathbf{k}$ onto the plane $3x - y + 2z = 7$.

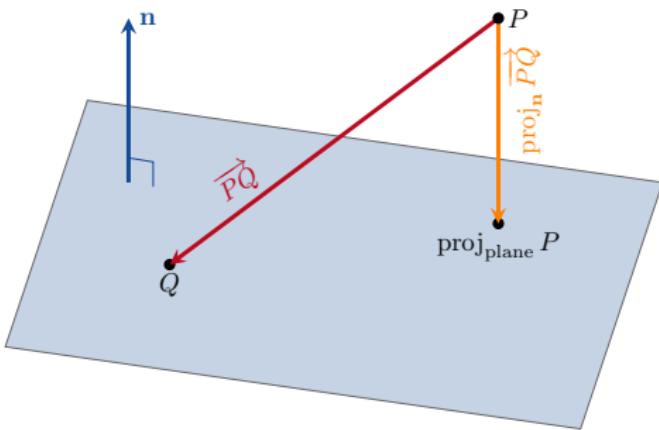
solution: Clearly $\mathbf{n} = 3\mathbf{i} - \mathbf{j} + 2\mathbf{k}$ and

$$\begin{aligned}\text{proj}_{\mathbf{n}} \mathbf{u} &= \left(\frac{\mathbf{u} \cdot \mathbf{n}}{\|\mathbf{n}\|^2} \right) \mathbf{n} = \left(\frac{3 - 2 + 6}{3^2 + (-1)^2 + 2^2} \right) (3\mathbf{i} - \mathbf{j} + 2\mathbf{k}) \\ &= \frac{1}{2} (3\mathbf{i} - \mathbf{j} + 2\mathbf{k}) = \frac{3}{2}\mathbf{i} - \frac{1}{2}\mathbf{j} + \mathbf{k}.\end{aligned}$$

Therefore

$$\begin{aligned}\text{proj}_{\text{plane}} \mathbf{u} &= \mathbf{u} - \text{proj}_{\mathbf{n}} \mathbf{u} \\ &= (\mathbf{i} + 2\mathbf{j} + 3\mathbf{k}) - \left(\frac{3}{2}\mathbf{i} - \frac{1}{2}\mathbf{j} + \mathbf{k} \right) \\ &= -\frac{1}{2}\mathbf{i} + \frac{5}{2}\mathbf{j} + 2\mathbf{k}.\end{aligned}$$

Projection of a Point onto a Plane



16. Projections



Definition

Let P be a point and let $Ax + By + Cz = D$ be a plane. Let Q be a point on the plane and let $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ denote a vector normal to the plane.

The projection of the point P onto this plane is

$$\text{proj}_{\text{plane}} P = P + \text{proj}_{\mathbf{n}} \overrightarrow{PQ}.$$

16. Projections

Example

Find the projection of the point $P(1, 2, -4)$ on the plane $2x + y + 4z = 2$.

solution: Note first that $\mathbf{n} = 2\mathbf{i} + \mathbf{j} + 4\mathbf{k}$ and that the point $Q(1, 0, 0)$ lies on the plane. Since

$$\overrightarrow{PQ} = Q - P = (1, 0, 0) - (1, 2, -4) = (0, -2, 4) = -2\mathbf{j} + 4\mathbf{k},$$

we have

$$\begin{aligned}\text{proj}_{\mathbf{n}} \overrightarrow{PQ} &= \left(\frac{\overrightarrow{PQ} \cdot \mathbf{n}}{\|\mathbf{n}\|^2} \right) \mathbf{n} = \left(\frac{0 - 2 + 16}{2^2 + 1^2 + 4^2} \right) (2\mathbf{i} + \mathbf{j} + 4\mathbf{k}) \\ &= \left(\frac{14}{21} \right) (2\mathbf{i} + \mathbf{j} + 4\mathbf{k}) = \frac{2}{3} (2\mathbf{i} + \mathbf{j} + 4\mathbf{k}) \\ &= \frac{4}{3}\mathbf{i} + \frac{2}{3}\mathbf{j} + \frac{8}{3}\mathbf{k}.\end{aligned}$$

16. Projections



Therefore

$$\begin{aligned}\text{proj}_{\text{plane}} P &= P + \text{proj}_{\mathbf{n}} \overrightarrow{PQ} \\ &= (1, 2, -4) + \left(\frac{4}{3}, \frac{2}{3}, \frac{8}{3} \right) \\ &= \left(\frac{7}{3}, \frac{8}{3}, -\frac{4}{3} \right).\end{aligned}$$

16. Projections



We should double check that the point $(\frac{7}{3}, \frac{8}{3}, -\frac{4}{3})$ is on the plane $2x + y + 4z = 2$.

$$2x + y + 4z = 2 \left(\frac{7}{3}\right) + \left(\frac{8}{3}\right) + 4 \left(-\frac{4}{3}\right) = \frac{14}{3} + \frac{8}{3} - \frac{16}{3} = \frac{6}{3} = 2 \quad \checkmark$$

Projection of a Line onto a Plane

Let L be a line passing through the point P in the direction \mathbf{v} .

Let $Ax + By + Cz = D$ be a plane with normal vector

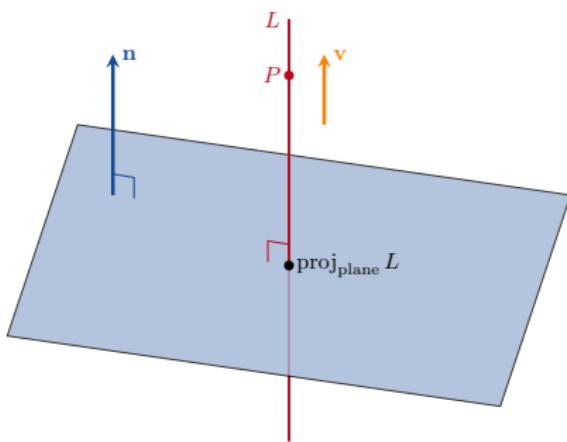
$$\mathbf{n} = Ai + Bj + Ck.$$

There are three cases to consider:

- 1 The line is orthogonal to the plane ($\mathbf{v} \times \mathbf{n} = \mathbf{0}$);
- 2 The line is parallel to the plane ($\mathbf{v} \cdot \mathbf{n} = 0$); and
- 3 The line is not parallel to the plane and is not orthogonal to the plane ($\mathbf{v} \cdot \mathbf{n} \neq 0$ and $\mathbf{v} \times \mathbf{n} \neq \mathbf{0}$).

16. Projections

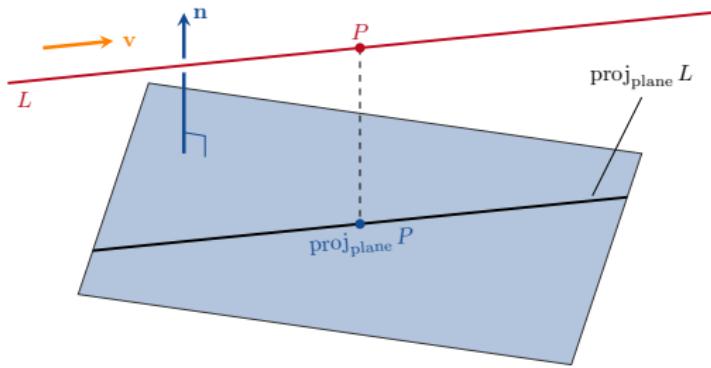
A Line Orthogonal to a Plane ($\mathbf{v} \times \mathbf{n} = 0$)



This is the easiest case: The projection of the line onto the plane is just the point where they intersect. Therefore

$$\text{proj}_{\text{plane}} L = \text{proj}_{\text{plane}} P.$$

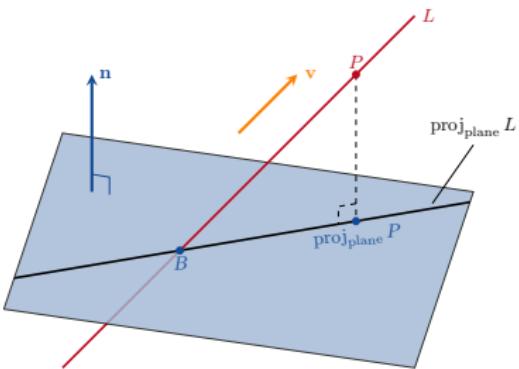
A Line Parallel to a Plane ($\mathbf{v} \cdot \mathbf{n} = 0$)



We can see that

$$\text{proj}_{\text{plane}} L = \left(\begin{array}{l} \text{the line passing through the} \\ \text{point } \text{proj}_{\text{plane}} P \text{ in the direction} \\ \mathbf{v}. \end{array} \right)$$

A Line which is Neither Parallel to nor Orthogonal to the Plane



If $\mathbf{v} \cdot \mathbf{n} \neq 0$, then the line must intersect the plane at some point B . Assuming $B \neq P$, we have

$$\text{proj}_{\text{plane}} L = \left(\begin{array}{l} \text{the line passing through} \\ \text{the points } B \text{ and} \\ \text{proj}_{\text{plane}} P. \end{array} \right)$$

16. Projections

Example

Find the projection of the line $x = 7 + 6t$, $y = -3 + 15t$, $z = 10 - 12t$ onto the plane $2x + 5y - 4z = 13$.

solution:

- 1** Find \mathbf{v} and \mathbf{n} .

$$\mathbf{v} = 6\mathbf{i} + 15\mathbf{j} - 12\mathbf{k}$$

$$\mathbf{n} = 2\mathbf{i} + 5\mathbf{j} - 4\mathbf{k}$$

- 2** Does the line intersect the plane?

Since

$$\mathbf{v} \cdot \mathbf{n} = 12 + 75 + 48 = 135 \neq 0,$$

the answer is yes, the line does intersect the plane.

16. Projections

- 3** Find the point of intersection.

We calculate that

$$13 = 2x + 5y - 4z \\ = 2(7 + 6t) + 5(-3 + 15t) - 4(10 - 12t)$$

$$= 14 + 12t - 15 + 75t - 40 + 48t$$

$$= -41 + 135t$$

$$54 = 135t$$

$$2 = 5t$$

$$\frac{2}{5} = t.$$

Hence the point of intersection is

$$B(x, y, z)|_{t=\frac{2}{5}} = B(7 + 6t, -3 + 15t, 10 - 12t)|_{t=\frac{2}{5}} \\ = B(9.4, 3, 5.2)$$

16. Projections



- 4 Is the line orthogonal to the plane?

Since

$$\mathbf{v} \times \mathbf{n} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 6 & 15 & -12 \\ 2 & 5 & -4 \end{vmatrix} = 0\mathbf{i} + 0\mathbf{j} + 0\mathbf{k} = \mathbf{0},$$

the answer is yes, the line is orthogonal to the plane.

16. Projections



- 5 Find $\text{proj}_{\text{plane}} L$.

The projection of the line on the plane is the point

$$\text{proj}_{\text{plane}} L = B(9.4, 3, 5.2).$$

16. Projections

Example

Find the projection of the line $x = 1 + 4t$, $y = 2 + 4t$, $z = 3 + 4t$ onto the plane $3x + 4y - 7z = 27$.

solution:

- 1 Find \mathbf{v} and \mathbf{n} .

$$\mathbf{v} = 4\mathbf{i} + 4\mathbf{j} + 4\mathbf{k}$$

$$\mathbf{n} = 3\mathbf{i} + 4\mathbf{j} - 7\mathbf{k}$$

- 2 Does the line intersect the plane?

Since

$$\mathbf{v} \cdot \mathbf{n} = 12 + 16 - 28 = 0,$$

the line does not intersect the plane. Therefore the line is parallel to the plane.

16. Projections



- 3 Find a point on $\text{proj}_{\text{plane}} L$.

$P(1, 2, 3)$ lies on the original line and $Q(9, 0, 0)$ lies on the plane. So

$$\begin{aligned}\overrightarrow{PQ} &= Q - P = (9, 0, 0) - (1, 2, 3) = (8, -2, -3) \\ &= 8\mathbf{i} - 2\mathbf{j} - 3\mathbf{k}\end{aligned}$$

and

$$\begin{aligned}\text{proj}_{\mathbf{n}} \overrightarrow{PQ} &= \left(\frac{\overrightarrow{PQ} \cdot \mathbf{n}}{\|\mathbf{n}\|^2} \right) \mathbf{n} = \left(\frac{24 - 8 + 21}{9 + 16 + 49} \right) \mathbf{n} \\ &= \left(\frac{37}{74} \right) \mathbf{n} = \frac{1}{2} \mathbf{n}.\end{aligned}$$

16. Projections



Therefore

$$\begin{aligned}\text{proj}_{\text{plane}} P &= P + \text{proj}_{\mathbf{n}} \overrightarrow{PQ} \\ &= (1, 2, 3) + \left(\frac{3}{2}, 2, -\frac{7}{2} \right) \\ &= \left(\frac{5}{2}, 4, -\frac{1}{2} \right).\end{aligned}$$

We should quickly double check that our $\text{proj}_{\text{plane}} P$ really is on the plane:

$$\begin{aligned}3x + 4y - 7z &= 3\left(\frac{5}{2}\right) + 4(4) - 7\left(-\frac{1}{2}\right) \\ &= \frac{15}{2} + 16 + \frac{7}{2} = 27.\end{aligned}$$
 ✓

16. Projections



- 4 Find $\text{proj}_{\text{plane}} L$.

The projection of the original line on the plane is the line passing through the point $\text{proj}_{\text{plane}} P = \left(\frac{5}{2}, 4, -\frac{1}{2}\right)$ in the direction $\mathbf{v} = 4\mathbf{i} + 4\mathbf{j} + 4\mathbf{k}$, which has parametrised equations

$$x = \frac{5}{2} + 4t, \quad y = 4 + 4t, \quad z = -\frac{1}{2} + 4t.$$

16. Projections



Example

Find the projection of the line $x = 15 + 15t$, $y = -12 - 15t$, $z = 17 + 11t$ on the plane $13x - 9y + 16z = 69$.

solution:

- 1 Find \mathbf{v} and \mathbf{n} .

$$\mathbf{v} = 15\mathbf{i} - 15\mathbf{j} + 11\mathbf{k}$$

$$\mathbf{n} = 13\mathbf{i} - 9\mathbf{j} + 16\mathbf{k}$$

- 2 Does the line intersect the plane?

Since

$$\mathbf{v} \cdot \mathbf{n} = 506 \neq 0,$$

the line intersects the plane.

16. Projections



- 3 Find the point of intersection.

We calculate that

$$\begin{aligned} 69 &= 13x - 9y + 16z \\ &= 13(15 + 15t) - 9(-12 - 15t) + 16(17 + 11t) \\ &= 195 + 195t + 108 + 135t + 272 + 176t \\ &= 575 + 506t \end{aligned}$$

$$-506 = 506t$$

$$-1 = t.$$

Thus the line intersects the plane at

$$\begin{aligned} B(x, y, z)|_{t=-1} &= B(15 + 15t, -12 - 15t, 17 + 11t)|_{t=-1} \\ &= B(0, 3, 6). \end{aligned}$$

16. Projections



- 4 Is the line orthogonal to the plane?

Since

$$\mathbf{v} \times \mathbf{n} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 15 & -15 & 11 \\ 13 & -9 & 16 \end{vmatrix} = -141\mathbf{i} - 97\mathbf{j} + 60\mathbf{k} \neq \mathbf{0},$$

the line is not orthogonal to the plane.

16. Projections



- 5 Find another point on $\text{proj}_{\text{plane}} L$.

The point $P(15, -12, 17)$ lies on the original line. Since $\overrightarrow{PB} = (-15, 15, -11)$ and

$$\text{proj}_{\mathbf{n}} \overrightarrow{PB} = \left(\frac{\overrightarrow{PB} \cdot \mathbf{n}}{\|\mathbf{n}\|^2} \right) \mathbf{n} = \left(\frac{-506}{506} \right) \mathbf{n} = -\mathbf{n}$$

we have that

$$\begin{aligned}\text{proj}_{\text{plane}} P &= P + \text{proj}_{\mathbf{n}} \overrightarrow{PB} \\ &= (15, -12, 17) + (-13, 9, -16) = (2, -3, 1).\end{aligned}$$

16. Projections



- 6 Find $\text{proj}_{\text{plane } L}$.

Let

\mathbf{v}_2 = the vector from B to $\text{proj}_{\text{plane } P} = 2\mathbf{i} - 6\mathbf{j} - 5\mathbf{k}$.

Then $\text{proj}_{\text{plane } L}$ is the line passing through $B(0, 3, 6)$ in the direction $\mathbf{v}_2 = 2\mathbf{i} - 6\mathbf{j} - 5\mathbf{k}$ which has parametrised equations

$$x = 2t, \quad y = 3 - 6t, \quad z = 6 - 5t.$$

Next Time

- 17. Combinatorics: Basic Counting Principles
- 18. Combinatorics: Permutations and Combinations
- 19. Introduction to Probability