Calculus III
Lecture 4

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https://github.com/tmilev/freecalc

2020

Outline

1. Equations of Lines
   - Line from point and direction
   - Line from two points

Outline

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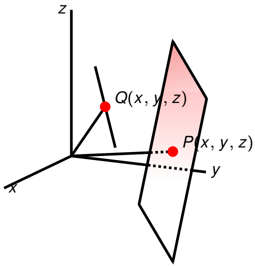
Main Questions



What condition(s) should

- the position vector
- the coordinates

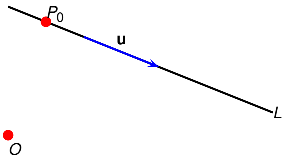
of a point satisfy for it to be on a specific

- line L
- plane $\mathcal{P}$?

Condition(s) in terms of:

- position vector $\Rightarrow$ vector (system of) equations;
- coordinates $\Rightarrow$ scalar equations.

Line from Point and Direction



- Suppose we have line L that passes through point P_0 and has non-zero direction $\mathbf{u}$.

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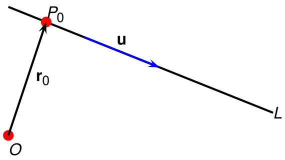

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- Denote by $\mathbf{r}_0 = \mathbf{OP}_0$ the position vector of P_0.

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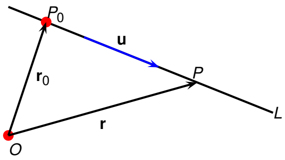

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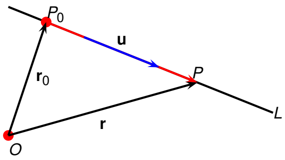

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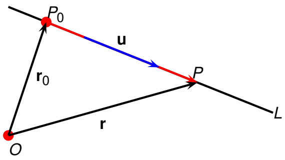

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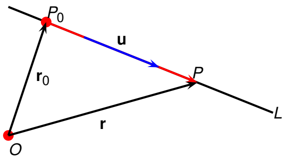

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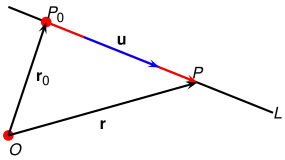

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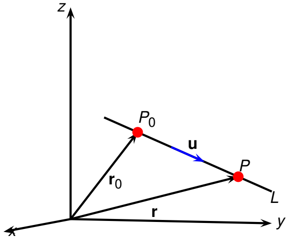
Definition

The equation

$$\mathbf{r} = \mathbf{r}_0 + t\mathbf{u}$$

is called a parametric equation of the the line L.

Line from Point and Direction



- Point $P_0(x_0, y_0, z_0)$, $\mathbf{r}_0 = (x_0, y_0, z_0)$;
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L- line with direction $\mathbf{u}$ passing through P_0

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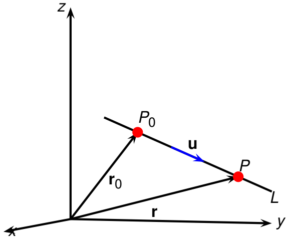

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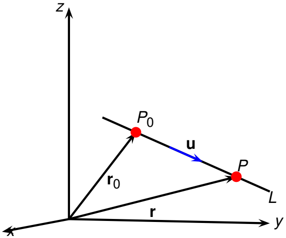

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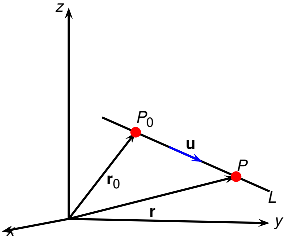

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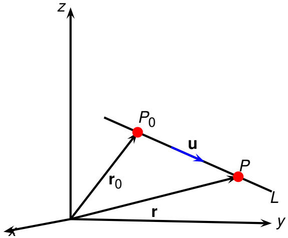

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Definition

The equations

$$\left| \begin{array}{ll} x & = x_0 + tu_1 \\ y & = y_0 + tu_2 \\ z & = z_0 + tu_3 \end{array} \right. , t \in \mathbb{R}$$

are called parametric scalar equations of the line L.

$$\left| \begin{array}{ll} x & = x_0 + tu_1 \\ y & = y_0 + tu_2 \\ z & = z_0 + tu_3 \end{array} \right. \implies \boxed{\frac{x - x_0}{u_1} = \frac{y - y_0}{u_2} = \frac{z - z_0}{u_3}}$$

Symmetric equations

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- Caution! Symmetric equations are valid for $u_1, u_2, u_3 \neq 0$. For example if $u_2 = 0$ the equations should be:

$$\frac{x - x_0}{u_1} = \frac{z - z_0}{u_3} \quad \text{and} \quad y = y_0$$

Example

L - line with direction $\mathbf{u} = (4, 5, 6)$ passing through $P_0(1, 2, 3)$. Find

- a parametric vectorial equation of L;
- a parametric scalar equation of L;
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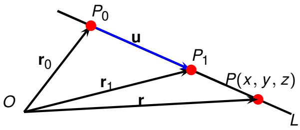
Line from Two Points



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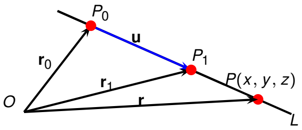

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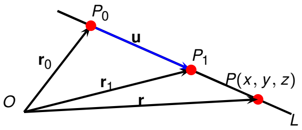

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Parametric equation of a line L:

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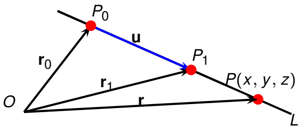

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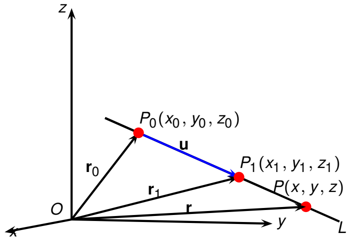

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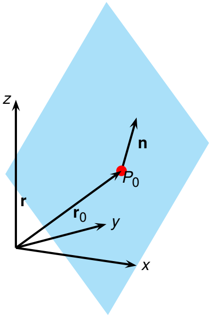
Plane from Point and Normal



- Point P_0, with position vector $\mathbf{r}_0$;
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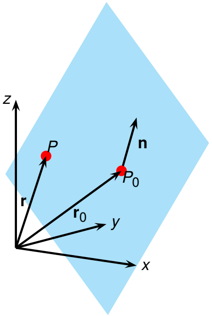
- Goal: describe plane passing through P_0 and orthogonal to $\mathbf{n}$.

Plane from Point and Normal



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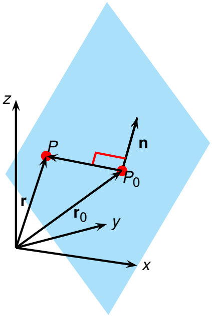

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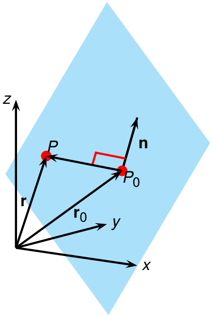

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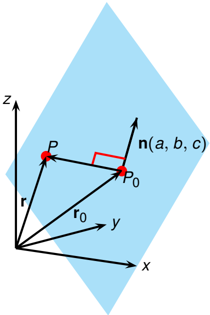
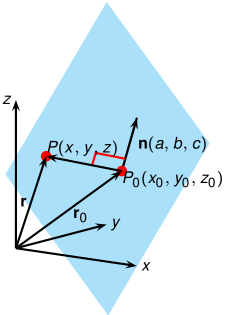


- Point P_0, with position vector $\mathbf{r}_0$; $\mathbf{r}_0 = (x_0, y_0, z_0)$
- Direction $\mathbf{n}$, non-zero vector. $\mathbf{n} = (a, b, c)$
- Goal: describe plane passing through P_0 and orthogonal to $\mathbf{n}$.
- Point P with position $\mathbf{r}$ is on $\mathcal{P} \Leftrightarrow$
- $\mathbf{P_0P} = \mathbf{r} - \mathbf{r}_0$ is orthogonal (normal) to $\mathbf{n} \Leftrightarrow$
- Implicit vectorial equation: $(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.

Plane from Point and Normal



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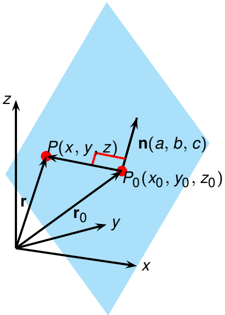

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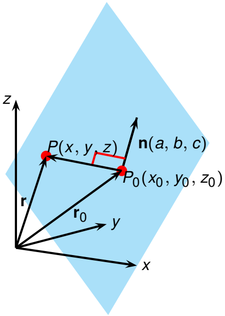

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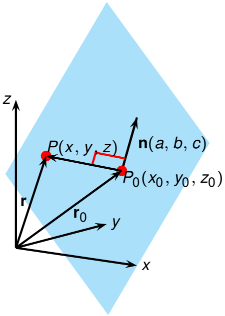

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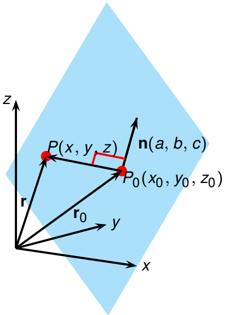

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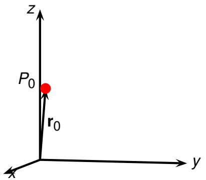

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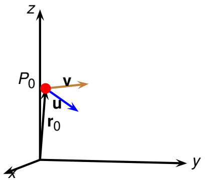

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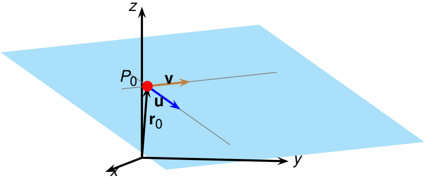

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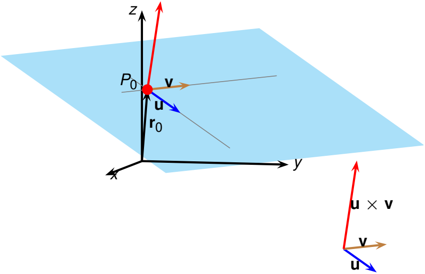

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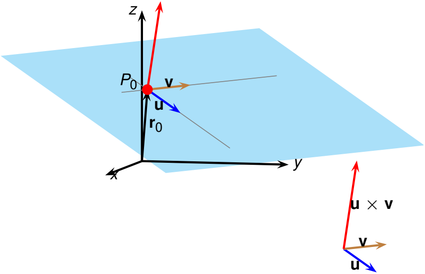

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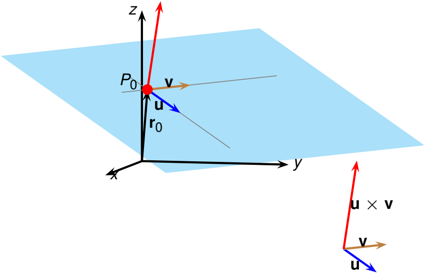

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$$\mathrm{Vol}(R(\mathbf{r} - \mathbf{r}_0, \mathbf{u}, \mathbf{v})) = 0$$

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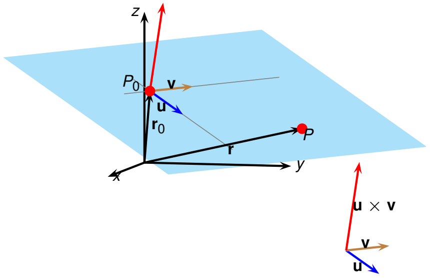

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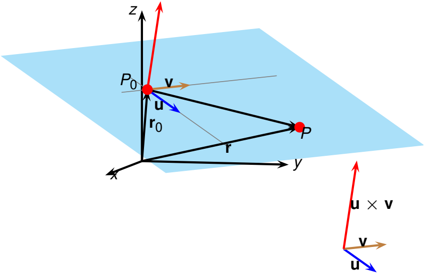

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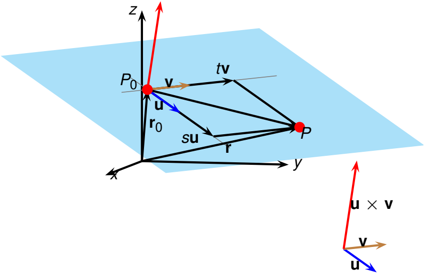

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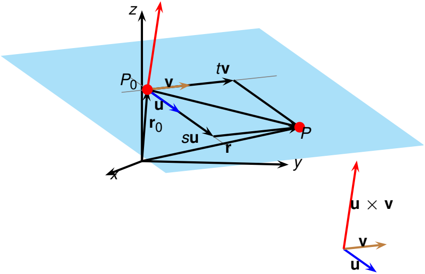

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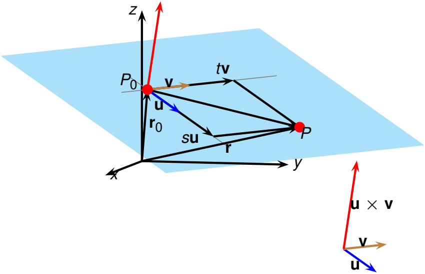

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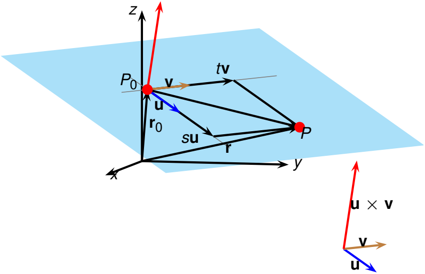

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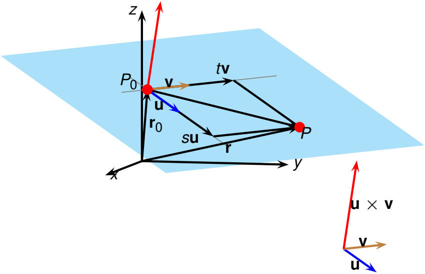

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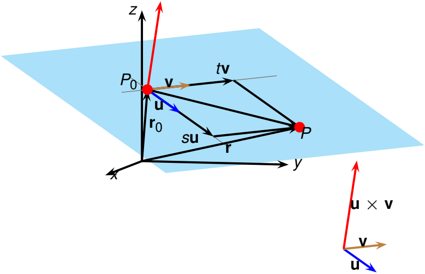

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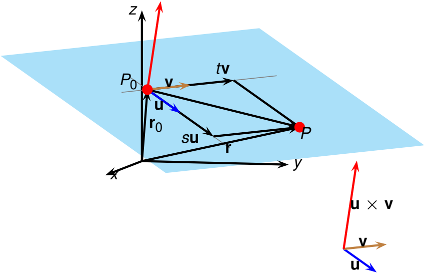

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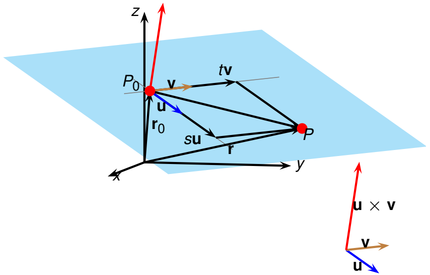

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Parametric scalar equations:

Example

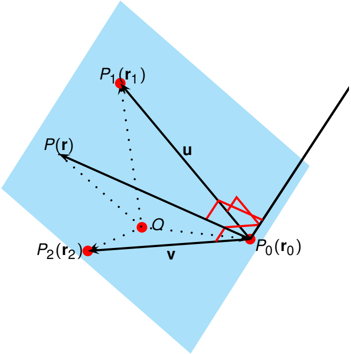
Find equations of a plane passing through $P_0(1,2,3)$ and parallel to the vectors $\mathbf{u} = (-1,0,2)$, $\mathbf{v} = (0,-2,1)$.

$$\mathbf{n} = \mathbf{u} \times \mathbf{v} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ -1 & 0 & 2 \\ 0 & -2 & 1 \end{vmatrix} = 4\mathbf{i} + \mathbf{j} + 2\mathbf{k}$$

$\Rightarrow$ implicit scalar equation given by:
$4(x-1) + 1(y-2) + 2(z-3) = 0 \Longleftrightarrow 4x + y + 2z = 12$
Parametric vectorial equation:
$(x,y,z) = (1,2,3) + s(-1,0,2) + t(0,-2,1)$
Parametric scalar equations:

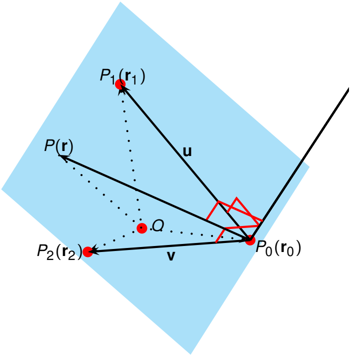
$$\left| \begin{array}{ll} x & = 1 - s \\ y & = 2 - 2t \\ z & = 3 + 2s + t \end{array} \right. \qquad s, t \text{ real parameters.}$$

Plane from Three Points



- Given: three non-collinear points $P_0(\mathbf{r}_0)$, $P_1(\mathbf{r}_1)$, $P_2(\mathbf{r}_2)$.
- Goal: find equations fo plane $\mathcal{P}$ passing through P_0, P_1, and P_2.

Plane from Three Points



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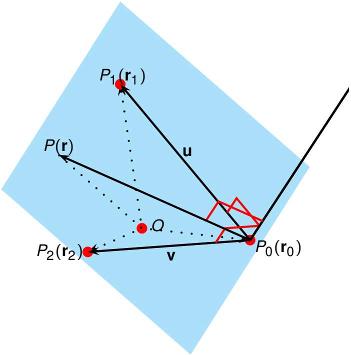
- The plane is parallel to $\mathbf{u} = \mathbf{P}_0\mathbf{P}_1 = \mathbf{r}_1 - \mathbf{r}_0$ and passing through $P_0 \Rightarrow$ this problem was solved previously.

Plane from Three Points



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- The plane is parallel to $\mathbf{u} = \mathbf{P}_0\mathbf{P}_1 = \mathbf{r}_1 - \mathbf{r}_0$ and passing through P_0 $\Rightarrow$ this problem was solved previously.

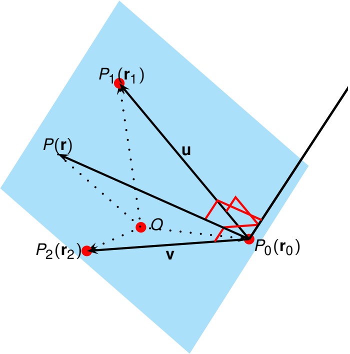
Normal $\mathbf{n} = \mathbf{u} \times \mathbf{v} = (\mathbf{r}_1 - \mathbf{r}_0) \times (\mathbf{r}_2 - \mathbf{r}_0)$
Implicit equation:

$$(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$$

$$\boxed{(\mathbf{r} - \mathbf{r}_0) \cdot [(\mathbf{r}_1 - \mathbf{r}_0) \times (\mathbf{r}_2 - \mathbf{r}_0)] = 0}$$

$$\mathrm{Vol}(R(\mathbf{P}_0\mathbf{P}, \mathbf{P}_0\mathbf{P}_1, \mathbf{P}_0\mathbf{P}_2)) = 0$$

Plane from Three Points



- Given: three non-collinear points $P_0(\mathbf{r}_0)$, $P_1(\mathbf{r}_1)$, $P_2(\mathbf{r}_2)$.
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- The plane is parallel to $\mathbf{u} = \mathbf{P}_0\mathbf{P}_1 = \mathbf{r}_1 - \mathbf{r}_0$ and passing through $P_0 \Rightarrow$ this problem was solved previously.

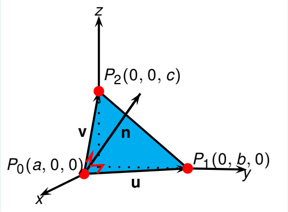
Implicit equation: $(\mathbf{r} - \mathbf{r}_0) \cdot [(\mathbf{r}_1 - \mathbf{r}_0) \times (\mathbf{r}_2 - \mathbf{r}_0)] = 0$

Let the points have coordinates $P_0(x_0, y_0, z_0)$, $P_1(x_1, y_1, z_1)$, $P_2(x_2, y_2, z_2)$. $P(x, y, z)$ is on plane $\mathcal{P}$:

Implicit scalar equation: $\begin{vmatrix} x - x_0 & y - y_0 & z - z_0 \\ x_1 - x_0 & y_1 - y_0 & z_1 - z_0 \\ x_2 - x_0 & y_2 - y_0 & z_2 - z_0 \end{vmatrix} = 0 .$

Example

Let $P_0(a,0,0)$, $P_1(0,b,0)$ $P_2(0,0,c)$ be three points, $a,b,c \neq 0$. Find plane $\mathcal{P}$ passing through P_0, P_1, P_2 (i.e., plane with prescribed x,y,z-intercepts).



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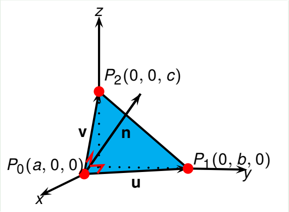
$\mathcal{P}$: parallel to



Example

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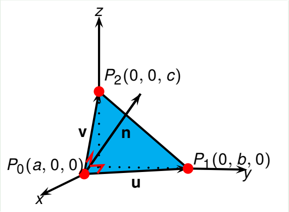
$\mathcal{P}$: parallel to
$\mathbf{P}_0\mathbf{P}_1 = (-a, b, 0), \mathbf{P}_0\mathbf{P}_2 = (-a, 0, c)$.



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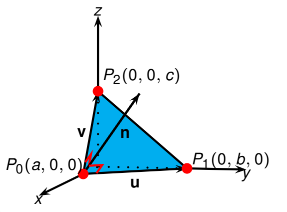

$\mathcal{P}$: parallel to
$\mathbf{P_0P_1} = (-a, b, 0), \mathbf{P_0P_2} = (-a, 0, c)$.
Normal:

Example

Let $P_0(a,0,0)$, $P_1(0,b,0)$ $P_2(0,0,c)$ be three points, $a,b,c\neq 0$. Find plane $\mathcal{P}$ passing through P_0, P_1, P_2 (i.e., plane with prescribed x,y,z-intercepts).

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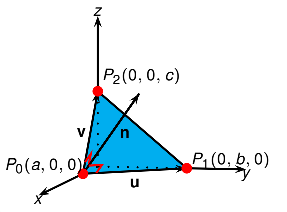

$$\mathbf{n} = \mathbf{P}_0\mathbf{P}_1\times\mathbf{P}_0\mathbf{P}_2 = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ -a & b & 0 \\ -a & 0 & c \end{vmatrix} = bc\mathbf{i}+ac\mathbf{j}+ab\mathbf{k}.$$

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Let $P_0(a, 0, 0)$, $P_1(0, b, 0)$ $P_2(0, 0, c)$ be three points, $a, b, c \neq 0$. Find plane $\mathcal{P}$ passing through P_0, P_1, P_2 (i.e., plane with prescribed x, y, z-intercepts).

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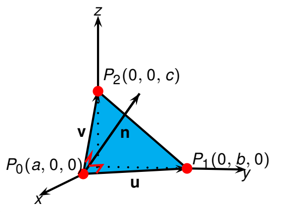

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Implicit scalar equation of plane:

Example

Let $P_0(a,0,0)$, $P_1(0,b,0)$ $P_2(0,0,c)$ be three points, $a,b,c\neq 0$. Find plane $\mathcal{P}$ passing through P_0, P_1, P_2 (i.e., plane with prescribed x,y,z-intercepts).

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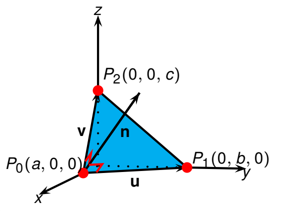

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Implicit scalar equation of plane:

$$(x-a, y, z)\cdot(bc, ac, ab) \quad = \quad 0$$

Example

Let $P_0(a,0,0)$, $P_1(0,b,0)$ $P_2(0,0,c)$ be three points, $a,b,c\neq 0$. Find plane $\mathcal{P}$ passing through P_0, P_1, P_2 (i.e., plane with prescribed x,y,z-intercepts).

$\mathcal{P}$: parallel to
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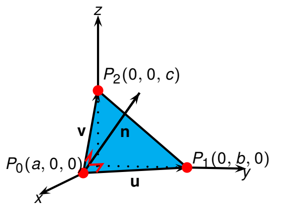

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Implicit scalar equation of plane:

$$\begin{aligned} (x-a,y,z)\cdot(bc,ac,ab) &= 0 \\ bcx+acy+abz &= abc \end{aligned}$$

Example

Let $P_0(a,0,0)$, $P_1(0,b,0)$ $P_2(0,0,c)$ be three points, $a,b,c \neq 0$. Find plane $\mathcal{P}$ passing through P_0, P_1, P_2 (i.e., plane with prescribed x,y,z-intercepts).

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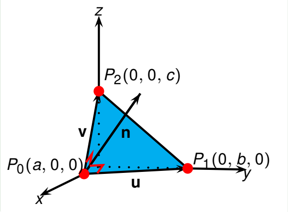

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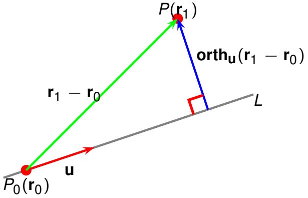
Implicit scalar equation of plane:

$$\begin{aligned} (x-a,y,z)\cdot(bc,ac,ab) &= 0 \\ bcx + acy + abz &= abc \\ \frac{x}{a} + \frac{y}{b} + \frac{z}{c} &= 1 \end{aligned}$$

Relationships betwee points lines and planes

- So far we studied the following geometric objects/
  - Points: $P(\mathbf{r})$.
  - Lines: L: $\mathbf{r} = \mathbf{r}_0 + t\mathbf{u}$
  - Planes: $\mathcal{P}$: $(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$
- We investigate the following relationships/geometric quantities:
  - Parallelism
  - Perpendicularity
  - Angles
  - Distances
  - Intersections

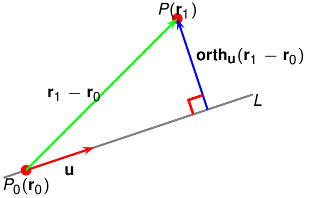
Point and line



Distance from P to L:

- Given: Point $P(\mathbf{r}_1)$,
- line L : $\quad \mathbf{r} = \mathbf{r}_0 + t\mathbf{u}$.
- Goal: find the distance between P and L.

Point and line

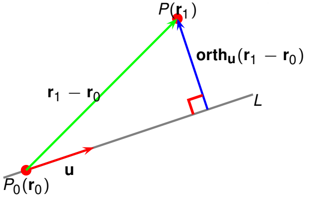


- Given: Point $P(\mathbf{r}_1)$,
- line $L: \quad \mathbf{r} = \mathbf{r}_0 + t\mathbf{u}$.
- Goal: find the distance between P and L.

Distance from P to L:

$$d(P, L) = \left|\mathbf{orth}_{\mathbf{u}}(\mathbf{r}_1 - \mathbf{r}_0)\right|$$

Point and line



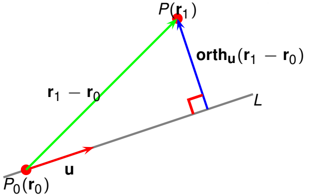
- Given: Point $P(\mathbf{r}_1)$,
- line $L: \quad \mathbf{r} = \mathbf{r}_0 + t\mathbf{u}$.
- Goal: find the distance between P and L.

Distance from P to L:

$$d(P, L) = \left|\mathbf{orth}_{\mathbf{u}}(\mathbf{r}_1 - \mathbf{r}_0)\right|$$

$$d(P, L) = \left|\mathbf{r}_1 - \mathbf{r}_0 - \frac{(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{u}}{\mathbf{u} \cdot \mathbf{u}}\mathbf{u}\right|$$

Point and line



- Given: Point $P(\mathbf{r}_1)$,
- line $L: \quad \mathbf{r} = \mathbf{r}_0 + t\mathbf{u}$.
- Goal: find the distance between P and L.

Distance from P to L:

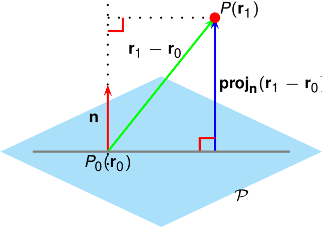
$$d(P, L) = \left|\mathbf{orth_u}(\mathbf{r}_1 - \mathbf{r}_0)\right|$$

$$d(P, L) = \left|\mathbf{r}_1 - \mathbf{r}_0 - \frac{(\mathbf{r}_1 - \mathbf{r}_0)\cdot\mathbf{u}}{\mathbf{u}\cdot\mathbf{u}}\mathbf{u}\right|$$

$$d(P, L) = \frac{|(\mathbf{r}_1 - \mathbf{r}_0)\times\mathbf{u}|}{|\mathbf{u}|}$$

Valid only in 3 dimensions!

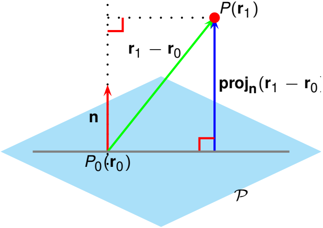
Distance between point and plane



- Given: point $P(\mathbf{r}_1) = (x_1, y_1, z_1)$,
- plane $\mathcal{P}$: $\quad (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: find the distance between P and $\mathcal{P}$.

Distance from P to $\mathcal{P}$:

Distance between point and plane



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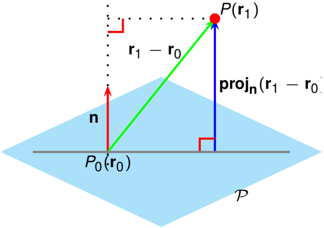
- Goal: find the distance between P and $\mathcal{P}$.

Distance from P to $\mathcal{P}$:

$$\begin{aligned} d(P, \mathcal{P}) &= |\mathbf{proj_n}(\mathbf{r}_1 - \mathbf{r}_0)| \\ d(P, \mathcal{P}) &= \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}|}{|\mathbf{n}|} \end{aligned}$$

Distance between point and plane



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Distance from P to $\mathcal{P}$:

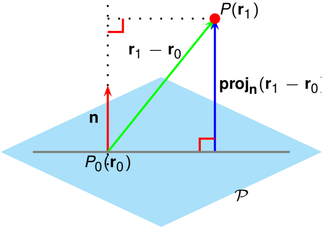
$$d(P, \mathcal{P}) = |\mathbf{proj_n}(\mathbf{r}_1 - \mathbf{r}_0)|$$

$$d(P, \mathcal{P}) = \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}|}{|\mathbf{n}|}$$

Scalar equation:

$$\mathcal{P} : \quad ax + by + cz + d = (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} \quad = \quad 0$$

Distance between point and plane



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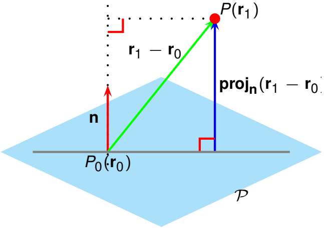
Scalar equation:

$$\begin{aligned} \mathcal{P}: \quad ax + by + cz + d = (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} &= 0 \\ \mathbf{n} &= (a, b, c) \end{aligned}$$

Distance between point and plane



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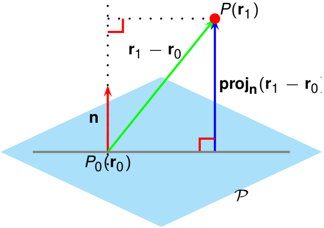
Distance between point and plane



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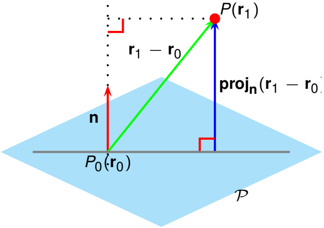
Distance between point and plane



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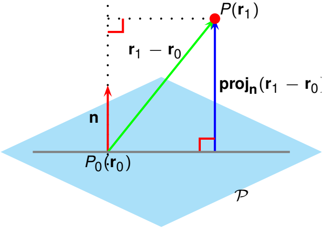
Scalar equation:

$$\begin{aligned} \mathcal{P}: \quad ax + by + cz + d = (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} &= 0 \\ \mathbf{n} &= (a, b, c) \\ d(P, \mathcal{P}) = \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}|}{|\mathbf{n}|} &= \frac{|ax_1 + by_1 + cz_1 + d|}{\sqrt{a^2 + b^2 + c^2}} \end{aligned}$$

Distance between point and plane



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- plane $\mathcal{P}: \quad (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: find the distance between P and $\mathcal{P}$.

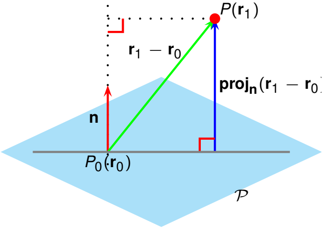
Distance from P to $\mathcal{P}$:

$$\begin{aligned} d(P,\mathcal{P}) &= |\mathbf{proj}_{\mathbf{n}}(\mathbf{r}_1 - \mathbf{r}_0)| \\ d(P,\mathcal{P}) &= \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}|}{|\mathbf{n}|} \end{aligned}$$

Scalar equation:

$$\begin{aligned} \mathcal{P}: \quad ax + by + cz + d = (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} &= 0 \\ \mathbf{n} &= (a, b, c) \\ d(P,\mathcal{P}) = \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}|}{|\mathbf{n}|} &= \frac{|ax_1 + by_1 + cz_1 + d|}{\sqrt{a^2 + b^2 + c^2}} \end{aligned}$$

Distance between point and plane



- Given: point $P(\mathbf{r}_1) = (x_1, y_1, z_1)$,
- plane $\mathcal{P}: \quad (\mathbf{r} - \mathbf{r}_0)\cdot \mathbf{n} = 0$.
- Goal: find the distance between P and $\mathcal{P}$.

Distance from P to $\mathcal{P}$:

$$\begin{aligned} d(P,\mathcal{P}) &= |\mathbf{proj_n}(\mathbf{r}_1 - \mathbf{r}_0)| \\ d(P,\mathcal{P}) &= \frac{|(\mathbf{r}_1 - \mathbf{r}_0)\cdot \mathbf{n}|}{|\mathbf{n}|} \end{aligned}$$

Scalar equation:

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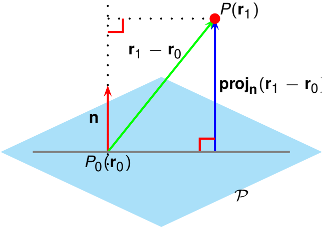
Distance between point and plane



- Given: point $P(\mathbf{r}_1) = (x_1, y_1, z_1)$,
- plane $\mathcal{P}$: $(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: find the distance between P and $\mathcal{P}$.

Distance from P to $\mathcal{P}$:

$$\begin{aligned} d(P, \mathcal{P}) &= |\mathbf{proj}_{\mathbf{n}}(\mathbf{r}_1 - \mathbf{r}_0)| \\ d(P, \mathcal{P}) &= \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}|}{|\mathbf{n}|} \end{aligned}$$

Scalar equation:

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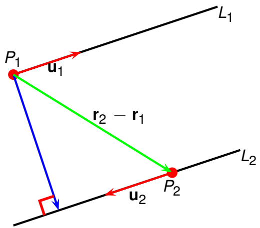
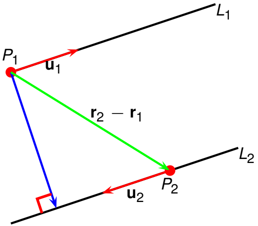
Parallel lines



- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} &=& \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} &=& \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
- Goal: distance between lines.

Parallel lines

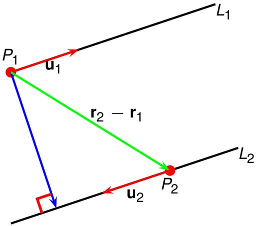
Parallel lines



- Given: lines $\begin{array}{rcl} L_1 : \ \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2 : \ \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
- Goal: distance between lines.

Parallel lines $L_1 || L_2 \iff \mathbf{u}_1, \mathbf{u}_2$ collinear $\iff \boxed{\mathbf{u}_1 \times \mathbf{u}_2 = \mathbf{0}}$

Parallel lines

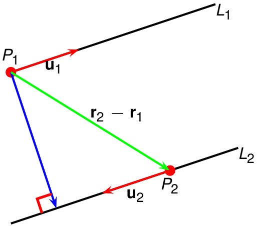


- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} &=& \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} &=& \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
- Goal: distance between lines.

Parallel lines $L_1 || L_2 \iff \mathbf{u}_1, \mathbf{u}_2$ collinear $\iff \boxed{\mathbf{u}_1 \times \mathbf{u}_2 = \mathbf{0}}$ Distance:

$$d = d(L_1, L_2) = d(P_1, L_2) = d(P_2, L_1)$$

Parallel lines



- Given: lines $\begin{array}{rcl} L_1: \ \mathbf{r} &=& \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \ \mathbf{r} &=& \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
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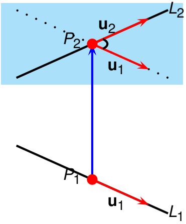
Parallel lines $L_1 || L_2 \iff \mathbf{u}_1, \mathbf{u}_2$ collinear $\iff \boxed{\mathbf{u}_1 \times \mathbf{u}_2 = \mathbf{0}}$ Distance:

$$d = d(L_1, L_2) = d(P_1, L_2) = d(P_2, L_1)$$

$$d = d(L_1, L_2) = |\mathbf{orth}_{\mathbf{u}_1}(\mathbf{r}_2 - \mathbf{r}_1)|$$

$$\boxed{d = \frac{|(\mathbf{r}_2 - \mathbf{r}_1) \times \mathbf{u}_1|}{|\mathbf{u}_1|} = \frac{|(\mathbf{r}_2 - \mathbf{r}_1) \times \mathbf{u}_2|}{|\mathbf{u}_2|}}$$

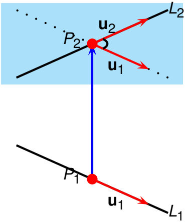
Angle between lines



- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
- Goal: find angle between L_1 and L_2.

Perpendicular lines

Angle between lines



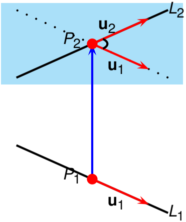
- Given: lines $\begin{array}{rcl} L_1: \ \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \ \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
- Goal: find angle between L_1 and L_2.

Perpendicular lines $L_1 \perp L_2 \iff \mathbf{u}_1 \perp \mathbf{u}_2$

$\iff$

$$\boxed{\mathbf{u}_1 \cdot \mathbf{u}_2 = 0}$$

Angle between lines



- Given: lines $\begin{array}{lrcl} L_1: & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
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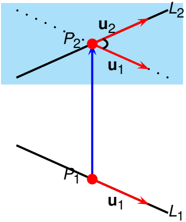
Perpendicular lines $L_1 \perp L_2 \iff \mathbf{u}_1 \perp \mathbf{u}_2$ $\iff$

$$\boxed{\mathbf{u}_1 \cdot \mathbf{u}_2 = 0}$$

Angle between lines

Angle between lines



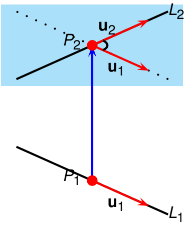
- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
- Goal: find angle between L_1 and L_2.

Perpendicular lines $L_1 \perp L_2 \iff \mathbf{u}_1 \perp \mathbf{u}_2$ $\iff$

$$\boxed{\mathbf{u}_1 \cdot \mathbf{u}_2 = 0}$$

Angle between lines α: angle between $L_1, L_2 \iff \alpha$: acute angle $\mathbf{u}_1, \mathbf{u}_2$

Angle between lines



- Given: lines $\begin{array}{lcl} L_1: & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$.
- Goal: find angle between L_1 and L_2.

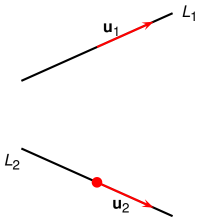
Perpendicular lines $L_1 \perp L_2 \iff \mathbf{u}_1 \perp \mathbf{u}_2$ $\iff$

$$\boxed{\mathbf{u}_1 \cdot \mathbf{u}_2 = 0}$$

Angle between lines α: angle between $L_1, L_2 \iff \alpha$: acute angle $\mathbf{u}_1, \mathbf{u}_2 \iff$

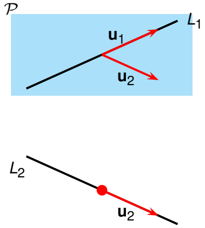
$$\boxed{\alpha = \arccos\left(\frac{|\mathbf{u}_1 \cdot \mathbf{u}_2|}{|\mathbf{u}_1|\,|\mathbf{u}_2|}\right)}$$

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} &=& \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} &=& \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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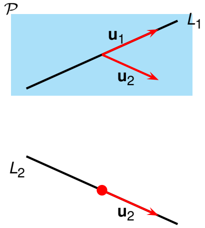
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.
- Construct plane $\mathcal{P}$ with directions $\mathbf{u}_1$, $\mathbf{u}_2$ and passing through L_1.

Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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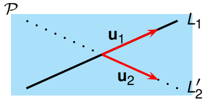
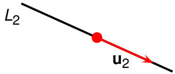
- Construct plane $\mathcal{P}$ with directions $\mathbf{u}_1$, $\mathbf{u}_2$ and passing through L_1.
- Distance b-n L_2 and points on $\mathcal{P}$ is constant.

Distance between non-parallel lines





- Given: lines $\begin{array}{lcl} L_1: & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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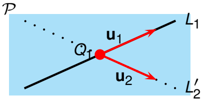
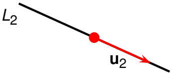
- Construct plane $\mathcal{P}$ with directions $\mathbf{u}_1$, $\mathbf{u}_2$ and passing through L_1.
- Distance b-n L_2 and points on $\mathcal{P}$ is constant.
- Project L_2 orthogonally on $\mathcal{P}$; let the projection be L_2'.

Distance between non-parallel lines





- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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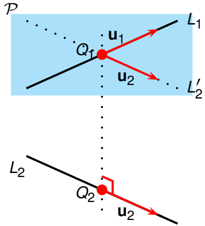
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

- Construct plane $\mathcal{P}$ with directions $\mathbf{u}_1, \mathbf{u}_2$ and passing through L_1.
- Distance b-n L_2 and points on $\mathcal{P}$ is constant.
- Project L_2 orthogonally on $\mathcal{P}$; let the projection be L_2'.
- Let L_2' and L_1 intersect in point Q_1.

Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1: & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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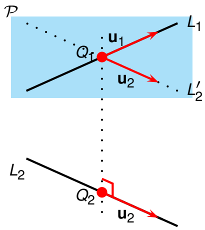
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

- Construct plane $\mathcal{P}$ with directions $\mathbf{u}_1, \mathbf{u}_2$ and passing through L_1.
- Distance b-n L_2 and points on $\mathcal{P}$ is constant.
- Project L_2 orthogonally on $\mathcal{P}$; let the projection be L_2'.
- Let L_2' and L_1 intersect in point Q_1.
- Let Q_2 be the heel of the perpendicular from Q_1 onto Q_2.

Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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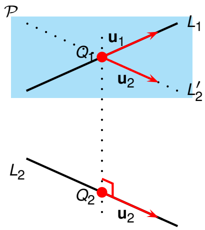
- Construct plane $\mathcal{P}$ with directions $\mathbf{u}_1, \mathbf{u}_2$ and passing through L_1.
- Distance b-n L_2 and points on $\mathcal{P}$ is constant.
- Project L_2 orthogonally on $\mathcal{P}$; let the projection be L_2'.
- Let L_2' and L_1 intersect in point Q_1.
- Let Q_2 be the heel of the perpendicular from Q_1 onto Q_2.
- $\Rightarrow Q_1Q_2 = d(L_1, L_2)$.

Distance between non-parallel lines



- Given: lines $\begin{array}{lccl} L_1: & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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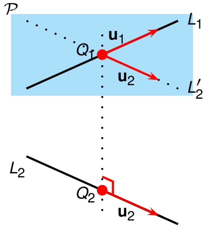
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

- Construct plane $\mathcal{P}$ with directions $\mathbf{u}_1, \mathbf{u}_2$ and passing through L_1.
- Distance b-n L_2 and points on $\mathcal{P}$ is constant.
- Project L_2 orthogonally on $\mathcal{P}$; let the projection be L_2'.
- Let L_2' and L_1 intersect in point Q_1.
- Let Q_2 be the heel of the perpendicular from Q_1 onto Q_2.
- $\Rightarrow Q_1Q_2 = d(L_1, L_2)$.
- $|Q_1Q_2| = d(L_1, L_2)$.

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1: \ \mathbf{r} &=& \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \ \mathbf{r} &=& \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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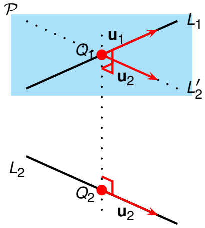
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

- $|Q_1 Q_2| = d(L_1, L_2)$.

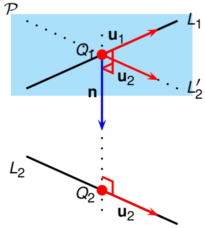
Distance between non-parallel lines



- $|Q_1Q_2| = d(L_1, L_2)$.
- $\mathbf{Q}_1\mathbf{Q}_2 \perp L_1, L_2$

- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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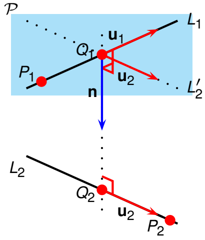
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

- $|Q_1 Q_2| = d(L_1, L_2)$.
- $\mathbf{Q}_1\mathbf{Q}_2 \perp L_1, L_2 \Rightarrow \mathbf{Q}_1\mathbf{Q}_2$ is proportional to $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2$.

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
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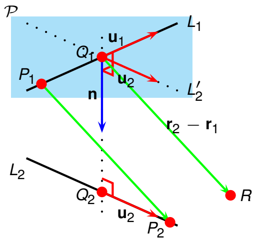
- $|Q_1Q_2| = d(L_1, L_2)$.
- $\mathbf{Q}_1\mathbf{Q}_2 \perp L_1, L_2 \Rightarrow \mathbf{Q}_1\mathbf{Q}_2$ is proportional to $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2$.
- Pick arbitrary points on L_1, L_2 - say, the base points $P_1(\mathbf{r}_1), P_2(\mathbf{r}_2)$.

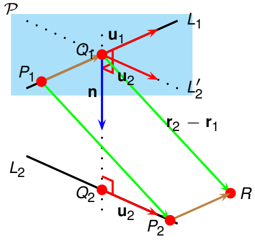
Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1 : & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2 : & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

- $|Q_1Q_2| = d(L_1, L_2)$.
- $\mathbf{Q}_1\mathbf{Q}_2 \perp L_1, L_2 \Rightarrow \mathbf{Q}_1\mathbf{Q}_2$ is proportional to $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2$.
- Pick arbitrary points on L_1, L_2 - say, the base points $P_1(\mathbf{r}_1), P_2(\mathbf{r}_2)$.
- Let R be such that $\mathbf{Q}_1\mathbf{R} = \mathbf{P}_1\mathbf{P}_2 = \mathbf{r}_2 - \mathbf{r}_1$.

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1 : \quad \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2 : \quad \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
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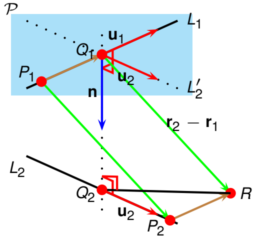
- Pick arbitrary points on L_1, L_2 - say, the base points $P_1(\mathbf{r}_1), P_2(\mathbf{r}_2)$.
- Let R be such that $\mathbf{Q}_1\mathbf{R} = \mathbf{P}_1\mathbf{P}_2 = \mathbf{r}_2 - \mathbf{r}_1$.
- Then $\mathbf{P}_2\mathbf{R}$ is proportional to $\mathbf{u}_1$.

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1: \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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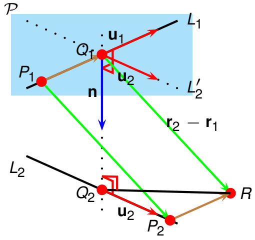
- Let R be such that $\mathbf{Q}_1\mathbf{R} = \mathbf{P}_1\mathbf{P}_2 = \mathbf{r}_2 - \mathbf{r}_1$.
- Then $\mathbf{P}_2\mathbf{R}$ is proportional to $\mathbf{u}_1$.
- $\Rightarrow \mathbf{Q}_2\mathbf{R} = \mathbf{Q}_2\mathbf{P}_2 + \mathbf{P}_2\mathbf{R}$ is perpendicular to $\mathbf{n}$.

Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1 : & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2 : & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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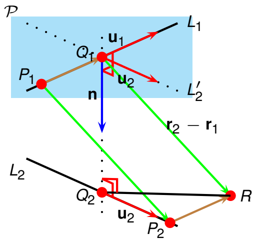
- Pick arbitrary points on L_1, L_2 - say, the base points $P_1(\mathbf{r}_1), P_2(\mathbf{r}_2)$.
- Let R be such that $\mathbf{Q}_1\mathbf{R} = \mathbf{P}_1\mathbf{P}_2 = \mathbf{r}_2 - \mathbf{r}_1$.
- Then $\mathbf{P}_2\mathbf{R}$ is proportional to $\mathbf{u}_1$.
- $\Rightarrow \mathbf{Q}_2\mathbf{R} = \mathbf{Q}_2\mathbf{P}_2 + \mathbf{P}_2\mathbf{R}$ is perpendicular to $\mathbf{n}$.
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj}_{\mathbf{n}}(\mathbf{r}_2 - \mathbf{r}_1)$.

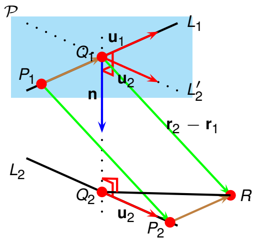
Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1: \mathbf{r} &=& \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} &=& \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.

- $\Rightarrow \mathbf{Q_1Q_2} = \mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)$.

Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1: \mathbf{r} &=& \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: \mathbf{r} &=& \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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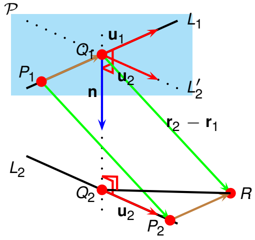
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)$.
- $d(L_1, L_2) = |\mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)|$

Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1: & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2: & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
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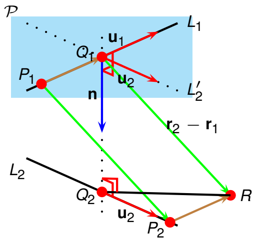
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)$.
- $d(L_1, L_2) = |\mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot \mathbf{n}|}{|\mathbf{n}|}}$

Distance between non-parallel lines



- Given: lines $\begin{array}{rcl} L_1 : \ \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2 : \ \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
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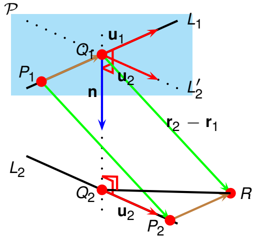
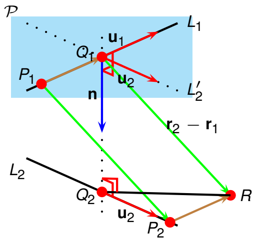
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj}_{\mathbf{n}}(\mathbf{r}_2 - \mathbf{r}_1)$.
- $d(L_1, L_2) = |\mathbf{proj}_{\mathbf{n}}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot \mathbf{n}|}{|\mathbf{n}|}} = \dfrac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot (\mathbf{u}_1 \times \mathbf{u}_2)|}{|\mathbf{u}_1 \times \mathbf{u}_2|}$

Distance between non-parallel lines



- Given: lines $\begin{array}{lcl} L_1 : & \mathbf{r} & = & \mathbf{r}_1 + t\mathbf{u}_1 \\ L_2 : & \mathbf{r} & = & \mathbf{r}_2 + s\mathbf{u}_2 \end{array}$
- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
- Goal: find distance between the lines = $d(L_1, L_2)$ = shortest distance b-n points on the two lines.
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)$.
- $d(L_1, L_2) = |\mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot \mathbf{n}|}{|\mathbf{n}|}} = \frac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot (\mathbf{u}_1 \times \mathbf{u}_2)|}{|\mathbf{u}_1 \times \mathbf{u}_2|}$
- If lines are intersecting we know $d(L_1, L_2) = 0$.

Distance between non-parallel lines



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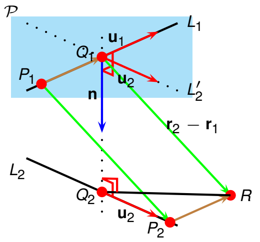
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj}_{\mathbf{n}}(\mathbf{r}_2 - \mathbf{r}_1)$.
- $d(L_1, L_2) = |\mathbf{proj}_{\mathbf{n}}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot \mathbf{n}|}{|\mathbf{n}|}} = \frac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot (\mathbf{u}_1 \times \mathbf{u}_2)|}{|\mathbf{u}_1 \times \mathbf{u}_2|}$
- If lines are intersecting we know $d(L_1, L_2) = 0$. Since the lines intersect L_2 and L_2' coincide.

Distance between non-parallel lines



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- The lines are skew or intersecting, i.e., $\mathbf{n} = \mathbf{u}_1 \times \mathbf{u}_2 \neq \mathbf{0}$.
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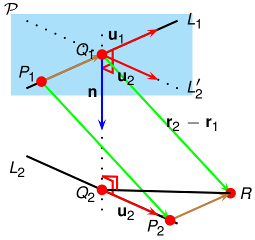
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj}_{\mathbf{n}}(\mathbf{r}_2 - \mathbf{r}_1)$.
- $d(L_1, L_2) = |\mathbf{proj}_{\mathbf{n}}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot \mathbf{n}|}{|\mathbf{n}|}} = \frac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot (\mathbf{u}_1 \times \mathbf{u}_2)|}{|\mathbf{u}_1 \times \mathbf{u}_2|}$
- If lines are intersecting we know $d(L_1, L_2) = 0$. Since the lines intersect L_2 and L_2' coincide. $\Rightarrow (\mathbf{r}_2 - \mathbf{r}_1) \cdot (\mathbf{u}_1 \times \mathbf{u}_2) = 0$

Distance between non-parallel lines



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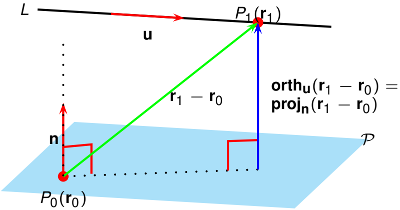
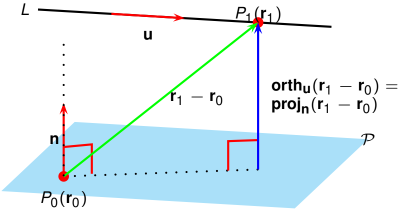
- $\Rightarrow \mathbf{Q}_1\mathbf{Q}_2 = \mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)$.
- $d(L_1, L_2) = |\mathbf{proj_n}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1)\cdot \mathbf{n}|}{|\mathbf{n}|}} = \frac{|(\mathbf{r}_2 - \mathbf{r}_1)\cdot(\mathbf{u}_1 \times \mathbf{u}_2)|}{|\mathbf{u}_1 \times \mathbf{u}_2|}$
- If lines are intersecting we know $d(L_1, L_2) = 0$. Since the lines intersect L_2 and L_2' coincide. $\Rightarrow (\mathbf{r}_2 - \mathbf{r}_1)\cdot(\mathbf{u}_1 \times \mathbf{u}_2) = 0 \Rightarrow$ the formula $d(L_1, L_2) = \frac{|(\mathbf{r}_2 - \mathbf{r}_1)\cdot(\mathbf{u}_1 \times \mathbf{u}_2)|}{|\mathbf{u}_1 \times \mathbf{u}_2|} = 0$ produces the expected result.

Distance between parallel line and plane



- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}: \quad (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- The plane and the line are parallel,
- Goal: find distance between the the two.

Distance between parallel line and plane



- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
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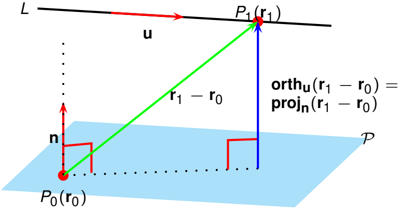
- The plane and the line are parallel, i.e. $\mathbf{u} \cdot \mathbf{n} = 0$.
- Goal: find distance between the the two.

Distance between parallel line and plane



- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
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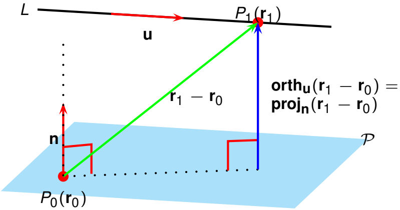
- The plane and the line are parallel, i.e. $\mathbf{u} \cdot \mathbf{n} = 0$.
- Goal: find distance between the the two.

Distance from L to $\mathcal{P}$: $d(L, \mathcal{P}) = d(P_1, \mathcal{P})$

Distance between parallel line and plane



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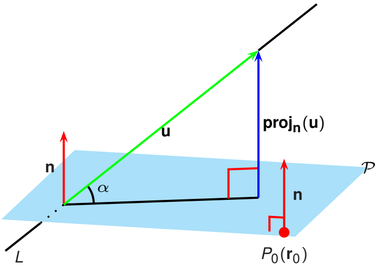
Distance from L to $\mathcal{P}$: $d(L, \mathcal{P}) = d(P_1, \mathcal{P})$

$$d(L, \mathcal{P}) = |\mathbf{orth_u}(\mathbf{r}_1 - \mathbf{r}_0)| = \mathbf{proj_n}(\mathbf{r}_1 - \mathbf{r}_0)|$$

$$d(L, \mathcal{P}) = \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \times \mathbf{u}|}{|\mathbf{u}|} = \frac{|(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}|}{|\mathbf{n}|}$$

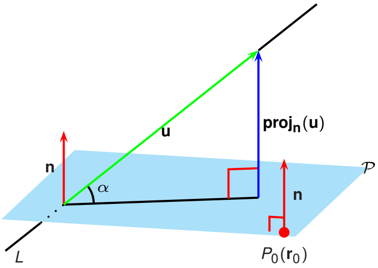
Angle between line and plane



- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}: \quad (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: Find/define angle between line and plane.

Line perpendicular to plane

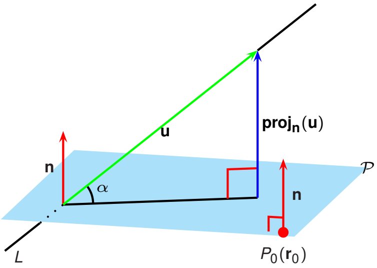
Angle between line and plane



- Given: line L : $\mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}$: $(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: Find/define angle between line and plane.

Line perpendicular to plane $\Leftrightarrow \mathbf{u} \| \mathbf{n}$

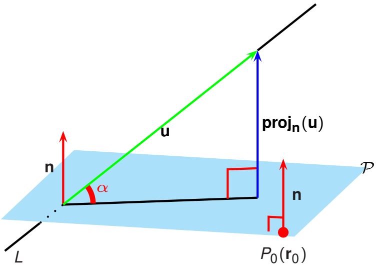
Angle between line and plane



- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}: \quad (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: Find/define angle between line and plane.

Line perpendicular to plane $\Leftrightarrow \mathbf{u} \| \mathbf{n} \Leftrightarrow \boxed{\mathbf{u} \times \mathbf{n} = \mathbf{0}}$

Angle between line and plane



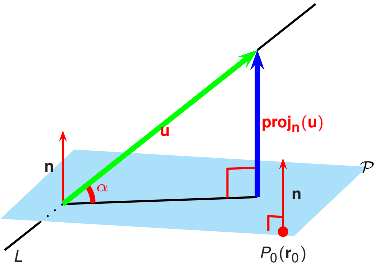
- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}: \quad (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: Find/define angle between line and plane.

Line perpendicular to plane $\Leftrightarrow \mathbf{u} \| \mathbf{n} \Leftrightarrow \boxed{\mathbf{u} \times \mathbf{n} = \mathbf{0}}$

Angle between line and plane α: angle between L, $\mathcal{P}$.

$\sin\alpha \quad =$

Angle between line and plane



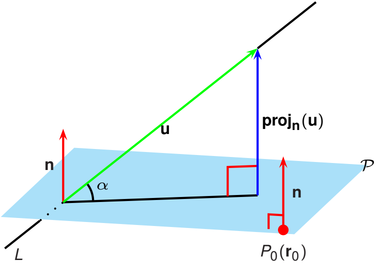
- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}: \quad (\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: Find/define angle between line and plane.

Line perpendicular to plane $\Leftrightarrow \mathbf{u} \| \mathbf{n} \Leftrightarrow \boxed{\mathbf{u} \times \mathbf{n} = \mathbf{0}}$

Angle between line and plane α: angle between L, $\mathcal{P}$.

$$\sin\alpha = \frac{|\mathrm{proj}_{\mathbf{n}}\mathbf{u}|}{|\mathbf{u}|}$$

Angle between line and plane



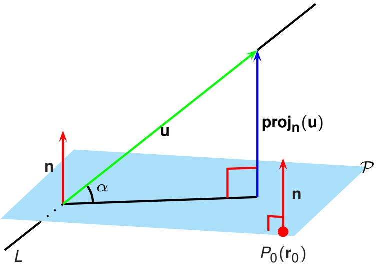
- Given: line L : $\mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}$: $(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: Find/define angle between line and plane.

Line perpendicular to plane $\Leftrightarrow \mathbf{u} \| \mathbf{n} \Leftrightarrow \boxed{\mathbf{u} \times \mathbf{n} = \mathbf{0}}$

Angle between line and plane α: angle between L, $\mathcal{P}$.

$$\sin\alpha = \frac{|\mathrm{proj}_{\mathbf{n}}\mathbf{u}|}{|\mathbf{u}|} = \frac{|\mathbf{u}\cdot\mathbf{n}|}{|\mathbf{n}||\mathbf{u}|}$$

Angle between line and plane



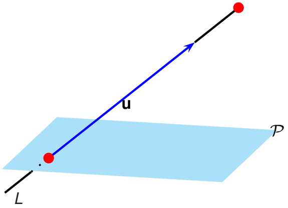
- Given: line L : $\mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- plane $\mathcal{P}$: $(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$.
- Goal: Find/define angle between line and plane.

Line perpendicular to plane $\Leftrightarrow \mathbf{u} \| \mathbf{n} \Leftrightarrow \boxed{\mathbf{u} \times \mathbf{n} = \mathbf{0}}$

Angle between line and plane α: angle between L, $\mathcal{P}$.

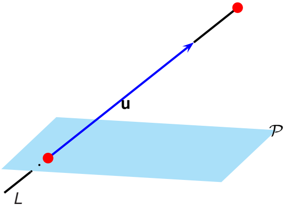
$$\begin{aligned} \sin\alpha &= \frac{|\mathbf{proj_n u}|}{|\mathbf{u}|} = \frac{|\mathbf{u}\cdot\mathbf{n}|}{|\mathbf{n}||\mathbf{u}|} \\ \alpha &= \arcsin\left(\frac{|\mathbf{u}\cdot\mathbf{n}|}{|\mathbf{u}||\mathbf{n}|}\right) \end{aligned}$$

Intersection between line and plane



- Given: line $L: \quad \mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
- $\mathbf{r}_1 = (x_1, y_1, z_1)$, $u = (p, q, r)$,
- plane $\mathcal{P} : ax + by + cz - d = 0$.
- Goal: find the intersection between line and plane.

Intersection between line and plane



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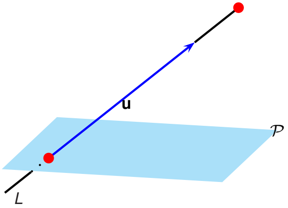
Let $P_0(\mathbf{r}_0)$ be a point on the plane.

Intersection between line and plane



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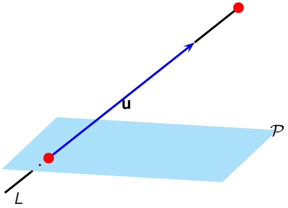
Intersection between line and plane



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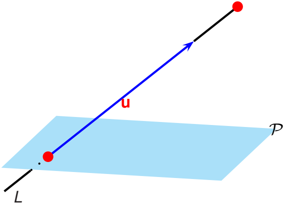
Intersection between line and plane



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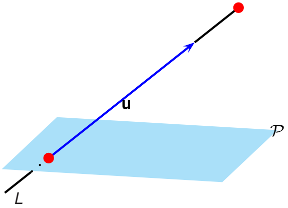
Intersection between line and plane



- Given: line L : $\mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$,
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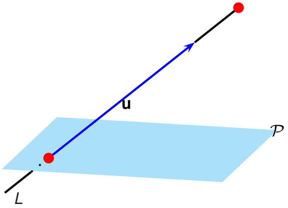

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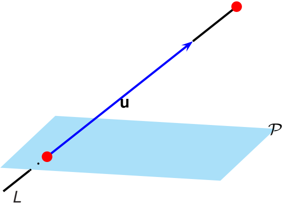
$$(\mathbf{r}_1 + t\mathbf{u} - \mathbf{r}_0) \cdot \mathbf{n} = 0$$

Intersection between line and plane



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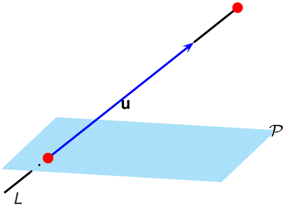
Intersection between line and plane



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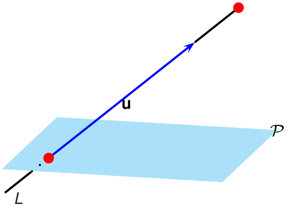
$$
\begin{aligned}
(\mathbf{r}_1 + t\mathbf{u} - \mathbf{r}_0) \cdot \mathbf{n} &= 0 \\
(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n} + t\mathbf{u} \cdot \mathbf{n} &= 0
\end{aligned}
$$

Intersection between line and plane



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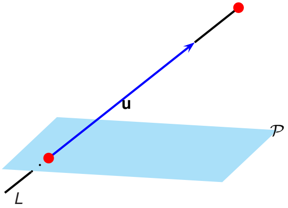
\begin{aligned}
(\mathbf{r}_1 + t\mathbf{u} - \mathbf{r}_0) \cdot \mathbf{n} &= 0 \\
(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n} + t\mathbf{u} \cdot \mathbf{n} &= 0 \\
t &= -\frac{(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}}{\mathbf{u} \cdot \mathbf{n}}
\end{aligned}
$$

Intersection between line and plane



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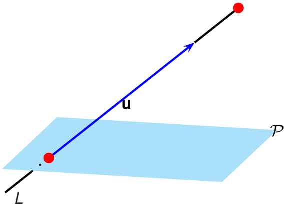
$$
\begin{aligned}
(\mathbf{r}_1 + t\mathbf{u} - \mathbf{r}_0) \cdot \mathbf{n} &= 0 \\
(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n} + t\mathbf{u} \cdot \mathbf{n} &= 0 \\
t &= -\frac{(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}}{\mathbf{u} \cdot \mathbf{n}} \\
\mathbf{r} &= \mathbf{r}_1 - \frac{(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n}}{\mathbf{u} \cdot \mathbf{n}} \mathbf{u}
\end{aligned}
$$

Intersection between line and plane



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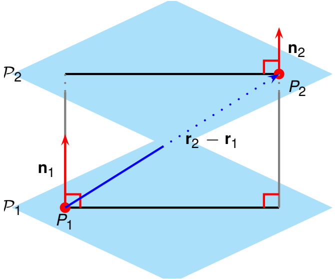
- Goal: find the intersection between line and plane.

Let $P_0(\mathbf{r}_0)$ be a point on the plane. Then a point $P(\mathbf{r})$, $\mathbf{r} = (x, y, z)$ is on the plane if $(\mathbf{r} - \mathbf{r}_0) \cdot \mathbf{n} = 0$. A point $P(\mathbf{r})$ on the line is of the form $\mathbf{r} = \mathbf{r}_1 + t\mathbf{u}$, therefore P lies on both the line and the plane if:

$$
\begin{aligned}
(\mathbf{r}_1 + t\mathbf{u} - \mathbf{r}_0) \cdot \mathbf{n} &= 0 \\
(\mathbf{r}_1 - \mathbf{r}_0) \cdot \mathbf{n} + t\mathbf{u} \cdot \mathbf{n} &= 0 \\
t &= -\frac{(\mathbf{r}_1 - \mathbf{r}_0)\cdot\mathbf{n}}{\mathbf{u}\cdot\mathbf{n}} \\
\mathbf{r} &= \mathbf{r}_1 - \frac{(\mathbf{r}_1 - \mathbf{r}_0)\cdot\mathbf{n}}{\mathbf{u}\cdot\mathbf{n}}\mathbf{u} \\
&= (x_1, y_1, z_1) - \frac{ax_1 + by_1 + cz_1 - d}{ap + bq + cr}(p, q, r)
\end{aligned}
$$

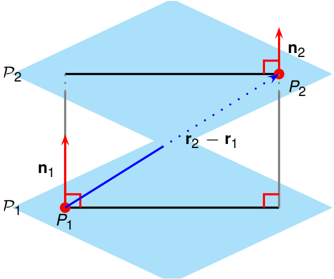
Parallel planes



Planes are parallel

- Given: planes
$$\begin{array}{lrcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0 \end{array}.$$
- Goal: Establish whether planes are parallel, find distance b-n planes.

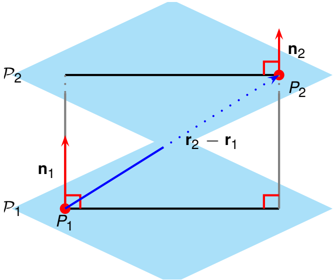
Parallel planes



- Given: planes
$$\begin{array}{rcl} \mathcal{P}_1: \quad (\mathbf{r}-\mathbf{r}_1)\cdot \mathbf{n}_1 &=& 0 \\ \mathcal{P}_2: \quad (\mathbf{r}-\mathbf{r}_2)\cdot \mathbf{n}_2 &=& 0 \end{array}.$$
- Goal: Establish whether planes are parallel, find distance b-n planes.

Planes are parallel $\mathcal{P}_1 || \mathcal{P}_2 \Leftrightarrow \mathbf{n}_1, \mathbf{n}_2$ collinear $\Leftrightarrow \boxed{\mathbf{n}_1 \times \mathbf{n}_2 = \mathbf{0}}$.

Parallel planes

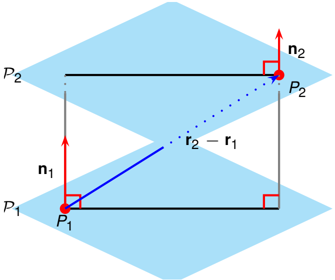


- Given: planes
$$\begin{array}{rcl} \mathcal{P}_1: \quad (\mathbf{r}-\mathbf{r}_1)\cdot \mathbf{n}_1 &=& 0 \\ \mathcal{P}_2: \quad (\mathbf{r}-\mathbf{r}_2)\cdot \mathbf{n}_2 &=& 0 \end{array}.$$
- Goal: Establish whether planes are parallel, find distance b-n planes.

Planes are parallel $\mathcal{P}_1 || \mathcal{P}_2 \Leftrightarrow \mathbf{n}_1, \mathbf{n}_2$ collinear $\Leftrightarrow \boxed{\mathbf{n}_1 \times \mathbf{n}_2 = \mathbf{0}}$.

Distance: $\quad d(\mathcal{P}_1, \mathcal{P}_2) = |\mathbf{proj}_{\mathbf{n}_1}(\mathbf{r}_2 - \mathbf{r}_1)|$

Parallel planes

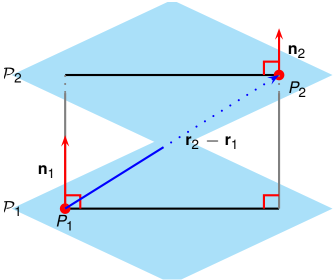


- Given: planes
$$\begin{array}{rcl} \mathcal{P}_1 : \quad (\mathbf{r}-\mathbf{r}_1)\cdot \mathbf{n}_1 &=& 0 \\ \mathcal{P}_2 : \quad (\mathbf{r}-\mathbf{r}_2)\cdot \mathbf{n}_2 &=& 0 \end{array}.$$
- Goal: Establish whether planes are parallel, find distance b-n planes.

Planes are parallel $\mathcal{P}_1 || \mathcal{P}_2 \Leftrightarrow \mathbf{n}_1, \mathbf{n}_2$ collinear $\Leftrightarrow \boxed{\mathbf{n}_1 \times \mathbf{n}_2 = \mathbf{0}}$.

Distance: $\quad d(\mathcal{P}_1, \mathcal{P}_2) = |\mathbf{proj}_{\mathbf{n}_1}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1)\cdot \mathbf{n}_1|}{|\mathbf{n}_1|}}$

Parallel planes



- Given: planes
$$\begin{array}{rcl} \mathcal{P}_1 : \quad (\mathbf{r} - \mathbf{r}_1) \cdot \mathbf{n}_1 & = & 0 \\ \mathcal{P}_2 : \quad (\mathbf{r} - \mathbf{r}_2) \cdot \mathbf{n}_2 & = & 0 \end{array} .$$
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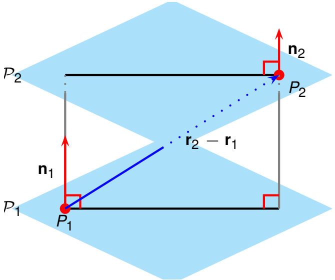
Assume $\mathbf{n}_1 = \mathbf{n}_2 = (a, b, c)$

Parallel planes



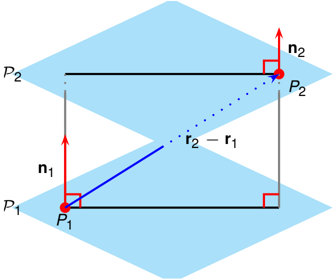
- Given: planes
$$\begin{array}{rcl}\mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot \mathbf{n}_1 & = & 0\\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot \mathbf{n}_2 & = & 0\end{array}.$$
- Goal: Establish whether planes are parallel, find distance b-n planes.

Planes are parallel $\mathcal{P}_1 || \mathcal{P}_2 \Leftrightarrow \mathbf{n}_1, \mathbf{n}_2$ collinear $\Leftrightarrow \boxed{\mathbf{n}_1 \times \mathbf{n}_2 = \mathbf{0}}$.

Distance: $d(\mathcal{P}_1, \mathcal{P}_2) = |\mathbf{proj}_{\mathbf{n}_1}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1)\cdot \mathbf{n}_1|}{|\mathbf{n}_1|}}$

Assume $\mathbf{n}_1 = \mathbf{n}_2 = (a, b, c) \Rightarrow$ plane eq-ns: $\begin{array}{l}\mathcal{P}_1: ax + by + cz = d_1\\ \mathcal{P}_2: ax + by + cz = d_2\end{array}.$

Parallel planes



- Given: planes
$$\begin{array}{rcl} \mathcal{P}_1: & (\mathbf{r} - \mathbf{r}_1) \cdot \mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r} - \mathbf{r}_2) \cdot \mathbf{n}_2 & = & 0 \end{array}.$$
- Goal: Establish whether planes are parallel, find distance b-n planes.

Planes are parallel $\mathcal{P}_1 || \mathcal{P}_2 \Leftrightarrow \mathbf{n}_1, \mathbf{n}_2$ collinear $\Leftrightarrow \boxed{\mathbf{n}_1 \times \mathbf{n}_2 = \mathbf{0}}$.

Distance: $\quad d(\mathcal{P}_1, \mathcal{P}_2) = |\mathbf{proj}_{\mathbf{n}_1}(\mathbf{r}_2 - \mathbf{r}_1)| = \boxed{\dfrac{|(\mathbf{r}_2 - \mathbf{r}_1) \cdot \mathbf{n}_1|}{|\mathbf{n}_1|}}$

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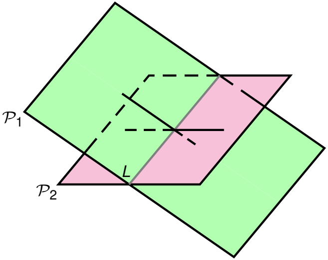
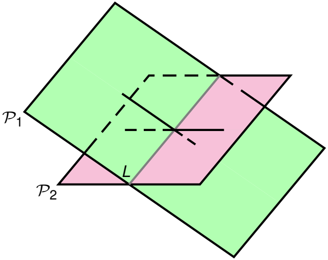
$$\Rightarrow \boxed{d(\mathcal{P}_1, \mathcal{P}_2) = \frac{|d_2 - d_1|}{\sqrt{a^2 + b^2 + c^2}}}$$

Angle between planes



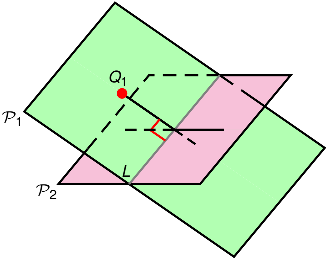
- Given: planes $\begin{array}{rl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 = 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 = 0 \end{array}$
- Goal: define and find the angle between the two planes.

Angle between planes



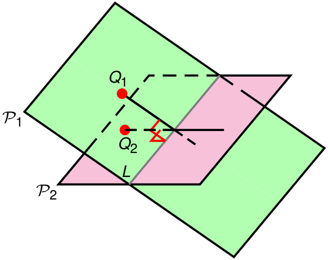
- Given: planes $\begin{array}{rrcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Let L - intersection line of two planes.

Angle between planes



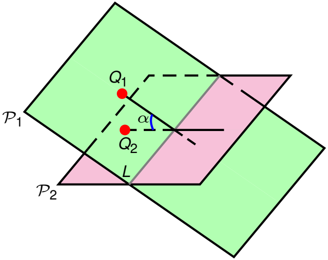
- Given: planes $\begin{array}{rcl}\mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0\\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0\end{array}$
- Goal: define and find the angle between the two planes.
- Let L - intersection line of two planes.
- In $\mathcal{P}_1$, drop perpendicular from arbitrary point Q_1 to L.

Angle between planes



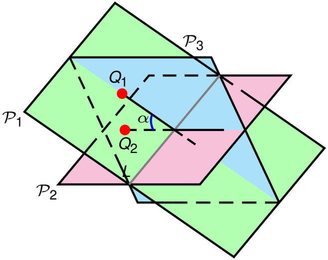
- Given: planes $\begin{array}{rcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Let L - intersection line of two planes.
- In $\mathcal{P}_1$, drop perpendicular from arbitrary point Q_1 to L.
- In $\mathcal{P}_2$, raise a perpendicular from the perpendicular heel.

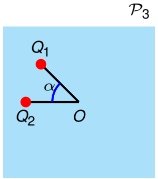
Angle between planes



- Given: planes $\begin{array}{rcl} \mathcal{P}_1 : \quad (\mathbf{r} - \mathbf{r}_1) \cdot \mathbf{n}_1 & = & 0 \\ \mathcal{P}_2 : \quad (\mathbf{r} - \mathbf{r}_2) \cdot \mathbf{n}_2 & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Let L - intersection line of two planes.
- In $\mathcal{P}_1$, drop perpendicular from arbitrary point Q_1 to L.
- In $\mathcal{P}_2$, raise a perpendicular from the perpendicular heel.
- Define angle α b-n $\mathcal{P}_1, \mathcal{P}_2$ = acute angle b-n two perpendiculars.

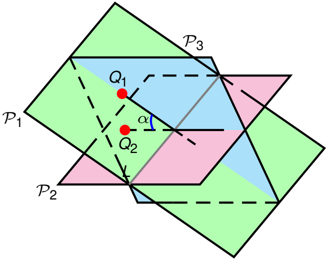
Angle between planes



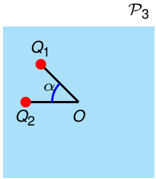


- Given: planes $\begin{array}{lcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Let L - intersection line of two planes.
- In $\mathcal{P}_1$, drop perpendicular from arbitrary point Q_1 to L.
- In $\mathcal{P}_2$, raise a perpendicular from the perpendicular heel.
- Define angle α b-n $\mathcal{P}_1, \mathcal{P}_2$ = acute angle b-n two perpendiculars.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.

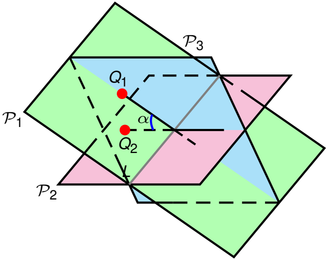
Angle between planes



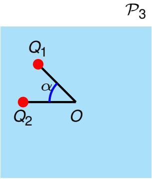
- Given: planes $\begin{aligned}\mathcal{P}_1: \quad (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 &= 0\\ \mathcal{P}_2: \quad (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 &= 0\end{aligned}$
- Goal: define and find the angle between the two planes.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.



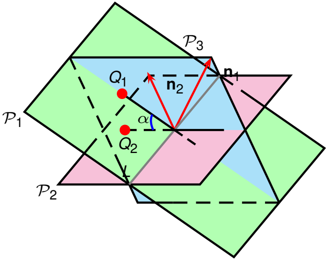
Angle between planes

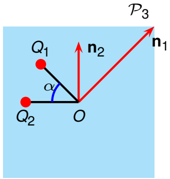


- Given: planes $\begin{aligned} \mathcal{P}_1 : \quad (\mathbf{r} - \mathbf{r}_1) \cdot \mathbf{n}_1 &= 0 \\ \mathcal{P}_2 : \quad (\mathbf{r} - \mathbf{r}_2) \cdot \mathbf{n}_2 &= 0 \end{aligned}$
- Goal: define and find the angle between the two planes.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.
- $\mathcal{P}_3$ is orthogonal to L.



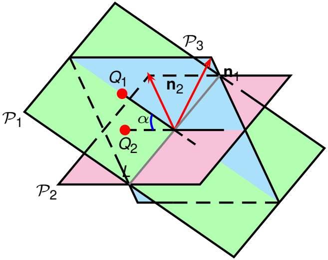
Angle between planes

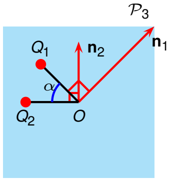




- Given: planes $\begin{array}{rcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot \color{red}{\mathbf{n}_1} & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot \color{red}{\mathbf{n}_2} & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.
- $\mathcal{P}_3$ is orthogonal to L.
- $\Rightarrow \mathcal{P}_3$ contains the normal vectors $\mathbf{n}_1, \mathbf{n}_2$.

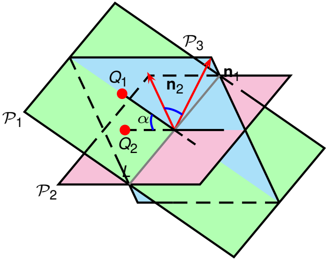
Angle between planes

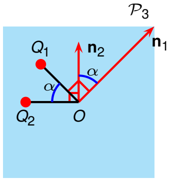




- Given: planes $\begin{array}{rcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.
- $\mathcal{P}_3$ is orthogonal to L.
- $\Rightarrow \mathcal{P}_3$ contains the normal vectors $\mathbf{n}_1, \mathbf{n}_2$.
- $\mathbf{n}_1 \perp \mathbf{OQ}_1$ and $\mathbf{n}_2 \perp \mathbf{OQ}_2$.

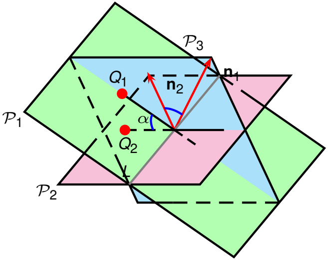
Angle between planes

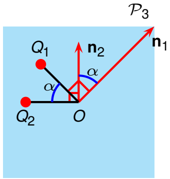




- Given: planes $\begin{array}{lrcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.
- $\mathcal{P}_3$ is orthogonal to L.
- $\Rightarrow \mathcal{P}_3$ contains the normal vectors $\mathbf{n}_1, \mathbf{n}_2$.
- $\mathbf{n}_1 \perp \mathbf{OQ}_1$ and $\mathbf{n}_2 \perp \mathbf{OQ}_2$.
- $$\begin{array}{rcl} \alpha & = & \text{acute}\angle(\mathbf{n}_1, \mathbf{n}_2) \\ \alpha & = & \arccos\left(\frac{|\mathbf{n}_1\cdot\mathbf{n}_2|}{|\mathbf{n}_1|\,|\mathbf{n}_2|}\right) \end{array}$$

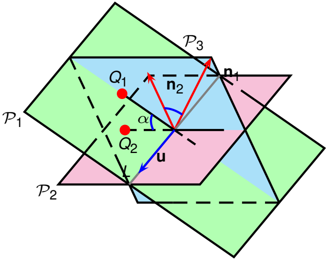
Angle between planes

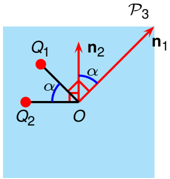




- Given: planes $\begin{array}{rcl}\mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0\\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0\end{array}$
- Goal: define and find the angle between the two planes.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.
- $\mathcal{P}_3$ is orthogonal to L.
- $\Rightarrow \mathcal{P}_3$ contains the normal vectors $\mathbf{n}_1$, $\mathbf{n}_2$.
- $\mathbf{n}_1 \perp \mathbf{OQ}_1$ and $\mathbf{n}_2 \perp \mathbf{OQ}_2$.
- $$\begin{array}{rcl}\alpha & = & \text{acute}\angle(\mathbf{n}_1, \mathbf{n}_2)\\ \alpha & = & \arccos\left(\frac{|\mathbf{n}_1\cdot\mathbf{n}_2|}{|\mathbf{n}_1|\,|\mathbf{n}_2|}\right)\end{array}$$
- $\perp$ planes: $\Rightarrow \alpha = \frac{\pi}{2} \iff \boxed{\mathbf{n}_1\cdot\mathbf{n}_2 = 0}$.

Angle between planes





- Given: planes $\begin{array}{rrcl} \mathcal{P}_1: & (\mathbf{r}-\mathbf{r}_1)\cdot\mathbf{n}_1 & = & 0 \\ \mathcal{P}_2: & (\mathbf{r}-\mathbf{r}_2)\cdot\mathbf{n}_2 & = & 0 \end{array}$
- Goal: define and find the angle between the two planes.
- Consider the plane $\mathcal{P}_3$ spanned by the two constructed perpendiculars.
- $\mathcal{P}_3$ is orthogonal to L.
- $\Rightarrow \mathcal{P}_3$ contains the normal vectors $\mathbf{n}_1, \mathbf{n}_2$.
- $\mathbf{n}_1 \perp \mathbf{OQ}_1$ and $\mathbf{n}_2 \perp \mathbf{OQ}_2$.
- $$\begin{array}{rcl} \alpha & = & \text{acute}\angle(\mathbf{n}_1, \mathbf{n}_2) \\ \alpha & = & \arccos\left(\frac{|\mathbf{n}_1\cdot\mathbf{n}_2|}{|\mathbf{n}_1||\mathbf{n}_2|}\right) \end{array}$$
- $\perp$ planes: $\Rightarrow \alpha = \frac{\pi}{2} \iff \boxed{\mathbf{n}_1\cdot\mathbf{n}_2 = 0}$.
- Direction of L is $\mathbf{u} = \mathbf{n}_1 \times \mathbf{n}_2$.