Métodos Matemáticos de Bioingeniería

Grado en Ingeniería Biomédica

Lecture 3

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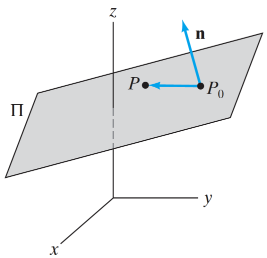
Coordinate Equations of Planes

Planes in $\mathbb{R}^3$

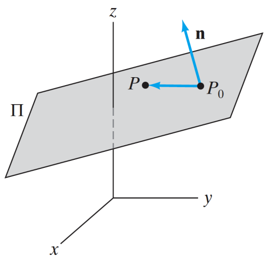
- A plane Π in $\mathbb{R}^3$ is determined uniquely by the following geometric information:
  - A particular point $P_0(x_0, y_0, z_0)$ in the plane
  - A particular vector $\mathbf{n} = A\mathbf{i} + B\mathbf{j} + C\mathbf{k}$ that is normal (perpendicular) to the plane



Π is the set of all points $P(x, y, z)$ in space such that $\overrightarrow{P_0P}$ is perpendicular to $\mathbf{n}$

Coordinate Equations of Planes

Planes in $\mathbb{R}^3$

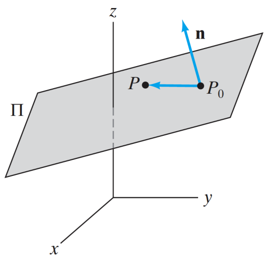


- Π is defined by the vector equation

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

Coordinate Equations of Planes

Planes in $\mathbb{R}^3$



- Since $\overrightarrow{P_0P} = (x - x_0)\mathbf{i} + (y - y_0)\mathbf{j} + (z - z_0)\mathbf{k}$ equation may be rewritten

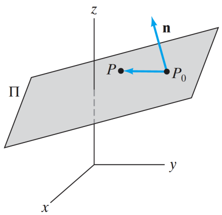
$$(A\mathbf{i} + B\mathbf{j} + C\mathbf{k}) \cdot ((x - x_0)\mathbf{i} + (y - y_0)\mathbf{j} + (z - z_0)\mathbf{k}) = 0$$

or

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

Coordinate Equations of Planes

Planes in $\mathbb{R}^3$



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

- This is equivalent to

$$Ax + By + Cz = D$$

where $D = Ax_0 + By_0 + Cz_0$

Coordinate Equations of Planes

Example 1

- The plane through the point $(3, 2, 1)$ with normal vector $2\mathbf{i} - \mathbf{j} + 4\mathbf{k}$ has equation

$$(2\mathbf{i} - \mathbf{j} + 4\mathbf{k}) \cdot ((x-3)\mathbf{i} + (y-2)\mathbf{j} + (z-1)\mathbf{k}) = 0 \iff$$
$$\iff 2(x-3) - (y-2) + 4(z-1) = 0 \iff 2x - y + 4z = 8$$

Coordinate Equations of Planes

Example 2

Given the plane with equation

$$7x + 2y - 3z = 1$$

find a normal vector to the plane and identify three points that lie on that plane

- A possible normal vector is $\mathbf{n} = 7\mathbf{i} + 2\mathbf{j} - 3\mathbf{k}$
- However, any nonzero scalar multiple of **n** will do just as well
- Algebraically, the effect of using a scalar multiple of **n** as normal is to multiply by such a scalar the equation

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

- Finding three points in the plane is not difficult

Coordinate Equations of Planes

Example 2

Given the plane with equation

$$7x + 2y - 3z = 1$$

find a normal vector to the plane and identify three points that lie on that plane

- First, let $y = z = 0$ in the defining equation and solve for x

$$7x + 2 \cdot 0 - 3 \cdot 0 = 1 \iff 7x = 1 \iff x = \frac{1}{7}$$

- Thus $(\frac{1}{7}, 0, 0)$ is a point on the plane

Coordinate Equations of Planes

Example 2

Given the plane with equation

$$7x + 2y - 3z = 1$$

find a normal vector to the plane and identify three points that lie on that plane

- Next, let $x = z = 0$ and solve for y

$$7 \cdot 0 + 2y - 3 \cdot 0 = 1 \iff y = \frac{1}{2}$$

- Thus $(0, \frac{1}{2}, 0)$ is a point on the plane

Coordinate Equations of Planes

Example 2

Given the plane with equation

$$7x + 2y - 3z = 1$$

find a normal vector to the plane and identify three points that lie on that plane

- Finally, let $x = y = 0$ and solve for z

$$7 \cdot 0 + 2 \cdot 0 - 3 \cdot z = 1 \iff z = -\frac{1}{3}$$

- Thus $(0, 0, -\frac{1}{3})$ is a point on the plane

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

Two different approaches

- There are two ways to solve this problem
- The first approach is algebraic and rather uninspired
- The second method of solution is cleaner and more geometric

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1, 2, 0)$, $P_1(3, 1, 2)$, and $P_2(0, 1, 1)$

First approach

- Any plane must have an equation of the form

$$Ax + By + Cz = D$$

  for suitable constants A, B, C, and D
- Thus, we need only to substitute the coordinates of P_0, P_1, and P_2 into this equation and solve for A, B, C, and D

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points
$P_0(1, 2, 0)$, $P_1(3, 1, 2)$, and $P_2(0, 1, 1)$

First approach

$$Ax + By + Cz = D$$

- Substitution of P_0 gives $A + 2B = D$
- Substitution of P_1 gives $3A + B + 2C = D$
- Substitution of P_2 gives $B + C = D$

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

First approach

- Hence, we must solve a system of 3 equations in 4 unknowns

$$\begin{cases} A + 2B = D \\ 3A + B + 2C = D \\ B + C = D \end{cases}$$

- In general, such a system has either no solution or else infinitely many solutions

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1, 2, 0)$, $P_1(3, 1, 2)$, and $P_2(0, 1, 1)$

First approach

- Hence, we must solve a system of 3 equations in 4 unknowns

$$\begin{cases} A + 2B = D \\ 3A + B + 2C = D \\ B + C = D \end{cases}$$

- We must be in the latter case, since we know that the three points P_0, P_1, and P_2 lie on some plane

Some set of constants A, B, C, and D must exist

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

First approach

- We can choose a value for one of A, B, C, or D, and then the other values will be determined

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

First approach

$$\begin{cases} A+2B=D \\ 3A+B+2C=D \\ B+C=D \end{cases}$$

- Multiply the first equation by 3, and subtract it from the second equation

$$\begin{cases} A+2B=D \\ -5B+2C=-2D \\ B+C=D \end{cases}$$

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

First approach

$$\begin{cases} A+2B=D \\ -5B+2C=-2D \\ B+C=D \end{cases}$$

- Now, multiply the third equation by 5 and add it to the second

$$\begin{cases} A+2B=D \\ -7C=3D \\ B+C=D \end{cases}$$

Coordinate Equations of Planes

Example 4

A plane is determined by
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Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

First approach

$$\begin{cases} A+2B=D \\ -7C=3D \\ B+C=D \end{cases}$$

- Multiply the third equation by 2 and subtract it from the first

$$\begin{cases} A-2C=-D \\ -7C=3D \\ B+C=D \end{cases}$$

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

First approach

$$\begin{cases} A - 2C = -D \\ -7C = 3D \\ B + C = D \end{cases}$$

- By adding appropriate multiples of the second equation to both the first and third equations

$$\begin{cases} A = -\frac{1}{7}D \\ 7C = 3D \\ B = \frac{4}{7}D \end{cases}$$

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

First approach

$$\begin{cases} A = -\frac{1}{7}D \\ 7C = 3D \\ B = \frac{4}{7}D \end{cases}$$

- Thus, if in we take $D = -7$ (for example), then $A = 1, B = -4, C = -3$, and the equation of the plane is

$$x - 4y - 3z = \ -7$$

Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

Second approach

- The idea is to make use of equation

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

- Therefore, we need to know
  - The coordinates of a particular point on the plane (no problem, we are given three such points), and
  - A vector $\mathbf{n}$ normal to the plane

Coordinate Equations of Planes

Example 4

A plane is determined by
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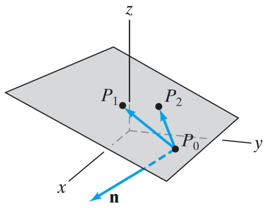
Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

Second approach



- The vectors $\overrightarrow{P_0P_1}$ and $\overrightarrow{P_0P_2}$ both lie in the plane

Coordinate Equations of Planes

Example 4

A plane is determined by
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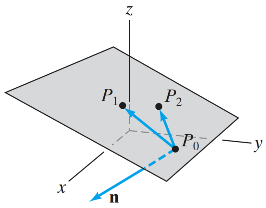
Find an equation of the plane that contains the points $P_0(1, 2, 0)$, $P_1(3, 1, 2)$, and $P_2(0, 1, 1)$

Second approach



- In particular, the normal vector **n** must be perpendicular to both $\overrightarrow{P_0P_1}$ and $\overrightarrow{P_0P_2}$

Coordinate Equations of Planes

Example 4

A plane is determined by
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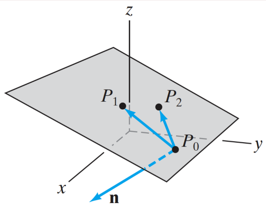
Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

Second approach



- Consequently, the cross product $\overrightarrow{P_0P_1} \times \overrightarrow{P_0P_2}$ provides just what we need

Coordinate Equations of Planes

Example 4

A plane is determined by
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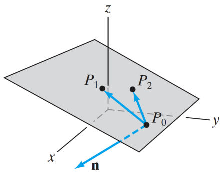
Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

Second approach



$$\mathbf{n} = \overrightarrow{P_0P_1} \times \overrightarrow{P_0P_2} = (2\mathbf{i} - \mathbf{j} + 2\mathbf{k}) \times (-\mathbf{i} - \mathbf{j} + \mathbf{k}) = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 2 & -1 & 2 \\ -1 & -1 & 1 \end{vmatrix}$$

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

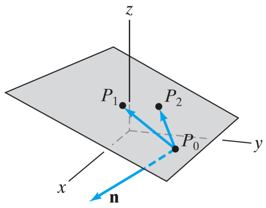
Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

Second approach



- We take $P_0(1,2,0)$ to be the particular point in equation

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

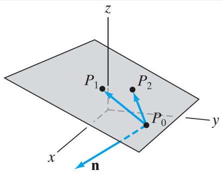
Coordinate Equations of Planes

Example 4

A plane is determined by
three (noncollinear) points

Find an equation of the plane that contains the points $P_0(1,2,0)$, $P_1(3,1,2)$, and $P_2(0,1,1)$

Second approach



$$(\mathbf{i} - 4\mathbf{j} - 3\mathbf{k}) \cdot ((x-1)\mathbf{i} + (y-2)\mathbf{j} + z\mathbf{k}) = 0$$

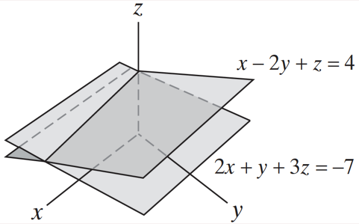
or
$$(x-1) - 4(y-2) - 3z = 0$$

Coordinate Equations of Planes

Example 5

- Consider the two planes having equations

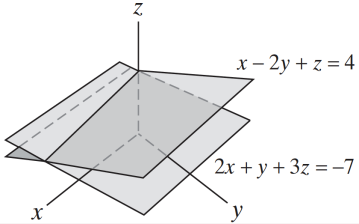
$$x - 2y + z = 4 \text{ and } 2x + y + 3z = -7$$



- Determine a set of parametric equations for their line of intersection

Coordinate Equations of Planes

Example 5



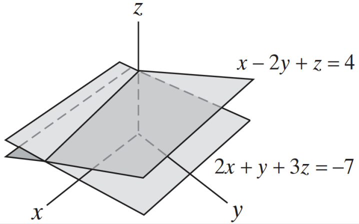
- We use Proposition 2.1

$$\mathbf{r}(t) = \mathbf{b} + t\mathbf{a}$$

- Thus, we need to find
  - A point on the line, and
  - A vector parallel to the line

Coordinate Equations of Planes

Example 5

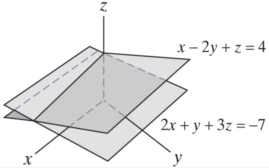


- First, we find the the coordinates (x, y, z) of a point on the line
- This coordinates must satisfy the system of simultaneous equations given by the two planes

$$\begin{cases} x - 2y + z = 4 \\ 2x + y + 3z = -7 \end{cases}$$

Coordinate Equations of Planes

Example 5



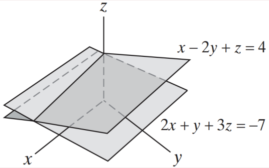
$$\begin{cases} x - 2y + z = 4 \\ 2x + y + 3z = -7 \end{cases}$$

- From the equations it is not too difficult to produce a single solution (x, y, z)
- For example, if we let $z = 0$ we obtain the simpler system

$$\begin{cases} x - 2y = 4 \\ 2x + y = -7 \end{cases}$$

Coordinate Equations of Planes

Example 5



$$\begin{cases} x - 2y = 4 \\ 2x + y = -7 \end{cases}$$

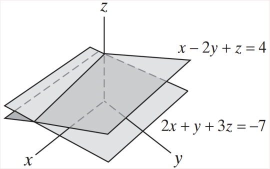
- The solution to the system of equations is readily calculated to be

$$x = -2, y = -3$$

- Thus, $(-2, -3, 0)$ are the coordinates of a point on the line

Coordinate Equations of Planes

Example 5



- Second, we find a vector parallel to the line of intersection
- Note that such a vector must be perpendicular to the two normal vectors to the planes
- The normal vectors to the planes are

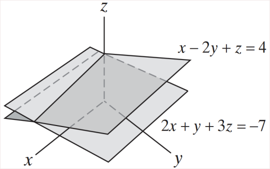
$$\mathbf{i} - 2\mathbf{j} + \mathbf{k} \text{ and } 2\mathbf{i} + \mathbf{j} + 3\mathbf{k}$$

- A vector parallel to the line of intersection is given by

$$(\mathbf{i} - 2\mathbf{j} + \mathbf{k}) \times (2\mathbf{i} + \mathbf{j} + 3\mathbf{k}) = -7\mathbf{i} - \mathbf{j} + 5\mathbf{k}$$

Coordinate Equations of Planes

Example 5



- Hence, Proposition 2.1 implies that a vector parametric equation for the line is

$$\mathbf{r}(t) = (-2\mathbf{i} - 3\mathbf{j}) + t(-7\mathbf{i} - \mathbf{j} + 5\mathbf{k})$$

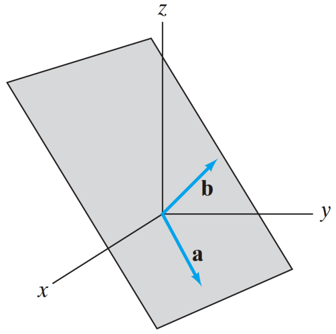
- And a standard set of parametric equations is

$$\begin{cases} x = -7t - 2 \\ y = -t - 3 \\ z = 5t \end{cases}$$

Parametric Equations of Planes

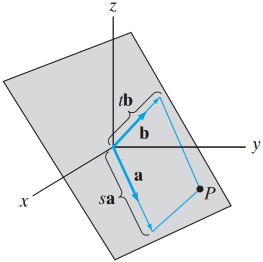
Parametric Equations of Planes Through the Origin in $\mathbb{R}^3$

- Suppose that $\mathbf{a} = (a_1, a_2, a_3)$ and $\mathbf{b} = (b_1, b_2, b_3)$ are two nonzero, nonparallel vectors in $\mathbb{R}^3$
- Then, $\mathbf{a}$ and $\mathbf{b}$ determine a plane in $\mathbb{R}^3$ that passes through the origin



Parametric Equations of Planes

Parametric Equations of Planes Through the Origin in $\mathbb{R}^3$

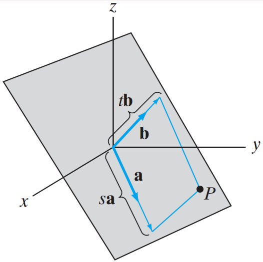


- To find the coordinates of a point $P(x, y, z)$ in this plane, draw a parallelogram
  - Whose sides are parallel to a and b, and
  - That has two opposite vertices at the origin and at P
- There exist scalars s and t so that the position vector of P is

$$\overrightarrow{OP} = s\mathbf{a} + t\mathbf{b}$$

Parametric Equations of Planes

Parametric Equations of Planes Through the Origin in $\mathbb{R}^3$

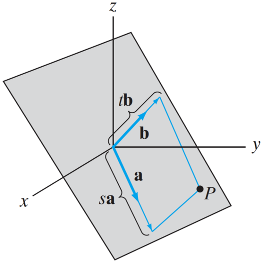


- The plane may be described as

$$\Pi_0 \equiv \{\mathbf{x} \in \mathbb{R}^3 | \mathbf{x} = s\,\mathbf{a} + t\mathbf{b};\, s, t \in \mathbb{R}\}$$

Parametric Equations of Planes

General Parametric Equations of Planes in $\mathbb{R}^3$

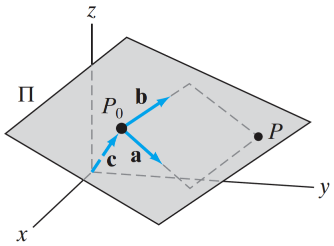


- Now, we seek to describe a general plane Π not necessarily passing through the origin
- Let $\mathbf{c} = (c_1, c_2, c_3) = \overrightarrow{OP_0}$ denote the position vector of a particular point P_0 in Π
- Let **a** and **b** be two (nonzero, nonparallel) vectors that determine the plane through the origin Π_0 parallel to Π

Parametric Equations of Planes

General Parametric Equations of Planes in $\mathbb{R}^3$

- We parallel translate **a** and **b** so that their tails are at the head of **c**

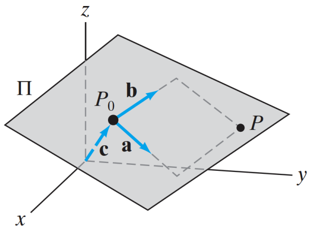


- The position vector of any point $P(x, y, z)$ in Π may be described as

$$\overrightarrow{OP} = s\mathbf{a} + t\mathbf{b} + \mathbf{c}$$

Parametric Equations of Planes

Proposition 5.1



A vector parametric equation for the plane

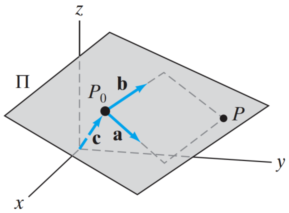
- Containing the point $P_0(c_1, c_2, c_3)$ whose position vector is $\overrightarrow{OP_0} = \mathbf{c}$, and
- Parallel to the nonzero, nonparallel vectors **a** and **b**

is

$$\mathbf{x}(s,t) = s\mathbf{a} + t\mathbf{b} + \mathbf{c} \qquad t, s \in \mathbb{R}$$

Parametric Equations of Planes

Proposition 5.1



$$\mathbf{x}(s,t) = s\mathbf{a} + t\mathbf{b} + \mathbf{c}$$

- By taking components in formula, we readily obtain a set of parametric equations for Π

$$\Pi \equiv \begin{cases} x = sa_1 + tb_1 + c_1 \\ y = sa_2 + tb_2 + c_2 \\ z = sa_3 + tb_3 + c_3 \end{cases} \quad t, s \in \mathbb{R}$$

Parametric Equations of Planes

Parametric Lines vs Parametric planes

- We need to use one parameters t to describe a line

$$\Lambda \equiv \begin{cases} x = a_1 t + b_1 \\ y = a_2 t + b_2 \\ z = a_3 t + b_3 \end{cases} \quad t \in \mathbb{R}$$

A line is a one-dimensional object

- We need to use two parameters s and t to describe a plane

$$\Pi \equiv \begin{cases} x = s a_1 + t b_1 + c_1 \\ y = s a_2 + t b_2 + c_2 \\ z = s a_3 + t b_3 + c_3 \end{cases} \quad t, s \in \mathbb{R}$$

A plane is a two-dimensional object

Parametric Equations of Planes

Example 6

Find a set of parametric equations for the plane that passes through the point $(1, 0, -1)$ and is parallel to the vectors $3\mathbf{i} - \mathbf{k}$ and $2\mathbf{i} + 5\mathbf{j} + 2\mathbf{k}$

$$\mathbf{x}(s,t) = s\mathbf{a} + t\mathbf{b} + \mathbf{c}$$

- From formula, any point on the plane is specified by

$$\begin{aligned} \mathbf{x}(s,t) &= s(3\mathbf{i} - \mathbf{k}) + t(2\mathbf{i} + 5\mathbf{j} + 2\mathbf{k}) + (\mathbf{i} - \mathbf{k}) \\ &= (3s + 2t + 1)\mathbf{i} + 5t\mathbf{j} + (2t - s - 1)\mathbf{k} \end{aligned}$$

- The individual parametric equation may be read off as

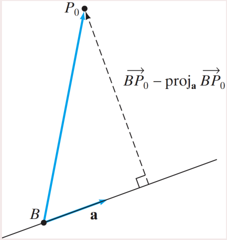
$$\begin{cases} x = 3s + 2t + 1 \\ y = 5t & \qquad t, s \in \mathbb{R} \\ z = 2t - s - 1 \end{cases}$$

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2, 1, 3)$ and the line $\mathbf{l}(t) = t(-1, 1, -2) + (2, 3, -2)$ in two ways

Method 1



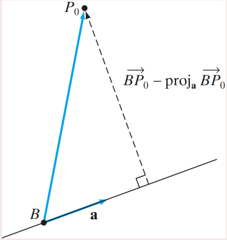
- From the vector parametric equations for the line, we read off
  - A point B on the line, namely, $B = (2, 3, -2)$, and
  - A vector $\mathbf{a}$ parallel to the line, namely, $\mathbf{a} = (-1, 1, -2)$

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2,1,3)$ and the line $\mathbf{l}(t) = t(-1,1,-2) + (2,3,-2)$ in two ways

Method 1



- The desired distance between P_0 and the line is provided by the length of the vector

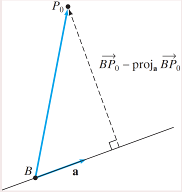
$$\overrightarrow{BP_0} - \text{proj}_{\mathbf{a}}\overrightarrow{BP_0}$$

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2,1,3)$ and the line $\mathbf{l}(t) = t(-1,1,-2) + (2,3,-2)$ in two ways

Method 1



$$\begin{aligned}
\overrightarrow{BP_0} &= (2,1,3) - (2,3,-2) = (0,-2,5) \\
\text{proj}_{\mathbf{a}}\overrightarrow{BP_0} &= \left(\frac{\mathbf{a}\cdot\overrightarrow{BP_0}}{\mathbf{a}\cdot\mathbf{a}}\right)\mathbf{a} = \left(\frac{(-1,1,-2)\cdot(0,-2,5)}{(-1,1,-2)\cdot(-1,1,-2)}\right)(-1,1,-2) \\
&= (2,-2,4)
\end{aligned}$$

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2,1,3)$ and the line $\mathbf{l}(t) = t(-1,1,-2) + (2,3,-2)$ in two ways

Method 1

$$\begin{aligned} \overrightarrow{BP_0} &= (0,-2,5) \\ \text{proj}_{\mathbf{a}}\overrightarrow{BP_0} &= (2,-2,4) \end{aligned}$$

- The desired distance is

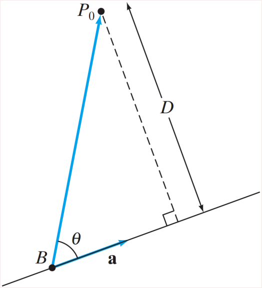
$$\begin{aligned} \|\overrightarrow{BP_0} - \text{proj}_{\mathbf{a}}\overrightarrow{BP_0}\| &= \|(0,-2,5) - (2,-2,4)\| \\ &= \|(-2,0,1)\| = \sqrt{5} \end{aligned}$$

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2, 1, 3)$ and the line $\mathbf{l}(t) = t(-1, 1, -2) + (2, 3, -2)$ in two ways

Method 2



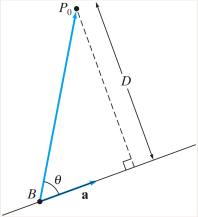
- In this case, we use a little trigonometry

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2,1,3)$ and the line $\mathbf{l}(t) = t(-1,1,-2) + (2,3,-2)$ in two ways

Method 2



- If θ denotes the angle between the vectors $\mathbf{a}$ and $\overrightarrow{BP_0}$

$$\sin\theta = \frac{D}{\|\overrightarrow{BP_0}\|}$$

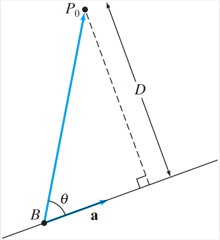
where D denotes the distance between P_0 and the line

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2,1,3)$ and the line $\mathbf{l}(t) = t(-1,1,-2) + (2,3,-2)$ in two ways

Method 2



- Hence

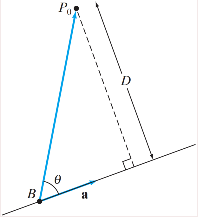
$$D = \|\overrightarrow{BP_0}\| \sin\theta = \frac{\|\mathbf{a}\|\|\overrightarrow{BP_0}\|\sin\theta}{\|\mathbf{a}\|} = \frac{\|\mathbf{a}\times\overrightarrow{BP_0}\|}{\|\mathbf{a}\|}$$

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2,1,3)$ and the line $\mathbf{l}(t) = t(-1,1,-2) + (2,3,-2)$ in two ways

Method 2



- Therefore, we calculate

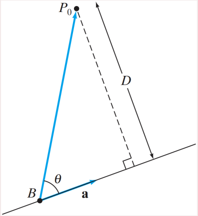
$$\mathbf{a} \times \overrightarrow{BP_0} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ -1 & 1 & -2 \\ 0 & -2 & 5 \end{vmatrix} = \mathbf{i} + 5\mathbf{j} + 2\mathbf{k}$$

Distance Problems

Example 7. Distance between a point and a line

Find the distance between the point $P_0(2,1,3)$ and the line $\mathbf{l}(t) = t(-1,1,-2) + (2,3,-2)$ in two ways

Method 2



- So that the distance sought is

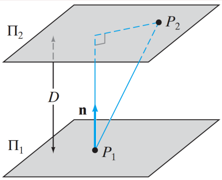
$$D = \frac{\|\mathbf{a} \times \overrightarrow{BP_0}\|}{\|a\|} = \frac{\|\mathbf{i} + 5\mathbf{j} + 2\mathbf{k}\|}{\|-\mathbf{i} + \mathbf{j} - 2\mathbf{k}\|} = \frac{\sqrt{30}}{\sqrt{6}} = \sqrt{5}$$

Distance Problems

Example 8. Distance between parallel planes

Compute the distance between the parallel planes

$$\Pi_1 : 2x - 2y + z = 5 \quad \text{and} \quad \Pi_2 : 2x - 2y + z = 20$$



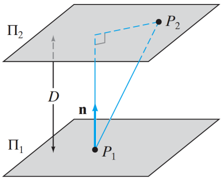
- The desired distance D is given by $\|\text{proj}_{\mathbf{n}} \overrightarrow{P_1 P_2}\|$ where
  - P_1 is a point on Π_1
  - P_2 is a point on Π_2, and
  - $\mathbf{n}$ is a vector normal to both planes

Distance Problems

Example 8. Distance between parallel planes

Compute the distance between the parallel planes

$$\Pi_1 : 2x - 2y + z = 5 \quad \text{and} \quad \Pi_2 : 2x - 2y + z = 20$$



- The vector **n** that is normal to both planes may be read directly from the equation for either Π_1 or Π_2 as

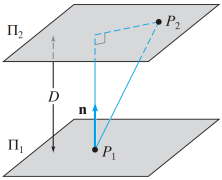
$$\mathbf{n} = 2\mathbf{i} - 2\mathbf{j} + \mathbf{k}$$

Distance Problems

Example 8. Distance between parallel planes

Compute the distance between the parallel planes

$$\Pi_1 : 2x - 2y + z = 5 \quad \text{and} \quad \Pi_2 : 2x - 2y + z = 20$$



- It is not hard to find a point P_1 on Π_1, for instance, the point $P_1(0, 0, 5)$
- Similarly, take $P_2(0, 0, 20)$ for a point on Π_2
- Then

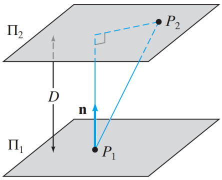
$$\overrightarrow{P_1P_2} = (0, 0, 15)$$

Distance Problems

Example 8. Distance between parallel planes

Compute the distance between the parallel planes

$$\Pi_1 : 2x - 2y + z = 5 \quad \text{and} \quad \Pi_2 : 2x - 2y + z = 20$$



$$\overrightarrow{P_1P_2} = (0, 0, 15) \quad \text{and} \quad \mathbf{n} = 2\mathbf{i} - 2\mathbf{j} + \mathbf{k}$$

$$\text{proj}_{\mathbf{n}}\overrightarrow{P_1P_2} = \left(\frac{\mathbf{n} \cdot \overrightarrow{P_1P_2}}{\mathbf{n} \cdot \mathbf{n}}\right)\mathbf{n} = \left(\frac{(2, -2, -1)\textit{errata} \cdot (0, 0, 15)}{(2, -2, 1) \cdot (2, -2, 1)}\right)(2, -2, 1$$

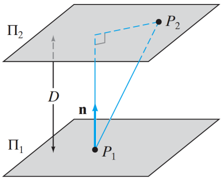
$$= -\frac{15}{9}(2, -2, 1) = -\frac{5}{3}(2, -2, 1)$$

Distance Problems

Example 8. Distance between parallel planes

Compute the distance between the parallel planes

$$\Pi_1 : 2x - 2y + z = 5 \quad \text{and} \quad \Pi_2 : 2x - 2y + z = 20$$



$$\text{proj}_{\mathbf{n}} \overrightarrow{P_1P_2} = -\frac{5}{3}(2, -2, 1)$$

- Hence, the distance D that we seek is

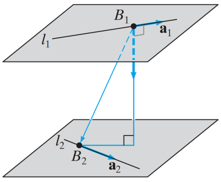
$$D = \|\text{proj}_{\mathbf{n}} \overrightarrow{P_1P_2}\| = \frac{5}{3}\sqrt{9} = 5$$

Distance Problems

Example 9. Distance between two skew lines

Two lines in $\mathbb{R}^3$ are said to be **skew**
if they are neither intersecting nor parallel

- The lines must lie in parallel planes, and
- The distance between the lines is equal to the distance between the planes



Find the distance between the two skew lines

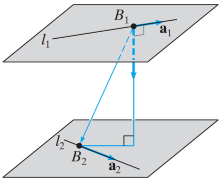
$$\mathbf{l}_1(t) = t(2,1,3) + (0,5,-1) \quad \text{and} \quad \mathbf{l}_2(t) = t(1,-1,0) + (-1,2,0)$$

Distance Problems

Example 9. Distance between two skew lines

Find the distance between the two skew lines

$$\mathbf{l}_1(t) = t(2,1,3) + (0,5,-1) \quad \text{and} \quad \mathbf{l}_2(t) = t(1,-1,0) + (-1,2,0)$$



- We need to find the length of the projection of the vector between a point on each line onto a vector **n** that is
  - Perpendicular to both lines, and
  - Perpendicular to the parallel planes that contain the lines

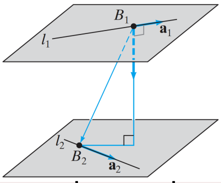
$$\|\text{proj}_{\mathbf{n}} \overrightarrow{B_1 B_2}\|$$

Distance Problems

Example 9. Distance between two skew lines

Find the distance between the two skew lines

$$\mathbf{l}_1(t) = t(2,1,3) + (0,5,-1) \quad \text{and} \quad \mathbf{l}_2(t) = t(1,-1,0) + (-1,2,0)$$



- From the vector parametric equations for the lines
  - Point $B_1(0,5,-1)$ is on the first line, and
  - Point $B_2(-1,2,0)$ is on the second line
  - Hence

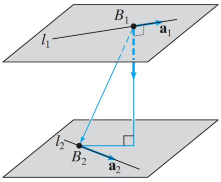
$$\overrightarrow{B_1B_2} = (-1,2,0) - (0,5,-1) = (-1,-3,1)$$

Distance Problems

Example 9. Distance between two skew lines

Find the distance between the two skew lines

$$\mathbf{l}_1(t) = t(2,1,3) + (0,5,-1) \quad \text{and} \quad \mathbf{l}_2(t) = t(1,-1,0) + (-1,2,0)$$



- For a vector $\mathbf{n}$ that is perpendicular to both lines, we may use

$$\mathbf{n} = \mathbf{a}_1 \times \mathbf{a}_2$$

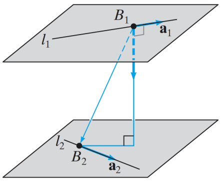
  - $\mathbf{a}_1 = (2,1,3)$ is a vector parallel to the first line, and
  - $\mathbf{a}_2 = (1,-1,0)$ is a vector parallel to the second line

Distance Problems

Example 9. Distance between two skew lines

Find the distance between the two skew lines

$$\mathbf{l}_1(t) = t(2,1,3) + (0,5,-1) \quad \text{and} \quad \mathbf{l}_2(t) = t(1,-1,0) + (-1,2,0)$$



- $\mathbf{n} = \mathbf{a}_1 \times \mathbf{a}_2$
  - $\mathbf{a}_1 = (2,1,3)$ is a vector parallel to the first line, and
  - $\mathbf{a}_2 = (1,-1,0)$ is parallel to the second line

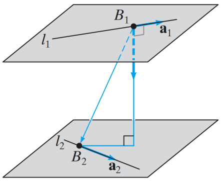
$$\mathbf{n} = \mathbf{a}_1 \times \mathbf{a}_2 = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ 2 & 1 & 3 \\ 1 & -1 & 0 \end{vmatrix} = 3\mathbf{i} + 3\mathbf{j} - 3\mathbf{k}$$

Distance Problems

Example 9. Distance between two skew lines

Find the distance between the two skew lines

$$\mathbf{l}_1(t) = t(2,1,3) + (0,5,-1) \quad \text{and} \quad \mathbf{l}_2(t) = t(1,-1,0) + (-1,2,0)$$



$$\mathbf{n} = 3\mathbf{i} + 3\mathbf{j} - 3\mathbf{k} \quad \text{and} \quad \overrightarrow{B_1B_2} = (-1,-3,1)$$

$$\text{proj}_{\mathbf{n}}\overrightarrow{B_1B_2} = \left(\frac{\mathbf{n}\cdot\overrightarrow{B_1B_2}}{\mathbf{n}\cdot\mathbf{n}}\right)\mathbf{n} = \left(\frac{(-1,-3,1)\cdot(3,3,-3)}{(3,3,-3)\cdot(3,3,-3)}\right)(3,3,-3)$$

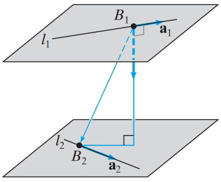
$$= \quad -\frac{15}{27}(3,3,-3) = -\frac{5}{3}(1,1,-1)$$

Distance Problems

Example 9. Distance between two skew lines

Find the distance between the two skew lines

$$\mathbf{l}_1(t) = t(2,1,3) + (0,5,-1) \quad \text{and} \quad \mathbf{l}_2(t) = t(1,-1,0) + (-1,2,0)$$



$$\text{proj}_{\mathbf{n}}\overrightarrow{B_1B_2} = -\frac{5}{3}(1,1,-1)$$

- The desired distance is

$$\|\text{proj}_{\mathbf{n}}\overrightarrow{B_1B_2}\| = \frac{5}{3}\sqrt{3}$$