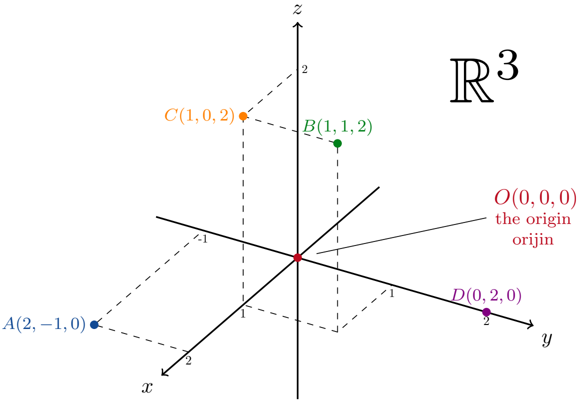
Lecture 3

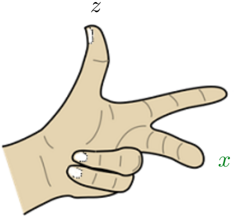
- 11.1 Three-Dimensional Coordinate Systems
- 11.2 Vectors
- 11.3 The Dot Product

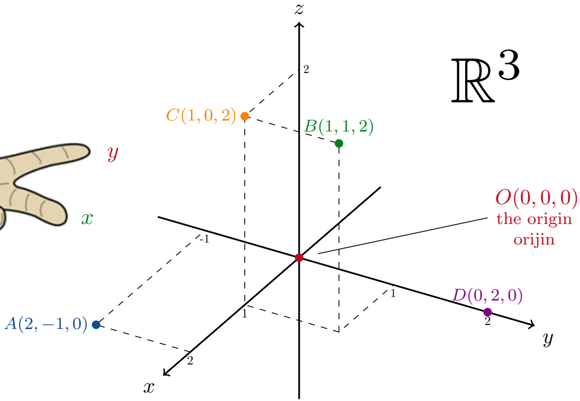
Three-Dimensional Coordinate Systems



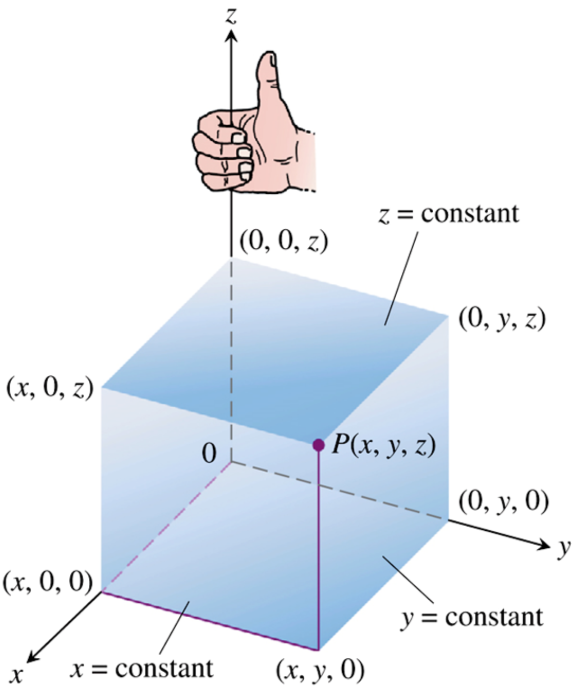
z
2
$\mathbb{R}^3$
$C(1,0,2)$
$B(1,1,2)$
$O(0,0,0)$
the origin
orijin
-1
1
$D(0,2,0)$
$A(2,-1,0)$
1
2
2
y
x

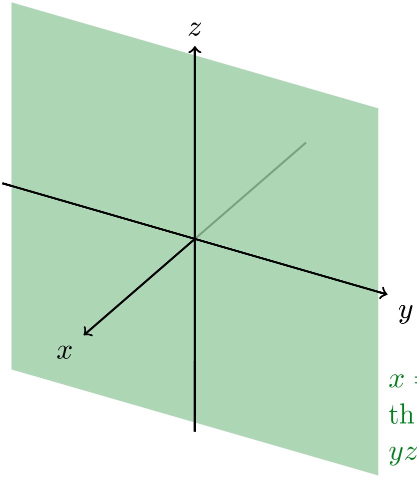
11.1 Three-Dimensional Coordinate Systems



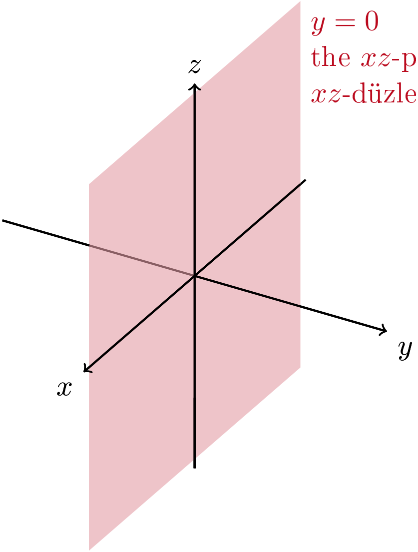


$\mathbb{R}^3$

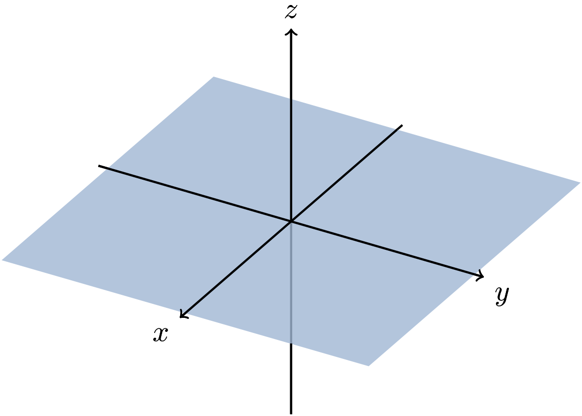

z
(0, 0, z)
z = constant
(0, y, z)
(x, 0, z)
P(x, y, z)
0
(0, y, 0)
y
(x, 0, 0)
y = constant
x
x = constant
(x, y, 0)



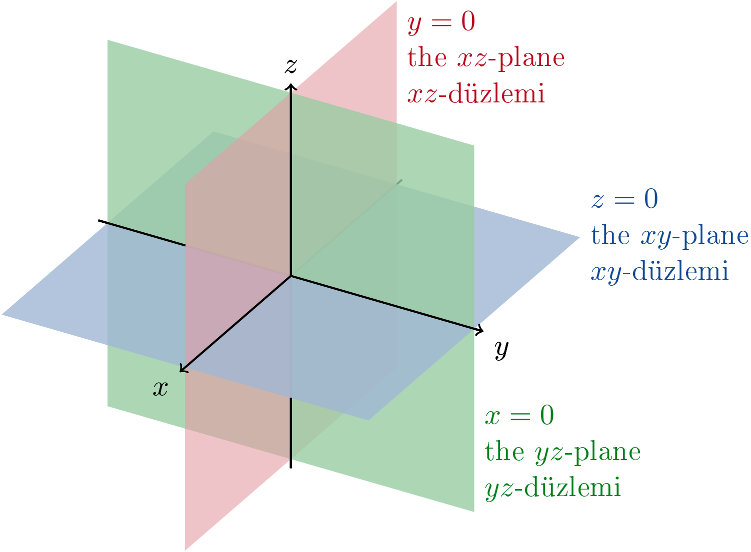
$x = 0$
the yz-plane
yz-düzlemi

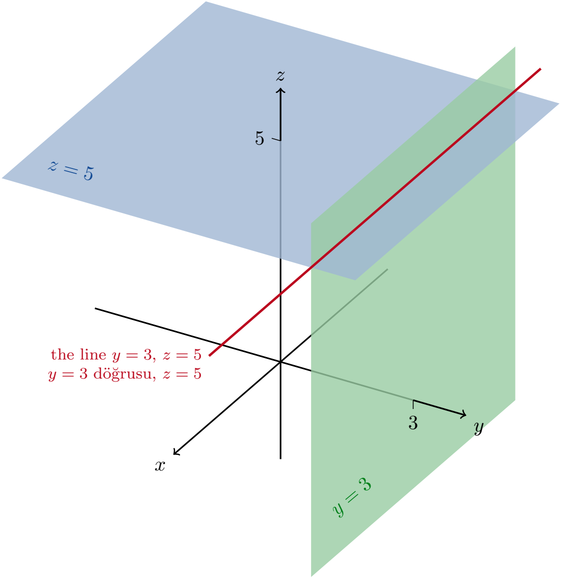


$y = 0$
the xz-plane
xz-düzlemi



$z = 0$
the xy-plane
xy-düzlemi


z
y
x
$y = 0$
the xz-plane
xz-düzlemi
$z = 0$
the xy-plane
xy-düzlemi
$x = 0$
the yz-plane
yz-düzlemi


z
5
$z = 5$
the line $y = 3$, $z = 5$
$y = 3$ döğrusu, $z = 5$
3
y
x
$y = 3$

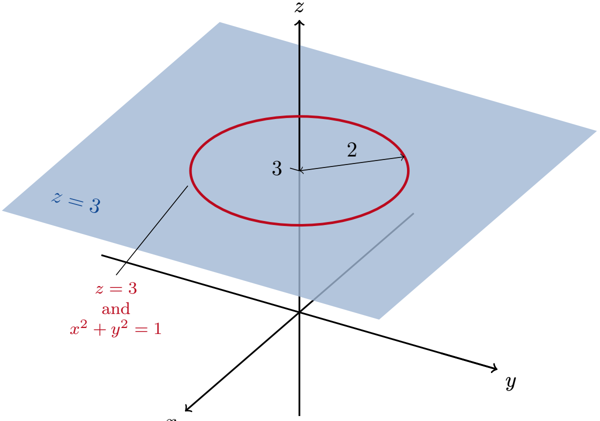
EXAMPLE 1 We interpret these equations and inequalities geometrically.

(a) $z \geq 0$	The half-space consisting of the points on and above the xy-plane.
(b) $x = -3$	The plane perpendicular to the x-axis at $x = -3$. This plane lies parallel to the yz-plane and 3 units behind it.
(c) $z = 0, x \leq 0, y \geq 0$	The second quadrant of the xy-plane.
(d) $x \geq 0, y \geq 0, z \geq 0$	The first octant.
(e) $-1 \leq y \leq 1$	The slab between the planes $y = -1$ and $y = 1$ (planes included).
(f) $y = -2, z = 2$	The line in which the planes $y = -2$ and $z = 2$ intersect. Alternatively, the line through the point $(0, -2, 2)$ parallel to the x-axis. ■

Example

Which points $P(x, y, z)$ satisfy $x^2 + y^2 = 4$ and $z = 3$?

We know that $z = 3$ is a horizontal plane and we recognise that $x^2 + y^2 = 4$ is the equation of a circle of radius 2.



Distance in $\mathbb{R}^3$

Definition

The set
$$\{(x, y, z) \mid x, y, z \in \mathbb{R}\}$$
is denoted by $\mathbb{R}^3$.

Definition

The *distance* between $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ is

$$\|P_1P_2\| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}.$$

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Example

The distance between $A(2, 1, 5)$ and $B(-2, 3, 0)$ is

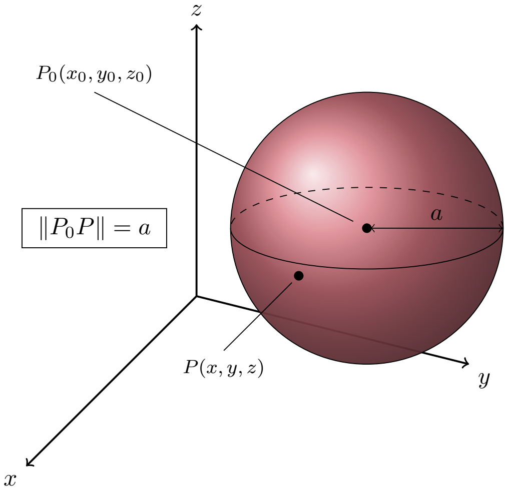
$$\|P_1P_2\| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}.$$

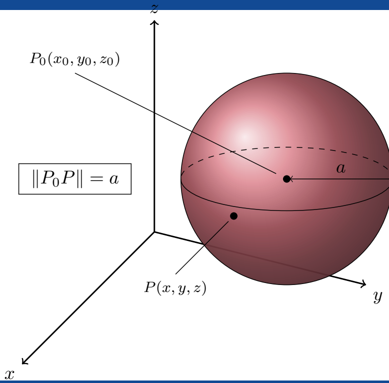
Example

The distance between $A(2, 1, 5)$ and $B(-2, 3, 0)$ is

$$\begin{aligned}\|AB\| &= \sqrt{((-2) - 2)^2 + (3 - 1)^2 + (0 - 5)^2} \\ &= \sqrt{16 + 4 + 25} = \sqrt{45} \\ &= 3\sqrt{5} \approx 6.7.\end{aligned}$$

Spheres





Definition

The *standard equation for a sphere* of radius a centred at $P_0(x_0, y_0, z_0)$ is

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Example

Find the centre and radius of the sphere

$$x^2 + y^2 + z^2 + 3x - 4z + 1 = 0.$$

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Example

Find the centre and radius of the sphere

$$x^2 + y^2 + z^2 + 3x - 4z + 1 = 0.$$

First we need to put this equation into the standard form.

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Since $(x-b)^2 = x^2 - 2b + b^2$ we have that

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

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Since $(x-b)^2 = x^2 - 2b + b^2$ we have that

$$x^2 + y^2 + z^2 + 3x - 4z + 1 = 0$$

$$(x^2 + 3x) + y^2 + (z^2 - 4z) = -1$$

$$\left(x^2 + 3x + \frac{9}{4}\right) - \frac{9}{4} + y^2 + (z^2 - 4z + 4) - 4 = -1$$

$$(x-x_0)^2+(y-y_0)^2+(z-z_0)^2=a^2.$$

Since $(x-b)^2 = x^2 - 2b + b^2$ we have that

$$\begin{aligned}
x^2+y^2+z^2+3x-4z+1&=0\\
(x^2+3x)+y^2+(z^2-4z)&=-1\\
\left(x^2+3x+\frac{9}{4}\right)-\frac{9}{4}+y^2+(z^2-4z+4)-4&=-1\\
\left(x^2+3x+\frac{9}{4}\right)+y^2+(z^2-4z+4)&=-1+\frac{9}{4}+4
\end{aligned}$$

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Since $(x-b)^2 = x^2 - 2b + b^2$ we have that

$$\begin{aligned}
x^2 + y^2 + z^2 + 3x - 4z + 1 &= 0 \\
(x^2 + 3x) + y^2 + (z^2 - 4z) &= -1 \\
\left(x^2 + 3x + \frac{9}{4}\right) - \frac{9}{4} + y^2 + (z^2 - 4z + 4) - 4 &= -1 \\
\left(x^2 + 3x + \frac{9}{4}\right) + y^2 + (z^2 - 4z + 4) &= -1 + \frac{9}{4} + 4 \\
\left(x + \frac{3}{2}\right)^2 + y^2 + (z-2)^2 &= \frac{21}{4}.
\end{aligned}$$

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Since $(x - b)^2 = x^2 - 2b + b^2$ we have that

$$\begin{aligned}
x^2 + y^2 + z^2 + 3x - 4z + 1 &= 0 \\
(x^2 + 3x) + y^2 + (z^2 - 4z) &= -1 \\
\left(x^2 + 3x + \frac{9}{4}\right) - \frac{9}{4} + y^2 + (z^2 - 4z + 4) - 4 &= -1 \\
\left(x^2 + 3x + \frac{9}{4}\right) + y^2 + (z^2 - 4z + 4) &= -1 + \frac{9}{4} + 4 \\
\left(x + \frac{3}{2}\right)^2 + y^2 + (z - 2)^2 &= \frac{21}{4}.
\end{aligned}$$

The centre is at $P_0(x_0, y_0, z_0) = P_0(-\frac{3}{2}, 0, 2)$ and the radius is $a = \sqrt{\frac{21}{4}} = \frac{\sqrt{3}\sqrt{7}}{2}$.

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Example

Find the centre and radius of the sphere

$$x^2 + y^2 + z^2 + 6x - 6y + 6z = 7.$$

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = a^2.$$

Since $(x - b)^2 = x^2 - 2b + b^2$ we have that

$$\begin{aligned}
x^2 + y^2 + z^2 + 6x - 6y + 6z &= 7 \\
(x^2 + 6x) + (y^2 - 6y) + (z^2 + 6z) &= 7 \\
(x^2 + 6x + 9) - 9 + (y^2 - 6y + 9) - 9 + (z^2 + 6z + 9) - 9 &= 7 \\
(x^2 + 6x + 9) + (y^2 - 6y + 9) + (z^2 + 6z + 9) &= 7 + 9 \\
(x + 3)^2 + (y - 3)^2 + (z + 3)^2 &= 16
\end{aligned}$$

The centre is at $P_0(x_0, y_0, z_0) = P_0(-3, 3, -3)$ and the radius is $a = \sqrt{16} = 4$.

EXAMPLE 5 Here are some geometric interpretations of inequalities and equations involving spheres.

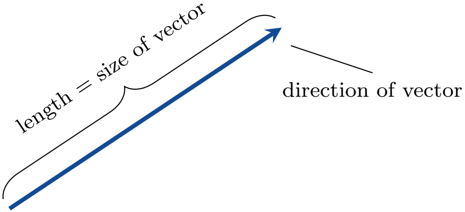
(a) $x^2 + y^2 + z^2 < 4$	The interior of the sphere $x^2 + y^2 + z^2 = 4$.
(b) $x^2 + y^2 + z^2 \leq 4$	The solid ball bounded by the sphere $x^2 + y^2 + z^2 = 4$. Alternatively, the sphere $x^2 + y^2 + z^2 = 4$ together with its interior.
(c) $x^2 + y^2 + z^2 > 4$	The exterior of the sphere $x^2 + y^2 + z^2 = 4$.
(d) $x^2 + y^2 + z^2 = 4, z \leq 0$	The lower hemisphere cut from the sphere $x^2 + y^2 + z^2 = 4$ by the xy-plane (the plane $z = 0$).

■

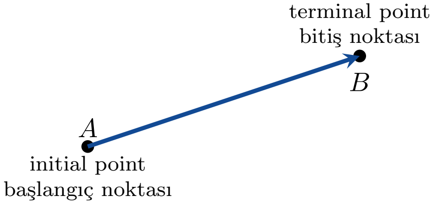
11.2

Vectors

For some quantities (mass, time, distance, ...) we only need a number. For some quantities (velocity, force, ...) we need a number and a direction.



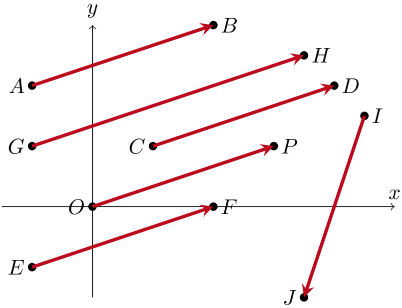
A *vector* is an object which has a size (length) and a direction.



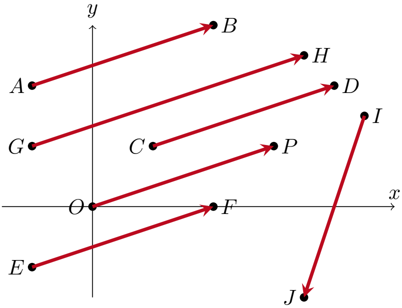
Definition

The vector $\overrightarrow{AB}$ has *initial point* A and *terminal point* B.

The *length* of $\overrightarrow{AB}$ is written $\left\|\overrightarrow{AB}\right\|$ (or $\left|\overrightarrow{AB}\right|$).



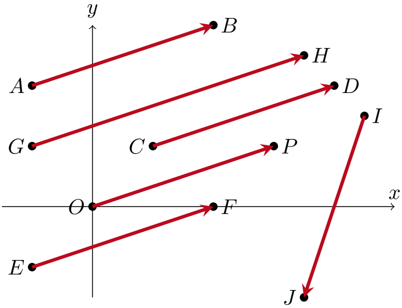
Two vectors are equal if they have the same length and the same direction.



Two vectors are equal if they have the same length and the same direction.

We can say that

$$\overrightarrow{AB} = \overrightarrow{CD} = \overrightarrow{EF} = \overrightarrow{OP}.$$



Two vectors are equal if they have the same length and the same direction.

We can say that

$$\overrightarrow{AB} = \overrightarrow{CD} = \overrightarrow{EF} = \overrightarrow{OP}.$$

Note that $\overrightarrow{AB} \neq \overrightarrow{GH}$ because the lengths are different, and $\overrightarrow{AB} \neq \overrightarrow{IJ}$ because the directions are different.

Notation

When we use a computer, we use bold letters for vectors: $\mathbf{u}$, $\mathbf{v}$, $\mathbf{w}$, $\ldots$.

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If we type $a\mathbf{u} + b\mathbf{v}$ or write $a\underline{u} + b\underline{v}$, then

- a and b are numbers; and
- $\mathbf{u}$, $\mathbf{v}$, $\underline{u}$ and $\underline{v}$ are vectors.

Definition

In $\mathbb{R}^2$: If $\mathbf{v}$ has initial point $(0,0)$ and terminal point (v_1, v_2), then the *component form* of $\mathbf{v}$ is $\mathbf{v} = (v_1, v_2)$.

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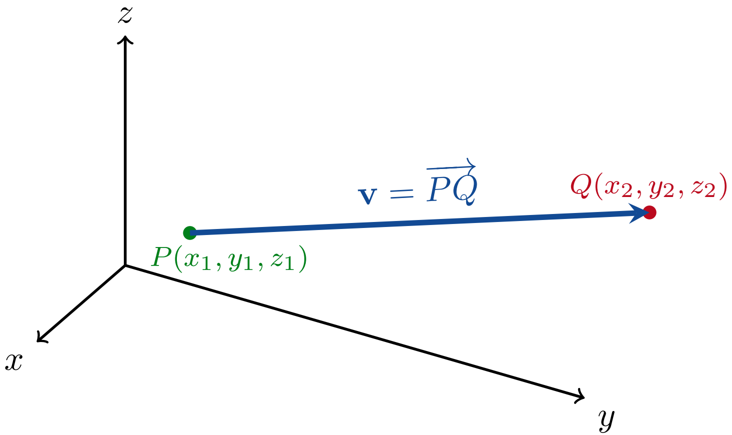
In $\mathbb{R}^3$: If $\mathbf{v}$ has initial point $(0,0,0)$ and terminal point (v_1, v_2, v_3), then the *component form* of $\mathbf{v}$ is $\mathbf{v} = (v_1, v_2, v_3)$.



$$(v_1, v_2, v_3) = \mathbf{v} = (x_2 - x_1, y_2 - y_1, z_2 - z_1)$$

Definition

In $\mathbb{R}^2$: The *norm* (or *length*) of $\mathbf{v} = (v_1, v_2)$ is

$$\|\mathbf{v}\| = \sqrt{v_1^2 + v_2^2}$$

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In $\mathbb{R}^3$: The *norm* of $\mathbf{v} = \overrightarrow{PQ}$ is

$$\begin{aligned} \|\mathbf{v}\| &= \sqrt{v_1^2 + v_2^2 + v_3^2} \\ &= \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}. \end{aligned}$$

11.2 Vectors

Definition

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The vectors $\mathbf{0} = (0, 0)$ and $\mathbf{0} = (0, 0, 0)$ have norm $\|\mathbf{0}\| = 0$.

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The vectors $\mathbf{0} = (0, 0)$ and $\mathbf{0} = (0, 0, 0)$ have norm $\|\mathbf{0}\| = 0$. If $\mathbf{v} \neq \mathbf{0}$, then $\|\mathbf{v}\| > 0$.

Example

Find (1) the component form; and (2) the norm of the vector with initial point $P(-3, 4, 1)$ and terminal point $Q(-5, 2, 2)$.

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1. $\mathbf{v} = (v_1, v_2, v_3) = Q - P = (-5,2,2) - (-3,4,1)$
   $= (-2,-2,1).$

Example

Find (1) the component form; and (2) the norm of the vector with initial point $P(-3,4,1)$ and terminal point $Q(-5,2,2)$.

1. $\mathbf{v} = (v_1, v_2, v_3) = Q - P = (-5,2,2) - (-3,4,1)$
   $= (-2,-2,1).$
2. $\|\mathbf{v}\| = \sqrt{v_1^2 + v_2^2 + v_3^2} = \sqrt{(-2)^2 + (-2)^2 + 1^2} = \sqrt{9} = 3.$

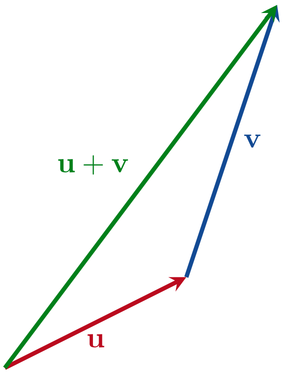
EXAMPLE 2 A small cart is being pulled along a smooth horizontal floor with a 20-lb force **F** making a 45° angle to the floor (Figure 12.11). What is the *effective* force moving the cart forward?

Solution The effective force is the horizontal component of $\mathbf{F} = \langle a, b \rangle$, given by

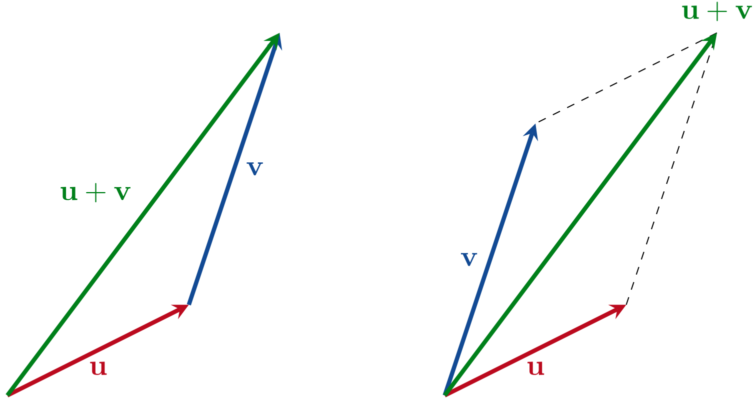
$$a = |\mathbf{F}| \cos 45° = (20)\left(\frac{\sqrt{2}}{2}\right) \approx 14.14 \text{ lb}.$$

Notice that **F** is a two-dimensional vector. ■

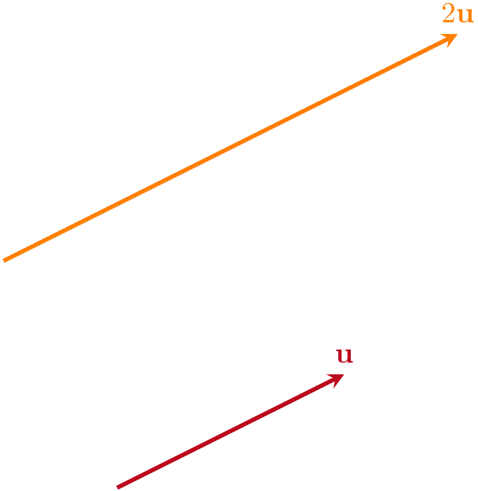
Vector Algebra: Addition



Vector Algebra: Addition



Vector Algebra: Multiplication by a Constant



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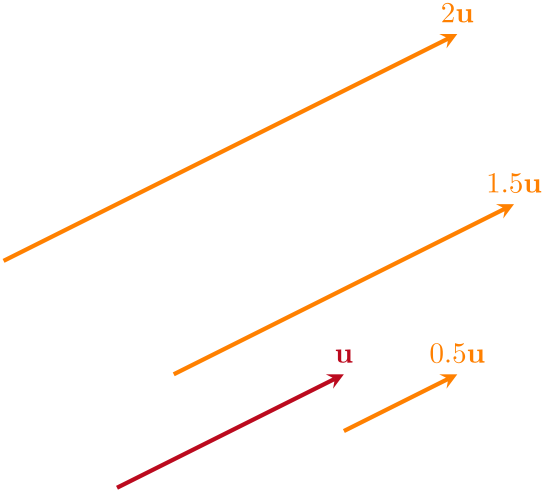
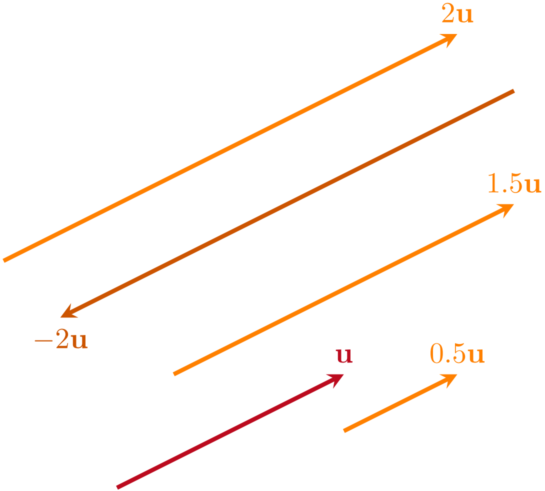
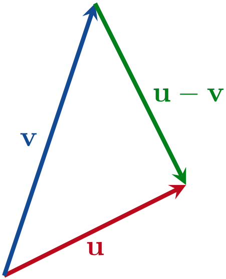


Vector Algebra: Multiplication by a Constant



Vector Algebra: Subtraction

$$\mathbf{v} + (\mathbf{u} - \mathbf{v}) = \mathbf{u}$$



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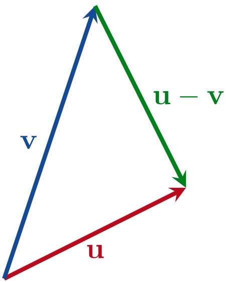

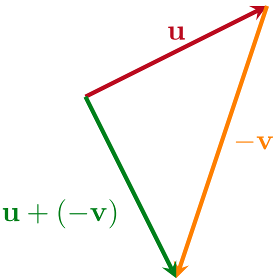

Let $\mathbf{u} = (u_1, u_2, u_3)$ and $\mathbf{v} = (v_1, v_2, v_3)$ be vectors. Let k be a number.

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$$\mathbf{u} + \mathbf{v} = (u_1 + v_1, u_2 + v_2, u_3 + v_3)$$

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$$\mathbf{u} + \mathbf{v} = (u_1 + v_1, u_2 + v_2, u_3 + v_3)$$

and

$$k\mathbf{u} = (ku_1, ku_2, ku_3).$$

Note that

$$
\begin{aligned}
\|k\mathbf{u}\| &= \|(ku_1, ku_2, ku_3)\| \\
&= \\
&= \\
&= \\
&= \\
&= \qquad\qquad .
\end{aligned}
$$

Note that

$$\begin{aligned} \|k\mathbf{u}\| &= \|(ku_1, ku_2, ku_3)\| \\ &= \sqrt{(ku_1)^2 + (ku_2)^2 + (ku_3)^2} \\ &= \\ &= \\ &= \\ &= \qquad . \end{aligned}$$

Note that

$$\begin{aligned}
\|k\mathbf{u}\| &= \|(ku_1, ku_2, ku_3)\| \\
&= \sqrt{(ku_1)^2 + (ku_2)^2 + (ku_3)^2} \\
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&= \sqrt{k^2}\sqrt{u_1^2 + u_2^2 + u_3^2} \\
&= |k| \, \|\mathbf{u}\| \, .
\end{aligned}$$

The vector $-\mathbf{u} = (-1)\mathbf{u}$ has the same length as $\mathbf{u}$, but points in the opposite direction.

Example

Let $\mathbf{u} = (-1, 3, 1)$ and $\mathbf{v} = (4, 7, 0)$.

Find $2\mathbf{u} + 3\mathbf{v}$, $\mathbf{u} - \mathbf{v}$, and $\left\| \frac{1}{2}\mathbf{u} \right\|$.

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3. $\left\| \frac{1}{2}\mathbf{u} \right\| = \frac{1}{2} \|\mathbf{u}\| = \frac{1}{2}\sqrt{(-1)^2 + 3^2 + 1^2} = \frac{1}{2}\sqrt{11}$.

Properties of Vector Operations

Let $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{w}$ be vectors. Let a and b be numbers. Then

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3. $\mathbf{u}+\mathbf{0}=\mathbf{u}$;
4. $\mathbf{u}+(-\mathbf{u})=\mathbf{0}$;
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6. $1\mathbf{u}=\mathbf{u}$;
7. $a(b\mathbf{u})=(ab)\mathbf{u}$;

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Properties of Vector Operations

Let $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{w}$ be vectors. Let a and b be numbers. Then

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5. $0\mathbf{u} = \mathbf{0}$;
6. $1\mathbf{u} = \mathbf{u}$;
7. $a(b\mathbf{u}) = (ab)\mathbf{u}$;
8. $a(\mathbf{u} + \mathbf{v}) = a\mathbf{u} + a\mathbf{v}$;
9. $(a + b)\mathbf{u} = a\mathbf{u} + b\mathbf{u}$.

Remark

We **can not** multiply vectors. Never never never never write "$\mathbf{uv}$".

Unit Vectors

Definition

$\mathbf{u}$ is called a *unit vector* $\iff \|\mathbf{u}\| = 1.$

Example

$\mathbf{u} = (2^{-\frac{1}{2}}, \frac{1}{2}, -\frac{1}{2})$ is a unit vector because

$$\|\mathbf{u}\| = \sqrt{\left(\frac{1}{\sqrt{2}}\right)^2 + \left(\frac{1}{2}\right)^2 + \left(-\frac{1}{2}\right)^2} = \sqrt{\frac{1}{2} + \frac{1}{4} + \frac{1}{4}} = 1.$$

Standard Unit Vectors

In $\mathbb{R}^2$: The *standard unit vectors* are $\mathbf{i} = (1, 0)$ and $\mathbf{j} = (0, 1)$.

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In $\mathbb{R}^3$: The *standard unit vectors* are $\mathbf{i} = (1, 0, 0)$, $\mathbf{j} = (0, 1, 0)$ and $\mathbf{k} = (0, 0, 1)$. Any vector $\mathbf{v} \in \mathbb{R}^3$ can be written

$$\begin{aligned} \mathbf{v} &= (v_1, v_2, v_3) = (v_1, 0, 0) + (0, v_2, 0) + (0, 0, v_3) \\ &= v_1\mathbf{i} + v_2\mathbf{j} + v_3\mathbf{k}. \end{aligned}$$

Normalising a Vector

If $\|\mathbf{v}\| \neq 0$, then $\frac{\mathbf{v}}{\|\mathbf{v}\|}$ is a unit vector because

$$\left\| \frac{\mathbf{v}}{\|\mathbf{v}\|} \right\| = \left\| \frac{1}{\|\mathbf{v}\|} \mathbf{v} \right\| = \frac{1}{\|\mathbf{v}\|} \|\mathbf{v}\| = 1.$$

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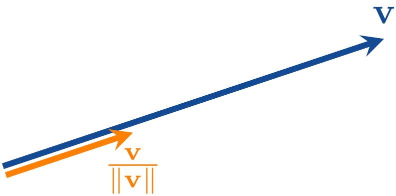
Clearly $\frac{\mathbf{v}}{\|\mathbf{v}\|}$ and $\mathbf{v}$ point in the same direction.



Example

Find a unit vector $\mathbf{u}$ which points in the same direction as $\overrightarrow{P_1P_2}$, where $P_1(1,0,1)$ and $P_2(3,2,0)$.

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We calculate that

$$\overrightarrow{P_1P_2} = P_2 - P_1 = (3,2,0) - (1,0,1) = (2,2,-1) = 2\mathbf{i} + 2\mathbf{j} - \mathbf{k}$$

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and that

$$\left\|\overrightarrow{P_1P_2}\right\| = \sqrt{2^2 + 2^2 + (-1)^2} = 3.$$

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and that

$$\left\|\overrightarrow{P_1P_2}\right\| = \sqrt{2^2 + 2^2 + (-1)^2} = 3.$$

The required unit vector is

$$\mathbf{u} = \frac{\overrightarrow{P_1P_2}}{\left\|\overrightarrow{P_1P_2}\right\|} = \frac{2\mathbf{i} + 2\mathbf{j} - \mathbf{k}}{3} = \frac{2}{3}\mathbf{i} + \frac{2}{3}\mathbf{j} - \frac{1}{3}\mathbf{k}.$$

EXAMPLE 5 If $\mathbf{v} = 3\mathbf{i} - 4\mathbf{j}$ is a velocity vector, express $\mathbf{v}$ as a product of its speed times its direction of motion.

Solution Speed is the magnitude (length) of $\mathbf{v}$:

$$|\mathbf{v}| = \sqrt{(3)^2 + (-4)^2} = \sqrt{9 + 16} = 5.$$

The unit vector $\mathbf{v}/|\mathbf{v}|$ is the direction of $\mathbf{v}$:

$$\frac{\mathbf{v}}{|\mathbf{v}|} = \frac{3\mathbf{i} - 4\mathbf{j}}{5} = \frac{3}{5}\mathbf{i} - \frac{4}{5}\mathbf{j}.$$

So

$$\mathbf{v} = 3\mathbf{i} - 4\mathbf{j} = \underbrace{5}_{\substack{\text{Length} \\ \text{(speed)}}}\Big(\underbrace{\frac{3}{5}\mathbf{i} - \frac{4}{5}\mathbf{j}}_{\text{Direction of motion}}\Big).$$

■

If $\mathbf{v} \neq \mathbf{0}$, then

1. $\dfrac{\mathbf{v}}{|\mathbf{v}|}$ is a unit vector called the direction of $\mathbf{v}$;

2. the equation $\mathbf{v} = |\mathbf{v}|\dfrac{\mathbf{v}}{|\mathbf{v}|}$ expresses $\mathbf{v}$ as its length times its direction.

EXAMPLE 6 A force of 6 newtons is applied in the direction of the vector $\mathbf{v} = 2\mathbf{i} + 2\mathbf{j} - \mathbf{k}$. Express the force $\mathbf{F}$ as a product of its magnitude and direction.

Solution The force vector has magnitude 6 and direction $\dfrac{\mathbf{v}}{|\mathbf{v}|}$, so

$$\mathbf{F} = 6\frac{\mathbf{v}}{|\mathbf{v}|} = 6\frac{2\mathbf{i} + 2\mathbf{j} - \mathbf{k}}{\sqrt{2^2 + 2^2 + (-1)^2}} = 6\frac{2\mathbf{i} + 2\mathbf{j} - \mathbf{k}}{3}$$

$$= 6\left(\frac{2}{3}\mathbf{i} + \frac{2}{3}\mathbf{j} - \frac{1}{3}\mathbf{k}\right).$$

Midpoint of a Line Segment

Vectors are often useful in geometry. For example, the coordinates of the midpoint of a line segment are found by averaging.

The **midpoint** M of the line segment joining points $P_1(x_1, y_1, z_1)$ and $P_2(x_2, y_2, z_2)$ is the point

$$\left(\frac{x_1 + x_2}{2}, \frac{y_1 + y_2}{2}, \frac{z_1 + z_2}{2}\right).$$

To see why, observe (Figure 12.16) that

$$\begin{aligned}\overrightarrow{OM} &= \overrightarrow{OP_1} + \frac{1}{2}(\overrightarrow{P_1P_2}) = \overrightarrow{OP_1} + \frac{1}{2}(\overrightarrow{OP_2} - \overrightarrow{OP_1}) \\ &= \frac{1}{2}(\overrightarrow{OP_1} + \overrightarrow{OP_2}) \\ &= \frac{x_1 + x_2}{2}\mathbf{i} + \frac{y_1 + y_2}{2}\mathbf{j} + \frac{z_1 + z_2}{2}\mathbf{k}.\end{aligned}$$

EXAMPLE 7 The midpoint of the segment joining $P_1(3, -2, 0)$ and $P_2(7, 4, 4)$ is

$$\left(\frac{3 + 7}{2}, \frac{-2 + 4}{2}, \frac{0 + 4}{2}\right) = (5, 1, 2).$$

Please read the final two examples in this section of the textbook.

Break

We will continue at 2pm

The Dot Product

11.3 The Dot Product

Definition

In $\mathbb{R}^2$, the *dot product* of $\mathbf{u} = (u_1, u_2) = u_1\mathbf{i} + u_2\mathbf{j}$ and $\mathbf{v} = (v_1, v_2) = v_1\mathbf{i} + v_2\mathbf{j}$ is

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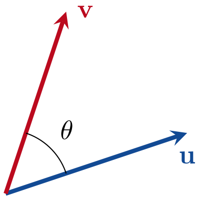
Definition

In $\mathbb{R}^3$, the *dot product* of $\mathbf{u} = (u_1, u_2, u_3) = u_1\mathbf{i} + u_2\mathbf{j} + u_3\mathbf{k}$ and $\mathbf{v} = (v_1, v_2, v_3) = v_1\mathbf{i} + v_2\mathbf{j} + v_3\mathbf{k}$ is

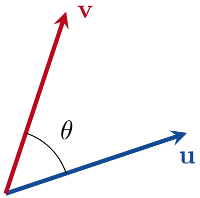
$$\mathbf{u} \bullet \mathbf{v} = u_1v_1 + u_2v_2 + u_3v_3.$$



Theorem

The angle between $\mathbf{u}$ *and* $\mathbf{v}$ *is*

$$\theta = \cos^{-1}\left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{u}\|\,\|\mathbf{v}\|}\right).$$



Theorem

The angle between $\mathbf{u}$ *and* $\mathbf{v}$ *is*

$$\theta = \cos^{-1}\left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{u}\|\,\|\mathbf{v}\|}\right).$$

This means that

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

Example

$$
\begin{aligned}
(1,-2,-1)\bullet(-6,2,-3) &= (1\times -6)+(-2\times 2)+(-1\times -3)\\
&= -6-4+3=-7.
\end{aligned}
$$

Example

$$\begin{aligned}(1,-2,-1)\cdot(-6,2,-3) &= (1\times -6)+(-2\times 2)+(-1\times -3)\\ &= -6-4+3=-7.\end{aligned}$$

Example

$$\begin{aligned}(\tfrac{1}{2}\mathbf{i}+3\mathbf{j}+\mathbf{k})\cdot(4\mathbf{i}-\mathbf{j}+2\mathbf{k}) &= (\tfrac{1}{2}\times 4)+(3\times -1)+(1\times 2)\\ &= 2-3+2=1.\end{aligned}$$

$$\theta = \cos^{-1}\left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{u}\|\,\|\mathbf{v}\|}\right).$$

Example

Find the angle between $\mathbf{u} = \mathbf{i} - 2\mathbf{j} - 2\mathbf{k}$ and $\mathbf{v} = 6\mathbf{i} + 3\mathbf{j} + 2\mathbf{k}$.

$$\theta = \cos^{-1}\left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{u}\|\,\|\mathbf{v}\|}\right).$$

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Find the angle between $\mathbf{u} = \mathbf{i} - 2\mathbf{j} - 2\mathbf{k}$ and $\mathbf{v} = 6\mathbf{i} + 3\mathbf{j} + 2\mathbf{k}$.

Since

$$\begin{aligned}\mathbf{u}\cdot\mathbf{v} &= (1,-2,-2)\cdot(6,3,2) = (1\times 6) + (-2\times 3) + (-2\times 2)\\ &= 6 - 6 - 4 = -4,\end{aligned}$$

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$$\|\mathbf{u}\| = \sqrt{1^2 + (-2)^2 + (-2)^2} = \sqrt{9} = 3$$

and

$$\|\mathbf{v}\| = \sqrt{6^2 + 3^2 + 2^2} = \sqrt{49} = 7,$$

$$\theta = \cos^{-1}\left(\frac{\mathbf{u} \bullet \mathbf{v}}{\|\mathbf{u}\| \, \|\mathbf{v}\|}\right).$$

Example

Find the angle between $\mathbf{u} = \mathbf{i} - 2\mathbf{j} - 2\mathbf{k}$ and $\mathbf{v} = 6\mathbf{i} + 3\mathbf{j} + 2\mathbf{k}$.

Since

$$\begin{aligned} \mathbf{u} \bullet \mathbf{v} &= (1, -2, -2) \bullet (6, 3, 2) = (1 \times 6) + (-2 \times 3) + (-2 \times 2) \\ &= 6 - 6 - 4 = -4, \end{aligned}$$

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Example

Find the angle between $\mathbf{u} = \mathbf{i} - 2\mathbf{j} - 2\mathbf{k}$ and $\mathbf{v} = 6\mathbf{i} + 3\mathbf{j} + 2\mathbf{k}$.

Since

$$\begin{aligned}\mathbf{u} \bullet \mathbf{v} &= (1, -2, -2) \bullet (6, 3, 2) = (1 \times 6) + (-2 \times 3) + (-2 \times 2) \\ &= 6 - 6 - 4 = -4,\end{aligned}$$

$$\|\mathbf{u}\| = \sqrt{1^2 + (-2)^2 + (-2)^2} = \sqrt{9} = 3$$

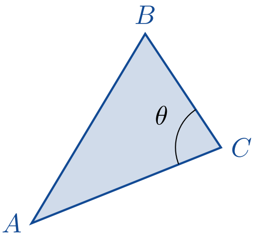
and

$$\|\mathbf{v}\| = \sqrt{6^2 + 3^2 + 2^2} = \sqrt{49} = 7,$$

we have that

$$\theta = \cos^{-1}\left(\frac{\mathbf{u} \bullet \mathbf{v}}{\|\mathbf{u}\| \, \|\mathbf{v}\|}\right) = \cos^{-1}\left(-\frac{4}{21}\right) \approx 1.76 \text{ radians} \approx 98.5^\circ.$$

$$\theta = \cos^{-1}\left(\frac{\mathbf{u}\bullet\mathbf{v}}{\|\mathbf{u}\|\,\|\mathbf{v}\|}\right).$$



Example

If $A(0,0)$, $B(3,5)$ and $C(5,2)$, find $\theta = \measuredangle ACB$.

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θ is the angle between $\overrightarrow{CA}$ and $\overrightarrow{CB}$. We calculate that

$$\begin{aligned}
\overrightarrow{CA} &= A - C = (0,0) - (5,2) = (-5,-2), \\
\overrightarrow{CB} &= B - C = (3,5) - (5,2) = (-2,3), \\
\overrightarrow{CA} \bullet \overrightarrow{CB} &= (-5,-2) \bullet (-2,3) = 4, \\
\left\| \overrightarrow{CA} \right\| &= \sqrt{(-5)^2 + (-2)^2} = \sqrt{29}
\end{aligned}$$

and

$$\left\| \overrightarrow{CB} \right\| = \sqrt{(-2)^2 + 3^2} = \sqrt{13}.$$

θ is the angle between $\overrightarrow{CA}$ and $\overrightarrow{CB}$. We calculate that

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\overrightarrow{CA} &= A - C = (0,0) - (5,2) = (-5,-2), \\
\overrightarrow{CB} &= B - C = (3,5) - (5,2) = (-2,3), \\
\overrightarrow{CA} \cdot \overrightarrow{CB} &= (-5,-2) \cdot (-2,3) = 4, \\
\left\| \overrightarrow{CA} \right\| &= \sqrt{(-5)^2 + (-2)^2} = \sqrt{29}
\end{aligned}$$

and

$$\left\| \overrightarrow{CB} \right\| = \sqrt{(-2)^2 + 3^2} = \sqrt{13}.$$

Therefore

$$\begin{aligned}
\theta &= \cos^{-1} \left(\frac{\overrightarrow{CA} \cdot \overrightarrow{CB}}{\left\| \overrightarrow{CA} \right\| \left\| \overrightarrow{CB} \right\|} \right) = \cos^{-1} \left(\frac{4}{\sqrt{29}\sqrt{13}} \right) \\
&\approx 78.1^\circ \approx 1.36 \text{ radians.}
\end{aligned}$$

Definition

$\mathbf{u}$ and $\mathbf{v}$ are *orthogonal* $\iff$ $\mathbf{u} \cdot \mathbf{v} = 0$.

11.3 The Dot Product

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Remark

Recall that

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Recall that

$$\mathbf{u} \bullet \mathbf{v} = \|\mathbf{u}\| \, \|\mathbf{v}\| \cos\theta.$$

Therefore

$$\mathbf{u} \text{ and } \mathbf{v} \text{ are orthogonal} \iff \begin{pmatrix} \mathbf{u} = \mathbf{0} \\ \text{or} \\ \mathbf{v} = \mathbf{0} \\ \text{or} \\ \theta = 90^\circ. \end{pmatrix}$$

Example

$\mathbf{u} = (3, -2)$ and $\mathbf{v} = (4, 6)$ are orthogonal because
$\mathbf{u} \cdot \mathbf{v} = (3, -2) \cdot (4, 6) = (3 \times 4) + (-2 \times 6) = 12 - 12 = 0.$

Example

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Example

$\mathbf{u} = 3\mathbf{i} - 2\mathbf{j} + \mathbf{k}$ and $\mathbf{v} = 2\mathbf{j} + 4\mathbf{k}$ are orthogonal because
$\mathbf{u} \bullet \mathbf{v} = (3 \times 0) + (-2 \times 2) + (1 \times 4) = 0 - 4 + 4 = 0.$

Example

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Example

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$\mathbf{u} \cdot \mathbf{v} = (3 \times 0) + (-2 \times 2) + (1 \times 4) = 0 - 4 + 4 = 0.$

Example

$\mathbf{0}$ is orthogonal to every vector $\mathbf{u}$ because
$\mathbf{0} \cdot \mathbf{u} = (0, 0, 0) \cdot (u_1, u_2, u_3) = 0u_1 + 0u_2 + 0u_3 = 0.$

Properties of the Dot Product

Let $\mathbf{u}$, $\mathbf{v}$ and $\mathbf{w}$ be vectors. Let k be a number. Then

1. $\mathbf{u} \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{u}$;

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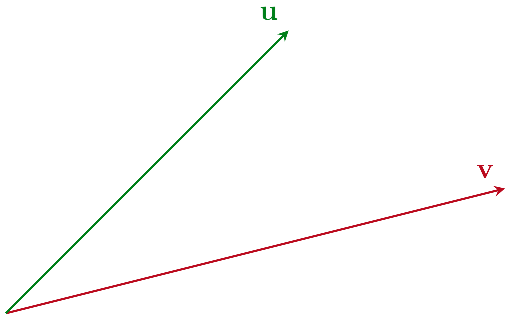
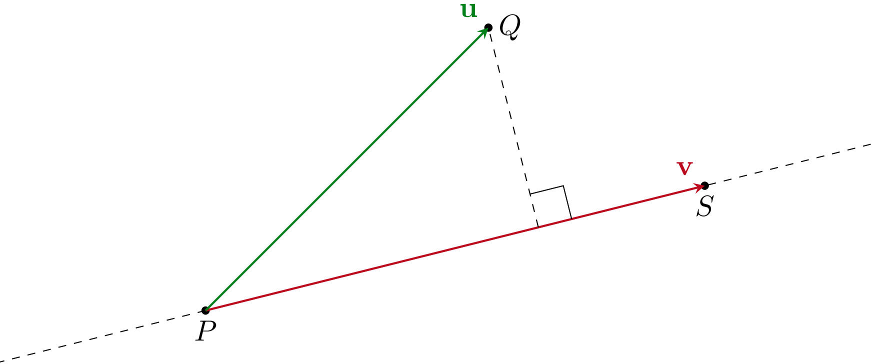
4. $\mathbf{u} \cdot \mathbf{u} = \|\mathbf{u}\|^2$; and
5. $\mathbf{0} \cdot \mathbf{u} = 0$.

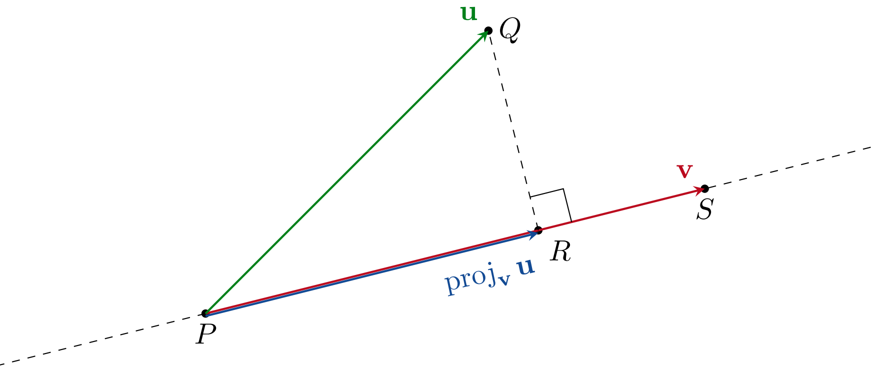
Vector Projections



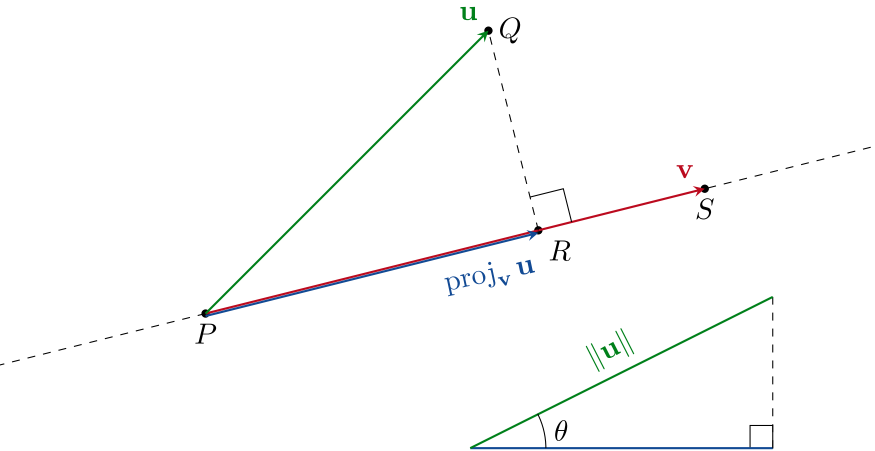
Vector Projections



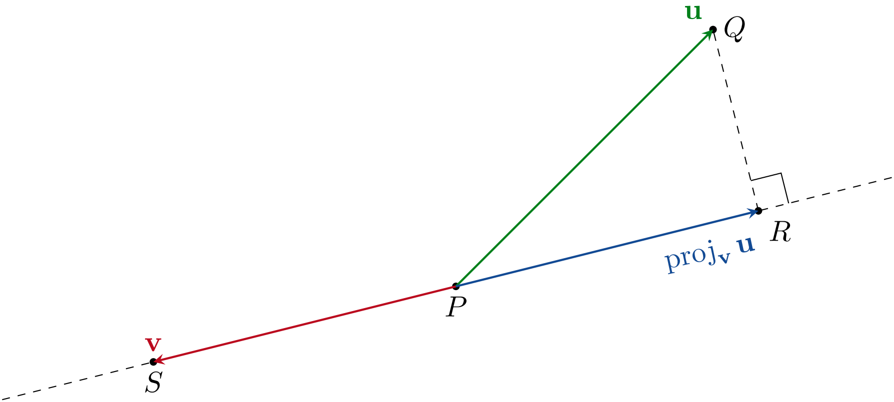
Vector Projections

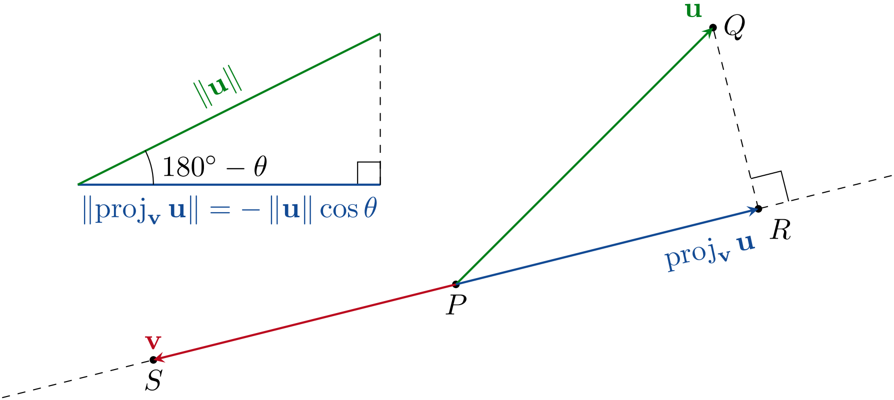


Vector Projections



$$\|\mathrm{proj}_{\mathbf{v}}\,\mathbf{u}\| = \|\mathbf{u}\|\cos\theta$$


u
Q
R
$\text{proj}_{\mathbf{v}}\,\mathbf{u}$
P
v
S



$\|\mathbf{u}\|$
$180° - \theta$
$\|\text{proj}_{\mathbf{v}}\,\mathbf{u}\| = -\,\|\mathbf{u}\|\cos\theta$
$\mathbf{u}$
Q
R
$\text{proj}_{\mathbf{v}}\,\mathbf{u}$
P
$\mathbf{v}$
S

Definition

The *vector projection* of $\mathbf{u}$ onto $\mathbf{v}$ is the vector

$$\operatorname{proj}_{\mathbf{v}} \mathbf{u} = \overrightarrow{PR}.$$

Now

$$\operatorname{proj}_{\mathbf{v}} \mathbf{u} = \left(\text{length of } \operatorname{proj}_{\mathbf{v}} \mathbf{u}\right) \begin{pmatrix} \text{a unit vector in} \\ \text{the same} \\ \text{direction as } \mathbf{v} \end{pmatrix}$$

$$=$$

$$=$$

$$=$$

$$=$$

Now

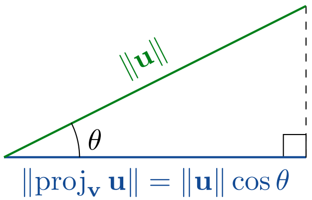
$$\operatorname{proj}_{\mathbf{v}} \mathbf{u} = \left(\text{length of } \operatorname{proj}_{\mathbf{v}} \mathbf{u}\right) \begin{pmatrix} \text{a unit vector in} \\ \text{the same} \\ \text{direction as } \mathbf{v} \end{pmatrix}$$

$$= \|\operatorname{proj}_{\mathbf{v}} \mathbf{u}\| \left(\frac{\mathbf{v}}{\|\mathbf{v}\|}\right)$$

$$=$$

$$=$$

$$=$$



Now

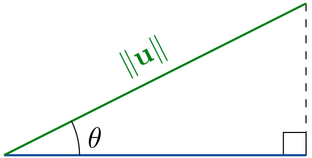
$$\operatorname{proj}_{\mathbf{v}}\mathbf{u} = \left(\text{length of } \operatorname{proj}_{\mathbf{v}}\mathbf{u}\right)\left(\begin{array}{c}\text{a unit vector in}\\ \text{the same}\\ \text{direction as } \mathbf{v}\end{array}\right)$$

$$= \|\operatorname{proj}_{\mathbf{v}}\mathbf{u}\|\left(\frac{\mathbf{v}}{\|\mathbf{v}\|}\right)$$

$$= \|\mathbf{u}\|\,(\cos\theta)\left(\frac{\mathbf{v}}{\|\mathbf{v}\|}\right)$$

$$=$$

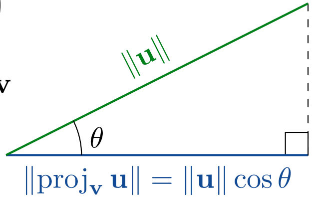
$$=$$



$\|\operatorname{proj}_{\mathbf{v}}\mathbf{u}\| = \|\mathbf{u}\|\cos\theta$

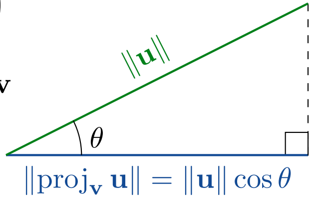
Now

$$
\begin{aligned}
\mathrm{proj}_{\mathbf{v}}\,\mathbf{u} &= (\text{length of } \mathrm{proj}_{\mathbf{v}}\,\mathbf{u}) \begin{pmatrix} \text{a unit vector in} \\ \text{the same} \\ \text{direction as } \mathbf{v} \end{pmatrix} \\
&= \left\|\mathrm{proj}_{\mathbf{v}}\,\mathbf{u}\right\| \left(\frac{\mathbf{v}}{\|\mathbf{v}\|}\right) \\
&= \|\mathbf{u}\|\,(\cos\theta) \left(\frac{\mathbf{v}}{\|\mathbf{v}\|}\right) \\
&= \left(\frac{\|\mathbf{u}\|\,\|\mathbf{v}\|\cos\theta}{\|\mathbf{v}\|^2}\right)\mathbf{v} \\
&=
\end{aligned}
$$

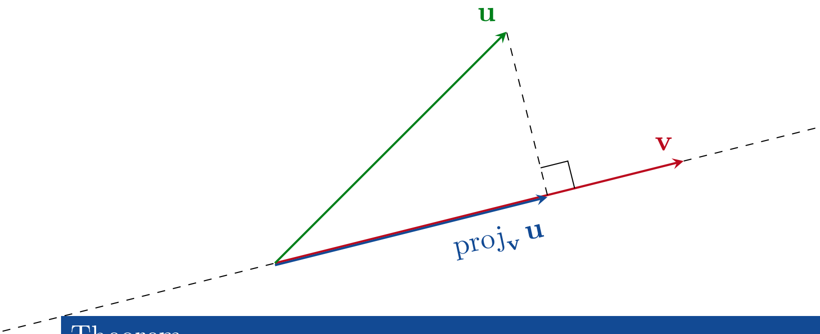


Now

$$\begin{aligned}
\operatorname{proj}_{\mathbf{v}} \mathbf{u} &= (\text{length of } \operatorname{proj}_{\mathbf{v}} \mathbf{u}) \begin{pmatrix} \text{a unit vector in} \\ \text{the same} \\ \text{direction as } \mathbf{v} \end{pmatrix} \\
&= \|\operatorname{proj}_{\mathbf{v}} \mathbf{u}\| \left(\frac{\mathbf{v}}{\|\mathbf{v}\|} \right) \\
&= \|\mathbf{u}\| (\cos\theta) \left(\frac{\mathbf{v}}{\|\mathbf{v}\|} \right) \\
&= \left(\frac{\|\mathbf{u}\| \, \|\mathbf{v}\| \cos\theta}{\|\mathbf{v}\|^2} \right) \mathbf{v} \\
&= \left(\frac{\mathbf{u} \cdot \mathbf{v}}{\|\mathbf{v}\|^2} \right) \mathbf{v}.
\end{aligned}$$



Since this is an important formula, we write it as a theorem.



Theorem

The vector projection of $\mathbf{u}$ *onto* $\mathbf{v}$ *is*

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

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

Example

Find the vector projection of $\mathbf{u} = 6\mathbf{i} + 3\mathbf{j} + 2\mathbf{k}$ onto $\mathbf{v} = \mathbf{i} - 2\mathbf{j} - 2\mathbf{k}$.

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

Example

Find the vector projection of $\mathbf{u} = 6\mathbf{i} + 3\mathbf{j} + 2\mathbf{k}$ onto $\mathbf{v} = \mathbf{i} - 2\mathbf{j} - 2\mathbf{k}$.

$$\begin{aligned}\text{proj}_{\mathbf{v}}\,\mathbf{u} &= \left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{v}\|^2}\right)\mathbf{v} = \left(\frac{6-6-4}{1+4+4}\right)(\mathbf{i} - 2\mathbf{j} - 2\mathbf{k}) \\ &= -\frac{4}{9}\mathbf{i} + \frac{8}{9}\mathbf{j} + \frac{8}{9}\mathbf{k}.\end{aligned}$$

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

Example

Find the vector projection of $\mathbf{F} = 5\mathbf{i} + 2\mathbf{j}$ onto $\mathbf{v} = \mathbf{i} - 3\mathbf{j}$.

$$\begin{aligned} \operatorname{proj}_{\mathbf{v}} \mathbf{F} &= \left(\frac{\mathbf{F} \cdot \mathbf{v}}{\|\mathbf{v}\|^2} \right) \mathbf{v} = \left(\frac{5-6}{1+9} \right) (\mathbf{i} - 3\mathbf{j}) \\ &= -\frac{1}{10}\mathbf{i} + \frac{3}{10}\mathbf{j}. \end{aligned}$$

$$\operatorname{proj}_{\mathbf{v}} \mathbf{u} = \left(\frac{\mathbf{u} \bullet \mathbf{v}}{\|\mathbf{v}\|^2} \right) \mathbf{v}$$

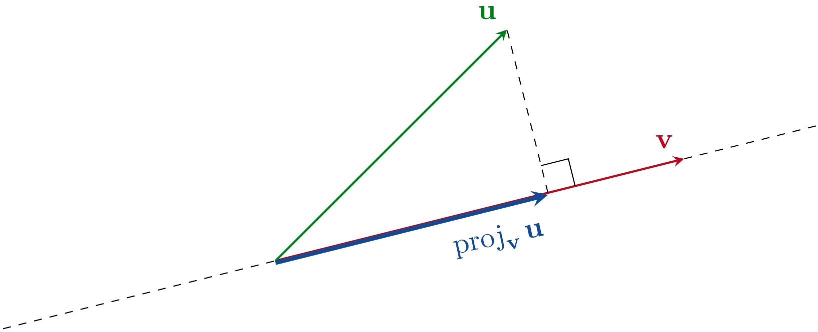
Example

Verify that the vector $\mathbf{u} - \operatorname{proj}_{\mathbf{v}} \mathbf{u}$ is orthogonal to $\operatorname{proj}_{\mathbf{v}} \mathbf{u}$.

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

Example

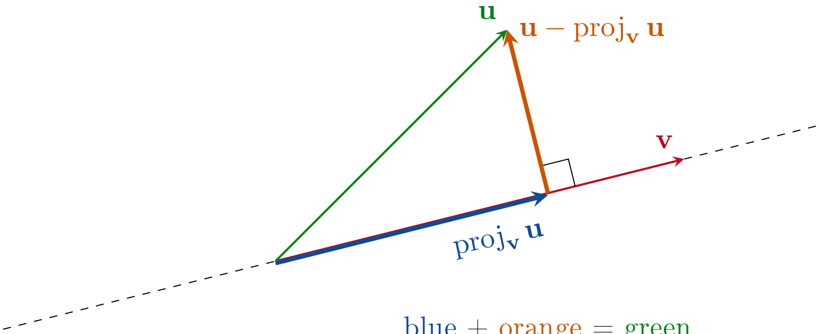
Verify that the vector $\mathbf{u} - \operatorname{proj}_{\mathbf{v}} \mathbf{u}$ is orthogonal to $\operatorname{proj}_{\mathbf{v}} \mathbf{u}$.



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

Example

Verify that the vector $\mathbf{u} - \operatorname{proj}_{\mathbf{v}} \mathbf{u}$ is orthogonal to $\operatorname{proj}_{\mathbf{v}} \mathbf{u}$.



blue + orange = green

$$\boxed{\operatorname{proj}_{\mathbf{v}} \mathbf{u} = \left(\frac{\mathbf{u} \bullet \mathbf{v}}{\|\mathbf{v}\|^2}\right) \mathbf{v}}$$

Clearly

$$\operatorname{proj}_{\mathbf{v}} \mathbf{u} = \left(\frac{\mathbf{u} \bullet \mathbf{v}}{\|\mathbf{v}\|^2}\right) \mathbf{v} = \big(\text{a number}\big)\mathbf{v}$$

is parallel to $\mathbf{v}$.

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

Clearly

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

is parallel to $\mathbf{v}$. So it is enough to show that $\mathbf{u} - \text{proj}_{\mathbf{v}}\,\mathbf{u}$ is orthogonal to $\mathbf{v}$.

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

Clearly

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

is parallel to $\mathbf{v}$. So it is enough to show that $\mathbf{u} - \operatorname{proj}_{\mathbf{v}} \mathbf{u}$ is orthogonal to $\mathbf{v}$.

Since

$$\begin{aligned}
(\mathbf{u} - \operatorname{proj}_{\mathbf{v}} \mathbf{u}) \cdot \mathbf{v} &= \\
&= \\
&= \\
&= 0
\end{aligned}$$

we have shown that $\mathbf{u} - \operatorname{proj}_{\mathbf{v}} \mathbf{u}$ is orthogonal to $\mathbf{v}$.

$$\boxed{\mathrm{proj}_{\mathbf{v}}\,\mathbf{u} = \left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{v}\|^2}\right)\mathbf{v}}$$

Clearly

$$\mathrm{proj}_{\mathbf{v}}\,\mathbf{u} = \left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{v}\|^2}\right)\mathbf{v} = \big(\text{a number}\big)\mathbf{v}$$

is parallel to $\mathbf{v}$. So it is enough to show that $\mathbf{u} - \mathrm{proj}_{\mathbf{v}}\,\mathbf{u}$ is orthogonal to $\mathbf{v}$.
Since

$$\begin{aligned}(\mathbf{u} - \mathrm{proj}_{\mathbf{v}}\,\mathbf{u})\cdot\mathbf{v} &= \mathbf{u}\cdot\mathbf{v} - \left(\frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{v}\|^2}\right)\mathbf{v}\cdot\mathbf{v} \\ &= \mathbf{u}\cdot\mathbf{v} - \frac{\mathbf{u}\cdot\mathbf{v}}{\|\mathbf{v}\|^2}\|\mathbf{v}\|^2 \\ &= \mathbf{u}\cdot\mathbf{v} - \mathbf{u}\cdot\mathbf{v} \\ &= 0\end{aligned}$$

we have shown that $\mathbf{u} - \mathrm{proj}_{\mathbf{v}}\,\mathbf{u}$ is orthogonal to $\mathbf{v}$.

Next Time

- 11.4 The Cross Product
- 11.5 Lines and Planes in Space