Vector Properties

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Contents

***Abstract*—This book provides a computational approach to school geometry based on the NCERT textbooks from Class 6-12. Links to sample Python codes are available in the text.**

1 Direction Vector

1.1. Find the direction vector of the line, which makes an angle of $30°$ with the y-axis measured anticlockwise.

1.2. Find the direction vectors and and y-intercepts of the following lines

a) $\begin{pmatrix} 1 & 7 \end{pmatrix} \mathbf{x} = 0.$

b) $\begin{pmatrix} 6 & 3 \end{pmatrix} \mathbf{x} = 5.$

c) $\begin{pmatrix} 0 & 1 \end{pmatrix} \mathbf{x} = 0.$

1.3. Find a unit vector in the direction of $\mathbf{A} + \mathbf{B}$, where

$$\mathbf{A} = \begin{pmatrix} 2 \\ 2 \\ -5 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 2 \\ 1 \\ 3 \end{pmatrix}. \tag{1.3.1}$$

Solution: Let

$$\mathbf{C} = \mathbf{A} + \mathbf{B} \tag{1.3.2}$$

$$\tag{1.3.3}$$

$$\therefore \mathbf{C} = \begin{pmatrix} 4 \\ 3 \\ -2 \end{pmatrix} \tag{1.3.4}$$

$$\text{and } \|\mathbf{C}\| = \sqrt{(4)^2 + (3)^2 + (-2)^2} \tag{1.3.5}$$

$$= \sqrt{29} \tag{1.3.6}$$

Thus, the unit vector in the direction of $\mathbf{C}$ is

$$\frac{\mathbf{C}}{\|\mathbf{C}\|} = \frac{1}{\sqrt{29}} \begin{pmatrix} 4 \\ 3 \\ -2 \end{pmatrix} \tag{1.3.7}$$

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1.4. If $\mathbf{a} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} 2 \\ -1 \\ 3 \end{pmatrix}, \mathbf{c} = \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix}$, find a unit vector parallel to the vector $2\mathbf{a} - \mathbf{b} + 3\mathbf{c}$.
Solution:

$$\mathbf{d} = \mathbf{2a} - \mathbf{b} + \mathbf{3c} \tag{1.4.1}$$

$$= 2\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} - \begin{pmatrix} 2 \\ -1 \\ 3 \end{pmatrix} + 3\begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix} \tag{1.4.2}$$

$$= \begin{pmatrix} 3 \\ -3 \\ 2 \end{pmatrix} \tag{1.4.3}$$

Hence,

$$\|\mathbf{d}\| = \sqrt{3^2 + (-3)^2 + 2^2} = \sqrt{22} \tag{1.4.4}$$

$$\implies \frac{\mathbf{d}}{\|\mathbf{d}\|} = \frac{1}{\sqrt{22}} \begin{pmatrix} 3 \\ -3 \\ 2 \end{pmatrix} \tag{1.4.5}$$

is the unit vector parallel to given vector.

1.5. Find a vector of magnitude 5 units, and parallel to the resultant of the vectors $\mathbf{a} = \begin{pmatrix} 2 \\ 3 \\ -1 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix}$,
Solution:

1.6. Show that the unit direction vector inclined equally to the coordinate axes is $\begin{pmatrix} \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \end{pmatrix}$.
Solution:

1.7. Find a unit vector that makes an angle of $90°, 135°$ and $45°$ with the positive x, y and z axis respectively. **Solution:**

1.8. Show that the line through the points $\begin{pmatrix} 4 \\ 7 \\ 8 \end{pmatrix}$,

$\begin{pmatrix} 2 \\ 3 \\ 4 \end{pmatrix}$ is parallel to the line through the points $\begin{pmatrix} -1 \\ -2 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 2 \\ 5 \end{pmatrix}$.

Solution:

1.9. Find a vector $\mathbf{x}$ in the direction of $\begin{pmatrix} 1 \\ -2 \end{pmatrix}$ such that $\|\mathbf{x}\| = 7$. **Solution:** Let $\mathbf{x} = k\begin{pmatrix} 1 \\ -2 \end{pmatrix}$. Then

$$\|\mathbf{x}\| = |k| \left\| \begin{pmatrix} 1 \\ -2 \end{pmatrix} \right\| = 7 \tag{1.9.1}$$

$$\implies |k| = \frac{7}{\sqrt{5}} \tag{1.9.2}$$

$$\text{or, } \mathbf{x} = \frac{7}{\sqrt{5}} \begin{pmatrix} 1 \\ -2 \end{pmatrix} \tag{1.9.3}$$

1.10. Find the direction vector of PQ, where

$$\mathbf{P} = \begin{pmatrix} 2 \\ 3 \\ 0 \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} -1 \\ -2 \\ -4 \end{pmatrix} \tag{1.10.1}$$

Solution: The direction vector of PQ is

$$\mathbf{P} - \mathbf{Q} = \begin{pmatrix} 3 \\ 5 \\ 4 \end{pmatrix}, \tag{1.10.2}$$

1.11. Find the slope of a line, which passes through the origin, and the mid-point of the line segment joining the points $\mathbf{P} = \begin{pmatrix} 0 \\ -4 \end{pmatrix}$ and $\mathbf{B} = \begin{pmatrix} 8 \\ 0 \end{pmatrix}$. **Solution:**

1.12. The slope of a line is double of the slope of another line. If the tangent of the angle between them is $\frac{1}{3}$, find the slopes of the lines. **Solution:**

1.13. Find a unit vector that makes an angle of $90°, 60°$ and $30°$ with the positive x, y and z axis respectively.
Solution: The direction vector is

$$\mathbf{x} = \begin{pmatrix} \cos 90° \\ \cos 60° \\ \cos 30° \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{pmatrix} \tag{1.13.1}$$

$\because \|\mathbf{x}\| = 1$, it is the desired unit vector.

1.14. Find the direction vectors and slopes of the lines passing through the points

a) $\begin{pmatrix} 3 \\ -2 \end{pmatrix}$ and $\begin{pmatrix} -1 \\ 4 \end{pmatrix}$.
b) $\begin{pmatrix} 3 \\ -2 \end{pmatrix}$ and $\begin{pmatrix} 7 \\ -2 \end{pmatrix}$.
c) $\begin{pmatrix} 3 \\ -2 \end{pmatrix}$ and $\begin{pmatrix} 3 \\ 4 \end{pmatrix}$.
d) Making an inclination of $60°$ with the positive direction of the x-axis.

Solution:

a) If the direction vector is

$$\begin{pmatrix} 1 \\ m \end{pmatrix}, \tag{1.14.1}$$

the slope is m. Thus, the direction vector is

$$\begin{pmatrix} -1 \\ 4 \end{pmatrix} - \begin{pmatrix} 3 \\ -2 \end{pmatrix} = \begin{pmatrix} -4 \\ 6 \end{pmatrix} = -\frac{1}{4}\begin{pmatrix} -4 \\ 6 \end{pmatrix} \tag{1.14.2}$$

$$= \begin{pmatrix} 1 \\ -\frac{3}{2} \end{pmatrix} \implies m = -\frac{3}{2} \tag{1.14.3}$$

b) The direction vector is

$$\begin{pmatrix} 7 \\ -2 \end{pmatrix} - \begin{pmatrix} 3 \\ -2 \end{pmatrix} = \begin{pmatrix} 4 \\ 0 \end{pmatrix} \tag{1.14.4}$$

$$= \begin{pmatrix} 1 \\ 0 \end{pmatrix} \implies m = 0 \tag{1.14.5}$$

c) The direction vector is

$$\begin{pmatrix} 3 \\ 4 \end{pmatrix} - \begin{pmatrix} 3 \\ -2 \end{pmatrix} = \begin{pmatrix} 0 \\ 6 \end{pmatrix} \tag{1.14.6}$$

$$= \begin{pmatrix} 1 \\ \infty \end{pmatrix} \implies m = \infty \tag{1.14.7}$$

d) The slope is $m = \tan 60° = \sqrt{3}$ and the direction vector is

$$\begin{pmatrix} 1 \\ \sqrt{3} \end{pmatrix} \tag{1.14.8}$$

1.15. If the angle between two lines is $\frac{\pi}{4}$ and the slope of one of the lines is $\frac{1}{4}$ find the slope of the other line.

Solution: The angle θ between two lines is given by

$$\tan\theta = \frac{m_1 - m_2}{1 + m_1 m_2} \tag{1.15.1}$$

$$\implies 1 = \frac{m_1 - \frac{1}{4}}{1 + \frac{m_1}{4}} \tag{1.15.2}$$

$$\text{or } m_1 = \frac{5}{3} \tag{1.15.3}$$

1.16. If the points $\mathbf{A} = \begin{pmatrix} 6 \\ 1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 8 \\ 2 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} 9 \\ 4 \end{pmatrix}, \mathbf{D} = \begin{pmatrix} p \\ 3 \end{pmatrix}$ are the vertices of a parallelogram, taken in order, find the value of p.
Solution: In the parallelogram $ABCD$, AC and BD bisect each other. This can be used to find p.

1.17. Without using distance formula, show that points $\begin{pmatrix} -2 \\ -1 \end{pmatrix}$, $\begin{pmatrix} 4 \\ 0 \end{pmatrix}$, $\begin{pmatrix} 3 \\ 3 \end{pmatrix}$ and $\begin{pmatrix} -3 \\ 2 \end{pmatrix}$ are the vertices of a parallelogram.
Solution:

1.18. The two opposite vertices of a square are $\begin{pmatrix} -1 \\ 2 \end{pmatrix}$, $\begin{pmatrix} 3 \\ 2 \end{pmatrix}$. Find the coordinates of the other two vertices.
Solution:

1.19. Find the direction vectors of the sides of a triangle with vertices $\mathbf{A} = \begin{pmatrix} 3 \\ 5 \\ -4 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} -1 \\ 1 \\ 2 \end{pmatrix}$, and $\mathbf{C} = \begin{pmatrix} -5 \\ -5 \\ -2 \end{pmatrix}$
Solution:

1.20. Find a unit vector in the direction of

$$\begin{pmatrix} 1 \\ 1 \\ -2 \end{pmatrix}. \tag{1.20.1}$$

Solution:

1.21. Find a unit vector in the direction of $\begin{pmatrix} 2 \\ -1 \\ -2 \end{pmatrix}$.
Solution:

1.22. Find a unit vector in the direction of the line passing through $\begin{pmatrix} -2 \\ 4 \\ -5 \end{pmatrix}$ and $\begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}$.
Solution:

2 Norm

2.1. Find a point on the x-axis, which is equidistant from the points $\begin{pmatrix} 7 \\ 6 \end{pmatrix}$ and $\begin{pmatrix} 3 \\ 4 \end{pmatrix}$.
Solution:

2.2. Write down a unit vector in the xy-plane, makeing an angle of $30°$ with the positive direction of the x-axis.
Solution:

2.3. Find the value of x for which $x\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$ is a unit vector.
Solution:

2.4. If

$$\mathbf{a} = \begin{pmatrix} 1 \\ 2 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} 2 \\ 1 \end{pmatrix}, \tag{2.4.1}$$

verify if
a) $\|\mathbf{a}\| = \|\mathbf{b}\|$
b) $\mathbf{a} = \mathbf{b}$
Solution:
a) $\|\mathbf{a}\| = \|\mathbf{b}\|, \mathbf{a} \neq \mathbf{b}$.

2.5. Find a unit vector in the direction of $\begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix}$.
Solution: The unit vector is given by

$$\frac{\begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix}}{\left\| \begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix} \right\|} = \frac{1}{\sqrt{14}} \begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix} \tag{2.5.1}$$

2.6. Find the distance between the points

$$\mathbf{P} = \begin{pmatrix} 1 \\ -3 \\ 4 \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} -4 \\ 1 \\ 2 \end{pmatrix} \tag{2.6.1}$$

Solution:
The distance is given by $\|\mathbf{P} - \mathbf{Q}\|$

2.7. Find $\|\mathbf{a} - \mathbf{b}\|$, if

$$\|\mathbf{a}\| = 2, \|\mathbf{b}\| = 3, \mathbf{a}^T\mathbf{b} = 4. \tag{2.7.1}$$

Solution:

2.8. If $\mathbf{a}$ is a unit vector and

$$(\mathbf{x} - \mathbf{a})(\mathbf{x} + \mathbf{a}) = 8, \tag{2.8.1}$$

then find $\mathbf{x}$.
Solution:

$$(\mathbf{x}-\mathbf{a})(\mathbf{x}+\mathbf{a}) = \|\mathbf{x}\|^2 - \|\mathbf{a}\|^2 \tag{2.8.2}$$
$$\implies \|\mathbf{x}\|^2 = 9 \text{ or, } \|\mathbf{x}\| = 3. \tag{2.8.3}$$

2.9. Find the point on the x-axis which is equidistant from

$$\begin{pmatrix}2\\-5\end{pmatrix}, \begin{pmatrix}-2\\9\end{pmatrix}, \tag{2.9.1}$$

Solution:

2.10. Find the values of y for which the distance between the points

$$\mathbf{P} = \begin{pmatrix}2\\-3\end{pmatrix}, \mathbf{Q} = \begin{pmatrix}10\\y\end{pmatrix} \tag{2.10.1}$$

is 10 units. **Solution:**

2.11. A town B is located 36km east and 15 km north of the town A. How would you find the distance from town A to town B without actually measuring it?
Solution:

2.12. Find the unit normal vector of the plane

$$\begin{pmatrix}6 & -3 & -2\end{pmatrix}\mathbf{x} = 1. \tag{2.12.1}$$

Solution: The normal vector is

$$\mathbf{n} = \begin{pmatrix}6 & -3 & -2\end{pmatrix} \tag{2.12.2}$$
$$\because \|\mathbf{n}\| = 7, \tag{2.12.3}$$

the unit normal vector is

$$\frac{\mathbf{n}}{\|\mathbf{n}\|} = \frac{1}{7}\begin{pmatrix}6 & -3 & -2\end{pmatrix} \tag{2.12.4}$$

2.13. Find the condition for $\mathbf{x} = \begin{pmatrix}x_1\\x_2\end{pmatrix}$ to be equidistant from the points $\begin{pmatrix}7\\1\end{pmatrix}, \begin{pmatrix}3\\5\end{pmatrix}$.
Solution: From the given information,

$$\left\|\mathbf{x} - \begin{pmatrix}7\\1\end{pmatrix}\right\|^2 = \left\|\mathbf{x} - \begin{pmatrix}3\\5\end{pmatrix}\right\|^2 \tag{2.13.1}$$

$$\implies \|\mathbf{x}\|^2 + \left\|\begin{pmatrix}7\\1\end{pmatrix}\right\|^2 - 2\begin{pmatrix}7 & 1\end{pmatrix}\mathbf{x}$$
$$= \|\mathbf{x}\|^2 + \left\|\begin{pmatrix}3\\5\end{pmatrix}\right\|^2 - 2\begin{pmatrix}3 & 5\end{pmatrix}\mathbf{x} \tag{2.13.2}$$

which can be simplified to obtain

$$\begin{pmatrix}1 & -1\end{pmatrix}\mathbf{x} = 2 \tag{2.13.3}$$

which is the desired condition. The following code plots Fig. **??**clearly showing that the above equation is the perpendicular bisector of AB.

```
codes/line/line_perp_bisect.py
```

2.14. Find a point on the y-axis which is equidistant from the points $\mathbf{A} = \begin{pmatrix}6\\5\end{pmatrix}, \mathbf{B} = \begin{pmatrix}-4\\3\end{pmatrix}$.
Solution:

2.15. Find the equation of set of points $\mathbf{P}$ such that

$$PA^2 + PB^2 = 2k^2, \tag{2.15.1}$$

$$\mathbf{A} = \begin{pmatrix}3\\4\\5\end{pmatrix}, \mathbf{B} = \begin{pmatrix}-1\\3\\-7\end{pmatrix}, \tag{2.15.2}$$

respectively. **Solution:**

2.16. Find the equation of the set of points $\mathbf{P}$ such that its distances from the points $\mathbf{A} = \begin{pmatrix}3\\4\\-5\end{pmatrix}, \mathbf{B} = \begin{pmatrix}-2\\1\\4\end{pmatrix}$ are equal.
Solution:

3 Section

3.1. Find $\mathbf{R}$ which divides the line joining the points

$$\mathbf{P} = 2\mathbf{a} + \mathbf{b} \tag{3.1.1}$$
$$\mathbf{Q} = \mathbf{a} - \mathbf{b} \tag{3.1.2}$$

externally in the ratio $1 : 2$.

3.2. If

$$\mathbf{P} = 3\mathbf{a} - 2\mathbf{b} \tag{3.2.1}$$
$$\mathbf{Q} = \mathbf{a} + \mathbf{b} \tag{3.2.2}$$

find $\mathbf{R}$, which divides PQ in the ratio $2 : 1$

a) internally,
b) externally.

Solution:

3.3. Draw a line segement of length 7.6 cm and divide it in the ratio $5 : 8$.
Solution: Let the end points of the line be

$$\mathbf{A} = \begin{pmatrix}0\\0\end{pmatrix}, \mathbf{B} = \begin{pmatrix}7.6\\0\end{pmatrix} \tag{3.3.1}$$

Using section formula, the point $\mathbf{C}$

$$\mathbf{C} = \frac{k\mathbf{B} + \mathbf{A}}{k+1} \tag{3.3.2}$$

If $\mathbf{C}$ divides AB in the ratio

$$m = \frac{5}{8}, \tag{3.3.3}$$

then,

$$\frac{\left\|\mathbf{C} - \mathbf{A}\right\|^2}{\left\|\mathbf{B} - \mathbf{C}\right\|^2} = m^2 \tag{3.3.4}$$

$$\implies \frac{\frac{k^2\left\|\mathbf{B}-\mathbf{A}\right\|^2}{(k+1)^2}}{\frac{\left\|\mathbf{B}-\mathbf{A}\right\|^2}{(k+1)^2}} = m^2 \tag{3.3.5}$$

$$\implies k = m \tag{3.3.6}$$

upon substituting from (**??**) and simplifying. (**??**) is known as the section formula. The following code plots Fig. **??**

```
codes/line/draw_section.py
```

3.4. Find the coordinates of the point which divides the line segment joining the points $\begin{pmatrix} 4 \\ -3 \end{pmatrix}$ and $\begin{pmatrix} 8 \\ 5 \end{pmatrix}$ in the ratio $3:1$ internally.
Solution: Using (**??**), the desired point is

$$\mathbf{P} = \frac{3\begin{pmatrix} 4 \\ -3 \end{pmatrix} + \begin{pmatrix} 8 \\ 5 \end{pmatrix}}{4} \tag{3.4.1}$$

3.5. In what ratio does the point $\begin{pmatrix} -4 \\ 6 \end{pmatrix}$ divide the line segment joining the points

$$\mathbf{A} = \begin{pmatrix} -6 \\ 10 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 3 \\ -8 \end{pmatrix} \tag{3.5.1}$$

Solution: Use (**??**).

3.6. Find the coordinates of the points of trisection of the line segement joining the points

$$\mathbf{A} = \begin{pmatrix} 2 \\ -2 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} -7 \\ 4 \end{pmatrix} \tag{3.6.1}$$

Solution: Using (**??**), the coordinates are

$$\mathbf{P} = \frac{2\mathbf{A} + \mathbf{B}}{3} \tag{3.6.2}$$

$$\mathbf{Q} = \frac{\mathbf{A} + 2\mathbf{B}}{3} \tag{3.6.3}$$

3.7. Find the ratio in which the y-axis divides the line segment joining the points $\begin{pmatrix} 5 \\ -6 \end{pmatrix}$ and $\begin{pmatrix} -1 \\ -4 \end{pmatrix}$.
Solution: Let the corresponding point on the y-axis be $\begin{pmatrix} 0 \\ y \end{pmatrix}$. If the ratio be $k:1$, using (**??**), the coordinates are

$$\begin{pmatrix} 0 \\ y \end{pmatrix} = k\begin{pmatrix} 5 \\ -6 \end{pmatrix} + \begin{pmatrix} -1 \\ -4 \end{pmatrix} \tag{3.7.1}$$

$$\implies 0 = 5k - 1 \implies k = \frac{1}{5} \tag{3.7.2}$$

3.8. Find the coordinates of the point which divides the join of

$$\begin{pmatrix} -1 \\ 7 \end{pmatrix}, \begin{pmatrix} 4 \\ -3 \end{pmatrix} \tag{3.8.1}$$

in the ratio $2:3$.
Solution:

3.9. Find the coordinates of the points of trisection of the line segment joining $\begin{pmatrix} 4 \\ -1 \end{pmatrix}$ and $\begin{pmatrix} -2 \\ -3 \end{pmatrix}$.
Solution:

3.10. Find the ratio in which the line segment joining the points $\begin{pmatrix} -3 \\ 10 \end{pmatrix}$ and $\begin{pmatrix} 6 \\ -8 \end{pmatrix}$ is divided by $\begin{pmatrix} -1 \\ 6 \end{pmatrix}$.
Solution:

3.11. Find the ratio in whcih the line segment joining $\mathbf{A} = \begin{pmatrix} 1 \\ -5 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} -4 \\ 5 \end{pmatrix}$ is divided by the x-axis. Also find the coordinates of the point of division.
Solution:

3.12. If $\begin{pmatrix} 1 \\ 2 \end{pmatrix}$, $\begin{pmatrix} 4 \\ y \end{pmatrix}$, $\begin{pmatrix} x \\ 6 \end{pmatrix}$ and $\begin{pmatrix} 3 \\ 5 \end{pmatrix}$ are the vertices of a parallelogram taken in order, find x and y.
Solution:

3.13. If $\mathbf{A} = \begin{pmatrix} -2 \\ -2 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 2 \\ -4 \end{pmatrix}$ respectively, find the coordinates of $\mathbf{P}$ such that $AP = \frac{3}{7}AB$ and $\mathbf{P}$ lies on the line segment AB.
Solution:

3.14. Find the coordinates of the points which divide the line segment joining $\mathbf{A} = \begin{pmatrix} -2 \\ 2 \end{pmatrix}, \mathbf{B} =$

$\begin{pmatrix}2\\8\end{pmatrix}$ into four equal parts.

Solution:

4 Projection

4.1. Find the projection of the vector

$$\begin{pmatrix}1\\3\\7\end{pmatrix} \tag{4.1.1}$$

on the vector

$$\begin{pmatrix}7\\-1\\8\end{pmatrix} \tag{4.1.2}$$

Solution:

4.2. Find the projection of the vector

$$\mathbf{a} = \begin{pmatrix}2\\3\\2\end{pmatrix} \tag{4.2.1}$$

on the vector

$$\mathbf{b} = \begin{pmatrix}1\\2\\1\end{pmatrix}. \tag{4.2.2}$$

Solution: The projection of $\mathbf{a}$ on $\mathbf{b}$ is shown in Fig. **??**. It has magnitude $\|\mathbf{a}\| \cos\theta$ and is in the direction of $\mathbf{b}$. Thus, the projection is defined as

$$\left(\|\mathbf{a}\| \cos\theta\right) \frac{\mathbf{b}}{\|\mathbf{b}\|} = \frac{\left(\mathbf{a}^T\mathbf{b}\right)\|\mathbf{a}\|}{\|\mathbf{b}\|}\mathbf{b} \tag{4.2.3}$$

5 Applications

5.1. Find the perpendicular distances of the following lines from the origin and angle between the perpendicular and the positive x-axis.

a) $\begin{pmatrix}1 & -\sqrt{3}\end{pmatrix}\mathbf{x} = -8.$

b) $\begin{pmatrix}0 & 1\end{pmatrix}\mathbf{x} = 2.$

c) $\begin{pmatrix}1 & -1\end{pmatrix}\mathbf{x} = 4.$

5.2. Find $\|\mathbf{a}\|$ and $\|\mathbf{b}\|$ if

$$\left(\mathbf{a}+\mathbf{b}\right)^T\left(\mathbf{a}-\mathbf{b}\right) = 8 \tag{5.2.1}$$

$$\|\mathbf{a}\| = 8\|\mathbf{b}\| \tag{5.2.2}$$

5.3. Evaluate the product

$$\left(3\mathbf{a}-5\mathbf{b}\right)^T\left(2\mathbf{a}+7\mathbf{b}\right) \tag{5.3.1}$$

5.4. Find $\|\mathbf{a}\|$ and $\|\mathbf{b}\|$, if

$$\|\mathbf{a}\| = \|\mathbf{b}\|, \tag{5.4.1}$$

$$\mathbf{a}^T\mathbf{b} = \frac{1}{2} \tag{5.4.2}$$

and the angle between $\mathbf{a}$ and $\mathbf{b}$ is $60°$.

5.5. Show that

$$\left(\|\mathbf{a}\|\mathbf{b} + \|\mathbf{b}\|\mathbf{a}\right) \perp \left(\|\mathbf{a}\|\mathbf{b} - \|\mathbf{b}\|\mathbf{a}\right) \tag{5.5.1}$$

$$\tag{5.5.2}$$

5.6. If $\mathbf{a}^T\mathbf{a} = 0$ and $\mathbf{a}\mathbf{b} = 0$, what can be concluded about the vector $\mathbf{b}$?

5.7. If $\mathbf{a}, \mathbf{b}, \mathbf{c}$ are unit vectors such that

$$\mathbf{a}+\mathbf{b}+\mathbf{c} = 0, \tag{5.7.1}$$

find the value of

$$\mathbf{a}^T\mathbf{b} + \mathbf{b}^T\mathbf{c} + \mathbf{c}^T\mathbf{a}. \tag{5.7.2}$$

5.8. If $\mathbf{a} \neq \mathbf{0}, \lambda \neq 0$, then $\|\lambda\mathbf{a}\| = 1$ if

a) $\lambda = 1$

b) $\lambda = -1$

c) $\|\mathbf{a}\| = |\lambda|$

d) $\|\mathbf{a}\| = \frac{1}{|\lambda|}$

5.9. If a unit vector $\mathbf{a}$ makes angles $\frac{\pi}{3}$ with the x-axis and $\frac{\pi}{4}$ with the y-axis and an acute angle θ with the z-axis, find θ and $\mathbf{a}$.

5.10. Show that

$$\left(\mathbf{a}-\mathbf{b}\right)\times\left(\mathbf{a}+\mathbf{b}\right) = 2\left(\mathbf{a}\times\mathbf{b}\right) \tag{5.10.1}$$

5.11. If $\mathbf{a}^T\mathbf{b} = 0$ and $\mathbf{a}\times\mathbf{b} = \mathbf{0}$, what can you conclude about $\mathbf{a}$ and $\mathbf{b}$?

5.12. Find $\mathbf{x}$ if $\mathbf{a}$ is a unit vector such that

$$\left(\mathbf{x}-\mathbf{a}\right)^T\left(\mathbf{x}+\mathbf{a}\right) = 12. \tag{5.12.1}$$

5.13. If $\|\mathbf{a}\| = 3, \|\mathbf{b}\| = \frac{\sqrt{2}}{3}$, then $\mathbf{a}\times\mathbf{b}$ is a unit vector if the angle between $\mathbf{a}$ and $\mathbf{b}$ is

a) $\frac{\pi}{6}$

b) $\frac{\pi}{4}$

c) $\frac{\pi}{3}$

d) $\frac{\pi}{2}$

5.14. Prove that

$$\left(\mathbf{a}+\mathbf{b}\right)^T\left(\mathbf{a}+\mathbf{b}\right) = \|\mathbf{a}\|^2 + \|\mathbf{b}\|^2 \tag{5.14.1}$$

$$\iff \mathbf{a} \perp \mathbf{b}. \tag{5.14.2}$$

5.15. If θ is the angle between two vectors $\mathbf{a}$ and $\mathbf{b}$, then $\mathbf{a}^T\mathbf{b} \geq$ only when

a) $0 < \theta < \frac{\pi}{2}$
b) $0 \le \theta \le \frac{\pi}{2}$
c) $0 < \theta < \pi$
d) $0 \le \theta \le \pi$

5.16. Let $\mathbf{a}$ and $\mathbf{b}$ be two unit vectors and θ be the angle between them. Then $\mathbf{a}+\mathbf{b}$ is a unit vector if

a) $\theta = \frac{\pi}{4}$
b) $\theta = \frac{\pi}{3}$
c) $\theta = \frac{\pi}{2}$
d) $\theta = \frac{2\pi}{3}$

5.17. If θ is the angle between any two vectors $\mathbf{a}$ and $\mathbf{b}$, then $\left\|\mathbf{a}^T\mathbf{b}\right\| = \|\mathbf{a}\times\mathbf{b}\|$ when θ is equal to

a) 0
b) $\frac{\pi}{4}$
c) $\frac{\pi}{2}$
d) π.

5.18. A bullet fired at an angle of 30° with the horizontal hits the ground 3.0 km away. By adjusting its angle of projection, can one hope to hit a target 5.0 km away ? Assume the muzzle speed to be fixed, and neglect air resistance.

5.19. A fighter plane flying horizontally at an altitude of 1.5 km with speed 720 km/h passes directly overhead an anti-aircraft gun. At what angle from the vertical should the gun be fired for the shell with muzzle speed 600 ms^{-1} to hit the plane ? At what minimum altitude should the pilot fly the plane to avoid being hit ? (Take g = 10ms^{-2}).

5.20. Consider the collision depicted in Fig. **??** to be between two billiard balls with equal masses $m_1 = m_2$. The first ball is called the cue while the second ball is called the target. The billiard player wants to 'sink' the target ball in a corner pocket, which is at an angle $\theta_2 = 37°$. Assume that the collosion is elastic and that friction and rotational motion are not important. Obtain θ_1.

5.21. Rain is falling vertically with a speed of 35 ms^{-1} . Winds starts blowing after sometime with a speed of 12 ms^{-1} in east to west direction. In which direction should a boy waiting at a bus stop hold his umbrella ?
Solution:

5.22. A motorboat is racing towards north at 25 km/h and the water current in that region is 10 km/h in the direction of 60° east of south. Find the resultant velocity of the boat.
Solution:

5.23. Rain is falling vertically with a speed of 35 ms^{-1} . A woman rides a bicycle with a speed of 12 ms^{-1} in east to west direction. What is the direction in which she should hold her umbrella ?
Solution:

5.24. A hiker stands on the edge of a cliff 490 m above the ground and throws a stone horizontally with an initial speed of 15 ms^{-1} . Neglecting air resistance, find the time taken by the stone to reach the ground, and the speed with which it hits the ground. (Take g = 9.8 ms^{-2}).
Solution:

5.25. Rain is falling vertically with a speed of 30 ms^{-1}. A woman rides a bicycle with a speed of 10 ms^{-1} in the north to south direction. What is the direction in which she should hold her umbrella?
Solution:

5.26. A man can swim with a speed of 4.0 km/h in still water. How long does he take to cross a river 1.0 km wide if the river flows steadily at 3.0 km/h and he makes his strokes normal to the river current? How far down the river does he go when he reaches the other bank ?
Solution:

5.27. In a harbour, wind is blowing at the speed of 72 km/h and the flag on the mast of a boat anchored in the harbour flutters along the N-E direction. If the boat starts moving at a speed of 51 km/h to the north, what is the direction of the flag on the mast of the boat ?
Solution:

5.28. Find the intercepts cut off by the plane $\begin{pmatrix}2 & 1 & 1\end{pmatrix}\mathbf{x} = 5$.

6 Locus

6.1. The sum of the perpendicular distances of a variable point $\mathbf{P}$ from the lines

$$\begin{pmatrix}1 & 1\end{pmatrix}\mathbf{x} = 0 \tag{6.1.1}$$

$$\begin{pmatrix}3 & -2\end{pmatrix}\mathbf{x} = -7 \tag{6.1.2}$$

is always 10. Show that $\mathbf{P}$ must move on a line.