

# MATRICES

## In Geometry

---



G. V. V. Sharma

## ABOUT THIS BOOK

This book introduces matrices through high school coordinate geometry. This approach makes it easier for beginners to learn Python for scientific computing. All problems in the book are from NCERT mathematics textbooks from Class 9-12. The content is sufficient for industry jobs and covers nearly all matrix prerequisites for machine learning. There is no copyright, so readers are free to print and share.

July 26, 2024

Github: <https://github.com/gadepall/matgeo>

License: <https://creativecommons.org/licenses/by-sa/3.0/>

and

<https://www.gnu.org/licenses/fdl-1.3.en.html>

First manual appeared in January 2018

First edition published on July 10, 2024

In this edition, some incorrect solutions were removed. Many figures redrawn. More problems added.

## CONTENTS

<b>1</b>	<b>Vector Arithmetic</b>	<b>5</b>
1.1	Formulae . . . . .	5
1.2	Point Vectors . . . . .	6
1.3	Section Formula . . . . .	11
1.4	Rank . . . . .	16
1.5	Length . . . . .	17
1.6	Unit Vector . . . . .	21
<b>2</b>	<b>Vector Multiplication</b>	<b>27</b>
2.1	Formulae . . . . .	27
2.2	Scalar Product . . . . .	29
2.3	Orthogonality . . . . .	34
2.4	Vector Product . . . . .	44
2.5	Miscellaneous . . . . .	54
<b>3</b>	<b>Constructions</b>	<b>62</b>
3.1	Formulae . . . . .	62
3.2	Triangle . . . . .	62
3.3	Quadrilateral . . . . .	66
<b>4</b>	<b>Linear Forms</b>	<b>67</b>
4.1	Formulae . . . . .	67
4.2	Parameters . . . . .	69
4.3	Equation . . . . .	70
4.4	Parallel . . . . .	83
4.5	Perpendicular . . . . .	86
4.6	Angle . . . . .	98
4.7	Intersection . . . . .	100
4.8	Miscellaneous . . . . .	106
<b>5</b>	<b>Matrices</b>	<b>115</b>
5.1	Formulae . . . . .	115
5.2	Equation . . . . .	115
5.3	Inverse . . . . .	119
5.4	Cayley-Hamilton Theoerm . . . . .	121
5.5	Application . . . . .	123
5.6	Chemistry . . . . .	127
<b>6</b>	<b>Skew Lines</b>	<b>130</b>
6.1	Formulae . . . . .	130
6.2	Least Squares . . . . .	131
6.3	Singular Value Decomposition . . . . .	137

<b>7</b>	<b>Circle</b>	142
7.1	Formulae . . . . .	142
7.2	Equation . . . . .	142
7.3	Miscellaneous . . . . .	157
<b>8</b>	<b>Conics</b>	158
8.1	Formulae . . . . .	158
8.2	Equation . . . . .	160
8.3	Miscellaneous . . . . .	176
8.4	Quadratic Equations . . . . .	181
<b>9</b>	<b>Intersection of Conics</b>	184
9.1	Formulae . . . . .	184
9.2	Chords . . . . .	184
9.3	Curves . . . . .	200
<b>10</b>	<b>Tangent And Normal</b>	203
10.1	Formulae . . . . .	203
10.2	Circle . . . . .	204
10.3	Conic . . . . .	205
10.4	Construction . . . . .	220
<b>Appendix A: Triangle</b>		221
A.1	Sides . . . . .	221
A.2	Formulae . . . . .	226
A.3	Median . . . . .	228
A.4	Altitude . . . . .	231
A.5	Perpendicular Bisector . . . . .	234
A.6	Angle Bisector . . . . .	237
A.7	Eigenvalues and Eigenvectors . . . . .	239
A.8	Formulae . . . . .	241
A.9	Matrices . . . . .	241
<b>Appendix B: Conic Section</b>		244
B.1	Equation . . . . .	244
B.2	Standard Conic . . . . .	248
B.3	Conic Lines . . . . .	250
B.4	Tangent and Normal . . . . .	253

### 1.1 Formulae

1.1.1. The *direction vector* of  $AB$  is defined as

$$\mathbf{m} = \mathbf{B} - \mathbf{A} = \kappa \begin{pmatrix} 1 \\ m \end{pmatrix} \quad (1.1.1.1)$$

where  $m$  is the slope of  $AB$ . We also say that

$$\mathbf{m} \equiv \begin{pmatrix} 1 \\ m \end{pmatrix} \quad (1.1.1.2)$$

1.1.2. The lines with direction vectors  $\mathbf{m}_1$  and  $\mathbf{m}_2$  respectively, are parallel if

$$\mathbf{m}_1 \equiv \mathbf{m}_2 \quad (1.1.2.1)$$

1.1.3. If  $ABCD$  be a parallelogram with  $AB \parallel CD$ ,

$$\mathbf{B} - \mathbf{A} = \mathbf{C} - \mathbf{D} \quad (1.1.3.1)$$

1.1.4. If  $\mathbf{D}$  divides  $BC$  in the ratio  $k : 1$ ,

$$\mathbf{D} = \frac{k\mathbf{C} + \mathbf{B}}{k + 1} \quad (1.1.4.1)$$

1.1.5. If  $PQRS$  is formed by joining the mid points of  $ABCD$ ,

$$\mathbf{P} = \frac{1}{2}(\mathbf{A} + \mathbf{B}), \mathbf{Q} = \frac{1}{2}(\mathbf{B} + \mathbf{C}) \quad (1.1.5.1)$$

$$\mathbf{R} = \frac{1}{2}(\mathbf{C} + \mathbf{D}), \mathbf{S} = \frac{1}{2}(\mathbf{D} + \mathbf{A}) \quad (1.1.5.2)$$

$$\implies \mathbf{P} - \mathbf{Q} = \mathbf{S} - \mathbf{R}. \quad (1.1.5.3)$$

Hence,  $PQRS$  is a parallelogram from (1.1.3.1).

1.1.6. In 2D space, the basis vectors are defined as

$$\mathbf{e}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \mathbf{e}_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \quad (1.1.6.1)$$

1.1.7. The length of a vector is defined as

$$\|\mathbf{x}\| \triangleq \sqrt{\mathbf{x}^\top \mathbf{x}} \quad (1.1.7.1)$$

For example, if

$$\mathbf{x} = \begin{pmatrix} 3 \\ 4 \end{pmatrix}, \quad (1.1.7.2)$$

$$\mathbf{x}^\top \mathbf{x} = \begin{pmatrix} 3 & 4 \end{pmatrix} \begin{pmatrix} 3 \\ 4 \end{pmatrix} \quad (1.1.7.3)$$

$$= 3 \times 3 + 4 \times 4 = 25 \quad (1.1.7.4)$$

yielding

$$\|\mathbf{x}\| = 5. \quad (1.1.7.5)$$

(1.1.7.3) is known as the scalar product.

1.1.8. The unit vector in the direction of  $\mathbf{x}$  is

$$\frac{\mathbf{x}}{\|\mathbf{x}\|} \quad (1.1.8.1)$$

1.1.9. Points  $\mathbf{A}, \mathbf{B}, \mathbf{C}$  are defined to be collinear if

$$\text{rank}(\mathbf{B} - \mathbf{A} \quad \mathbf{C} - \mathbf{A}) = 1 \quad (1.1.9.1)$$

1.1.10.

$$\text{rank} \mathbf{A} = \text{rank} \mathbf{A}^\top \quad (1.1.10.1)$$

1.1.11. In the 2D space, the unit direction vector is defined as

$$\mathbf{m} = \begin{pmatrix} \cos \alpha \\ \cos \beta \end{pmatrix} \quad (1.1.11.1)$$

where  $\alpha, \beta$  are the angles made by the vector with the axes.

1.1.12. Code for plotting points and vector arithmetic

```
codes/book/points.py
```

1.1.13. Code for section formula

```
codes/book/section.py
```

1.1.14. Code for matrix rank

```
codes/book/rank.py
```

1.1.15. Code for vector length

```
codes/book/dist.py
```

## 1.2 Point Vectors

1.2.1 Find the values of  $x$  and  $y$  so that the vectors  $2\hat{i} + 3\hat{j}$  and  $x\hat{i} + y\hat{j}$  are equal.

**Solution:** From the given informatin,

$$\begin{pmatrix} 2 \\ 3 \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} \quad (1.2.1.1)$$

$$\Rightarrow x = 2, y = 3 \quad (1.2.1.2)$$

1.2.2 Find the values of  $x, y, z$  so that the vectors  $x\hat{i} + 2\hat{j} + z\hat{k}$  and  $2\hat{i} + y\hat{j} + \hat{k}$  are equal.

1.2.3 Find the sum of the vectors  $\mathbf{a} = \hat{i} - 2\hat{j} + \hat{k}$ ,  $\mathbf{b} = -2\hat{i} + 4\hat{j} + 5\hat{k}$  and  $\mathbf{c} = \hat{i} - 6\hat{j} - 7\hat{k}$ .

1.2.4 Find the slope of a line, which passes through the origin and the mid point of the line segment joining the points  $\mathbf{P}(0, -4)$  and  $\mathbf{B}(8, 0)$ .

**Solution:** The mid point of  $PB$  is

$$\mathbf{M} = \frac{1}{2}(\mathbf{P} + \mathbf{B}) = \begin{pmatrix} 4 \\ -2 \end{pmatrix} \quad (1.2.4.1)$$

which, from (1.1.1.1), is equal to the direction vector of  $OM$ , where  $\mathbf{O}$  is the origin.

$$\therefore \mathbf{M} \equiv \begin{pmatrix} 1 \\ -\frac{1}{2} \end{pmatrix}, m = -\frac{1}{2} \quad (1.2.4.2)$$

which, from (1.1.1.1), is the desired slope. See Fig. 1.2.4.1.

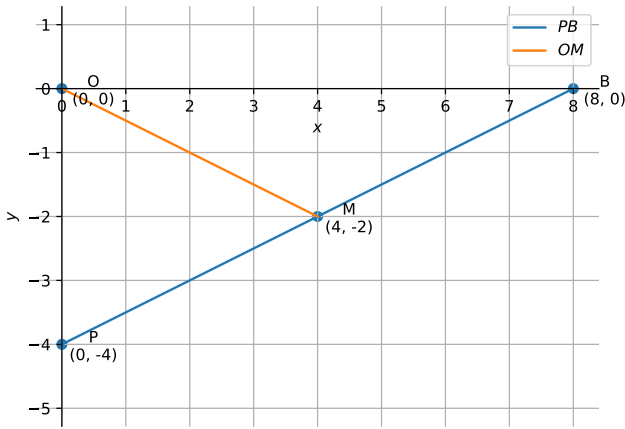


Fig. 1.2.4.1

1.2.5 Find the angle between x-axis and the line joining points  $(3, -1)$  and  $(4, -2)$ .

**Solution:** The direction vector of the given line is

$$\begin{pmatrix} 4 \\ -2 \end{pmatrix} - \begin{pmatrix} 3 \\ -1 \end{pmatrix} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \Rightarrow m = -1 \quad (1.2.5.1)$$

Hence, the desired angle is  $135^\circ$ .

1.2.6 A line passes through  $\mathbf{A}(x_1, y_1)$  and  $\mathbf{B}(h, k)$ . If slope of the line is  $m$ , show that  $(k - y_1) = m(h - x_1)$ .

**Solution:** The direction vector

$$\mathbf{B} - \mathbf{A} = \begin{pmatrix} h - x_1 \\ k - y_1 \end{pmatrix} \equiv \begin{pmatrix} 1 \\ \frac{k - y_1}{h - x_1} \end{pmatrix} \quad (1.2.6.1)$$

$$\implies m = \frac{k - y_1}{h - x_1}, \quad (1.2.6.2)$$

yielding the desired result.

- 1.2.7 Show that the line through the points  $(4, 7, 8)$ ,  $(2, 3, 4)$  is parallel to the line through the points  $(-1, -2, 1)$ ,  $(1, 2, 5)$ .

**Solution:**

$$\begin{pmatrix} 4 \\ 7 \\ 8 \end{pmatrix} - \begin{pmatrix} 2 \\ 3 \\ 4 \end{pmatrix} = \begin{pmatrix} -1 \\ -2 \\ 1 \end{pmatrix} - \begin{pmatrix} 1 \\ 2 \\ 5 \end{pmatrix} \equiv \begin{pmatrix} 2 \\ 4 \\ 4 \end{pmatrix} \quad (1.2.7.1)$$

which means that the given lines have the same direction vector and are hence parallel.

- 1.2.8 The vector having initial and terminal points as  $(-2, 5, 0)$  and  $(3, 7, 4)$ , respectively is **Solution:** The desired vector is

$$\begin{pmatrix} 3 \\ 7 \\ 4 \end{pmatrix} - \begin{pmatrix} -2 \\ 5 \\ 0 \end{pmatrix} = \begin{pmatrix} 5 \\ 2 \\ 4 \end{pmatrix} \quad (1.2.8.1)$$

- 1.2.9 Find the vector joining the points  $\mathbf{P}(2, 3, 0)$  and  $\mathbf{Q}(-1, -2, -4)$  directed from  $\mathbf{P}$  to  $\mathbf{Q}$ .

- 1.2.10 Without using distance formula, show that points  $\mathbf{A}(-2, -1)$ ,  $\mathbf{B}(4, 0)$ ,  $\mathbf{C}(3, 3)$  and  $\mathbf{D}(-3, 2)$  are the vertices of a parallelogram.

**Solution:** From (1.1.3.1),

$$\mathbf{A} - \mathbf{B} = \mathbf{D} - \mathbf{C} = \begin{pmatrix} -6 \\ -1 \end{pmatrix} \quad (1.2.10.1)$$

Hence,  $ABCD$  is a parallelogram. See Fig. 1.2.10.1.



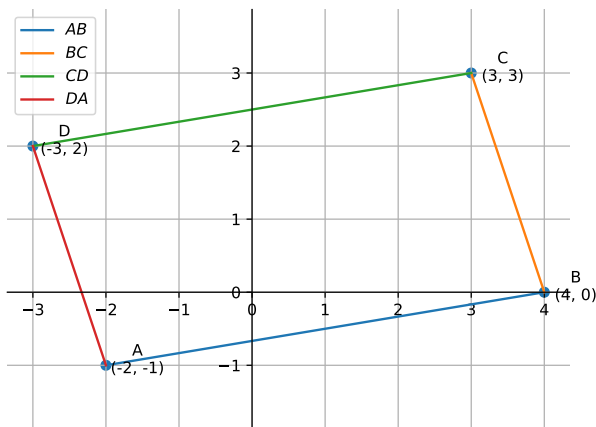


Fig. 1.2.10.1

- 1.2.11 If the points  $A(6, 1)$ ,  $B(8, 2)$ ,  $C(9, 4)$  and  $D(p, 3)$  are the vertices of a parallelogram, taken in order, find the value of  $p$ .
- 1.2.12 If  $(1, 2)$ ,  $(4, y)$ ,  $(x, 6)$  and  $(3, 5)$  are the vertices of a parallelogram taken in order, find  $x$  and  $y$ .
- 1.2.13 The fourth vertex  $D$  of a parallelogram  $ABCD$  whose three vertices are  $A(-2, 3)$ ,  $B(6, 7)$  and  $C(8, 3)$  is
- 1.2.14 Verify if the points  $A(4, 3)$ ,  $B(6, 4)$ ,  $C(5, -6)$  and  $D(-3, 5)$  are the vertices of a parallelogram.
- 1.2.15 A girl walks 4 km towards west, then she walks 3 km in a direction  $30^\circ$  east of north and stops. Determine the girl's displacement from her initial point of departure.

**Solution:** See Fig. 1.2.15.1. Let the initial position be

$$\mathbf{A} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad (1.2.15.1)$$

After going west, the position becomes

$$\mathbf{B} = \begin{pmatrix} -4 \\ 0 \end{pmatrix} \quad (1.2.15.2)$$

If the final position be  $C$ , from the given information,

$$\mathbf{C} - \mathbf{B} = 3 \begin{pmatrix} \cos 60^\circ \\ \sin 60^\circ \end{pmatrix} \Rightarrow \mathbf{C} = \begin{pmatrix} -\frac{5}{2} \\ \frac{3\sqrt{3}}{2} \end{pmatrix} \quad (1.2.15.3)$$

which is the desired displacement.

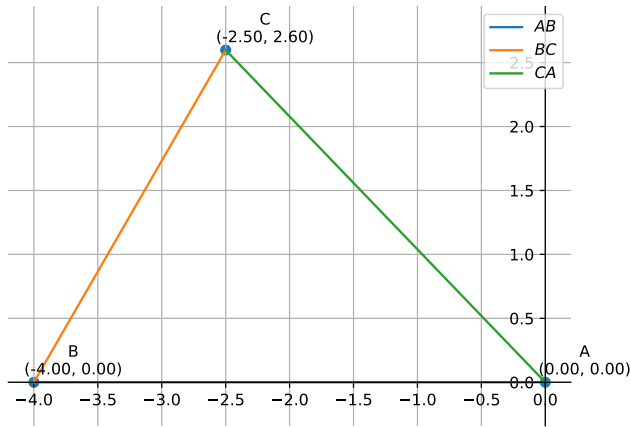


Fig. 1.2.15.1

- 1.2.16  $(-1, 2, 1), (1, -2, 5), (4, -7, 8)$  and  $(2, -3, 4)$  are the vertices of a parallelogram.
- 1.2.17 Three vertices of a parallelogram  $ABCD$  are  $A(3, -1, 2), B(1, -2, 4)$  and  $C(-1, 1, 2)$ . Find the coordinates of the fourth vertex.
- 1.2.18 If the origin is the centroid of the triangle  $PQR$  with vertices  $P(2a, 2, 6), Q(-4, 3b, -10)$  and  $R(8, 14, 2c)$ , then find the values of  $a, b$  and  $c$ .
- 1.2.19 Find the slope of lines
- Passing through the points  $(3, -2)$  and  $(-1, 4)$
  - Passing through the points  $(3, -2)$  and  $(7, -2)$
  - passing through the points  $(3, -2)$  and  $(3, 4)$
  - Making inclination of  $60^\circ$  with the positive direction of x-axis.
- 1.2.20 The centroid of a triangle  $ABC$  is at the point  $(1, 1, 1)$ . If the coordinates of  $A$  and  $B$  are  $(3, -5, 7)$  and  $(-1, 7, -6)$ , respectively find the coordinates of the point  $C$ .
- 1.2.21 Represent graphically a displacement of  $40 \text{ km}, 30^\circ$  west of south.
- 1.2.22 Rain is falling vertically with a speed of  $35 \text{ ms}^{-1}$ . Winds starts blowing after sometime with a speed of  $12 \text{ ms}^{-1}$  in east to west direction. In which direction should a boy waiting at a bus stop hold his umbrella ?
- 1.2.23 A motorboat is racing towards north at  $25 \text{ km/h}$  and the water current in that region is  $10 \text{ km/h}$  in the direction of  $60^\circ$  east of south. Find the resultant velocity of the boat.
- 1.2.24 Rain is falling vertically with a speed of  $35 \text{ ms}^{-1}$ . A woman rides a bicycle with a speed of  $12 \text{ ms}^{-1}$  in east to west direction. What is the direction in which she should hold her umbrella ?
- 1.2.25 Rain is falling vertically with a speed of  $30 \text{ ms}^{-1}$ . A woman rides a bicycle with a

speed of  $10 \text{ ms}^{-1}$  in the north to south direction. What is the direction in which she should hold her umbrella?

- 1.2.26 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 ?
- 1.2.27 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 ?
- 1.2.28 In which quadrant or on which axis do each of the points  $(-2, 4)$ ,  $(3, -1)$ ,  $(-1, 0)$ ,  $(1, 2)$  and  $(-3, -5)$  lie? Verify your answer by locating them on the Cartesian plane.
- 1.2.29 Plot the points  $(x, y)$  given in Table 1.2.29.

x	-2	-1	0	1	3
y	8	7	-1.25	3	-1

TABLE 1.2.29

### 1.3 Section Formula

- 1.3.1 Find the coordinates of the point which divides the join of  $(-1, 7)$  and  $(4, -3)$  in the ratio 2:3.

**Solution:** Using section formula (1.1.4.1), the desired point is

$$\frac{1}{1 + \frac{3}{2}} \left( \begin{pmatrix} 4 \\ -3 \end{pmatrix} + \frac{3}{2} \begin{pmatrix} -1 \\ 7 \end{pmatrix} \right) = \begin{pmatrix} 1 \\ 3 \end{pmatrix} \quad (1.3.1.1)$$

See Fig. 1.3.1.1

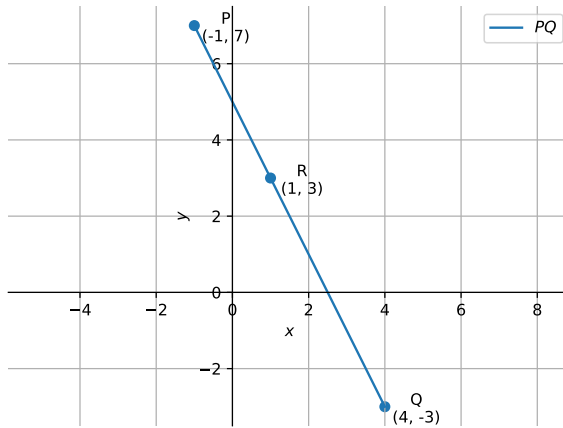


Fig. 1.3.1.1

- 1.3.2 Find the coordinates of the point **R** on the line segment joining the points **P**(-1, 3) and **Q**(2, 5) such that  $PR = \frac{3}{5}PQ$ .
- 1.3.3 Find the ratio in which the point **P**( $\frac{3}{4}, \frac{5}{12}$ ) divides the line segment joining the points **A**( $\frac{1}{2}, \frac{3}{2}$ ) and **B**(2, -5).
- 1.3.4 Find the coordinates of the point which divides the line segment joining the points (4, -3) and (8, 5) in the ratio 3 : 1 internally.
- 1.3.5 Find the coordinates of the point **P** on **AD** such that  $AP : PD = 2 : 1$ .
- 1.3.6 If the point **P**(2, 1) lies on the line segment joining points **A**(4, 2) and **B**(8, 4), then
- $AP = \frac{1}{3}AB$
  - $AP = PE$
  - $PB = \frac{1}{3}AB$
  - $AP = \frac{1}{2}AB$
- 1.3.7 Find the ratio in which the line segment joining the points (-3, 10) and (6, -8) is divided by (-1, 6).

**Solution:** Using section formula,

$$\begin{pmatrix} -1 \\ 6 \end{pmatrix} = \frac{\begin{pmatrix} -3 \\ 10 \end{pmatrix} + k \begin{pmatrix} 6 \\ -8 \end{pmatrix}}{1 + k} \quad (1.3.7.1)$$

$$\Rightarrow 7k \begin{pmatrix} 1 \\ -2 \end{pmatrix} = 2 \begin{pmatrix} 1 \\ -2 \end{pmatrix} \quad (1.3.7.2)$$

$$\text{or, } k = \frac{2}{7}. \quad (1.3.7.3)$$

- 1.3.8 Find the position vector of the mid point of the vector joining the points **P**(2, 3, 4)

and  $\mathbf{Q}(4, 1, -2)$ .

**Solution:** The desired vector is

$$\frac{1}{2} \begin{pmatrix} 2 \\ 3 \\ 4 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 4 \\ 1 \\ -2 \end{pmatrix} = \begin{pmatrix} 3 \\ 2 \\ 1 \end{pmatrix} \quad (1.3.8.1)$$

1.3.9 Let  $\mathbf{A}(4, 2)$ ,  $\mathbf{B}(6, 5)$  and  $\mathbf{C}(1, 4)$  be the vertices of  $\triangle ABC$ .

- a) If  $\mathbf{A}$  and  $\mathbf{B}$  are  $(-2, -2)$  and  $(2, -4)$ , respectively, find the coordinates of  $\mathbf{P}$  such that  $AP = \frac{3}{7}AB$  and  $\mathbf{P}$  lies on the line segment  $AB$ .

**Solution:** Using section formula,

$$\mathbf{P} = \frac{1}{1 + \frac{3}{4}} \left( \begin{pmatrix} -2 \\ -2 \end{pmatrix} + \frac{3}{4} \begin{pmatrix} 2 \\ -4 \end{pmatrix} \right) = \begin{pmatrix} -\frac{2}{7} \\ -\frac{20}{7} \end{pmatrix} \quad (1.3.9.1)$$

- b) Find the coordinates of the points which divide the line segment joining  $A(-2, 2)$  and  $B(2, 8)$  into four equal parts.

**Solution:** Using section formula,

$$\mathbf{R}_k = \frac{\mathbf{B} + k\mathbf{A}}{1 + k}, k = \frac{i}{n - i}, 0 < i < n \quad (1.3.9.2)$$

for  $n = 4$ . See Fig. 1.3.9.1.

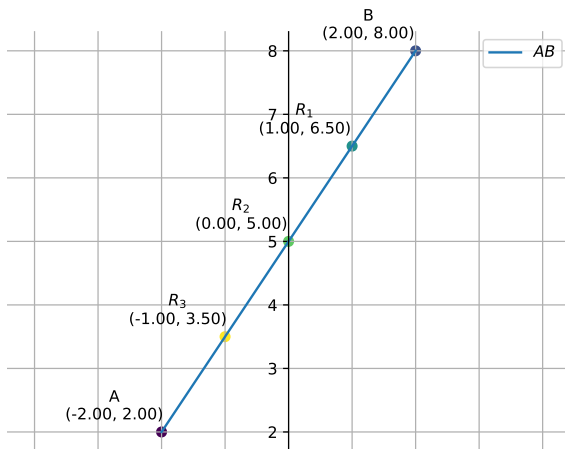


Fig. 1.3.9.1

- c) In what ratio does the point  $(-4, 6)$  divide the line segment joining the points  $\mathbf{A}(-6, 0)$  and  $\mathbf{B}(3, -8)$ ?
- d) Given that  $\mathbf{P}(3, 2, -4)$ ,  $\mathbf{Q}(5, 4, -6)$  and  $\mathbf{R}(9, 8, -10)$  are collinear. Find the ratio in which  $\mathbf{Q}$  divides  $PR$ .

- e) Points  $A(-6, 10)$ ,  $B(-4, 6)$  and  $C(3, -8)$  are collinear such that  $AB = \frac{2}{9}AC$ .
- f) The point which divides the line segment joining the points  $P(7, -6)$  and  $Q(3, 4)$  in the ratio  $1 : 2$  internally lies in which quadrant?
- g) Find the coordinates of the points of trisection of the line segment joining  $(4, -1)$  and  $(-2, 3)$ .

**Solution:** Using section formula,

$$\mathbf{R} = \frac{1}{1 + \frac{1}{2}} \left( \begin{pmatrix} 4 \\ -1 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} -2 \\ 3 \end{pmatrix} \right) = \begin{pmatrix} 2 \\ \frac{-5}{3} \end{pmatrix} \quad (1.3.9.3)$$

$$\mathbf{S} = \frac{1}{1 + \frac{2}{1}} \left( \begin{pmatrix} 4 \\ -1 \end{pmatrix} + \frac{2}{1} \begin{pmatrix} -2 \\ 3 \end{pmatrix} \right) = \begin{pmatrix} 0 \\ \frac{-7}{3} \end{pmatrix} \quad (1.3.9.4)$$

which are the desired points of trisection.

- h) Find the coordinates of the points which trisect the line segment joining the points  $P(4, 2, -6)$  and  $Q(10, -16, 6)$ .
- i) Find the coordinates of the points of trisection (i.e. points dividing to three equal parts) of the line segment joining the points  $A(2, -2)$  and  $B(-7, 4)$ .
- j) Point  $P(5, -3)$  is one of the two points of trisection of line segment joining the points  $A(7, -2)$  and  $B(1, -5)$
- k) Find the position vector of a point  $\mathbf{R}$  which divides the line joining two points  $\mathbf{P}$  and  $\mathbf{Q}$  whose position vectors are  $\hat{i} + 2\hat{j} - \hat{k}$  and  $-\hat{i} + \hat{j} + \hat{k}$  respectively, in the ratio  $2 : 1$
- internally
  - externally
- l) Find the coordinates of the point which divides the line segment joining the points which divides the line segment joining the points  $(-2, 3, 5)$  and  $(1, -4, 6)$  in the ratio
- $2 : 3$  internally,
  - $2 : 3$  externally
- m) Find the coordinates of the point which divides the line segment joining the points  $(1, -2, 3)$  and  $(3, 4, -5)$  in the ratio  $2 : 3$
- internally, and
  - externally
- n) Consider two points  $\mathbf{P}$  and  $\mathbf{Q}$  with position vectors  $\overrightarrow{OP} = 3\vec{a} - 2\vec{b}$  and  $\overrightarrow{OQ} = \vec{a} + \vec{b}$ . Find the position vector of a point  $\mathbf{R}$  which divides the line joining  $\mathbf{P}$  and  $\mathbf{Q}$  in the ratio  $2 : 1$ ,
- internally, and
  - externally.
- o) The median from  $\mathbf{A}$  meets  $BC$  at  $\mathbf{D}$ . Find the coordinates of the point  $\mathbf{D}$ .
- p) Find the coordinates of points  $\mathbf{Q}$  and  $\mathbf{R}$  on medians  $BE$  and  $CF$  respectively such that  $BQ : QE = 2 : 1$  and  $CR : RF = 2 : 1$ .
- q) What do you observe?
- r) If  $\mathbf{A}, \mathbf{B}$  and  $\mathbf{C}$  are the vertices of  $\triangle ABC$ , find the coordinates of the centroid of the triangle.

**Solution:**

$$\mathbf{D} = \frac{\mathbf{B} + \mathbf{C}}{2} = \left(\frac{7}{2}, \frac{9}{2}\right), \quad \mathbf{E} = \frac{\mathbf{A} + \mathbf{C}}{2} = \left(\frac{5}{2}, \frac{3}{2}\right) \quad (1.3.9.5)$$

$$\mathbf{F} = \frac{\mathbf{A} + \mathbf{B}}{2} = \left(\frac{5}{2}, \frac{11}{2}\right), \quad \mathbf{G} = \mathbf{Q} = \mathbf{R} = \frac{1}{3} \begin{pmatrix} 11 \\ 11 \end{pmatrix} \quad (1.3.9.6)$$

is the centroid. See Fig. 1.3.9.2.

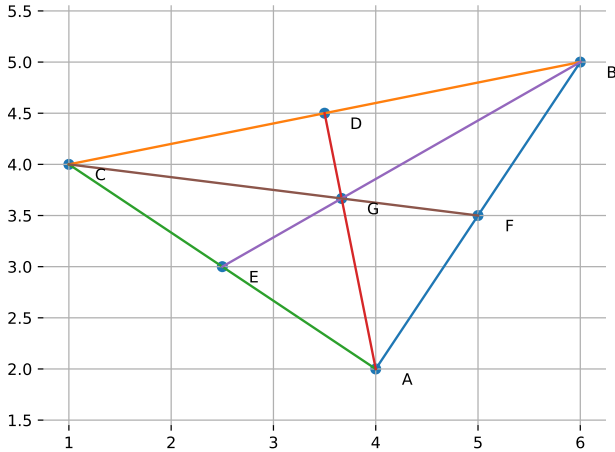


Fig. 1.3.9.2

- 1.3.10 If  $\mathbf{P}(9a - 2, -b)$  divides line segment joining  $\mathbf{A}(3a + 1, -3)$  and  $\mathbf{B}(8a, 5)$  in the ratio 3:1, find the values of  $a$  and  $b$ .
- 1.3.11 Find the position vector of a point  $\mathbf{R}$  which divides the line joining two points  $\mathbf{P}$  and  $\mathbf{Q}$  whose position vectors are  $2\mathbf{a} + \mathbf{b}$  and  $\mathbf{a} - 3\mathbf{b}$  externally in the ratio 1 : 2.
- 1.3.12 The position vector of the point which divides the join of points  $2\mathbf{a} - 3\mathbf{b}$  and  $\mathbf{a} + \mathbf{b}$  in the ratio 3:1 is
- 1.3.13 If  $\mathbf{a}$  and  $\mathbf{b}$  are the position vectors of  $\mathbf{A}$  and  $\mathbf{B}$ , respectively, find the position vector of a point  $\mathbf{C}$  in  $BA$  produced such that  $BC = 1.5BA$ .
- 1.3.14 Find the position vector of a point  $\mathbf{R}$  which divides the line joining two points  $\mathbf{P}$  and  $\mathbf{Q}$  whose position vectors are  $(2\mathbf{a} + \mathbf{b})$  and  $(\mathbf{a} - 3\mathbf{b})$  externally in the ratio 1 : 2. Also, show that  $\mathbf{P}$  is the mid point of the line segment  $RQ$ .

### 1.4 Rank

1.4.1 Prove that the three points  $(3, 0)$ ,  $(-2, -2)$  and  $(8, 2)$  are collinear.

**Solution:** From (1.1.9.1), the collinearity matrix can be expressed as

$$\begin{pmatrix} -5 & -2 \\ 5 & 2 \end{pmatrix} \xleftrightarrow{R_2 \leftarrow -R_1 + R_2} \begin{pmatrix} -5 & -2 \\ 0 & 0 \end{pmatrix} \quad (1.4.1.1)$$

which is a rank 1 matrix. The above process is known as row reduction, where we try to obtain zero rows in the matrix using arithmetic operations. The number of nonzero rows in the row reduced matrix (also known as *echelon form*) is defined as the rank. Fig. 1.4.1.1.

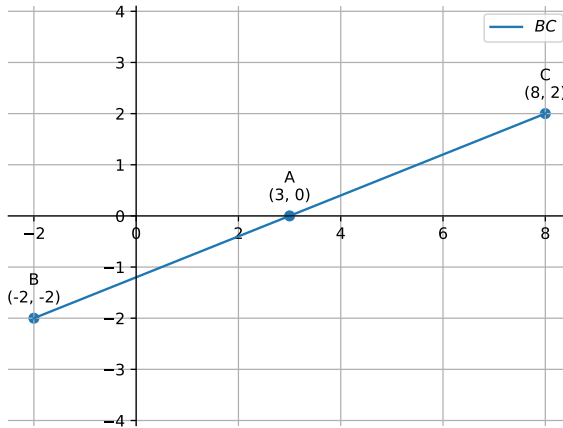


Fig. 1.4.1.1

1.4.2 Show that the points  $\mathbf{A}(1, 2, 7)$ ,  $\mathbf{B}(2, 6, 3)$  and  $\mathbf{C}(3, 10, -1)$  are collinear.

**Solution:** The matrix

$$(\mathbf{B} - \mathbf{A} \quad \mathbf{C} - \mathbf{A})^T = \begin{pmatrix} 1 & 4 & -4 \\ 2 & 8 & -8 \end{pmatrix} \quad (1.4.2.1)$$

$$\xleftrightarrow{R_2 = R_2 - 2R_1} \begin{pmatrix} 1 & 4 & -4 \\ 0 & 0 & 0 \end{pmatrix} \quad (1.4.2.2)$$

which has rank 1. Using (1.1.10.1), we conclude that the given points are collinear.

1.4.3 Determine if the points  $(1, 5)$ ,  $(2, 3)$  and  $(-2, -11)$  are collinear.

1.4.4 Show that the vectors  $2\hat{i} - 3\hat{j} + 4\hat{k}$  and  $-4\hat{i} + 6\hat{j} - 8\hat{k}$  are collinear.

1.4.5 Show that the points  $(2, 3, 4)$ ,  $(-1, -2, 1)$ ,  $(5, 8, 7)$  are collinear.

1.4.6 In each of the following, find the value of  $k$ , for which the points are collinear.

a)  $(7, -2)$ ,  $(5, 1)$ ,  $(3, k)$

b)  $(8, 1)$ ,  $(k, -4)$ ,  $(2, -5)$



1.4.7 Find a relation between  $x$  and  $y$  if the points  $(x, y)$ ,  $(1, 2)$  and  $(7, 0)$  are collinear.

1.4.8 If three points  $(x, -1)$ ,  $(2, 1)$  and  $(4, 5)$  are collinear, find the value of  $x$ .

1.4.9 If three points  $(h, 0)$ ,  $(a, b)$  and  $(0, k)$  lie on a line, show that

$$\frac{a}{h} + \frac{b}{k} = 1 \quad (1.4.9.1)$$

1.4.10 Show that the points **A**(1, -2, -8), **B**(5, 0, -2) and **C**(11, 3, 7) are collinear, and find the ratio in which **B** divides  $AC$ .

1.4.11 If the points **A**(1, 2), **O**(0, 0) and **C**( $a, b$ ) are collinear, then find the relation between  $a$  and  $b$ .

1.4.12 Point  $(-4, 2)$  lies on the line segment joining the points **A**(-4, 6) and **B**(-4, -6).

1.4.13 The points  $(0, 5)$ ,  $(0, -9)$  and  $(3, 6)$  are collinear.

1.4.14 Points **A**(3, 1), **B**(12, -2) and **C**(0, 2) cannot be the vertices of a triangle.

1.4.15 Find the value of  $m$  if the points  $(5, 1)$ ,  $(-2, -3)$  and  $(8, 2m)$  are collinear.

1.4.16 Find the values of  $k$  if the points **A**( $k + 1, 2k$ ), **B**( $3k, 2k + 3$ ) and **C**( $5k - 1, 5k$ ) are collinear.

1.4.17 Using vectors, find the value of  $k$  such that the points  $(k, -10, 3)$ ,  $(1, -1, 3)$  and  $(3, 5, 3)$  are collinear.

1.4.18 The points **A**(2, 1), **B**(0, 5), **C**(-1, 2) are collinear.

1.4.19 The vectors  $\lambda\hat{i} + \lambda\hat{j} + 2\hat{k}$ ,  $\hat{i} + \lambda\hat{j} - \hat{k}$  and  $2\hat{i} - \hat{j} + \lambda\hat{k}$  are coplanar if  $\lambda =$

1.4.20 Show that the points  $(-2, 3, 5)$ ,  $(1, 2, 3)$  and  $(7, 0, -1)$  are collinear.

1.4.21 Show that points **A**( $a, b + c$ ), **B**( $b, c + a$ ), **C**( $c, a + b$ ) are collinear.

1.4.22 Show that the points **A**(2, -3, 4), **B**(-1, 2, 1) and **C**(0,  $\frac{1}{3}$ , 2) are collinear.

1.4.23 Are **A**(3, 1), **B**(6, 4) and **C**(8, 6) collinear?

1.4.24 Find the values of  $k$  if the points **A**(2, 3), **B**(4,  $k$ ) and **C**(6, -3) are collinear.

1.4.25 Three points **P**( $h, k$ ), **Q**( $x_1, y_1$ ) and **R**( $x_2, y_2$ ) lie on a line. Show that  $(h - x_1)(y_2 - y_1) = (k - y_1)(x_2 - x_1)$ .

1.4.26 Show that the points **P**(-2, 3, 5), **Q**(1, 2, 3) and **R**(7, 0, -1) are collinear.

1.4.27 Prove that the three points  $(-4, 6, 10)$ ,  $(2, 4, 6)$  and  $(14, 0, -2)$  are collinear.

1.4.28 Show that the points **A**( $-2\hat{i} + 3\hat{j} + 5\hat{k}$ ), **B**( $\hat{i} + 2\hat{j} + 3\hat{k}$ ) and **C**( $7\hat{i} - \hat{k}$ ) are collinear.

1.4.29 Show that the points **A**(2, 3, -4), **B**(1, -2, 3) and **C**(3, 8, -11) are collinear.

## 1.5 Length

1.5.1 Compute the magnitude of the following vectors:

$$\mathbf{a} = \hat{i} + \hat{j} + \hat{k} \quad (1.5.1.1)$$

$$\mathbf{b} = 2\hat{i} - 7\hat{j} - 3\hat{k} \quad (1.5.1.2)$$

$$\mathbf{c} = \frac{1}{\sqrt{3}}\hat{i} + \frac{1}{\sqrt{3}}\hat{j} - \frac{1}{3}\hat{k} \quad (1.5.1.3)$$

**Solution:** Let

$$\mathbf{a} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} 2 \\ -7 \\ 3 \end{pmatrix}, \mathbf{c} = \begin{pmatrix} \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{3}} \end{pmatrix} \quad (1.5.1.4)$$

Then

$$\mathbf{a}^\top \mathbf{a} = \begin{pmatrix} 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = 3 \quad (1.5.1.5)$$

$$\Rightarrow \|\mathbf{a}\| = \sqrt{3}, \quad (1.5.1.6)$$

from (1.1.7.1). Similarly,

$$\|\mathbf{b}\| = \sqrt{\mathbf{b}^\top \mathbf{b}} = \sqrt{62}, \quad (1.5.1.7)$$

$$\|\mathbf{c}\| = \sqrt{\mathbf{c}^\top \mathbf{c}} = 1 \quad (1.5.1.8)$$

1.5.2 Find the distance between the following pairs of points

- (i) (2, 3, 5) and (4, 3, 1)
- (ii) (-3, 7, 2) and (2, 4, -1)
- (iii) (-1, 3, -4) and (1, -3, 4)
- (iv) (2, -1, 3) and (-2, 1, 3)

1.5.3 Find the lengths of the medians of the triangle with vertices  $\mathbf{A}(0, 0, 6)$ ,  $\mathbf{B}(0, 4, 0)$  and  $\mathbf{C}(6, 0, 0)$ .

1.5.4 Find the coordinates of a point on Y axis which is at a distance of  $5\sqrt{2}$  from the point  $\mathbf{P}(3, -2, 5)$ .

1.5.5 If  $\mathbf{A}$  and  $\mathbf{B}$  be the points (3, 4, 5) and (-1, 3, -7) respectively, find the equation of the set of the points  $\mathbf{P}$  such that  $PA^2 + PB^2 = K^2$  where  $K$  is a constant.

1.5.6 Find the distances between the following pairs of points

- a) (2, 3), (4, 1)
- b) (-5, 7), (-1, 3)
- c)  $(a, b)$ ,  $(-a, -b)$

**Solution:**

a)

$$\therefore \mathbf{A} - \mathbf{B} = \begin{pmatrix} 2 \\ 3 \\ 3 \end{pmatrix} - \begin{pmatrix} 4 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} -2 \\ 2 \\ 2 \end{pmatrix}, \quad (1.5.6.1)$$

$$(\mathbf{A} - \mathbf{B})^\top (\mathbf{A} - \mathbf{B}) = 8 \quad (1.5.6.2)$$

Thus, the desired distance is

$$d = \|\mathbf{A} - \mathbf{B}\| = \sqrt{8} \quad (1.5.6.3)$$

b)

$$\mathbf{C} - \mathbf{D} = \begin{pmatrix} -5 \\ 7 \end{pmatrix} - \begin{pmatrix} -1 \\ 3 \end{pmatrix} = \begin{pmatrix} -4 \\ 4 \end{pmatrix} \quad (1.5.6.4)$$

$$\Rightarrow (\mathbf{C} - \mathbf{D})^\top (\mathbf{C} - \mathbf{D}) = 32 \quad (1.5.6.5)$$

Thus,

$$d = \|\mathbf{C} - \mathbf{D}\| = 4\sqrt{2} \quad (1.5.6.6)$$

c)

$$\mathbf{E} - \mathbf{F} = \begin{pmatrix} a \\ b \end{pmatrix} - \begin{pmatrix} -a \\ -b \end{pmatrix} = \begin{pmatrix} 2a \\ 2b \end{pmatrix} \quad (1.5.6.7)$$

$$\Rightarrow (\mathbf{E} - \mathbf{F})^\top (\mathbf{E} - \mathbf{F}) = 4a^2 + 4b^2 \quad (1.5.6.8)$$

Thus,

$$d = \|\mathbf{E} - \mathbf{F}\| = 2\sqrt{a^2 + b^2} \quad (1.5.6.9)$$

1.5.7 Find the distance between the points (0, 0) and (36, 15).

**Solution:**

$$\mathbf{A} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} 36 \\ 15 \end{pmatrix} \quad (1.5.7.1)$$

$$\Rightarrow d = \|\mathbf{A} - \mathbf{B}\| = 39 \quad (1.5.7.2)$$

1.5.8 Find the point on the X axis which is equidistant from (2, -5) and (-2, 9).

**Solution:** The input parameters for this problem are available in Table 1.5.8

Symbol	Value	Description
<b>A</b>	$\begin{pmatrix} 2 \\ -5 \end{pmatrix}$	First point
<b>B</b>	$\begin{pmatrix} -2 \\ 9 \end{pmatrix}$	Second point
<b>O</b>	?	Desired point

TABLE 1.5.8

If **O** lies on the  $x$ -axis and is equidistant from the points **A** and **B**,

$$\|\mathbf{O} - \mathbf{A}\| = \|\mathbf{A} - \mathbf{B}\| \quad (1.5.8.1)$$

$$\Rightarrow \|\mathbf{O} - \mathbf{A}\|^2 = \|\mathbf{O} - \mathbf{B}\|^2 \quad (1.5.8.2)$$

$$\Rightarrow \|\mathbf{O}\|^2 - 2\mathbf{O}^\top \mathbf{A} + \|\mathbf{A}\|^2 = \|\mathbf{O}\|^2 - 2\mathbf{O}^\top \mathbf{B} + \|\mathbf{B}\|^2, \quad (1.5.8.3)$$

which can be simplified to obtain

$$(\mathbf{A} - \mathbf{B})^\top \mathbf{O} = \frac{\|\mathbf{A}\|^2 - \|\mathbf{B}\|^2}{2}. \quad (1.5.8.4)$$

$$\therefore \mathbf{O} = x\mathbf{e}_1, \quad (1.5.8.5)$$

$$x = \frac{\|\mathbf{A}\|^2 - \|\mathbf{B}\|^2}{2(\mathbf{A} - \mathbf{B})^\top \mathbf{e}_1}. \quad (1.5.8.6)$$

Substituting from Table 1.5.8 in (1.5.8.6),  $x = -7$ . Thus,

$$\mathbf{O} = \begin{pmatrix} -7 \\ 0 \end{pmatrix}. \quad (1.5.8.7)$$

See Fig. 1.5.8.1.

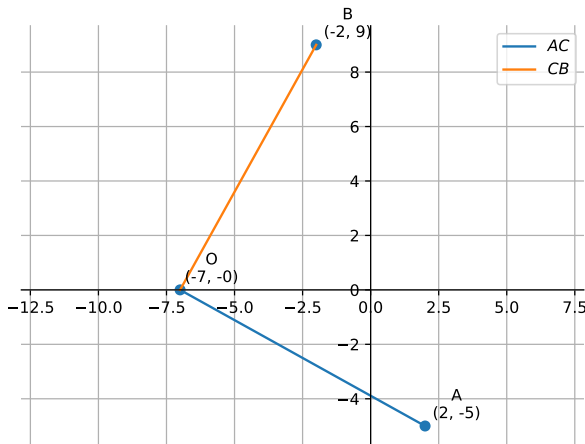


Fig. 1.5.8.1

- 1.5.9 Find the values of  $y$  for which the distance between the points  $\mathbf{P}(2, -3)$  and  $\mathbf{Q}(10, y)$  is 10 units.
- 1.5.10 If  $\mathbf{Q}(0, 1)$  is equidistant from  $\mathbf{P}(5, -3)$  and  $\mathbf{R}(x, 6)$ , find the values of  $x$ . Also find the distances  $QR$  and  $PR$ .
- 1.5.11 Find a relation between  $x$  and  $y$  such that the point  $(x, y)$  is equidistant from the point  $(3, 6)$  and  $(-3, 4)$ .
- 1.5.12 Find a point on the X axis, which is equidistant from the points  $\begin{pmatrix} 7 \\ 6 \end{pmatrix}$  and  $\begin{pmatrix} 3 \\ 4 \end{pmatrix}$ .
- 1.5.13 The distance between the points  $\mathbf{A}(0, 6)$  and  $\mathbf{B}(0, -2)$  is
- 1.5.14 The distance of the point  $\mathbf{P}(-6, 8)$  from the origin is
- 1.5.15 The distance between the points  $(0, 5)$  and  $(-5, 0)$  is
- 1.5.16  $AOBC$  is a rectangle whose three vertices are vertices  $\mathbf{A}(0, 3)$ ,  $\mathbf{O}(0, 0)$  and  $\mathbf{B}(5, 0)$ .  
The length of its diagonal is
- 1.5.17 The perimeter of a triangle with vertices  $(0, 4)$ ,  $(0, 0)$  and  $(3, 0)$  is

- 1.5.18 If the distance between the points  $(4, P)$  and  $(1, 0)$  is 5, then the value of  $P$  is
- 1.5.19 Find the points on the  $X$  axis which are at a distance on  $2\sqrt{5}$  from the point  $(7, -4)$ . How many such points are there?
- 1.5.20 Find the value of  $a$ , if the if the distance between the points  $\mathbf{A}(-3, -14)$  and  $\mathbf{B}(a, -5)$  is 9 units.
- 1.5.21 Find a point which is equidistant from the points  $\mathbf{A}(-5, 4)$  and  $(-1, 6)$ . How many such points are there ?
- 1.5.22 If the point  $\mathbf{A}(2, -4)$  is equidistant from  $\mathbf{P}(3, 8)$  and  $\mathbf{Q}(-10, y)$ , find the values of  $y$ . Also find distance  $PQ$ .
- 1.5.23 If  $(a, b)$  is the mid-point of the line segment joining the point  $\mathbf{A}(10, -6)$  and  $\mathbf{B}(k, 4)$  and  $a - 2b = 18$ , find the value of  $a, b$  and the distance  $AB$ .
- 1.5.24 Find a relation between  $x$  and  $y$  such that the point  $(x, y)$  is equidistant from the points  $(7, 1)$  and  $(3, 5)$ .
- 1.5.25 Find a point on the  $Y$  axis which is equidistant from the points  $\mathbf{A}(6, 5)$  and  $\mathbf{B}(-4, 3)$ .
- 1.5.26 Find the equation of set of points  $\mathbf{P}$  such that  $PA^2 + PB^2 = 2k^2$ , where  $\mathbf{A}$  and  $\mathbf{B}$  are the points  $(3, 4, 5)$  and  $(-1, 3, -7)$ , respectively.
- 1.5.27 Find the equation of the set of the points  $\mathbf{P}$  such that its distances from the points  $\mathbf{A}(3, 4, -5)$  and  $\mathbf{B}(-2, 1, 4)$  are equal.
- 1.5.28 Find a vector in the direction of vector  $\vec{a} = \hat{i} - 2\hat{j}$  that has magnitude 7 units.

### 1.6 Unit Vector

- 1.6.1 Find the value of  $x$  for which  $x(\hat{i} + \hat{j} + \hat{k})$  is a unit vector.

**Solution:**

$$\because \mathbf{x} = x \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \|\mathbf{x}\| = 1 \implies x\sqrt{3} = 1 \quad (1.6.1.1)$$

$$\text{or, } x = \frac{1}{\sqrt{3}} \quad (1.6.1.2)$$

- 1.6.2 For given vectors,  $\mathbf{a} = 2\hat{i} - \hat{j} + 2\hat{k}$  and  $\mathbf{b} = -\hat{i} + \hat{j} - \hat{k}$ , find the unit vector in the direction of the vector  $\mathbf{a} + \mathbf{b}$ .

**Solution:**

$$\because \mathbf{a} + \mathbf{b} = \begin{pmatrix} 2 \\ -1 \\ 2 \end{pmatrix} + \begin{pmatrix} -1 \\ 1 \\ -1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix}, \quad (1.6.2.1)$$

$$\|\mathbf{a} + \mathbf{b}\| = \sqrt{2} \quad (1.6.2.2)$$

$$\implies \frac{\mathbf{a} + \mathbf{b}}{\|\mathbf{a} + \mathbf{b}\|} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \quad (1.6.2.3)$$

which, from (1.1.8.1) is the desired the unit vector.

- 1.6.3 Find a vector in the direction of vector  $5\hat{i} - \hat{j} + 2\hat{k}$  which has magnitude 8 units.

**Solution:** Let the required vector be

$$c \begin{pmatrix} 5 \\ -1 \\ 2 \end{pmatrix}. \quad (1.6.3.1)$$

From the given information,

$$\left\| c \begin{pmatrix} 5 \\ -1 \\ 2 \end{pmatrix} \right\| = 8 \quad (1.6.3.2)$$

$$\Rightarrow |c| = \frac{4\sqrt{30}}{15} \quad (1.6.3.3)$$

1.6.4 Find the unit vector in the direction of sum of vectors  $\mathbf{a} = 2\hat{i} - \hat{j} + \hat{k}$  and  $\mathbf{b} = 2\hat{j} + \hat{k}$ .

1.6.5 If  $\mathbf{a} = \hat{i} + \hat{j} + 2\hat{k}$  and  $\mathbf{b} = 2\hat{i} + \hat{j} - 2\hat{k}$ , find the unit vector in the direction of

a)  $6\mathbf{a}$

b)  $2\mathbf{a} - \mathbf{b}$

1.6.6 Find a unit vector in the direction of  $\overrightarrow{PQ}$ , where  $\mathbf{P}$  and  $\mathbf{Q}$  have co-ordinates (5, 0, 8) and (3, 3, 2), respectively.

1.6.7 The vector in the direction of the vector  $\hat{i} - 2\hat{j} + 2\hat{k}$  that has magnitude 9 is

a)  $\hat{i} - 2\hat{j} + 2\hat{k}$

b)  $\hat{i} - 2\hat{j}$

c)  $3(\hat{i} - 2\hat{j} + 2\hat{k})$

d)  $9(\hat{i} - 2\hat{j} + 2\hat{k})$

1.6.8 Find the unit vector in the direction of the vector  $\mathbf{a} = \hat{i} + \hat{j} + 2\hat{k}$ .

1.6.9 Find the unit vector in the direction of vector  $\overrightarrow{PQ}$ , where  $\mathbf{P}$  and  $\mathbf{Q}$  are the points (1, 2, 3) and (4, 5, 6), respectively.

1.6.10 Find a vector of magnitude 5 units, and parallel to the resultant of the vectors  $\mathbf{a} = 2\hat{i} + 3\hat{j} - \hat{k}$  and  $\mathbf{b} = \hat{i} - 2\hat{j} + \hat{k}$ .

1.6.11 If  $\mathbf{a} = \hat{i} + \hat{j} + \hat{k}$ ,  $\mathbf{b} = 2\hat{i} - \hat{j} + 3\hat{k}$  and  $\mathbf{c} = \hat{i} - 2\hat{j} + \hat{k}$ , find a unit vector parallel to the vector  $2\mathbf{a} - \mathbf{b} + 3\mathbf{c}$ .

**Solution:**

$$2\mathbf{a} - \mathbf{b} + 3\mathbf{c} = \begin{pmatrix} 3 \\ -3 \\ 2 \end{pmatrix} \Rightarrow \frac{2\mathbf{a} - \mathbf{b} + 3\mathbf{c}}{\|2\mathbf{a} - \mathbf{b} + 3\mathbf{c}\|} = \frac{1}{\sqrt{22}} \begin{pmatrix} 3 \\ -3 \\ 2 \end{pmatrix} \quad (1.6.11.1)$$

1.6.12 Find a vector of magnitude 5 units, and parallel to the resultant of the vectors  $\mathbf{a} = 2\hat{i} + 3\hat{j} - \hat{k}$  and  $\mathbf{b} = \hat{i} - 2\hat{j} + \hat{k}$ .

**Solution:**

$$\because \mathbf{a} = \begin{pmatrix} 2 \\ 3 \\ -1 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix} \quad (1.6.12.1)$$

$$\mathbf{a} + \mathbf{b} = \begin{pmatrix} 3 \\ 1 \\ 0 \end{pmatrix} \Rightarrow \|\mathbf{a} + \mathbf{b}\| = \sqrt{10} \quad (1.6.12.2)$$

From problem 1.6.2, the unit vector in the direction of  $\mathbf{a} + \mathbf{b}$  is

$$\frac{\mathbf{a} + \mathbf{b}}{\|\mathbf{a} + \mathbf{b}\|} = \frac{1}{\sqrt{10}} \begin{pmatrix} 3 \\ 1 \\ 0 \end{pmatrix} \quad (1.6.12.3)$$

The desired vector can then be expressed as

$$\pm \frac{5}{\sqrt{10}} \begin{pmatrix} 3 \\ 1 \\ 0 \end{pmatrix} \quad (1.6.12.4)$$

- 1.6.13 If a line makes angles  $90^\circ, 135^\circ, 45^\circ$  with X, Y and Z axis respectively. Find its direction cosines.

**Solution:** From (1.1.11.1), the direction vector is

$$\mathbf{A} = \begin{pmatrix} \cos 90^\circ \\ \cos 135^\circ \\ \cos 45^\circ \end{pmatrix} = \begin{pmatrix} 0 \\ -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} \quad (1.6.13.1)$$

- 1.6.14 Find the direction cosines of the vector joining the points  $\mathbf{A} (1, 2, -3)$  and  $\mathbf{B}(-1, -2, 1)$ , directed from  $\mathbf{A}$  to  $\mathbf{B}$ .

**Solution:** The unit vector in the direction of AB is

$$\frac{\mathbf{B} - \mathbf{A}}{\|\mathbf{B} - \mathbf{A}\|} = \frac{1}{3} \begin{pmatrix} -1 \\ -2 \\ 2 \end{pmatrix} \quad (1.6.14.1)$$

and the direction cosines are the elements of the above vector.

- 1.6.15 Show that the vector  $\hat{i} + \hat{j} + \hat{k}$  is equally inclined to the axes OX, OY and OZ.

**Solution:** Since all entries of the given vector

$$\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \quad (1.6.15.1)$$

are equal, it is equally inclined to the axes.

- 1.6.16 If a line has the direction ratios  $-18, 12, -4$ , then what are its direction cosines?

**Solution:** Let

$$\mathbf{A} = \begin{pmatrix} -18 \\ 12 \\ -4 \end{pmatrix} \quad (1.6.16.1)$$

Then the unit direction vector of the line is

$$\frac{\mathbf{A}}{\|\mathbf{A}\|} = \begin{pmatrix} \frac{-9}{11} \\ \frac{6}{11} \\ \frac{-2}{11} \end{pmatrix} \quad (1.6.16.2)$$

1.6.17 Find the direction cosines of the sides of a triangle whose vertices are  $\begin{pmatrix} 3 \\ 5 \\ -4 \end{pmatrix}$ ,  $\begin{pmatrix} -1 \\ 1 \\ 2 \end{pmatrix}$  and  $\begin{pmatrix} -5 \\ -5 \\ -2 \end{pmatrix}$ .

**Solution:** Let the vertices be

$$\mathbf{A} = \begin{pmatrix} 3 \\ 5 \\ -4 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} -1 \\ 1 \\ 2 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} -5 \\ -5 \\ -2 \end{pmatrix} \quad (1.6.17.1)$$

The direction vectors of the sides are,

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} 4 \\ 4 \\ -6 \end{pmatrix} = \mathbf{m}_1, \mathbf{B} - \mathbf{C} = \begin{pmatrix} 4 \\ 6 \\ 4 \end{pmatrix} = \mathbf{m}_2, \quad (1.6.17.2)$$

$$\mathbf{C} - \mathbf{A} = \begin{pmatrix} -8 \\ -10 \\ 2 \end{pmatrix} = \mathbf{m}_3, \quad (1.6.17.3)$$

The corresponding unit vectors are then obtained as

$$\begin{pmatrix} \frac{2}{\sqrt{17}} \\ \frac{2}{\sqrt{17}} \\ \frac{-3}{\sqrt{17}} \end{pmatrix}, \begin{pmatrix} \frac{2}{\sqrt{17}} \\ \frac{3}{\sqrt{17}} \\ \frac{2}{\sqrt{17}} \end{pmatrix}, \begin{pmatrix} \frac{-4}{\sqrt{42}} \\ \frac{-5}{\sqrt{42}} \\ \frac{1}{\sqrt{42}} \end{pmatrix} \quad (1.6.17.4)$$

1.6.18 Find the direction cosines of the vector  $\hat{i} + 2\hat{j} + 3\hat{k}$ .

**Solution:** The unit vector in the direction of the given vector is

$$\mathbf{A} = \frac{1}{\sqrt{14}} \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} \quad (1.6.18.1)$$

1.6.19 Find the direction cosines of a line which makes equal angles with the coordinate axes.

**Solution:** Let  $\alpha$  be the angle made by the line with the axes. The unit direction



vector can be expressed as

$$\mathbf{x} = \begin{pmatrix} \cos \alpha \\ \cos \alpha \\ \cos \alpha \end{pmatrix} \Rightarrow \|\mathbf{x}\| = 1 \quad (1.6.19.1)$$

$$\text{or, } \cos \alpha = \frac{1}{\sqrt{3}} \quad (1.6.19.2)$$

Thus the unit direction vector of the given line is

$$\mathbf{x} = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \quad (1.6.19.3)$$

1.6.20 If a unit vector  $\vec{a}$  makes angles  $\frac{\pi}{3}$  with  $\hat{i}$ ,  $\frac{\pi}{4}$  with  $\hat{j}$  and an acute angle  $\theta$  with  $\hat{k}$ , then find  $\theta$  and hence, the components of  $\vec{a}$ .

**Solution:** From the given information,

$$\mathbf{a} = \begin{pmatrix} \cos \frac{\pi}{3} \\ \cos \frac{\pi}{4} \\ \cos \theta \end{pmatrix} = \begin{pmatrix} \frac{1}{2} \\ \frac{1}{\sqrt{2}} \\ \cos \theta \end{pmatrix} \quad (1.6.20.1)$$

$$\because \|\mathbf{a}\| = 1, \quad (1.6.20.2)$$

$$\frac{1}{4} + \frac{1}{2} + \cos^2 \theta = 1 \quad (1.6.20.3)$$

$$\Rightarrow \cos \theta = \frac{1}{2} \quad (1.6.20.4)$$

$\because \theta$  is an acute angle. Hence

$$\mathbf{a} = \begin{pmatrix} \frac{1}{2} \\ \frac{1}{\sqrt{2}} \\ \frac{1}{2} \end{pmatrix} \quad (1.6.20.5)$$

1.6.21 Write down a unit vector in XY-plane, making an angle of  $30^\circ$  with the positive direction of X axis.

1.6.22 A vector  $\mathbf{r}$  is inclined at equal angles to the three axis. If the magnitude of  $\mathbf{r}$  is  $2\sqrt{3}$  units, find  $\mathbf{r}$ .

1.6.23 The direction cosines of the vector  $(2\hat{i} + 2\hat{j} - \hat{k})$  are \_\_\_\_\_.

1.6.24 A vector  $\mathbf{r}$  has a magnitude 14 and direction ratios 2, 3, -6. Find the direction cosines and components of  $\mathbf{r}$ , given that  $\mathbf{r}$  makes an acute angle with X axis.

1.6.25 Find the unit vector in the direction of vector  $\vec{a} = 2\hat{i} + 3\hat{j} + \hat{k}$ .

1.6.26 Find the unit vector in the direction of the sum of the vectors,  $\vec{a} = 2\hat{i} + 2\hat{j} - 5\hat{k}$  and  $\vec{b} = 2\hat{i} + \hat{j} + 3\hat{k}$ .

1.6.27 Write the direction ratios of the vector  $\vec{a} = \hat{i} + \hat{j} - \hat{k}$  and hence calculate its direction cosines.

- 1.6.28 Find the direction cosines of the unit vector perpendicular to the plane  $\vec{r} \cdot (6\hat{i} - 3\hat{j} - 2\hat{k}) + 1 = 0$  passing through the origin.
- 1.6.29 If a line makes angle  $90^\circ$ ,  $60^\circ$  and  $30^\circ$  with the positive direction of X, Y and Z axes respectively, find its direction cosines.
- 1.6.30 If a line has direction ratios  $2, -1, -2$ , determine its direction cosines.
- 1.6.31 Find the direction cosines of the line passing through the two points  $(-2, 4, -5)$  and  $(1, 2, 3)$ .

## 2 VECTOR MULTIPLICATION

## 2.1 Formulae

2.1.1. The angle  $\theta$  between  $\mathbf{a}, \mathbf{b}$ , is given by

$$\cos \theta = \frac{\mathbf{a}^\top \mathbf{b}}{\|\mathbf{a}\| \|\mathbf{b}\|} \quad (2.1.1.1)$$

2.1.2. The equation of a line is given by

$$\mathbf{x} = \mathbf{h} + \kappa \mathbf{m} \quad (2.1.2.1)$$

2.1.3. For

$$\mathbf{m}^\top \mathbf{n} = 0, \quad (2.1.3.1)$$

which means that  $\mathbf{m} \perp \mathbf{n}$ , (2.1.2.1) can be expressed as

$$\mathbf{n}^\top \mathbf{x} = \mathbf{n}^\top \mathbf{h} + \kappa \mathbf{n}^\top \mathbf{m} \quad (2.1.3.2)$$

$$\implies \mathbf{n}^\top \mathbf{x} = c \quad (2.1.3.3)$$

for

$$c = \mathbf{n}^\top \mathbf{h}. \quad (2.1.3.4)$$

$\mathbf{n}$  is defined to be the *normal vector* of the line. In 3D, (2.1.3.3) represents a plane.

2.1.4. Mathematically, the projection of  $\mathbf{A}$  on  $\mathbf{B}$  is defined as

$$\mathbf{C} = k\mathbf{B}, \text{ such that } (\mathbf{A} - \mathbf{C})^\top \mathbf{C} = 0 \quad (2.1.4.1)$$

yielding

$$(\mathbf{A} - k\mathbf{B})^\top \mathbf{B} = 0 \quad (2.1.4.2)$$

$$\text{or, } k = \frac{\mathbf{A}^\top \mathbf{B}}{\|\mathbf{B}\|^2} \implies \mathbf{C} = \frac{\mathbf{A}^\top \mathbf{B}}{\|\mathbf{B}\|^2} \mathbf{B} \quad (2.1.4.3)$$

2.1.5. If  $\mathbf{A}, \mathbf{B}$  are unit vectors,

$$(\mathbf{A} - \mathbf{B})^\top (\mathbf{A} + \mathbf{B}) = \|\mathbf{A}\|^2 - \|\mathbf{B}\|^2 = 0 \quad (2.1.5.1)$$

2.1.6. If

$$\mathbf{A}^\top \mathbf{A} = \mathbf{I}, \quad (2.1.6.1)$$

then  $\mathbf{A}$  is an *orthogonal* matrix. This also means that its rows and columns are unit vectors and mutually perpendicular.

2.1.7. The determinant

$$\begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix} = a_1 b_2 - a_2 b_1. \quad (2.1.7.1)$$

2.1.8. Let

$$\mathbf{A} = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \equiv a_1 \vec{i} + a_2 \vec{j} + a_3 \vec{j}, \quad (2.1.8.1)$$

$$\mathbf{B} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix}, \quad (2.1.8.2)$$

and

$$\begin{aligned} \mathbf{A}_{ij} &= \begin{pmatrix} a_i \\ a_j \end{pmatrix}, \\ \mathbf{B}_{ij} &= \begin{pmatrix} b_i \\ b_j \end{pmatrix}. \end{aligned} \quad (2.1.8.3)$$

2.1.9. The *cross product* or *vector product* of  $\mathbf{A}, \mathbf{B}$  is defined as

$$\mathbf{A} \times \mathbf{B} = \begin{pmatrix} |\mathbf{A}_{23} & \mathbf{B}_{23}| \\ |\mathbf{A}_{31} & \mathbf{B}_{31}| \\ |\mathbf{A}_{12} & \mathbf{B}_{12}| \end{pmatrix} \quad (2.1.9.1)$$

2.1.10. Verify that

$$\mathbf{A} \times \mathbf{B} = -\mathbf{B} \times \mathbf{A} \quad (2.1.10.1)$$

$$\mathbf{A} \times \mathbf{A} = \mathbf{0} \quad (2.1.10.2)$$

2.1.11. If

$$\mathbf{A} \times \mathbf{B} = \mathbf{0}, \quad (2.1.11.1)$$

$\mathbf{A}$  and  $\mathbf{B}$  are linearly independent, i.e., they are points on the same line.

2.1.12.

$$\|\mathbf{A} \times \mathbf{B}\| = \|\mathbf{A}\| \times \|\mathbf{B}\| \sin \theta \quad (2.1.12.1)$$

where  $\theta$  is the angle between the vectors.

2.1.13.

$$ar(ABCD) = \frac{1}{2} ((\mathbf{C} - \mathbf{A}) \times (\mathbf{D} - \mathbf{B})) \quad (2.1.13.1)$$

$$(2.1.13.2)$$

2.1.14. The area of  $\triangle ABC$  is

$$\frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C})\| \quad (2.1.14.1)$$

2.1.15. The affine transformation is given by

$$\mathbf{x} = \mathbf{P}\mathbf{y} + \mathbf{c} \quad (2.1.15.1)$$

where  $\mathbf{c}$  is the translation vector.

2.1.16. The matrix

$$\mathbf{P} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \quad (2.1.16.1)$$

is defined to be the rotation matrix.

2.1.17.

$$\mathbf{P}^\top \mathbf{P} = \mathbf{I} \quad (2.1.17.1)$$

$\mathbf{P}$  is known as as *orthogonal* matrix.

2.1.18. Given vertices  $\mathbf{A}, \mathbf{C}$  of a square, the other two vertices are given by

$$\begin{aligned} \mathbf{B} &= \|\mathbf{C} - \mathbf{A}\| \cos \frac{\pi}{4} \mathbf{P}\mathbf{e}_1 + \mathbf{A} \\ \mathbf{D} &= \|\mathbf{C} - \mathbf{A}\| \cos \frac{\pi}{4} \mathbf{P}\mathbf{e}_2 + \mathbf{A} \end{aligned} \quad (2.1.18.1)$$

2.1.19. Code for orthogonality

codes/book/orth.py

2.1.20. Code for cross product

codes/book/cross.py

## 2.2 Scalar Product

2.2.1 Find the angle between two vectors  $\vec{a}$  and  $\vec{b}$  with magnitudes  $\sqrt{3}$  and 2 respectively having  $\vec{a} \cdot \vec{b} = \sqrt{6}$ .

**Solution:** From the given information,

$$\|\mathbf{a}\| = \sqrt{3}, \|\mathbf{b}\| = 2, \mathbf{a}^\top \mathbf{b} = \sqrt{6} \quad (2.2.1.1)$$

Substituting in (2.1.1.1),

$$\cos \theta = \frac{1}{\sqrt{2}} \quad (2.2.1.2)$$

$$\text{or, } \theta = 45^\circ \quad (2.2.1.3)$$

2.2.2 Find the angle between the the vectors  $\hat{i} - 2\hat{j} + 3\hat{k}$  and  $3\hat{i} - 2\hat{j} + \hat{k}$ .

**Solution:** Let

$$\mathbf{a} = \begin{pmatrix} 1 \\ -2 \\ 3 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} 3 \\ -2 \\ 1 \end{pmatrix}, \quad (2.2.2.1)$$

From problem 2.2.1,

$$\cos \theta = \frac{\mathbf{a}^\top \mathbf{b}}{\|\mathbf{a}\| \|\mathbf{b}\|} = \frac{10}{\sqrt{14} \times \sqrt{14}} = \frac{5}{7} \quad (2.2.2.2)$$

2.2.3 Evaluate the product  $(3\vec{a} - 5\vec{b}) \cdot (2\vec{a} + 7\vec{b})$ .

**Solution:**

$$\begin{aligned}(3\mathbf{a} - 5\mathbf{b})^\top (2\mathbf{a} + 7\mathbf{b}) &= 3\mathbf{a}^\top (2\mathbf{a} + 7\mathbf{b}) - 5\mathbf{b}^\top (2\mathbf{a} + 7\mathbf{b}) \\ &= 6\|\mathbf{a}\|^2 - 35\|\mathbf{b}\|^2 + 11\mathbf{a}^\top \mathbf{b} \quad (2.2.3.1)\end{aligned}$$

2.2.4 If the vertices **A**, **B**, **C** of a triangle  $ABC$  are  $(1, 2, 3)$ ,  $(-1, 0, 0)$ ,  $(0, 1, 2)$ , respectively, then find  $\angle ABC$ .

**Solution:** From the given information,

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} 2 \\ 2 \\ 3 \end{pmatrix}, \mathbf{C} - \mathbf{B} = \begin{pmatrix} 1 \\ 1 \\ 2 \end{pmatrix} \quad (2.2.4.1)$$

$$\Rightarrow \angle ABC = \cos^{-1} \frac{(\mathbf{A} - \mathbf{B})^\top (\mathbf{C} - \mathbf{B})}{\|\mathbf{A} - \mathbf{B}\| \|\mathbf{C} - \mathbf{B}\|} \quad (2.2.4.2)$$

$$= \cos^{-1} \frac{10}{\sqrt{102}} \quad (2.2.4.3)$$

$$(2.2.4.4)$$

2.2.5 The slope of a line is double of the slope of another line. If tangent of the angle between them is  $1/3$ , find the slopes of the lines.

**Solution:** The direction vectors of the lines can be expressed as

$$\mathbf{m}_1 = \begin{pmatrix} 1 \\ m \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 1 \\ 2m \end{pmatrix} \quad (2.2.5.1)$$

If the angle between the lines be  $\theta$ ,

$$\tan \theta = \frac{1}{3} \Rightarrow \cos \theta = \frac{3}{\sqrt{10}} \quad (2.2.5.2)$$

Thus,

$$\frac{3}{\sqrt{10}} = \frac{\mathbf{m}_1^\top \mathbf{m}_2}{\|\mathbf{m}_1\| \|\mathbf{m}_2\|} \quad (2.2.5.3)$$

$$= \frac{2m^2 + 1}{\sqrt{m^2 + 1} \sqrt{4m^2 + 1}} \quad (2.2.5.4)$$

$$\Rightarrow \frac{9}{10} = \frac{4m^4 + 4m^2 + 1}{4m^4 + 5m^2 + 1} \quad (2.2.5.5)$$

$$\text{or, } 4m^4 - 5m^2 + 1 = 0 \quad (2.2.5.6)$$

yielding

$$m = \pm \frac{1}{2}, \pm 1 \quad (2.2.5.7)$$

2.2.6 Find angle between the lines,  $\sqrt{3}x + y = 1$  and  $x + \sqrt{3}y = 1$ .

**Solution:** From (2.1.3.3), the normal vectors of the given lines can be expressed as

$$\mathbf{n}_1 = \begin{pmatrix} \sqrt{3} \\ 1 \end{pmatrix}, \mathbf{n}_2 = \begin{pmatrix} 1 \\ \sqrt{3} \end{pmatrix} \quad (2.2.6.1)$$

The angle between the lines can then be obtained as

$$\cos \theta = \frac{\mathbf{n}_1^\top \mathbf{n}_2}{\|\mathbf{n}_1\| \|\mathbf{n}_2\|} = \frac{\sqrt{3}}{2} \quad (2.2.6.2)$$

$$\text{or, } \theta = 30^\circ \quad (2.2.6.3)$$

2.2.7 Find the angle between the vectors  $2\hat{i} - \hat{j} + \hat{k}$  and  $3\hat{i} + 4\hat{j} - \hat{k}$ .

2.2.8 The angles between two vectors  $\mathbf{a}, \mathbf{b}$  with magnitude  $\sqrt{3}, 4$  respectively, and  $\mathbf{a} \cdot \mathbf{b} = 2\sqrt{3}$  is

2.2.9 Find the angle between the lines

$$\vec{r} = 3\hat{i} - 2\hat{j} + 6\hat{k} + \lambda(2\hat{i} + \hat{j} + 2\hat{k}) \text{ and} \quad (2.2.9.1)$$

$$\vec{r} = (2\hat{j} - 5\hat{k}) + \mu(6\hat{i} + 3\hat{j} + 2\hat{k}) \quad (2.2.9.2)$$

**Solution:** The given lines can be expressed in the form of (2.1.2.1) as

$$\mathbf{x} = \begin{pmatrix} 3 \\ -2 \\ 6 \end{pmatrix} + \kappa_1 \begin{pmatrix} 2 \\ 1 \\ 2 \end{pmatrix} \quad (2.2.9.3)$$

$$\mathbf{x} = \begin{pmatrix} 0 \\ 2 \\ -5 \end{pmatrix} + \kappa_2 \begin{pmatrix} 6 \\ 3 \\ 2 \end{pmatrix} \quad (2.2.9.4)$$

From the above, it is obvious that the direction vectors of the two lines are

$$\mathbf{m}_1 = \begin{pmatrix} 2 \\ 1 \\ 2 \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 6 \\ 3 \\ 2 \end{pmatrix} \quad (2.2.9.5)$$

From (2.1.1.1), the angle between the two lines is obtained as

$$\cos \theta = \frac{19}{21} \quad (2.2.9.6)$$

2.2.10 The vectors  $\mathbf{a} = 3\hat{i} - 2\hat{j} + 2\hat{k}$  and  $\mathbf{b} = \hat{i} - 2\hat{k}$  are the adjacent sides of a parallelogram. The acute angle between its diagonals is \_\_\_\_\_.

2.2.11 The sine of the angle between the straight line

$$\frac{x-2}{3} = \frac{y-3}{4} = \frac{z-4}{5} \quad (2.2.11.1)$$

and the plane

$$2x - 2y + z = 5 \quad (2.2.11.2)$$

is **Solution:** The given line can be expressed in the form (2.1.2.1) as

$$\mathbf{x} = \begin{pmatrix} 2 \\ 3 \\ 4 \end{pmatrix} + \kappa_1 \begin{pmatrix} 3 \\ 4 \\ 5 \end{pmatrix} \quad (2.2.11.3)$$

Hence the direction vector of this line is

$$\begin{pmatrix} 3 \\ 4 \\ 5 \end{pmatrix} \quad (2.2.11.4)$$

From (2.1.3.3), the normal vector of the given plane is

$$\begin{pmatrix} 2 \\ -2 \\ 1 \end{pmatrix} \quad (2.2.11.5)$$

Thus, the cosine of the angle between the two is obtained from (2.1.1.1) as

$$\frac{\sqrt{2}}{10}, \quad (2.2.11.6)$$

which is sine of the angle between the plane and the line.

2.2.12 The plane  $2x - 3y + 6z - 11 = 0$  makes an angle  $\sin^{-1}(\alpha)$  with x-axis. The value of  $\alpha$  is equal to

2.2.13 Find the angle between the vectors  $2\hat{i} - \hat{j} + \hat{k}$  and  $3\hat{i} + 4\hat{j} - \hat{k}$ .

2.2.14 The angles between two vectors **a** and **b** with magnitude  $\sqrt{3}$  and 4, respectively, and **a**, **b** =  $2\sqrt{3}$  is

2.2.15 The angle between the line

$$\vec{r} = (5\hat{i} - \hat{j} - 4\hat{k}) + \lambda(2\hat{i} - \hat{j} + \hat{k}) \quad (2.2.15.1)$$

and the plane

$$\vec{r} \cdot (3\hat{i} - 4\hat{j} - \hat{k}) + 5 = 0 \quad (2.2.15.2)$$

is  $\sin^{-1}\left(\frac{5}{2\sqrt{91}}\right)$ .

2.2.16 The angle between the planes

$$\vec{r} \cdot (2\hat{i} - 3\hat{j} + \hat{k}) = 1 \text{ and} \quad (2.2.16.1)$$

$$\vec{r} \cdot (\hat{i} - \hat{j}) = 4 \quad (2.2.16.2)$$

is  $\cos^{-1}\left(\frac{-5}{\sqrt{58}}\right)$ .

2.2.17 Find the angle between the lines

$$y = (2 - \sqrt{3})(x + 5) \text{ and} \quad (2.2.17.1)$$

$$y = (2 + \sqrt{3})(x - 7). \quad (2.2.17.2)$$

2.2.18 The unit vector normal to the plane  $x + 2y + 3z - 6 = 0$  is  $\frac{1}{\sqrt{14}}\hat{i} + \frac{2}{\sqrt{14}}\hat{j} + \frac{3}{\sqrt{14}}\hat{k}$ .

2.2.19 The scalar product of the vector  $\hat{i} + \hat{j} + \hat{k}$  with a unit vector along the sum of vectors



$2\hat{i} + 4\hat{j} - 5\hat{k}$  and  $\lambda\hat{i} + 2\hat{j} + 3\hat{k}$  is equal to one. Find the value of  $\lambda$ .

2.2.20 Find the angle between the following pairs of lines.

a)

$$\vec{r} = 2\hat{i} - 5\hat{j} + \hat{k} + \lambda(3\hat{i} + 2\hat{j} + 6\hat{k}) \text{ and} \quad (2.2.20.1)$$

$$\vec{r} = 7\hat{i} - 6\hat{k} + \mu(\hat{i} + 2\hat{j} + 2\hat{k}) \quad (2.2.20.2)$$

b)

$$\vec{r} = 3\hat{i} + \hat{j} - 2\hat{k} + \lambda(\hat{i} - \hat{j} - 2\hat{k}) \text{ and} \quad (2.2.20.3)$$

$$\vec{r} = 2\hat{i} - \hat{j} - 56\hat{k} + \mu(3\hat{i} - 5\hat{j} - 4\hat{k}) \quad (2.2.20.4)$$

c)

$$\frac{x-2}{2} = \frac{y-1}{5} = \frac{z+3}{-3} \text{ and } \frac{x+2}{-1} = \frac{y-4}{8} = \frac{z-5}{4}. \quad (2.2.20.5)$$

d)

$$\frac{x}{2} = \frac{y}{2} = \frac{z}{1} \text{ and } \frac{x-5}{4} = \frac{y-2}{1} = \frac{z-3}{8}. \quad (2.2.20.6)$$

2.2.21 If the co-ordinates of the points **A**, **B**, **C**, **D** be (1, 2, 3), (4, 5, 7), (-4, 3, -6) and (2, 9, 2) respectively, then find the angle between the lines  $\overline{AB}$  and  $\overline{CD}$ .

2.2.22 If the angle between two lines is  $\frac{\pi}{4}$  and slope of one of the lines is  $\frac{1}{2}$ , find the slope of the other line.

2.2.23 Find the angle between two vectors  $\vec{a}$  and  $\vec{b}$  with magnitudes 1 and 2 respectively and when  $\vec{a} \cdot \vec{b} = 1$ .

2.2.24 Find angle  $\theta$  between the vectors  $\vec{a} = \hat{i} + \hat{j} - \hat{k}$  and  $\vec{b} = \hat{i} - \hat{j} + \hat{k}$ .

2.2.25 If  $\hat{i} + \hat{j} + \hat{k}$ ,  $2\hat{i} + 5\hat{j}$ ,  $3\hat{i} + 2\hat{j} - 3\hat{k}$  and  $\hat{i} - 6\hat{j} - \hat{k}$  are the position vectors of points **A**, **B**, **C** and **D** respectively, then find the angle between  $\overline{AB}$  and  $\overline{CD}$ . Deduce that  $\overline{AB}$  and  $\overline{CD}$  are collinear.

2.2.26 Find the angle between the pair of lines given by

$$\vec{r} = 3\hat{i} + 2\hat{j} - 4\hat{k} + \lambda(\hat{i} + 2\hat{j} + 2\hat{k}) \quad (2.2.26.1)$$

$$\text{and } \vec{r} = 5\hat{i} + 2\hat{j} + \mu(3\hat{i} + 2\hat{j} + 6\hat{k}) \quad (2.2.26.2)$$

2.2.27 Find the angle between the pair of lines:

$$\frac{x+3}{3} = \frac{y-1}{5} = \frac{z+3}{4} \quad (2.2.27.1)$$

$$\text{and } \frac{x+1}{1} = \frac{y-4}{1} = \frac{z+5}{2} \quad (2.2.27.2)$$

2.2.28 Find the angle between the two planes  $2x + y - 2z = 5$  and  $3x - 6y - 2z = 7$  using vector method.

2.2.29 Find the angle between the two planes  $3x - 6y + 2z = 7$  and  $2x + 2y - 2z = 5$ .

2.2.30 Find the angle between the line  $\frac{x+1}{2} = \frac{y}{3} = \frac{z-3}{6}$  and the plane  $10x + 2y - 11z = 3$ .

## 2.3 Orthogonality

2.3.1 Name the type of quadrilateral formed, if any, by the following points, and give reasons for your answer

a)  $\mathbf{A}(-1, -2), \mathbf{B}(1, 0), \mathbf{C}(-1, 2), \mathbf{D}(-3, 0)$

b)  $\mathbf{A}(-3, 5), \mathbf{B}(3, 1), \mathbf{C}(0, 3), \mathbf{D}(-1, -4)$

c)  $\mathbf{A}(4, 5), \mathbf{B}(7, 6), \mathbf{C}(4, 3), \mathbf{D}(1, 2)$

**Solution:** See Table 2.3.1, Fig. 2.3.1.1, Fig. 2.3.1.2. and Fig. 2.3.1.3. In b), forming the collinearity matrix

$$(\mathbf{B} - \mathbf{A} \quad \mathbf{C} - \mathbf{B}) = \begin{pmatrix} 6 & -3 \\ -4 & 2 \end{pmatrix} \xleftarrow{R_2 \rightarrow R_2 + \frac{2}{3}R_1} = \begin{pmatrix} 6 & -3 \\ 0 & 0 \end{pmatrix} \quad (2.3.1.1)$$

which is a rank 1 matrix. Hence,  $\mathbf{A}, \mathbf{B}, \mathbf{C}$  are collinear.

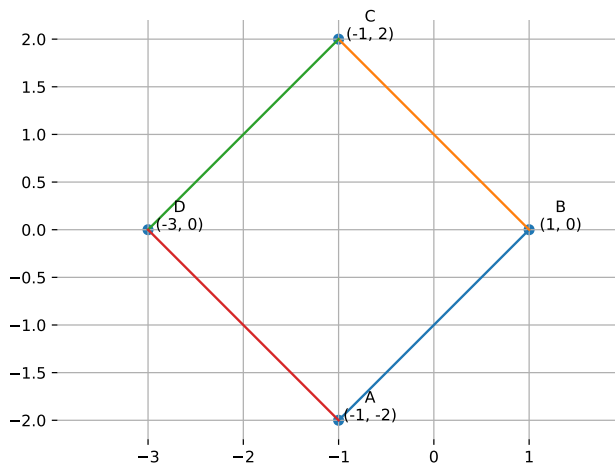


Fig. 2.3.1.1

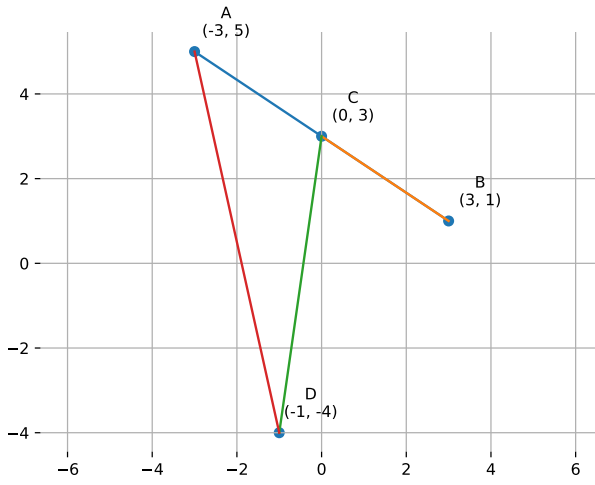


Fig. 2.3.1.2

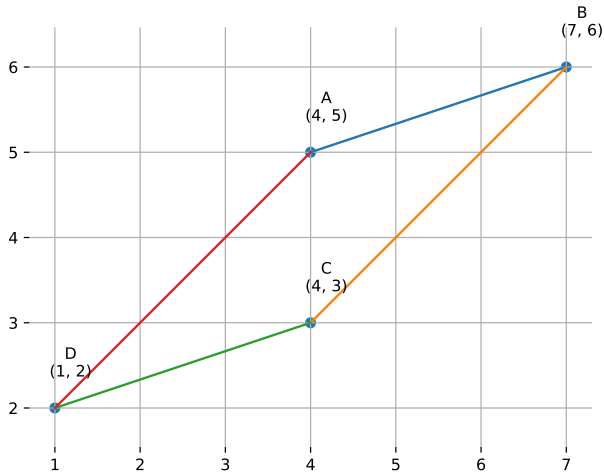


Fig. 2.3.1.3

	$\mathbf{B} - \mathbf{A} = \mathbf{C} - \mathbf{D}?$	$(\mathbf{B} - \mathbf{A})^\top (\mathbf{C} - \mathbf{B}) = 0?$	$(\mathbf{C} - \mathbf{A})^\top (\mathbf{D} - \mathbf{B}) = 0$	<b>Geometry</b>
a)	Yes	Yes	Yes	Square
b)	No	-	-	Triangle
c)	Yes	No	No	Parallelogram

TABLE 2.3.1

2.3.2 Find the projection of the vector  $\hat{i} + 3\hat{j} + 7\hat{k}$  on the vector  $7\hat{i} - \hat{j} + 8\hat{k}$ .

**Solution:** Let

$$\mathbf{A} = \begin{pmatrix} 1 \\ 3 \\ 7 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 7 \\ -1 \\ 8 \end{pmatrix} \quad (2.3.2.1)$$

The projection of  $\mathbf{A}$  on  $\mathbf{B}$  is defined as the foot of the perpendicular from  $\mathbf{A}$  to  $\mathbf{B}$  and obtained in (2.1.4.3). Substituting numerical values,

$$\mathbf{C} = \frac{10}{19} \begin{pmatrix} 7 \\ -1 \\ 8 \end{pmatrix} \quad (2.3.2.2)$$

2.3.3 Find the projection of the vector  $\hat{i} - \hat{j}$  on the vector  $\hat{i} + \hat{j}$ .

**Solution:** The given points are

$$\mathbf{A} = \begin{pmatrix} 1 \\ -1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (2.3.3.1)$$

Since

$$\mathbf{A}^\top \mathbf{B} = 0, \quad (2.3.3.2)$$

from (2.1.4.3), the projection vector is the origin. See Fig. 2.3.3.1.

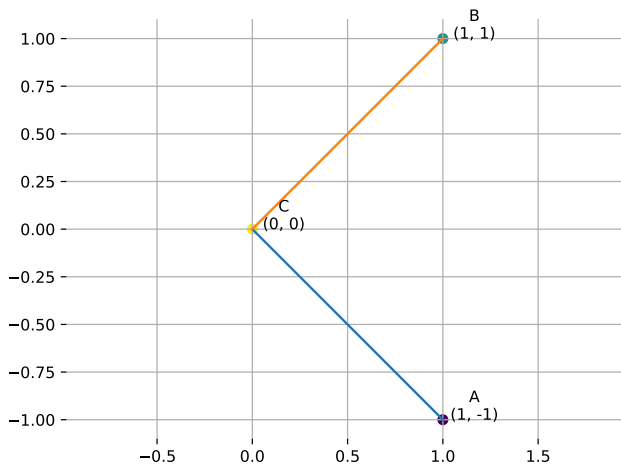


Fig. 2.3.3.1

2.3.4 Show that each of the given three vectors is a unit vector:  $\frac{1}{7}(2\hat{i} + 3\hat{j} + 6\hat{k})$ ,  $\frac{1}{7}(3\hat{i} - 6\hat{j} + 2\hat{k})$ ,  $\frac{1}{7}(6\hat{i} + 2\hat{j} - 3\hat{k})$ . Also, show that they are mutually perpendicular to each other.

**Solution:**

$$\mathbf{A} = \begin{pmatrix} \frac{2}{7} & \frac{3}{7} & \frac{6}{7} \\ \frac{3}{7} & -\frac{6}{7} & \frac{2}{7} \\ \frac{6}{7} & \frac{2}{7} & -\frac{3}{7} \end{pmatrix} \quad (2.3.4.1)$$

is an orthogonal matrix satisfying (2.1.6.1), which verifies the given conditions.

2.3.5 Show that the vectors  $2\hat{i} - \hat{j} + \hat{k}$ ,  $\hat{i} - 3\hat{j} - 5\hat{k}$  and  $3\hat{i} - 4\hat{j} - 4\hat{k}$  from the vertices of a right angled triangle.

**Solution:**

$$\mathbf{A} = \begin{pmatrix} 2 \\ -1 \\ 1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 1 \\ -3 \\ -5 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} 3 \\ -4 \\ -4 \end{pmatrix}, \quad (2.3.5.1)$$

$$\Rightarrow \mathbf{B} - \mathbf{C} = \begin{pmatrix} -2 \\ 1 \\ -1 \end{pmatrix}, \mathbf{C} - \mathbf{A} = \begin{pmatrix} 1 \\ -3 \\ -5 \end{pmatrix}, \quad (2.3.5.2)$$

$$\text{or, } (\mathbf{B} - \mathbf{C})^\top (\mathbf{C} - \mathbf{A}) = 0 \quad (2.3.5.3)$$

2.3.6 Show that the points **A**, **B** and **C** with position vectors,  $3\hat{i} - 4\hat{j} - 4\hat{k}$ ,  $2\hat{i} - \hat{j} + \hat{k}$  and  $\hat{i} - 3\hat{j} - 5\hat{k}$ , respectively, form the vertices of a right angled triangle.

**Solution:**

$$\mathbf{B} - \mathbf{A} = \begin{pmatrix} -1 \\ 3 \\ 5 \end{pmatrix}, \mathbf{C} - \mathbf{B} = \begin{pmatrix} -1 \\ -2 \\ -6 \end{pmatrix}, \mathbf{C} - \mathbf{A} = \begin{pmatrix} -2 \\ 1 \\ -1 \end{pmatrix}, \quad (2.3.6.1)$$

$$\Rightarrow (\mathbf{B} - \mathbf{A})^\top (\mathbf{C} - \mathbf{A}) = 0 \quad (2.3.6.2)$$

Hence,  $\triangle ABC$  is right angled at  $\mathbf{A}$ .

2.3.7 Let  $\mathbf{a} = \hat{i} + 4\hat{j} + 2\hat{k}$ ,  $\mathbf{b} = 3\hat{i} - 2\hat{j} + 7\hat{k}$  and  $\mathbf{c} = 2\hat{i} - \hat{j} + 4\hat{k}$ . Find a vector  $\mathbf{d}$  which is perpendicular to both  $\mathbf{a}$  and  $\mathbf{b}$ , and  $\mathbf{c} \cdot \mathbf{d} = 15$ .

**Solution:** From the given information,

$$\mathbf{a}^\top \mathbf{d} = 0 \quad (2.3.7.1)$$

$$\mathbf{b}^\top \mathbf{d} = 0 \quad (2.3.7.2)$$

$$\mathbf{c}^\top \mathbf{d} = 15 \quad (2.3.7.3)$$

yielding

$$\begin{pmatrix} \mathbf{a}^\top \\ \mathbf{b}^\top \\ \mathbf{c}^\top \end{pmatrix} \mathbf{d} = \begin{pmatrix} 0 \\ 0 \\ 15 \end{pmatrix} \quad (2.3.7.4)$$

$$\Rightarrow \begin{pmatrix} 1 & 4 & 2 \\ 3 & -2 & 7 \\ 2 & -1 & 4 \end{pmatrix} \mathbf{d} = \begin{pmatrix} 0 \\ 0 \\ 15 \end{pmatrix} \quad (2.3.7.5)$$

Forming the augmented matrix,

$$\begin{pmatrix} 1 & 4 & 2 & | & 0 \\ 3 & -2 & 7 & | & 0 \\ 2 & -1 & 4 & | & 15 \end{pmatrix} \xrightarrow[R_3 \leftarrow R_3 - 2R_1]{R_2 \leftarrow R_2 - 3R_1} \begin{pmatrix} 1 & 4 & 2 & | & 0 \\ 0 & -14 & 1 & | & 0 \\ 0 & -9 & 0 & | & 15 \end{pmatrix} \xrightarrow{R_3 \leftarrow R_3 - \frac{9}{14}R_2} \begin{pmatrix} 1 & 4 & 2 & | & 0 \\ 0 & -14 & 1 & | & 0 \\ 0 & 0 & -\frac{9}{14} & | & 15 \end{pmatrix} \quad (2.3.7.6)$$

yielding

$$\mathbf{d} = \begin{pmatrix} \frac{160}{3} \\ -\frac{5}{3} \\ -\frac{70}{3} \end{pmatrix} \quad (2.3.7.7)$$

upon back substitution.

2.3.8  $ABCD$  is a rectangle formed by the points  $\mathbf{A}(-1, -1)$ ,  $\mathbf{B}(-1, 4)$ ,  $\mathbf{C}(5, 4)$  and  $\mathbf{D}(5, -1)$ .  $\mathbf{P}, \mathbf{Q}, \mathbf{R}$  and  $\mathbf{S}$  are the mid-points of  $AB, BC, CD$  and  $DA$  respectively. Is the quadrilateral  $PQRS$  a square? a rectangle? or a rhombus? Justify your answer.

**Solution:** See Fig. 2.3.8.1. From (1.1.5.3),  $PQRS$  is a parallelogram.

$$\mathbf{P} = \frac{3}{2}, \mathbf{Q} = \begin{pmatrix} 2 \\ 4 \end{pmatrix}, \mathbf{R} = \begin{pmatrix} 5 \\ \frac{3}{2} \end{pmatrix}, \mathbf{S} = \begin{pmatrix} 2 \\ -1 \end{pmatrix} \quad (2.3.8.1)$$

$$\Rightarrow (\mathbf{Q} - \mathbf{P})^\top (\mathbf{R} - \mathbf{Q}) \neq 0 \quad (2.3.8.2)$$

$$(\mathbf{R} - \mathbf{P})^\top (\mathbf{S} - \mathbf{Q}) = 0 \quad (2.3.8.3)$$

Therefore  $PQRS$  is a rhombus.

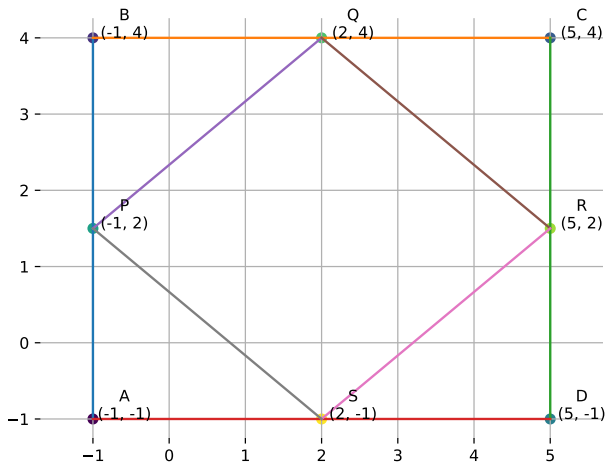


Fig. 2.3.8.1

2.3.9 Without using the Baudhayana theorem, show that the points  $\mathbf{A}(4, 4)$ ,  $\mathbf{B}(3, 5)$  and  $\mathbf{C}(-1, -1)$  are the vertices of a right angled triangle.

**Solution:** See Fig. 2.3.9.1.

$$\mathbf{C} - \mathbf{A} = \begin{pmatrix} -5 \\ -5 \end{pmatrix}, \mathbf{A} - \mathbf{B} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (2.3.9.1)$$

$$\Rightarrow (\mathbf{C} - \mathbf{A})^\top (\mathbf{A} - \mathbf{B}) = 0 \quad (2.3.9.2)$$

Thus,  $AB \perp AC$ .

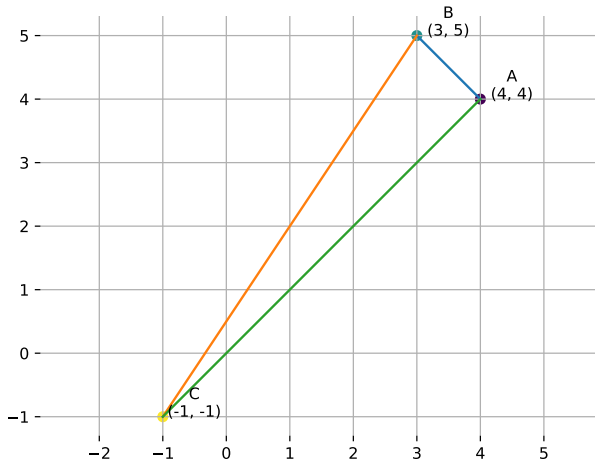


Fig. 2.3.9.1

2.3.10 In the following cases, determine whether the given planes are parallel or perpendicular, and in case they are neither, find the angles between them.

- a)  $7x + 5y + 6z + 30 = 0$  and  $3x - y - 10z + 4 = 0$
- b)  $2x + y + 3z - 2 = 0$  and  $x - 2y + 5 = 0$
- c)  $2x - 2y + 4z + 5 = 0$  and  $3x - 3y + 6z - 1 = 0$
- d)  $2x - y + 3z - 1 = 0$  and  $2x - y + 3z + 3 = 0$
- e)  $4x + 8y + z - 8 = 0$  and  $y + z - 4 = 0$

**Solution:** See Table 2.3.10.



TABLE 2.3.10

$\mathbf{n}_1$	$\mathbf{n}_1$	$\mathbf{n}_1^\top \mathbf{n}_2$	$\ \mathbf{n}_1\ $	$\ \mathbf{n}_2\ $	Angle
$\begin{pmatrix} 7 \\ 5 \\ 6 \end{pmatrix}$	$\begin{pmatrix} 3 \\ -1 \\ -10 \end{pmatrix}$	-44	$\sqrt{110}$	$\sqrt{110}$	$\cos^{-1} -\frac{2}{5}$
$\begin{pmatrix} 2 \\ 1 \\ 3 \end{pmatrix}$	$\begin{pmatrix} 1 \\ -2 \\ 0 \end{pmatrix}$	0			perpendicular
$\begin{pmatrix} 2 \\ -2 \\ 4 \end{pmatrix}$	$\begin{pmatrix} 3 \\ -3 \\ 6 \end{pmatrix}$	36	$\sqrt{24}$	$\sqrt{54}$	parallel
$\begin{pmatrix} 2 \\ -1 \\ 3 \end{pmatrix}$	$\begin{pmatrix} 2 \\ -1 \\ 3 \end{pmatrix}$	14	$\sqrt{14}$	$\sqrt{14}$	parallel
$\begin{pmatrix} 4 \\ 8 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 1 \\ 1 \end{pmatrix}$	9	9	$\sqrt{2}$	$45^\circ$

2.3.11 Show that the line joining the origin to the point  $\mathbf{P}(2, 1, 1)$  is perpendicular to the line determined by the points  $\mathbf{A}(3, 5, -1)$ ,  $\mathbf{B}(4, 3, -1)$ .

**Solution:**

$$(\mathbf{A} - \mathbf{B})^\top \mathbf{P} = \begin{pmatrix} -1 & 2 & 0 \end{pmatrix} \begin{pmatrix} 2 \\ 1 \\ 1 \end{pmatrix} = 0 \quad \square \quad (2.3.11.1)$$

2.3.12 Find a unit vector perpendicular to each of the vectors  $\vec{a} + \vec{b}$  and  $\vec{a} - \vec{b}$ , where  $\vec{a} = 3\hat{i} + 2\hat{j} + 2\hat{k}$  and  $\vec{b} = \hat{i} + 2\hat{j} - 2\hat{k}$ .

**Solution:** Let the desired vector be  $\mathbf{x}$ . Then,

$$(\mathbf{a} + \mathbf{b} \quad \mathbf{a} - \mathbf{b})^\top \mathbf{x} = 0 \quad (2.3.12.1)$$

$$(2.3.12.2)$$

$$\therefore \mathbf{a} + \mathbf{b} = \begin{pmatrix} \mathbf{a} & \mathbf{b} \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (2.3.12.3)$$

$$\mathbf{a} - \mathbf{b} = \begin{pmatrix} \mathbf{a} & \mathbf{b} \end{pmatrix} \begin{pmatrix} 1 \\ -1 \end{pmatrix}, \quad (2.3.12.4)$$

(2.3.12.2) can be expressed as

$$\left\{ \begin{pmatrix} \mathbf{a} & \mathbf{b} \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \right\}^T \mathbf{x} = 0 \quad (2.3.12.5)$$

$$\Rightarrow \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}^T \begin{pmatrix} \mathbf{a} & \mathbf{b} \end{pmatrix}^T \mathbf{x} = 0 \quad (2.3.12.6)$$

$$\Rightarrow \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}^T \begin{pmatrix} \mathbf{a} & \mathbf{b} \end{pmatrix}^T \mathbf{x} = 0 \quad (2.3.12.7)$$

$$\text{or, } \begin{pmatrix} \mathbf{a} & \mathbf{b} \end{pmatrix}^T \mathbf{x} = 0 \quad (2.3.12.8)$$

which can be expressed as

$$\begin{pmatrix} 3 & 2 & 2 \\ 1 & 2 & -2 \end{pmatrix} \xrightarrow[R_2 = \frac{R_2}{4}]{R_2 = 3R_2 - R_1} \begin{pmatrix} 3 & 2 & 2 \\ 0 & 1 & -2 \end{pmatrix} \quad (2.3.12.9)$$

$$\xrightarrow[R_1 = \frac{R_1}{3}]{R_1 = R_1 - 2R_2} \begin{pmatrix} 1 & 0 & 2 \\ 0 & 1 & -2 \end{pmatrix} \quad (2.3.12.10)$$

yielding

$$\begin{aligned} x_1 + 2x_3 &= 0 \\ x_2 - 2x_3 &= 0 \end{aligned} \Rightarrow \mathbf{x} = x_3 \begin{pmatrix} -2 \\ 2 \\ 1 \end{pmatrix} \quad (2.3.12.11)$$

Thus, the desired unit vector is

$$\mathbf{x} = \frac{1}{3} \begin{pmatrix} -2 \\ 2 \\ 1 \end{pmatrix} \quad (2.3.12.12)$$

2.3.13 If  $\vec{a} = 2\hat{i} + 2\hat{j} + 3\hat{k}$ ,  $\vec{b} = -\hat{i} + 2\hat{j} + \hat{k}$  and  $\vec{c} = 3\hat{i} + \hat{j}$  are such that  $\vec{a} + \lambda\vec{b}$  is perpendicular to  $\vec{c}$ , then find the value of  $\lambda$ .

**Solution:**

$$\therefore (\mathbf{a} + \lambda\mathbf{b})^T \mathbf{c} = 0, \quad (2.3.13.1)$$

$$\lambda = -\frac{\mathbf{a}^T \mathbf{c}}{\mathbf{b}^T \mathbf{c}} = 8, \quad (2.3.13.2)$$

upon substituting numerical values.

2.3.14 Check whether (5, -2), (6, 4) and (7, -2) are the vertices of an isosceles triangle.

2.3.15 The perpendicular bisector of the line segment joining the points **A**(1, 5) and **B**(4, 6) cuts the y-axis at

2.3.16 The point which lies on the perpendicular bisector of the line segment joining the points **A**(-2, -5) and **B**(2, 5) is

- a) (0, 0)
- b) (0, 2)
- c) (2, 0)
- d) (-2, 0)

- 2.3.17 The points  $(-4, 0)$ ,  $(4, 0)$ ,  $(0, 3)$  are the vertices of
- right triangle
  - isosceles triangle
  - equilateral triangle
  - scalene triangle
- 2.3.18 The point  $A(2, 7)$  lies on the perpendicular bisector of line segment joining the points  $P(6, 5)$  and  $Q(0, -4)$ .
- 2.3.19 The points  $A(-1, -2)$ ,  $B(4, 3)$ ,  $C(2, 5)$  and  $D(-3, 0)$  in that order form a rectangle.
- 2.3.20 Name the type of triangle formed by the points  $A(-5, 6)$ ,  $B(-4, -2)$ , and  $C(7, 5)$ .
- 2.3.21 What type of a quadrilateral do the points  $A(2, -2)$ ,  $B(7, 3)$ ,  $C(11, -1)$ , and  $D(6, -6)$  taken in that order, form?
- 2.3.22 Find the coordinates of the point  $Q$  on the  $x$ -axis which lies on the perpendicular bisector of the line segment joining the points  $A(-5, -2)$  and  $B(4, -2)$ . Name the type of triangle formed by points  $Q$ ,  $A$  and  $B$ .
- 2.3.23 The points  $A(2, 9)$ ,  $B(a, 5)$  and  $C(5, 5)$  are the vertices of a triangle  $ABC$  right angled at  $B$ . Find the values of  $a$  and hence the area of  $\triangle ABC$ .
- 2.3.24 Find a vector of magnitude 6, which is perpendicular to both the vectors  $2\hat{i} - \hat{j} + 2\hat{k}$  and  $4\hat{i} - \hat{j} + 3\hat{k}$ .
- 2.3.25 If  $A, B, C, D$  are the points with position vectors  $\hat{i} + \hat{j} - \hat{k}$ ,  $2\hat{i} - \hat{j} + 3\hat{k}$ ,  $2\hat{i} - 3\hat{k}$ ,  $3\hat{i} - 2\hat{j} + \hat{k}$ , respectively, find the projection of  $\overrightarrow{AB}$  along  $\overrightarrow{CD}$ .
- 2.3.26 Find the value of  $\lambda$  such that the vectors  $\mathbf{a} = 2\hat{i} + \lambda\hat{j} + \hat{k}$  and  $\mathbf{b} = \hat{i} + 2\hat{j} + 3\hat{k}$  are orthogonal.
- 2.3.27 The number of vectors of unit length perpendicular to the vectors  $\mathbf{a} = 2\hat{i} + \hat{j} + 2\hat{k}$  and  $\mathbf{b} = \hat{j} + \hat{k}$  is
- 2.3.28 Find the equation of a plane which bisects perpendicularly the line joining the points  $A(2, 3, 4)$  and  $B(4, 5, 8)$  at right angles.
- 2.3.29  $\overrightarrow{AB} = 3\hat{i} - \hat{j} + \hat{k}$  and  $\overrightarrow{CD} = -3\hat{i} + 2\hat{j} + 4\hat{k}$  are two vectors. The position vectors of the points  $A$  and  $C$  are  $6\hat{i} + 7\hat{j} + 4\hat{k}$  and  $-9\hat{j} + 2\hat{k}$ , respectively. Find the position vector of a point  $P$  on the line  $AB$  and a point  $Q$  on the line  $CD$  such that  $\overrightarrow{PQ}$  is perpendicular to  $\overrightarrow{AB}$  and  $\overrightarrow{CD}$  both.
- 2.3.30 Line joining the points  $(3, -4)$  and  $(-2, 6)$  is perpendicular to the line joining the points  $(-3, 6)$  and  $(9, -18)$ .
- 2.3.31 Verify the following:
- $(0, 7, -10)$ ,  $(1, 6, -6)$  and  $(4, 9, -6)$  are the vertices of an isosceles triangle.
  - $(0, 7, 10)$ ,  $(-1, 6, 6)$  and  $(-4, 9, 6)$  are the vertices of a right angled triangle.
- 2.3.32 Show that the line through the points  $(1, -1, 2)$ ,  $(3, 4, -2)$  is perpendicular to the line through the points  $(0, 3, 2)$  and  $(3, 5, 6)$ .
- 2.3.33 Find the values of  $p$  so that the lines  $\frac{1-x}{3} = \frac{7y-14}{2p} = \frac{z-3}{2}$  and  $\frac{7-7x}{3p} = \frac{y-5}{1} = \frac{6-z}{5}$  are at right angles.
- 2.3.34 Show that the lines  $\frac{x-5}{7} = \frac{y+2}{-5} = \frac{z}{1}$  and  $\frac{x}{1} = \frac{y}{2} = \frac{z}{3}$  are perpendicular to each other.
- 2.3.35 Do the points  $(3, 2)$ ,  $(-2, -3)$  and  $(2, 3)$  form a triangle? If so, name the type of triangle formed.
- 2.3.36 Show that the points  $(1, 7)$ ,  $(4, 2)$ ,  $(-1, -1)$  and  $(-4, 4)$  are the vertices of a square.
- 2.3.37 Line through the points  $(-2, 6)$  and  $(4, 8)$  is perpendicular to the line through the

points  $(8, 12)$  and  $(x, 24)$ . Find the value of  $x$ .

2.3.38 Find the angle between the lines  $y - \sqrt{3}x - 5 = 0$  and  $\sqrt{3}y - x + 6 = 0$ .

2.3.39 Are the points  $\mathbf{A}(3, 6, 9)$ ,  $\mathbf{B}(10, 20, 30)$  and  $\mathbf{C}(24, -41, 5)$  the vertices of a right angled triangle?

2.3.40 Show that the points  $\mathbf{A}(1, 2, 3)$ ,  $\mathbf{B}(-1, -2, -1)$ ,  $\mathbf{C}(2, 3, 2)$  and  $\mathbf{D}(4, 7, 6)$  are the vertices of a parallelogram  $ABCD$ , but it is not a rectangle.

2.3.41 Show that the points  $\mathbf{A}(2\hat{i} - \hat{j} + \hat{k})$ ,  $\mathbf{B}(\hat{i} - 3\hat{j} - 5\hat{k})$ ,  $\mathbf{C}(3\hat{i} - 4\hat{j} - 4\hat{k})$  are the vertices of a right angled triangle.

2.3.42 If  $\vec{a} = 5\hat{i} - \hat{j} - 3\hat{k}$  and  $\vec{b} = \hat{i} + 3\hat{j} - 5\hat{k}$ , then show that the vectors  $\vec{a} + \vec{b}$  and  $\vec{a} - \vec{b}$  are perpendicular.

2.3.43 Find the projection of the vector  $\vec{a} = 2\hat{i} + 3\hat{j} + 2\hat{k}$  on the vector  $\vec{b} = \hat{i} + 2\hat{j} + \hat{k}$ .

2.3.44 Find a unit vector perpendicular to each of the vectors  $(\vec{a} + \vec{b})$  and  $(\vec{a} - \vec{b})$ , where  $\vec{a} = \hat{i} + \hat{j} + \hat{k}$ ,  $\vec{b} = \hat{i} + 2\hat{j} + 3\hat{k}$ .

## 2.4 Vector Product

2.4.1 Find  $|\vec{a} \times \vec{b}|$ , if  $\vec{a} = \hat{i} - 7\hat{j} + 7\hat{k}$  and  $\vec{b} = 3\hat{i} - 2\hat{j} + 2\hat{k}$ .

**Solution:** From (2.1.8.3),

$$|\mathbf{A}_{23} \quad \mathbf{B}_{23}| = \begin{vmatrix} -7 & -2 \\ 7 & 2 \end{vmatrix} = 0 \quad (2.4.1.1)$$

$$|\mathbf{A}_{31} \quad \mathbf{B}_{31}| = \begin{vmatrix} 1 & 3 \\ 7 & 2 \end{vmatrix} = -19 \quad (2.4.1.2)$$

$$|\mathbf{A}_{12} \quad \mathbf{B}_{12}| = \begin{vmatrix} 1 & 3 \\ -7 & -2 \end{vmatrix} = 19, \quad (2.4.1.3)$$

$$\|\mathbf{a} \times \mathbf{b}\| = \left\| \begin{pmatrix} |\mathbf{A}_{23} \quad \mathbf{B}_{23}| \\ |\mathbf{A}_{31} \quad \mathbf{B}_{31}| \\ |\mathbf{A}_{12} \quad \mathbf{B}_{12}| \end{pmatrix} \right\| = 19\sqrt{2} \quad (2.4.1.4)$$

from (2.1.9.1).

2.4.2 Find  $\lambda$  and  $\mu$  if  $(2\hat{i} + 6\hat{j} + 27\hat{k}) \times (\hat{i} + \lambda\hat{j} + \mu\hat{k}) = \vec{0}$ .

**Solution:** From Formula 2.1.11, performing row reduction,

$$\begin{pmatrix} 2 & 6 & 27 \\ 1 & \lambda & \mu \end{pmatrix} \xrightarrow{R_2 \leftarrow 2R_2 - R_1} \begin{pmatrix} 2 & 6 & 27 \\ 0 & 2\lambda - 6 & 2\mu - 27 \end{pmatrix} \quad (2.4.2.1)$$

For the above matrix to have rank 1,

$$\mu = \frac{27}{2}, \lambda = 3. \quad (2.4.2.2)$$

2.4.3 Find the area of the triangle with vertices  $A(1, 1, 2)$ ,  $B(2, 3, 5)$  and  $C(1, 5, 5)$ .

**Solution:**

$$\therefore \mathbf{B} - \mathbf{A} = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix}, \mathbf{C} - \mathbf{A} = \begin{pmatrix} 0 \\ 4 \\ 3 \end{pmatrix}, \quad (2.4.3.1)$$

$$\frac{1}{2} \left\| \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} \times \begin{pmatrix} 0 \\ 4 \\ 3 \end{pmatrix} \right\| = \frac{1}{2} \left\| \begin{pmatrix} -6 \\ 3 \\ 4 \end{pmatrix} \right\| = \frac{\sqrt{61}}{2} \quad (2.4.3.2)$$

using (2.1.13.2), which is the the desired area.

2.4.4 Find the area of the parallelogram whose adjacent sides are determined by the vectors  $\vec{a} = \hat{i} - \hat{j} + 3\hat{k}$  and  $\vec{b} = 2\hat{i} - 7\hat{j} + \hat{k}$ .

**Solution:** From (2.1.14.1), the desired area is obtained as

$$\left\| \begin{pmatrix} 1 \\ -1 \\ 3 \end{pmatrix} \times \begin{pmatrix} 2 \\ -7 \\ 1 \end{pmatrix} \right\| = \left\| \begin{pmatrix} 20 \\ 5 \\ -5 \end{pmatrix} \right\| = 15\sqrt{2} \quad (2.4.4.1)$$

2.4.5 Find the area of a rhombus if its vertices are  $A(3, 0)$ ,  $B(4, 5)$ ,  $C(-1, 4)$  and  $D(-2, -1)$  taken in order.

**Solution:** The area of the rhombus is

$$\left\| (\mathbf{A} - \mathbf{D}) \times (\mathbf{B} - \mathbf{A}) \right\| = \left| \begin{vmatrix} 5 & 1 \\ 1 & 5 \end{vmatrix} \right| = 24 \quad (2.4.5.1)$$

2.4.6 Let the vectors  $\vec{a}$  and  $\vec{b}$  be such that  $|\vec{a}| = 3$  and  $|\vec{b}| = \frac{\sqrt{2}}{3}$ , then  $\vec{a} \times \vec{b}$  is a unit vector, if the angle between  $\vec{a}$  and  $\vec{b}$  is

- a)  $\frac{\pi}{6}$   
b)  $\frac{\pi}{4}$

- c)  $\frac{\pi}{3}$   
d)  $\frac{\pi}{2}$

**Solution:** From the given information and (2.1.12.1)

$$\|\mathbf{a} \times \mathbf{b}\| = \|\mathbf{a}\| \|\mathbf{b}\| \sin \theta = 1 \quad (2.4.6.1)$$

$$\Rightarrow \sin \theta = \frac{1}{\|\mathbf{a}\| \|\mathbf{b}\|} = \frac{1}{\sqrt{2}} \quad (2.4.6.2)$$

$$\Rightarrow \theta = \frac{\pi}{4} \quad (2.4.6.3)$$

2.4.7 Area of a rectangle having vertices A, B, C and D with position vectors  $-\hat{i} + \frac{1}{2}\hat{j} + 4\hat{k}$ ,  $\hat{i} + \frac{1}{2}\hat{j} + 4\hat{k}$ ,  $\hat{i} - \frac{1}{2}\hat{j} + 4\hat{k}$  and  $-\hat{i} - \frac{1}{2}\hat{j} + 4\hat{k}$ , respectively is

**Solution:** Since

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} -2 \\ 0 \\ 0 \end{pmatrix} \quad (2.4.7.1)$$

$$\mathbf{C} - \mathbf{B} = \begin{pmatrix} 0 \\ -1 \\ 0 \end{pmatrix} \quad (2.4.7.2)$$

area of the rectangle is

$$\|(\mathbf{A} - \mathbf{B}) \times (\mathbf{C} - \mathbf{B})\| = 2 \quad (2.4.7.3)$$

2.4.8 Find the area of the triangle whose vertices are

a)  $(2, 3), (-1, 0), (2, -4)$

b)  $(-5, -1), (3, -5), (5, 2)$

**Solution:** See Table 2.4.8.

TABLE 2.4.8

	$\mathbf{A} - \mathbf{B}$	$\mathbf{A} - \mathbf{C}$	$\frac{1}{2} \ (\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C})\ $
a)	$\begin{pmatrix} 3 \\ 3 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 7 \end{pmatrix}$	$\frac{21}{2}$
b)	$\begin{pmatrix} -8 \\ 4 \end{pmatrix}$	$\begin{pmatrix} -10 \\ -3 \end{pmatrix}$	32

2.4.9 Find the area of the triangle formed by joining the mid-points of the sides of the triangle whose vertices are  $A(0, -1), B(2, 1)$  and  $C(0, 3)$ . Find the ratio of this area to the area of the given triangle.

**Solution:** Using (1.1.4.1), the mid point coordinates are given by

$$\mathbf{P} = \frac{1}{2}(\mathbf{A} + \mathbf{B}) = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (2.4.9.1)$$

$$\mathbf{Q} = \frac{1}{2}(\mathbf{B} + \mathbf{C}) = \begin{pmatrix} 1 \\ 2 \end{pmatrix} \quad (2.4.9.2)$$

$$\mathbf{R} = \frac{1}{2}(\mathbf{A} + \mathbf{C}) = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (2.4.9.3)$$

$$\therefore \mathbf{P} - \mathbf{Q} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, \mathbf{Q} - \mathbf{R} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (2.4.9.4)$$

$$ar(PQR) = \frac{1}{2} \|(\mathbf{P} - \mathbf{Q}) \times (\mathbf{Q} - \mathbf{R})\| = 1 \quad (2.4.9.5)$$

Similarly,

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} -2 \\ -2 \end{pmatrix}, \mathbf{A} - \mathbf{C} = \begin{pmatrix} 0 \\ -4 \end{pmatrix} \quad (2.4.9.6)$$

$$\Rightarrow \text{ar}(ABC) = \frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C})\| = 4 \quad (2.4.9.7)$$

$$\Rightarrow \frac{\text{ar}(PQR)}{\text{ar}(ABC)} = \frac{1}{4} \quad (2.4.9.8)$$

See Fig. 2.4.9.1

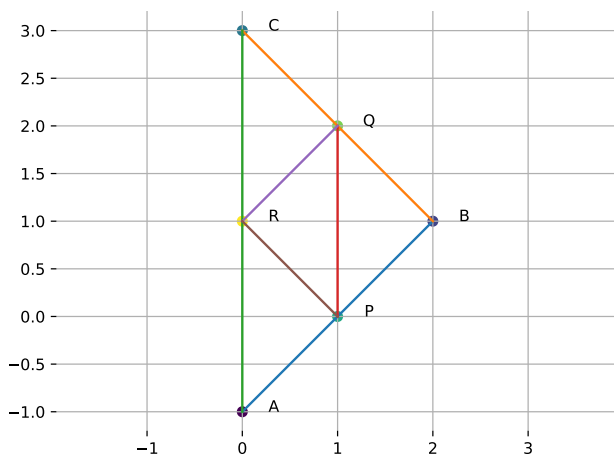


Fig. 2.4.9.1

2.4.10 Find the area of the quadrilateral whose vertices, taken in order, are  $A(-4, -2)$ ,  $B(-3, -5)$ ,  $C(3, -2)$  and  $D(2, 3)$ .

**Solution:** See Fig. 2.4.10.1

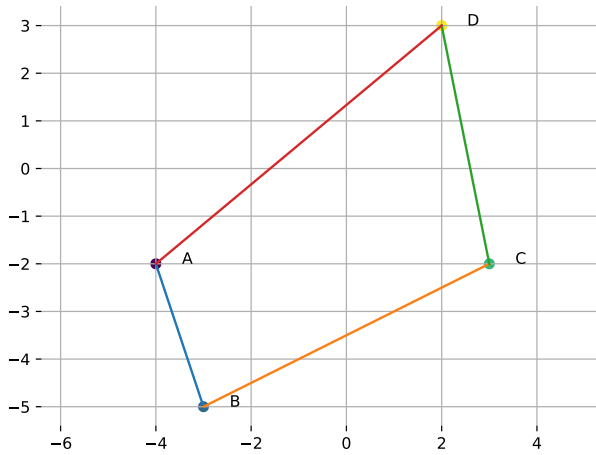


Fig. 2.4.10.1

$$\because \mathbf{A} - \mathbf{B} = \begin{pmatrix} -1 \\ 3 \end{pmatrix}, \mathbf{A} - \mathbf{D} = \begin{pmatrix} -6 \\ -5 \end{pmatrix}, \quad (2.4.10.1)$$

$$\mathbf{B} - \mathbf{C} = \begin{pmatrix} -6 \\ -5 \end{pmatrix}, \mathbf{B} - \mathbf{D} = \begin{pmatrix} -3 \\ -8 \end{pmatrix}, \quad (2.4.10.2)$$

$$ar(ABD) = \frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{D})\| = \frac{23}{2} \quad (2.4.10.3)$$

$$ar(BCD) = \frac{1}{2} \|(\mathbf{B} - \mathbf{C}) \times (\mathbf{B} - \mathbf{D})\| = \frac{33}{2} \quad (2.4.10.4)$$

$$\Rightarrow ar(ABCD) = ar(ABD) + ar(BCD) = 28 \quad (2.4.10.5)$$

2.4.11 Verify that a median of a triangle divides it into two triangles of equal areas for  $\triangle ABC$  whose vertices are  $\mathbf{A}(4, -6)$ ,  $\mathbf{B}(3, 2)$ , and  $\mathbf{C}(5, 2)$ .



**Solution:**

$$\mathbf{D} = \frac{\mathbf{B} + \mathbf{C}}{2} = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \quad (2.4.11.1)$$

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} 1 \\ -4 \end{pmatrix}, \mathbf{A} - \mathbf{D} = \begin{pmatrix} 0 \\ -6 \end{pmatrix} \quad (2.4.11.2)$$

$$\Rightarrow \text{ar}(ABD) = \frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{D})\| = 3 \quad (2.4.11.3)$$

$$\mathbf{A} - \mathbf{C} = \begin{pmatrix} -1 \\ -8 \end{pmatrix}, \mathbf{A} - \mathbf{D} = \begin{pmatrix} 0 \\ -6 \end{pmatrix} \quad (2.4.11.4)$$

$$\Rightarrow \text{ar}(ACD) = \frac{1}{2} \|(\mathbf{A} - \mathbf{C}) \times (\mathbf{A} - \mathbf{D})\| \quad (2.4.11.5)$$

$$= 3 = \text{ar}(ABD) \quad (2.4.11.6)$$

See Fig. 2.4.11.1.

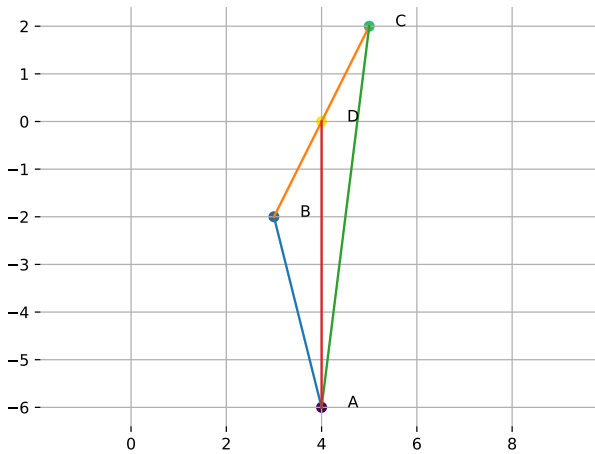


Fig. 2.4.11.1

2.4.12 The two adjacent sides of a parallelogram are  $\mathbf{a} = 2\hat{i} - 4\hat{j} + 5\hat{k}$  and  $\mathbf{b} = \hat{i} - 2\hat{j} - 3\hat{k}$ . Find the unit vector parallel to its diagonal. Also, find its area.

**Solution:** The diagonals of the parallelogram are given by

$$\mathbf{a} + \mathbf{b} = \begin{pmatrix} 3 \\ -6 \\ 2 \end{pmatrix}, \mathbf{a} - \mathbf{b} = \begin{pmatrix} 1 \\ -2 \\ 8 \end{pmatrix} \quad (2.4.12.1)$$

and the corresponding unit vectors are

$$\frac{\mathbf{a} + \mathbf{b}}{\|\mathbf{a} + \mathbf{b}\|} = \begin{pmatrix} \frac{3}{\sqrt{45}} \\ -\frac{6}{\sqrt{45}} \\ \frac{2}{\sqrt{45}} \end{pmatrix}, \quad \frac{\mathbf{a} - \mathbf{b}}{\|\mathbf{a} - \mathbf{b}\|} = \begin{pmatrix} \frac{1}{\sqrt{69}} \\ -\frac{2}{\sqrt{69}} \\ \frac{8}{\sqrt{69}} \end{pmatrix} \quad (2.4.12.2)$$

The area of the parallelogram is given by

$$\|\mathbf{a} \times \mathbf{b}\| = \left\| \begin{pmatrix} 22 \\ -11 \\ 0 \end{pmatrix} \right\| = \sqrt{605} \quad (2.4.12.3)$$

2.4.13 The vertices of a  $\triangle ABC$  are  $\mathbf{A}(4, 6)$ ,  $\mathbf{B}(1, 5)$  and  $\mathbf{C}(7, 2)$ . A line is drawn to intersect sides  $AB$  and  $AC$  at  $\mathbf{D}$  and  $\mathbf{E}$  respectively, such that  $\frac{AD}{AB} = \frac{AE}{AC} = \frac{1}{4}$ . Calculate the area of  $\triangle ADE$  and compare it with the area of the  $\triangle ABC$ .

**Solution:** See Fig. 2.4.13.1.

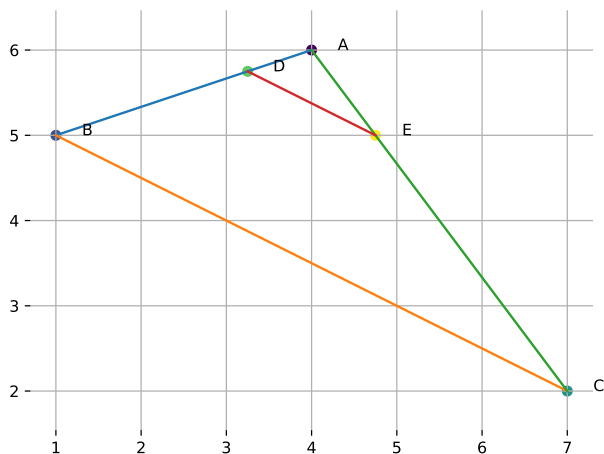


Fig. 2.4.13.1

Using section formula (1.1.4.1),

$$\mathbf{D} = \frac{3\mathbf{A} + \mathbf{B}}{4} = \frac{1}{4} \begin{pmatrix} 13 \\ 23 \end{pmatrix} \quad (2.4.13.1)$$

$$\mathbf{E} = \frac{3\mathbf{A} + \mathbf{C}}{4} = \frac{1}{4} \begin{pmatrix} 19 \\ 20 \end{pmatrix} \quad (2.4.13.2)$$

$$\mathbf{A} - \mathbf{D} = \frac{1}{4} \begin{pmatrix} 3 \\ 1 \end{pmatrix}, \mathbf{A} - \mathbf{E} = \frac{1}{4} \begin{pmatrix} -3 \\ 1 \end{pmatrix} \quad (2.4.13.3)$$

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} 3 \\ 1 \end{pmatrix}, \mathbf{B} - \mathbf{C} = \begin{pmatrix} -6 \\ 3 \end{pmatrix} \quad (2.4.13.4)$$

yielding

$$ar(ABD) = \frac{1}{2} \|(\mathbf{A} - \mathbf{D}) \times (\mathbf{A} - \mathbf{E})\| = \frac{15}{32} \quad (2.4.13.5)$$

$$ar(ABC) = \frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{B} - \mathbf{C})\| = \frac{15}{2} \quad (2.4.13.6)$$

$$\implies \frac{ar(ADE)}{ar(ABC)} = \frac{1}{16} \quad (2.4.13.7)$$

2.4.14 Draw a quadrilateral in the Cartesian plane, whose vertices are

$$\mathbf{A} = \begin{pmatrix} -4 \\ 5 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 0 \\ 7 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} 5 \\ -5 \end{pmatrix}, \mathbf{D} = \begin{pmatrix} -4 \\ -2 \end{pmatrix}. \quad (2.4.14.1)$$

Also, find its area.

**Solution:** See Fig. 2.4.14.1. From (2.1.13.2),

$$ar(ABCD) = \frac{121}{2} \quad (2.4.14.2)$$

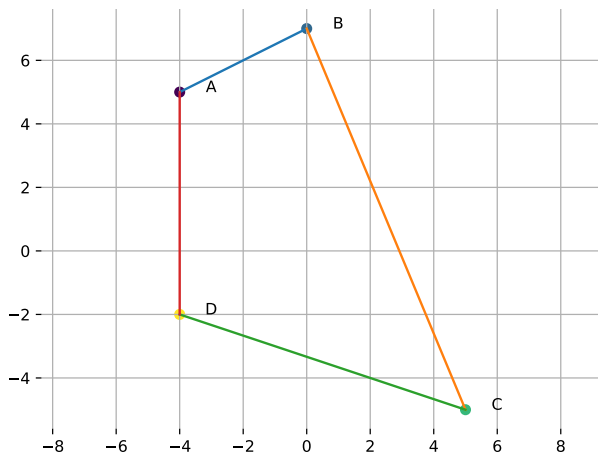


Fig. 2.4.14.1: Plot of quadrilateral  $ABCD$

- 2.4.15 Find the area of region bounded by the triangle whose vertices are  $(1, 0)$ ,  $(2, 2)$  and  $(3, 1)$ .
- 2.4.16 Find the area of region bounded by the triangle whose vertices are  $(-1, 0)$ ,  $(1, 3)$  and  $(3, 2)$ .
- 2.4.17 Find the area of the  $\triangle ABC$ , coordinates of whose vertices are  $A(2, 0)$ ,  $B(4, 5)$  and  $C(6, 3)$ .
- 2.4.18 The area of a triangle with vertices  $A(3, 0)$ ,  $B(7, 0)$  and  $C(8, 4)$  is
- 14
  - 28
  - 8
  - 6
- 2.4.19 Find the area of the triangle whose vertices are  $(-8, 4)$ ,  $(-6, 6)$  and  $(-3, 9)$ .
- 2.4.20 If  $D\left(-\frac{1}{2}, \frac{5}{2}\right)$ ,  $E(7, 3)$  and  $F\left(\frac{7}{2}, \frac{7}{2}\right)$  are the midpoints of sides of  $\triangle ABC$ , find the area of the  $\triangle ABC$ .
- 2.4.21 Find the sine of the angle between the vectors  $\mathbf{a} = 3\hat{i} + \hat{j} + 2\hat{k}$  and  $\mathbf{b} = 2\hat{i} - 2\hat{j} + 4\hat{k}$ .
- 2.4.22 Using vectors, find the area of  $\triangle ABC$  with vertices  $A(1, 2, 3)$ ,  $B(2, -1, 4)$  and  $C(4, 5, -1)$ .
- 2.4.23 Find the area of the parallelogram whose diagonals are  $2\hat{i} - \hat{j} + \hat{k}$  and  $\hat{i} + 3\hat{j} - \hat{k}$ .
- 2.4.24 The vector from origin to the points A and B are  $\mathbf{a} = 2\hat{i} - 3\hat{j} + 2\hat{k}$  and  $\mathbf{b} = 2\hat{i} + 3\hat{j} + \hat{k}$ , respectively, then the area of  $\triangle OAB$  is
- 340
  - $\sqrt{25}$
  - $\sqrt{229}$
  - $\frac{1}{2}\sqrt{229}$
- 2.4.25 If  $\mathbf{a} = \hat{i} + \hat{j} + \hat{k}$  and  $\mathbf{b} = \hat{j} - \hat{k}$ , find a vector  $\mathbf{c}$  such that  $\mathbf{a} \times \mathbf{c} = \mathbf{b}$  and  $\mathbf{a} \cdot \mathbf{c} = 3$ .

- 2.4.26 The area of the quadrilateral ABCD, where  $A(0, 4, 1)$ ,  $B(2, 3, -1)$ ,  $C(4, 5, 0)$  and  $D(2, 6, 2)$ , is equal to
- 9 sq. units
  - 18 sq. units
  - 27 sq. units
  - 81 sq. units
- 2.4.27 Find the area of region bounded by the triangle whose vertices are  $(-1, 1)$ ,  $(0, 5)$  and  $(3, 2)$ .
- 2.4.28 The value of  $\hat{i} \cdot (\hat{j} \times \hat{k}) + \hat{j} \cdot (\hat{i} \times \hat{k}) + \hat{k} \cdot (\hat{i} \times \hat{j})$  is
- 0
  - 1
  - 1
  - 3
- 2.4.29 The value of  $\hat{i} \cdot (\hat{j} \times \hat{k}) + \hat{j} \cdot (\hat{i} \times \hat{k}) + \hat{k} \cdot (\hat{i} \times \hat{j})$  is
- 0
  - 1
  - 1
  - 3
- 2.4.30 Find area of the triangle with vertices at the point given in each of the following:
- $(1, 0)$ ,  $(6, 0)$ ,  $(4, 3)$
  - $(2, 7)$ ,  $(1, 1)$ ,  $(10, 8)$
  - $(-2, -3)$ ,  $(3, 2)$ ,  $(-1, 8)$
- 2.4.31 If area of triangle is 35 square units with vertices  $(2, 6)$ ,  $(5, -4)$  and  $(k, 4)$ . Then  $k$  is:
- 12
  - 2
  - 12, -2
  - 12, -2
- 2.4.32 Find values of  $k$  if area of triangle is 4 square units and vertices are
- $(k, 0)$ ,  $(4, 0)$ ,  $(0, 2)$
  - $(-2, 0)$ ,  $(0, 4)$ ,  $(0, k)$
- 2.4.33 Find the area of the triangle whose vertices are  $(1, -1)$ ,  $(-4, 6)$  and  $(-3, 5)$ .
- 2.4.34 Find the area of a triangle formed by the points  $A(5, 2)$ ,  $B(4, 7)$  and  $(7, -4)$ .
- 2.4.35 Find the area of the triangle formed by the points  $P(-1.5, 3)$ ,  $Q(6, -2)$  and  $R(-3, 4)$ .
- 2.4.36 If  $A(-5, 7)$ ,  $B(-4, -5)$ ,  $C(-1, -6)$  and  $D(4, 5)$  are the vertices of a quadrilateral, find the area of quadrilateral ABCD.
- 2.4.37 Find the area of the triangle whose vertices are  $(3, 8)$ ,  $(-4, 2)$  and  $(5, 1)$ .
- 2.4.38 Find  $|\vec{a} \times \vec{b}|$ , if  $\vec{a} = 2\hat{i} + \hat{j} + 3\hat{k}$ , and  $\vec{b} = 3\hat{i} + 5\hat{j} - 2\hat{k}$ .
- 2.4.39 Find the area of a triangle having the points  $A(1, 1, 1)$ ,  $B(1, 2, 3)$  and  $C(2, 3, 1)$  as its vertices.
- 2.4.40 Find the area of a parallelogram whose adjacent sides are given by the vectors  $\vec{a} = 3\hat{i} + \hat{j} + 4\hat{k}$  and  $\vec{b} = \hat{i} - \hat{j} + \hat{k}$ .

## 2.5 Miscellaneous

2.5.1 The two opposite vertices of a square are  $\mathbf{A}(-1, 2)$  and  $\mathbf{C}(3, 2)$ . Find the coordinates of the other two vertices.

**Solution:**

$$\mathbf{C} - \mathbf{A} = \begin{pmatrix} 4 \\ 0 \end{pmatrix} \equiv \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \implies \phi = 0^\circ \quad (2.5.1.1)$$

where  $\phi$  is the angle made by  $AC$  with the x-axis. Also, the diagonal

$$d = \|\mathbf{C} - \mathbf{A}\| = 4 \quad (2.5.1.2)$$

a) We start with the square in Fig. 2.5.1.1, with vertices as columns of the matrix

$$\mathbf{y} = \frac{d}{\sqrt{2}} \begin{pmatrix} 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \end{pmatrix} \quad (2.5.1.3)$$

in (2.1.15.1).

b) The next square, obtained as

$$\mathbf{P}\mathbf{y}, \quad (2.5.1.4)$$

which is a rotated version of Fig. 2.5.1.1, is available in Fig. 2.5.1.2. The angle of rotation

$$\theta = \phi - \frac{\pi}{4} \quad (2.5.1.5)$$

c) The desired square is obtained using (2.1.15.1) as

$$\mathbf{x} = \mathbf{P}\mathbf{y} + \begin{pmatrix} \mathbf{A} & \mathbf{A} & \mathbf{A} & \mathbf{A} \end{pmatrix} = \begin{pmatrix} -1 & 1 & 3 & 1 \\ 2 & 0 & 2 & 4 \end{pmatrix} \quad (2.5.1.6)$$

and available in Fig. 2.5.1.3. The 2nd and 4th columns in the above matrix are  $\mathbf{B}$  and  $\mathbf{C}$  respectively.

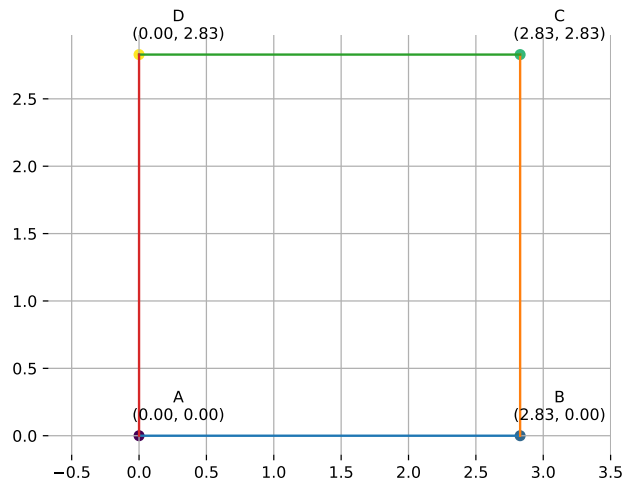


Fig. 2.5.1.1

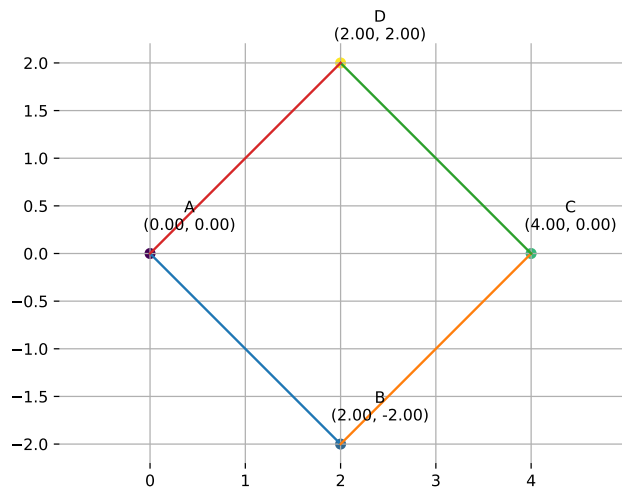


Fig. 2.5.1.2

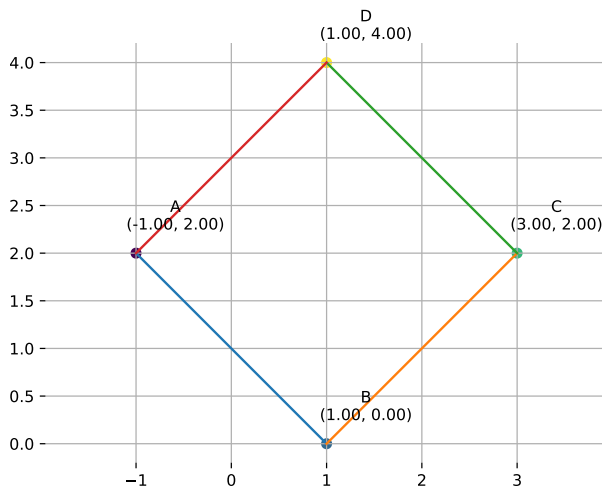
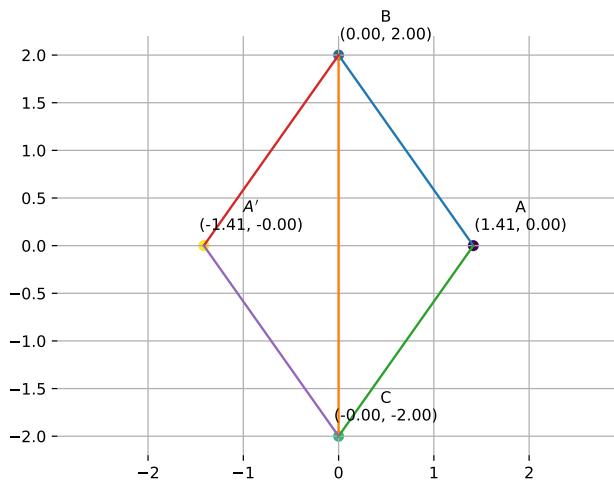


Fig. 2.5.1.3

2.5.2 The base of an equilateral triangle with side  $2a$  lies along the y-axis such that the mid-point of the base is at the origin. Find the vertices of the triangle.

**Solution:**

Fig. 2.5.2.1:  $a = 2$ .



See Fig. 2.5.2.1. Let the base be  $BC$ . From the given information,

$$\mathbf{B} = a\mathbf{e}_2, \mathbf{C} = -a\mathbf{e}_2 \quad (2.5.2.1)$$

Since  $\mathbf{A}$  lies on the  $x$ -axis,

$$\mathbf{A} = k\mathbf{e}_1 \quad (2.5.2.2)$$

and

$$\|\mathbf{A} - \mathbf{C}\|^2 = (2a)^2 \quad (2.5.2.3)$$

$$\Rightarrow \|\mathbf{A}\|^2 + \|\mathbf{C}\|^2 - 2\mathbf{A}^\top \mathbf{C} = 4a^2 \quad (2.5.2.4)$$

$$\Rightarrow k^2 + a^2 = 4a^2 \quad (2.5.2.5)$$

yielding

$$k = \pm a\sqrt{3} \quad (2.5.2.6)$$

Thus,

$$\mathbf{A} = \pm \sqrt{3}a\mathbf{e}_1 \quad (2.5.2.7)$$

2.5.3 Let  $\mathbf{a}$  and  $\mathbf{b}$  be two unit vectors and  $\theta$  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)  $\theta = \frac{2\pi}{3}$

**Solution:**

$$\because \|\mathbf{a}\| = \|\mathbf{b}\| = 3\|\mathbf{a} + \mathbf{b}\| = 1, \quad (2.5.3.1)$$

$$\|\mathbf{a} + \mathbf{b}\|^2 = 1^2 \quad (2.5.3.2)$$

$$\Rightarrow \|\mathbf{a}\|^2 + \|\mathbf{b}\|^2 + 2\mathbf{a}^\top \mathbf{b} = 1 \quad (2.5.3.3)$$

$$\Rightarrow (\|\mathbf{a}\| \|\mathbf{b}\| \cos \theta) = \frac{-1}{2} \quad (2.5.3.4)$$

$$\Rightarrow \cos \theta = \frac{-1}{2}, \text{ or, } \theta = \frac{2\pi}{3} \quad (2.5.3.5)$$

2.5.4 Show that the tangent of an angle between the lines

$$\frac{x}{a} + \frac{y}{b} = 1 \text{ and} \quad (2.5.4.1)$$

$$\frac{x}{a} - \frac{y}{b} = 1 \quad (2.5.4.2)$$

is  $\frac{2ab}{a^2 - b^2}$ .

2.5.5 Find  $\left| \vec{x} \right|$ , if for a unit vector  $\vec{a}$ ,  $(\vec{x} - \vec{a}) \cdot (\vec{x} + \vec{a}) = 12$ .

**Solution:** From the given information,

$$(\mathbf{x} - \mathbf{a})^\top (\mathbf{x} + \mathbf{a}) = 12 \quad (2.5.5.1)$$

$$\implies \|\mathbf{x}\|^2 - \|\mathbf{a}\|^2 = 12 \quad (2.5.5.2)$$

$$\implies \|\mathbf{x}\| = \sqrt{13} \quad (2.5.5.3)$$

2.5.6 Find  $|\vec{a}|$  and  $|\vec{b}|$ , if  $(\vec{a} + \vec{b}) \cdot (\vec{a} - \vec{b}) = 8$  and  $|\vec{a}| = 8|\vec{b}|$ .

**Solution:**

$$\because (\mathbf{a} + \mathbf{b})^\top (\mathbf{a} - \mathbf{b}) = 8, \|\mathbf{a}\| = 8\|\mathbf{b}\|, \quad (2.5.6.1)$$

$$\|\mathbf{a}\|^2 - \|\mathbf{b}\|^2 = 8 \quad (2.5.6.2)$$

$$\implies \|8\mathbf{b}\|^2 - \|\mathbf{b}\|^2 = 8 \quad (2.5.6.3)$$

$$\implies \|\mathbf{b}\| = \frac{2\sqrt{2}}{3\sqrt{7}} \quad (2.5.6.4)$$

Thus,

$$\|\mathbf{a}\| = 8\|\mathbf{b}\| = \frac{16\sqrt{2}}{3\sqrt{7}} \quad (2.5.6.5)$$

2.5.7 Find the magnitude of two vectors  $\vec{a}$  and  $\vec{b}$ , having the same magnitude and such that the angle between them is  $60^\circ$  and their scalar product is  $\frac{1}{2}$ .

**Solution:** Given

$$\|\mathbf{a}\| = \|\mathbf{b}\|, \cos \theta = \frac{1}{2}, \mathbf{a}^\top \mathbf{b} = \frac{1}{2}, \quad (2.5.7.1)$$

$$\implies \frac{1}{2} = \frac{\frac{1}{2}}{\|\mathbf{a}\|^2} \implies \|\mathbf{a}\| = \|\mathbf{b}\| = 1 \quad (2.5.7.2)$$

by using the definition of the scalar product in (2.1.1.1).

2.5.8 Show that  $|\vec{a}|\vec{b} + |\vec{b}|\vec{a}$  is perpendicular to  $|\vec{a}|\vec{b} - |\vec{b}|\vec{a}$ , for any two nonzero vectors  $\vec{a}$  and  $\vec{b}$ .

**Solution:**

$$\|\mathbf{a}\|\mathbf{b} + \|\mathbf{b}\|\mathbf{a} = \|\mathbf{a}\|\|\mathbf{b}\|\left(\frac{\mathbf{b}}{\|\mathbf{b}\|} + \frac{\mathbf{a}}{\|\mathbf{a}\|}\right) \quad (2.5.8.1)$$

$$\|\mathbf{a}\|\mathbf{b} - \|\mathbf{b}\|\mathbf{a} = \|\mathbf{a}\|\|\mathbf{b}\|\left(\frac{\mathbf{b}}{\|\mathbf{b}\|} - \frac{\mathbf{a}}{\|\mathbf{a}\|}\right) \quad (2.5.8.2)$$

$$\implies (\|\mathbf{a}\|\mathbf{b} + \|\mathbf{b}\|\mathbf{a})^\top (\|\mathbf{a}\|\mathbf{b} - \|\mathbf{b}\|\mathbf{a}) = 0 \quad (2.5.8.3)$$

from (2.1.5.1).

2.5.9 If  $\mathbf{a}, \mathbf{b}, \mathbf{c}$  are unit vectors such that  $\mathbf{a} + \mathbf{b} + \mathbf{c} = 0$ , then the value of  $\mathbf{a} \cdot \mathbf{b} + \mathbf{b} \cdot \mathbf{c} + \mathbf{c} \cdot \mathbf{a}$  is

- 1
- 3
- $\frac{-3}{2}$
- None of these

**Solution:**

$$\begin{aligned}
 & \|\mathbf{a} + \mathbf{b} + \mathbf{c}\|^2 = 0 \\
 \Rightarrow & \|\mathbf{a}\|^2 + \|\mathbf{b}\|^2 + \|\mathbf{c}\|^2 + 2(\mathbf{a}^\top \mathbf{b} + \mathbf{b}^\top \mathbf{c} + \mathbf{c}^\top \mathbf{a}) = 0 \\
 \Rightarrow & 3 + 2(\mathbf{a}^\top \mathbf{b} + \mathbf{b}^\top \mathbf{c} + \mathbf{c}^\top \mathbf{a}) = 0 \\
 \Rightarrow & \mathbf{a}^\top \mathbf{b} + \mathbf{b}^\top \mathbf{c} + \mathbf{c}^\top \mathbf{a} = -\frac{3}{2} \quad (2.5.9.1)
 \end{aligned}$$

2.5.10 If either vector  $\vec{a} = 0$  or  $\vec{b} = 0$ , then  $\vec{a} \cdot \vec{b} = 0$ . But the converse need not be true. Justify your answer with an example.

**Solution:**

$$\mathbf{a} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \mathbf{b} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (2.5.10.1)$$

$$\Rightarrow \mathbf{a}^\top \mathbf{b} = 0 \quad (2.5.10.2)$$

2.5.11 Prove that  $(\mathbf{a} + \mathbf{b}) \cdot (\mathbf{a} + \mathbf{b}) = |\mathbf{a}|^2 + |\mathbf{b}|^2$ , if and only if  $\mathbf{a}, \mathbf{b}$  are perpendicular, given  $\mathbf{a} \neq 0, \mathbf{b} \neq 0$ .

**Solution:**

$$\because (\mathbf{a} + \mathbf{b})^\top (\mathbf{a} + \mathbf{b}) = \|\mathbf{a}\|^2 + \|\mathbf{b}\|^2, \quad (2.5.11.1)$$

$$\|\mathbf{a}\|^2 + \|\mathbf{b}\|^2 + 2\mathbf{a}^\top \mathbf{b} = \|\mathbf{a}\|^2 + \|\mathbf{b}\|^2 \quad (2.5.11.2)$$

$$\Rightarrow \mathbf{a}^\top \mathbf{b} = 0 \quad (2.5.11.3)$$

2.5.12 If  $l_1, m_1, n_1$  and  $l_2, m_2, n_2$  are the direction cosines of two mutually perpendicular lines, show that the direction cosines of the line perpendicular to both these are  $m_1 n_2 - m_2 n_1, n_1 l_2 - n_2 l_1, l_1 m_2 - l_2 m_1$ .

**Solution:**

$$\mathbf{P} = \begin{pmatrix} l_1 & l_2 & m_1 n_2 - m_2 n_1 \\ m_1 & m_2 & n_1 l_2 - n_2 l_1 \\ n_1 & n_2 & l_1 m_2 - l_2 m_1 \end{pmatrix} \quad (2.5.12.1)$$

satisfies (2.1.6.1). Hence, the three vectors are mutually perpendicular.

2.5.13 Find the angle between the lines whose direction ratios are  $a, b, c$  and  $b-c, c-a, a-b$ .

**Solution:**

$$\because \begin{pmatrix} a & b & c \end{pmatrix} \begin{pmatrix} b-c \\ c-a \\ a-b \end{pmatrix} = 0, \theta = \frac{\pi}{2} \quad (2.5.13.1)$$

2.5.14 The value of the expression  $|\mathbf{a} \times \mathbf{b}| + (\mathbf{a} \cdot \mathbf{b})$  is \_\_\_\_\_

2.5.15 If  $|\mathbf{a} \times \mathbf{b}|^2 + |\mathbf{a} \cdot \mathbf{b}|^2 = 144$  and  $|\mathbf{a}| = 4$ , then  $|\mathbf{b}|$  is equal to \_\_\_\_\_.

2.5.16 If the directions cosines of a line are  $(k, k, k)$  then

a)  $k > 0$

b)  $0 < k < 1$

c)  $k = 1$

d)  $k = \frac{1}{\sqrt{3}}$  or  $-\frac{1}{\sqrt{3}}$

- 2.5.17 Find the position vector of a point A in space such that  $\overrightarrow{OA}$  is inclined at  $60^\circ$  to OX and at  $45^\circ$  to OY and  $|\overrightarrow{OA}| = 10$  units.
- 2.5.18 If  $(-4, 3)$  and  $(4, 3)$  are two vertices of an equilateral triangle. Find the coordinates of the third vertex, given that the origin lies in the interior of the triangle.
- 2.5.19 **A**(6, 1), **B**(8, 2) and **C**(9, 4) are three vertices of a parallelogram ABCD. If **C** is the midpoint of DC find the area of  $\triangle ADE$ .
- 2.5.20 If the points **A**(1, -2), **B**(2, 3), **C**(a, 2) and **D**(-4 - 3) form parallelogram, find the value of  $a$  and height of the parallelogram taking AB as base.
- 2.5.21 Ayush starts walking from his house to office. Instead of going to the office directly, he goes to a bank first, from there to his daughter school and then reaches the office what is the extra distance travelled by Ayush in reaching his office? If the house is situated at (2, 4), bank at (5, 8), school at (13, 14) and office at (13, 26) and coordinates are in km.
- 2.5.22 Find the angle between the lines whose direction cosines are given by the equations  $l + m + n = 0$ ,  $l^2 + m^2 - n^2 = 0$ .
- 2.5.23 If a variable line in two adjacent positions has directions cosines  $l, m, n$  and  $l + \delta l, m + \delta m, n + \delta n$ , show that the small angle  $\delta\theta$  between the two positions is given by

$$\delta\theta^2 = \delta l^2 + \delta m^2 + \delta n^2 \quad (2.5.23.1)$$

- 2.5.24 The vector  $\mathbf{a} + \mathbf{b}$  bisects the angle between the non-collinear vectors  $\mathbf{a}$  and  $\mathbf{b}$  if \_\_\_\_\_.
- 2.5.25 If  $\mathbf{a}$  and  $\mathbf{b}$  are adjacent sides of a rhombus, then  $\mathbf{a} \cdot \mathbf{b} = 0$ .
- 2.5.26 If **A**, **B**, **C** are mutually perpendicular vectors of equal magnitudes, show that the  $\mathbf{A} + \mathbf{B} + \mathbf{C}$  is equally inclined to **A**, **B** and **C**.
- 2.5.27 Projection vector of  $\mathbf{a}$  on  $\mathbf{b}$  is

- a)  $\left( \frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{b}|^2} \right)$
- b)  $\frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{b}|}$
- c)  $\frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{a}|}$
- d)  $\left( \frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{a}|^2} \right)$

- 2.5.28 If  $\mathbf{a}$  is any non-zero vector, then  $(\mathbf{a} \cdot \hat{i})\hat{i} + (\mathbf{a} \cdot \hat{j})\hat{j} + (\mathbf{a} \cdot \hat{k})\hat{k}$  equals \_\_\_\_\_.
- 2.5.29 If **a**, **b**, **c** are the three vectors such that  $\mathbf{a} + \mathbf{b} + \mathbf{c} = 0$  and  $|\mathbf{a}| = 2$ ,  $|\mathbf{b}| = 3$ ,  $|\mathbf{c}| = 5$ , the value of  $\mathbf{a} \cdot \mathbf{b} + \mathbf{b} \cdot \mathbf{c} + \mathbf{c} \cdot \mathbf{a}$  is
- a) 0
  - b) 1
  - c) -19
  - d) 38

- 2.5.30 If  $\mathbf{r} \cdot \mathbf{a} = 0$ ,  $\mathbf{r} \cdot \mathbf{b} = 0$  and  $\mathbf{r} \cdot \mathbf{c} = 0$  for some non-zero vector  $\mathbf{r}$ , then the value of  $\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c})$  is \_\_\_\_\_.
- 2.5.31 If  $|\mathbf{a} + \mathbf{b}| = |\mathbf{a} - \mathbf{b}|$ , then the vectors  $\mathbf{a}$  and  $\mathbf{b}$  are orthogonal.
- 2.5.32 Prove that the lines  $x = py + q$ ,  $z = ry + s$  and  $x = p'y + q'$ ,  $z = r'y + s'$  are perpendicular if  $pp' + rr' + 1 = 0$ .
- 2.5.33 Show that the straight lines whose direction cosines are given by  $2l + 2m - n = 0$

and  $mn + nl + lm = 0$  are at right angles.

- 2.5.34 If  $l_1, m_1, n_1; l_2, m_2, n_2; l_3, m_3, n_3$  are the direction cosines of the three mutually perpendicular lines, prove that the line whose direction cosines are proportional to  $l_1 + l_2 + l_3, m_1 + m_2 + m_3, n_1 + n_2 + n_3$  make angles with them.
- 2.5.35 Assuming that straight lines work as the plane mirror for a point, find the image of the point  $(1, 2)$  in the line  $x - 3y + 4 = 0$ .
- 2.5.36 Find  $|\vec{a} - \vec{b}|$ , if two vectors  $\vec{a}$  and  $\vec{b}$  are such that  $|\vec{a}| = 2, |\vec{b}| = 3$  and  $\vec{a} \cdot \vec{b} = 4$ .
- 2.5.37 If  $\vec{a}$  is a unit vector and  $(\vec{x} - \vec{a}) \cdot (\vec{x} + \vec{a}) = 8$ , then find  $|\vec{x}|$ .
- 2.5.38 Let  $\vec{a}, \vec{b}$ , and  $\vec{c}$  are three vectors such that  $|\vec{a}| = 3, |\vec{b}| = 4, |\vec{c}| = 5$  and each one of them being perpendicular to the sum of the other two, find  $|\vec{a} + \vec{b} + \vec{c}|$ .
- 2.5.39 If with reference to the right handed system of mutually perpendicular unit vectors  $\hat{i}, \hat{j}$  and  $\hat{k}$ ,  $\vec{\alpha} = 3\hat{i} - \hat{j}, \vec{\beta} = 2\hat{i} + \hat{j} - 3\hat{k}$ , then express  $\vec{\beta}$  in the form  $\vec{\beta} = \vec{\beta}_1 + \vec{\beta}_2$  where  $\vec{\beta}_1$  is parallel to  $\vec{\alpha}$  and  $\vec{\beta}_2$  is perpendicular to  $\vec{\alpha}$ .
- 2.5.40 Three vectors  $\vec{a}, \vec{b}$  and  $\vec{c}$  satisfy the condition  $\vec{a} + \vec{b} + \vec{c} = 0$ . Evaluate the quantity  $\mu = \vec{a} \cdot \vec{b} + \vec{b} \cdot \vec{c} + \vec{c} \cdot \vec{a}$ , if  $|\vec{a}| = 3, |\vec{b}| = 4$  and  $|\vec{c}| = 2$ .
- 2.5.41 A line makes angles  $\alpha, \beta, \gamma$  and  $\delta$  with the diagonals of a cube, prove that

$$\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma + \cos^2 \delta = \frac{4}{3}. \quad (2.5.41.1)$$

## 3 CONSTRUCTIONS

## 3.1 Formulae

3.1.1. Construct a  $\triangle ABC$  given  $a, \angle B$  and  $K = b + c$ .

**Solution:** Using the cosine formula in  $\triangle ABC$ ,

$$b^2 = a^2 + c^2 - 2ac \cos B \quad (3.1.1.1)$$

$$\implies (K - c)^2 = a^2 + c^2 - 2ac \cos B \quad (3.1.1.2)$$

$$\implies c = \frac{K^2 - a^2}{2(K - a \cos B)} \quad (3.1.1.3)$$

The coordinates of  $\triangle ABC$  can then be expressed as

$$\mathbf{A} = c \begin{pmatrix} \cos B \\ \sin B \end{pmatrix}, \mathbf{B} = \mathbf{0}, \mathbf{C} = \begin{pmatrix} a \\ 0 \end{pmatrix}. \quad (3.1.1.4)$$

3.1.2. Construct a  $\triangle ABC$  given  $\angle B, \angle C$  and  $K = a + b + c$ .

**Solution:**

$$a + b + c = K \quad (3.1.2.1)$$

$$b \cos C + c \cos B - a = 0 \quad (3.1.2.2)$$

$$b \sin C - c \sin B = 0 \quad (3.1.2.3)$$

resulting in the matrix equation

$$\begin{pmatrix} 1 & 1 & 1 \\ -1 & \cos C & \cos B \\ 0 & \sin C & -\sin B \end{pmatrix} \begin{pmatrix} a \\ b \\ c \end{pmatrix} = K \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad (3.1.2.4)$$

which can be solved to obtain all the sides.  $\triangle ABC$  can then be plotted using

$$\mathbf{A} = \begin{pmatrix} a \\ b \end{pmatrix}, \mathbf{B} = \mathbf{0}, \mathbf{C} = \begin{pmatrix} a \\ 0 \end{pmatrix} \quad (3.1.2.5)$$

## 3.2 Triangle

3.2.1 Construct a triangle  $ABC$  in which  $BC = 7\text{cm}$ ,  $\angle B = 75^\circ$  and  $AB + AC = 13\text{cm}$ .

**Solution:** From (3.1.1.3) and (3.1.1.4), we obtain Fig. 3.2.1.1.

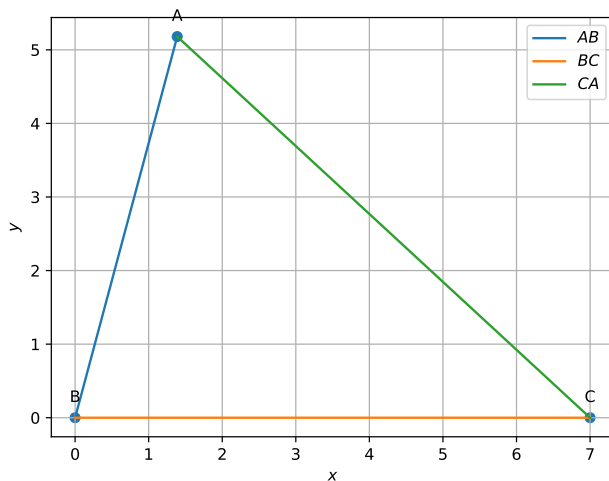


Fig. 3.2.1.1

3.2.2 Construct a triangle  $ABC$  in which  $BC = 8\text{cm}$ ,  $\angle B = 45^\circ$  and  $AB - AC = 3.5\text{cm}$ .

**Solution:** See Fig. 3.2.2.1.

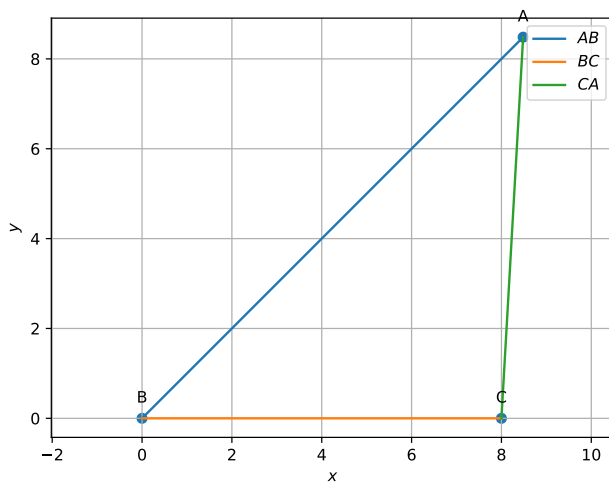


Fig. 3.2.2.1

3.2.3 Construct a triangle  $ABC$  in which  $BC = 6\text{cm}$ ,  $\angle B = 60^\circ$  and  $AC - AB = 2\text{cm}$ .

**Solution:** See Fig. 3.2.3.1 obtained by substituting  $K = -2$ .

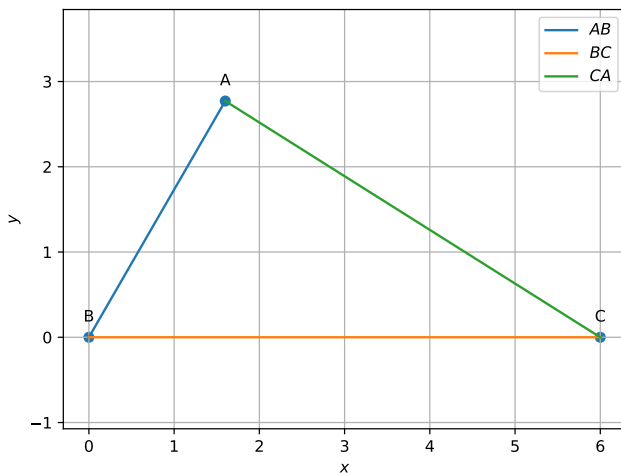


Fig. 3.2.3.1

3.2.4 Construct a right triangle whose base is  $12\text{cm}$  and sum of its hypotenuse and other side is  $18\text{cm}$ .

**Solution:** For  $a = 12$ ,  $\angle B = 90^\circ$ ,  $b + c = 18$ , we obtain Fig. 3.2.4.1.

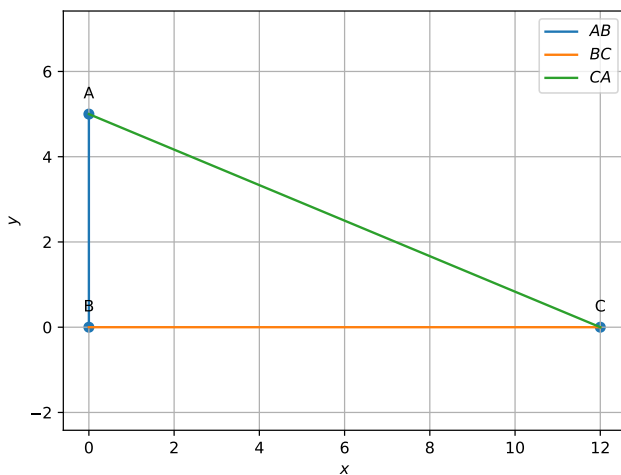


Fig. 3.2.4.1

3.2.5 Construct a triangle  $ABC$  in which  $\angle B = 30^\circ$ ,  $\angle C = 90^\circ$  and  $AB + BC + CA = 11\text{cm}$ .



**Solution:** From (3.1.2.4) and (3.1.2.5), Fig. 3.2.5.1 is generated.

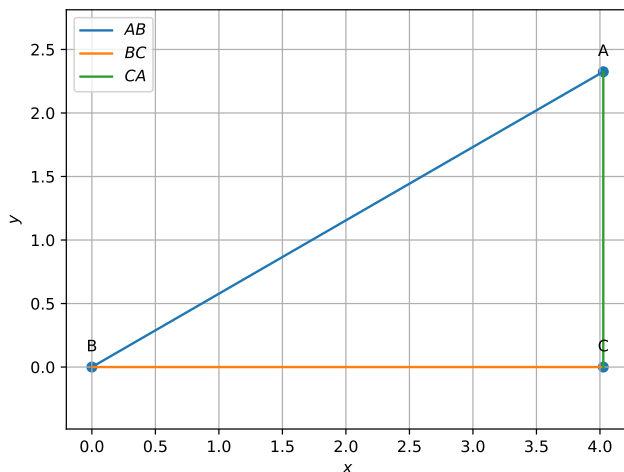


Fig. 3.2.5.1

- 3.2.6 Draw a right triangle  $ABC$  in which  $BC = 12\text{cm}$ ,  $AB = 5\text{cm}$  and  $\angle B = 90^\circ$ .
- 3.2.7 Draw an isosceles triangle  $ABC$  in which  $AB = AC = 6\text{cm}$  and  $BC = 6\text{cm}$ .
- 3.2.8 Draw a triangle  $ABC$  in which  $AB = 5\text{cm}$ ,  $BC = 6\text{cm}$  and  $\angle ABC = 60^\circ$ .
- 3.2.9 Draw a triangle  $ABC$  in which  $AB = 4\text{cm}$ ,  $BC = 6\text{cm}$  and  $AC = 9\text{cm}$ .
- 3.2.10 Draw a triangle  $ABC$  in which  $BC = 6\text{cm}$ ,  $CA = 5\text{cm}$  and  $AB = 4\text{cm}$ .
- 3.2.11 Is it possible to construct a triangle with lengths of its sides as  $4\text{cm}$ ,  $3\text{cm}$  and  $7\text{cm}$ ?  
Give reason for your answer.
- 3.2.12 Is it possible to construct a triangle with lengths of its sides as  $9\text{cm}$ ,  $7\text{cm}$  and  $17\text{cm}$ ?  
Give reason for your answer.
- 3.2.13 Is it possible to construct a triangle with lengths of its sides as  $8\text{cm}$ ,  $7\text{cm}$  and  $4\text{cm}$ ?  
Give reason for your answer.
- 3.2.14 Two sides of a triangle are of lengths  $5\text{cm}$  and  $1.5\text{cm}$ . The length of the third side of the triangle cannot be
- $3.6\text{cm}$
  - $4.1\text{cm}$
  - $3.8\text{cm}$
  - $3.4\text{cm}$
- 3.2.15 The construction of a triangle  $ABC$ , given that  $BC = 6\text{cm}$ ,  $\angle B = 45^\circ$  is not possible when difference of  $AB$  and  $AC$  is equal to
- $6.9\text{cm}$
  - $5.2\text{cm}$
  - $5.0\text{cm}$

d) 4.0cm

3.2.16 The construction of a triangle  $ABC$ , given that  $BC = 6\text{cm}$ ,  $\angle C = 60^\circ$  is possible when difference of  $AB$  and  $AC$  is equal to

a) 3.2cm

b) 3.1cm

c) 3cm

d) 2.8cm

3.2.17 Construct a triangle whose sides are 3.6cm, 3.0cm and 4.8cm. Bisect the smallest angle and measure each part.

3.2.18 Construct a triangle  $ABC$  in which  $BC = 5\text{cm}$ ,  $\angle B = 60^\circ$  and  $AC + AB = 7.5\text{cm}$ .

Construct each of the following and give justification :

3.2.19 A triangle if its perimeter is 10.4cm and two angles are  $45^\circ$  and  $120^\circ$ .

3.2.20 A triangle  $PQR$  given that  $QR = 3\text{cm}$ ,  $\angle PQR = 45^\circ$  and  $QP - PR = 2\text{cm}$ .

3.2.21 A right triangle when one side is 3.5cm and sum of other sides and the hypotenuse is 5.5cm.

3.2.22 An equilateral triangle if its altitude is 3.2cm.

Write true or false in each of the following. Give reasons for your answer:

3.2.23 A triangle  $ABC$  can be constructed in which  $AB = 5\text{cm}$ ,  $\angle A = 45^\circ$  and  $BC + AC = 5\text{cm}$ .

3.2.24 A triangle  $ABC$  can be constructed in which  $BC = 6\text{cm}$ ,  $\angle B = 30^\circ$  and  $AC - AB = 4\text{cm}$ .

3.2.25 A triangle  $ABC$  can be constructed in which  $\angle B = 105^\circ$ ,  $\angle C = 90^\circ$  and  $AB + BC + AC = 10\text{cm}$ .

3.2.26 A triangle  $ABC$  can be constructed in which  $\angle B = 60^\circ$ ,  $\angle C = 45^\circ$  and  $AB + BC + AC = 12\text{cm}$ .

3.2.27 Draw a right triangle  $ABC$  in which  $BC = 12\text{ cm}$ ,  $AB = 5\text{ cm}$  and  $\angle B = 90^\circ$ .

3.2.28 Draw a triangle  $ABC$  in which  $AB = 4\text{ cm}$ ,  $BC = 6\text{cm}$  and  $AC = 9$ .

3.2.29 Draw a triangle  $ABC$  in which  $AB = 5\text{ cm}$ ,  $BC = 6\text{cm}$  and  $\angle ABC = 60^\circ$ .

3.2.30 Draw a parallelogram  $ABCD$  in which  $BC = 5\text{ cm}$ ,  $AB = 3\text{ cm}$  and  $\angle ABC = 60^\circ$ , divide it into triangles  $ACB$  and  $ABD$  by the diagonal  $BD$ . Construct the triangle  $BD'C'$  similar to  $\triangle BDC$  with scale factor  $\frac{4}{3}$ . Draw the line segment  $D'A'$  parallel to  $DA$  where  $A'$  lies on extended side  $BA$ . Is  $A'BC'D'$  a parallelogram?

3.2.31 Draw a triangle  $ABC$  in which  $BC = 6\text{ cm}$ ,  $CA = 5\text{ cm}$  and  $AB = 4\text{ cm}$ .

### 3.3 Quadrilateral

3.3.1 Draw a quadrilateral in the Cartesian plane, whose vertices are  $(-4, 5)$ ,  $(0, 7)$ ,  $(5, -5)$  and  $(-4, -2)$ .

3.3.2 Draw a parallelogram  $ABCD$  in which  $BC = 5\text{cm}$ ,  $AB = 3\text{cm}$  and  $\angle ABC = 60^\circ$ , divide it into triangles  $ACB$  and  $ABD$  by the diagonal  $BD$ .

3.3.3 Construct a square of side 3cm.

3.3.4 Construct a rectangle whose adjacent sides are of lengths 5cm and 3.5cm.

3.3.5 Construct a rhombus whose side is of length 3.4cm and one of its angles is  $45^\circ$ .

3.3.6 Construct a rhombus whose diagonals are 4 cm and 6 cm in lengths.

## 4 LINEAR FORMS

## 4.1 Formulae

4.1.1. The equation of a line is given by

$$y = mx + c \quad (4.1.1.1)$$

$$\Rightarrow \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x \\ mx + c \end{pmatrix} = \begin{pmatrix} 0 \\ c \end{pmatrix} + x \begin{pmatrix} 1 \\ m \end{pmatrix} \quad (4.1.1.2)$$

yielding

$$\mathbf{x} = \mathbf{h} + \kappa \mathbf{m}. \quad (4.1.1.3)$$

where  $\mathbf{h}$  is any point on the line and

$$\mathbf{m} = \begin{pmatrix} 1 \\ m \end{pmatrix} \quad (4.1.1.4)$$

is the direction vector.

4.1.2. For

$$\mathbf{m}^\top \mathbf{n} = 0, \quad (4.1.2.1)$$

(4.1.1.3) can be expressed as

$$\mathbf{n}^\top \mathbf{x} = \mathbf{n}^\top \mathbf{h} + \kappa \mathbf{n}^\top \mathbf{m} \quad (4.1.2.2)$$

$$\Rightarrow \mathbf{n}^\top (\mathbf{x} - \mathbf{h}) = 0 \quad (4.1.2.3)$$

$$\text{or, } \mathbf{n}^\top \mathbf{x} = c$$

for

$$c = \mathbf{n}^\top \mathbf{h}. \quad (4.1.2.4)$$

where

$$\mathbf{n} = \begin{pmatrix} -m \\ 1 \end{pmatrix} \quad (4.1.2.5)$$

is defined to be the *normal vector* of the line. In 3D, (4.1.2.3) represents a plane.

4.1.3. If  $\mathbf{A}, \mathbf{B}, \mathbf{C}$  are collinear, from (4.1.2.3),

$$\mathbf{n}^\top \mathbf{A} = c \quad (4.1.3.1)$$

$$\mathbf{n}^\top \mathbf{B} = c \quad (4.1.3.2)$$

$$\mathbf{n}^\top \mathbf{C} = c \quad (4.1.3.3)$$

which can be expressed as

$$\begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix}^T \mathbf{n} = c \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \quad (4.1.3.4)$$

$$\equiv \begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix}^T \mathbf{n} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \quad (4.1.3.5)$$

$$\Rightarrow \begin{pmatrix} 1 & 1 & 1 \\ \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix}^T \begin{pmatrix} \mathbf{n} \\ -1 \end{pmatrix} = \mathbf{0} \quad (4.1.3.6)$$

4.1.4. The equation of a line that does not pass through the origin can be expressed as

$$\mathbf{n}^T \mathbf{x} = 1 \quad (4.1.4.1)$$

4.1.5. Let the perpendicular distance from the origin to a line be  $p$  and the angle made by the perpendicular with the positive  $x$ -axis be  $\theta$ . Then

$$p \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix} \quad (4.1.5.1)$$

is a point on the line as well as the normal vector. Hence, the equation of the line is

$$p \begin{pmatrix} \cos \theta & \sin \theta \end{pmatrix} \left\{ \mathbf{x} - p \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix} \right\} = 0 \quad (4.1.5.2)$$

$$\Rightarrow \begin{pmatrix} \cos \theta & \sin \theta \end{pmatrix} \mathbf{x} = p \quad (4.1.5.3)$$

4.1.6. Let  $\mathbf{Q}$  be the foot of the perpendicular from  $\mathbf{P}$  to the line

$$\mathbf{n}^T \mathbf{x} = c \quad (4.1.6.1)$$

From (4.1.1.3)

$$\mathbf{Q} = \mathbf{P} + k\mathbf{n} \quad (4.1.6.2)$$

$$\Rightarrow PQ = \|\mathbf{Q} - \mathbf{P}\| = |k| \|\mathbf{n}\| \quad (4.1.6.3)$$

is the distance from  $\mathbf{Q}$  to the line in (4.1.6.1). From (4.1.6.2),

$$\mathbf{n}^T \mathbf{Q} = \mathbf{n}^T \mathbf{P} + k \|\mathbf{n}\|^2 \quad (4.1.6.4)$$

$$\Rightarrow |k| = \frac{|\mathbf{n}^T (\mathbf{Q} - \mathbf{P})|}{\|\mathbf{n}\|^2} \quad (4.1.6.5)$$

$$\Rightarrow PQ = |k| \|\mathbf{n}\| = \frac{|\mathbf{n}^T \mathbf{P} - c|}{\|\mathbf{n}\|} \quad (4.1.6.6)$$

upon substituting from (4.1.6.3).

4.1.7. The foot of the perpendicular is given by

$$\begin{pmatrix} \mathbf{m} & \mathbf{n} \end{pmatrix}^T \mathbf{Q} = \begin{pmatrix} \mathbf{m}^T \mathbf{P} \\ c \end{pmatrix} \quad (4.1.7.1)$$

4.1.8. The distance between the parallel lines

$$\begin{aligned}\mathbf{n}^\top \mathbf{x} &= c_1 \\ \mathbf{n}^\top \mathbf{x} &= c_2\end{aligned}\tag{4.1.8.1}$$

is given by

$$d = \frac{|c_1 - c_2|}{\|\mathbf{n}\|}\tag{4.1.8.2}$$

4.1.9. The reflection of point  $\mathbf{Q}$  w.r.t a line is given by

$$\mathbf{R} = \mathbf{Q} - \frac{2(\mathbf{n}^\top \mathbf{Q} - c)}{\|\mathbf{n}\|} \mathbf{n}\tag{4.1.9.1}$$

4.1.10. Code for line in 2D using direction vector

```
codes/book/linear.py
```

4.1.11. Code for line in 2D using normal vector

```
codes/book/linorm.py
```

4.1.12. Code for line in 3D

```
codes/book/points3d.py
```

4.1.13. Code for plane

```
codes/book/plane.py
```

4.1.14. Code for foot of the perpendicular

```
codes/book/perp.py
```

4.1.15. Code for intersection of lines

```
codes/book/linsect.py
```

## 4.2 Parameters

Find the direction and normal vectors of each of the following lines

4.2.1  $2x + 3y = 9$

4.2.2  $x - \frac{y}{5} - 10 = 10$

4.2.3  $-2x + 3y = 6$

4.2.4  $x = 3y$

4.2.5  $2x = -5y$

4.2.6  $3x + 2 = 0$

4.2.7  $y - 2 = 0$

4.2.8  $5 = 2x$

4.2.9  $x + y = 4$

4.2.10  $x - y = 2$

4.2.11  $y = 3x$

4.2.12  $3 = 2x + y$

4.2.13  $y = x$

4.2.14  $x + y = 0$

4.2.15  $y = 2x$

4.2.16  $2 + 3y = 7x$

4.2.17  $y = x + 2$

4.2.18  $y = x - 2$

4.2.19  $y = -x + 2$

4.2.20  $x + 2y = 6$

4.2.21  $F = \frac{9}{5}C + 32$

Show that two lines  $a_1x + b_1y + c_1 = 0$  and  $a_2x + b_2y + c_2 = 0$  where  $b_1b_2 - 2 \neq 0$  are

4.2.22 parallel if  $\frac{a_1}{b_1} = \frac{a_2}{b_2}$  and

4.2.23 Perpendicular if  $a_1a_2 - b_1b_2 = 0$ .

### 4.3 Equation

Find the equation of line

4.3.1 passing through the point  $\mathbf{P} = (-4, 3)$  with slope  $\frac{1}{2}$ .

**Solution:** From (4.1.2.5),

$$\mathbf{n} \equiv \begin{pmatrix} \frac{1}{2} \\ -1 \end{pmatrix} \Rightarrow \begin{pmatrix} \frac{1}{2} & -1 \end{pmatrix} \mathbf{x} = -5 \quad (4.3.1.1)$$

using (4.1.2.3). See Fig. 4.3.1.1.

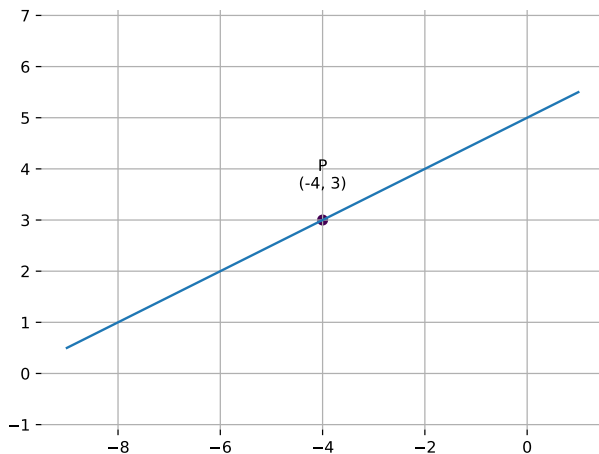


Fig. 4.3.1.1

4.3.2 passing through  $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$  with slope  $m$ .

**Solution:**

$$\therefore \mathbf{n} = \begin{pmatrix} m \\ -1 \end{pmatrix}, \quad (4.3.2.1)$$

the desired equation is

$$(m \quad -1) \left( \mathbf{x} - \begin{pmatrix} 0 \\ 0 \end{pmatrix} \right) = 0 \quad (4.3.2.2)$$

$$\Rightarrow (m \quad -1) \mathbf{x} = 0 \quad (4.3.2.3)$$

4.3.3 passing through  $\mathbf{A} = \begin{pmatrix} 2 \\ 2\sqrt{3} \end{pmatrix}$  and inclined with the x-axis at an angle of  $75^\circ$ .

**Solution:**

$$\mathbf{m} = \begin{pmatrix} 1 \\ \tan 75^\circ \end{pmatrix} \Rightarrow \mathbf{n} = \begin{pmatrix} 2 + \sqrt{3} \\ -1 \end{pmatrix} \quad (4.3.3.1)$$

$$\Rightarrow (2 + \sqrt{3} \quad -1) \mathbf{x} = (2 + \sqrt{3} \quad -1) \begin{pmatrix} 2 \\ 2\sqrt{3} \end{pmatrix} \quad (4.3.3.2)$$

$$= 4 \quad (4.3.3.3)$$

is the desired equation.

4.3.4 intersecting the x-axis at a distance of 3 units to the left of origin with slope of -2.

**Solution:** From the given information,

$$\mathbf{A} = \begin{pmatrix} -3 \\ 0 \end{pmatrix}, \mathbf{n} = \begin{pmatrix} 2 \\ 1 \end{pmatrix}. \quad (4.3.4.1)$$

The desired equation of the line is

$$\Rightarrow (2 \quad 1) \left( \mathbf{x} - \begin{pmatrix} -3 \\ 0 \end{pmatrix} \right) = 0 \quad (4.3.4.2)$$

$$\text{or, } (2 \quad 1) \mathbf{x} = -6 \quad (4.3.4.3)$$

See Fig. 4.3.4.1.

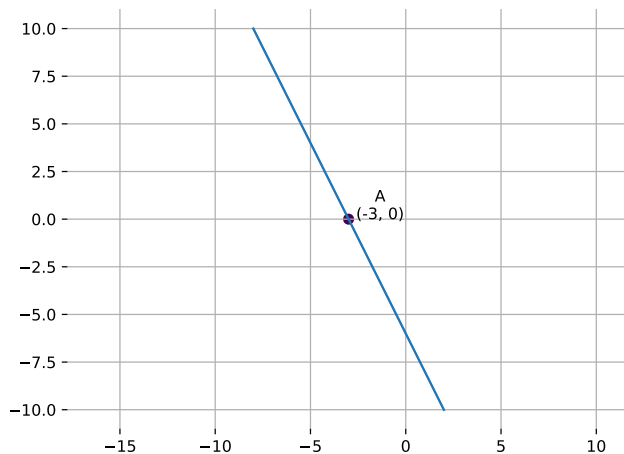


Fig. 4.3.4.1

4.3.5 intersecting the y-axis at a distance of 2 units above the origin and making an angle of  $30^\circ$  with positive direction of the x-axis.

**Solution:**

$$\mathbf{n} = \begin{pmatrix} -\frac{1}{\sqrt{3}} \\ 1 \end{pmatrix}, \mathbf{A} = \begin{pmatrix} 0 \\ 2 \end{pmatrix}. \quad (4.3.5.1)$$

Hence, the equation of the line is given by

$$\left(-\frac{1}{\sqrt{3}} \quad 1\right) \left(\mathbf{x} - \begin{pmatrix} 0 \\ 2 \end{pmatrix}\right) = 0 \quad (4.3.5.2)$$

$$\text{or, } \left(-\frac{1}{\sqrt{3}} \quad 1\right) \mathbf{x} = 2 \quad (4.3.5.3)$$

4.3.6 passing through (1, 2) and making angle  $30^\circ$  with y-axis.

4.3.7 passing through the points  $\mathbf{A} \begin{pmatrix} -1 \\ 1 \end{pmatrix}$  and  $\mathbf{B} \begin{pmatrix} 2 \\ -4 \end{pmatrix}$ .

**Solution:** From (4.1.3.5),

$$\begin{pmatrix} -1 & 1 \\ 2 & -4 \end{pmatrix} \mathbf{n} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (4.3.7.1)$$

$$\Rightarrow \left( \begin{array}{cc|c} -1 & 1 & 1 \\ 2 & -4 & 1 \end{array} \right) \xleftrightarrow{R_2 \leftarrow R_2 + 2R_1} \left( \begin{array}{cc|c} -1 & 1 & 1 \\ 0 & -2 & 3 \end{array} \right) \quad (4.3.7.2)$$

$$\xleftrightarrow{R_1 \leftarrow 2R_1 + R_2} \left( \begin{array}{cc|c} -2 & 0 & 5 \\ 0 & -2 & 3 \end{array} \right) \Rightarrow \mathbf{n} = -\frac{1}{2} \begin{pmatrix} 5 \\ 3 \end{pmatrix} \quad (4.3.7.3)$$



Thus, from (4.1.4.1), the equation of the line is

$$\begin{pmatrix} 5 & 3 \end{pmatrix} \mathbf{x} = -2 \quad (4.3.7.4)$$

See Fig. 4.3.7.1.

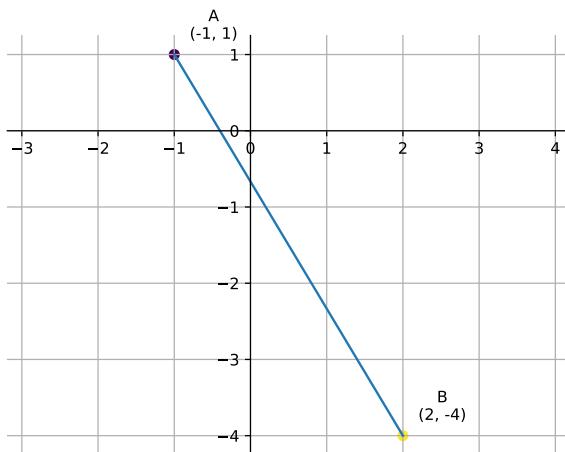


Fig. 4.3.7.1

4.3.8 passing through the points  $(3, 4, -7)$  and  $(1, -1, 6)$ .

4.3.9 The vector equation of the line

$$\frac{x-5}{3} = \frac{y+4}{7} = \frac{z-6}{2}$$

is \_\_\_\_\_.

4.3.10 The vector equation of the line

$$\frac{x-5}{3} = \frac{y+4}{7} = \frac{z-6}{2}$$

is \_\_\_\_\_.

4.3.11 The vertices of triangle  $PQR$  are  $\mathbf{P}(2, 1)$ ,  $\mathbf{Q}(-2, 3)$ ,  $\mathbf{R}(4, 5)$ . Find the equation of the median through  $\mathbf{R}$ .

**Solution:** Using section formula, the mid point of  $PQ$  is

$$\mathbf{A} = \frac{\mathbf{P} + \mathbf{Q}}{2} = \begin{pmatrix} 0 \\ 2 \end{pmatrix} \quad (4.3.11.1)$$

Following the approach in Problem 4.3.7,

$$\left( \begin{array}{cc|c} 4 & 5 & 1 \\ 0 & 2 & 1 \end{array} \right) \xrightarrow[R_2 \leftarrow -4R_2]{R_1 \leftarrow -2R_1 - 5R_2} \left( \begin{array}{cc|c} 8 & 0 & -3 \\ 0 & 8 & 4 \end{array} \right) \Rightarrow \mathbf{n} = \frac{1}{8} \begin{pmatrix} -3 \\ 4 \end{pmatrix}$$

Thus, the equation of the line is

$$(-3 \quad 4)\mathbf{x} = 8 \quad (4.3.11.2)$$

4.3.12 Find the equations of the planes that pass through the points

a)  $\mathbf{A} = \begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 6 \\ 4 \\ -5 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} -4 \\ -2 \\ 3 \end{pmatrix}$

b)  $\mathbf{A} = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 1 \\ 2 \\ 1 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} -2 \\ 2 \\ -1 \end{pmatrix}$

**Solution:**

a) From (4.1.3.5),

$$\begin{aligned} & \begin{pmatrix} 1 & 1 & -1 \\ 6 & 4 & -5 \\ -4 & -2 & 3 \end{pmatrix} \mathbf{n} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \Rightarrow \begin{pmatrix} 1 & 1 & -1 & | & 1 \\ 6 & 4 & -5 & | & 1 \\ -4 & -2 & 3 & | & 1 \end{pmatrix} \\ & \xleftrightarrow[R_3 \leftarrow R_3 + 4R_1]{R_2 \leftarrow R_2 - 6R_1} \begin{pmatrix} 1 & 1 & -1 & | & 1 \\ 0 & -2 & 1 & | & -5 \\ 0 & 2 & -1 & | & 5 \end{pmatrix} \xleftrightarrow[R_1 \leftarrow 2R_1 + R_2]{R_3 \leftarrow R_3 + R_2} \begin{pmatrix} 2 & 0 & -1 & | & -3 \\ 0 & 2 & -1 & | & 5 \\ 0 & 0 & 0 & | & 0 \end{pmatrix} \end{aligned}$$

Since we obtain a 0 row, the given points are collinear. The direction vector of the line is

$$\mathbf{m} = \mathbf{B} - \mathbf{C} \equiv \begin{pmatrix} 5 \\ 3 \\ -4 \end{pmatrix} \quad (4.3.12.1)$$

and the equation of a line is given by,

$$\mathbf{x} = \mathbf{A} + \kappa \mathbf{m} \quad (4.3.12.2)$$

$$= \begin{pmatrix} 1 \\ 1 \\ -1 \end{pmatrix} + \kappa \begin{pmatrix} 5 \\ 3 \\ -4 \end{pmatrix} \quad (4.3.12.3)$$

See Fig. 4.3.12.1.

b) In this case,

$$\begin{pmatrix} 1 & 1 & 0 \\ 1 & 2 & 1 \\ -2 & 2 & -1 \end{pmatrix} \mathbf{n} = \mathbf{1} \quad (4.3.12.4)$$

$$\begin{aligned} & \Rightarrow \begin{pmatrix} 1 & 1 & 0 & | & 1 \\ 1 & 2 & 1 & | & 1 \\ -2 & 2 & -1 & | & 1 \end{pmatrix} \xleftrightarrow[R_3 \leftarrow R_3 + 2R_1]{R_2 \leftarrow R_2 - R_1} \begin{pmatrix} 1 & 1 & 0 & | & 1 \\ 0 & 1 & 1 & | & 0 \\ 0 & 4 & -1 & | & 3 \end{pmatrix} \\ & \xleftrightarrow[R_3 \leftarrow R_3 - 4R_2]{R_1 \leftarrow R_1 - R_2} \begin{pmatrix} 1 & 0 & -1 & | & 1 \\ 0 & 1 & 1 & | & 0 \\ 0 & 0 & -5 & | & 3 \end{pmatrix} \xleftrightarrow[R_2 \leftarrow 5R_2 + R_3]{R_1 \leftarrow 5R_1 - R_3} \begin{pmatrix} 5 & 0 & 0 & | & 2 \\ 0 & 5 & 0 & | & 3 \\ 0 & 0 & 5 & | & -3 \end{pmatrix} \end{aligned}$$

Hence, the equation of the plane is

$$(2 \ 3 \ -3)\mathbf{x} = 5 \quad (4.3.12.5)$$

See Fig. 4.3.12.2.

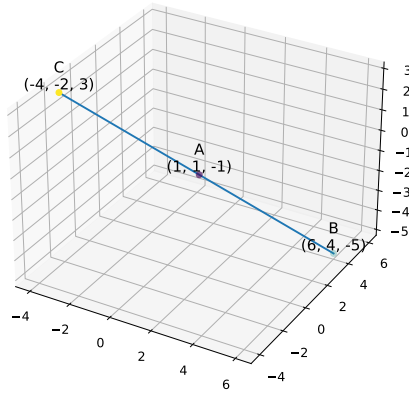


Fig. 4.3.12.1

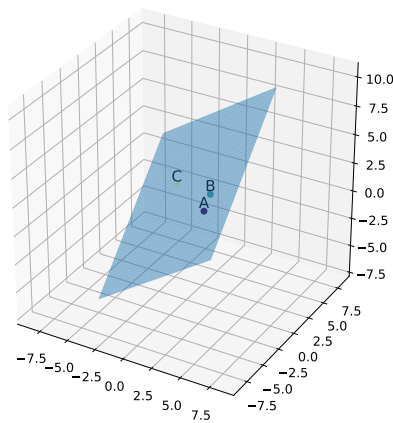


Fig. 4.3.12.2

- 4.3.13 Find the equation of the plane through the points  $(2, 1, 0)$ ,  $(3, -2, -2)$  and  $(3, 1, 7)$ .
- 4.3.14 A plane passes through the points  $(2, 0, 0)$ ,  $(0, 3, 0)$  and  $(0, 0, 4)$ . The equation of the plane is \_\_\_\_\_.
- 4.3.15 If the intercept of a line between the coordinate axes is divided by the point  $(-5, 4)$  in the ratio  $1:2$  then find the equation of the line.
- 4.3.16 Find the equation of a line that cuts off equal intercepts on the coordinate axes and passes through the point  $(2, 3)$ .

**Solution:** Let  $(a, 0)$  and  $(0, a)$  be the intercept points.

$$\mathbf{m} = \begin{pmatrix} a \\ 0 \end{pmatrix} - \begin{pmatrix} 0 \\ a \end{pmatrix} \equiv \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (4.3.16.1)$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (4.3.16.2)$$

and the equation of the line is

$$\begin{pmatrix} 1 & 1 \end{pmatrix} \left( \mathbf{x} - \begin{pmatrix} 2 \\ 3 \end{pmatrix} \right) = 0 \quad (4.3.16.3)$$

$$\Rightarrow \begin{pmatrix} 1 & 1 \end{pmatrix} \mathbf{x} = 5 \quad (4.3.16.4)$$

See Fig. 4.3.16.1.

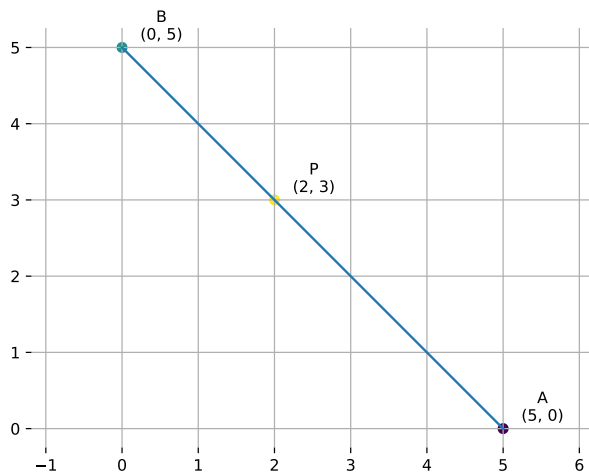


Fig. 4.3.16.1

- 4.3.17 Find the equation of a line passing through a point  $(2, 2)$  and cutting off intercepts on the axes whose sum is 9.

**Solution:** Let the intercept points be

$$\mathbf{P} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} 0 \\ b \end{pmatrix} \text{ and } \mathbf{R} = \begin{pmatrix} 2 \\ 2 \end{pmatrix} \quad (4.3.17.1)$$

be the given point. Forming the collinearity matrix from (4.1.3.6),

$$(\mathbf{P} - \mathbf{Q} \quad \mathbf{P} - \mathbf{R}) = \begin{pmatrix} a & a-2 \\ -b & -2 \end{pmatrix} \quad (4.3.17.2)$$

which is singular if

$$ab - 2(a + b) = 0 \implies ab = 18 \quad (4.3.17.3)$$

$$\therefore a + b = 9. \quad (4.3.17.4)$$

$\therefore a, b$  are the roots of

$$x^2 - 9x + 18 = 0. \quad (4.3.17.5)$$

yielding

$$\begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} 6 \\ 3 \end{pmatrix}, \begin{pmatrix} 3 \\ 6 \end{pmatrix} \quad (4.3.17.6)$$

Since

$$\mathbf{m} = \begin{pmatrix} a \\ -b \end{pmatrix}, \mathbf{n} = \begin{pmatrix} b \\ a \end{pmatrix} \equiv \begin{pmatrix} 1 \\ 2 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \end{pmatrix} \quad (4.3.17.7)$$

Thus, the possible equations of the line are

$$\begin{pmatrix} 1 & 2 \end{pmatrix} \mathbf{x} = 6 \quad (4.3.17.8)$$

$$\begin{pmatrix} 2 & 1 \end{pmatrix} \mathbf{x} = 6 \quad (4.3.17.9)$$

See Fig. 4.3.17.1.

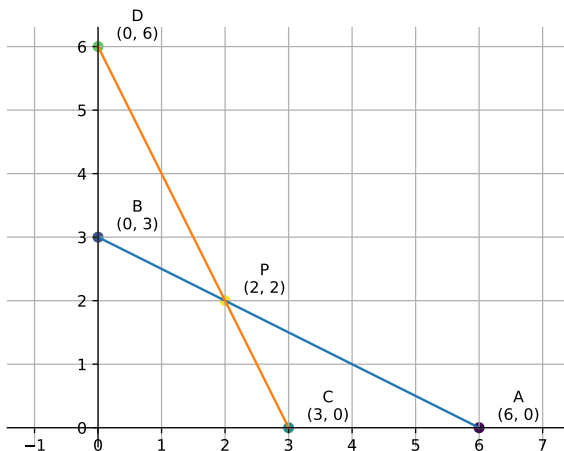


Fig. 4.3.17.1

- 4.3.18 Find the equation of the line which passes through the point (3, 4) and cuts off intercepts from the coordinate axes such that their sum is 14.
- 4.3.19 Find the equation of the straight line which passes through the point (1, -2) and cuts off equal intercepts from axes.
- 4.3.20 Find the equation of the line which passes through the point (-4, 3) and the portion of the line intercepted between the axes is divided internally in ratio 5:3 by this point.
- 4.3.21 Consider the following population and year graph in Fig. 4.3.21.1. Find the slope of the line AB and using it, find what will be the population in the year 2010.

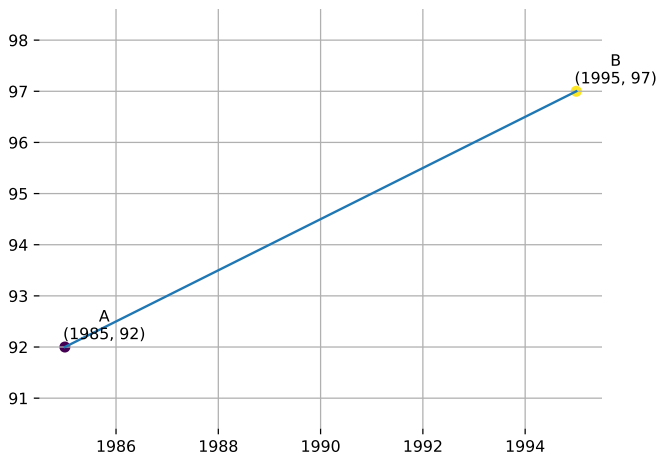


Fig. 4.3.21.1

**Solution:** The direction vector of the line in Fig. 4.3.21.1 is

$$\mathbf{m} = \mathbf{B} - \mathbf{A} = \begin{pmatrix} 2 \\ 1 \end{pmatrix} \quad (4.3.21.1)$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 1 \\ -2 \end{pmatrix} \quad (4.3.21.2)$$

The equation of the line is then given by

$$\mathbf{n}^T(\mathbf{x} - \mathbf{A}) = 0 \quad (4.3.21.3)$$

$$\Rightarrow \begin{pmatrix} 1 & -2 \end{pmatrix} \mathbf{x} = 1801 \quad (4.3.21.4)$$

$$\Rightarrow \begin{pmatrix} 1 & -2 \end{pmatrix} \begin{pmatrix} 2010 \\ y \end{pmatrix} = 1801 \quad (4.3.21.5)$$

$$\Rightarrow y = \frac{209}{2} \quad (4.3.21.6)$$

4.3.22 Slope of a line which cuts off intercepts of equal length on the axes is

- a) -1
- b) -0
- c) 2
- d)  $\sqrt{3}$

4.3.23 If the coordinates of middle point of the portion of a line intercepted between the coordinate axes is (3, 2), then the equation of the line will be

- a)  $2x + 3y = 12$
- b)  $3x + 2y = 12$
- c)  $4x - 3y = 6$

d)  $5x - 2y = 10$

4.3.24 If the line  $\frac{x}{a} + \frac{y}{b} = 1$  passes the points (2, -3) and (4, -5), then (a, b) is

- a) (1, 1)
- b) (-1, 1)
- c) (1, -1)
- d) (-1, -1)

4.3.25 The intercepts made by the plane  $2x - 3y + 5z + 4 = 0$  on the co-ordinate axis are  $(-2, \frac{4}{3}, -\frac{4}{5})$ .

4.3.26 The line  $\vec{r} = 2\hat{i} - 3\hat{j} - \hat{k} + \lambda(\hat{i} - \hat{j} + 2\hat{k})$  lies in the plane  $\vec{r} \cdot (3\hat{i} + \hat{j} - \hat{k}) + 2 = 0$ .

4.3.27 Find the equation of the line joining (1, 2) and (3, 6).

4.3.28 Find the equation of the line joining (3, 1) and (9, 3).

4.3.29 If the point (3, 4) lies on the line  $3y = ax + 7$ , find the value of  $a$ .

4.3.30 Find the equation of the line that passes through the point with position vector  $2\hat{i} - \hat{j} + 4\hat{k}$  and is in direction  $\hat{i} + 2\hat{j} - \hat{k}$ .

4.3.31 The cartesian equation of a line is  $\frac{x-5}{3} = \frac{y+4}{7} = \frac{z-6}{2}$ . Write its vector form.

4.3.32 Find the equation of the line that passes through the origin and (5, -2, 3).

4.3.33 Find the equation of the line that passes through the points (3, -2, -5), (3, -2, 6).

4.3.34 Find the coordinates of the point where the line through (5, 1, 6) and (3, 4, 1) crosses the YZ-plane.

4.3.35 Find the coordinates of the point where the line through (5, 1, 6) and (3, 4, 1) crosses the ZX-plane.

4.3.36 Find the coordinates of the point where the line through (3, -4, -5) and (2, -3, 1) crosses the plane  $2x + y + z = 7$ .

4.3.37 Find the equation of the line through (-2, 3) with slope -4

4.3.38 Write the equation of the line through the points (1, -1) and (3, 5).

4.3.39 Write the equation of the lines for which  $\tan \theta = \frac{1}{2}$ , where  $\theta$  is the inclination of the line and

- a) y-intercept is  $\frac{-3}{2}$
- b) x-intercept is 4.

4.3.40 Find the equation of the lines which makes intercepts -3 and 2 on the x- and y-axes respectively.

4.3.41 Equation of a line is  $3x - 4y + 10 = 0$ , Find its

- a) Slope
- b) x and y-intercepts.

4.3.42 The Fahrenheit temperature  $F$  and absolute temperature  $K$  satisfy a linear equation. Given that  $K = 273$  when  $F = 32$  and that  $K = 373$  when  $F = 212$ . Express  $K$  in terms of  $F$  and find the value of  $F$ , when  $K = 0$ .

4.3.43 A line is such that its segment between the lines  $5x - y + 4 = 0$  and  $3x + 4y - 4 = 0$  is bisected at the point (1, 5). Obtain its equation.

4.3.44 Find the vector equations of the plane passing through the points  $R(2, 5, -3)$ ,  $S(-2, -3, 5)$  and  $T(5, 3, -3)$ .

4.3.45 Find the equation of the plane with intercepts 2, 3 and 4 on the x, y and z - axis respectively.



4.3.46 Show that the lines

$$\frac{x-a+d}{\alpha-\delta} = \frac{y-a}{\alpha} = \frac{z-a-d}{\alpha+\delta} \quad (4.3.46.1)$$

$$\text{and} \quad (4.3.46.2)$$

$$\frac{x-a+c}{\beta-\gamma} = \frac{y-b}{\beta} = \frac{z-b-c}{\beta+\gamma} \quad (4.3.46.3)$$

are coplanar.

4.3.47 Show that the lines

$$\frac{x+3}{-3} = \frac{y-1}{1} = \frac{z-5}{5} \text{ and} \quad (4.3.47.1)$$

$$\frac{x+1}{-1} = \frac{y-2}{2} = \frac{z-5}{5}. \quad (4.3.47.2)$$

are coplanar.

4.3.48 Find the equation for the line passing through the points  $(-1, 0, 2)$  and  $(3, 4, 6)$ .

4.3.49 The Cartesian equation of a line is

$$\frac{x+3}{2} = \frac{y-5}{4} = \frac{z+6}{2} \quad (4.3.49.1)$$

Find the vector equation for the line.

4.3.50 Determine the ratio in which the line  $2x + y - 4 = 0$  divides the line segment joining the points  $\mathbf{A}(2, -2)$  and  $\mathbf{B}(3, 7)$ .

**Solution:** The given equation can be expressed as

$$(2 \quad 1) \mathbf{x} = 4 \quad (4.3.50.1)$$

Using section formula in (4.3.50.1),

$$\mathbf{n}^T \left( \frac{k\mathbf{B} + \mathbf{A}}{k+1} \right) = c \quad (4.3.50.2)$$

$$\Rightarrow k = \frac{c - \mathbf{n}^T \mathbf{A}}{\mathbf{n}^T \mathbf{B} - c} \quad (4.3.50.3)$$

upon simplification. Substituting numerical values,

$$k = \frac{2}{9} \quad (4.3.50.4)$$

See Fig. 4.3.50.1.

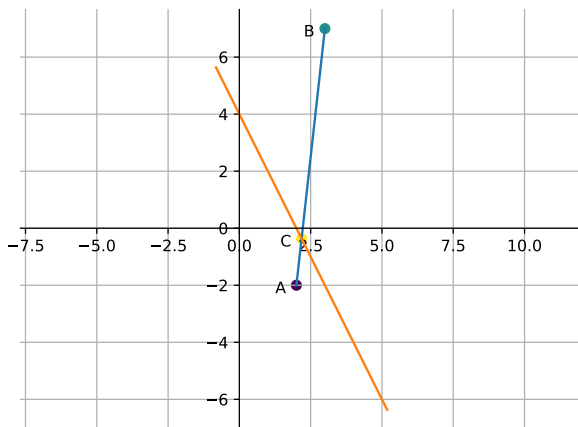


Fig. 4.3.50.1

- 4.3.51 The line segment joining the points **A**(3, 2) and **B**(5, 1) is divided at the point **P** in the ratio 1:2 which lies on  $3x - 18y + k = 0$ . Find the value of  $k$ .
- 4.3.52 Find the ratio in which the line  $2x + 3y - 5 = 0$  divides the line segment joining the points (8, -9) and (2, 1). Also find the coordinates of the point of division.
- 4.3.53 Find the ratio in which the  $YZ$  plane divides the line segment formed by joining the points (-2, 4, 7) and (3, -5, 8).
- 4.3.54 Find the ratio in which the line segment joining the points (4, 8, 10) and (6, 10, -8) is divided by the  $YZ$  plane.
- 4.3.55 Find the ratio in which the  $Y$  axis divides the line segment joining the points (5, -6) and (-1, -4). Also find the point of intersection.
- 4.3.56 In what ratio does the  $X$  axis divide the line segment joining the points (-4, -6) and (-1, 7)? Find the coordinates of the point of division.
- 4.3.57 Find the ratio in which the line segment joining **A**(1, -5) and **B**(-4, 5) is divided by the  $X$  axis. Also find the coordinates of the point of division.
- 4.3.58 A line intersects the  $Y$  axis and  $X$  axis at the points **P** and **Q**, respectively. If (2, 5) is the mid-point of  $PQ$ , then the coordinates of **P** and **Q** are, respectively
- (0, -5) and (2, 0)
  - (0, -10) and (-4, 0)
  - (0, 4) and (-10, 0)
  - (0, -10) and (4, 0)
- 4.3.59 Check which of the following are solutions of the equation  $x - 2y = 4$  and which are not
- (0, 2)
  - (2, 0)

- c)  $(4, 0)$   
 d)  $(\sqrt{2}, 4\sqrt{2})$   
 e)  $(1, 1)$

4.3.60 Equations of the diagonals of the square formed by the lines  $x = 0$ ,  $y = 0$ ,  $x = 1$  and  $y = 1$  are

#### 4.4 Parallel

4.4.1 Find the vector equation of the line passing through  $\begin{pmatrix} 1 & 2 & 3 \end{pmatrix}^T$  and parallel to the planes  $\begin{pmatrix} 1 & -1 & 2 \end{pmatrix} \mathbf{x} = 5$  and  $\begin{pmatrix} 3 & 1 & 1 \end{pmatrix} \mathbf{x} = 6$ .

**Solution:** The direction vector of the line is given by

$$\begin{pmatrix} 1 & -1 & 2 \\ 3 & 1 & 1 \end{pmatrix} \mathbf{m} = 0 \xrightarrow{R_2 \rightarrow -\frac{3}{4}R_1 + \frac{1}{4}R_2} \begin{pmatrix} 1 & -1 & 2 \\ 0 & 1 & -\frac{5}{4} \end{pmatrix} \\ \xrightarrow{R_1 \rightarrow R_1 + R_2} \begin{pmatrix} 1 & 0 & \frac{3}{4} \\ 0 & 1 & -\frac{5}{4} \end{pmatrix} \\ \Rightarrow \mathbf{m} = \begin{pmatrix} -3 \\ 5 \\ 4 \end{pmatrix}$$

$\therefore$  the equation of the line is

$$\mathbf{x} = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} + \lambda \begin{pmatrix} -3 \\ 5 \\ 4 \end{pmatrix} \quad (4.4.1.1)$$

4.4.2 Find the equation of the plane with an intercept 3 on the Y-axis and parallel to ZOY-Plane.

**Solution:** The normal vector to the ZOY plane is

$$\mathbf{n} = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}. \quad (4.4.2.1)$$

Since, Y-axis has the intercept 3, the desired plane passes through the point

$$\mathbf{P} = \begin{pmatrix} 0 \\ 3 \\ 0 \end{pmatrix}. \quad (4.4.2.2)$$

Thus, the equation of the plane is given by,

$$\mathbf{n}^T (\mathbf{x} - \mathbf{P}) = 0 \quad (4.4.2.3)$$

$$\Rightarrow \begin{pmatrix} 0 & 1 & 0 \end{pmatrix} \mathbf{x} = 3 \quad (4.4.2.4)$$

See Fig. 4.4.2.1.

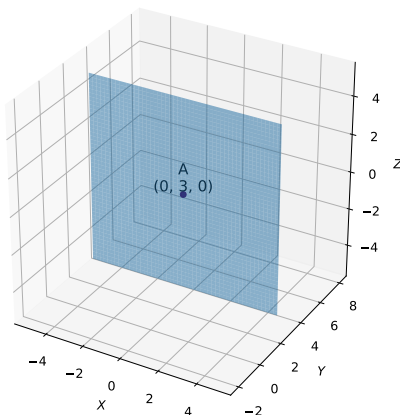


Fig. 4.4.2.1

4.4.3 Find the equation of the line parallel to the line  $3x - 4y + 2 = 0$  and passing through the point  $(-2, 3)$ .

**Solution:**

$$(3 \quad -4)\mathbf{x} = (3 \quad -4)\begin{pmatrix} -2 \\ 3 \end{pmatrix} = -18 \quad (4.4.3.1)$$

is the required equation of the line.

4.4.4 Find the equation of the line through the point  $(0, 2)$  making an angle  $\frac{2\pi}{3}$  with the positive X-axis. Also find the equation of the line parallel to it and crossing the Y-axis at a distance of 2 units below the origin.

**Solution:** The equation of the first line is

$$(\sqrt{3} \quad 1)\left(\mathbf{x} - \begin{pmatrix} 0 \\ 2 \end{pmatrix}\right) = 0 \quad (4.4.4.1)$$

$$\Rightarrow (\sqrt{3} \quad 1)\mathbf{x} = 2 \quad (4.4.4.2)$$

The equation of the second line is

$$(\sqrt{3} \quad 1)\left(\mathbf{x} - \begin{pmatrix} 0 \\ -2 \end{pmatrix}\right) = 0 \quad (4.4.4.3)$$

$$\Rightarrow (\sqrt{3} \quad 1)\mathbf{x} = -2 \quad (4.4.4.4)$$

See Fig. 4.4.4.1.

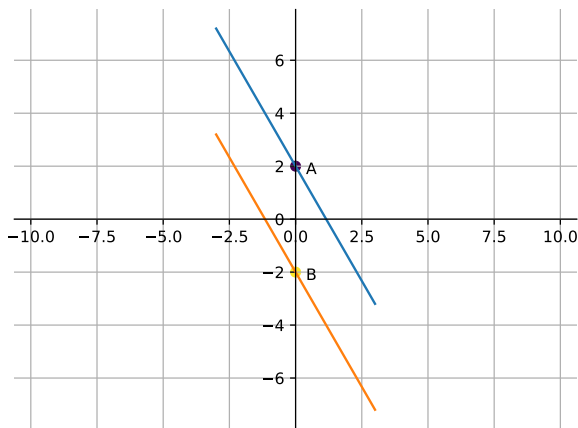


Fig. 4.4.4.1

- 4.4.5 Find the vector equation of the line which is parallel to the vector  $3\hat{i} - 2\hat{j} + 6\hat{k}$  and passes through the point  $(1, -2, 3)$ .
- 4.4.6 Find the equations of the line passing through the point  $(3, 0, 1)$  and parallel to the planes  $x + 2y = 0$  and  $3y - z = 0$ .
- 4.4.7 The equation of a line, which is parallel to  $2\hat{i} + \hat{j} + 3\hat{k}$  and passes through the point  $(5, -2, 4)$  is  $\frac{x-5}{2} = \frac{y+2}{-1} = \frac{z-4}{3}$ .
- 4.4.8 The value of  $\lambda$  for which the vectors  $3\hat{i} - 6\hat{j} + \hat{k}$  and,  $2\hat{i} - 4\hat{j} + \lambda\hat{k}$  are parallel is
- $\frac{2}{3}$
  - $\frac{3}{2}$
  - $\frac{5}{2}$
  - $\frac{2}{5}$
- 4.4.9 Equation of the line passing through  $(1, 2)$  and parallel to the line  $y = 3x - 1$  is
- $y + 2 = x + 1$
  - $y + 2 = 3(x + 1)$
  - $y - 2 = 3(x - 1)$
  - $y - 2 = x - 1$
- 4.4.10 Find the equation of the line which passes through the point  $(1, 2, 3)$  and is parallel to the vector  $3\hat{i} + 2\hat{j} - 2\hat{k}$
- 4.4.11 Find the cartesian equation of the line which passes through the point  $(-2, 4, -5)$  and parallel to the line given by  $\frac{x+3}{3} = \frac{y-4}{5} = \frac{z+8}{6}$ .
- 4.4.12 Find the equation of the plane passing through  $(a, b, c)$  and parallel to the plane  $\vec{r} \cdot (\hat{i} + \hat{j} + \hat{k}) = 2$ .

4.4.13 Find the equations of the lines parallel to axes and passing through  $(2, 3)$ .

4.4.14 Find the equation of the line through the point  $(5, 2, -4)$  and which is parallel to the vector  $3\hat{i} + 2\hat{j} - 8\hat{k}$ .

#### 4.5 Perpendicular

4.5.1 Find the values of  $\theta$  and  $p$ , if the equation  $x \cos \theta + y \sin \theta = p$  is the normal form of the line  $\sqrt{3}x + y + 2 = 0$ .

**Solution:**

$$\mathbf{n} = \begin{pmatrix} \sqrt{3} \\ 1 \end{pmatrix}, c = -2 \quad (4.5.1.1)$$

$$\Rightarrow \theta = \tan^{-1} \left( \frac{1}{\sqrt{3}} \right) = \frac{\pi}{6}, p = \frac{|c|}{\|\mathbf{n}\|} = 1 \quad (4.5.1.2)$$

4.5.2 Reduce the following equations into normal form. Find their perpendicular distances from the origin and angle between perpendicular and the positive  $x$ -axis.

a)  $x - \sqrt{3}y + 8 = 0$

b)  $y - 2 = 0$

c)  $x - y = 4$

**Solution:** See Table 4.5.2. (4.1.6.6) was used for computing the distance from the origin.

	$\mathbf{n}$	Angle	$c$	Distance
a)	$\begin{pmatrix} 1 \\ -\sqrt{3} \end{pmatrix}$	$\tan^{-1}(-\sqrt{3}) = \frac{2\pi}{3}$	-8	4
b)	$\begin{pmatrix} 0 \\ 1 \end{pmatrix}$	$\tan^{-1} \infty = \frac{\pi}{2}$	2	2
c)	$\begin{pmatrix} 1 \\ -1 \end{pmatrix}$	$\tan^{-1}(-1) = \frac{3\pi}{4}$	4	$2\sqrt{2}$

TABLE 4.5.2

4.5.3 In each of the following cases, determine the direction cosines of the normal to the plane and the distance from the origin.

a)  $z = 2$

b)  $x + y + z = 1$

c)  $2x + 3y - z = 5$

d)  $5y + 8 = 0$

**Solution:** See Table 4.5.3. (4.1.6.6) was used for computing the distance from the origin.

	$\mathbf{n}$	$c$	Distance
a)	$\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$	2	2
b)	$\begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$	1	$\frac{1}{\sqrt{3}}$
c)	$\begin{pmatrix} 2 \\ 3 \\ -1 \end{pmatrix}$	5	$\frac{5}{\sqrt{14}}$
d)	$\begin{pmatrix} 0 \\ -5 \\ 0 \end{pmatrix}$	8	$\frac{8}{5}$

TABLE 4.5.3

4.5.4 Find the distance of the point  $(-1, 1)$  from the line  $12(x + 6) = 5(y - 2)$ .

**Solution:**

$$\mathbf{n} = \begin{pmatrix} 12 \\ -5 \end{pmatrix}, c = -82 \quad (4.5.4.1)$$

$$\Rightarrow d = \frac{\left| \begin{pmatrix} 12 & -5 \end{pmatrix} \begin{pmatrix} -1 \\ 1 \end{pmatrix} - (-82) \right|}{\sqrt{12^2 + (-5)^2}} = 5 \quad (4.5.4.2)$$

4.5.5 Find the coordinates of the foot of the perpendicular from  $(-1, 3)$  to the line  $3x - 4y - 16 = 0$ .

**Solution:** Substituting

$$\mathbf{P} = \begin{pmatrix} -1 \\ 3 \end{pmatrix}, \mathbf{n} = \begin{pmatrix} 3 \\ -4 \end{pmatrix}, c = 16 \quad (4.5.5.1)$$

in (4.1.7.1), the desired foot of the perpendicular is then given by

$$\begin{pmatrix} 4 & 3 \\ 3 & -4 \end{pmatrix} \mathbf{Q} = \begin{pmatrix} 4 & 3 \\ 16 \end{pmatrix} \begin{pmatrix} -1 \\ 3 \end{pmatrix} = \begin{pmatrix} 5 \\ 16 \end{pmatrix} \quad (4.5.5.2)$$

$$\Rightarrow \begin{pmatrix} 4 & 3 & 5 \\ 3 & -4 & 16 \end{pmatrix} \xleftrightarrow{R_2 = R_2 - \frac{3}{4}R_1} \begin{pmatrix} 4 & 3 & 5 \\ 0 & -\frac{25}{4} & \frac{49}{4} \end{pmatrix} \quad (4.5.5.3)$$

$$\xleftrightarrow{R_2 = \frac{-4}{25}} \begin{pmatrix} 4 & 3 & 5 \\ 0 & 1 & -\frac{49}{25} \end{pmatrix} \xleftrightarrow{R_1 = \frac{1}{4}R_1} \begin{pmatrix} 1 & \frac{3}{4} & \frac{5}{4} \\ 0 & 1 & -\frac{49}{25} \end{pmatrix} \quad (4.5.5.4)$$

$$\xleftrightarrow{R_1 = R_1 - \frac{3}{4}R_2} \begin{pmatrix} 1 & 0 & \frac{68}{25} \\ 0 & 1 & -\frac{49}{25} \end{pmatrix} \Rightarrow \mathbf{Q} = \begin{pmatrix} \frac{68}{25} \\ -\frac{49}{25} \end{pmatrix} \quad (4.5.5.5)$$

See Fig. 4.5.5.1.

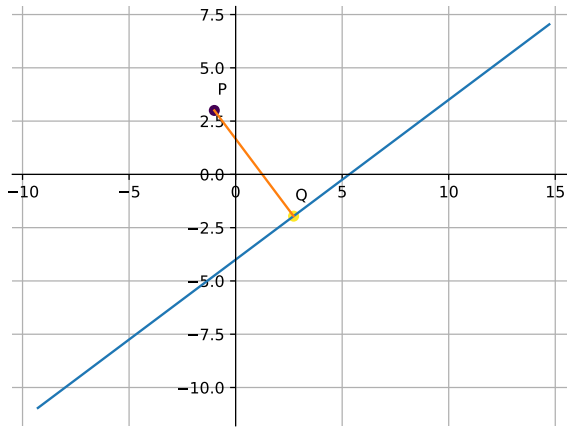


Fig. 4.5.5.1

4.5.6 In the triangle  $ABC$  with vertices  $\mathbf{A}(2, 3)$ ,  $\mathbf{B}(4, -1)$  and  $\mathbf{C}(1, 2)$ , find the equation and length of altitude from the vertex  $\mathbf{A}$ .

**Solution:**

a) The normal vector of the altitude from  $\mathbf{A}$  is,

$$\mathbf{m}_{BC} = \begin{pmatrix} 1 \\ -1 \end{pmatrix}, \because \mathbf{n}_{BC} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}. \quad (4.5.6.1)$$

The equation of the desired altitude is given by

$$\mathbf{m}_{BC}^T \mathbf{x} = \mathbf{m}_{BC}^T \mathbf{A} \quad (4.5.6.2)$$

$$\Rightarrow \begin{pmatrix} 1 & -1 \end{pmatrix} \mathbf{x} = -1 \quad (4.5.6.3)$$

b) The equation of line  $BC$  is given by,

$$\mathbf{n}_{BC}^T \mathbf{x} = \mathbf{n}_{BC}^T \mathbf{B} \quad (4.5.6.4)$$

$$\Rightarrow \begin{pmatrix} 1 & 1 \end{pmatrix} \mathbf{x} = 3 \quad (4.5.6.5)$$

From (4.1.6.6), the length of the desired altitude is

$$d = \sqrt{2} \quad (4.5.6.6)$$

4.5.7 Find the points on the  $x$ -axis, whose distances from the line  $\frac{x}{3} + \frac{y}{4} = 1$  are 4 units.

**Solution:** Let the desired point be

$$\mathbf{P} = x\mathbf{e}_1 = \begin{pmatrix} x \\ 0 \end{pmatrix} \quad (4.5.7.1)$$



From the distance formula,

$$d = \frac{|\mathbf{n}^\top \mathbf{P} - c|}{\|\mathbf{n}\|} = \frac{|x\mathbf{n}^\top \mathbf{e}_1 - c|}{\|\mathbf{n}\|} \quad (4.5.7.2)$$

$$\Rightarrow x = \frac{\pm d \|\mathbf{n}\| + c}{\mathbf{n}^\top \mathbf{e}_1} \quad (4.5.7.3)$$

Substituting

$$\mathbf{n} = \begin{pmatrix} 4 \\ 3 \end{pmatrix}, c = 12, d = 4, \quad (4.5.7.4)$$

$$x = 8, -2 \quad (4.5.7.5)$$

See Fig. 4.5.7.1.

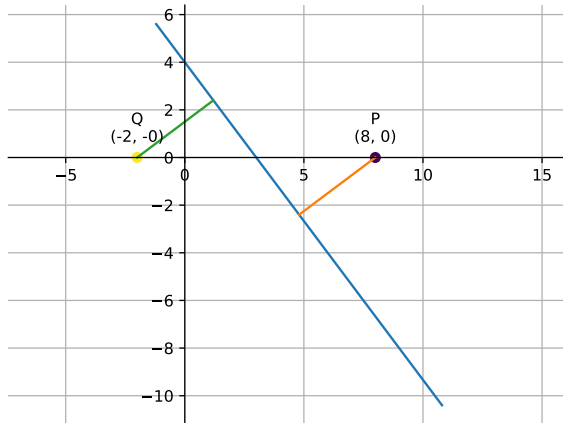


Fig. 4.5.7.1

4.5.8 What are the points on the y-axis whose distance from the line  $\frac{x}{3} + \frac{y}{4} = 1$  is 4 units.

**Solution:** Following the approach in Problem 4.5.7,

$$y = \frac{\pm d \|\mathbf{n}\| + c}{\mathbf{n}^\top \mathbf{e}_2} = \frac{32}{3}, \frac{-8}{3}. \quad (4.5.8.1)$$

4.5.9 Find the distance between parallel lines

a)  $15x + 8y - 34 = 0$  and  $15x + 8y + 31 = 0$

b)  $l(x + y) + p = 0$  and  $l(x + y) - r = 0$

**Solution:** From (4.1.8.1), the desired values are available in Table 4.5.9.

	<b>n</b>	$c_1$	$c_2$	$d$
a)	$\begin{pmatrix} 15 \\ 8 \end{pmatrix}$	34	-31	$\frac{65}{17}$
b)	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\frac{-p}{l}$	$\frac{r}{l}$	$\frac{ p-r }{l\sqrt{2}}$

TABLE 4.5.9

4.5.10 Find the equation of a line which is equidistant from parallel lines  $9x + 6y - 7 = 0$  and  $3x + 2y + 6 = 0$ .

**Solution:** Given

$$c_1 = \frac{7}{3}, c_2 = -6. \quad (4.5.10.1)$$

From (4.1.8.1), we need to find  $c$  such that,

$$|c - c_1| = |c - c_2| \implies c = \frac{c_1 + c_2}{2} = -\frac{11}{6}. \quad (4.5.10.2)$$

Hence, the desired equation is

$$(3 \ 2)\mathbf{x} = -\frac{11}{6} \quad (4.5.10.3)$$

See Fig. 4.5.10.1.

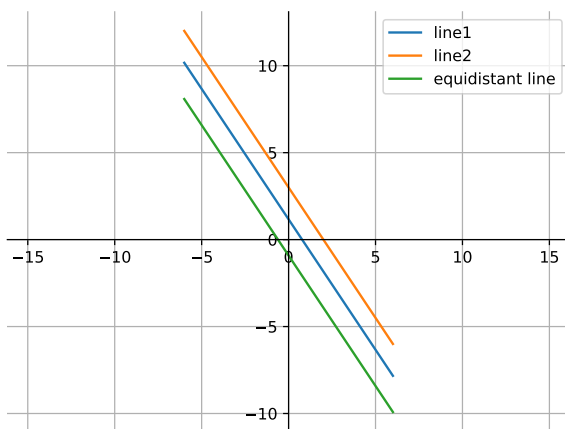


Fig. 4.5.10.1

4.5.11 Find the equation of a line drawn perpendicular to the line  $\frac{x}{4} + \frac{y}{6} = 1$  through the point where it meets the y-axis

**Solution:** The given line parameters are

$$\mathbf{n} = \begin{pmatrix} 3 \\ 2 \end{pmatrix}, c = 12, \mathbf{m} = \begin{pmatrix} -2 \\ 3 \end{pmatrix}. \quad (4.5.11.1)$$

and the point on the  $y$ -axis is

$$\mathbf{A} = \begin{pmatrix} 0 \\ 6 \end{pmatrix}. \quad (4.5.11.2)$$

Thus, the equation of the desired line is

$$\mathbf{m}^\top (\mathbf{x} - \mathbf{A}) = 0 \quad (4.5.11.3)$$

$$\Rightarrow \begin{pmatrix} -2 & 3 \end{pmatrix} \mathbf{x} = -18 \quad (4.5.11.4)$$

4.5.12 Find the equation of a line whose perpendicular distance from the origin is 5 units and the angle made by the perpendicular with the positive  $x$ -axis is  $30^\circ$ .

**Solution:** From (4.1.5.3), Thus, the equation of lines are

$$\left( \frac{\sqrt{3}}{2} \quad \frac{1}{2} \right) \mathbf{x} = \pm 5 \quad (4.5.12.1)$$

4.5.13 Find the equation of the line passing through  $(-3, 5)$  and perpendicular to the line through the points  $(2, 5)$  and  $(-3, 6)$ .

**Solution:** See Fig. 4.5.13.1.

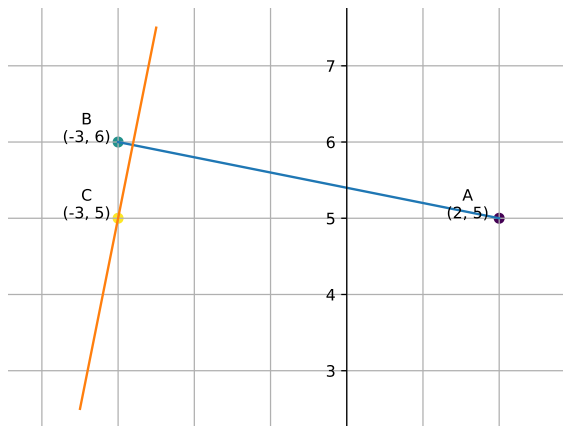


Fig. 4.5.13.1

The normal vector is

$$\mathbf{n} = \begin{pmatrix} 2 \\ 5 \end{pmatrix} - \begin{pmatrix} -3 \\ 6 \end{pmatrix} = \begin{pmatrix} 5 \\ -1 \end{pmatrix} \quad (4.5.13.1)$$

Thus, the equation of the line is

$$(5 \ -1) \left( \mathbf{x} - \begin{pmatrix} -3 \\ 5 \end{pmatrix} \right) = 0 \quad (4.5.13.2)$$

$$\Rightarrow (5 \ -1) \mathbf{x} = -20 \quad (4.5.13.3)$$

4.5.14 The perpendicular from the origin to a line meets it at the point  $(-2, 9)$ . Find the equation of the line.

**Solution:** It is obvious that the normal vector to the line is

$$\mathbf{n} = \begin{pmatrix} 2 \\ -9 \end{pmatrix} - \mathbf{0} = \begin{pmatrix} 2 \\ -9 \end{pmatrix} \quad (4.5.14.1)$$

Hence, the equation of the line is

$$(2 \ -9) \left( \mathbf{x} - \begin{pmatrix} 2 \\ -9 \end{pmatrix} \right) = 0 \quad (4.5.14.2)$$

$$\Rightarrow (2 \ -9) \mathbf{x} = 85 \quad (4.5.14.3)$$

See Fig. 4.5.14.1.

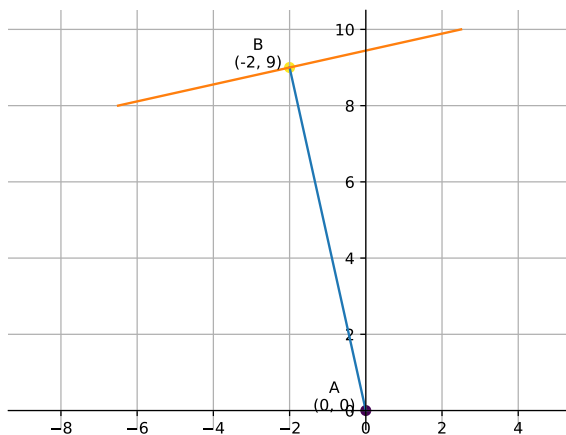


Fig. 4.5.14.1

4.5.15 Find the equation of line perpendicular to the line  $x - 7y + 5 = 0$  and having  $x$  intercept 3

**Solution:** The desired equation is

$$(7 \ 1) \left( \mathbf{x} - \begin{pmatrix} 3 \\ 0 \end{pmatrix} \right) = 0 \quad (4.5.15.1)$$

$$\implies (7 \ 1) \mathbf{x} = 21 \quad (4.5.15.2)$$

4.5.16 Find the equation of the line passing through the point  $(1, 2, -4)$  and perpendicular to the two lines

$$\frac{x-8}{3} = \frac{y+19}{-16} = \frac{z-10}{7} \text{ and} \quad (4.5.16.1)$$

$$\frac{x-15}{3} = \frac{y-29}{8} = \frac{z-5}{-5} \quad (4.5.16.2)$$

**Solution:** The direction vector of the desired line is given by

$$\begin{pmatrix} 3 & -16 & 7 \\ 3 & 8 & -5 \end{pmatrix} \mathbf{m} = 0 \xrightarrow{R_2 \leftarrow R_2 - R_1} \begin{pmatrix} 3 & -16 & 7 \\ 0 & 24 & -12 \end{pmatrix} \\ \xrightarrow{R_1 \leftarrow R_1 + \frac{2}{3}R_2} \begin{pmatrix} 3 & 0 & -1 \\ 0 & 24 & -12 \end{pmatrix} \xrightarrow{R_2 \leftarrow R_2/12} \begin{pmatrix} 3 & 0 & -1 \\ 0 & 2 & -1 \end{pmatrix}$$

yielding

$$\mathbf{m} = \begin{pmatrix} 2 \\ 3 \\ 6 \end{pmatrix} \quad (4.5.16.3)$$

Hence the vector equation of the line passing through  $(1, 2, -4)$  is,

$$\mathbf{x} = \begin{pmatrix} 1 \\ 2 \\ -4 \end{pmatrix} + \kappa \begin{pmatrix} 2 \\ 3 \\ 6 \end{pmatrix} \quad (4.5.16.4)$$

4.5.17 The perpendicular from the origin to the line  $y = mx + c$  meets it at the point  $(-1, 2)$ . Find the values of  $m$  and  $c$ .

**Solution:** From Problem 4.5.14,

$$\mathbf{n} = \begin{pmatrix} -1 \\ 2 \end{pmatrix} \implies m = \frac{1}{2} \quad (4.5.17.1)$$

Also, from the given equation of the line and the given point,

$$c = (-m \ 1) \begin{pmatrix} -1 \\ 2 \end{pmatrix} = \frac{5}{2} \quad (4.5.17.2)$$

4.5.18 A line perpendicular to the line segment joining the points  $\mathbf{P}(1, 0)$  and  $\mathbf{Q}(2, 3)$  divides it in the ratio  $1 : n$ . Find the equation of the line.

**Solution:** The direction vector of  $PQ$  is

$$\mathbf{Q} - \mathbf{P} = \begin{pmatrix} 1 \\ 3 \end{pmatrix} \quad (4.5.18.1)$$

Using section formula,

$$\mathbf{R} = \frac{\mathbf{Q} + n\mathbf{P}}{1+n} \quad (4.5.18.2)$$

is the point of intersection. The equation of the desired line is

$$\mathbf{m}^T (\mathbf{x} - \mathbf{R}) = 0 \quad (4.5.18.3)$$

$$\Rightarrow \begin{pmatrix} 1 & 3 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 1 & 3 \end{pmatrix} \begin{pmatrix} \frac{2+n}{1+n} \\ \frac{1+\frac{3}{2}n}{1+n} \end{pmatrix} \quad (4.5.18.4)$$

$$= \frac{11+n}{1+n} \quad (4.5.18.5)$$

4.5.19 Find the vector equation of a plane which is at a distance of 7 units from the origin and normal to the vector  $3\hat{i} + 5\hat{j} - 6\hat{k}$ .

**Solution:** From the given information,

$$\mathbf{n} = \begin{pmatrix} 3 \\ 5 \\ -6 \end{pmatrix}, d = \frac{|c|}{\|\mathbf{n}\|} = 7 \quad (4.5.19.1)$$

$$\Rightarrow c = \pm 7\sqrt{70} \quad (4.5.19.2)$$

4.5.20 Find the equation of a plane which is at a distance  $3\sqrt{3}$  units from origin and the normal to which is equally inclined to the coordinate axis.

4.5.21 If the line drawn from the point  $(-2, -1, -3)$  meets a plane at right angle at the point  $(1, -3, 3)$ , find the equation of the plane.

4.5.22 Find the equation of the plane through the points  $(2, 1, -1)$  and  $(-1, 3, 4)$ , and perpendicular to the plane  $x - 2y + 4z = 10$ .

4.5.23 If the foot of perpendicular drawn from the origin to a plane is  $(5, -3, -2)$ , then the equation of the plane is  $\vec{r} \cdot (5\hat{i} - 3\hat{j} - 2\hat{k}) = 38$ .

4.5.24  $\mathbf{P}(0, 2)$  is the point of intersection of y-axis and perpendicular bisector of line segment joining the points  $\mathbf{A}(-1, 1)$  and  $\mathbf{B}(3, 3)$ .

4.5.25 The distance of the point  $\mathbf{P}(2, 3)$  from the x-axis is

- a) 2
- b) 3
- c) 1
- d) 5

4.5.26 Find the foot of perpendicular from the point  $(2, 3, -8)$  to the line

$$\frac{4-x}{2} = \frac{y}{6} = \frac{1-z}{3}.$$

Also, find the perpendicular distance from the given point to the line.

4.5.27 Find the distance of a point  $(2, 4, -1)$  from the line

$$\frac{x+5}{1} = \frac{y+3}{4} = \frac{z-6}{-9}$$

- 4.5.28 Find the length and the foot of perpendicular from the point  $\left(1, \frac{3}{2}, 2\right)$  to the plane  $2x - 2y + 4z + 5 = 0$ .
- 4.5.29 Show that the points  $(\hat{i} - \hat{j} + 3\hat{k})$  and  $3(\hat{i} + \hat{j} + \hat{k})$  are equidistant from the plane  $\vec{r} \cdot (5\hat{i} + 2\hat{j} - 7\hat{k}) + 9 = 0$  and lie on opposite side of it.
- 4.5.30 The distance of the plane  $\vec{r} \cdot \left(\frac{2}{7}\hat{i} + \frac{3}{7}\hat{j} - \frac{6}{7}\hat{k}\right) = 1$  from the origin is
- 1
  - 7
  - $\frac{1}{7}$
  - None of these
- 4.5.31 Find the equation of the line passing through the point (5, 2) and perpendicular to the line joining the points (2, 3) and (3, -1).
- 4.5.32 Find the points on the line  $x + y = 4$  which lie at a unit distance from the line  $4x + 3y = 10$ .
- 4.5.33 Find the equation of a straight line on which length of perpendicular from the origin is four units and the line makes an angle of  $120^\circ$  with the positive direction of  $x$ -axis.
- 4.5.34 Find the equation of one of the sides of an isosceles right angled triangle whose hypotenuse is given by  $3x + 4y = 4$  and the opposite vertex of the hypotenuse is (2, 2).
- 4.5.35 In what direction should a line be drawn through the point (1, 2) so that its point of intersection with line  $x + y = 4$  is at a distance  $\sqrt{63}$ .
- 4.5.36 The equation of the straight line passing through the point (3, 2) and perpendicular to the line  $y = x$  is
- $x - y = 5$
  - $x + y = 5$
  - $x + y = 1$
  - $x - y = 1$
- 4.5.37 The equation of the line passing through the point (1, 2) and perpendicular to the line  $x + y + 1 = 0$  is
- $y - x + 1 = 0$
  - $y - x - 1 = 0$
  - $y - x + 2 = 0$
  - $y - x - 1 = 0$
- 4.5.38 The distance of the point of intersection of the lines  $2x - 3y + 5 = 0$  and  $3x + 4y = 0$  from the line  $5x - 2y = 0$  is
- $\frac{130}{17\sqrt{29}}$
  - $\frac{13}{7\sqrt{29}}$
  - $\frac{130}{7}$
  - none of these
- 4.5.39 The equations of the lines passing through the point (1, 0) and at a distance  $\frac{\sqrt{3}}{2}$  from the origin, are
- $\sqrt{3}x + y - \sqrt{3} = 0, \sqrt{3}x - y - \sqrt{3} = 0$

- b)  $\sqrt{3}x + y + \sqrt{3} = 0$ ,  $\sqrt{3}x - y + \sqrt{3} = 0$   
 c)  $x + \sqrt{3}y - \sqrt{3} = 0$ ,  $\sqrt{3}y - \sqrt{3} = 0$   
 d) None of these.

4.5.40 The coordinates of the foot of perpendiculars from the point (2, 3) on the line  $y = 3x + 4$  is given by

- a)  $\frac{37}{10}, \frac{-1}{10}$   
 b)  $\frac{-1}{10}, \frac{37}{10}$   
 c)  $\frac{10}{37}, -10$   
 d)  $\frac{37}{3}, \frac{-1}{3}$

4.5.41 A point equidistant from the lines  $4x + 3y + 10 = 0$ ,  $5x - 12y + 26 = 0$  and  $7x + 24y - 50 = 0$  is

- a) (1, -1)  
 b) (1, 1)  
 c) (0, 0)  
 d) (0, 1)

4.5.42 A line passes through (2, 2) and is perpendicular to the line  $3x + y = 3$ . Its y-intercept is

- a)  $\frac{1}{3}$   
 b)  $\frac{2}{3}$   
 c) 1  
 d)  $\frac{4}{3}$

4.5.43 The ratio in which the line  $3x + 4y + 2 = 0$  divides the distance between the lines  $3x + 4y + 5 = 0$  and  $3x + 4y - 5 = 0$  is

- a) 1:2  
 b) 3:7  
 c) 2:3  
 d) 2:5

4.5.44 Find the vector equation of the line passing through (1, 2, 3) and perpendicular to the plane  $\vec{r} \cdot (\hat{i} + 2\hat{j} - 5\hat{k}) + 9 = 0$ .

4.5.45 Find the equation of the plane passing through the point (-1, 3, 2) and perpendicular to each of the planes  $x + 2y + 3z = 5$  and  $3x + 3y + z = 0$ .

4.5.46 If the points (1, 1,  $p$ ) and (-3, 0, 1) be equidistant from the plane  $\vec{r} \cdot (3\hat{i} + 4\hat{j} - 12\hat{k}) + 13 = 0$ , then find the value of  $p$ .

4.5.47 If  $O$  be the origin and the coordinates of  $P$  be (1, 2, -3), then find the equation of the plane passing through  $P$  and perpendicular to  $OP$ .

4.5.48 Find the vector equations of the line passing through the point (1, 2, -4) and perpendicular to the two lines:

$$\frac{x-8}{3} = \frac{y+19}{-16} = \frac{z-10}{7} \text{ and } \frac{x-15}{3} = \frac{y-29}{8} = \frac{z-5}{-5}. \quad (4.5.48.1)$$

4.5.49 Distance between the two planes:  $2x + 3y + 4z = 4$  and  $4x + 6y + 8z = 12$  is

- a) 2 units  
 b) 4 units



c) 8 units

d)  $\frac{2}{\sqrt{29}}$  units

4.5.50 Find the equation of the line whose perpendicular distance from the origin is 4 units and the angle which the normal makes with positive direction of x-axis is  $15^\circ$ .

4.5.51 Find the distance of the point  $(3, -5)$  from the line  $3x - 4y - 26 = 0$ .

4.5.52 Find the distance between the parallel lines  $3x - 4y + 7 = 0$  and  $3x - 4y + 5 = 0$ .

4.5.53 Find the equation of a line perpendicular to the line  $x + 2y + 3 = 0$  and passing through the point  $(1, -2)$ .

4.5.54 Reduce the equation  $\sqrt{3}x + y - 8 = 0$  into normal form. Find the values of  $p$  and  $\omega$ .

4.5.55 Show that the path of a moving point such that its distances from two lines  $3x - 2y = 5$  and  $3x + 2y = 5$  are equal is a straight line.

4.5.56 Find the distance of the line  $4x - y - 0$  from the point  $p(4, 1)$  measured along the line making an angle of  $135^\circ$  with the positive x-axis.

4.5.57 Find the coordinates of the foot of the perpendicular drawn from the origin to the plane  $2x - 3y + 4z - 6 = 0$ .

4.5.58 Find the equation of the plane which passes through the point  $(5, 2, -4)$  and perpendicular to the line with direction ratios  $2, 3, -1$ .

4.5.59 Find the equation of the plane that contains the point  $(1, -1, 2)$  and is perpendicular to each of the planes  $2x + 3y - 2z = 5$  and  $x + 2y - 3z = 8$ .

4.5.60 Find the distance between the point  $P(6, 5, 9)$  and the plane determined by the points  $A(3, -12), B(5, 2, 4)$  and  $C(-1, -1, 6)$

4.5.61 Find the distance of a point  $(2, 5, -3)$  from the plane  $\vec{r} \cdot (6\hat{i} - 3\hat{j} + 2\hat{k}) = 4$ .

4.5.62 Find the distance of the plane  $2x - 3y + 4z - 6 = 0$  from the origin.

4.5.63 Find the vector equation of the plane which is at a distance of  $\frac{6}{\sqrt{29}}$  from the origin and its normal vector from the origin is  $2\hat{i} - 3\hat{j} + 4\hat{k}$ .

4.5.64 Find the distance between the lines  $l_1$  and  $l_2$  given by

$$\vec{r} = \hat{i} + 2\hat{j} - 4\hat{k} + \lambda(2\hat{i} + 3\hat{j} + 6\hat{k}) \quad (4.5.64.1)$$

$$\text{and } \vec{r} = 3\hat{i} + 3\hat{j} - 5\hat{k} + \mu(2\hat{i} + 3\hat{j} + 6\hat{k}) \quad (4.5.64.2)$$

4.5.65 Find the shortest distance between the lines  $l_1$  and  $l_2$  whose vector equations are

$$\vec{r} = \hat{i} + \hat{j} + \lambda(2\hat{i} - \hat{j} + \hat{k}) \quad (4.5.65.1)$$

$$\text{and } \vec{r} = 2\hat{i} + \hat{j} - \hat{k} + \mu(3\hat{i} - 5\hat{j} + 2\hat{k}) \quad (4.5.65.2)$$

4.5.66 The line through the points  $(h, 3)$  and  $(4, 1)$  intersects the line  $7x - 9y - 19 = 0$  at a right angle. Find the value of  $h$ .

**Solution:** The direction vectors of the given lines are

$$\left( \begin{matrix} 4-h \\ -2 \end{matrix} \right), \left( \begin{matrix} 9 \\ 7 \end{matrix} \right) \quad (4.5.66.1)$$

$$\Rightarrow \left( \begin{matrix} 9 & 7 \end{matrix} \right) \left( \begin{matrix} 4-h \\ -2 \end{matrix} \right) = 0 \quad (4.5.66.2)$$

$$\Rightarrow h = \frac{22}{9} \quad (4.5.66.3)$$

See Fig. 4.5.66.1.

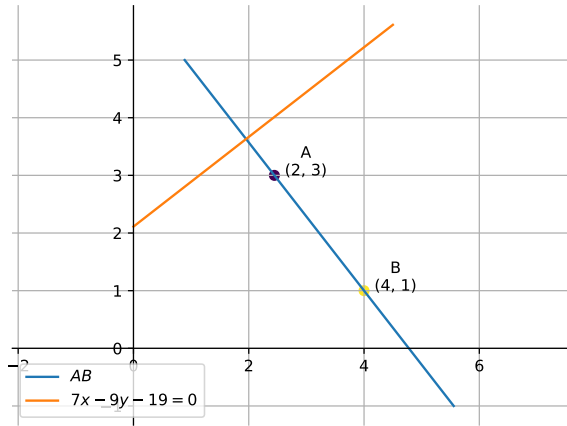


Fig. 4.5.66.1

4.5.67 If the lines  $\frac{x-1}{-3} = \frac{y-2}{2k} = \frac{z-3}{2}$  and  $\frac{x-1}{3k} = \frac{y-1}{1} = \frac{z-6}{-5}$  are perpendicular, find the value of  $k$ .

**Solution:** From the given information,

$$\mathbf{m}_1 = \begin{pmatrix} -3 \\ 2k \\ 2 \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 3k \\ 1 \\ -5 \end{pmatrix} \quad (4.5.67.1)$$

$$\Rightarrow \begin{pmatrix} -3 & 2k & 2 \end{pmatrix}^\top \begin{pmatrix} 3k \\ 1 \\ -5 \end{pmatrix} = 0 \quad (4.5.67.2)$$

$$\Rightarrow k = -\frac{10}{7} \quad (4.5.67.3)$$

## 4.6 Angle

4.6.1 Two lines passing through the point (2, 3) intersect each other at an angle of  $60^\circ$ . If the slope of one line is 2, find the equation of the other line.

**Solution:** Using the scalar product

$$\cos 60^\circ = \frac{1}{2} = \frac{\begin{pmatrix} 1 & 2 \end{pmatrix} \begin{pmatrix} 1 \\ m \end{pmatrix}}{\sqrt{5} \sqrt{m^2 + 1}} \quad (4.6.1.1)$$

$$\Rightarrow 11m^2 + 16m - 1 = 0 \quad (4.6.1.2)$$

$$\text{or, } m = \frac{-8 \pm 5\sqrt{3}}{11} \quad (4.6.1.3)$$

So, the desired equation of the line is

$$\left( \frac{-8 \pm 5\sqrt{3}}{11} \quad -1 \right) \mathbf{x} = \left( \frac{-8 \pm 5\sqrt{3}}{11} \quad -1 \right) \begin{pmatrix} 2 \\ 3 \end{pmatrix} \quad (4.6.1.4)$$

$$= \frac{-49 \pm 16\sqrt{3}}{11} \quad (4.6.1.5)$$

4.6.2 Find the equation of the lines through the point (3, 2) which make an angle of  $45^\circ$  with the line  $x-2y = 3$ .

**Solution:** Following the approach in Problem 4.6.1,

$$\cos 45^\circ = \frac{1}{\sqrt{2}} = \frac{\begin{pmatrix} 2 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ m \end{pmatrix}}{\left\| \begin{pmatrix} 2 \\ 1 \end{pmatrix} \right\| \left\| \begin{pmatrix} 1 \\ m \end{pmatrix} \right\|} \quad (4.6.2.1)$$

$$\Rightarrow 3m^2 - 8m - 3 = 0 \quad (4.6.2.2)$$

$$\text{or, } m = -\frac{1}{3}, 3 \quad (4.6.2.3)$$

Thus, the desired equations are

$$\begin{pmatrix} 1 & 3 \end{pmatrix} \left\{ \mathbf{x} - \begin{pmatrix} 3 \\ 2 \end{pmatrix} \right\} = 0 \quad (4.6.2.4)$$

$$\Rightarrow \begin{pmatrix} 1 & 3 \end{pmatrix} \mathbf{x} = 9 \quad (4.6.2.5)$$

and

$$\begin{pmatrix} 3 & -1 \end{pmatrix} \left\{ \mathbf{x} - \begin{pmatrix} 3 \\ 2 \end{pmatrix} \right\} = 0 \quad (4.6.2.6)$$

$$\Rightarrow \begin{pmatrix} 3 & -1 \end{pmatrix} \mathbf{x} = 7 \quad (4.6.2.7)$$

See Fig. 4.6.2.1.

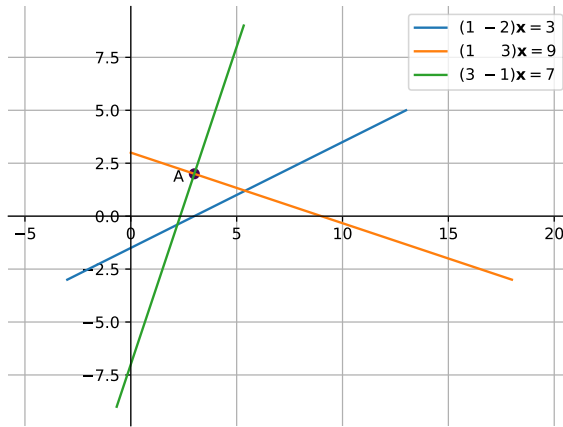


Fig. 4.6.2.1

- 4.6.3 Find the equations of the two lines through the origin which intersect the line  $\frac{x-3}{2} = \frac{y-3}{1} = \frac{z}{1}$  at angles of  $\frac{\pi}{3}$  each.
- 4.6.4 The equations of the lines which pass through the point (3, -2) and are inclined at  $60^\circ$  to the line  $\sqrt{3}x + y = 1$  is
- $y + 2 = 0, \sqrt{3}x - y - 2 - 3\sqrt{3} = 0$
  - $x - 2 = 0, \sqrt{3}x - y + 2 + 3\sqrt{3} = 0$
  - $\sqrt{3}x - y - 2 - 3\sqrt{3} = 0$
  - None of these
- 4.6.5 Equations of the lines through the point (3,2) and making an angle of  $40^\circ$  with the line  $x - 2y = 3$  are \_\_\_\_\_.

#### 4.7 Intersection

- 4.7.1 Find the equation of the plane through the intersection of the planes  $3x - y + 2z - 4 = 0$  and  $x + y + z - 2 = 0$  and the point  $\begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix}$ .

**Solution:** The parameters of the given planes are

$$\mathbf{n}_1 = \begin{pmatrix} 3 \\ -1 \\ 2 \end{pmatrix}, \mathbf{n}_2 = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, c_1 = 4, c_2 = 2. \quad (4.7.1.1)$$

The intersection of the planes is given as

$$\mathbf{n}_1^T \mathbf{x} - c_1 + \lambda (\mathbf{n}_2^T \mathbf{x} - c_2) = 0 \quad (4.7.1.2)$$

where

$$\lambda = \frac{c_1 - \mathbf{n}_1^\top \mathbf{P}}{\mathbf{n}_2^\top \mathbf{P} - c_2} = -\frac{2}{3} \quad (4.7.1.3)$$

upon substituting

$$\mathbf{P} = \begin{pmatrix} 2 \\ 2 \\ 1 \end{pmatrix}. \quad (4.7.1.4)$$

in (4.7.1.3) along with the numerical values in (4.7.1.1). Now, substituting (4.7.1.3) in (4.7.1.2), the equation of plane is

$$(7 \quad -5 \quad 4)\mathbf{x} = 8 \quad (4.7.1.5)$$

4.7.2 Find the equation of the line parallel to y-axis and drawn through the point of intersection of the lines  $x - 7y + 5 = 0$  and  $3x + y = 0$ .

**Solution:** Following the approach in Problem 4.7.1, the desired equation is

$$(1 \quad -7)\mathbf{x} - 5 + k(3 \quad 1)\mathbf{x} = 0 \quad (4.7.2.1)$$

$$\Rightarrow (1 + 3k \quad -7 + k)\mathbf{x} = 5 \quad (4.7.2.2)$$

$$\Rightarrow \begin{pmatrix} 1 + 3k \\ -7 + k \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ 0 \end{pmatrix} \text{ or, } k = 7, \alpha = 22. \quad (4.7.2.3)$$

The desired equation is then given by

$$(1 \quad 0)\mathbf{x} = \frac{5}{22} \quad (4.7.2.4)$$

The intersection of the lines is obtained using the augmented matrix as

$$\left( \begin{array}{cc|c} 1 & -7 & -5 \\ 3 & 1 & 0 \end{array} \right) \xleftarrow[R_1=22R_1+7R_2]{R_2=R_2-3R_1} \left( \begin{array}{cc|c} 22 & 0 & -5 \\ 0 & 22 & 15 \end{array} \right) \quad (4.7.2.5)$$

$$\Rightarrow \mathbf{x} = \frac{5}{22} \begin{pmatrix} -1 \\ 3 \end{pmatrix} \quad (4.7.2.6)$$

See Fig. 4.7.2.1.

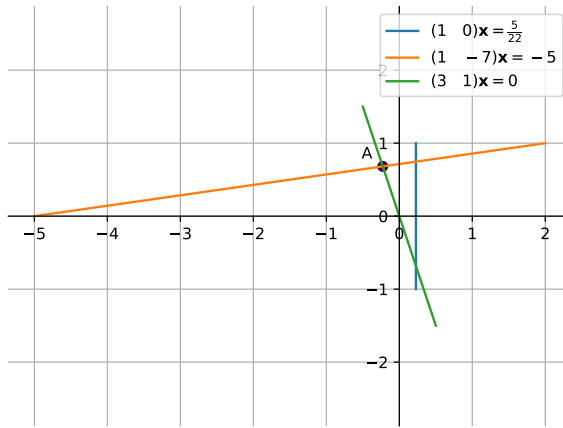


Fig. 4.7.2.1

4.7.3 A person standing at the junction (crossing) of two straight paths represented by the equations

$$(2 \ -3)\mathbf{x} = -4 \quad (4.7.3.1)$$

and

$$(3 \ 4)\mathbf{x} = 5 \quad (4.7.3.2)$$

wants to reach the path whose equation is

$$(6 \ -7)\mathbf{x} = -8 \quad (4.7.3.3)$$

Find equation of the path that he should follow.

**Solution:** The junction of (4.7.3.1) and (4.7.3.2) is obtained as

$$\begin{pmatrix} 2 & -3 & -4 \\ 3 & 4 & 5 \end{pmatrix} \xrightarrow{R_2 \rightarrow 2R_2 - 3R_1} \begin{pmatrix} 2 & -3 & -4 \\ 0 & 17 & 22 \end{pmatrix} \xrightarrow{R_1 \rightarrow 17R_1 + 3R_2} \begin{pmatrix} 17 & 0 & -1 \\ 0 & 17 & 22 \end{pmatrix} \Rightarrow \mathbf{A} = \frac{1}{17} \begin{pmatrix} -1 \\ -22 \end{pmatrix}$$

Clearly, the man should follow the path perpendicular to (4.7.3.3) from **A** to reach it in the shortest time. The normal vector of (4.7.3.3) is

$$\begin{pmatrix} 6 \\ -7 \end{pmatrix} \Rightarrow \mathbf{n} = \begin{pmatrix} 7 \\ 6 \end{pmatrix} \quad (4.7.3.4)$$

and the equation of the desired line is

$$(7 \ 6)\mathbf{x} = \frac{1}{17}(7 \ 6)\begin{pmatrix} -1 \\ 22 \end{pmatrix} = \frac{125}{17} \quad (4.7.3.5)$$

See Fig. 4.7.3.1.

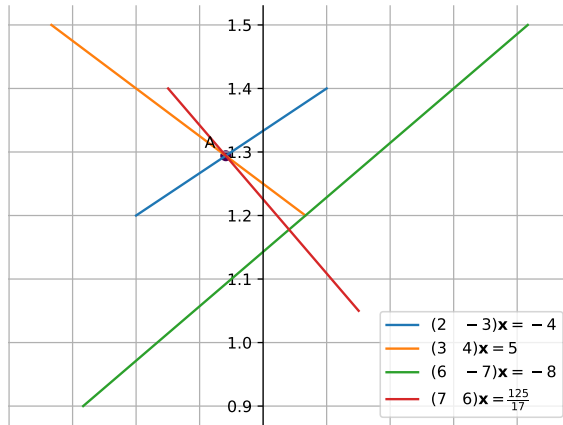


Fig. 4.7.3.1

4.7.4 Find the equation of the line passing through the point of intersection of the lines  $4x + 7y - 3 = 0$  and  $2x - 3y + 1 = 0$  that has equal intercepts on the axes.

**Solution:** From Problem 4.7.1, the intersection of the lines is given by

$$(4 + 2k \ 7 - 3k)\mathbf{x} = 3 - k \quad (4.7.4.1)$$

$$\Rightarrow \begin{pmatrix} 4 + 2k \\ 7 - 3k \end{pmatrix} = \alpha \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (4.7.4.2)$$

from Problem 4.3.16, yielding,

$$\left( \begin{array}{cc|c} 1 & -2 & 4 \\ 1 & 3 & 7 \end{array} \right) \xrightarrow{R_2=R_2-R_1} \left( \begin{array}{cc|c} 1 & -2 & 4 \\ 0 & 5 & 3 \end{array} \right) \quad (4.7.4.3)$$

$$\text{or, } k = \frac{3}{5} \quad (4.7.4.4)$$

Substituting the above in (4.7.4.1), the desired equation is

$$(1 \ 1)\mathbf{x} = \frac{6}{13} \quad (4.7.4.5)$$

See Fig. 4.7.4.1.

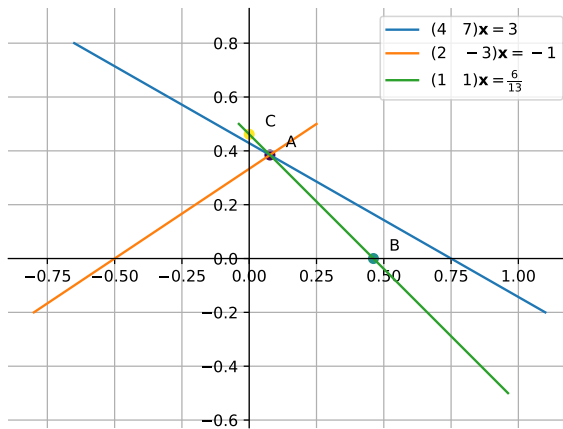


Fig. 4.7.4.1

4.7.5 Find the value of  $p$  so that the three lines  $3x + y - 2 = 0$ ,  $px + 2y - 3 = 0$  and  $2x - y - 3 = 0$  may intersect at one point.

**Solution:** Performing row operations on the matrix

$$\begin{aligned}
 &\begin{pmatrix} 3 & 1 & -2 \\ p & 2 & -3 \\ 2 & -1 & -3 \end{pmatrix} \xrightarrow{\substack{R_2=3R_2-pR_1 \\ R_3=3R_3-2R_1}} \begin{pmatrix} 3 & 1 & -2 \\ 0 & 6-p & -9+2p \\ 0 & -5 & -5 \end{pmatrix} \\
 &\xrightarrow{R_3=R_3(6-p)+5R_2} \begin{pmatrix} 3 & 1 & -2 \\ 0 & 6-p & -9+2p \\ 0 & 0 & -75+15p \end{pmatrix} \\
 &\implies p = 5
 \end{aligned}$$

Substituting this value in the above, we obtain

$$\begin{pmatrix} 3 & 1 & -2 \\ 0 & 1 & 1 \\ 0 & 0 & 0 \end{pmatrix} \quad (4.7.5.1)$$

yielding

$$\mathbf{x} = \begin{pmatrix} -1 \\ 1 \end{pmatrix} \quad (4.7.5.2)$$

as the point of intersection. See Fig. 4.7.5.1.



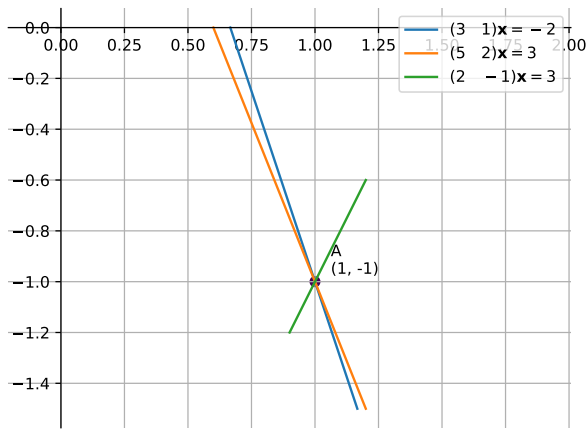


Fig. 4.7.5.1

4.7.6 Show that the lines

$$\frac{x-1}{2} = \frac{y-2}{3} = \frac{z-3}{4}$$

and

$$\frac{x-4}{5} = \frac{y-1}{2} = z$$

intersect. Also, find their point of intersection.

4.7.7 The area of the region bounded by the curve  $y = x + 1$  and the lines  $x = 2$  and  $x = 3$  is

- $\frac{7}{2}$  sq units
- $\frac{9}{2}$  sq units
- $\frac{11}{2}$  sq units
- $\frac{13}{2}$  sq units

4.7.8 Compute the area bounded by the line  $x + 2y = 2$ ,  $y - x = 1$  and  $2x + y = 7$ .

4.7.9 Find the area bounded by the lines  $y = 4x + 5$ ,  $y = 5 - x$  and  $4y = x + 5$ .

4.7.10 Find the equation of the plane which is perpendicular to the plane  $5x + 3y + 6z + 8 = 0$  and which contains the line of intersection of the planes  $x + 2y + 3z - 4 = 0$  and  $2x + y - z + 5 = 0$ .

4.7.11 Point  $\mathbf{P}(0, 2)$  is the point of intersection of the y-axis and the perpendicular bisector of line segment joining the points  $\mathbf{A}(-1, 1)$  and  $\mathbf{B}(3, 3)$ .

4.7.12 Prove that the line through  $\mathbf{A}(0, -1, -1)$  and  $\mathbf{B}(4, 5, 1)$  intersects the line through  $\mathbf{C}(3, 9, 4)$  and  $\mathbf{D}(-4, 4, 4)$ .

4.7.13 Find the equation of the plane through the intersection of the planes  $\vec{r} \cdot (\hat{i} + 3\hat{j}) - 6 = 0$  and  $\vec{r} \cdot (3\hat{i} - \hat{j} - 4\hat{k}) = 0$ , whose perpendicular distance from origin is unity.

- 4.7.14 Find the equation of the line passing through the point of intersection of  $2x + y = 5$  and  $x + 3y + 8 = 0$  and parallel to the line  $3x + 4y = 7$ .
- 4.7.15 Find the equations of the lines through the point of intersection of the line  $x - y + 1 = 0$  and  $2x - 3y + 5 = 0$  and whose distance from the point  $(3, 2)$  is  $\frac{7}{5}$ .
- 4.7.16 The straight line  $5x + 4y = 0$  passes through the point of intersection of the straight lines  $x + 2y - 10 = 0$  and  $2x + y + 5 = 0$ .
- 4.7.17 Find the equation of the plane passing through the line of intersection of the planes  $\vec{r} \cdot (\hat{i} + \hat{j} + \hat{k}) = 1$  and  $\vec{r} \cdot (2\hat{i} + 3\hat{j} - \hat{k}) + 4 = 0$  and parallel to the  $X$  axis.
- 4.7.18 Find the equation of the plane which contains the line of intersection of the planes  $\vec{r} \cdot (\hat{i} + 2\hat{j} + 3\hat{k}) - 4 = 0$ ,  $\vec{r} \cdot (2\hat{i} + \hat{j} - \hat{k}) + 5 = 0$  and which is perpendicular to the plane  $\vec{r} \cdot (5\hat{i} + 3\hat{j} - 6\hat{k}) + 8 = 0$ .
- 4.7.19 Find the distance of the point  $(-1, -5, -10)$  from the point of intersection of the line  $\vec{r} = 2\hat{i} - \hat{j} - 2\hat{k} + \lambda(3\hat{i} + 4\hat{j} + 2\hat{k})$  and the plane  $\vec{r} \cdot (\hat{i} - \hat{j} + \hat{k}) = 5$ .
- 4.7.20 Show that the area of the triangle formed by the lines  $y = m_1x + c_1$ ,  $y = m_2x + c_2$  and  $x = 0$  is  $\frac{(c_1 - c_2)^2}{2|m_1 - m_2|}$ .
- 4.7.21 If the lines  $2x + y - 3 = 0$ ,  $5x + ky - 3 = 0$  and  $3x - y - 2 = 0$  are concurrent, find the value of  $k$ .
- 4.7.22 Find the vector equation of the plane passing through the intersection of the planes  $\vec{r} \cdot (\hat{i} + \hat{j} + \hat{k}) = 6$  and  $\vec{r} \cdot (2\hat{i} + 3\hat{j} + 4\hat{k}) = -5$ , and the point  $(1, 1, 1)$ .
- 4.7.23 Find the coordinates of the point where the line through the points  $\mathbf{A}(3, 4, 1)$  and  $\mathbf{B}(5, 1, 6)$  crosses the  $XY$  plane.

#### 4.8 Miscellaneous

- 4.8.1 For which values of  $a$  and  $b$  does the following pair of linear equations have an infinite number of solutions?

$$2x + 3y = 7 \quad (4.8.1.1)$$

$$(a - b)x + (a - b)y = 3a + b - 2 \quad (4.8.1.2)$$

- 4.8.2 For which value of  $k$  will the following pair of linear equations have no solution?

$$3x + y = 1 \quad (4.8.2.1)$$

$$(2k - 1)x + (k - 1)y = 2k + 1 \quad (4.8.2.2)$$

- 4.8.3 Find the values of  $k$  for which the line

$$(k - 3)x - (4 - k^2)y + k^2 - 7k + 6 = 0 \quad (4.8.3.1)$$

is

- Parallel to the  $x$ -axis
- Parallel to the  $Y$  axis
- Passing through the origin

**Solution:**

$$\mathbf{n} = \left( \begin{matrix} k - 3 \\ -4 + k^2 \end{matrix} \right), c = -k^2 + 7k - 6 \quad (4.8.3.2)$$

a)

$$\begin{pmatrix} k-3 \\ -4+k^2 \end{pmatrix} = \alpha \begin{pmatrix} 0 \\ 1 \end{pmatrix} \Rightarrow k=3, \quad (4.8.3.3)$$

$$\Rightarrow \begin{pmatrix} 0 & 5 \end{pmatrix} \mathbf{x} = 6 \quad (4.8.3.4)$$

upon substituting from (4.8.3.2).

b) In this case,

$$\begin{pmatrix} k-3 \\ -4+k^2 \end{pmatrix} = \beta \begin{pmatrix} 1 \\ 0 \end{pmatrix} \Rightarrow k = \pm 2 \quad (4.8.3.5)$$

$$\Rightarrow \begin{pmatrix} -1 & 0 \end{pmatrix} \mathbf{x} = 4, \quad k=2 \quad (4.8.3.6)$$

$$\begin{pmatrix} -5 & 0 \end{pmatrix} \mathbf{x} = -24, \quad k=-2 \quad (4.8.3.7)$$

c) In this case,

$$-k^2 + 7k - 6 = 0 \Rightarrow k=1, k=6 \quad (4.8.3.8)$$

$$\Rightarrow \begin{pmatrix} -2 & -3 \end{pmatrix} \mathbf{x} = 0, \quad k=1 \quad (4.8.3.9)$$

$$\begin{pmatrix} 3 & 32 \end{pmatrix} \mathbf{x} = 0, \quad k=6 \quad (4.8.3.10)$$

4.8.4 Find the equations of the lines, which cutoff intercepts on the axes whose sum and product are 1 and -6 respectively.

**Solution:** Let the intercepts be  $a$  and  $b$ . Then

$$a+b=1, ab=-6 \quad (4.8.4.1)$$

$$\Rightarrow a=3, b=-2 \quad (4.8.4.2)$$

Thus, the possible intercepts are

$$\begin{pmatrix} 3 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ -2 \end{pmatrix}, \begin{pmatrix} -2 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 3 \end{pmatrix} \quad (4.8.4.3)$$

From (4.1.3.5),

$$\begin{pmatrix} 3 & 0 \\ 0 & -2 \end{pmatrix} \mathbf{n} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (4.8.4.4)$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} \frac{1}{3} \\ -\frac{1}{2} \end{pmatrix} \quad (4.8.4.5)$$

$$\text{or, } \begin{pmatrix} 2 & -3 \end{pmatrix} \mathbf{x} = 6 \quad (4.8.4.6)$$

using (4.1.4.1). Similarly, the other line can be obtained as

$$\begin{pmatrix} 3 & -2 \end{pmatrix} \mathbf{x} = -6 \quad (4.8.4.7)$$

4.8.5 A ray of light passing through the point  $\mathbf{P} = (1, 2)$  reflects on the x-axis at point  $\mathbf{A}$  and the reflected ray passes through the point  $\mathbf{Q} = (5, 3)$ . Find the coordinates of  $\mathbf{A}$ .

**Solution:** From (4.1.9.1), the reflection of **Q** is

$$\mathbf{R} = \begin{pmatrix} 5 \\ -3 \end{pmatrix} \quad (4.8.5.1)$$

Letting

$$\mathbf{A} = \begin{pmatrix} x \\ 0 \end{pmatrix}, \quad (4.8.5.2)$$

since **P**, **A**, **R** are collinear, from (4.1.3.6),

$$\begin{pmatrix} 1 & 1 & 2 \\ 1 & 5 & -3 \\ 1 & x & 0 \end{pmatrix} \xrightarrow[\begin{smallmatrix} R_2=R_2-R_1 \\ R_3=R_3-R_1 \end{smallmatrix}]{\begin{smallmatrix} R_2=R_2-R_1 \\ R_3=R_3-R_1 \end{smallmatrix}} \begin{pmatrix} 1 & 1 & 2 \\ 0 & 4 & -5 \\ 0 & x-1 & -2 \end{pmatrix} \quad (4.8.5.3)$$

$$\xleftrightarrow{R_3=4R_3-(x-1)R_2} \begin{pmatrix} 1 & 1 & 2 \\ 0 & 4 & -5 \\ 0 & 0 & 5x-13 \end{pmatrix} \Rightarrow x = \frac{13}{5} \quad (4.8.5.4)$$

See Fig. 4.8.5.1.

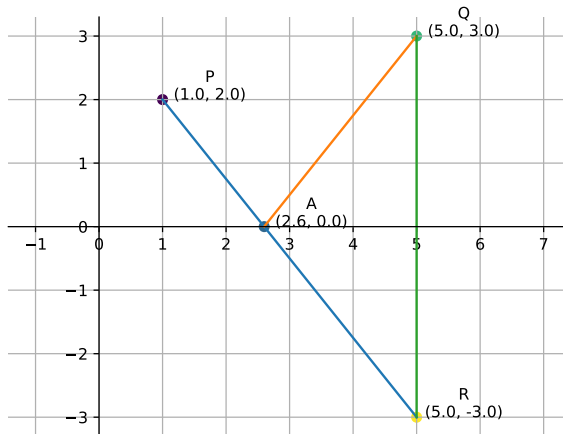


Fig. 4.8.5.1

4.8.6 The owner of a milk store finds that he can sell 980 litres of milk each week at ₹ 14/litre and 1220 litres of milk each week at ₹ 16/litre. Assuming a linear relationship between selling price and demand, how many litres could he sell weekly at ₹ 17/ litre?

4.8.7 Prove that in any  $\triangle ABC$ ,  $\cos A = \frac{b^2+c^2-a^2}{2bc}$ , where a, b, c are the magnitudes of the sides opposite to the vertices **A**, **B**, **C** respectively.

4.8.8 Distance of the point  $(\alpha, \beta, \gamma)$  from y-axis is

- a)  $\beta$
- b)  $|\beta|$
- c)  $|\beta + \gamma|$
- d)  $\sqrt{\alpha^2 + \gamma^2}$

4.8.9 The reflection of the point  $(\alpha, \beta, \gamma)$  in the  $XY$  plane is

- a)  $\alpha, \beta, 0$
- b)  $(0, 0, \gamma)$
- c)  $(-\alpha, -\beta, \gamma)$
- d)  $(\alpha, \beta, -\gamma)$

4.8.10 The plane  $ax + by = 0$  is rotated about its line of intersection with the plane  $z = 0$  through an angle  $\alpha$ . Prove that the equation of the plane in its new position is

$$ax + by \pm (\sqrt{a^2 + b^2} \tan \alpha)z = 0.$$

4.8.11 The locus represented by  $xy + yz = 0$  is

- a) A pair of perpendicular lines
- b) A pair of parallel lines
- c) A pair of parallel planes
- d) A pair of perpendicular planes

4.8.12 For what values of  $a$  and  $b$  the intercepts cut off on the coordinate axes by the line  $ax + by + 8 = 0$  are equal in length but opposite in signs to those cut off by the line  $2x - 3y = 0$  on the axes.

4.8.13 If the equation of the base of an equilateral triangle is  $x + y = 2$  and the vertex is  $(2, -1)$ , then find the length of the side of the triangle.

4.8.14 A variable line passes through a fixed point  $\mathbf{P}$ . The algebraic sum of the perpendiculars drawn from the points  $(2, 0)$ ,  $(0, 2)$  and  $(1, 1)$  on the line is zero. Find the coordinates of the point  $\mathbf{P}$ .

4.8.15 A straight line moves so that the sum of the reciprocals of its intercepts made on the axes is constant. Show that the line passes through a fixed point.

4.8.16 If the sum of the distances of a moving point in a plane from the axes is  $l$ , then find the locus of the point.

4.8.17  $\mathbf{P}_1, \mathbf{P}_2$  are points on either of the two lines  $y - \sqrt{3}|x| = 2$  at a distance of 5 units from their point of intersection. Find the coordinates of the foot of the perpendiculars drawn from  $\mathbf{P}_1, \mathbf{P}_2$  on the bisector of the angle between the given lines.

4.8.18 If  $p$  is the length of perpendicular from the origin on the line  $\frac{x}{a} + \frac{y}{b} = 1$  and  $a^2, p^2, b^2$  are in A.P, then show that  $a^4 + b^4 = 0$ .

4.8.19 The point  $(4, 1)$  undergoes the following two successive transformations :

- a) Reflection about the line  $y = x$
- b) Translation through a distance 2 units along the positive  $x$ -axis

Then the final coordinates of the point are

- a)  $(4, 3)$
- b)  $(3, 4)$
- c)  $(1, 4)$
- d)  $\frac{7}{2}, \frac{7}{2}$

- 4.8.20 One vertex of the equilateral with centroid at the origin and one side as  $x + y - 2 = 0$  is
- $(-1, -1)$
  - $(2, 2)$
  - $(-2, -2)$
  - $(2, -2)$
- 4.8.21 If  $a, b, c$  are in A.P., then the straight lines  $ax + by + c = 0$  will always pass through \_\_\_\_\_.
- 4.8.22 The points  $(3, 4)$  and  $(2, -6)$  are situated on the \_\_\_\_\_ of the line  $3x - 4y - 8 = 0$ .
- 4.8.23 A point moves so that square of its distance from the point  $(3, -2)$  is numerically equal to its distance from the line  $5x - 12y = 3$ . The equation of its locus is
- 4.8.24 Locus of the mid-points of the portion of the line  $x \sin \theta + y \cos \theta = p$  intercepted between the axes is \_\_\_\_\_.
- State whether the following statements are true or false. Justify.
- 4.8.25 If the vertices of a triangle have integral coordinates, then the triangle can not be equilateral.
- 4.8.26 The line  $\frac{x}{a} + \frac{y}{b} = 1$  moves in such a way that  $\frac{1}{a^2} + \frac{1}{b^2} = \frac{1}{c^2}$ , where  $c$  is a constant. The locus of the foot of the perpendicular from the origin on the given line is  $x^2 + y^2 = c^2$ .
- 4.8.27 Match the following

- |   |  |
|---|--|
| 1. The coordinates of the points <b>P</b> and <b>Q</b> on the line $x + 5y = 13$ which are at a distance of 2 units from the line $12x - 5y + 26 = 0$ are | a) $(3, 1), (-7, 11)$                                      |
| 2. The coordinates of the point on the line $x + y = 4$ , which are at a unit distance from the line $4x + 3y - 10 = 0$ are                               | b) $-\frac{1}{11}, \frac{11}{3}, \frac{4}{3}, \frac{7}{3}$ |
| 3. The coordinates of the point on the line joining <b>A</b> $(-2, 5)$ and <b>B</b> $(3, 1)$ such that $AP = PQ = QB$ are                                 | c) $1, \frac{12}{5}, -3, \frac{16}{5}$                     |

TABLE 4.8.27

- 4.8.28 The value of the  $\lambda$ , if the lines  $(2x + 3y + 4) + \lambda(6x - y + 12) = 0$  are

- |   |                               |
|---|-------------------------------|
| 1. parallel to $Y$ axis is              | a) $\lambda = -\frac{3}{4}$   |
| 2. perpendicular to $7x + y - 4 = 0$ is | b) $\lambda = -\frac{1}{3}$   |
| 3. passes through $(1, 2)$ is           | c) $\lambda = -\frac{17}{41}$ |
| 4. parallel to $X$ axis is              | d) $\lambda = 3$              |

TABLE 4.8.28

- 4.8.29 The equation of the line through the intersection of the lines  $2x - 3y = 0$  and  $4x - 5y = 2$  and

1. through the point (2, 1) is                      a)  $2x - y = 4$
2. perpendicular to the line                      b)  $x + y - 5 = 0$
3. parallel to the line  $3x - 4y + 5 = 0$  is      c)  $x - y - 1 = 0$
4. equally inclined to the axes is              d)  $3x - 4y - 1 = 0$

TABLE 4.8.29

4.8.30 Point  $\mathbf{R}(h, k)$  divides a line segment between the axes in the ratio 1: 2. Find the equation of the line.

**Solution:** Choosing the intercept points in Problem 4.3.17,

$$\mathbf{R} = \frac{2\mathbf{A} + \mathbf{B}}{3} \Rightarrow \begin{pmatrix} h \\ k \end{pmatrix} = \frac{1}{3} \begin{pmatrix} 2a \\ b \end{pmatrix} \quad (4.8.30.1)$$

$$\text{or, } \begin{pmatrix} b \\ a \end{pmatrix} = \mathbf{n} \equiv \begin{pmatrix} 2k \\ h \end{pmatrix} \quad (4.8.30.2)$$

Thus, the equation of the line is given by,

$$(2k \ h) \mathbf{x} = (2k \ h) \begin{pmatrix} h \\ k \end{pmatrix} = 3hk \quad (4.8.30.3)$$

4.8.31 The tangent of the angle between the lines whose intercepts on the axes are  $a, -b$  and  $b, -a$ , respectively, is

a)  $\frac{a^2 - b^2}{ab}$

b)  $\frac{b^2 - a^2}{2}$

c)  $\frac{b^2 - a^2}{2ab}$

d) none of these

4.8.32 Prove that the line through the point  $(x_1, y_1)$  and parallel to the line  $Ax + By + C = 0$  is  $A(x - x_1) + B(y - y_1) = 0$ .

**Solution:** The equation of the desired line is

$$(A \ B) \left( \mathbf{x} - \begin{pmatrix} x_1 \\ y_1 \end{pmatrix} \right) = 0 \quad (4.8.32.1)$$

$$\Rightarrow (A \ B) \mathbf{x} = Ax_1 + By_1 \quad (4.8.32.2)$$

4.8.33 If  $p$  and  $q$  are the lengths of perpendiculars from the origin to the lines  $x \cos \theta - y \sin \theta = k \cos 2\theta$  and  $x \sec \theta + y \operatorname{cosec} \theta = k$ , respectively, prove that  $p^2 + 4q^2 = k^2$

**Solution:** The line parameters are

$$\mathbf{n}_1 = \begin{pmatrix} \cos \theta \\ -\sin \theta \end{pmatrix}, c_1 = k \cos 2\theta \quad (4.8.33.1)$$

$$\mathbf{n}_2 = \begin{pmatrix} \sin \theta \\ \cos \theta \end{pmatrix}, c_2 = \frac{1}{2} k \sin 2\theta \quad (4.8.33.2)$$

From (4.1.6.6),

$$p = \frac{|\mathbf{n}_1^\top \mathbf{x} - c_1|}{\|\mathbf{n}_1\|} = |k \cos 2\theta| \quad (4.8.33.3)$$

$$q = \frac{|\mathbf{n}_2^\top \mathbf{x} - c_2|}{\|\mathbf{n}_2\|} = \left| \frac{1}{2} k \sin 2\theta \right| \quad (4.8.33.4)$$

$$\implies p^2 + 4q^2 = k^2 \quad (4.8.33.5)$$

4.8.34 If  $p$  is the length of perpendicular from origin to the line whose intercepts on the axes are  $a$  and  $b$ , then show that

$$\frac{1}{p^2} = \frac{1}{a^2} + \frac{1}{b^2} \quad (4.8.34.1)$$

**Solution:** Let the intercept points be

$$\begin{pmatrix} a \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ b \end{pmatrix}, \because \mathbf{n} = \begin{pmatrix} b \\ a \end{pmatrix}, \quad (4.8.34.2)$$

The line equation is,

$$\begin{pmatrix} b & a \end{pmatrix} \left( \mathbf{x} - \begin{pmatrix} a \\ 0 \end{pmatrix} \right) = 0 \quad (4.8.34.3)$$

$$\implies \begin{pmatrix} b & a \end{pmatrix} \mathbf{x} = ab \quad (4.8.34.4)$$

From (4.1.6.6), the perpendicular distance from the origin to the line is

$$p = \frac{ab}{\sqrt{a^2 + b^2}} \implies (4.8.34.1) \quad (4.8.34.5)$$

4.8.35 Find perpendicular distance from the origin to the line joining the points  $(\cos \theta, \sin \theta)$  and  $(\cos \phi, \sin \phi)$ .

**Solution:** The equation of the line is

$$(\sin \phi - \sin \theta \quad \cos \theta - \cos \phi) \mathbf{x} = \sin(\phi - \theta) \quad (4.8.35.1)$$

and from (4.1.6.6), the distance is

$$d = \frac{\sin(\phi - \theta)}{2 \sin\left(\frac{\phi - \theta}{2}\right)} = \cos\left(\frac{\phi - \theta}{2}\right) \quad (4.8.35.2)$$

4.8.36 Prove that the products of the lengths of the perpendiculars drawn from the points  $\begin{pmatrix} \sqrt{a^2 - b^2} & 0 \end{pmatrix}^\top$  and  $\begin{pmatrix} -\sqrt{a^2 - b^2} & 0 \end{pmatrix}^\top$  to the line  $\frac{x}{a} \cos \theta + \frac{y}{b} \sin \theta = 1$  is  $b^2$ .

**Solution:** The input parameters for (4.1.6.6) are

$$\mathbf{n} = \begin{pmatrix} \frac{\cos \theta}{a} \\ \frac{\sin \theta}{b} \end{pmatrix}, c = 1, \mathbf{P} = \pm \begin{pmatrix} \sqrt{a^2 - b^2} \\ 0 \end{pmatrix} \quad (4.8.36.1)$$



The product of the distances is

$$d_1 d_2 = \frac{|(\mathbf{n}^\top \mathbf{P})^2 - c^2|}{\|\mathbf{n}\|} = \frac{\left| \frac{\cos^2 \theta (a^2 - b^2)}{a^2} - 1 \right|}{\frac{\cos^2 \theta}{a^2} + \frac{\sin^2 \theta}{b^2}} \quad (4.8.36.2)$$

$$= \frac{(b^2 \cos^2 \theta + a^2 \sin^2 \theta) a^2 b^2}{(b^2 \cos^2 \theta + a^2 \sin^2 \theta) a^2} = b^2 \quad (4.8.36.3)$$

4.8.37 **O** is the origin and **A** is  $(a, b, c)$ . Find the direction cosines of the line OA and the equation of the plane through **A** at right angle to OA.

4.8.38 Two systems of rectangular axis have the same origin. If a plane cuts them at distances  $a, b, c$  and  $a', b', c'$ , respectively, from the origin, prove that

$$\frac{1}{a^2} + \frac{1}{b^2} + \frac{1}{c^2} = \frac{1}{a'^2} + \frac{1}{b'^2} + \frac{1}{c'^2}$$

4.8.39 Equation of the line passing through the point  $(a \cos^3 \theta, a \sin^3 \theta)$  and perpendicular to the line  $x \sec \theta + y \csc \theta = a$  is  $x \cos \theta - y \sin \theta = a \sin 2\theta$ .

4.8.40 The distance between the lines  $y = mx + c$ , and  $y = mx + c^2$  is

4.8.41 Find the area of the triangle formed by the lines  $y - x = 0$ ,  $x + y = 0$ , and  $x - k = 0$ .

**Solution:** The vertices of the triangle can be expressed using the equations

$$\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \mathbf{A} = \mathbf{0} \quad (4.8.41.1)$$

$$\begin{pmatrix} 1 & 1 \\ 1 & 0 \end{pmatrix} \mathbf{B} = \begin{pmatrix} 0 \\ k \end{pmatrix} \quad (4.8.41.2)$$

$$\begin{pmatrix} 1 & 0 \\ -1 & 1 \end{pmatrix} \mathbf{C} = \begin{pmatrix} k \\ 0 \end{pmatrix} \quad (4.8.41.3)$$

from which

$$\mathbf{A} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} k \\ -k \end{pmatrix}, \mathbf{C} = \begin{pmatrix} k \\ k \end{pmatrix} \quad (4.8.41.4)$$

are trivially obtained. Thus,

$$ar(ABC) = \frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C})\| \quad (4.8.41.5)$$

$$= \frac{1}{2} \left\| \begin{pmatrix} -k \\ k \end{pmatrix} \times \begin{pmatrix} -k \\ k \end{pmatrix} \right\| = k^2 \quad (4.8.41.6)$$

4.8.42 The lines  $ax + 2y + 1 = 0$ ,  $bx + 3y + 1 = 0$  and  $cx + 4y + 1 = 0$  are concurrent if  $a, b, c$  are in G.P.

4.8.43 **P** $(a, b)$  is the mid-point of the line segment between axes. Show that the equation of the line is  $\frac{x}{a} + \frac{y}{b} = 2$

**Solution:** From Problem 4.3.17,

$$\mathbf{n} = \begin{pmatrix} b \\ a \end{pmatrix} \quad (4.8.43.1)$$

$$\Rightarrow \begin{pmatrix} b & a \end{pmatrix} \left( \mathbf{x} - \begin{pmatrix} a \\ b \end{pmatrix} \right) = 0 \quad (4.8.43.2)$$

$$\text{or, } \begin{pmatrix} b & a \end{pmatrix} \mathbf{x} = 2ab. \quad (4.8.43.3)$$

is the desired line equation.

- 4.8.44 Find the equation of the set of points which are equidistant from the points  $(1, 2, 3)$  and  $(3, 2, -1)$ .
- 4.8.45 Find the equation of the set of points  $\mathbf{P}$ , the sum of whose distances from  $\mathbf{A}(4, 0, 0)$  and  $\mathbf{B}(-4, 0, 0)$  is equal to 10.
- 4.8.46 If  $\mathbf{A} = \begin{pmatrix} 0 & -\tan \frac{\alpha}{2} \\ \tan \frac{\alpha}{2} & 0 \end{pmatrix}$  and  $\mathbf{I}$  is the identity matrix of order 2, show that  $\mathbf{I} + \mathbf{A} = (\mathbf{I} - \mathbf{A}) \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix}$ .
- 4.8.47 Find the values of  $\theta$  and  $p$ , if the equation  $x \cos \theta + y \sin \theta = p$  is the normal form of the line  $\sqrt{3}x + y + 2 = 0$ .
- 4.8.48 Find the image of the point  $(3, 8)$  with respect to the line  $x + 3y = 7$  assuming the line to be a plane mirror.
- 4.8.49 Prove that if a plane has the intercept  $a, b, c$  and is at a distance of  $p$  units from the origin, then  $\frac{1}{a^2} + \frac{1}{b^2} + \frac{1}{c^2} = \frac{1}{p^2}$ .
- 4.8.50 The planes  $2x - y + 4z = 5$  and  $5x - 2.5y + 10z = 6$  are
- Perpendicular
  - Parallel
  - Intersect  $y$  axis
  - Pass through  $(0, 0, \frac{5}{4})$

## 5 MATRICES

## 5.1 Formulae

5.1.1. The characteristic equation for a matrix  $\mathbf{A}$  is

$$f(\lambda) = |\mathbf{A} - \lambda \mathbf{I}| = 0 \quad (5.1.1.1)$$

5.1.2. Cayley-Hamilton theorem

$$f(\lambda) = f(\mathbf{A}) = 0 \quad (5.1.2.1)$$

5.1.3. Code for Cayley-Hamilton Theorem

```
codes/book/cayley.py
```

5.1.4. Code for balancing chemical equations

```
codes/book/chembal.py
```

## 5.2 Equation

Solve the following system of linear equations.

5.2.1

$$2x + 5y = 1$$

$$3x + 2y = 7$$

5.2.6

$$2x - 3y = 8$$

$$4x - 6y = 9$$

5.2.2

$$5x - 4y + 8 = 0$$

$$7x + 6y - 9 = 0$$

5.2.7

$$\frac{3}{2}x + \frac{5}{3}y = 7$$

$$9x - 10y = 14$$

5.2.3

$$9x + 3y + 12 = 0$$

$$18x + 6y + 24 = 0$$

5.2.8

$$5x - 3y = 11$$

$$-10x + 6y = -22$$

5.2.4

$$6x - 3y + 10 = 0$$

$$2x - y + 9 = 0$$

5.2.9

$$\frac{4}{3}x + 2y = 8$$

$$2x + 3y = 12$$

5.2.5

$$3x + 2y = 5$$

$$2x - 3y = 7$$

5.2.10

$$x + y = 5$$

$$2x + y = 10$$

5.2.11

$$\begin{aligned}x - y &= 8 \\3x - 3y &= 16\end{aligned}$$

5.2.12

$$\begin{aligned}2x + y - 6 &= 0 \\4x - 2y + 4 &= 0\end{aligned}$$

5.2.13

$$\begin{aligned}2x - 2y - 2 &= 0 \\4x - 4y - 5 &= 0\end{aligned}$$

5.2.14

$$\begin{aligned}x - 3y - 3 &= 0 \\3x - 9y - 2 &= 0\end{aligned}$$

5.2.15

$$\begin{aligned}2x + y &= 5 \\3x + 2y &= 8\end{aligned}$$

5.2.16

$$\begin{aligned}3x - 5y &= 20 \\6x - 10y &= 40\end{aligned}$$

5.2.17

$$\begin{aligned}x - 3y - 7 &= 0 \\3x - 3y - 15 &= 0\end{aligned}$$

5.2.18

$$\begin{aligned}8x + 5y &= 9 \\3x + 2y &= 4\end{aligned}$$

5.2.19

$$\begin{aligned}x + y &= 14 \\x - y &= 4\end{aligned}$$

5.2.20

$$\begin{aligned}3x - y &= 3 \\9x - 3y &= 9\end{aligned}$$

5.2.21

$$\begin{aligned}02x + 03y &= 13 \\04x + 05y &= 23\end{aligned}$$

5.2.22

$$\begin{aligned}\sqrt{2x} + \sqrt{3y} &= 0 \\\sqrt{3x} - \sqrt{8y} &= 0\end{aligned}$$

5.2.23

$$\begin{aligned}\frac{3x}{2} - \frac{5y}{2} &= -2 \\\frac{x}{3} + \frac{y}{2} &= \frac{13}{6}\end{aligned}$$

5.2.24

$$\begin{aligned}px + qy &= p - q \\qx - py &= p + q\end{aligned}$$

5.2.25

$$\begin{aligned}ax + by &= c \\bx + ay &= 1 + c\end{aligned}$$

5.2.26

$$\begin{aligned}\frac{x}{a} - \frac{y}{b} &= 0 \\ax + by &= a^2 + b^2\end{aligned}$$

5.2.27

$$\begin{aligned}(a - b)x + (a + b)y &= a^2 - 2ab - b^2 \\(a + b)(x + y) &= a^2 + b^2\end{aligned}$$

5.2.28

$$\begin{aligned}152x - 378y &= -74 \\-378x + 152y &= -604\end{aligned}$$

5.2.29

$$\begin{aligned}5x - 8y + 1 &= 0 \\3x - \frac{24}{5}y + \frac{3}{5} &= 0\end{aligned}$$

5.2.30

$$\begin{aligned}x + 3y &= 6 \\2x - 3y &= 12\end{aligned}$$

5.2.31

$$\begin{aligned}7x - 15y &= 2 \\x + 2y &= 3\end{aligned}$$

5.2.32

$$\begin{aligned}2x + 3y &= 8 \\4x + 6y &= 7\end{aligned}$$

5.2.33

$$\begin{aligned}x + 2y - 4 &= 0 \\2x + 4y - 12 &= 0\end{aligned}$$

5.2.34

$$\begin{aligned}x + 2y - 4 &= 0 \\2x + 4y - 12 &= 0\end{aligned}$$

5.2.35

$$\begin{aligned}x + y &= 5 \\2x - 3y &= 4\end{aligned}$$

5.2.36

$$\begin{aligned}3x + 4y &= 10 \\2x - 2y &= 2\end{aligned}$$

5.2.37

$$\begin{aligned}3x - 5y - 4 &= 0 \\9x &= 2y + 7\end{aligned}$$

5.2.38

$$\begin{aligned}\frac{x}{2} + \frac{2y}{3} &= -1 \\x - \frac{y}{3} &= 0\end{aligned}$$

5.2.39

$$\begin{aligned}\frac{1}{2x} + \frac{1}{3y} &= 2 \\\frac{1}{3x} + \frac{1}{2y} &= \frac{13}{6}\end{aligned}$$

5.2.40

$$\begin{aligned}\frac{2}{\sqrt{x}} + \frac{3}{\sqrt{y}} &= 2 \\\frac{4}{\sqrt{x}} - \frac{9}{\sqrt{y}} &= -1\end{aligned}$$

5.2.41

$$\begin{aligned}\frac{4}{x} + 3y &= 14 \\\frac{3}{x} - 4y &= 23\end{aligned}$$

5.2.42

$$\begin{aligned}\frac{5}{x-1} + \frac{1}{y-2} &= 2 \\\frac{6}{x-1} - \frac{3}{y-2} &= 1\end{aligned}$$

5.2.43

$$\begin{aligned}\frac{7x-2y}{xy} &= 5 \\\frac{8x+7y}{xy} &= 15\end{aligned}$$

5.2.44

$$\begin{aligned}6x + 3y &= 6xy \\2x + 4y &= 5xy\end{aligned}$$

5.2.45

$$\begin{aligned}\frac{10}{x+y} + \frac{2}{x-y} &= 4 \\\frac{15}{x+y} - \frac{5}{x-y} &= -2\end{aligned}$$

5.2.46

$$\begin{aligned}\frac{1}{3x+y} + \frac{1}{3x-y} &= \frac{3}{4} \\\frac{1}{2(3x+y)} - \frac{1}{2(3x-y)} &= \frac{-1}{8}\end{aligned}$$

5.2.47

$$\begin{aligned}x + 2y &= 2 \\ 2x + 3y &= 3\end{aligned}$$

5.2.48

$$\begin{aligned}2x - y &= 5 \\ x + y &= 4\end{aligned}$$

5.2.49

$$\begin{aligned}x + 3y &= 5 \\ 2x + 6y &= 8\end{aligned}$$

5.2.50

$$\begin{aligned}x + y + z &= 1 \\ 2x + 3y + 2z &= 2 \\ ax + ay + 2az &= 4\end{aligned}$$

5.2.51

$$\begin{aligned}3x - y - 2z &= 2 \\ 2y - z &= -1 \\ 3x - 5y &= 3\end{aligned}$$

5.2.52

$$\begin{aligned}5x - y + 4z &= 5 \\ 2x + 3y + 5z &= 2 \\ 5x - 2y + 6z &= -1\end{aligned}$$

5.2.53

$$\begin{aligned}5x + 2y &= 4 \\ 7x + 3y &= 5\end{aligned}$$

5.2.54

$$\begin{aligned}2x - y &= -2 \\ 3x + 4y &= 3\end{aligned}$$

5.2.55

$$\begin{aligned}4x - 3y &= 3 \\ 3x - 5y &= 7\end{aligned}$$

5.2.56

$$\begin{aligned}5x + 2y &= 3 \\ 3x + 2y &= 5\end{aligned}$$

5.2.57

$$\begin{aligned}\frac{2}{x} + \frac{3}{y} &= 13 \\ \frac{5}{x} + \frac{4}{y} &= -2\end{aligned}$$

5.2.58

$$\begin{aligned}\frac{5}{x-1} + \frac{1}{y-2} &= 2 \\ \frac{6}{x-1} - \frac{3}{y-2} &= 1\end{aligned}$$

5.2.59

$$\begin{aligned}2x + y + z &= 1 \\ x - 2y - z &= \frac{3}{2} \\ 3y - 5z &= 9\end{aligned}$$

5.2.60

$$\begin{aligned}x - y + z &= 4 \\ 2x + y - 3z &= 0 \\ x + y + z &= 2\end{aligned}$$

5.2.61

$$\begin{aligned}2x + 3y + 3z &= 5 \\ x - 2y + z &= -4 \\ 3x - y - 2z &= 3\end{aligned}$$

5.2.62

$$\begin{aligned}x - y + 2z &= 7 \\ 3x + 4y - 5z &= -5 \\ 2x - y + 3z &= 12\end{aligned}$$

5.2.63

$$\begin{aligned}x - y + 2z &= 1 \\ 2z - 3z &= 1 \\ 3x - 2y + 4z &= 2\end{aligned}$$

5.2.64

$$3x - 2y + 3z = 8$$

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

$$4x - 3y + 2z = 4$$

5.2.65 Solve

$$\begin{pmatrix} x + y + z \\ x + z \\ y + z \end{pmatrix} = \begin{pmatrix} 9 \\ 5 \\ 7 \end{pmatrix}$$

5.2.66

$$\mathbf{X} + \mathbf{Y} = \begin{pmatrix} 7 & 0 \\ 2 & 5 \end{pmatrix}$$

$$\mathbf{X} - \mathbf{Y} = \begin{pmatrix} 3 & 0 \\ 0 & 4 \end{pmatrix}.$$

5.2.67

$$\mathbf{X} + \mathbf{Y} = \begin{pmatrix} 5 & 2 \\ 0 & 9 \end{pmatrix}$$

$$\mathbf{X} - \mathbf{Y} = \begin{pmatrix} 3 & 6 \\ 0 & -1 \end{pmatrix}$$

5.2.68

$$2\mathbf{X} + 3\mathbf{Y} = \begin{pmatrix} 2 & 3 \\ 4 & 0 \end{pmatrix}$$

$$3\mathbf{X} + 2\mathbf{Y} = \begin{pmatrix} 2 & -2 \\ -1 & 5 \end{pmatrix}$$

5.2.5 If

$$x \begin{pmatrix} 2 \\ 3 \end{pmatrix} + y \begin{pmatrix} -1 \\ 1 \end{pmatrix} = \begin{pmatrix} 10 \\ 5 \end{pmatrix} \quad (5.2.5.1)$$

find the values of  $x$  and  $y$ .

5.2.6 Solve  $2x + 3y = 11$  and  $2x + 4y = -24$  and hence find the value of  $m$  for which  $y = mx + 3$ .

5.2.7 For which values of  $p$  does the pair of equations given below have a unique solution.

$$4x + py + 8 = 0 \quad (5.2.7.1)$$

$$2x + 2y + 2 = 0 \quad (5.2.7.2)$$

5.2.8 For what values of  $k$  will the following pair of linear equations have infinitely many solutions.

$$kx + 3y - (k - 3) = 0 \quad (5.2.8.1)$$

$$12x + ky - k = 0 \quad (5.2.8.2)$$

5.2.9 Find the values of  $a, b, c$  and  $d$  from the following equation

$$\begin{pmatrix} 2a + b & a - 2b \\ 5c - d & 4c + d \end{pmatrix} = \begin{pmatrix} 4 & -3 \\ 11 & 24 \end{pmatrix} \quad (5.2.9.1)$$

### 5.3 Inverse

Using elementary transformations, find the inverse of each of the following matrices

$$5.3.1 \begin{pmatrix} 2 & 3 \\ -4 & -6 \end{pmatrix}$$

$$5.3.2 \begin{pmatrix} 1 & -2 \\ 4 & 3 \end{pmatrix}$$

$$5.3.3 \begin{pmatrix} 2 & 3 \\ 1 & 4 \end{pmatrix}$$

$$5.3.4 \begin{pmatrix} 2 & 4 \\ -1 & 2 \end{pmatrix}$$

$$5.3.5 \begin{pmatrix} 1 & 2 \\ 2 & 1 \end{pmatrix}$$

$$5.3.6 \begin{pmatrix} 10 & -2 \\ -5 & 1 \end{pmatrix}$$

$$5.3.7 \begin{pmatrix} 2 & 2 \\ 4 & 3 \end{pmatrix}$$

$$5.3.8 \begin{pmatrix} -1 & 5 \\ -3 & 2 \end{pmatrix}$$

$$5.3.9 \begin{pmatrix} 1 & 2 \\ 3 & 4 \end{pmatrix}$$

$$5.3.10 \begin{pmatrix} 1 & -1 & 2 \\ 2 & 3 & 5 \\ -2 & 0 & 1 \end{pmatrix}$$

$$5.3.11 \begin{pmatrix} 1 & -1 \\ 2 & 3 \end{pmatrix}$$

$$5.3.12 \begin{pmatrix} 2 & 1 \\ 1 & 1 \end{pmatrix}$$

$$5.3.13 \begin{pmatrix} 1 & 3 \\ 2 & 7 \end{pmatrix}$$

$$5.3.14 \begin{pmatrix} 2 & 3 \\ 5 & 7 \end{pmatrix}$$

$$5.3.15 \begin{pmatrix} 2 & 1 \\ 7 & 4 \end{pmatrix}$$

$$5.3.16 \begin{pmatrix} 2 & 5 \\ 1 & 3 \end{pmatrix}$$

$$5.3.17 \begin{pmatrix} 3 & 1 \\ 5 & 2 \end{pmatrix}$$

$$5.3.18 \begin{pmatrix} 4 & 5 \\ 3 & 4 \end{pmatrix}$$

$$5.3.19 \begin{pmatrix} 3 & 10 \\ 2 & 7 \end{pmatrix}$$

$$5.3.20 \begin{pmatrix} 3 & -1 \\ -4 & 2 \end{pmatrix}$$

$$5.3.21 \begin{pmatrix} 2 & -6 \\ 1 & -2 \end{pmatrix}$$

$$5.3.22 \begin{pmatrix} 6 & -3 \\ -2 & 1 \end{pmatrix}$$

$$5.3.23 \begin{pmatrix} 2 & -3 \\ -1 & 2 \end{pmatrix}$$

$$5.3.24 \begin{pmatrix} 2 & 1 \\ 4 & 2 \end{pmatrix}$$

$$5.3.25 \begin{pmatrix} 2 & -3 & 3 \\ 2 & 2 & 3 \\ 3 & -2 & 2 \end{pmatrix}$$

$$5.3.26 \begin{pmatrix} 1 & 3 & -2 \\ -3 & 0 & -5 \\ 2 & 5 & 0 \end{pmatrix}$$

$$5.3.27 \begin{pmatrix} 2 & 0 & -1 \\ 5 & 1 & 0 \\ 0 & 1 & 3 \end{pmatrix}$$

$$5.3.28 \begin{pmatrix} 2 & 4 \\ -5 & -1 \end{pmatrix}$$

$$5.3.29 \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix}$$

$$5.3.30 \begin{pmatrix} x^2 - x + 1 & x - 1 \\ x + 1 & x + 1 \end{pmatrix}$$

$$5.3.31 \begin{pmatrix} 1 & 2 \\ 4 & 2 \end{pmatrix}$$

$$5.3.32 \begin{pmatrix} 1 & 0 & 1 \\ 0 & 1 & 2 \\ 0 & 0 & 4 \end{pmatrix}$$

$$5.3.33 \begin{pmatrix} 3 & -1 & -2 \\ 0 & 0 & 1 \\ 3 & -5 & 0 \end{pmatrix}$$

$$5.3.34 \begin{pmatrix} 3 & -4 & 5 \\ 1 & 1 & -2 \\ 2 & 3 & 1 \end{pmatrix}$$

$$5.3.35 \begin{pmatrix} 0 & 1 & 2 \\ -1 & 0 & -3 \\ -2 & 3 & 0 \end{pmatrix}$$

$$5.3.36 \begin{pmatrix} 2 & -1 & -2 \\ 0 & 2 & -1 \\ 3 & -5 & 0 \end{pmatrix}$$

$$5.3.37 \begin{pmatrix} 1 & 1 & -2 \\ 2 & 1 & -3 \\ 5 & 4 & -9 \end{pmatrix}$$

$$5.3.38 \begin{pmatrix} 1 & -1 & 2 \\ 3 & 0 & -2 \\ 1 & 0 & 3 \end{pmatrix}$$

$$5.3.39 \begin{pmatrix} 1 & 2 & 3 \\ 0 & 2 & 4 \\ 0 & 0 & 5 \end{pmatrix}$$

$$5.3.40 \begin{pmatrix} 1 & 0 & 0 \\ 3 & 3 & 0 \\ 5 & 2 & 1 \end{pmatrix}$$



$$5.3.41 \begin{pmatrix} 2 & 1 & 3 \\ 4 & -1 & 0 \\ -7 & 2 & 1 \end{pmatrix}$$

$$5.3.42 \begin{pmatrix} 1 & -1 & 2 \\ 0 & 2 & -3 \\ 3 & -2 & 4 \end{pmatrix}$$

$$5.3.43 \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha \\ 0 & \sin \alpha & -\cos \alpha \end{pmatrix}$$

$$5.3.44 \begin{pmatrix} 0 & 1 & 2 \\ 1 & 2 & 3 \\ 3 & 1 & 1 \end{pmatrix}$$

$$5.3.45 \begin{pmatrix} 1 & 2 & 4 \\ -1 & 3 & 0 \\ 4 & 1 & 0 \end{pmatrix}$$

$$5.3.46 \begin{pmatrix} 0 & \sin \alpha & -\cos \alpha \\ -\sin \alpha & 0 & \sin \beta \\ \cos \alpha & -\sin \beta & 0 \end{pmatrix}$$

$$5.3.47 \begin{pmatrix} 2 & -3 & 5 \\ 6 & 0 & 4 \\ 1 & 5 & -7 \end{pmatrix}$$

$$5.3.48 \begin{pmatrix} 2 & -3 & 5 \\ 6 & 0 & 4 \\ 1 & 5 & -7 \end{pmatrix}$$

$$5.3.49 \begin{pmatrix} 3 & 2 & 3 \\ 2 & 2 & 3 \\ 3 & 2 & 3 \end{pmatrix}$$

$$5.3.50 \begin{pmatrix} 102 & 18 & 36 \\ 1 & 3 & 4 \\ 17 & 3 & 6 \end{pmatrix}$$

$$5.3.51 \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \\ 7 & 8 & 9 \end{pmatrix}$$

$$5.3.52 \begin{pmatrix} 2 & -3 & 5 \\ 6 & 0 & 4 \\ 1 & 5 & -7 \end{pmatrix}$$

$$5.3.53 \begin{pmatrix} 1 & 3 & 3 \\ 1 & 4 & 3 \\ 1 & 3 & 4 \end{pmatrix}$$

5.3.10 Verify that  $(\mathbf{AB})^{-1} = \mathbf{B}^{-1}\mathbf{A}^{-1}$  for

a)  $\mathbf{A} = \begin{pmatrix} 2 & 3 \\ 1 & -4 \end{pmatrix}$  and  $\mathbf{B} = \begin{pmatrix} 1 & -2 \\ -1 & 3 \end{pmatrix}$ .

b)  $\mathbf{A} = \begin{pmatrix} 3 & 7 \\ 2 & 5 \end{pmatrix}$  and  $\mathbf{B} = \begin{pmatrix} 6 & 8 \\ 7 & 9 \end{pmatrix}$ .

5.3.11 If  $\mathbf{A} = \begin{pmatrix} 2 & -3 & 5 \\ 3 & 2 & -4 \\ 1 & 1 & -2 \end{pmatrix}$ , find  $\mathbf{A}^{-1}$ . Using  $\mathbf{A}^{-1}$ , solve the system of equations

$$2x - 3y + 5z = 11 \quad (5.3.11.1)$$

$$3x + 2y - 4z = -5 \quad (5.3.11.2)$$

$$x + y - 2z = -3 \quad (5.3.11.3)$$

5.3.12 Let  $\mathbf{A} = \begin{pmatrix} 2 & -1 \\ 3 & 4 \end{pmatrix}$ ,  $\mathbf{B} = \begin{pmatrix} 5 & 2 \\ 7 & 4 \end{pmatrix}$ ,  $\mathbf{C} = \begin{pmatrix} 2 & 5 \\ 3 & 8 \end{pmatrix}$ . Find a matrix  $\mathbf{D}$  such that  $\mathbf{CD} - \mathbf{AB} = \mathbf{0}$ .

#### 5.4 Cayley-Hamilton Theorem

5.4.1 Let  $\mathbf{A} = \begin{pmatrix} 3 & 1 \\ -1 & 2 \end{pmatrix}$ , show that

$$\mathbf{A}^2 - 5\mathbf{A} + 7\mathbf{I} = \mathbf{0}. \quad (5.4.1.1)$$

Hence find  $\mathbf{A}^{-1}$ .

**Solution:** From (5.1.1.1),

$$\begin{vmatrix} 3-\lambda & 1 \\ -1 & 2-\lambda \end{vmatrix} = 0 \quad (5.4.1.2)$$

$$\implies (3-\lambda)(2-\lambda) + 1 = 0 \quad (5.4.1.3)$$

$$\text{or, } \lambda^2 - 5\lambda + 7 = 0 \quad (5.4.1.4)$$

Using (5.1.2.1) in the above, (5.4.1.1) is obtained. Multiplying both sides of (5.4.1.1) by  $\mathbf{A}^{-1}$ ,

$$\mathbf{A} - 5\mathbf{I} + 7\mathbf{A}^{-1} = \mathbf{0} \quad (5.4.1.5)$$

$$\implies \mathbf{A}^{-1} = \frac{1}{7} (5\mathbf{I} - \mathbf{A}) = \frac{1}{7} \begin{pmatrix} 2 & -1 \\ 1 & 3 \end{pmatrix} \quad (5.4.1.6)$$

5.4.2 Find  $\mathbf{A}^2 - 5\mathbf{A} + 6\mathbf{I}$ , if  $\mathbf{A} = \begin{pmatrix} 2 & 0 & 1 \\ 2 & 1 & 3 \\ 1 & -1 & 0 \end{pmatrix}$ .

5.4.3 If  $\mathbf{A} = \begin{pmatrix} 1 & 0 & 2 \\ 0 & 2 & 1 \\ 2 & 0 & 3 \end{pmatrix}$ , prove that

$$\mathbf{A}^3 - 6\mathbf{A}^2 + 7\mathbf{A} + 2\mathbf{I} = \mathbf{0}. \quad (5.4.3.1)$$

**Solution:** From (5.1.1.1), the characteristic equation is

$$\begin{vmatrix} 1-\lambda & 0 & 2 \\ 0 & 2-\lambda & 1 \\ 2 & 0 & 3-\lambda \end{vmatrix} = 0 \quad (5.4.3.2)$$

which can be expanded to obtain

$$\lambda^3 - 6\lambda^2 + 7\lambda + 2 = 0 \quad (5.4.3.3)$$

upon simplification. Using the Cayley-Hamilton theorem in (5.1.2.1), (5.4.3.1) is obtained.

5.4.4 If  $\mathbf{A} = \begin{pmatrix} 3 & -2 \\ 4 & -2 \end{pmatrix}$  and  $\mathbf{I} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ , find  $k$  so that  $\mathbf{A}^2 = k\mathbf{A} - 2\mathbf{I}$ .

5.4.5 For the matrix  $\mathbf{A} = \begin{pmatrix} 3 & 2 \\ 1 & 1 \end{pmatrix}$ , find the numbers  $a$  and  $b$  such that  $\mathbf{A}^2 + a\mathbf{A} + b\mathbf{I} = \mathbf{0}$ .

5.4.6 For the matrix  $\mathbf{A} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 2 & 3 \\ 2 & -1 & 3 \end{pmatrix}$ . Show that  $\mathbf{A}^3 - 6\mathbf{A}^2 + 5\mathbf{A} + 11\mathbf{I} = \mathbf{0}$ . Hence, find

$\mathbf{A}^{-1}$ .

5.4.7 If  $\mathbf{A} = \begin{pmatrix} 2 & -1 & 1 \\ -1 & 2 & -1 \\ 1 & -1 & 2 \end{pmatrix}$ . Verify that  $\mathbf{A}^3 - 6\mathbf{A}^2 + 9\mathbf{A} - 4\mathbf{I} = \mathbf{0}$  and hence find  $\mathbf{A}^{-1}$ .

5.4.8 If  $\mathbf{A} = \begin{pmatrix} \alpha & \beta \\ \gamma & -\alpha \end{pmatrix}$  is such that  $\mathbf{A}^2 = \mathbf{I}$ , then

- a)  $1 + \alpha^2 + \beta\gamma = 0$
- b)  $1 - \alpha^2 + \beta\gamma = 0$
- c)  $1 - \alpha^2 - \beta\gamma = 0$
- d)  $1 + \alpha^2 - \beta\gamma = 0$

5.4.9 Let  $\mathbf{A} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$ , show that  $(a\mathbf{I} + b\mathbf{A})^n = a^n\mathbf{I} + na^{n-1}b\mathbf{A}$ .

5.4.10 If  $\mathbf{A} = \begin{pmatrix} 3 & 1 \\ -1 & 2 \end{pmatrix}$ , show that  $\mathbf{A}^2 - 5\mathbf{A} + 7\mathbf{I} = \mathbf{0}$ .

5.4.11 If  $\mathbf{A}$  is square matrix such that  $\mathbf{A}^2 = \mathbf{A}$ , then  $(\mathbf{I} + \mathbf{A})^3 - 7\mathbf{A}$  is equal to

- a)  $\mathbf{A}$
- b)  $\mathbf{I} - \mathbf{A}$
- c)  $\mathbf{I}$
- d)  $3\mathbf{A}$

5.4.12 If  $\mathbf{A} = \begin{pmatrix} 1 & 2 & 3 \\ 3 & -2 & 1 \\ 4 & 2 & 1 \end{pmatrix}$ , then show that  $\mathbf{A}^3 - 23\mathbf{A} - 40\mathbf{I} = \mathbf{0}$ .

5.4.13 Show that the matrix  $\mathbf{A} = \begin{pmatrix} 2 & 3 \\ 1 & 2 \end{pmatrix}$  satisfies the equation  $\mathbf{A}^2 - 4\mathbf{A} + \mathbf{I} = \mathbf{0}$ . Using this equation, find  $\mathbf{A}^{-1}$ .

## 5.5 Application

Form the pair of linear equations in the following problems and find their solutions graphically

5.5.1 A trust fund has ₹30000 that must be invested in two different types of bonds. The first bond pays 5% interest per year, and the second bond pays 7% interest per year. Determine how to divide ₹30000 among the 2 types of bonds. If the trust fund must obtain an annual total interest of

- a) ₹1800
- b) ₹2000

**Solution:** Let the desired division for both cases be

$$\begin{aligned} x_1 + x_2 &= 30000 \\ 0.05x_1 + 0.07x_2 &= 1800 \end{aligned} \implies \begin{pmatrix} 1 & 1 \\ 0.05 & 0.07 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} 30000 \\ 1800 \end{pmatrix} \quad (5.5.1.1)$$

$$\begin{aligned} y_1 + y_2 &= 30000 \\ 0.05y_1 + 0.07y_2 &= 2000 \end{aligned} \implies \begin{pmatrix} 1 & 1 \\ 0.05 & 0.07 \end{pmatrix} \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} 30000 \\ 2000 \end{pmatrix} \quad (5.5.1.2)$$

yielding

$$\begin{pmatrix} 1 & 1 \\ 0.05 & 0.07 \end{pmatrix} \begin{pmatrix} x_1 & y_1 \\ x_2 & y_2 \end{pmatrix} = \begin{pmatrix} 30000 & 30000 \\ 1800 & 2000 \end{pmatrix} \quad (5.5.1.3)$$

with the augmented matrix followed by row reduction

$$\begin{aligned}
 &\xleftrightarrow{R_2=R_2-0.05R_1} \left( \begin{array}{cc|cc} 1 & 1 & 30000 & 30000 \\ 0 & 0.02 & 300 & 500 \end{array} \right) \xleftrightarrow{R_2=50R_2} \left( \begin{array}{cc|cc} 1 & 1 & 30000 & 30000 \\ 0 & 1 & 15000 & 25000 \end{array} \right) \\
 &\xleftrightarrow{R_1=R_1-R_2} \left( \begin{array}{cc|cc} 1 & 0 & 115000 & 5000 \\ 0 & 1 & 15000 & 25000 \end{array} \right)
 \end{aligned}$$

Thus,

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} 15000 \\ 15000 \end{pmatrix}, \begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} 5000 \\ 25000 \end{pmatrix} \quad (5.5.1.4)$$

- 5.5.2 10 students of Class X took part in a Mathematics quiz. If the number of girls is 4 more than the number of boys, find the number of boys and girls who took part in the quiz.
- 5.5.3 5 pencils and 7 pens together cost ₹50 whereas 7 pencils and 5 pens together cost ₹46. Find the cost of one pencil and that of one pen.
- 5.5.4 Half the perimeter of a rectangular garden, whose length is  $4m$ , more than its width, is  $36m$ . Find the dimensions of the garden.
- 5.5.5 A part of monthly hostel charges is fixed and the remaining depends on the number of days one has taken food in the mess. When a student  $A$  takes food for 20 days she has to pay ₹1000 as hostel charges whereas a student  $B$  who takes food for 26 days, pays ₹1180 as hostel charges. Find the fixed charges and the cost of food per day.
- 5.5.6 A fraction becomes  $\frac{1}{3}$  when 1 is subtracted from the numerator and it becomes  $\frac{1}{4}$  when 8 is added to the denominator. Find the fraction.
- 5.5.7 Yash scored 40 marks in a test, getting 3 marks for each right answer and losing 1 mark for each wrong answer. Had 4 marks been awarded for each correct answer and 2 marks been deducted for each incorrect answer, then Yash would have scored 50 marks. How many questions were there in the test?
- 5.5.8 Places  $A$  and  $B$  are  $100km$  apart on a highway. One car starts from  $A$  and another from  $B$  at the same time. If the car travel in the same direction at different speeds, they meet in 5hrs. If they travel towards each other, they meet in 1hr. What are the speeds of the two cars?
- 5.5.9 The area of a rectangle gets reduced by 9 square units, if its length is reduced by 5 units and breadth is increased by 3 units. If we increase the length by 3 units and the breadth by 2 units, the area increases by 67 square units. Find the dimensions of the rectangle.
- 5.5.10 Narayan tells his daughter, ‘Seven years ago, I was seven times as old as you were then. Also, 3 years from now, I shall be 3 times as old as you will be.’ Find their ages.
- 5.5.11 The coach of a cricket team buys 3 bats and 6 balls for ₹3900. Later, she buys another bat and 3 more balls of the same kind for ₹3300. Find the cost of a bat and ball.
- 5.5.12 The cost of  $2kg$  of apples and  $1kg$  of grapes on a day was found to be ₹160. After a month, the cost of  $4kg$  of apples and  $2kg$  of grapes is ₹300. Assuming that the costs remain unchanged, find the cost of a kg of apples and grapes.

- 5.5.13 The difference between two numbers is 26 and one number is three times the other. Find them.
- 5.5.14 The larger of two supplementary angles exceeds the smaller by 18 degrees. Find them.
- 5.5.15 The coach of a cricket team buys 7 balls and 6 bats for ₹3800. Later, she buys 3 bats and 5 balls for ₹1750. Find the cost of each bat and each ball.
- 5.5.16 The taxi charges in a city consist of a fixed charge together with the charges for the distance covered. For a distance of 10 km, the charge paid is ₹105 and for a distance of 15 km, the charge paid is ₹155. What are the fixed charges and the charge per km? How much does a person have to pay for travelling a distance of 25 km ?
- 5.5.17 A fraction becomes  $\frac{9}{11}$  if 2 is added to both the numerator and the denominator. If 3 is added to both the numerator and the denominator, it becomes  $\frac{5}{6}$ . Find the fraction.
- 5.5.18 Five years hence, the age of Rahul will be three times that of his son. Five years ago, Rahul's age was seven times that of his son. What are their present ages?
- 5.5.19 If we add 1 to the numerator and subtract 1 from the denominator, a fraction reduces to 1. It becomes  $\frac{1}{2}$  if we only add 1 to the denominator. What is the fraction?
- 5.5.20 Five years ago, Minu was thrice as old as Sonu. Ten years later, Minu will be twice as old as Sonu. How old are Minu and Sonu?
- 5.5.21 The Sum of the digits of a two-digit number is 9. Also, nine times this number is twice the number obtained by reversing the order of the digits. Find the number.
- 5.5.22 Meena went to a bank to withdraw ₹2000. She asked the cashier to give her ₹50 and ₹100 notes only. Meena got 25 notes in all. Find how many notes of ₹50 and ₹100 she received.
- 5.5.23 A lending library has a fixed charge for the first three days and an additional charge for each day thereafter. Sarita paid ₹27 for seven days, while Susheela paid ₹21 for five days. Find the fixed charge and the charge for each extra day.
- 5.5.24 The ages of two friends Ani and Bijoya differ by 3 years. Ani's father Dharam is twice as old as Ani and Bijoya is twice as old as sister Kanta. The ages of Kanta and Dharam differ by 30 years. Find the ages of Ani and Bijoya.
- 5.5.25 One says, "Give me a hundred, Friend! I shall then become twice as rich as you ". The other "if you give me ten, i shall be six times as rich as you ". Tell me What is the amount of their (respective) capital? [From the bijaganita of Bhaskara II].
- 5.5.26 A train covered a certain distance at a uniform speed. If the train would have been 10 km/h faster, it would have taken 2 hours less than the scheduled time. And, if the train were slower by 10 km/h; it would have taken 3 hours more than the scheduled time. Find the distance covered by the train.
- 5.5.27 The students of a class are made to stand in rows. If 3 students are extra in a row, there would be 1 row less. If 3 students are less in a row, there would be 2 rows more. Find the number of students in the class.
- 5.5.28 Ritu can row downstream 20km in 2 hours, and upstream 4km in 2 hours. Find her speed of rowing in still water and the speed of the current.
- 5.5.29 2 women and 5 men can together finish an embroidery work in 4 days, while 3 women and 6 men can finish it in 3 days. Find the time taken by 1 women alone to finish the work, and also that taken by 1 man alone.
- 5.5.30 Rambha travels 300km to her home partly by train and partly by bus. She takes 4

hours if she travels  $60\text{km}$  by train and the remaining by bus. If she travels  $100\text{km}$  by train and the remaining by bus, she takes 10 minutes longer. Find the speed of the train and the bus separately

5.5.31 In a  $\triangle ABC$ ,  $\angle C = 3\angle B = 2(\angle A + \angle B)$ . Find the three angles.

5.5.32  $ABCD$  is a cyclic quadrilateral with angles

$$A = 4y + 20, B = -7x + 5, C = -4x, D = 3y - 5. \quad (5.5.32.1)$$

Find them.

5.5.33 Draw the graphs of the equations  $5x - y = 5$  and  $3x - y = 3$ . Determine the Co-ordinates of the vertices of the triangle formed by these lines and the  $y$  axis.

5.5.34 Draw the graphs of the equations  $x - y + 1 = 0$  and  $3x + 2y - 12 = 0$ . Determine the coordinates of the vertices of the triangle formed by these lines and the axis and shade the triangular region.

5.5.35 The cost of  $4\text{kg}$  onion,  $3\text{kg}$  wheat and  $2\text{kg}$  rice is ₹60. The cost of  $2\text{kg}$  onion,  $4\text{kg}$  wheat and  $6\text{kg}$  rice is ₹90. The cost of  $6\text{kg}$  onion,  $2\text{kg}$  wheat and  $3\text{kg}$  rice is ₹70. Find cost of each item per kg.

5.5.36 Romila went to a stationary shop and purchased 2 pencils and 3 erasers for ₹9. Her friend Sonali saw the new variety of pencils and erasers with Romila, and she also bought 4 pencils and 6 erasers of the same kind for ₹18. Represent this situation algebraically and graphically.

5.5.37 Champa went to a “Sale” to purchase some pants and skirts. When her friends asked her how many of each she had bought she answered, “The number of skirts is two less than twice the number of pants purchased. Also, the number of skirts is four less than four times the number of pants purchased”. Help her friends to find how many pants and skirts Champa bought.

5.5.38 Alwar tells his daughter, “Seven years ago, I was seven times as old as you were then. Also, three years from now, I shall be three times as old as you will be.” Represent this situation algebraically and graphically.

5.5.39 The cost of 2 pencils and 3 erasers is ₹9 and the cost of 4 pencils and 6 erasers is ₹18. Find the cost of each pencil and each eraser.

5.5.40 The ratio of incomes of two persons is 9:7 and the ratio of their expenditures is 4 : 3. If each of them manages to save ₹2000 per month, find their monthly incomes.

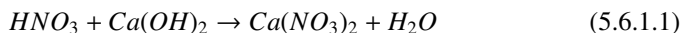
5.5.41 The sum of a two digit number and the number obtained by reversing the digits is 66. If the digits of the number differ by 2, find the number. How many such numbers are there?

5.5.42 A boat goes 30 km upstream and 44 km downstream in 10 hours. In 13 hours, it can go 40 km upstream and 55 km down-stream. Determine the speed of the stream and that of the boat in still water.

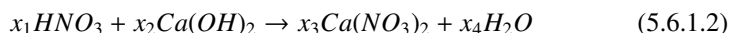
5.5.43 The sum of three numbers is 6. If we multiply the third number by 3 and add the second number to it, we get 11. By adding the first and third numbers, we get double of the second number. Find the numbers.

## 5.6 Chemistry

5.6.1. Balance the following chemical equation.



**Solution:** Let the balanced version of (5.6.1.1) be



which results in the following equations:

$$(x_1 + 2x_2 - 2x_4)H = 0 \quad (5.6.1.3)$$

$$(x_1 - 2x_3)N = 0 \quad (5.6.1.4)$$

$$(3x_1 + 2x_2 - 6x_3 - x_4)O = 0 \quad (5.6.1.5)$$

$$(x_2 - x_3)Ca = 0 \quad (5.6.1.6)$$

which can be expressed as

$$x_1 + 2x_2 + 0x_3 - 2x_4 = 0 \quad (5.6.1.7)$$

$$x_1 + 0x_2 - 2x_3 + 0x_4 = 0 \quad (5.6.1.8)$$

$$3x_1 + 2x_2 - 6x_3 - x_4 = 0 \quad (5.6.1.9)$$

$$0x_1 + x_2 - x_3 + 0x_4 = 0 \quad (5.6.1.10)$$

resulting in the matrix equation

$$\begin{pmatrix} 1 & 2 & 0 & -2 \\ 1 & 0 & -2 & 0 \\ 3 & 2 & -6 & -1 \\ 0 & 1 & -1 & 0 \end{pmatrix} \mathbf{x} = \mathbf{0}, \quad \mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} \quad (5.6.1.11)$$

(5.6.1.11) can be reduced as follows

$$\begin{pmatrix} 1 & 2 & 0 & -2 \\ 1 & 0 & -2 & 0 \\ 3 & 2 & -6 & -1 \\ 0 & 1 & -1 & 0 \end{pmatrix} \begin{array}{c} \xleftarrow{R_2 \leftarrow R_2 - R_1} \\ \xleftarrow{R_3 \leftarrow R_3 - R_1} \end{array} \begin{pmatrix} 1 & 2 & 0 & -2 \\ 0 & -2 & -2 & 2 \\ 0 & -\frac{4}{3} & -2 & \frac{5}{3} \\ 0 & 1 & -1 & 0 \end{pmatrix} \quad (5.6.1.12)$$

$$\begin{array}{c} \xleftarrow{R_2 \leftarrow -\frac{R_2}{2}} \\ \xleftarrow{R_3 \leftarrow -\frac{R_3}{2}} \end{array} \begin{pmatrix} 1 & 2 & 0 & -2 \\ 0 & 1 & 1 & -1 \\ 0 & -\frac{4}{3} & -2 & \frac{5}{3} \\ 0 & 1 & -1 & 0 \end{pmatrix} \begin{array}{c} \xleftarrow{R_3 \leftarrow R_3 + \frac{4}{3}R_2} \\ \xleftarrow{R_4 \leftarrow R_4 - R_2} \end{array} \begin{pmatrix} 1 & 2 & 0 & -2 \\ 0 & 1 & 1 & -1 \\ 0 & 0 & -\frac{2}{3} & \frac{1}{3} \\ 0 & 0 & -2 & 1 \end{pmatrix} \quad (5.6.1.13)$$

$$\begin{array}{c} \xleftarrow{R_1 \leftarrow R_1 - 2R_2} \\ \xleftarrow{R_3 \leftarrow -\frac{3}{2}R_3} \end{array} \begin{pmatrix} 1 & 0 & -2 & 0 \\ 0 & 1 & 1 & -1 \\ 0 & 0 & 1 & -\frac{1}{2} \\ 0 & 0 & -2 & 1 \end{pmatrix} \xleftarrow{R_4 \leftarrow R_4 + 2R_3} \begin{pmatrix} 1 & 0 & -2 & 0 \\ 0 & 1 & 1 & -1 \\ 0 & 0 & 1 & -\frac{1}{2} \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (5.6.1.14)$$

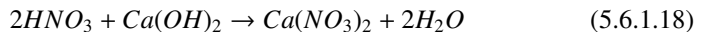
$$\begin{array}{c} \xleftarrow{R_1 \leftarrow R_1 + 2R_3} \\ \xleftarrow{R_2 \leftarrow R_2 - R_3} \end{array} \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 0 & -\frac{1}{2} \\ 0 & 0 & 1 & -\frac{1}{2} \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (5.6.1.15)$$

Thus,

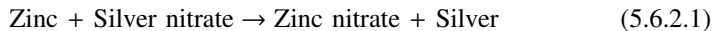
$$x_1 = x_4, x_2 = \frac{1}{2}x_4, x_3 = \frac{1}{2}x_4 \quad (5.6.1.16)$$

$$\Rightarrow \mathbf{x} = x_4 \begin{pmatrix} 1 \\ \frac{1}{2} \\ \frac{1}{2} \\ 1 \end{pmatrix} = \begin{pmatrix} 2 \\ 1 \\ 1 \\ 2 \end{pmatrix} \quad (5.6.1.17)$$

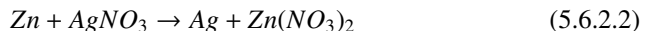
by substituting  $x_4 = 2$ . Hence, (5.6.1.2) finally becomes



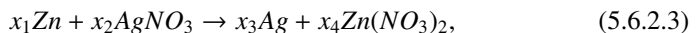
5.6.2. Balance the following chemical equation.



**Solution:** (5.6.2.1) can be written as



Suppose the balanced form of the equation is





which results in the following equations:

$$(x_1 - 2x_4)Zn = 0 \quad (5.6.2.4)$$

$$(x_2 - x_3)Ag = 0 \quad (5.6.2.5)$$

$$(x_3 - 2x_4)N = 0 \quad (5.6.2.6)$$

$$(3x_3 - 6x_4)O = 0 \quad (5.6.2.7)$$

which can be expressed as

$$x_1 + 0x_2 + 0x_3 - x_4 = 0 \quad (5.6.2.8)$$

$$0x_1 + x_2 - x_3 + 0x_4 = 0 \quad (5.6.2.9)$$

$$0x_1 + 0x_2 + x_3 - 2x_4 = 0 \quad (5.6.2.10)$$

$$0x_1 + 0x_2 + 3x_3 - 6x_4 = 0 \quad (5.6.2.11)$$

resulting in the matrix equation

$$\begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -2 \\ 0 & 0 & 3 & -6 \end{pmatrix} \mathbf{x} = \mathbf{0}, \quad \mathbf{x} = \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} \quad (5.6.2.12)$$

(5.6.2.12) can be reduced as

$$\begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -2 \\ 0 & 0 & 3 & -6 \end{pmatrix} \xleftrightarrow{R_4 \leftarrow R_4 - 3R_3} \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & -1 & 0 \\ 0 & 0 & 1 & -2 \\ 0 & 0 & 0 & 0 \end{pmatrix} \quad (5.6.2.13)$$

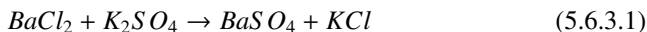
Thus,

$$x_1 = x_4, x_2 = 2x_4, x_3 = 2x_4 \implies \mathbf{x} = \begin{pmatrix} x_4 \\ 2x_4 \\ 2x_4 \\ x_4 \end{pmatrix} = x_4 \begin{pmatrix} 1 \\ 2 \\ 2 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 2 \\ 2 \\ 1 \end{pmatrix}, \quad x_4 = 1 \quad (5.6.2.14)$$

Hence, (5.6.2.3) finally becomes



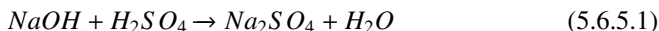
5.6.3. Write the balanced chemical equations for the following reaction.



5.6.4. Balance the following chemical equation.



5.6.5. Balance the following chemical equation.



## 6 SKEW LINES

## 6.1 Formulae

## 6.1.1. The lines

$$\begin{aligned} L_1 : \quad \mathbf{x} &= \mathbf{A} + \kappa_1 \mathbf{m}_1 \\ L_2 : \quad \mathbf{x} &= \mathbf{B} + \kappa_2 \mathbf{m}_2 \end{aligned} \quad (6.1.1.1)$$

will intersect if

$$\mathbf{A} + \kappa_1 \mathbf{m}_1 = \mathbf{B} + \kappa_2 \mathbf{m}_2 \quad (6.1.1.2)$$

$$\Rightarrow \begin{pmatrix} \mathbf{m}_1 & \mathbf{m}_2 \end{pmatrix} \begin{pmatrix} \kappa_1 \\ -\kappa_2 \end{pmatrix} = \mathbf{B} - \mathbf{A} \quad (6.1.1.3)$$

$$\Rightarrow \text{rank} \begin{pmatrix} \mathbf{M} & \mathbf{B} - \mathbf{A} \end{pmatrix} = 2 \quad (6.1.1.4)$$

where

$$\mathbf{M} = \begin{pmatrix} \mathbf{m}_1 & \mathbf{m}_2 \end{pmatrix} \quad (6.1.1.5)$$

6.1.2. If  $L_1, L_2$ , do not intersect, let

$$\begin{aligned} \mathbf{x}_1 &= \mathbf{A} + \kappa_1 \mathbf{m}_1 \\ \mathbf{x}_2 &= \mathbf{B} + \kappa_2 \mathbf{m}_2 \end{aligned} \quad (6.1.2.1)$$

be points on  $L_1, L_2$  respectively, that are closest to each other. Then, from (6.1.2.1)

$$\mathbf{x}_1 - \mathbf{x}_2 = \mathbf{A} - \mathbf{B} + \begin{pmatrix} \mathbf{m}_1 & \mathbf{m}_2 \end{pmatrix} \begin{pmatrix} \kappa_1 \\ -\kappa_2 \end{pmatrix} \quad (6.1.2.2)$$

Also,

$$(\mathbf{x}_1 - \mathbf{x}_2)^\top \mathbf{m}_1 = (\mathbf{x}_1 - \mathbf{x}_2)^\top \mathbf{m}_2 = 0 \quad (6.1.2.3)$$

$$\Rightarrow (\mathbf{x}_1 - \mathbf{x}_2)^\top \begin{pmatrix} \mathbf{m}_1 & \mathbf{m}_2 \end{pmatrix} = \mathbf{0} \quad (6.1.2.4)$$

$$\text{or, } \mathbf{M}^\top (\mathbf{x}_1 - \mathbf{x}_2) = \mathbf{0} \quad (6.1.2.5)$$

$$\Rightarrow \mathbf{M}^\top (\mathbf{A} - \mathbf{B}) + \mathbf{M}^\top \mathbf{M} \begin{pmatrix} \kappa_1 \\ -\kappa_2 \end{pmatrix} = \mathbf{0} \quad (6.1.2.6)$$

from (6.1.2.2), yielding

$$\mathbf{M}^\top \mathbf{M} \begin{pmatrix} \kappa_1 \\ -\kappa_2 \end{pmatrix} = \mathbf{M}^\top (\mathbf{B} - \mathbf{A}) \quad (6.1.2.7)$$

This is known as the *least squares solution*.

## 6.1.3. Perform the eigendecompositions

$$\mathbf{M}\mathbf{M}^\top = \mathbf{U}\mathbf{D}_1\mathbf{U}^\top \quad (6.1.3.1)$$

$$\mathbf{M}^\top \mathbf{M} = \mathbf{V}\mathbf{D}_2\mathbf{V}^\top \quad (6.1.3.2)$$

6.1.4. The following expression is known as *singular value decomposition*

$$\mathbf{M} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^\top \quad (6.1.4.1)$$

where  $\Sigma$  is diagonal with entries obtained as in (6.3.1.21). Substituting in (6.1.2.7),

$$\mathbf{V}\Sigma\mathbf{U}^\top\mathbf{U}\Sigma\mathbf{V}^\top\boldsymbol{\kappa} = \mathbf{V}\Sigma\mathbf{U}^\top(\mathbf{B} - \mathbf{A}) \quad (6.1.4.2)$$

$$\implies \mathbf{V}\Sigma^2\mathbf{V}^\top\boldsymbol{\kappa} = \mathbf{V}\Sigma\mathbf{U}^\top(\mathbf{B} - \mathbf{A}) \quad (6.1.4.3)$$

$$\implies \boldsymbol{\kappa} = (\mathbf{V}\Sigma^2\mathbf{V}^\top)^{-1}\mathbf{V}\Sigma\mathbf{U}^\top(\mathbf{B} - \mathbf{A}) \quad (6.1.4.4)$$

$$\implies \boldsymbol{\kappa} = \mathbf{V}\Sigma^{-2}\mathbf{V}^\top\mathbf{V}\Sigma\mathbf{U}^\top(\mathbf{B} - \mathbf{A}) \quad (6.1.4.5)$$

$$\implies \boldsymbol{\kappa} = \mathbf{V}\Sigma^{-1}\mathbf{U}^\top(\mathbf{B} - \mathbf{A}) \quad (6.1.4.6)$$

where  $\Sigma^{-1}$  is obtained by inverting the nonzero elements of  $\Sigma$ .

6.1.5. From (6.1.2.1),

$$\mathbf{x}_1 - \mathbf{x}_2 = \mathbf{A} + \kappa_1\mathbf{m}_1 - \mathbf{B} - \kappa_2\mathbf{m}_2 \quad (6.1.5.1)$$

$$= \mathbf{A} - \mathbf{B} + \mathbf{M}\boldsymbol{\kappa} \quad (6.1.5.2)$$

which, upon substitution from (6.1.4.1) yields

$$\mathbf{x}_1 - \mathbf{x}_2 = \mathbf{A} - \mathbf{B} + \mathbf{U}\Sigma\mathbf{V}^\top\mathbf{V}\Sigma^{-1}\mathbf{U}^\top(\mathbf{B} - \mathbf{A}) \quad (6.1.5.3)$$

$$= (\mathbf{A} - \mathbf{B})(\mathbf{I} - \mathbf{U}\Sigma\Sigma^{-1}\mathbf{U}^\top) \quad (6.1.5.4)$$

Thus,

$$\|\mathbf{x}_1 - \mathbf{x}_2\| = \left\| (\mathbf{A} - \mathbf{B})(\mathbf{I} - \mathbf{U}\Sigma\Sigma^{-1}\mathbf{U}^\top) \right\| \quad (6.1.5.5)$$

6.1.6. Least squares solution

codes/book/skew\_least.py

6.1.7. Least squares using builtin SVD

codes/book/skew\_builtin.py

6.1.8. Code linking eigenvalues and singular values

codes/book/skew\_svd.py

## 6.2 Least Squares

6.2.1 Find the shortest distance between the lines

$$\frac{x+1}{7} = \frac{y+1}{-6} = \frac{z+1}{1} \text{ and} \quad (6.2.1.1)$$

$$\frac{x-3}{1} = \frac{y-5}{-2} = \frac{z-7}{1} \quad (6.2.1.2)$$

**Solution:** The given lines can be written as

$$\begin{aligned}\mathbf{x} &= \begin{pmatrix} -1 \\ -1 \\ -1 \end{pmatrix} + \kappa_1 \begin{pmatrix} 7 \\ -6 \\ 1 \end{pmatrix} \\ \mathbf{x} &= \begin{pmatrix} 3 \\ 5 \\ 7 \end{pmatrix} + \kappa_2 \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix}\end{aligned}\tag{6.2.1.3}$$

with

$$\mathbf{A} = \begin{pmatrix} -1 \\ -1 \\ -1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 3 \\ 5 \\ 7 \end{pmatrix}, \mathbf{M} = \begin{pmatrix} 7 & 1 \\ -6 & -2 \\ 1 & 1 \end{pmatrix}\tag{6.2.1.4}$$

Substituting the above in (6.1.1.4),

$$\left( \begin{array}{cc|c} 7 & 1 & 4 \\ -6 & -2 & 6 \\ 1 & 1 & 8 \end{array} \right) \begin{array}{l} \xleftarrow{R_2 \leftarrow R_2 + \frac{6}{7}R_1} \\ \xleftarrow{R_3 \leftarrow R_3 - \frac{1}{7}R_1} \end{array}\tag{6.2.1.5}$$

$$\left( \begin{array}{cc|c} 7 & 1 & 4 \\ 0 & -\frac{8}{7} & \frac{66}{7} \\ 0 & \frac{6}{7} & -\frac{52}{7} \end{array} \right) \xleftarrow{R_3 \leftarrow R_3 + \frac{3}{4}R_2}\tag{6.2.1.6}$$

$$\left( \begin{array}{cc|c} 2 & 3 & 1 \\ 0 & -\frac{7}{2} & \frac{1}{2} \\ 0 & 0 & -\frac{5}{14} \end{array} \right)\tag{6.2.1.7}$$

The rank of the matrix is 3. So the given lines are skew. From (6.1.2.7)

$$\begin{pmatrix} 7 & -6 & 1 \\ 1 & -2 & 1 \end{pmatrix} \begin{pmatrix} 7 & 1 \\ -6 & -2 \\ 1 & 1 \end{pmatrix} \boldsymbol{\kappa} = \begin{pmatrix} 7 & -6 & 1 \\ 1 & -2 & 1 \end{pmatrix} \begin{pmatrix} 4 \\ 6 \\ 8 \end{pmatrix}\tag{6.2.1.8}$$

$$\Rightarrow \begin{pmatrix} 86 & 20 \\ 20 & 6 \end{pmatrix} \boldsymbol{\kappa} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}\tag{6.2.1.9}$$

$$\Rightarrow \begin{pmatrix} \kappa_1 \\ -\kappa_2 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}\tag{6.2.1.10}$$

From (6.2.1.3), the closest points are  $\mathbf{A}$  and  $\mathbf{B}$  and the minimum distance between the lines is given by

$$\|\mathbf{B} - \mathbf{A}\| = \left\| \begin{pmatrix} 4 \\ 6 \\ 8 \end{pmatrix} \right\| = 2\sqrt{29}\tag{6.2.1.11}$$

See Fig. 6.2.1.1.



Fig. 6.2.1.1

6.2.2 Find the shortest distance between the lines whose vector equations are

$$\mathbf{x} = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} + \kappa_1 \begin{pmatrix} 1 \\ -3 \\ 2 \end{pmatrix} \quad (6.2.2.1)$$

$$\mathbf{x} = \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix} + \kappa_2 \begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix}$$

**Solution:** In this case,

$$\mathbf{B} - \mathbf{A} = \begin{pmatrix} 3 \\ 3 \\ 3 \end{pmatrix} \quad (6.2.2.2)$$

$$\mathbf{M} = \begin{pmatrix} 1 & 2 \\ -3 & 3 \\ 2 & 1 \end{pmatrix}. \quad (6.2.2.3)$$

forming the matrix in (6.1.1.4),

$$\begin{pmatrix} 1 & 2 & 3 \\ -3 & 3 & 3 \\ 2 & 1 & 3 \end{pmatrix} \xleftrightarrow{R_2 \leftarrow R_2 + 3R_1} \begin{pmatrix} 1 & 2 & 3 \\ 0 & 9 & 12 \\ 2 & 1 & 3 \end{pmatrix}$$

$$\xleftrightarrow{R_3 \leftarrow R_3 - 2R_1} \begin{pmatrix} 1 & 2 & 3 \\ 0 & 9 & 12 \\ 0 & -3 & -3 \end{pmatrix} \xleftrightarrow{R_3 \leftarrow -3R_3 + R_2} \begin{pmatrix} 1 & 2 & 3 \\ 0 & 9 & 12 \\ 0 & 0 & 3 \end{pmatrix}$$

Clearly, the rank of this matrix is 3, and therefore, the lines are skew. From (6.1.2.7),

$$\begin{aligned}
 & \left( \begin{array}{cc|c} 14 & -5 & 0 \\ -5 & 14 & 18 \end{array} \right) \xleftrightarrow{R_1 \leftarrow R_1 + R_2} \left( \begin{array}{cc|c} 9 & 9 & 18 \\ -5 & 14 & 18 \end{array} \right) \\
 & \xleftrightarrow{R_1 \leftarrow \frac{R_1}{9}} \left( \begin{array}{cc|c} 1 & 1 & 2 \\ -5 & 14 & 18 \end{array} \right) \xleftrightarrow{R_2 \leftarrow R_2 + 5R_1} \left( \begin{array}{cc|c} 1 & 1 & 2 \\ 0 & 19 & 28 \end{array} \right) \\
 & \xleftrightarrow{R_1 \leftarrow \frac{R_1}{19}} \left( \begin{array}{cc|c} 19 & 0 & 10 \\ 0 & 19 & 28 \end{array} \right) \xleftrightarrow{R_2 \leftarrow \frac{R_2}{19}} \left( \begin{array}{cc|c} 19 & 0 & 10 \\ 0 & 1 & \frac{28}{19} \end{array} \right)
 \end{aligned}$$

yielding

$$\kappa = \frac{1}{19} \begin{pmatrix} 10 \\ 28 \end{pmatrix} \quad (6.2.2.4)$$

Substituting the above in (6.2.2.1),

$$\mathbf{x}_1 = \frac{1}{19} \begin{pmatrix} 29 \\ 8 \\ 77 \end{pmatrix}, \quad \mathbf{x}_2 = \frac{1}{19} \begin{pmatrix} 20 \\ 11 \\ 86 \end{pmatrix}. \quad (6.2.2.5)$$

Thus, the required distance is

$$\|\mathbf{x}_2 - \mathbf{x}_1\| = \frac{3}{\sqrt{19}} \quad (6.2.2.6)$$

See Fig. 6.2.2.1.

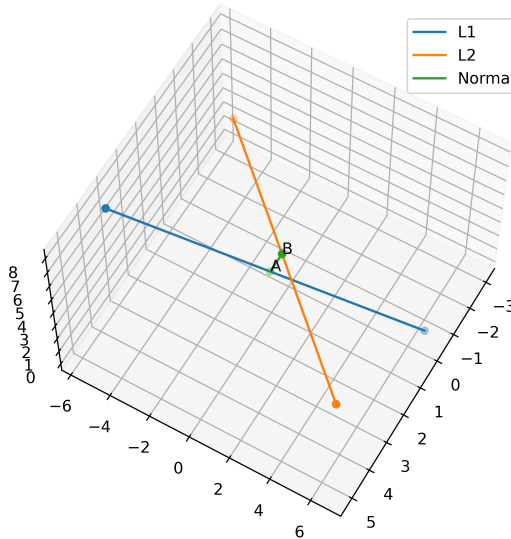


Fig. 6.2.2.1

6.2.3 Find the shortest distance between the lines  $l_1$  and  $l_2$  whose vector equations are

$$\vec{r} = \hat{i} + \hat{j} + \kappa(2\hat{i} - \hat{j} + \hat{k}) \text{ and} \quad (6.2.3.1)$$

$$\vec{r} = 2\hat{i} + \hat{j} - \hat{k} + \mu(3\hat{i} - 5\hat{j} + 2\hat{k}). \quad (6.2.3.2)$$

**Solution:** The given lines can be written in vector form as

$$\mathbf{x} = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} + \kappa_1 \begin{pmatrix} 2 \\ -1 \\ 1 \end{pmatrix}, \quad (6.2.3.3)$$

$$\mathbf{x} = \begin{pmatrix} 2 \\ 1 \\ -1 \end{pmatrix} + \kappa_2 \begin{pmatrix} 3 \\ -5 \\ 2 \end{pmatrix}$$

$$\mathbf{M} = \begin{pmatrix} 2 & 3 \\ -1 & -5 \\ 1 & 2 \end{pmatrix}, \mathbf{B} - \mathbf{A} = \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \quad (6.2.3.4)$$

Substituting the above in (6.1.1.4),

$$\begin{pmatrix} 2 & 3 & 1 \\ -1 & -5 & 0 \\ 1 & 2 & -1 \end{pmatrix} \xrightarrow[R_3 \leftarrow R_3 - \frac{1}{2}R_1]{R_2 \leftarrow R_2 + \frac{1}{2}R_1} \begin{pmatrix} 2 & 3 & 1 \\ 0 & -\frac{7}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & -\frac{3}{2} \end{pmatrix} \quad (6.2.3.5)$$

$$\xrightarrow{R_3 \leftarrow R_3 + 7R_2} \begin{pmatrix} 2 & 3 & 1 \\ 0 & -\frac{7}{2} & \frac{1}{2} \\ 0 & 0 & -10 \end{pmatrix} \quad (6.2.3.6)$$

The rank of the matrix is 3. So the given lines are skew. From (6.1.2.7),

$$\begin{pmatrix} 2 & -1 & 1 \\ 3 & -5 & 2 \end{pmatrix} \begin{pmatrix} 2 & 3 \\ -1 & -5 \\ 1 & 2 \end{pmatrix} \kappa = \begin{pmatrix} 2 & -1 & 1 \\ 3 & -5 & 2 \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \quad (6.2.3.7)$$

$$\Rightarrow \begin{pmatrix} 6 & 13 \\ 13 & 38 \end{pmatrix} \kappa = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (6.2.3.8)$$

The augmented matrix of the above equation (6.2.3.8) is given by,

$$\left( \begin{array}{cc|c} 6 & 13 & 1 \\ 13 & 38 & 1 \end{array} \right) \xrightarrow{R_2 \leftarrow R_2 - \frac{13}{6}R_1} \left( \begin{array}{cc|c} 6 & 13 & 1 \\ 0 & \frac{59}{6} & -\frac{7}{6} \end{array} \right) \quad (6.2.3.9)$$

$$\xrightarrow{R_1 \leftarrow R_1 - \frac{78}{59}R_2} \left( \begin{array}{cc|c} 6 & 0 & \frac{150}{59} \\ 0 & \frac{59}{6} & -\frac{7}{6} \end{array} \right) \quad (6.2.3.10)$$

yielding

$$\begin{pmatrix} \kappa_1 \\ -\kappa_2 \end{pmatrix} = \begin{pmatrix} \frac{25}{59} \\ -\frac{7}{59} \end{pmatrix} \quad (6.2.3.11)$$

Substituting in (6.2.3.3),

$$\mathbf{x}_1 = \frac{1}{59} \begin{pmatrix} 109 \\ 34 \\ 25 \end{pmatrix}, \mathbf{x}_2 = \frac{1}{59} \begin{pmatrix} 139 \\ 24 \\ -45 \end{pmatrix}. \quad (6.2.3.12)$$

The minimum distance between the lines is given by,

$$\|\mathbf{x}_2 - \mathbf{x}_1\| = \left\| \frac{1}{59} \begin{pmatrix} 30 \\ -10 \\ -70 \end{pmatrix} \right\| = \frac{10}{\sqrt{59}} \quad (6.2.3.13)$$

See Fig. 6.2.3.1.

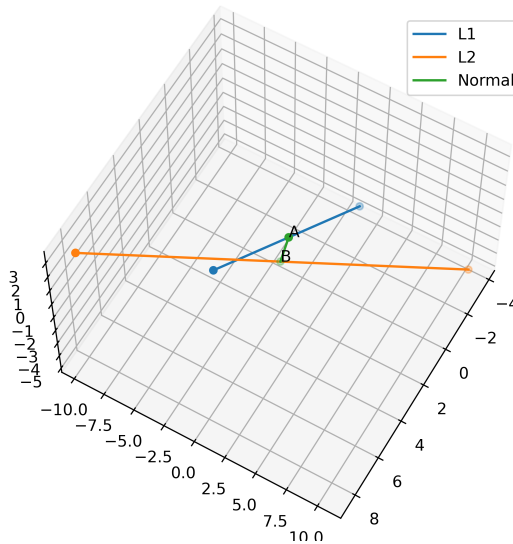


Fig. 6.2.3.1

6.2.4 Find the shortest distance between the lines given by

$$\vec{r} = (8 + 3\kappa\hat{i} - (9 + 16\kappa)\hat{j} + (10 + 7\kappa)\hat{k}) \text{ and} \quad (6.2.4.1)$$

$$\vec{r} = 15\hat{i} + 29\hat{j} + 5\hat{k} + \mu(3\hat{i} + 8\hat{j} - 5\hat{k}). \quad (6.2.4.2)$$

6.2.5 Find the shortest distance between the lines

$$\vec{r} = (\hat{i} + 2\hat{j} + \hat{k}) + \kappa(\hat{i} - \hat{j} + \hat{k}) \text{ and} \quad (6.2.5.1)$$

$$\vec{r} = 2\hat{i} - \hat{j} - \hat{k} + \mu(2\hat{i} + \hat{j} + 2\hat{k}) \quad (6.2.5.2)$$

6.2.6 Find the matrix  $\mathbf{X}$  so that  $\mathbf{X} \begin{pmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{pmatrix} = \begin{pmatrix} -7 & -8 & -9 \\ 2 & 4 & 6 \end{pmatrix}$ .



6.2.7 Find the shortest distance between the lines whose vector equations are

$$\vec{r} = (1 - t)\hat{i} + (t - 2)\hat{j} + (3 - 2t)\hat{k} \text{ and} \quad (6.2.7.1)$$

$$\vec{r} = (s + 1)\hat{i} + (2s - 1)\hat{j} - (2s + 1)\hat{k} \quad (6.2.7.2)$$

6.2.8 Find the shortest distance between the lines  $\vec{r} = 6\hat{i} + 2\hat{j} + 2\hat{k} + \lambda(\hat{i} - 2\hat{j} + 2\hat{k})$  and  $\vec{r} = -4\hat{i} - \hat{k} + \mu(3\hat{i} - 2\hat{j} - 2\hat{k})$ .

### 6.3 Singular Value Decomposition

6.3.1 Find the shortest distance between the lines whose vector equations are

$$\mathbf{x} = \begin{pmatrix} 1 \\ 2 \\ 3 \end{pmatrix} + \lambda_1 \begin{pmatrix} 1 \\ -3 \\ 2 \end{pmatrix} \quad (6.3.1.1)$$

and

$$\mathbf{x} = \begin{pmatrix} 4 \\ 5 \\ 6 \end{pmatrix} + \lambda_2 \begin{pmatrix} 2 \\ 3 \\ 1 \end{pmatrix} \quad (6.3.1.2)$$

**Solution:** From (6.2.2.3),

$$\mathbf{M}^T \mathbf{M} = \begin{pmatrix} 1 & -3 & 2 \\ 2 & 3 & 1 \end{pmatrix} \begin{pmatrix} 1 & 2 \\ -3 & 3 \\ 2 & 1 \end{pmatrix} = \begin{pmatrix} 14 & -5 \\ -5 & 14 \end{pmatrix} \quad (6.3.1.3)$$

$$\mathbf{M} \mathbf{M}^T = \begin{pmatrix} 1 & 2 \\ -3 & 3 \\ 2 & 1 \end{pmatrix} \begin{pmatrix} 1 & -3 & 2 \\ 2 & 3 & 1 \end{pmatrix} = \begin{pmatrix} 5 & 3 & 4 \\ 3 & 18 & -3 \\ 4 & -3 & 5 \end{pmatrix} \quad (6.3.1.4)$$

a) For  $\mathbf{M} \mathbf{M}^T$ , the characteristic polynomial is

$$\text{char} \mathbf{M} \mathbf{M}^T = \begin{vmatrix} \lambda - 5 & -3 & -4 \\ -3 & \lambda - 18 & 3 \\ -4 & 3 & \lambda - 5 \end{vmatrix} \quad (6.3.1.5)$$

$$= \lambda(\lambda - 9)(\lambda - 19) \quad (6.3.1.6)$$

Thus, the eigenvalues are given by

$$\lambda_1 = 19, \lambda_2 = 9, \lambda_3 = 0 \quad (6.3.1.7)$$

For  $\lambda_1$ , the augmented matrix formed from the eigenvalue-eigenvector equation is

$$\begin{pmatrix} -14 & 3 & 4 \\ 3 & -1 & -3 \\ 4 & -3 & -14 \end{pmatrix} \xrightarrow[R_1 \leftarrow \frac{R_1 + R_3}{-10}]{} \begin{pmatrix} 1 & 0 & 1 \\ 3 & -1 & -3 \\ 4 & -3 & -14 \end{pmatrix} \\ \xrightarrow[R_2 \leftarrow -R_2 + 3R_1]{R_3 \leftarrow R_3 - 4R_1} \begin{pmatrix} 1 & 0 & 1 \\ 0 & -1 & -6 \\ 0 & -3 & -18 \end{pmatrix} \xrightarrow[R_3 \leftarrow R_3 - 3R_2]{} \begin{pmatrix} 1 & 0 & 1 \\ 0 & -1 & -6 \\ 0 & 0 & 0 \end{pmatrix}$$

Hence, the normalized eigenvector is

$$\mathbf{u}_1 = \frac{1}{\sqrt{38}} \begin{pmatrix} -1 \\ -6 \\ 1 \end{pmatrix} \quad (6.3.1.8)$$

For  $\lambda_2$ , the augmented matrix formed from the eigenvalue-eigenvector equation is

$$\begin{pmatrix} -4 & 3 & 4 \\ 3 & 9 & -3 \\ 4 & 3 & -4 \end{pmatrix} \xrightarrow{R_3 \leftarrow R_1 + R_3} \begin{pmatrix} -4 & 3 & 4 \\ 3 & 9 & -3 \\ 0 & 0 & 0 \end{pmatrix} \\ \xrightarrow{R_1 \leftarrow \frac{R_1 - 3R_2}{-4}} \begin{pmatrix} 1 & 0 & -1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ \xrightarrow{R_2 \leftarrow \frac{4R_2 + 3R_1}{45}} \begin{pmatrix} 1 & 0 & -1 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Hence, the normalized eigenvector is

$$\mathbf{u}_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 1 \end{pmatrix} \quad (6.3.1.9)$$

For  $\lambda_3$ , the augmented matrix formed from the eigenvalue-eigenvector equation is

$$\begin{pmatrix} 5 & 3 & 4 \\ 3 & 18 & -3 \\ 4 & -3 & 5 \end{pmatrix} \xrightarrow{R_1 \leftarrow \frac{R_1 + R_3}{9}} \begin{pmatrix} 1 & 0 & 1 \\ 3 & 18 & -3 \\ 4 & -3 & 5 \end{pmatrix} \\ \xrightarrow{R_3 \leftarrow R_3 - 4R_1} \begin{pmatrix} 1 & 0 & 1 \\ 0 & 18 & -6 \\ 0 & -3 & 1 \end{pmatrix} \xrightarrow{R_2 \leftarrow R_2 - 3R_1} \begin{pmatrix} 1 & 0 & 1 \\ 0 & 18 & -6 \\ 0 & -3 & 1 \end{pmatrix} \\ \xrightarrow{R_2 \leftarrow \frac{R_2}{6}} \begin{pmatrix} 1 & 0 & 1 \\ 0 & 3 & -1 \\ 0 & 0 & 0 \end{pmatrix}$$

yielding

$$\mathbf{u}_3 = \frac{1}{\sqrt{19}} \begin{pmatrix} -3 \\ 1 \\ 3 \end{pmatrix} \quad (6.3.1.10)$$

Using (6.1.3.1), we see that

$$\mathbf{U} = \begin{pmatrix} -\frac{1}{\sqrt{38}} & \frac{1}{\sqrt{2}} & -\frac{3}{\sqrt{19}} \\ -\frac{6}{\sqrt{38}} & 0 & \frac{1}{\sqrt{19}} \\ \frac{1}{\sqrt{38}} & -\frac{1}{\sqrt{2}} & \frac{3}{\sqrt{19}} \end{pmatrix} \quad (6.3.1.11)$$

$$\mathbf{D}_1 = \begin{pmatrix} 19 & 0 & 0 \\ 0 & 9 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (6.3.1.12)$$

b) For  $\mathbf{M}^\top \mathbf{M}$ , the characteristic polynomial is

$$\text{char} \mathbf{M}^\top \mathbf{M} = \begin{vmatrix} \lambda - 14 & 5 \\ 5 & \lambda - 14 \end{vmatrix} \quad (6.3.1.13)$$

$$= (\lambda - 9)(\lambda - 19) \quad (6.3.1.14)$$

Thus, the eigenvalues are given by

$$\lambda_1 = 19, \lambda_2 = 9 \quad (6.3.1.15)$$

For  $\lambda_1$ , the augmented matrix formed from the eigenvalue-eigenvector equation is

$$\begin{pmatrix} -5 & -5 \\ -5 & -5 \end{pmatrix} \xrightarrow{R_1 \leftarrow R_1 - R_2} \begin{pmatrix} 0 & 0 \\ -5 & -5 \end{pmatrix} \quad (6.3.1.16)$$

Hence, the normalized eigenvector is

$$\mathbf{v}_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (6.3.1.17)$$

For  $\lambda_2$ , the augmented matrix formed from the eigenvalue-eigenvector equation is

$$\begin{pmatrix} 5 & -5 \\ -5 & 5 \end{pmatrix} \xrightarrow{R_1 \leftarrow R_1 + R_2} \begin{pmatrix} 0 & 0 \\ 5 & -5 \end{pmatrix} \quad (6.3.1.18)$$

Hence, the normalized eigenvector is

$$\mathbf{v}_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (6.3.1.19)$$

Thus, from (6.1.3.2),

$$\mathbf{V} = \begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}, \mathbf{D}_2 = \begin{pmatrix} 9 & 0 \\ 0 & 19 \end{pmatrix} \quad (6.3.1.20)$$

Using (6.3.1.15),

$$\mathbf{\Sigma} \triangleq \begin{pmatrix} \sqrt{\lambda_1} & 0 \\ 0 & \sqrt{\lambda_2} \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} \sqrt{19} & 0 \\ 0 & 3 \\ 0 & 0 \end{pmatrix} \quad (6.3.1.21)$$

and substituting into (6.1.4.6),

$$\kappa = \frac{1}{19} \begin{pmatrix} 10 \\ 28 \end{pmatrix} \quad (6.3.1.22)$$

which agrees with (6.2.2.4).

6.3.2 Find the shortest distance between the lines  $l_1$  and  $l_2$  whose vector equations are

$$\vec{r} = \hat{i} + \hat{j} + \lambda(2\hat{i} - \hat{j} + \hat{k}) \text{ and} \quad (6.3.2.1)$$

$$\vec{r} = 2\hat{i} + \hat{j} - \hat{k} + \mu(3\hat{i} - 5\hat{j} + 2\hat{k}). \quad (6.3.2.2)$$

**Solution:**

a) To check whether the given lines are skew, from (6.2.3.4) and (6.1.1.4),

$$\begin{pmatrix} 2 & 3 & 1 \\ -1 & -5 & 0 \\ 1 & 2 & -1 \end{pmatrix} \xleftrightarrow[R_3 \leftarrow R_3 - \frac{1}{2}R_1]{R_2 \leftarrow R_2 + \frac{1}{2}R_1} \begin{pmatrix} 2 & 3 & 1 \\ 0 & -\frac{7}{2} & \frac{1}{2} \\ 0 & \frac{1}{2} & -\frac{3}{2} \end{pmatrix} \\
 \xleftrightarrow{R_3 \leftarrow R_3 + 7R_2} \begin{pmatrix} 2 & 3 & 1 \\ 0 & -\frac{7}{2} & \frac{1}{2} \\ 0 & 0 & -10 \end{pmatrix}$$

The rank of the matrix is 3. So the given lines are skew.

b)

$$\mathbf{M}^\top \mathbf{M} = \begin{pmatrix} 2 & -1 & 1 \\ 3 & -5 & 2 \end{pmatrix} \begin{pmatrix} 2 & 3 \\ -1 & -5 \\ 1 & 2 \end{pmatrix} \quad (6.3.2.3)$$

$$= \begin{pmatrix} 6 & 13 \\ 13 & 38 \end{pmatrix} \quad (6.3.2.4)$$

$$\mathbf{M}\mathbf{M}^\top = \begin{pmatrix} 2 & 3 \\ -1 & -5 \\ 1 & 2 \end{pmatrix} \begin{pmatrix} 2 & -1 & 1 \\ 3 & -5 & 2 \end{pmatrix} \quad (6.3.2.5)$$

$$= \begin{pmatrix} 13 & -17 & 8 \\ -17 & 26 & -11 \\ 8 & -11 & 5 \end{pmatrix} \quad (6.3.2.6)$$

The characteristic polynomial of the matrix  $\mathbf{M}\mathbf{M}^\top$  is given by,

$$\text{char}(\mathbf{M}\mathbf{M}^\top) = \begin{vmatrix} 13 - \lambda & -17 & 8 \\ -17 & 26 - \lambda & -11 \\ 8 & -11 & 5 - \lambda \end{vmatrix} \quad (6.3.2.7)$$

$$= -\lambda^3 + 44\lambda^2 - 59\lambda \quad (6.3.2.8)$$

resulting in

$$\mathbf{U} = \begin{pmatrix} \frac{12 - \sqrt{17}}{\sqrt{5}\sqrt{68-6\sqrt{17}}} & \frac{12 + \sqrt{17}}{\sqrt{5}\sqrt{68+6\sqrt{17}}} & -\frac{3}{\sqrt{59}} \\ \frac{1-3\sqrt{17}}{\sqrt{5}\sqrt{68-6\sqrt{17}}} & \frac{1+3\sqrt{17}}{\sqrt{5}\sqrt{68+6\sqrt{17}}} & \frac{1}{\sqrt{59}} \\ \frac{\sqrt{5}}{\sqrt{68-6\sqrt{17}}} & \frac{\sqrt{5}}{\sqrt{68+6\sqrt{17}}} & \frac{7}{\sqrt{59}} \end{pmatrix} \quad (6.3.2.9)$$

and

$$\mathbf{D}_1 = \begin{pmatrix} 22 + 5\sqrt{17} & 0 & 0 \\ 0 & 22 - 5\sqrt{17} & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (6.3.2.10)$$

For  $\mathbf{M}^T \mathbf{M}$ , the characteristic polynomial is

$$\text{char}(\mathbf{M}^T \mathbf{M}) = \begin{vmatrix} 6 - \lambda & 13 \\ 13 & 38 - \lambda \end{vmatrix} \quad (6.3.2.11)$$

$$= \lambda^2 - 44\lambda + 59 \quad (6.3.2.12)$$

Thus, the eigenvalues are given by

$$\lambda_1 = 22 + 5\sqrt{17}, \quad \lambda_2 = 22 - 5\sqrt{17} \quad (6.3.2.13)$$

resulting in

$$\mathbf{V} = \begin{pmatrix} \frac{-16-5\sqrt{17}}{\sqrt{850+160\sqrt{17}}} & \frac{13}{\sqrt{850-160\sqrt{17}}} \\ \frac{13}{\sqrt{850+160\sqrt{17}}} & \frac{-16+5\sqrt{17}}{\sqrt{850-160\sqrt{17}}} \end{pmatrix} \quad (6.3.2.14)$$

$$\mathbf{D}_2 = \begin{pmatrix} 22 - 5\sqrt{17} & 0 \\ 0 & 22 + 5\sqrt{17} \end{pmatrix} \quad (6.3.2.15)$$

Therefore,

$$\mathbf{\Sigma} = \begin{pmatrix} \sqrt{22 + 5\sqrt{17}} & 0 \\ 0 & \sqrt{22 - 5\sqrt{17}} \\ 0 & 0 \end{pmatrix} \quad (6.3.2.16)$$

and substituting into (6.1.5.5),

$$\lambda = \begin{pmatrix} \frac{25}{59} \\ -\frac{7}{59} \end{pmatrix} \quad (6.3.2.17)$$

which agrees with (6.2.3.11).

6.3.3 Find the shortest distance between the lines given by

$$\vec{r} = (8 + 3\lambda\hat{i} - (9 + 16\lambda)\hat{j} + (10 + 7\lambda)\hat{k}) \text{ and} \quad (6.3.3.1)$$

$$\vec{r} = 15\hat{i} + 29\hat{j} + 5\hat{k} + \mu(3\hat{i} + 8\hat{j} - 5\hat{k}). \quad (6.3.3.2)$$

6.3.4 Find the shortest distance between the lines

$$\vec{r} = (\hat{i} + 2\hat{j} + \hat{k}) + \lambda(\hat{i} - \hat{j} + \hat{k}) \text{ and} \quad (6.3.4.1)$$

$$\vec{r} = 2\hat{i} - \hat{j} - \hat{k} + \mu(2\hat{i} + \hat{j} + 2\hat{k}) \quad (6.3.4.2)$$

6.3.5 Find the shortest distance between the lines

$$\frac{x+1}{7} = \frac{y+1}{-6} = \frac{z+1}{1} \text{ and} \quad (6.3.5.1)$$

$$\frac{x-3}{1} = \frac{y-5}{-2} = \frac{z-7}{1} \quad (6.3.5.2)$$

## 7 CIRCLE

## 7.1 Formulae

7.1.1. For a circle with centre  $\mathbf{c}$  and radius  $r$ ,

$$\mathbf{u} = -\mathbf{c}, f = \|\mathbf{u}\|^2 - r^2 \quad (7.1.1.1)$$

7.1.2. Given points  $\mathbf{x}_1, \mathbf{x}_2$  on the circle and the diameter

$$\mathbf{n}^\top \mathbf{x} = c, \quad (7.1.2.1)$$

the centre is given by

$$\begin{pmatrix} 2\mathbf{x}_1 & 2\mathbf{x}_2 & \mathbf{n} \\ 1 & 1 & 0 \end{pmatrix}^\top \begin{pmatrix} \mathbf{u} \\ f \\ c \end{pmatrix} = - \begin{pmatrix} \|\mathbf{x}_1\|^2 \\ \|\mathbf{x}_2\|^2 \\ c \end{pmatrix} \quad (7.1.2.2)$$

**Solution:** From (A.7.1.1),

$$\|\mathbf{x}_1\|^2 + 2\mathbf{u}^\top \mathbf{x}_1 + f = 0 \quad (7.1.2.3)$$

$$\|\mathbf{x}_2\|^2 + 2\mathbf{u}^\top \mathbf{x}_2 + f = 0$$

and (7.1.2.1) can be expressed as

$$\mathbf{u}^\top \mathbf{n} = -c \quad (7.1.2.4)$$

Clubbing (7.1.2.3) and (7.1.2.4), we obtain (7.1.2.2).

7.1.3. Given points  $\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3$  on the circle, the parameters are given by

$$\begin{pmatrix} 2\mathbf{x}_1 & 2\mathbf{x}_2 & 2\mathbf{x}_3 \\ 1 & 1 & 1 \end{pmatrix}^\top \begin{pmatrix} \mathbf{u} \\ f \\ c \end{pmatrix} = - \begin{pmatrix} \|\mathbf{x}_1\|^2 \\ \|\mathbf{x}_2\|^2 \\ \|\mathbf{x}_3\|^2 \end{pmatrix} \quad (7.1.3.1)$$

7.1.4. Code for circle

codes/book/circ.py

## 7.2 Equation

7.2.1 Find the equation of the circle passing through the points (4, 1) and (6, 5) and whose centre is on the line  $4x + y = 16$ .

**Solution:** Following Appendix 7.1.2,

$$\mathbf{x}_1 = \begin{pmatrix} 4 \\ 1 \end{pmatrix}, \mathbf{x}_2 = \begin{pmatrix} 6 \\ 5 \end{pmatrix}, \mathbf{n} = \begin{pmatrix} 4 \\ 1 \end{pmatrix}, c = -16. \quad (7.2.1.1)$$

Substituting in (7.1.2.2),

$$\begin{pmatrix} 8 & 2 & 1 \\ 12 & 10 & 1 \\ -4 & -1 & 0 \end{pmatrix} \begin{pmatrix} \mathbf{u} \\ f \\ c \end{pmatrix} = \begin{pmatrix} 16 \\ -61 \\ -17 \end{pmatrix} \quad (7.2.1.2)$$

The augmented matrix is expressed as

$$\left( \begin{array}{ccc|c} 8 & 2 & 1 & -17 \\ 12 & 10 & 1 & -61 \\ -4 & -1 & 0 & 16 \end{array} \right) \quad (7.2.1.3)$$

Performing a sequence of row operations to transform into an Echelon form

$$\begin{array}{l} \xleftrightarrow{R_3 \rightarrow R_3 + 2R_1} \\ \xleftrightarrow{R_2 \rightarrow R_2 + 3R_1} \end{array} \left( \begin{array}{ccc|c} -4 & -1 & 0 & 16 \\ 0 & 7 & 1 & -13 \\ 0 & 0 & 1 & 15 \end{array} \right) \quad (7.2.1.4)$$

$$\xleftrightarrow{R_2 \rightarrow R_2 - R_3} \left( \begin{array}{ccc|c} -4 & -1 & 0 & 16 \\ 0 & 7 & 0 & -28 \\ 0 & 0 & 1 & 15 \end{array} \right) \quad (7.2.1.5)$$

$$\xleftrightarrow{R_2 \rightarrow \frac{R_2}{7}, R_1 \rightarrow -\frac{R_1}{4}} \left( \begin{array}{ccc|c} 1 & \frac{1}{4} & 0 & -4 \\ 0 & 1 & 0 & -4 \\ 0 & 0 & 1 & 15 \end{array} \right) \quad (7.2.1.6)$$

$$\xleftrightarrow{R_1 \rightarrow R_1 - \frac{1}{4}R_2} \left( \begin{array}{ccc|c} 1 & 0 & 0 & -3 \\ 0 & 1 & 0 & -4 \\ 0 & 0 & 1 & 15 \end{array} \right) \quad (7.2.1.7)$$

So, from (7.2.1.7)

$$\mathbf{u} = -\begin{pmatrix} 3 \\ 4 \end{pmatrix}, \quad f = 15. \quad (7.2.1.8)$$

See Fig. 7.2.1.1.

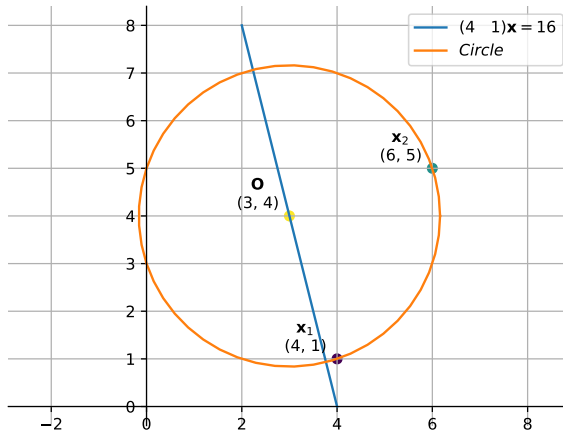


Fig. 7.2.1.1

7.2.2 Find the equation of the circle passing through the points  $\mathbf{x}_1(2, 3)$  and  $\mathbf{x}_2(-1, 1)$  and whose centre is on the line  $x - 3y - 11 = 0$ .

**Solution:** Substituting numerical values in (7.1.2.2),

$$\begin{pmatrix} 4 & 6 & 1 \\ -2 & 2 & 1 \\ -1 & 3 & 0 \end{pmatrix} \begin{pmatrix} \mathbf{u} \\ f \end{pmatrix} = \begin{pmatrix} -13 \\ -2 \\ 11 \end{pmatrix} \quad (7.2.2.1)$$

yielding

$$\mathbf{u} = \frac{1}{2} \begin{pmatrix} -7 \\ 5 \end{pmatrix}, \quad f = -14. \quad (7.2.2.2)$$

7.2.3 Find the equation of the circle with radius 5 whose centre lies on the  $X$  axis and passes through the point  $(2, 3)$ .

**Solution:** See Fig. 7.2.3.1.

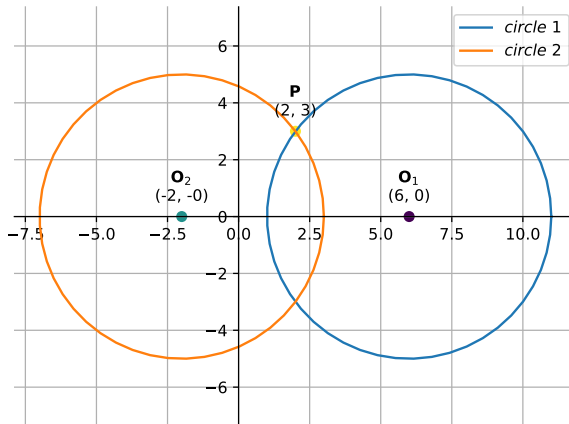


Fig. 7.2.3.1

From the given information, the following equations can be formulated using (A.7.1.1).

$$\|\mathbf{P}\|^2 + 2\mathbf{u}^T \mathbf{P} + f = 0 \quad (7.2.3.1)$$

$$\mathbf{u} = k\mathbf{e}_1 \quad (7.2.3.2)$$

$$\|\mathbf{u}\|^2 - f = r^2 \quad (7.2.3.3)$$

where

$$\mathbf{P} = \begin{pmatrix} 2 \\ 3 \end{pmatrix} \text{ and } r = 5 \quad (7.2.3.4)$$



From (7.2.3.1) and (7.2.3.3),

$$\|\mathbf{P}\|^2 + 2\mathbf{u}^\top \mathbf{P} + \|\mathbf{u}\|^2 = r^2 \quad (7.2.3.5)$$

Substituting from (7.2.3.2) in the above,

$$k^2 + 2k\mathbf{e}_1^\top \mathbf{P} + \|\mathbf{P}\|^2 - r^2 = 0 \quad (7.2.3.6)$$

resulting in

$$k = -\mathbf{e}_1^\top \mathbf{P} \pm \sqrt{(\mathbf{e}_1^\top \mathbf{P})^2 + r^2 - \|\mathbf{P}\|^2} \quad (7.2.3.7)$$

Substituting numerical values,

$$k = 2, -6 \quad (7.2.3.8)$$

resulting in circles with centre

$$-\mathbf{u} = \begin{pmatrix} -2 \\ 0 \end{pmatrix} \text{ or } \begin{pmatrix} 6 \\ 0 \end{pmatrix}. \quad (7.2.3.9)$$

This is verified in Fig. (7.2.3.1).

7.2.4 Find the equation of a circle with centre (2, 2) and passing through the point (4, 5).

**Solution:** From the given information

$$\mathbf{u} = -\begin{pmatrix} 2 \\ 2 \end{pmatrix}, \mathbf{A} = \begin{pmatrix} 4 \\ 5 \end{pmatrix} \quad (7.2.4.1)$$

$$\Rightarrow \|\mathbf{A}\|^2 + 2\mathbf{u}^\top \mathbf{A} + f = 0 \quad (7.2.4.2)$$

$$\Rightarrow f = -\|\mathbf{A}\|^2 - 2\mathbf{u}^\top \mathbf{A} = -5 \quad (7.2.4.3)$$

Hence the equation of circle is

$$\|\mathbf{x}\|^2 + 2 \begin{pmatrix} -2 & -2 \end{pmatrix} \mathbf{x} - 5 = 0 \quad (7.2.4.4)$$

7.2.5 Does the point (-2.5, 3.5) lie inside, outside or on the circle  $x^2 + y^2 = 25$ ?

**Solution:** See Table 7.2.5.

Condition	Inference
$\ \mathbf{x} - \mathbf{O}\ ^2 < r^2$	point lies inside the circle
$\ \mathbf{x} - \mathbf{O}\ ^2 > r^2$	point lies outside the circle
$\ \mathbf{x} - \mathbf{O}\ ^2 = r^2$	point lies on the circle

TABLE 7.2.5

The given circle equation can be expressed as

$$\|\mathbf{x}\|^2 = 25 \quad (7.2.5.1)$$

Let,

$$\mathbf{P} = \begin{pmatrix} -2.5 \\ 3.5 \end{pmatrix} \quad (7.2.5.2)$$

Since

$$\|\mathbf{P} - \mathbf{O}\|^2 = 18.5 < 25, \quad (7.2.5.3)$$

the point lies inside the given circle. See Fig. 7.2.5.1.

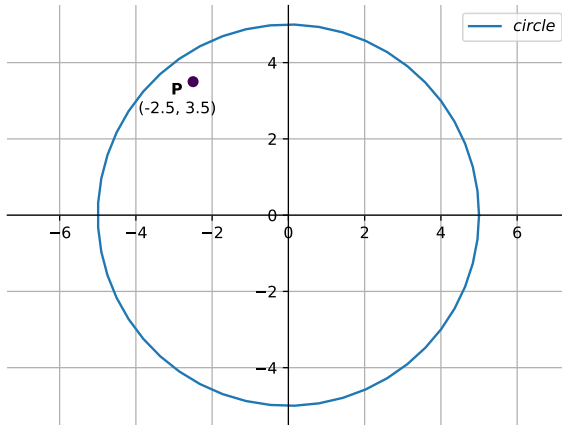


Fig. 7.2.5.1

7.2.6 Find the centre of a circle passing through the points  $(6, -6)$ ,  $(3, -7)$  and  $(3, 3)$ .

**Solution:** Substituting numerical values in (7.1.3.1),

$$\begin{pmatrix} 6 & -14 & 1 \\ 12 & -12 & 1 \\ 6 & 6 & 1 \end{pmatrix} \begin{pmatrix} \mathbf{u} \\ f \end{pmatrix} = \begin{pmatrix} -58 \\ -72 \\ -18 \end{pmatrix} \quad (7.2.6.1)$$

yielding

$$\mathbf{u} = \begin{pmatrix} -3 \\ 2 \end{pmatrix} \quad (7.2.6.2)$$

$$f = -12 \quad (7.2.6.3)$$

See Fig. 7.2.6.1.

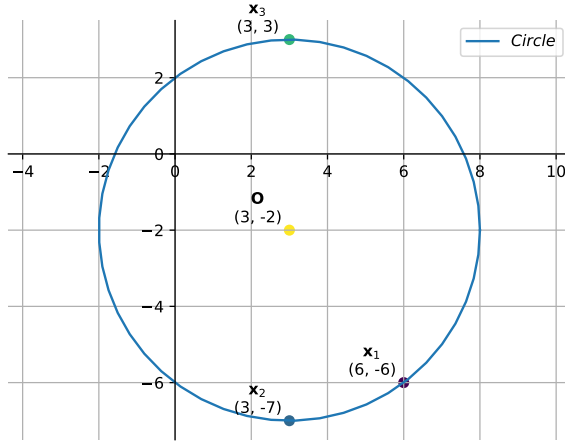


Fig. 7.2.6.1

7.2.7 Find the equation of the circle passing through  $(0, 0)$  and making intercepts  $a$  and  $b$  on the coordinate axes.

In each of the following exercises, find the equation of the circle with the following parameters

7.2.8 centre  $(0, 2)$  and radius 2

**Solution:** Substituting numerical values in (7.1.1.1),

$$\mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0 \quad (7.2.8.1)$$

Thus, the equation of circle is obtained as

$$\|\mathbf{x}\|^2 - 2 \begin{pmatrix} 0 & 2 \end{pmatrix} \mathbf{x} = 0 \quad (7.2.8.2)$$

See Fig. 7.2.8.1.

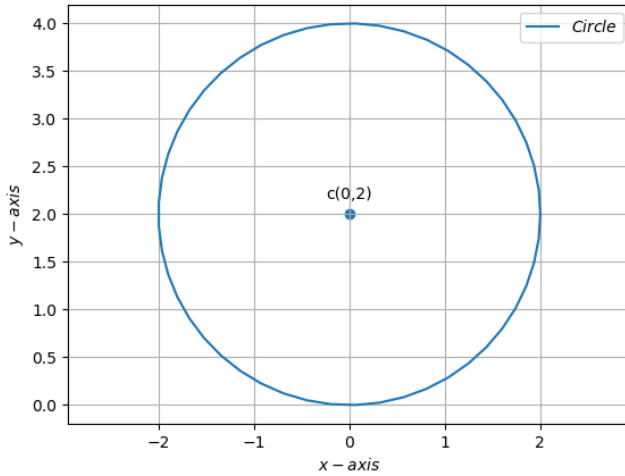


Fig. 7.2.8.1

7.2.9 centre  $(-2, 3)$  and radius 4

**Solution:** Given

$$\mathbf{u} = -\begin{pmatrix} -2 \\ 3 \end{pmatrix}, r = 4. \quad (7.2.9.1)$$

Substituting in (7.1.1.1),

$$f = -3 \quad (7.2.9.2)$$

The equation of the circle is then obtained as

$$\|\mathbf{x}\|^2 + 2 \begin{pmatrix} 2 & -3 \end{pmatrix} \mathbf{x} - 3 = 0 \quad (7.2.9.3)$$

See Fig. 7.2.9.1.

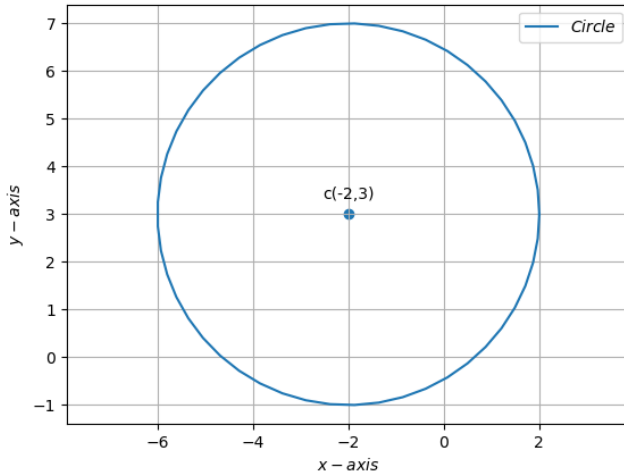


Fig. 7.2.9.1

7.2.10 centre  $\left(\frac{1}{2}, \frac{1}{4}\right)$  and radius  $\frac{1}{12}$

**Solution:** Substituting numerical values in (7.1.1.1),

$$f = \frac{11}{36} \quad (7.2.10.1)$$

Thus, the equation of the circle is

$$\|\mathbf{x}\|^2 + \left(-1 \quad -\frac{1}{2}\right)\mathbf{x} + \frac{11}{36} = 0 \quad (7.2.10.2)$$

See Fig. 7.2.10.1.

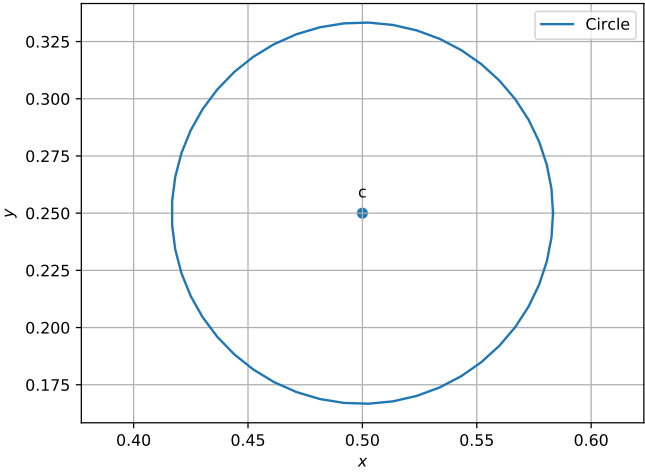


Fig. 7.2.10.1

7.2.11 centre (1, 1) and radius  $\sqrt{2}$

**Solution:** Substituting

$$r = \sqrt{2}, \mathbf{u} = \begin{pmatrix} -1 \\ -1 \end{pmatrix} \tag{7.2.11.1}$$

in (7.1.1.1),

$$f = 0 \tag{7.2.11.2}$$

Thus, the equation of the circle is

$$\|\mathbf{x}\|^2 - 2 \begin{pmatrix} 1 & 1 \end{pmatrix} \mathbf{x} = 0 \tag{7.2.11.3}$$

See Fig. 7.2.11.1.

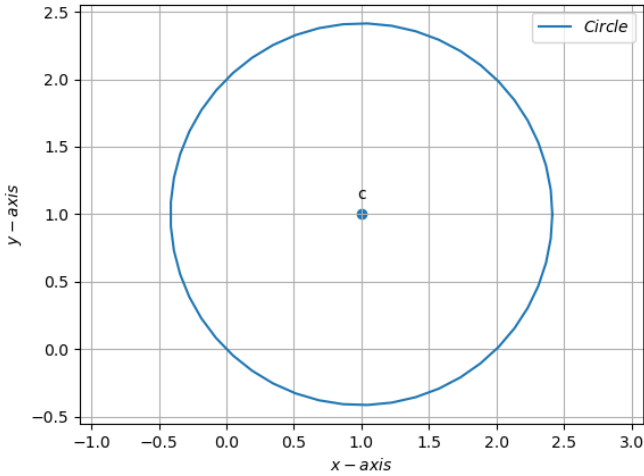


Fig. 7.2.11.1

In each of the following exercises, find the centre and radius of the circles.

$$7.2.12 \quad x^2 + y^2 + 10x - 6y - 2 = 0.$$

**Solution:** The circle parameters are

$$\mathbf{u} = \begin{pmatrix} 5 \\ -3 \end{pmatrix}, f = -2 \quad (7.2.12.1)$$

$$\Rightarrow \mathbf{c} = \begin{pmatrix} -5 \\ 3 \end{pmatrix}, r = \sqrt{\|\mathbf{u}\|^2 - f} = 6 \quad (7.2.12.2)$$

See Fig. 7.2.12.1.

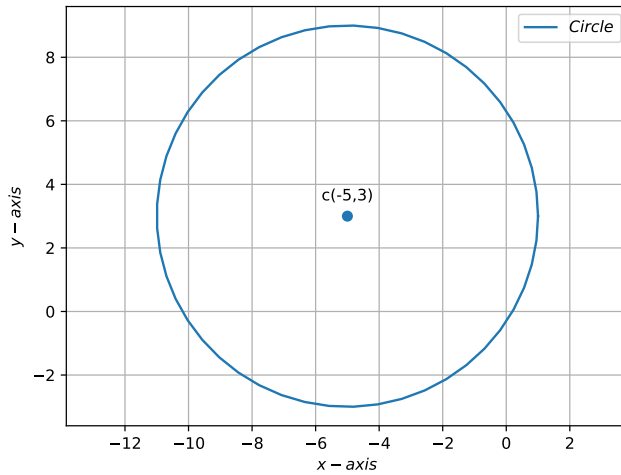


Fig. 7.2.12.1

$$7.2.13 \quad x^2 + y^2 - 4x - 8y - 45 = 0$$

**Solution:** The given circle can be expressed as

$$\|\mathbf{x}\|^2 + 2 \begin{pmatrix} -2 & -4 \end{pmatrix} \mathbf{x} - 45 = 0 \quad (7.2.13.1)$$

where

$$\mathbf{u} = \begin{pmatrix} -2 \\ -4 \end{pmatrix}, f = -45 \quad (7.2.13.2)$$

$$\Rightarrow \mathbf{c} = \begin{pmatrix} 2 \\ 4 \end{pmatrix}, r = \sqrt{65}. \quad (7.2.13.3)$$

See Fig. 7.2.13.1.



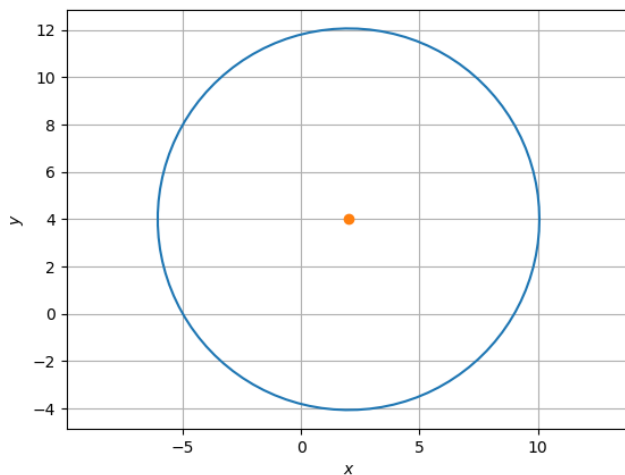


Fig. 7.2.13.1

$$7.2.14 \quad x^2 + y^2 - 8x + 10y - 12 = 0$$

**Solution:** From the given information,

$$\mathbf{u} = \begin{pmatrix} -4 \\ 5 \end{pmatrix}, f = -12 \quad (7.2.14.1)$$

$$\Rightarrow \mathbf{c} = \begin{pmatrix} 4 \\ -5 \end{pmatrix}, \quad (7.2.14.2)$$

$$r = \sqrt{\|\mathbf{u}\|^2 - f} = \sqrt{53} \quad (7.2.14.3)$$

See Fig. 7.2.14.1.

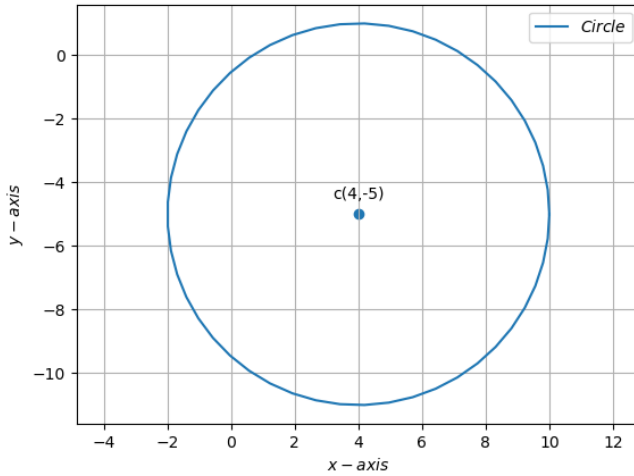


Fig. 7.2.14.1

$$7.2.15 \quad 2x^2 + 2y^2 - x = 0$$

**Solution:** The given equation can be expressed as

$$\|\mathbf{x}\|^2 + 2\left(\frac{-1}{4} \quad 0\right)\mathbf{x} = 0 \quad (7.2.15.1)$$

The centre of circle is then given by

$$\mathbf{u} = -\mathbf{c} = \begin{pmatrix} \frac{1}{4} \\ 0 \end{pmatrix} \quad (7.2.15.2)$$

and the radius of circle is obtained as

$$r = \sqrt{\|\mathbf{u}\|^2 - f} = \frac{1}{4} \quad (7.2.15.3)$$

See Fig. 7.2.15.1.

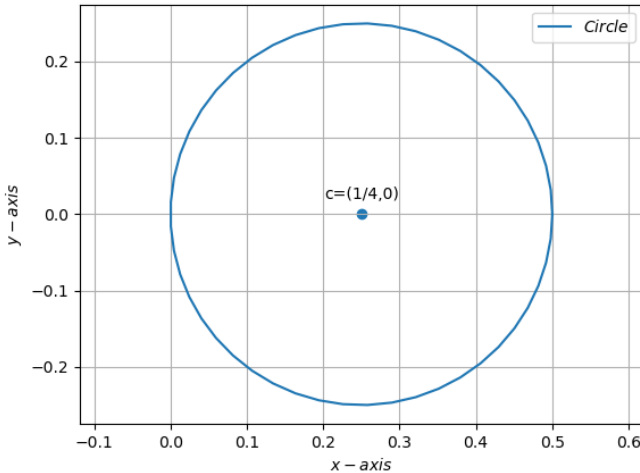


Fig. 7.2.15.1

7.2.16 The area of the circle centred at  $(1, 2)$  and passing through  $(4, 6)$  is

- a)  $5\pi$
- b)  $10\pi$
- c)  $25\pi$
- d) none of these

7.2.17 Equation of the circle with centre on the Y-axis and passing through the origin and the point  $(2, 3)$  is

- a)  $x^2 + y^2 + 6x + 6y + 3 = 0$
- b)  $x^2 + y^2 - 6x - 6y - 9 = 0$
- c)  $x^2 + y^2 - 6x - 6y + 9 = 0$
- d) none of these

7.2.18 Equation of the circle with centre on the y-axis and passing through the origin and the point  $(2, 3)$  is

- a)  $x^2 + y^2 + 13y = 0$
- b)  $3x^2 + 3y^2 + 13x + 3 = 0$
- c)  $6x^2 + 6y^2 - 13x = 0$
- d)  $x^2 + y^2 + 13x + 3 = 0$

7.2.19 Find the equation of a circle concentric with the circle  $x^2 + y^2 - 6x + 12y + 15 = 0$  and has double of its area.

7.2.20 If one end of a diameter of the circle  $x^2 + y^2 - 4x - 6y + 11 = 0$  is  $(3, 4)$ , then find the coordinate of the other end of the diameter.

7.2.21 Find the equation of the circle having  $(1, -2)$  as its centre and passing through the intersection of  $3x + y = 14$ ,  $2x + 5y = 18$ .

7.2.22 If the lines  $2x - 3y = 5$  and  $3x - 4y = 7$  are the diameters of a circle of area 154

square units, then obtain the equation of the circle.

- 7.2.23 Find the equation of the circle which passes through the points (2, 3) and (4, 5) and the centre lies on the straight line  $y - 4x + 3 = 0$ .
- 7.2.24 Find the equation of a circle passing through the point (7, 3) having radius 3 units and whose centre lies on the line  $y = x - 1$ .
- 7.2.25 The centre of a circle is  $(2a, a - 7)$ . Find the values of  $a$  if the circle passes through the point (11, -9) and has diameter  $10\sqrt{2}$  units.
- 7.2.26 A circle has its centre at the origin and a point  $P(5, 0)$  lies on it. The point  $Q(6, 8)$  lies outside the circle.
- 7.2.27 The point  $P(-2, 4)$  lies on circle of radius 6 and center  $C(3, 5)$ .
- 7.2.28 A circle drawn with origin as the centre passes through  $(\frac{13}{2}, 0)$ . The point which does not lie in the interior of the circle is
- $(\frac{-3}{4}, 1)$
  - $(2, \frac{7}{3})$
  - $(5, \frac{-1}{2})$
  - $(-6, \frac{-5}{2})$

State whether the statements are True or False

- 7.2.29 The line  $x^2 + 3y = 0$  is a diameter of the circle  $x^2 + y^2 + 6x + 2y = 0$ .
- 7.2.30 The point (1, 2) lies inside the circle  $x^2 + y^2 - 2x + 6y + 1 = 0$ .
- 7.2.31 Find the coordinates of a point **A**, where  $AB$  is the diameter of a circle whose centre is  $C(2, -3)$  and **B** is (1, 4).

**Solution:**

$$\mathbf{C} = \frac{\mathbf{A} + \mathbf{B}}{2} \implies \mathbf{A} = 2\mathbf{C} - \mathbf{B} = \begin{pmatrix} 3 \\ -10 \end{pmatrix} \quad (7.2.31.1)$$

See Fig. 7.2.31.1.

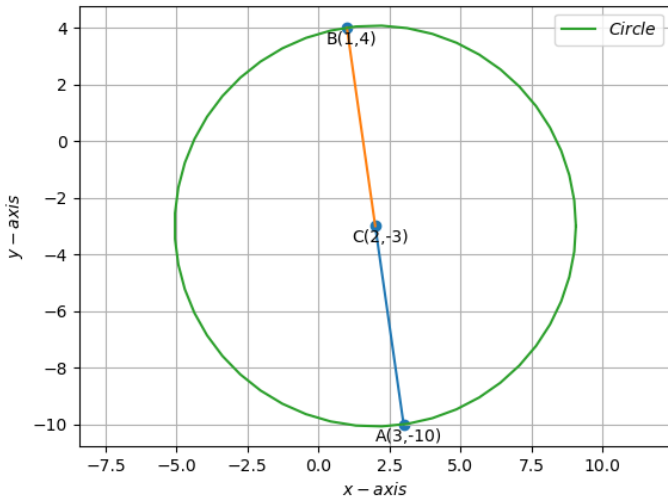


Fig. 7.2.31.1

### 7.3 Miscellaneous

7.3.1 Find the equation of the circle passing through  $(0,0)$  and making intercepts  $a$  and  $b$  on the coordinate axes.

7.3.2 Find the equation of a circle with centre  $(-a, -b)$  and radius  $\sqrt{a^2 - b^2}$ .

**Solution:** From (7.1.1.1),

$$\mathbf{u} = \begin{pmatrix} a \\ b \end{pmatrix}, f = 2b^2 \quad (7.3.2.1)$$

Thus, the equation of circle is

$$\|\mathbf{x}\|^2 + 2 \begin{pmatrix} a & b \end{pmatrix} \mathbf{x} + 2b^2 = 0 \quad (7.3.2.2)$$

7.3.3 The equation of a circle with origin as centre and passing through the vertices of an equilateral triangle whose median is of length  $3a$  is

- a)  $x^2 + y^2 = 9a^2$
- b)  $x^2 + y^2 = 16a^2$
- c)  $x^2 + y^2 = 4a^2$
- d)  $x^2 + y^2 = a^2$

7.3.4 Show that the point  $(x, y)$  given by  $x = \frac{2at}{1+t^2}$  and  $y = \frac{a(1-t^2)}{1+t^2}$  lies on a circle for all real values of  $t$  such that  $-1 \leq t \leq 1$  where  $a$  is any given real number.

7.3.5 If a circle passes through the point  $(0, 0)$ ,  $(a, 0)$  and  $(0, b)$  then find the coordinates of its centre.

7.3.6 The equation of the circle circumscribing the triangle whose sides are the lines  $y = x + 2$ ,  $3y = 4x$ ,  $2y = 3x$  is \_\_\_\_\_

## 8 CONICS

## 8.1 Formulae

8.1.1. The equation of a conic with directrix  $\mathbf{n}^\top \mathbf{x} = c$ , eccentricity  $e$  and focus  $\mathbf{F}$  is given by

$$\mathbf{g}(\mathbf{x}) = \mathbf{x}^\top \mathbf{V} \mathbf{x} + 2\mathbf{u}^\top \mathbf{x} + f = 0 \quad (8.1.1.1)$$

where

$$\mathbf{V} = \|\mathbf{n}\|^2 \mathbf{I} - e^2 \mathbf{n} \mathbf{n}^\top, \quad (8.1.1.2)$$

$$\mathbf{u} = ce^2 \mathbf{n} - \|\mathbf{n}\|^2 \mathbf{F}, \quad (8.1.1.3)$$

$$f = \|\mathbf{n}\|^2 \|\mathbf{F}\|^2 - c^2 e^2 \quad (8.1.1.4)$$

8.1.2. The eccentricity, directrices and foci of (8.1.1.1) are given by

$$e = \sqrt{1 - \frac{\lambda_1}{\lambda_2}} \quad (8.1.2.1)$$

$$\mathbf{n} = \sqrt{\lambda_2} \mathbf{p}_1,$$

$$c = \begin{cases} \frac{e \mathbf{u}^\top \mathbf{n} \pm \sqrt{e^2 (\mathbf{u}^\top \mathbf{n})^2 - \lambda_2 (e^2 - 1) (\|\mathbf{u}\|^2 - \lambda_2 f)}}{\lambda_2 e (e^2 - 1)} & e \neq 1 \\ \frac{\|\mathbf{u}\|^2 - \lambda_2 f}{2 \mathbf{u}^\top \mathbf{n}} & e = 1 \end{cases} \quad (8.1.2.2)$$

$$\mathbf{F} = \frac{ce^2 \mathbf{n} - \mathbf{u}}{\lambda_2} \quad (8.1.2.3)$$

8.1.3. For a symmetric matrix, from (A.7.7.1), we have the eigendecomposition

$$\mathbf{V} = \mathbf{P} \mathbf{D} \mathbf{P}^\top \quad (8.1.3.1)$$

where

$$\mathbf{P} = (\mathbf{p}_1 \quad \mathbf{p}_2), \quad \mathbf{P}^\top \mathbf{P} = \mathbf{I} \quad (8.1.3.2)$$

$$\mathbf{D} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix} \quad (8.1.3.3)$$

8.1.4. Using the affine transformation in (2.1.15.1), the conic in (8.1.1.1) can be expressed in standard form as

$$\mathbf{y}^\top \begin{pmatrix} \mathbf{D} \\ f_0 \end{pmatrix} \mathbf{y} = 1 \quad |\mathbf{V}| \neq 0 \quad (8.1.4.1)$$

$$\mathbf{y}^\top \mathbf{D} \mathbf{y} = -\eta \mathbf{e}_1^\top \mathbf{y} \quad |\mathbf{V}| = 0 \quad (8.1.4.2)$$

where

$$f_0 = \mathbf{u}^\top \mathbf{V}^{-1} \mathbf{u} - f \neq 0 \quad (8.1.4.3)$$

$$\eta = 2\mathbf{u}^\top \mathbf{p}_1 \quad (8.1.4.4)$$

$$\mathbf{e}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (8.1.4.5)$$

**Solution:** See Appendix B.1.5.

8.1.5.

a) The directrices for the standard conic are given by

$$\mathbf{e}_1^\top \mathbf{y} = \pm \sqrt{\left| \frac{f_0 \lambda_2}{\lambda_1 (\lambda_2 - \lambda_1)} \right|} \quad e \neq 1 \quad (8.1.5.1)$$

$$\mathbf{e}_1^\top \mathbf{y} = \frac{\eta}{2\lambda_2} \quad e = 1 \quad (8.1.5.2)$$

b) The foci of the standard conic are given by

$$\mathbf{F} = \begin{cases} \pm \sqrt{\left| f_0 \left( \frac{1}{\lambda_2} - \frac{1}{\lambda_1} \right) \right|} \mathbf{e}_1 & e \neq 1 \\ -\frac{\eta}{4\lambda_2} \mathbf{e}_1 & e = 1 \end{cases} \quad (8.1.5.3)$$

8.1.6. The equation of the minor and major axes for the ellipse/hyperbola are respectively given by

$$\mathbf{p}_i^\top (\mathbf{x} - \mathbf{c}) = 0, i = 1, 2 \quad (8.1.6.1)$$

The axis of symmetry for the parabola is also given by (8.1.6.1).

8.1.7. The center of the standard ellipse/hyperbola, defined to be the mid point of the line joining the foci, is the origin.

8.1.8. The principal (major) axis of the standard ellipse/hyperbola, defined to be the line joining the two foci is the  $x$ -axis.

8.1.9. The minor axis of the standard ellipse/hyperbola, defined to be the line orthogonal to the  $x$ -axis is the  $y$ -axis.

8.1.10. The axis of symmetry of the standard parabola, defined to be the line perpendicular to the directrix and passing through the focus, is the  $x$ -axis.

8.1.11. The point where the parabola intersects its axis of symmetry is called the vertex. For the standard parabola, the vertex is the origin.

8.1.12. The *focal length* of the standard parabola, defined to be the distance between the vertex and the focus, measured along the axis of symmetry, is  $\left| \frac{\eta}{4\lambda_2} \right|$

8.1.13. For the standard hyperbola/ellipse, the length of the major axis is

$$2 \sqrt{\left| \frac{f_0}{\lambda_1} \right|} \quad (8.1.13.1)$$

and the minor axis is

$$2 \sqrt{\left| \frac{f_0}{\lambda_2} \right|} \quad (8.1.13.2)$$

**Solution:** See Appendix B.3.4.

8.1.14. The latus rectum of a conic section is the chord that passes through the focus and is perpendicular to the major axis. The length of the latus rectum for a conic is given

by

$$l = \begin{cases} 2 \frac{\sqrt{|f_0 \lambda_1|}}{\lambda_2} & e \neq 1 \\ \frac{\eta}{\lambda_2} & e = 1 \end{cases} \quad (8.1.14.1)$$

**Solution:** See Appendix B.3.6.

## 8.2 Equation

In the each of the following exercises, find the coordinates of the focus, vertex, eccentricity, axis of the conic section, the equation of the directrix and the length of the latus rectum.

8.2.1  $y^2 = 12x$

**Solution:** See Table 8.2.5 and Fig. 8.2.1.1.

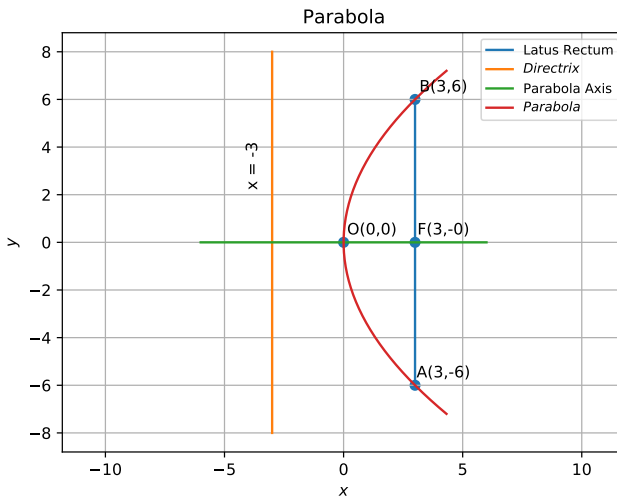


Fig. 8.2.1.1

8.2.2  $y^2 = -8x$

**Solution:** See Table 8.2.5 and Fig. 8.2.2.1.



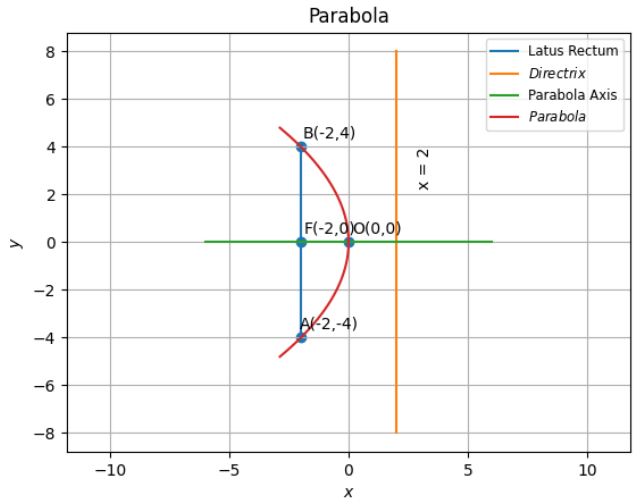


Fig. 8.2.2.1: Graph

8.2.3  $\frac{x^2}{36} + \frac{y^2}{16} = 1$

**Solution:** See Table 8.2.5 and Fig. 8.2.3.1.

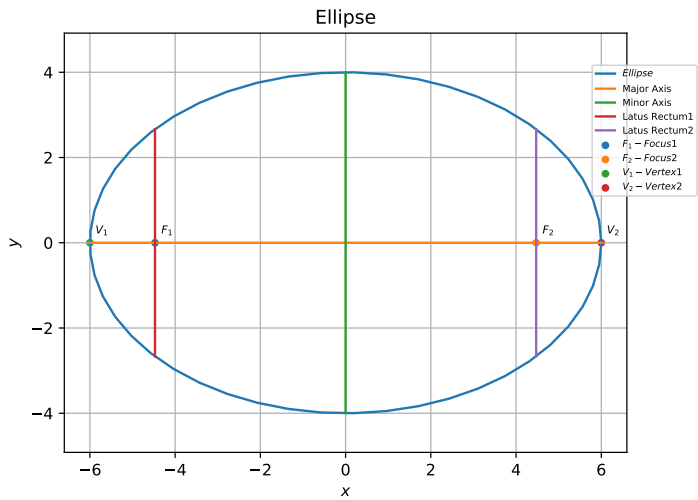


Fig. 8.2.3.1

8.2.4  $\frac{x^2}{16} + \frac{y^2}{9} = 1$

**Solution:** See Table 8.2.5 and Fig. 8.2.4.1.

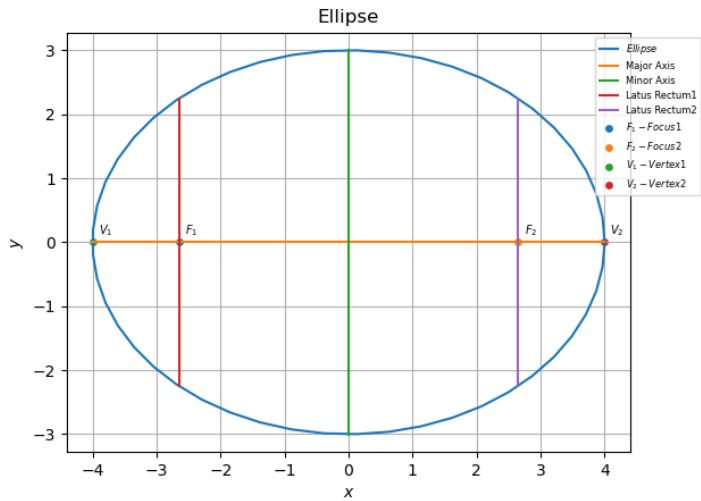


Fig. 8.2.4.1

8.2.5  $\frac{x^2}{16} - \frac{y^2}{9} = 1$ .

**Solution:** See Table 8.2.5 and Fig. 8.2.5.1.

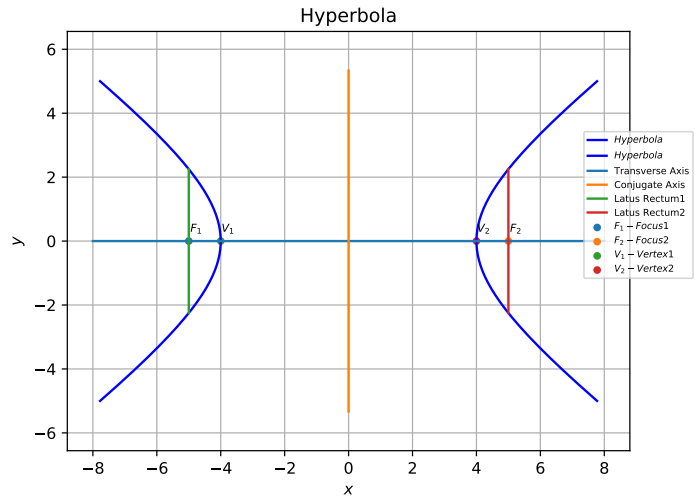


Fig. 8.2.5.1

TABLE 8.2.5

Input				Output		
Conic	$\mathbf{V}$	$\mathbf{u}$	$f$	$\mathbf{F}$	Directrix	Latus Rectum
$y^2 = 12x$	$\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$	$-6\mathbf{e}_1$	0	$3\mathbf{e}_1$	$\mathbf{e}_1^\top \mathbf{x} = -3$	12
$y^2 = -8x$	$\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$	$4\mathbf{e}_1$	0	$2\mathbf{e}_1$	$\mathbf{e}_1^\top \mathbf{x} = 2$	8
$\frac{x^2}{36} + \frac{y^2}{16} = 1$	$\begin{pmatrix} 4 & 0 \\ 0 & 9 \end{pmatrix}$	$\mathbf{0}$	-144	$2\sqrt{5}\mathbf{e}_1$	$\mathbf{e}_1^\top \mathbf{x} = \frac{18}{\sqrt{5}}$	$\frac{16}{3}$
$\frac{x^2}{16} + \frac{y^2}{9} = 1$	$\begin{pmatrix} 9 & 0 \\ 0 & 16 \end{pmatrix}$	$\mathbf{0}$	-144	$\pm\sqrt{7}\mathbf{e}_1$	$\mathbf{e}_1^\top \mathbf{x} = \frac{16}{\sqrt{7}}$	$\frac{9}{2}$
$\frac{x^2}{16} - \frac{y^2}{9} = 1$	$\begin{pmatrix} 9 & 0 \\ 0 & -16 \end{pmatrix}$	$\mathbf{0}$	-144	$\pm 5\mathbf{e}_1$	$\mathbf{e}_1^\top \mathbf{x} = \frac{16}{5}$	$\frac{9}{2}$

8.2.6  $\frac{x^2}{4} + \frac{y^2}{25} = 1$

**Solution:** From Table 8.2.10, it can be seen that this is not a standard ellipse, since  $\lambda_1 > \lambda_2$ . Hence  $\mathbf{P}$  plays a role and we need to use the affine transformation

$$\mathbf{x} = \mathbf{P}\mathbf{y} \tag{8.2.6.1}$$

So the value of  $\lambda_1$  and  $\lambda_2$  need to be interchanged for all calculations and in (8.1.5.1),  $\mathbf{e}_2$  becomes the normal vector. See Fig. 8.2.6.1.

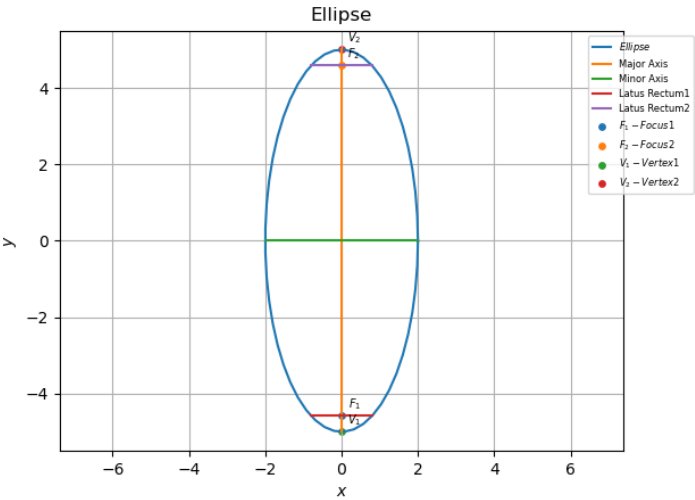


Fig. 8.2.6.1

8.2.7  $5y^2 - 9x^2 = 36$ .

**Solution:**

See Table 8.2.10 and Fig. 8.2.7.1. In Table 8.2.10, **P** shifts the negative eigenvalue to get the hyperbola in standard form.

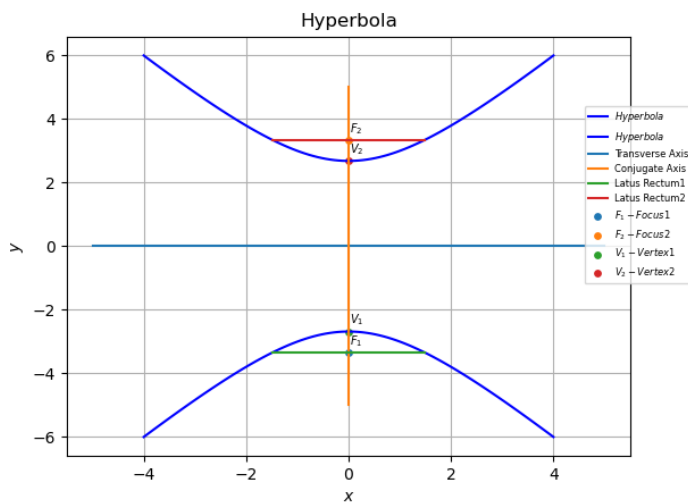


Fig. 8.2.7.1

$$8.2.8 \quad \frac{y^2}{9} - \frac{x^2}{27} = 1.$$

**Solution:**

See Table 8.2.10 and Fig. 8.2.8.1.

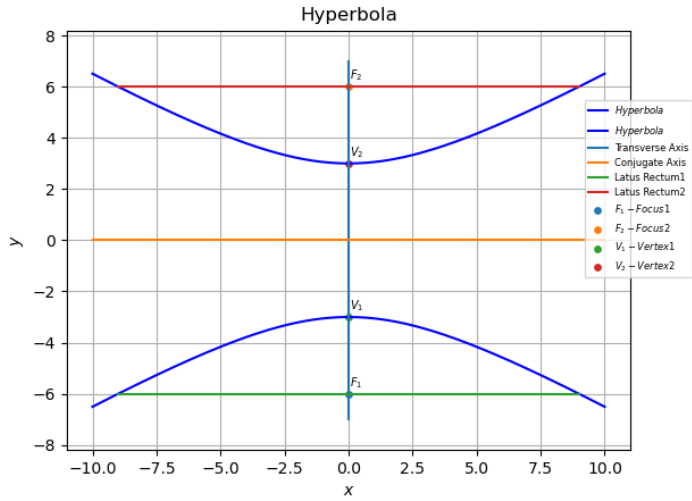


Fig. 8.2.8.1

8.2.9  $x^2 = -16y$

**Solution:** See Table 8.2.10 and Fig. 8.2.9.1.

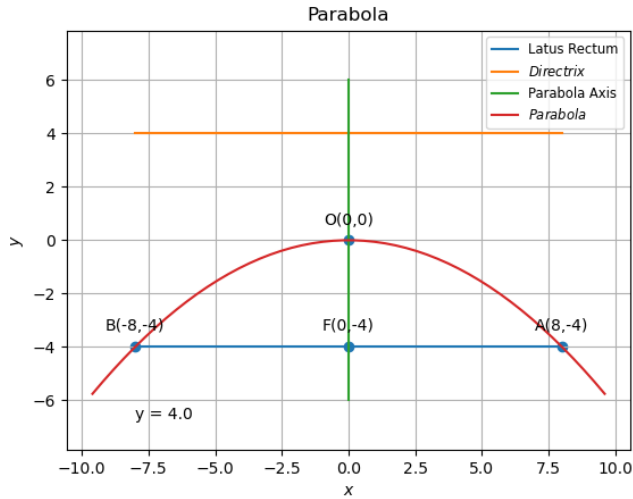


Fig. 8.2.9.1

8.2.10  $x^2 = 6y$

**Solution:** See Table 8.2.10 and Fig. 8.2.10.1.

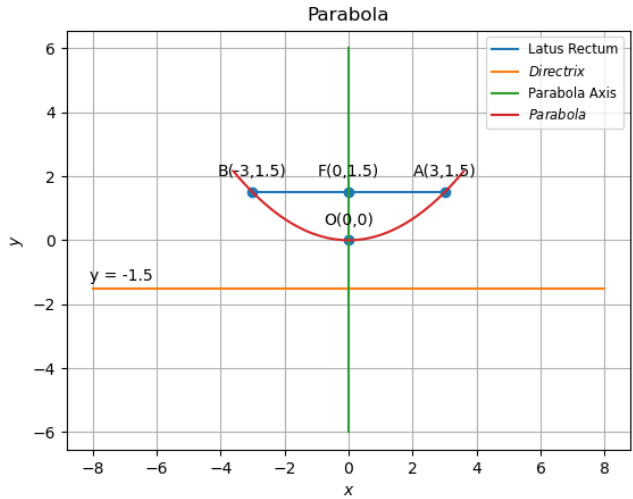


Fig. 8.2.10.1

TABLE 8.2.10

Input				Intermediate	Output		
Conic	<b>V</b>	<b>u</b>	<i>f</i>	<b>P</b>	<b>F</b>	Directrix	Latus Rectum
$\frac{x^2}{4} + \frac{y^2}{25} = 1$	$\begin{pmatrix} 25 & 0 \\ 0 & 4 \end{pmatrix}$	<b>0</b>	-100	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$\pm \sqrt{21} \mathbf{e}_2$	$\mathbf{e}_2^\top \mathbf{x} = \pm \frac{25}{\sqrt{21}}$	$\frac{8}{5}$
$5y^2 - 9x^2 = 36$	$\begin{pmatrix} -9 & 0 \\ 0 & 5 \end{pmatrix}$	<b>0</b>	-36	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$\pm 3 \sqrt{\frac{5}{14}} \mathbf{e}_2$	$\mathbf{e}_2^\top \mathbf{x} = \pm \frac{18}{\sqrt{70}}$	$4 \frac{\sqrt{5}}{3}$
$\frac{y^2}{9} - \frac{x^2}{27} = 1$	$\begin{pmatrix} -1 & 0 \\ 0 & 3 \end{pmatrix}$	<b>0</b>	-27	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$\pm 6 \mathbf{e}_2$	$\mathbf{e}_2^\top \mathbf{x} = \pm \frac{3}{2}$	18
$x^2 = -16y$	$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 8 \end{pmatrix}$	0	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$-4 \mathbf{e}_2$	$\mathbf{e}_2^\top \mathbf{x} = 4$	16
$x^2 = 6y$	$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$	$-\begin{pmatrix} 0 \\ 3 \end{pmatrix}$	0	$\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$	$\frac{3}{2} \mathbf{e}_2$	$\mathbf{e}_2^\top \mathbf{x} = -\frac{3}{2}$	6

- 8.2.11  $x^2=-9y$
- 8.2.12  $\frac{x^2}{25} + \frac{y^2}{100} = 1$
- 8.2.13  $\frac{x^2}{49} + \frac{y^2}{36} = 1$
- 8.2.14  $\frac{x^2}{100} + \frac{y^2}{400} = 1$
- 8.2.15  $36x^2 + 4y^2 = 144$
- 8.2.16  $16x^2 + y^2 = 16$
- 8.2.17  $4x^2 + 9y^2 = 36$
- 8.2.18  $y^2 = 10x$

In each of the following exercises, find the equation of the conic, that satisfies the given conditions.

- 8.2.19 foci  $(\pm 4, 0)$ , latus rectum of length 12.

**Solution:** The given information is available in Table 8.2.19. Since two foci are given, the conic cannot be a parabola.

a) The direction vector of  $F_1F_2$  is the normal vector of the directrix. Hence,

$$\mathbf{n} = \mathbf{F}_1 - \mathbf{F}_2 \equiv \mathbf{e}_1 \quad (8.2.19.1)$$

Substituting in (8.1.1.2), (8.1.1.3) and (8.1.1.4),

$$\mathbf{V} = \begin{pmatrix} 1 - e^2 & 0 \\ 0 & 1 \end{pmatrix} \quad (8.2.19.2)$$

$$\mathbf{u} = ce^2\mathbf{e}_1 - \mathbf{F} \quad (8.2.19.3)$$

$$f = 16 - c^2e^2 \quad (8.2.19.4)$$

b) From (8.2.19.2),

$$\lambda_1 = 1 - e^2, \lambda_2 = 1 \quad (8.2.19.5)$$

which upon substituting in (8.1.14.1), along with the value of the latus rectum from Table 8.2.19

$$6(1 - e^2) = \sqrt{|f|} \quad (8.2.19.6)$$

c) The centre of the conic is given by

$$\mathbf{c} = \frac{\mathbf{F}_1 + \mathbf{F}_2}{2} = \mathbf{0} \quad (8.2.19.7)$$

From (8.2.19.2), it is obvious that  $\mathbf{V}$  is invertible. Hence, from (8.2.19.7) and (B.1.5.9),

$$\mathbf{u} = \mathbf{0} \quad (8.2.19.8)$$

Substituting the above in (8.2.19.3),

$$\mathbf{F} = ce^2\mathbf{e}_1 \implies \|\mathbf{F}\| = 4 = ce^2 \quad (8.2.19.9)$$

d) From (8.1.4.3), (8.2.19.8) and (8.2.19.4),

$$36(1 - e^2)^2 = 16 - c^2e^2 \quad (8.2.19.10)$$

From (8.2.19.9) and (8.2.19.10)

$$\frac{4}{e\sqrt{e^2 - 1}} = 6 \quad (8.2.19.11)$$

$$\implies 9e^2(e^2 - 1) = 4 \quad (8.2.19.12)$$

$$\implies 9e^4 - 9e^2 - 4 = 0 \quad (8.2.19.13)$$

$$\text{or, } (3e^2 - 4)(12e^2 + 1) = 0 \quad (8.2.19.14)$$

yielding

$$e = \frac{4}{3} \quad (8.2.19.15)$$

as the only viable solution.

The equation of the conic is then obtained as

$$\mathbf{x}^T \begin{pmatrix} -\frac{1}{3} & 0 \\ 0 & 1 \end{pmatrix} \mathbf{x} + 4 = 0 \quad (8.2.19.16)$$

See Fig. 8.2.19.1.

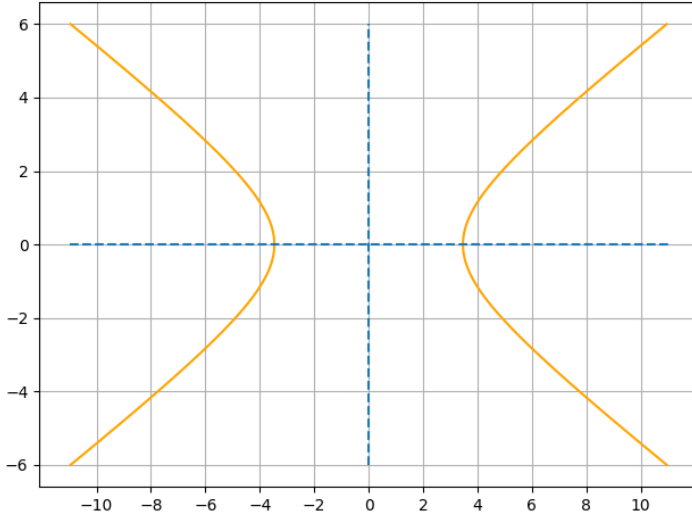


Fig. 8.2.19.1

Parameter	Description	Value
$\mathbf{F}_1$	Focus 1 of hyperbola	$\begin{pmatrix} 4 \\ 0 \end{pmatrix}$
$\mathbf{F}_2$	Focus 2 of hyperbola	$\begin{pmatrix} -4 \\ 0 \end{pmatrix}$
$l$	Length of latus rectum	12

TABLE 8.2.19

8.2.20 eccentricity  $e = \frac{4}{3}$ , vertices

$$\mathbf{P}_1 = \begin{pmatrix} 7 \\ 0 \end{pmatrix}, \mathbf{P}_2 = \begin{pmatrix} -7 \\ 0 \end{pmatrix} \quad (8.2.20.1)$$

**Solution:** The major axis of a conic is the chord which passes through the vertices of the conic. The direction vector of the major axis in this case is

$$\mathbf{P}_2 - \mathbf{P}_1 \equiv \mathbf{e}_1 = \mathbf{n} \quad (8.2.20.2)$$



which is the normal vector for the directrix. Since  $e > 1$ , the conic is a hyperbola. Substituting (8.2.20.2) in (8.1.1.2), (8.1.1.3) and (8.1.1.4),

$$\mathbf{V} = \begin{pmatrix} 1 - e^2 & 0 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} -\frac{7}{9} & 0 \\ 0 & 1 \end{pmatrix} \quad (8.2.20.3)$$

$$\mathbf{u} = ce^2\mathbf{e}_1 - \mathbf{F} \quad (8.2.20.4)$$

$$f = 16 - c^2e^2 \quad (8.2.20.5)$$

Thus,

$$\mathbf{V} = \begin{pmatrix} 1 - e^2 & 0 \\ 0 & 1 \end{pmatrix} \quad (8.2.20.6)$$

$$\mathbf{u} = ce^2\mathbf{e}_1 - \mathbf{F} \quad (8.2.20.7)$$

$$f = \|\mathbf{F}\|^2 - c^2e^2 \quad (8.2.20.8)$$

The centre of the hyperbola is

$$\mathbf{c} = \frac{\mathbf{P}_1 + \mathbf{P}_2}{2} = \mathbf{0} = \mathbf{u} \quad (8.2.20.9)$$

from (B.1.5.9). Substituting  $\mathbf{P}_1$  and  $\mathbf{P}_2$  in (8.1.1.1),

$$\mathbf{P}_1^\top \mathbf{V} \mathbf{P}_1 + 2\mathbf{u}^\top \mathbf{P}_1 + f = 0 \quad (8.2.20.10)$$

$$\mathbf{P}_2^\top \mathbf{V} \mathbf{P}_2 + 2\mathbf{u}^\top \mathbf{P}_2 + f = 0 \quad (8.2.20.11)$$

$$\implies f = \mathbf{P}_1^\top \mathbf{V} \mathbf{P}_1 = 49(e^2 - 1) = \frac{343}{9} \quad (8.2.20.12)$$

upon adding (8.2.20.11) and (8.2.20.10) and simplifying. Therefore, the equation of the conic is

$$\mathbf{x}^\top \begin{pmatrix} -\frac{7}{9} & 0 \\ 0 & 1 \end{pmatrix} \mathbf{x} + \frac{343}{9} = 0 \quad (8.2.20.13)$$

See Fig. 8.2.20.1.

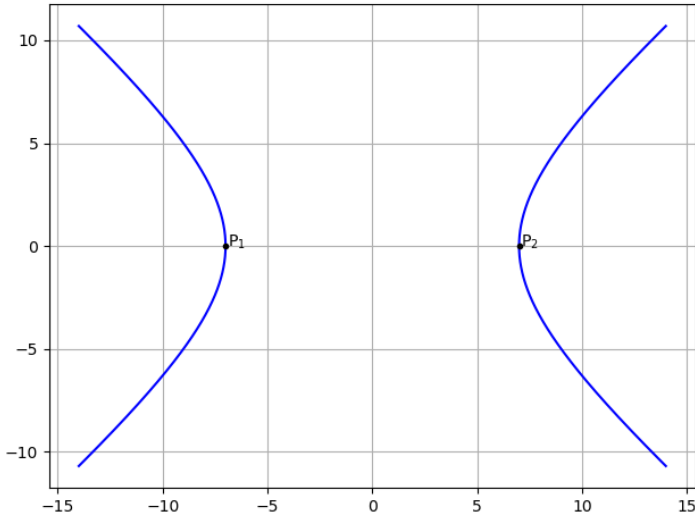


Fig. 8.2.20.1

8.2.21 centre at  $\mathbf{c}(0, 0)$ , major axis on the y-axis and passes through the points  $\mathbf{P}(3, 2)$  and  $\mathbf{Q}(1, 6)$ .

**Solution:** Since the major axis is along the y-axis,

$$\mathbf{n} = \mathbf{e}_2 \quad (8.2.21.1)$$

Thus,

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 1 - e^2 \end{pmatrix} \quad (8.2.21.2)$$

Since

$$\mathbf{c} = \mathbf{0}, \mathbf{u} = \mathbf{0}. \quad (8.2.21.3)$$

From (8.1.1.1),

$$\mathbf{P}^\top \mathbf{V} \mathbf{P} + 2\mathbf{u}^\top \mathbf{P} + f = 0 \quad (8.2.21.4)$$

$$\mathbf{Q}^\top \mathbf{V} \mathbf{Q} + 2\mathbf{u}^\top \mathbf{Q} + f = 0 \quad (8.2.21.5)$$

yielding

$$4e^2 - f = 13 \quad (8.2.21.6)$$

$$36e^2 - f = 37 \quad (8.2.21.7)$$

which can be formulated as the matrix equation

$$\begin{pmatrix} 4 & -1 \\ 36 & -1 \end{pmatrix} \begin{pmatrix} e^2 \\ f \end{pmatrix} = \begin{pmatrix} 13 \\ 37 \end{pmatrix} \quad (8.2.21.8)$$

The augmented matrix is given by,

$$\begin{aligned} & \begin{pmatrix} 4 & -1 & | & 13 \\ 36 & -1 & | & 37 \end{pmatrix} \xrightarrow{R_1 \leftarrow -\frac{R_1}{8}} \begin{pmatrix} 4 & 0 & | & 3 \\ 36 & -1 & | & 37 \end{pmatrix} \\ & \xrightarrow{R_2 \leftarrow R_2 - 9R_1} \begin{pmatrix} 4 & 0 & | & 3 \\ 0 & -1 & | & 10 \end{pmatrix} \xrightarrow{\begin{matrix} R_1 \leftarrow \frac{R_1}{4} \\ R_2 \leftarrow -R_2 \end{matrix}} \begin{pmatrix} 1 & 0 & | & \frac{3}{4} \\ 0 & 1 & | & -10 \end{pmatrix} \end{aligned}$$

Thus,

$$e^2 = \frac{3}{4}, \quad f = -10 \quad (8.2.21.9)$$

and the equation of the conic is given by

$$\mathbf{x}^\top \begin{pmatrix} 1 & 0 \\ 0 & \frac{1}{4} \end{pmatrix} \mathbf{x} - 10 = 0 \quad (8.2.21.10)$$

See Fig. 8.2.21.1.

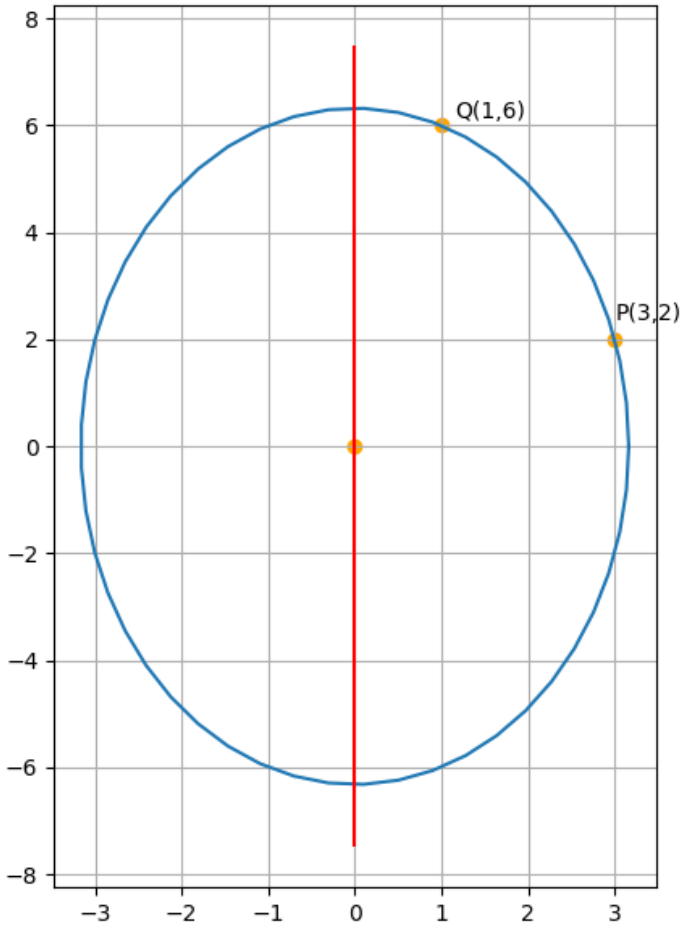


Fig. 8.2.21.1: Graph

8.2.22 major axis on the x-axis and passes through the points (4,3) and (6,2).

**Solution:** In this case,

$$\mathbf{n} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (8.2.22.1)$$

Thus,

$$\mathbf{V} = \begin{pmatrix} 1 - e^2 & 0 \\ 0 & 1 \end{pmatrix} \quad (8.2.22.2)$$

$$(8.2.22.3)$$

Since

$$\mathbf{c} = \mathbf{0}, \mathbf{u} = \mathbf{0}. \quad (8.2.22.4)$$

From (8.1.1.1),

$$\mathbf{P}^\top \mathbf{V} \mathbf{P} + 2\mathbf{u}^\top \mathbf{P} + f = 0 \quad (8.2.22.5)$$

$$\mathbf{Q}^\top \mathbf{V} \mathbf{Q} + 2\mathbf{u}^\top \mathbf{Q} + f = 0 \quad (8.2.22.6)$$

yielding

$$16e^2 - f = 25 \quad (8.2.22.7)$$

$$36e^2 - f = 40 \quad (8.2.22.8)$$

which can be formulated as the matrix equation

$$\begin{pmatrix} 16 & -1 \\ 36 & -1 \end{pmatrix} \begin{pmatrix} e^2 \\ f \end{pmatrix} = \begin{pmatrix} 25 \\ 40 \end{pmatrix} \quad (8.2.22.9)$$

and can be solved using the augmented matrix.

$$\begin{aligned} & \begin{pmatrix} 16 & -1 & 25 \\ 36 & -1 & 40 \end{pmatrix} \xrightarrow{R_1 \leftarrow R_1 - R_2} \begin{pmatrix} -20 & 0 & -15 \\ 36 & -1 & 40 \end{pmatrix} \\ & \xrightarrow{R_1 \leftarrow \frac{R_1}{-5}, R_2 \leftarrow -R_2} \begin{pmatrix} 4 & 0 & 3 \\ -36 & 1 & -40 \end{pmatrix} \xrightarrow{R_2 \leftarrow R_2 + 9R_1} \begin{pmatrix} 4 & 0 & 3 \\ 0 & 1 & -13 \end{pmatrix} \\ & \xrightarrow{R_1 \leftarrow \frac{R_1}{4}} \begin{pmatrix} 1 & 0 & \frac{3}{4} \\ 0 & 1 & -13 \end{pmatrix} \end{aligned}$$

Thus,

$$e^2 = \frac{3}{4}, f = -13 \quad (8.2.22.10)$$

and the equation of the conic is given by

$$\mathbf{x}^\top \begin{pmatrix} \frac{1}{4} & 0 \\ 0 & 1 \end{pmatrix} \mathbf{x} - 13 = 0 \quad (8.2.22.11)$$

See Fig. 8.2.22.1.

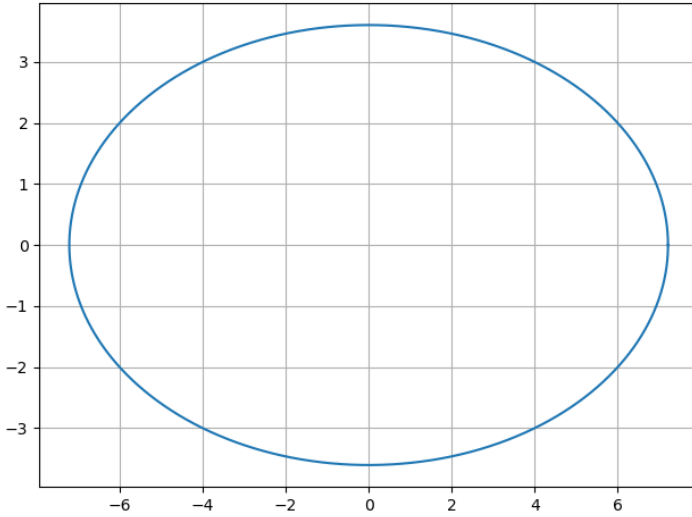


Fig. 8.2.22.1: Locus of the required ellipse.

8.2.23 vertices  $\begin{pmatrix} 0 \\ \pm 3 \end{pmatrix}$  and foci  $\begin{pmatrix} 0 \\ \pm 5 \end{pmatrix}$ .

**Solution:** Following the approach in the earlier problems, it is obvious that

$$\mathbf{n} = \mathbf{e}_2, \mathbf{c} = \mathbf{u} = \mathbf{0}. \quad (8.2.23.1)$$

Consequently,

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 1 - e^2 \end{pmatrix} \quad (8.2.23.2)$$

$$\mathbf{F} = ce^2\mathbf{e}_2 \implies \|\mathbf{F}\| = ce^2 = 5 \quad (8.2.23.3)$$

$$f = 25 - c^2e^2 \quad (8.2.23.4)$$

Since the vertices are on the conic,

$$\mathbf{v}_1^\top \mathbf{V} \mathbf{v}_1 + 2\mathbf{u}^\top \mathbf{v}_1 + f = 0 \quad (8.2.23.5)$$

$$\implies 9(1 - e^2) + f = 0 \quad (8.2.23.6)$$

$$(8.2.23.7)$$

Solving (8.2.23.7), (8.2.23.3) and (8.2.23.4),

$$c = \frac{9}{5}, \quad e = \frac{5}{3}, \quad (8.2.23.8)$$

yielding

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & -\frac{16}{9} \end{pmatrix}, \quad \mathbf{u} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \quad f = 16. \quad (8.2.23.9)$$

Thus, the desired equation of the hyperbola is

$$\mathbf{x}^T \begin{pmatrix} 1 & 0 \\ 0 & -\frac{16}{9} \end{pmatrix} \mathbf{x} + 16 = 0 \quad (8.2.23.10)$$

See Fig. 8.2.23.1.

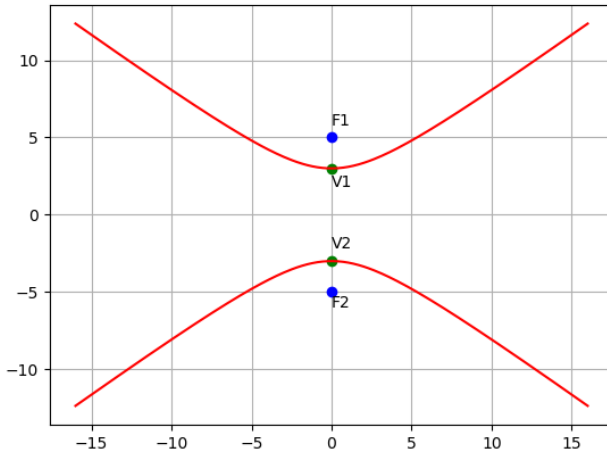


Fig. 8.2.23.1: Figure 1

8.2.24 vertices  $(0, \pm 5)$ , foci  $(0, \pm 8)$ .

8.2.25 focus  $(6, 0)$ ; directrix  $x = -6$

8.2.26 focus  $(0, -3)$ ; directrix  $y = 3$

8.2.27 vertex  $(0, 0)$ ; focus  $(3, 0)$

8.2.28 vertex  $(0, 0)$ ; focus  $(-2, 0)$

8.2.29 vertex  $(0, 0)$  passing through  $(2, 3)$  and axis is along  $x$ -axis

8.2.30 vertex  $(0, 0)$  passing through  $(5, 2)$  symmetric with respect to  $y$ -axis

8.2.31 vertices  $(\pm 5, 0)$ , foci  $(\pm 4, 0)$ .

8.2.32 vertices  $(\pm 0, 13)$ , foci  $(0, \pm 5)$ .

8.2.33 vertices  $(\pm 6, 0)$ , foci  $(\pm 4, 0)$ .

8.2.34 ends of major axis  $(\pm 3, 0)$ , ends of minor axis  $(0, \pm 2)$ .

8.2.35 ends of major axis  $(0, \pm \sqrt{5})$ , ends of minor axis  $(\pm 1, 0)$ .

8.2.36 length of major axis 26, foci  $(\pm 5, 0)$ .

8.2.37 length of minor axis 16, foci  $(0, \pm 6)$ .

8.2.38 foci  $(\pm 3, 0)$ ,  $a = 4$ .

8.2.39 vertex  $(0, 4)$ , focus  $(0, 2)$ .

8.2.40 vertex  $(-3, 0)$ , directrix  $x + 5 = 0$ .

8.2.41 focus  $(0, -3)$  and directrix  $y = 3$ .

8.2.42 directrix  $x = 0$ , focus at  $(6, 0)$ .

- 8.2.43 vertex at (0,4), focus at (0,2).
- 8.2.44 focus at (-1,2), directrix  $x - 2y + 3 = 0$ .
- 8.2.45 vertices  $(\pm 5, 0)$ , foci  $(\pm 7, 0)$ .
- 8.2.46 vertices  $(0 \pm 7)$ ,  $e = \frac{4}{3}$ .
- 8.2.47 foci  $(0, \pm \sqrt{10})$ , passing through (2,3).
- 8.2.48 vertices at  $(0, \pm 6)$ , eccentricity  $\frac{5}{3}$ .
- 8.2.49 focus (-1,-2), directrix  $x - 2y + 3 = 0$ .
- 8.2.50 eccentricity  $\frac{3}{2}$ , foci  $(\pm 2, 0)$ .
- 8.2.51 eccentricity  $\frac{2}{3}$ , latus rectum 5, centre (0,0).
- 8.2.52 If the parabola  $y^2 = 4ax$  passes through the point (3,2), then the length of its latus rectum is
- 8.2.53 Find the eccentricity of the hyperbola  $9y^2 - 4x^2 = 36$ .
- 8.2.54 Equation of the hyperbola with eccentricity  $\frac{3}{2}$  and foci at  $(\pm 2, 0)$  is
- $\frac{x^2}{4} - \frac{y^2}{5} = \frac{4}{9}$
  - $\frac{x^2}{9} - \frac{y^2}{9} = \frac{4}{9}$
  - $\frac{x^2}{4} - \frac{y^2}{9} = 1$
  - none of these.
- 8.2.55 Given the ellipse with equation  $9x^2 + 25y^2 = 225$ , find the eccentricity and foci.
- 8.2.56 Find the equation of the set of all points whose distance from (0,4) is  $\frac{2}{3}$  of their distance from the line  $y = 9$ .
- 8.2.57 The equation of the ellipse whose focus is (1,-1), directrix  $x - y - 3 = 0$  and eccentricity  $\frac{1}{2}$  is
- $7x^2 + 2xy + 7y^2 - 10x + 10y + 7 = 0$
  - $7x^2 + 2xy + 7y^2 + 7 = 0$
  - $7x^2 + 2xy + 7y^2 + 10x - 10y - 7 = 0$
  - none
- 8.2.58 The length of the latus rectum of the ellipse  $3x^2 + y^2 = 12$  is
- 4
  - 3
  - 8
  - $4\sqrt{3}$

### 8.3 Miscellaneous

- 8.3.1 The cable of a uniformly loaded suspension bridge hangs in the form of a parabola. The roadway which is horizontal and 100 m long is supported by vertical wires attached to the cable, the longest wire being 30 m and the shortest being 6 m. Find the length of a supporting wire attached to the roadway 18 m from the middle.

**Solution:** The parameters are then listed in Table 8.3.1.



<b>O</b>	Lowest point of cable	$\begin{pmatrix} 0 \\ 0 \end{pmatrix}$
$d$	Length of the cable	100 m
$d_1$	Length of longest wire	30 m
$d_2$	Length of shortest wire	6 m
<b>A</b>	End point of cable	$\begin{pmatrix} \frac{d}{2} \\ d_1 - d_2 \end{pmatrix}$
<b>B</b>	End point of cable	$\begin{pmatrix} -\frac{d}{2} \\ d_1 - d_2 \end{pmatrix}$

TABLE 8.3.1: points

For the conic,

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}. \quad (8.3.1.1)$$

Points **O**, **A**, and **B** are on conic, so we have

$$\mathbf{O}^\top \mathbf{V} \mathbf{O} + 2\mathbf{u}^\top \mathbf{O} + f = 0 \quad (8.3.1.2)$$

$$\mathbf{A}^\top \mathbf{V} \mathbf{A} + 2\mathbf{u}^\top \mathbf{A} + f = 0 \quad (8.3.1.3)$$

$$\mathbf{B}^\top \mathbf{V} \mathbf{B} + 2\mathbf{u}^\top \mathbf{B} + f = 0 \quad (8.3.1.4)$$

which can be expressed as

$$2\mathbf{O}^\top \mathbf{u} + f = -\mathbf{O}^\top \mathbf{V} \mathbf{O} \quad (8.3.1.5)$$

$$2\mathbf{A}^\top \mathbf{u} + f = -\mathbf{A}^\top \mathbf{V} \mathbf{A} \quad (8.3.1.6)$$

$$2\mathbf{B}^\top \mathbf{u} + f = -\mathbf{B}^\top \mathbf{V} \mathbf{B} \quad (8.3.1.7)$$

leading to the matrix equation

$$\begin{pmatrix} 2\mathbf{O}^\top & 1 \\ 2\mathbf{A}^\top & 1 \\ 2\mathbf{B}^\top & 1 \end{pmatrix} \begin{pmatrix} \mathbf{u} \\ f \end{pmatrix} = - \begin{pmatrix} \mathbf{O}^\top \mathbf{V} \mathbf{O} \\ \mathbf{A}^\top \mathbf{V} \mathbf{A} \\ \mathbf{B}^\top \mathbf{V} \mathbf{B} \end{pmatrix} \quad (8.3.1.8)$$

Substituting numerical values in the above equation,

$$\begin{pmatrix} 0 & 0 & 1 \\ 100 & 48 & 1 \\ -100 & 48 & 1 \end{pmatrix} \begin{pmatrix} \mathbf{u} \\ f \end{pmatrix} = - \begin{pmatrix} 0 \\ -2500 \\ -2500 \end{pmatrix} \quad (8.3.1.9)$$

$$\Rightarrow f = 0 \text{ and } \mathbf{u} = \begin{pmatrix} 0 \\ -\frac{625}{12} \end{pmatrix} \quad (8.3.1.10)$$

So, the equation of the parabola is

$$\mathbf{x}^\top \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{x} + 2 \begin{pmatrix} 0 & -\frac{625}{12} \end{pmatrix} \mathbf{x} = 0 \quad (8.3.1.11)$$

The desired point can be expressed as

$$\mathbf{D} = \begin{pmatrix} 18 \\ x_2 \end{pmatrix} \quad (8.3.1.12)$$

Substituting this in the parabola equation,

$$18^2 - \frac{6}{625}\lambda_2 = 0 \quad (8.3.1.13)$$

$$\Rightarrow \lambda_2 = \frac{1944}{625} \quad (8.3.1.14)$$

Thus, the length of a supporting wire attached to the roadway 18m from the middle is

$$\lambda_2 + d_2 = \frac{5694}{625}m \quad (8.3.1.15)$$

See Fig. 8.3.1.1.

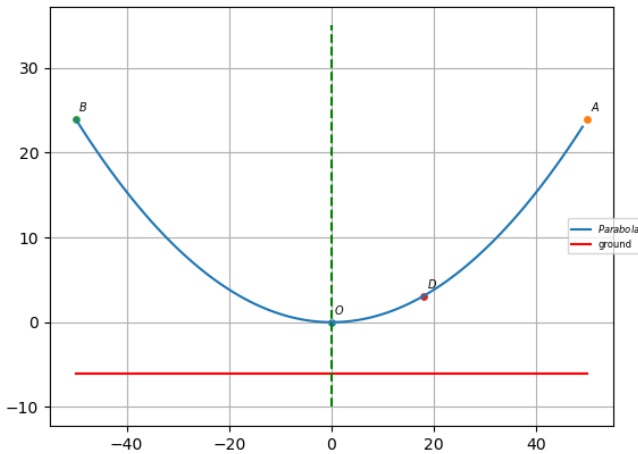


Fig. 8.3.1.1

8.3.2 Find the area of the triangle formed by the lines joining the vertex of the parabola

$$x^2 = 12y \quad (8.3.2.1)$$

to the ends of its latus rectum.

**Solution:** Rewriting (8.3.2.1) in matrix form,

$$\mathbf{x}^\top \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{x} + 2 \begin{pmatrix} 0 & -6 \end{pmatrix} \mathbf{x} = 0 \quad (8.3.2.2)$$

The above parabola can be expressed in standard form using

$$\mathbf{x} = \mathbf{P}\mathbf{y} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \mathbf{y} \quad (8.3.2.3)$$

yielding

$$\mathbf{y}^\top \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{x} + 2 \begin{pmatrix} -6 & 0 \end{pmatrix} \mathbf{x} = 0 \quad (8.3.2.4)$$

Hence, from (8.1.2.2),

$$\mathbf{n} = \mathbf{e}_1 \quad (8.3.2.5)$$

$$c = -\frac{36}{2 \times 6} = -3 \quad (8.3.2.6)$$

Substituting in (8.1.2.3) yields

$$\mathbf{F} = 3\mathbf{e}_1 \quad (8.3.2.7)$$

Thus, the equation of the latus rectum is

$$\mathbf{x} = \mathbf{F} + \kappa \mathbf{e}_2 \quad (8.3.2.8)$$

Substituting in (8.3.2.4) and simplifying,

$$\kappa = \pm 6 \quad (8.3.2.9)$$

Thus, the ends of the latus rectum are

$$\mathbf{y} = \begin{pmatrix} 3 \\ \pm 6 \end{pmatrix} \quad (8.3.2.10)$$

The relevant parameters with respect to (8.3.2.2) can now be obtained using (8.3.2.3). See Fig. 8.3.2.1. The area of the required triangle is

$$\text{ar}(\triangle OAB) = \frac{1}{2} \begin{vmatrix} 6 & 3 \\ -6 & 3 \end{vmatrix} = 18 \quad (8.3.2.11)$$

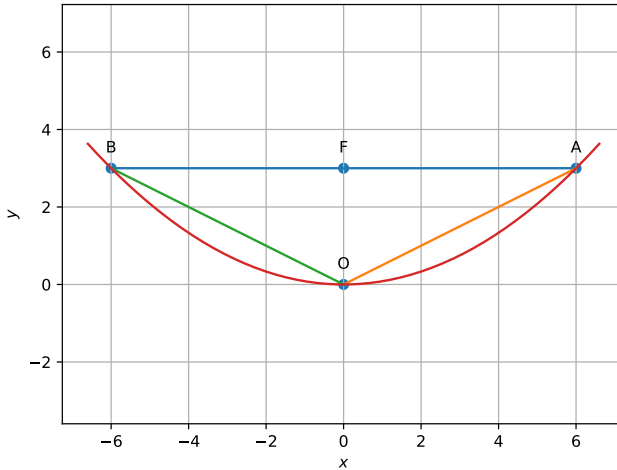


Fig. 8.3.2.1

- 8.3.3 A man running a racecourse notes that the sum of the distances from the two flag posts from him is always 10 m and the distance between the flag posts is 8 m. Find the equation of the posts traced by the man.
- 8.3.4 Find the coordinates of a point on the parabola  $y^2 = 8x$  whose focal distance is 4.
- 8.3.5 Show that the set of all points such that the difference of their distances from (4,0) and (-4,0) is always equal to 2 represent a hyperbola.
- 8.3.6 If the distance between the foci of a hyperbola is 16 and its eccentricity is  $\sqrt{2}$ , then obtain the equation of the hyperbola.
- 8.3.7 The eccentricity of the hyperbola whose latus rectum is 8 and conjugate axis is equal to half of the distance between the foci is
- $\frac{4}{3}$
  - $\frac{4}{\sqrt{3}}$
  - $\frac{2}{\sqrt{3}}$
  - none of these
- 8.3.8 The distance between the foci of a hyperbola is 16 and its eccentricity is  $\leq 2$ . Its equation is
- $x^2 - y^2 = 3^2$
  - $\frac{x^2}{4} - \frac{y^2}{9} = 1$
  - $2x - 3y^2 = 7$
  - none of these
- 8.3.9 If the latus rectum of an ellipse is equal to half of minor axis, then find its eccentricity.
- 8.3.10 If the eccentricity of an ellipse is  $\frac{5}{8}$  and the distance between its foci is 10 then find latus rectum of the ellipse.
- 8.3.11 Find the distance between the directrices of the ellipse  $\frac{x^2}{36} + \frac{y^2}{20}$

- 8.3.12 Find the equation of the set of all points the sum of whose distances from the points (3,0) and (9,0) is 12.
- 8.3.13 If  $P$  is a point on the ellipse  $\frac{x^2}{16} + \frac{y^2}{25} = 1$  whose foci are  $s$  and  $s'$  then  $Ps + Ps' = 8$ .
- 8.3.14 An arch is in the form of a parabola with its axis vertical. The arch is 10m high and 5m wide at the base. How wide is it 2m from the vertex of the parabola?
- 8.3.15 An equilateral triangle is inscribed in the parabola  $y^2 = 4ax$ , where one vertex is at the vertex of the parabola. Find the length of the side of the triangle.
- 8.3.16 An arch is in the form of a semi-ellipse. It is 8 m wide and 2 m high at the centre. Find the height of the arch at a point 1.5 m from one end.
- 8.3.17 A rod of length 12cm moves with its ends always touching the coordinate axes. Determine the equation of locus of a point  $P$  on the rod, which is 3cm from the end in contact with  $x$ -axis.

#### 8.4 Quadratic Equations

Find the roots of the following quadratic equations graphically.

- |  |  |
|--|--|
| 8.4.1 $(x-2)^2 + 1 = 2x - 3$             | 8.4.18 $4x^2 + 4\sqrt{3}x + 3 = 0$                                   |
| 8.4.2 $x(2x+3) = x^2 + 1$                | 8.4.19 $2x^2 + x + 4 = 0$  |
| 8.4.3 $(x+2)^3 = x^3 - 4$                | 8.4.20 $x - \frac{1}{x} = 3, x \neq 0$                               |
| 8.4.4 $x^2 - 3x - 10 = 0$                | 8.4.21 $\frac{1}{x+4} - \frac{1}{x-7} = \frac{11}{30}, x \neq -4, 7$ |
| 8.4.5 $2x^2 + x - 6 = 0$                 | 8.4.22 $2x^2 - 5x + 3 = 0$   |
| 8.4.6 $\sqrt{2}x^2 + 7x + 5\sqrt{2} = 0$ | 8.4.23 $6x^2 - x - 2 = 0$  |
| 8.4.7 $2x^2 - x + \frac{1}{8} = 0$       | 8.4.24 $3x^2 - 2\sqrt{6}x + 2 = 0$                                   |
| 8.4.8 $100x^2 - 20x + 1 = 0$             | 8.4.25 $5x^2 - 6x - 2 = 0$   |
| 8.4.9 $2x^2 - 3x + 5 = 0$                | 8.4.26 $4x^2 + 3x + 5 = 0$   |
| 8.4.10 $3x^2 - 4\sqrt{3}x + 4 = 0$       | 8.4.27 $3x^2 - 5x + 2 = 0$   |
| 8.4.11 $2x^2 - 6x + 3 = 0$               | 8.4.28 $x^2 + 4x + 5 = 0$  |
| 8.4.12 $(x+1)^2 = 2(x-3)$                | 8.4.29 $2x^2 - 2\sqrt{2}x + 1 = 0$                                   |
| 8.4.13 $x^2 - 2x = (-2)(3-x)$            | 8.4.30 $x + \frac{1}{x} = 3, x \neq 0$                               |
| 8.4.14 $(x-3)(2x-1) = x(x+5)$            | 8.4.31 $\frac{1}{x} - \frac{1}{x-2} = 3, x \neq 0, 2$                |
| 8.4.15 $(2x-1)(x-3) = (x+5)(x-1)$        | 8.4.32 $3x^2 - 2x + \frac{1}{3} = 0$                                 |
| 8.4.16 $2x^2 - 7x + 3 = 0$               | 8.4.33 $x^2 - 4x + 3 = 0$  |
| 8.4.17 $2x^2 + x - 4 = 0$                | 8.4.34 $2x^2 - 4x + 3 = 0$   |

Find the values of  $k$  for each of the following quadratic equations, so that they have equal roots. Verify your solution graphically.

- 8.4.18  $2x^2 = kx - 3 = 0$ .
- 8.4.19  $kx(x-2) + 6 = 0$ .

Represent the following situations graphically.

- 8.4.20 Janaki and Jivanti together have 45 marbles. Both of them lost 5 marbles each, and the product of the number of marbles they have is 124. We would like to find out how many marbles they had to start with.
- 8.4.21 A cottage industry produces a certain number of toys in a day. The cost of production of each toy (in rupees) was found to be 55 minus the number of toys produced in a day. On a particular day, the total cost of production was ₹750. We would like to find out the number of toys produced on that day.
- 8.4.22 Find two numbers whose sum is 27 and product is 182.
- 8.4.23 Find two consecutive positive integers, sum of whose squares is 365.
- 8.4.24 The altitude of a right triangle is 7 cm less than its base. If the hypotenuse is 13 cm, find the other two sides.
- 8.4.25 A cottage industry produces a certain number of pottery articles in a day. It was observed on a particular day that the cost of production of each article (in rupees) was 3 more than twice the number of articles produced on that day. If the total cost of production on that day was ₹90, find the number of articles produced and the cost of each article.
- 8.4.26 Is it possible to design a rectangular mango grove whose length is twice its breadth, and the area is  $800m^2$ ? If so, find its length and breadth.
- 8.4.27 Is the following situation possible? If so, determine their present ages.  
The sum of the ages of the two friends is 20 years. Four years ago, the product of their ages in years was 48.
- 8.4.28 Is it possible to design a rectangular park of perimeter 80m and area of  $400m^2$ . If so, find its length and breadth.
- 8.4.29 The area of rectangular plot is  $528m^2$ . The length of the plot (in metres) is one more than twice its breadth. We need to find the length and breadth of the plot.
- 8.4.30 The product of two consecutive positive integers is 306. We need to find the integers.
- 8.4.31 Rohan's mother is 26 years older than him. The product of their ages (in years) 3 years from now will be 360. We would like to find Rohan's present age.
- 8.4.32 A train travels a distance of 480km at a uniform speed. If the speed had been 8km/h less, then it would have taken 3 hours more to cover the same distance. We need to find the speed of the train.
- 8.4.33 The sum of the reciprocals of Ram's ages, (in years) 3 years ago and 5 years from now is  $\frac{1}{3}$ . Find his present age.
- 8.4.34 In a class test, the sum of Shefali's marks in Mathematics and English is 30. Had she got 2 marks more in Mathematics and 3 marks less in English, the product of their marks would have been 210. Find her marks in the two subjects.
- 8.4.35 The diagonal of a rectangular field is 60 metres more than the shorter side. If the longer side is 30 metres more than the shorter side, find the sides of the field.
- 8.4.36 The difference of squares of two numbers is 180. The square of the smaller number is 8 times the larger number. Find the two numbers.
- 8.4.37 A train travels 360 km at a uniform speed. If the speed had been 5 km/hr more, it would have taken 1 hour less for the same journey. Find the speed of the train.
- 8.4.38 Two water taps together can fill a tank in  $9\frac{3}{8}$  hours. The tap of larger diameter takes 10 hours. The tap of larger diameter takes 10 hours less than the smaller one to fill

the tank separately. Find the time in which each tap can separately fill the tank.

- 8.4.39 An express train takes 1 hour less than a passenger train to travel 132 km between Mysuru and Bengaluru (without taking into consideration the time they stop at intermediate stations). If the average speed of the express train is 11 km/h more than that of the passenger train, find the average speed of the two trains.
- 8.4.40 Sum of the areas of two squares is  $468m^2$ . If the difference of their perimeter is 24m, find the sides of the two squares.
- 8.4.41 A charity trust decides to build a prayer hall having a carpet area of 300 square metres with its length one metre more than twice its breadth. What should be the length and breadth of the hall?
- 8.4.42 A motor boat whose speed is 18 km/h in still water takes 1 hour more to go 24 km upstream than to return downstream to the same spot. Find the speed of the stream.
- 8.4.43 A pole has to be erected at a point on the boundary of a circular park of diameter 1.3 metres in such a way that the difference of its distances from two diametrically opposite fixed gates A and B on the boundary is 7 metres. Is it possible to do so? If yes, at what distances from the two gates should the pole be erected?
- 8.4.44 The area of a rectangle plot is  $528m^2$ . The length of the plot (in metres) is one more than twice its breadth. We need to find the length and breadth of the plot.
- 8.4.45 Find two consecutive odd positive integers, sum of whose squares is 290.
- 8.4.46 A rectangular park is to be designed whose breadth is 3 m less than its length. Its area is to be 4 square metres than the area of a park that has already been made in the shape of a isosceles triangle with its base as the breadth of the rectangular park and of altitude 12 m. Find its length and breadth.

## 9 INTERSECTION OF CONICS

### 9.1 Formulae

9.1.1 The points of intersection of the line

$$L : \quad \mathbf{x} = \mathbf{h} + \kappa \mathbf{m} \quad \kappa \in \mathbb{R} \quad (9.1.1.1)$$

with the conic section in (8.1.1.1) are given by

$$\mathbf{x}_i = \mathbf{h} + \kappa_i \mathbf{m} \quad (9.1.1.2)$$

where

$$\kappa_i = \frac{1}{\mathbf{m}^\top \mathbf{V} \mathbf{m}} \left( -\mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u}) \pm \sqrt{[\mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u})]^2 - g(\mathbf{h})(\mathbf{m}^\top \mathbf{V} \mathbf{m})} \right) \quad (9.1.1.3)$$

See B.3.1 for proof.

9.1.2 (8.1.1.1) represents a pair of straight lines if the matrix

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u}^\top & f \end{pmatrix} \quad (9.1.2.1)$$

is singular.

9.1.3 The intersection of two conics with parameters  $\mathbf{V}_i, \mathbf{u}_i, f_i, i = 1, 2$  is defined as

$$\mathbf{x}^\top (\mathbf{V}_1 + \mu \mathbf{V}_2) \mathbf{x} + 2(\mathbf{u}_1 + \mu \mathbf{u}_2)^\top \mathbf{x} + (f_1 + \mu f_2) = 0 \quad (9.1.3.1)$$

9.1.4 From (9.1.2.1), (9.1.3.1) represents a pair of straight lines if

$$\begin{vmatrix} \mathbf{V}_1 + \mu \mathbf{V}_2 & \mathbf{u}_1 + \mu \mathbf{u}_2 \\ (\mathbf{u}_1 + \mu \mathbf{u}_2)^\top & f_1 + \mu f_2 \end{vmatrix} = 0 \quad (9.1.4.1)$$

### 9.2 Chords

9.2.1 Find the area between the curves  $y = x$  and  $y = x^2$ .

**Solution:**



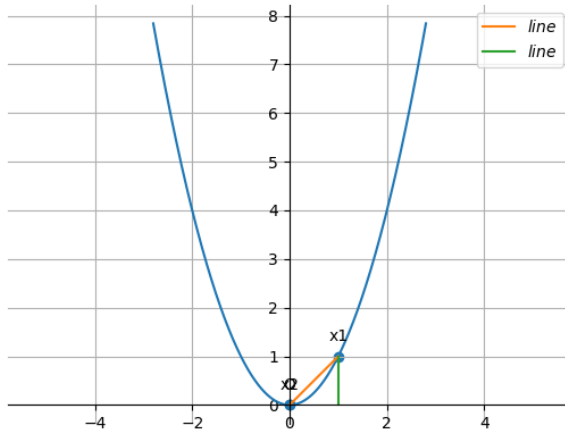


Fig. 9.2.1.1

The given curve can be expressed as a conic with parameters

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -\frac{1}{2} \end{pmatrix}, f = 0 \quad (9.2.1.1)$$

The given line parameters are

$$\mathbf{h} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (9.2.1.2)$$

Substituting the given parameters in (9.1.1.3),

$$\mathbf{x}_1 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \mathbf{x}_2 = \begin{pmatrix} 1 \\ 1 \end{pmatrix}. \quad (9.2.1.3)$$

From Fig. 9.2.1.1, the area bounded by the curve  $y = x^2$  and line  $y = x$  is given by

$$\int_0^1 \left( x - \frac{x^2}{2} \right) dx = \frac{1}{6} \quad (9.2.1.4)$$

9.2.2 Find the area of the region bounded by the curve  $y^2 = x$  and the lines  $x = 1$  and  $x = 4$  and the axis in the first quadrant.

**Solution:**

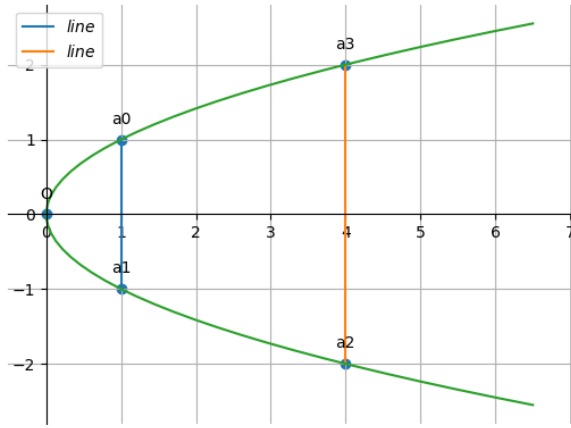


Fig. 9.2.2.1

The parameters of the conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = -\frac{1}{2} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, f = 0 \quad (9.2.2.1)$$

For the line  $x - 1 = 0$ , the parameters are

$$\mathbf{q}_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (9.2.2.2)$$

Substituting from the above in (9.1.1.3),

$$\kappa_i = 1, -1 \quad (9.2.2.3)$$

yielding the points of intersection

$$\mathbf{a}_0 = \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \mathbf{a}_1 = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (9.2.2.4)$$

Similarly, for the line  $x - 4 = 0$

$$\mathbf{q}_1 = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \mathbf{m}_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (9.2.2.5)$$

yielding

$$\kappa_i = 2, -2 \quad (9.2.2.6)$$

from which, the points of intersection are

$$\mathbf{a}_3 = \begin{pmatrix} 4 \\ 2 \end{pmatrix}, \mathbf{a}_2 = \begin{pmatrix} 4 \\ -2 \end{pmatrix} \quad (9.2.2.7)$$

See Fig. 9.2.2.1. Thus, the area of the parabola in between the lines  $x = 1$  and  $x = 4$  is given by

$$\int_0^4 \sqrt{x} dx - \int_0^1 \sqrt{x} dx = 14/3 \quad (9.2.2.8)$$

9.2.3 Find the area of the region bounded by the curve  $y^2 = 9x$  and the lines  $x = 2$  and  $x = 4$  and the axis in the first quadrant.

**Solution:**

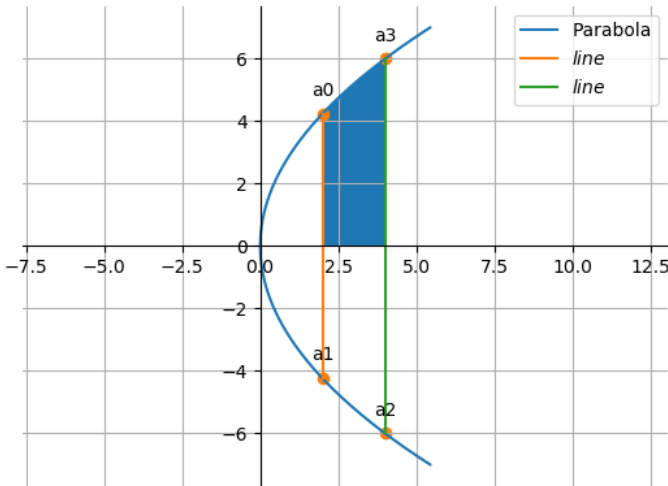


Fig. 9.2.3.1

The parameters of the conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = \frac{9}{2} \begin{pmatrix} 1 \\ 0 \end{pmatrix}, f = 0. \quad (9.2.3.1)$$

The parameters of the line  $x - 2 = 0$  are

$$\mathbf{q}_2 = \begin{pmatrix} 2 \\ 0 \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (9.2.3.2)$$

Substituting in (9.1.1.3),

$$\kappa_i = \pm 3\sqrt{2} \quad (9.2.3.3)$$

yielding

$$\mathbf{a}_0 = \begin{pmatrix} 2 \\ 3\sqrt{2} \end{pmatrix}, \mathbf{a}_1 = \begin{pmatrix} 2 \\ -3\sqrt{2} \end{pmatrix}. \quad (9.2.3.4)$$

Similarly, for the line  $x - 4 = 0$ ,

$$\mathbf{q}_1 = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \mathbf{m}_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (9.2.3.5)$$

yielding

$$\kappa_i = \pm 6. \quad (9.2.3.6)$$

Thus,

$$\mathbf{a}_3 = \begin{pmatrix} 4 \\ 6 \end{pmatrix}, \mathbf{a}_2 = \begin{pmatrix} 4 \\ -6 \end{pmatrix} \quad (9.2.3.7)$$

and from Fig. 9.2.3.1, the desired area of the parabola is

$$\int_0^4 3\sqrt{x} dx - \int_0^2 3\sqrt{x} dx = 16 - 4\sqrt{2} \quad (9.2.3.8)$$

9.2.4 Find the area of the region bounded by  $x^2 = 4y$ ,  $y = 2$ ,  $y = 4$  and the  $y$ -axis in the first quadrant.

9.2.5 Find the area of the region bounded by the ellipse  $\frac{x^2}{16} + \frac{y^2}{9} = 1$

9.2.6 Find the area of the region bounded by the ellipse  $\frac{x^2}{4} + \frac{y^2}{9} = 1$

9.2.7 Find the area of the region in the first quadrant enclosed by the  $x$ -axis, line  $x = \sqrt{3}y$  and circle  $x^2 + y^2 = 4$ .

**Solution:**

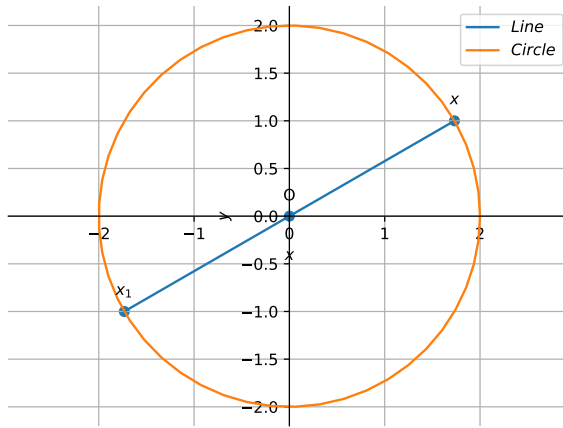


Fig. 9.2.7.1

From the given information, the parameters of the circle and line are

$$f = -4, \mathbf{u} = \mathbf{0}, \mathbf{V} = \mathbf{I}, \mathbf{m} = \begin{pmatrix} 1 \\ \sqrt{3} \end{pmatrix}, \mathbf{h} = \mathbf{0} \quad (9.2.7.1)$$

Substituting the above parameters in (9.1.1.3),

$$\mu = \sqrt{3} \quad (9.2.7.2)$$

yielding the desired point of intersection as

$$\mathbf{x} = \begin{pmatrix} \sqrt{3} \\ 1 \end{pmatrix} \quad (9.2.7.3)$$

Note that we have chosen only the point of intersection in the first quadrant as shown in Fig. 9.2.7.1. From (9.2.7.1), the angle between the given line and the x axis is

$$\theta = 30^\circ \quad (9.2.7.4)$$

and the area of the sector is

$$\frac{\theta}{360} \pi r^2 = \frac{\pi}{3} \quad (9.2.7.5)$$

9.2.8 Find the area of the smaller part of the circle  $x^2 + y^2 = a^2$  cut off by the line  $x = \frac{a}{\sqrt{2}}$ .

**Solution:**

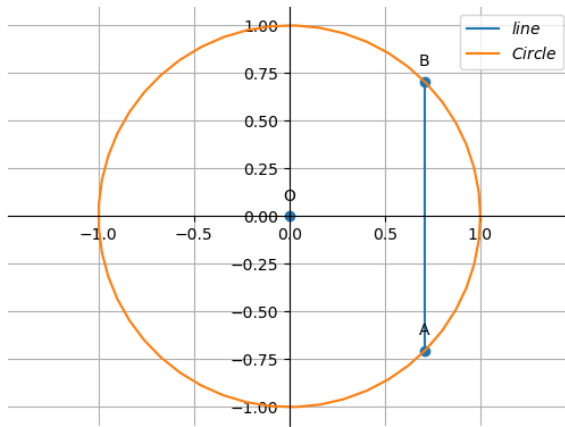


Fig. 9.2.8.1

The given circle can be expressed as a conic with parameters

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = 0, f = -a^2 \quad (9.2.8.1)$$

The given line parameters are

$$\mathbf{h} = \begin{pmatrix} \frac{a}{\sqrt{2}} \\ 0 \end{pmatrix}, \mathbf{m} = \mathbf{e}_2. \quad (9.2.8.2)$$

Substituting the above in (9.1.1.3),

$$\kappa = \pm \frac{a}{\sqrt{2}} \quad (9.2.8.3)$$

yielding the points of intersection of the line with circle as

$$\mathbf{A} = \begin{pmatrix} \frac{a}{\sqrt{2}} \\ -\frac{a}{\sqrt{2}} \end{pmatrix}, \mathbf{B} = \begin{pmatrix} \frac{a}{\sqrt{2}} \\ \frac{a}{\sqrt{2}} \end{pmatrix} \quad (9.2.8.4)$$

From Fig. 9.2.8.1, the total area of the portion is given by

$$ar(APQ) = 2ar(APR) \quad (9.2.8.5)$$

$$= 2 \int_0^{\frac{a}{\sqrt{2}}} \sqrt{a^2 - x^2} dx \quad (9.2.8.6)$$

$$= \frac{a^2}{2} \left( 1 + \frac{\pi}{2} \right) \quad (9.2.8.7)$$

9.2.9 The area between  $x = y^2$  and  $x = 4$  is divided into two equal parts by the line  $x = a$ , find the value of  $a$ .

**Solution:**

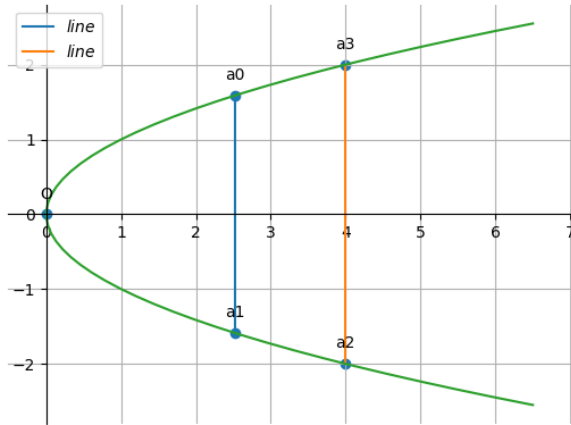


Fig. 9.2.9.1

The given conic parameters are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = -\frac{1}{2}\mathbf{e}_1, f = 0 \quad (9.2.9.1)$$

The parameters of the lines are

$$\mathbf{q}_2 = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{m}_2 = \mathbf{e}_2 \quad (9.2.9.2)$$

Substituting the above values in (9.1.1.3),

$$\mu_i = a, -a \quad (9.2.9.3)$$

yielding the points of intersection as

$$\mathbf{a}_0 = \begin{pmatrix} a \\ a \end{pmatrix}, \mathbf{a}_1 = \begin{pmatrix} a \\ -a \end{pmatrix} \quad (9.2.9.4)$$

Similarly, for the line  $x - 4 = 0$ ,

$$\mathbf{q}_1 = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \mathbf{m}_1 = \mathbf{e}_2 \quad (9.2.9.5)$$

yielding

$$\mu_i = 2, -2 \quad (9.2.9.6)$$

and

$$\mathbf{a}_3 = \begin{pmatrix} 4 \\ 2 \end{pmatrix}, \mathbf{a}_2 = \begin{pmatrix} 4 \\ -2 \end{pmatrix}. \quad (9.2.9.7)$$

Area between parabola and the line  $x = 4$  is divided equally by the line  $x = a$ . Thus, from Fig. 9.2.9.1,

$$A_1 = \int_0^a \sqrt{x} dx \quad (9.2.9.8)$$

$$A_2 = \int_a^4 \sqrt{x} dx \quad (9.2.9.9)$$

$$\text{and } A_1 = A_2 \quad (9.2.9.10)$$

$$\Rightarrow a = 4^{\frac{2}{3}} \quad (9.2.9.11)$$

9.2.10 Find the area of the region bounded by the parabola  $y = x^2$  and  $y = |x|$ .

9.2.11 Find the area bounded by the curve  $x^2 = 4y$  and the line  $x = 4y - 2$ .

**Solution:**

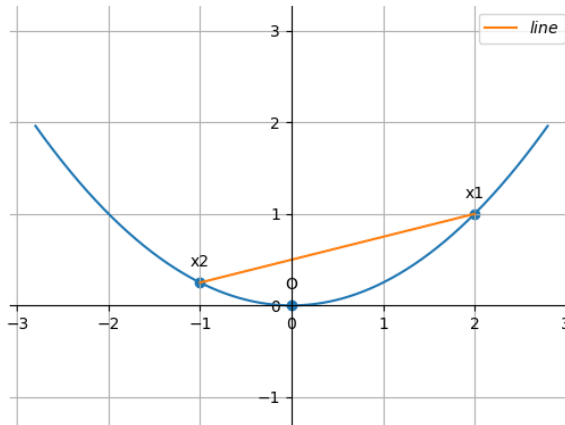


Fig. 9.2.11.1

The given curve can be expressed as a conic with parameters

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0 \quad (9.2.11.1)$$

The parameters of the given line are

$$\mathbf{q} = \begin{pmatrix} -2 \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} 4 \\ 1 \end{pmatrix} \quad (9.2.11.2)$$



The points of intersection can then be obtained from (9.1.1.3)

$$\therefore \mathbf{x}_1 = \begin{pmatrix} 2 \\ 1 \end{pmatrix}, \mathbf{x}_2 = \begin{pmatrix} -1 \\ \frac{1}{4} \end{pmatrix} \quad (9.2.11.3)$$

The desired area is then obtained from Fig. 9.2.11.1 as

$$A = \int_{x_2}^{x_1} [f(x) - g(x)] dx \quad (9.2.11.4)$$

$$= \int_{-1}^2 \left( \frac{x+2}{4} - \frac{x^2}{4} \right) dx \quad (9.2.11.5)$$

$$= \frac{9}{8} \quad (9.2.11.6)$$

9.2.12 Find the area of the region bounded by the curve  $y^2 = 4x$  and the line  $x = 3$ .

9.2.13 Area lying in the first quadrant and bounded by the circle  $x^2 + y^2 = 4$  and the lines  $x = 0$  and  $x = 2$  is

a)  $\pi$

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

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

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

9.2.14 Find the area of the region bounded by the curve  $y^2 = 4x$ , y-axis and the line  $y = 3$ .

**Solution:** In this case,

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} \quad (9.2.14.1)$$

$$\mathbf{u} = \begin{pmatrix} -2 \\ 0 \end{pmatrix} \quad (9.2.14.2)$$

$$f = 0 \quad (9.2.14.3)$$

For the given line  $y = 3$ , the parameters are

$$\mathbf{h} = \begin{pmatrix} 0 \\ 3 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (9.2.14.4)$$

The intersection of the line with the conic is obtained from (9.1.1.3) as

$$\kappa = \frac{9}{4} \quad (9.2.14.5)$$

The point of contact is given as

$$\mathbf{a}_0 = \begin{pmatrix} \frac{9}{4} \\ 3 \end{pmatrix} \quad (9.2.14.6)$$

From Fig. 9.2.14.1, the desired area of the region is obtained as

$$\int_0^3 \frac{y^2}{4} dy = \frac{1}{12} [y^3]_0^3 \quad (9.2.14.7)$$

$$= \frac{1}{12} (27 - 0) \quad (9.2.14.8)$$

$$= \frac{9}{4} \text{ sq.units} \quad (9.2.14.9)$$

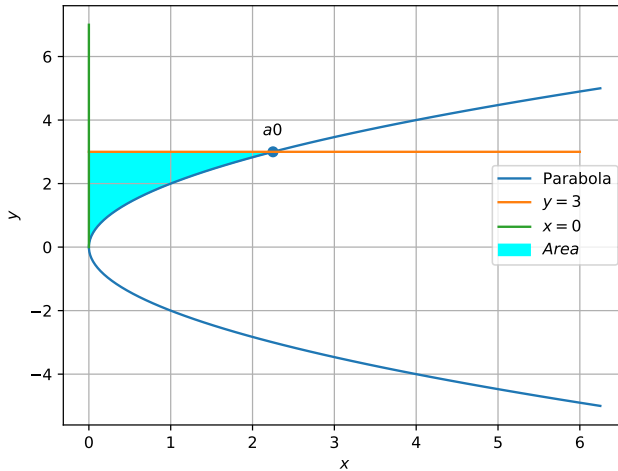


Fig. 9.2.14.1

9.2.15 Find the area of the region bounded by the curve  $x^2 = 4y$  and the lines  $y = 2$  and  $y = 4$  and the y-axis in the first quadrant.

**Solution:**

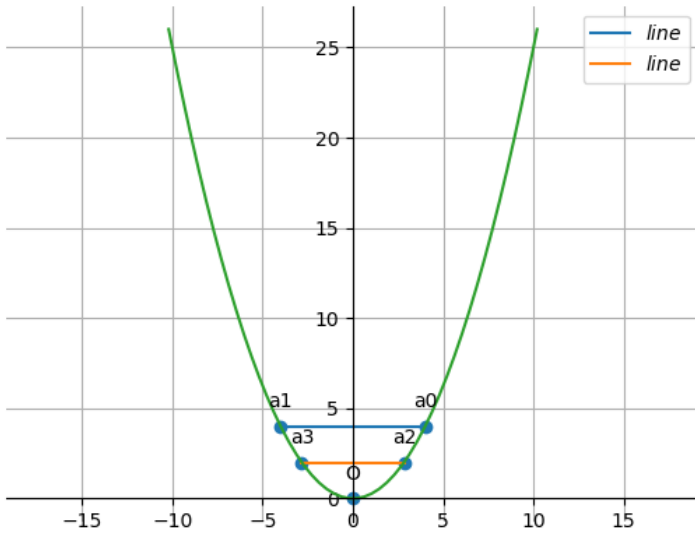


Fig. 9.2.15.1

The conic parameters are

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0 \quad (9.2.15.1)$$

The vector parameters of  $y - 4 = 0$  are

$$\mathbf{h}_1 = \begin{pmatrix} 0 \\ 4 \end{pmatrix}, \mathbf{m}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (9.2.15.2)$$

Substituting the above in (9.1.1.3),

$$\kappa_i = 4, -4 \quad (9.2.15.3)$$

yielding the points of intersection with the parabola as

$$\mathbf{a}_0 = \begin{pmatrix} 4 \\ 4 \end{pmatrix}, \mathbf{a}_1 = \begin{pmatrix} -4 \\ 4 \end{pmatrix} \quad (9.2.15.4)$$

Similarly, for the line  $y - 2 = 0$ , the vector parameters are

$$\mathbf{h}_2 = \begin{pmatrix} 0 \\ 2 \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (9.2.15.5)$$

yielding

$$\kappa_i = 2.8, -2.8 \quad (9.2.15.6)$$

and the points of intersection

$$\mathbf{a}_2 = \begin{pmatrix} 2.8 \\ 2 \end{pmatrix}, \mathbf{a}_3 = \begin{pmatrix} -2.8 \\ 2 \end{pmatrix} \quad (9.2.15.7)$$

From Fig. 9.2.15.1, the area of the parabola between the lines  $y = 2$  and  $y = 4$  is given by

$$\int_0^4 2\sqrt{y} dy - \int_0^2 2\sqrt{y} dy = 6.895 \quad (9.2.15.8)$$

9.2.16 Find the area enclosed by the parabola  $4y = 3x^2$  and the line  $2y = 3x + 12$ .

**Solution:**

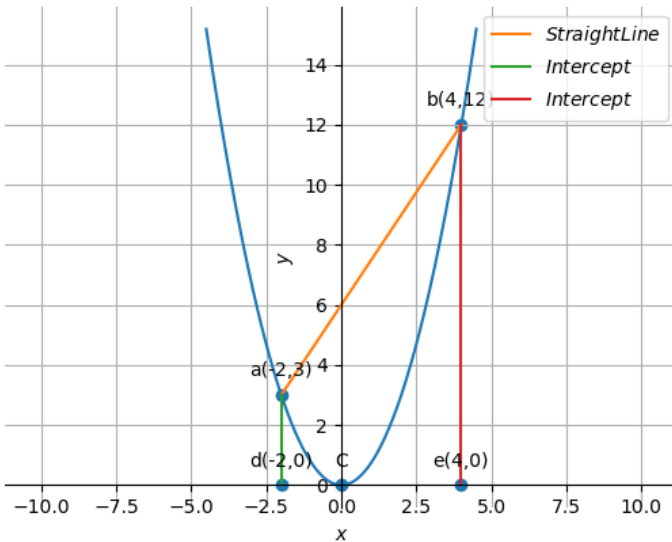


Fig. 9.2.16.1

The parameters of the given conic are

$$\mathbf{V} = \begin{pmatrix} 3 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0. \quad (9.2.16.1)$$

For the line, the parameters are

$$\mathbf{h} = \begin{pmatrix} -2 \\ 3 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} 2 \\ 3 \end{pmatrix} \quad (9.2.16.2)$$

yielding

$$\kappa = -2.5, 2.7 \quad (9.2.16.3)$$

upon substitution in (9.1.1.3) resulting in the points of intersection

$$\mathbf{A} = \begin{pmatrix} -2 \\ 3 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 4 \\ 12 \end{pmatrix}. \quad (9.2.16.4)$$

From Fig. 9.2.16.1, the desired area is

$$\int_{-2}^4 \frac{3x+12}{2} dx - \int_{-2}^4 \frac{3x^2}{4} dx = 27 \quad (9.2.16.5)$$

9.2.17 Find the area of the smaller region bounded by the ellipse  $\frac{x^2}{9} + \frac{y^2}{4} = 1$  and the line  $\frac{x}{3} + \frac{y}{2} = 1$ .

**Solution:**

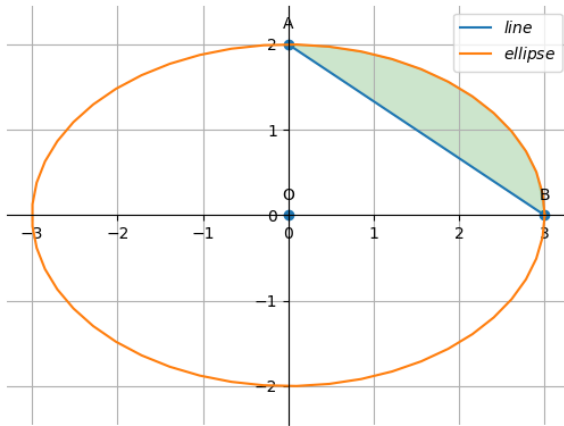


Fig. 9.2.17.1

The given ellipse can be expressed as conics with parameters

$$\mathbf{V} = \begin{pmatrix} b^2 & 0 \\ 0 & a^2 \end{pmatrix}, \mathbf{u} = 0, f = -(a^2 b^2). \quad (9.2.17.1)$$

The line parameters are

$$\mathbf{h} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} \frac{1}{b} \\ -\frac{1}{a} \end{pmatrix}. \quad (9.2.17.2)$$

Substituting the given parameters in (9.1.1.3),

$$\mu = 0, -6 \quad (9.2.17.3)$$

yielding the points of intersection

$$\mathbf{A} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 0 \\ b \end{pmatrix}. \quad (9.2.17.4)$$

From Fig. 9.2.17.1, the desired area is

$$\int_0^a \frac{b}{a} \sqrt{a^2 - x^2} dx - \int_0^a \frac{b}{a} (a - x) dx = \frac{ab}{2} \left( \frac{\pi}{2} - 1 \right) = 3 \left( \frac{\pi}{2} - 1 \right) \quad (9.2.17.5)$$

upon substituting  $a = 3, b = 2$ .

9.2.18 Find the area of the region bounded by the curve  $x^2 = y$  and the lines  $y = x + 2$  and the  $x$  axis.

9.2.19 Find the area bounded by the curve  $y = x|x|$ ,  $x$ -axis and the ordinates  $x = -1$  and  $x = 1$ .

9.2.20 Find the area of the region bounded by the curves  $y = x^2 + 2$ ,  $y = x$ ,  $x = 0$  and  $x = 3$ .

9.2.21 Find the smaller area enclosed by the circle  $x^2 + y^2 = 4$  and the line  $x + y = 2$ .

**Solution:**

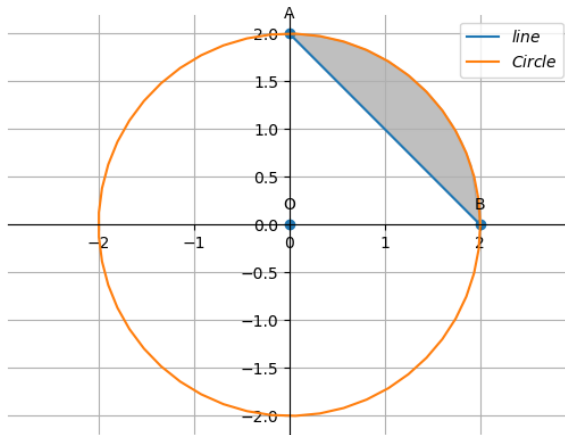


Fig. 9.2.21.1

The given circle can be expressed as conics with parameters,

$$\mathbf{V} = \begin{pmatrix} 4 & 0 \\ 0 & 4 \end{pmatrix}, \mathbf{u} = 0, f = -16 \quad (9.2.21.1)$$

The line parameters are

$$\mathbf{h} = \begin{pmatrix} 2 \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} \frac{1}{2} \\ -1 \end{pmatrix} \quad (9.2.21.2)$$

Substituting the parameters in (9.1.1.3),

$$\kappa = 0, -4 \quad (9.2.21.3)$$

yielding the points of intersection as

$$\mathbf{A} = \begin{pmatrix} 0 \\ 2 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 2 \\ 0 \end{pmatrix} \quad (9.2.21.4)$$

From Fig. 9.2.21.1, the desired area is

$$\int_0^2 \sqrt{4-x^2} dx - \int_0^2 (2-x) dx = \pi - 2 \quad (9.2.21.5)$$

- 9.2.22 Find the area of the region bounded by the curves  $y^2 = 9x$ ,  $y = 3x$ .
- 9.2.23 Find the area of the region bounded by the parabola  $y^2 = 2px$ ,  $x^2 = 2py$ .
- 9.2.24 Find the area of the region bounded by the curve  $y = x^2$  and  $y = x + 6$  and  $x = 0$ .
- 9.2.25 Find the area of the region bounded by the curve  $y^2 = 4x$ ,  $x^2 = 4y$ .
- 9.2.26 Find the area of the region included between  $y^2 = 9x$  and  $y = x$ .
- 9.2.27 Find the area of the region enclosed by the parabola  $x^2 = y$  and the line  $y = x + 2$ .
- 9.2.28 Find the area of region bounded by the line  $x = 2$  and the parabola  $y^2 = 8x$ .
- 9.2.29 Sketch the region  $(x, 0) : y = \sqrt{4-x^2}$  and  $x$ -axis. Find the area of the region using integration.
- 9.2.30 Calculate the area under the curve  $y = 2\sqrt{x}$  included between the lines  $x = 0$  and  $x = 1$ .
- 9.2.31 Using integration, find the area of the region bounded by the line  $2y = 5x + 7$ ,  $x$ -axis and the lines  $x = 2$  and  $x = 8$ .
- 9.2.32 Draw a rough sketch of the curve  $y = \sqrt{x-1}$  in the interval  $[1, 5]$ . Find the area under the curve and between the lines  $x = 1$  and  $x = 5$ .
- 9.2.33 Determine the area under the curve  $y = \sqrt{a^2 - x^2}$  included between the lines  $x = 0$  and  $x = a$ .
- 9.2.34 Find the area of the region bounded by  $y = \sqrt{x}$  and  $y = x$ .
- 9.2.35 Find the area enclosed by the curve  $y = -x^2$  and the straight line  $x + y + 2 = 0$ .
- 9.2.36 Find the area bounded by the curve  $y = \sqrt{x}$ ,  $x = 2y + 3$  in the first quadrant and  $x$ -axis.
- 9.2.37 Draw a rough sketch of the region  $(x, y) : y^2 \leq 6ax$  and  $x^2 + y^2 \leq 16a^2$ .
- 9.2.38 Draw a rough sketch of the given curve  $y = 1 + |x + 1|$ ,  $x = -3$ ,  $x = 3$ ,  $y = 0$ , and find the area of the region bounded by them, using integration.
- 9.2.39 The area of the region bounded by the curve  $x^2 = 4y$  and the straight line  $x = 4y - 2$  is
- $\frac{3}{8}$  sq units
  - $\frac{5}{8}$  sq units
  - $\frac{7}{8}$  sq units

d)  $\frac{9}{8}$  sq units

9.2.40 The area of the region bounded by the curve  $y = \sqrt{16 - x^2}$  and  $x$ -axis is

- a) 8 sq units
- b)  $20\pi$  sq units
- c)  $16\pi$  sq units
- d)  $256\pi$  sq units

9.2.41 Area of the region in the first quadrant enclosed by the  $x$ -axis, the line  $y = x$  and the circle  $x^2 + y^2 = 32$  is

- a)  $16\pi$  sq units
- b)  $4\pi$  sq units
- c)  $32\pi$  sq units
- d)  $24\pi$  sq units

9.2.42 The area of the region bounded by parabola  $y^2 = x$  and the straight line  $2y = x$  is

- a)  $\frac{4}{3}$  sq units
- b) 1 sq units
- c)  $\frac{2}{3}$  sq units
- d)  $\frac{1}{3}$  sq units

9.2.43 Find the equation of a circle whose centre is (3,1) and which cuts off a chord of length 6 units on the line  $2x - 5y + 18 = 0$ .

### 9.3 Curves

9.3.1 Find the area bounded by the curves  $(x - 1)^2 + y^2 = 1$  and  $x^2 + y^2 = 1$ .

**Solution:** The conic parameters for the two circles can be expressed as

$$\begin{aligned} \mathbf{V}_1 &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u}_1 = \begin{pmatrix} -1 \\ 0 \end{pmatrix}, f_1 = 0, \\ \mathbf{V}_2 &= \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u}_2 = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, f_2 = -1. \end{aligned} \quad (9.3.1.1)$$

On substituting from (9.3.1.1) in (9.1.4.1), we obtain

$$\begin{vmatrix} 1 + \mu & 0 & -1 \\ 0 & 1 + \mu & 0 \\ -1 & 0 & -\mu \end{vmatrix} = 0 \quad (9.3.1.2)$$

yielding

$$\Rightarrow \mu = -1. \quad (9.3.1.3)$$

Substituting (9.3.1.1) in (9.1.3.1), we obtain

$$\mathbf{x}^\top \begin{pmatrix} 0 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{x} + 2 \begin{pmatrix} -1 & 0 \end{pmatrix} \mathbf{x} + 1 = 0 \quad (9.3.1.4)$$

$$\Rightarrow \begin{pmatrix} -2 & 0 \end{pmatrix} \mathbf{x} = -1 \quad (9.3.1.5)$$



Therefore the intersection of the two circles is a line with parameters

$$\mathbf{m} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \mathbf{h} = \begin{pmatrix} \frac{1}{2} \\ 0 \end{pmatrix}. \quad (9.3.1.6)$$

The intersection parameters of the chord in (9.3.1.5) with the first circle in (9.3.1.1) is obtained from (9.1.1.3) as

$$\kappa_i = \pm \frac{\sqrt{3}}{2} \quad (9.3.1.7)$$

Hence the point of intersection are obtained from (9.1.1.2) as

$$\mathbf{a}_0 = \begin{pmatrix} \frac{1}{2} \\ \frac{\sqrt{3}}{2} \end{pmatrix}, \mathbf{a}_2 = \begin{pmatrix} \frac{1}{2} \\ -\frac{\sqrt{3}}{2} \end{pmatrix}. \quad (9.3.1.8)$$

The desired area of region is given as

$$\begin{aligned} & 2 \left( \int_0^{\frac{1}{2}} \sqrt{1 - (x-1)^2} dx + \int_{\frac{1}{2}}^1 \sqrt{1 - x^2} dx \right) \\ &= 2 \left[ \frac{1}{2} (x-1) \sqrt{1 - (x-1)^2} + \frac{1}{2} \sin^{-1} (x-1) \right]_0^{\frac{1}{2}} \\ &\quad + 2 \left[ \frac{x}{2} \sqrt{1 - x^2} + \frac{1}{2} \sin^{-1} x \right]_{\frac{1}{2}}^1 \\ &= \frac{2\pi}{3} - \frac{\sqrt{3}}{2} \quad (9.3.1.9) \end{aligned}$$

See Fig. 9.3.1.1.

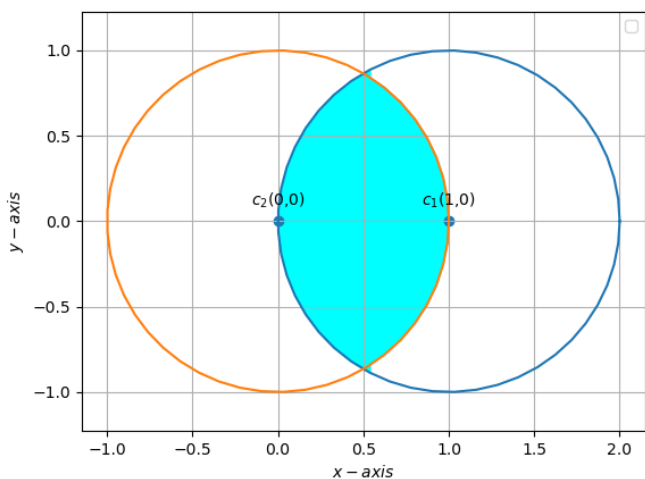


Fig. 9.3.1.1

9.3.2 Find the area of the circle  $4x^2 + 4y^2 = 9$  which is interior to the parabola  $x^2 = 4y$ .

9.3.3 Find the area of the circle  $x^2 + y^2 = 16$  exterior to the parabola  $y^2 = 6x$ .

9.3.4 Find the area of the region bounded by the curve  $y^2 = 2x$  and  $x^2 + y^2 = 4x$ .

## 10 TANGENT AND NORMAL

## 10.1 Formulae

10.1.1 If  $L$  in (9.1.1.1) touches (8.1.1.1) at exactly one point  $\mathbf{q}$ ,

$$\mathbf{m}^\top (\mathbf{V}\mathbf{q} + \mathbf{u}) = 0 \quad (10.1.1.1)$$

10.1.2 Given the point of contact  $\mathbf{q}$ , the equation of a tangent to (8.1.1.1) is

$$(\mathbf{V}\mathbf{q} + \mathbf{u})^\top \mathbf{x} + \mathbf{u}^\top \mathbf{q} + f = 0 \quad (10.1.2.1)$$

10.1.3 Given the point of contact  $\mathbf{q}$ , the equation of the normal to (8.1.1.1) is

$$(\mathbf{V}\mathbf{q} + \mathbf{u})^\top \mathbf{R}(\mathbf{x} - \mathbf{q}) = 0 \quad (10.1.3.1)$$

10.1.4 If  $\mathbf{V}^{-1}$  exists, given the normal vector  $\mathbf{n}$ , the tangent points of contact to (8.1.1.1) are given by

$$\begin{aligned} \mathbf{q}_i &= \mathbf{V}^{-1}(\kappa_i \mathbf{n} - \mathbf{u}), i = 1, 2 \\ \text{where } \kappa_i &= \pm \sqrt{\frac{f_0}{\mathbf{n}^\top \mathbf{V}^{-1} \mathbf{n}}} \end{aligned} \quad (10.1.4.1)$$

10.1.5 If  $\mathbf{V}$  is not invertible, given the normal vector  $\mathbf{n}$ , the point of contact to (8.1.1.1) is given by the matrix equation

$$\begin{pmatrix} \mathbf{u} + \kappa \mathbf{n} \\ \mathbf{V} \end{pmatrix}^\top \mathbf{q} = \begin{pmatrix} -f \\ \kappa \mathbf{n} - \mathbf{u} \end{pmatrix} \quad (10.1.5.1)$$

$$\text{where } \kappa = \frac{\mathbf{p}_1^\top \mathbf{u}}{\mathbf{p}_1^\top \mathbf{n}}, \quad \mathbf{V} \mathbf{p}_1 = 0 \quad (10.1.5.2)$$

10.1.6 For a conic/hyperbola, a line with normal vector  $\mathbf{n}$  cannot be a tangent if

$$\frac{\mathbf{u}^\top \mathbf{V}^{-1} \mathbf{u} - f}{\mathbf{n}^\top \mathbf{V}^{-1} \mathbf{n}} < 0 \quad (10.1.6.1)$$

10.1.7 For a circle, the points of contact are

$$\mathbf{q}_{ij} = \left( \pm r \frac{\mathbf{n}_j}{\|\mathbf{n}_j\|} - \mathbf{u} \right), \quad i, j = 1, 2 \quad (10.1.7.1)$$

10.1.8 A point  $\mathbf{h}$  lies on a normal to the conic in (8.1.1.1) if

$$\begin{aligned} &(\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}))^2 (\mathbf{n}^\top \mathbf{V}\mathbf{n}) \\ &\quad - 2(\mathbf{m}^\top \mathbf{V}\mathbf{n})(\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})\mathbf{n}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})) \\ &\quad + g(\mathbf{h})(\mathbf{m}^\top \mathbf{V}\mathbf{n})^2 = 0 \end{aligned} \quad (10.1.8.1)$$

10.1.9 A point  $\mathbf{h}$  lies on a tangent to the conic in (8.1.1.1) if

$$\mathbf{m}^\top [(\mathbf{V}\mathbf{h} + \mathbf{u})(\mathbf{V}\mathbf{h} + \mathbf{u})^\top - \mathbf{V}g(\mathbf{h})] \mathbf{m} = 0 \quad (10.1.9.1)$$

## 10.2 Circle

10.1 Find the points on the curve  $x^2 + y^2 - 2x - 3 = 0$  at which the tangents are parallel to the x-axis.

**Solution:** Given that

$$\mathbf{u} = \begin{pmatrix} -1 \\ 0 \end{pmatrix}, f = -3 \quad (10.1.1)$$

Hence, the centre and radius are given as

$$\mathbf{c} = -\mathbf{u} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, r = \sqrt{\|\mathbf{u}\|^2 - f} = 2 \quad (10.1.2)$$

From (10.1.7.1), the points of contact for the tangent are given by

$$\mathbf{q}_{ij} = \left( \pm r \frac{\mathbf{n}_j}{\|\mathbf{n}_j\|} - \mathbf{u} \right) \text{ i,j} = 1, 2 \quad (10.1.3)$$

Since, tangents are parallel to the x-axis, the normal is given as

$$\mathbf{n} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (10.1.4)$$

Substituting in (10.1.3) we get

$$\mathbf{q}_{11} = \left( \pm 2 \begin{pmatrix} 0 \\ 1 \end{pmatrix} - \begin{pmatrix} -1 \\ 0 \end{pmatrix} \right) \quad (10.1.5)$$

$$= \begin{pmatrix} 1 \\ -2 \end{pmatrix}, \begin{pmatrix} 1 \\ 2 \end{pmatrix} \quad (10.1.6)$$

Hence, the two points of contact are

$$\begin{pmatrix} 1 \\ 2 \end{pmatrix} \text{ and } \begin{pmatrix} 1 \\ -2 \end{pmatrix} \quad (10.1.7)$$

See Fig. 10.1.1.

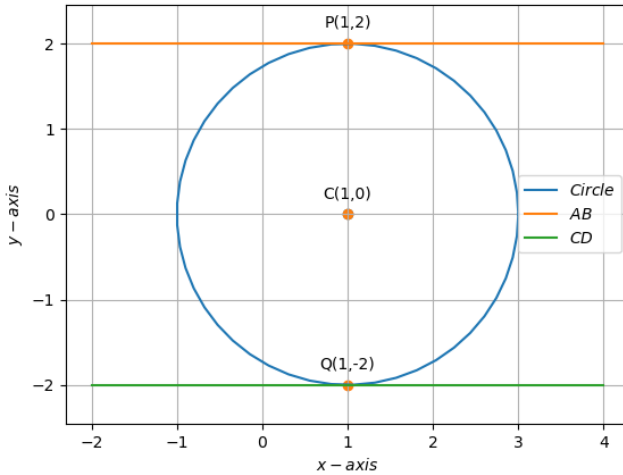


Fig. 10.1.1

- 10.2 Find the equation of a circle of radius 5 which is touching another circle  $x^2 + y^2 - 2x - 4y - 20 = 0$  at (5,5).
- 10.3 The equation of the circle having centre at (3,-4) and touching the line  $5x + 12y - 12 = 0$  is \_\_\_\_\_
- 10.4 Find the equation of the circle which touches both the axes in first quadrant and whose radius is  $a$ .
- 10.5 Find the equation of the circle which touches x-axis and whose centre is (1,2)
- 10.6 If the lines  $3x - 4y + 4 = 0$  and  $6x - 8y - 7 = 0$  are tangents to a circle, then find the radius of the circle.
- 10.7 Find the equation of a circle which touches both the axes and the line  $3x - 4y + 8 = 0$  and lies in the third quadrant.
- 10.8 At what points on the curve  $x^2 + y^2 - 2x - 4y + 1 = 0$ , the tangents are parallel to the y-axis?
- 10.9 The shortest distance from the point (2,7) to the circle  $x^2 + y^2 - 14x - 10y - 151 = 0$  is equal to 5.
- 10.10 If the line  $lx + my = 1$  is a tangent to the circle  $x^2 + y^2 = a^2$ , then the point (1,  $m$ ) lies on a circle.

### 10.3 Conic

- 10.3.1 Find the slope of the tangent to the curve  $y = \frac{x-1}{x-2}$ ,  $x \neq 2$  at  $x = 10$ .

**Solution:** The given equation of the curve can be rearranged as

$$xy - x - 2y + 1 = 0 \quad (10.3.1.1)$$

$$\Rightarrow \mathbf{x}^T \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix} \mathbf{x} + \begin{pmatrix} -1 & -2 \end{pmatrix} \mathbf{x} + 1 = 0 \quad (10.3.1.2)$$

Thus,

$$\mathbf{V} = \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix} \quad (10.3.1.3)$$

$$\mathbf{u} = -\begin{pmatrix} \frac{1}{2} \\ 1 \end{pmatrix} \quad (10.3.1.4)$$

$$f = 1 \quad (10.3.1.5)$$

$\therefore q_1 = 10$ , the point of contact can be obtained as

$$\mathbf{q} = \begin{pmatrix} q_1 \\ q_2 \end{pmatrix} = \begin{pmatrix} 10 \\ \frac{9}{8} \end{pmatrix} \quad (10.3.1.6)$$

From (10.1.1.1), the normal vector of the tangent to (10.3.1.2) is

$$\mathbf{n} = \begin{pmatrix} 1 \\ 64 \end{pmatrix} \Rightarrow \mathbf{m} = \begin{pmatrix} 1 \\ -\frac{1}{64} \end{pmatrix} \quad (10.3.1.7)$$

The eigenvector matrix

$$(\mathbf{p}_1 \quad \mathbf{p}_2) = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad (10.3.1.8)$$

which implies that the conic is a  $45^\circ$  rotated hyperbola. See Fig. 10.3.1.1.

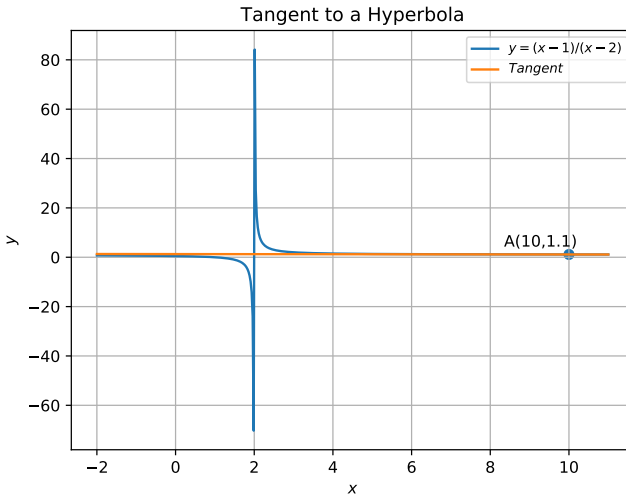


Fig. 10.3.1.1

10.3.2 Find a point on the curve

$$y = (x-2)^2 \quad (10.3.2.1)$$

at which a tangent is parallel to the chord joining the points (2,0) and (4,4).

**Solution:**

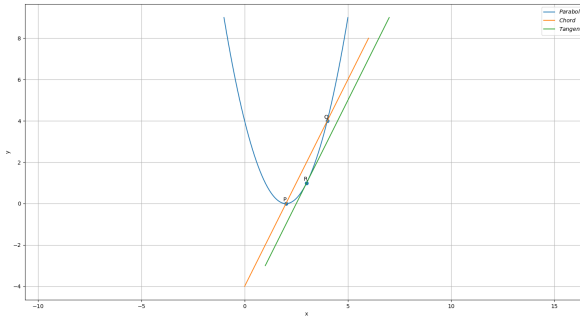


Fig. 10.3.2.1

The equation of the conic can be represented as

$$\mathbf{x}^T \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{x} + 2 \begin{pmatrix} -2 & -\frac{1}{2} \end{pmatrix} \mathbf{x} + 4 = 0 \quad (10.3.2.2)$$

So,

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u}^T = \begin{pmatrix} -2 & -\frac{1}{2} \end{pmatrix}, f = 4 \quad (10.3.2.3)$$

The direction vector of the line passing through (2,0) and (4,4) is

$$\mathbf{m} = \begin{pmatrix} 1 \\ 2 \end{pmatrix} \Rightarrow \mathbf{n} = \begin{pmatrix} 2 \\ -1 \end{pmatrix}. \quad (10.3.2.4)$$

The eigenvector corresponding to the zero eigenvalue is

$$\mathbf{p}_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad (10.3.2.5)$$

In (10.1.5.1),

$$\kappa = \frac{\begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} -2 \\ -\frac{1}{2} \end{pmatrix}}{\begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} 2 \\ -1 \end{pmatrix}} = \frac{1}{2} \quad (10.3.2.6)$$

Substituting  $\kappa$ , from (10.1.5.1),

$$\left( \left[ \begin{pmatrix} -2 \\ \frac{-1}{2} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 2 \\ -1 \end{pmatrix} \right]^T \right) \mathbf{q} = \begin{pmatrix} -4 \\ \frac{1}{2} \begin{pmatrix} 2 \\ -1 \end{pmatrix} - \begin{pmatrix} -2 \\ \frac{-1}{2} \end{pmatrix} \end{pmatrix} \quad (10.3.2.7)$$

$$\Rightarrow \begin{pmatrix} -1 & -1 \\ 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{q} = \begin{pmatrix} -4 \\ 3 \\ 0 \end{pmatrix} \quad (10.3.2.8)$$

yielding

$$\begin{pmatrix} -1 & -1 \\ 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{q} = \begin{pmatrix} -4 \\ 3 \\ 3 \end{pmatrix} \quad (10.3.2.9)$$

The augmented matrix is

$$\begin{aligned} & \begin{pmatrix} -1 & -1 & | & -4 \\ 1 & 0 & | & 3 \end{pmatrix} \xleftrightarrow{R_1 \leftarrow R_1 + 2R_2} \begin{pmatrix} 1 & -1 & | & 2 \\ 1 & 0 & | & 3 \end{pmatrix} \\ & \xleftrightarrow{R_2 \leftarrow R_2 - R_1} \begin{pmatrix} 1 & -1 & | & 2 \\ 0 & 1 & | & 1 \end{pmatrix} \xleftrightarrow{R_1 \leftarrow R_1 + R_2} \begin{pmatrix} 1 & 0 & | & 3 \\ 0 & 1 & | & 1 \end{pmatrix} \\ & \Rightarrow \mathbf{q} = \begin{pmatrix} 3 \\ 1 \end{pmatrix} \end{aligned}$$

which is the desired point of contact. See Fig. 10.3.2.1.

10.3.3 Find the equation of all lines having slope -1 that are tangents to the curve

$$y = \frac{1}{x-1}, x \neq 1 \quad (10.3.3.1)$$

**Solution:**



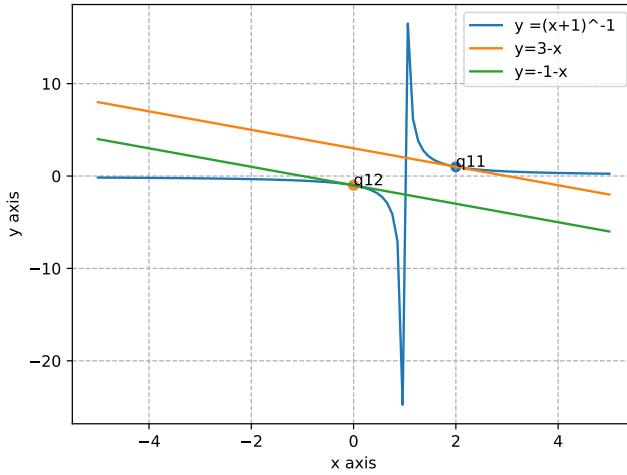


Fig. 10.3.3.1

From the given information,

$$\mathbf{V} = \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -\frac{1}{2} \end{pmatrix}, f = -1, m = -1 \quad (10.3.3.2)$$

From the above, the normal vector is

$$\mathbf{n} = \begin{pmatrix} -m \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (10.3.3.3)$$

From (10.1.4.1), the point(s) of contact are given by

$$\mathbf{q} = \mathbf{V}^{-1}(k_i \mathbf{n} - \mathbf{u}) \text{ where,} \quad (10.3.3.4)$$

$$k_i = \pm \sqrt{\frac{f_0}{\mathbf{n}^\top \mathbf{V}^{-1} \mathbf{n}}} \quad (10.3.3.5)$$

$$f_0 = f + \mathbf{u}^\top \mathbf{V}^{-1} \mathbf{u} \quad (10.3.3.6)$$

Substituting from (10.3.3.3) and (10.3.3.2) in the above,

$$\mathbf{q} = \begin{pmatrix} 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \end{pmatrix}. \quad (10.3.3.7)$$

From (10.1.2.1), the equations of tangents are given by

$$(\mathbf{V} \mathbf{q} + \mathbf{u})^\top \mathbf{x} + \mathbf{u}^\top \mathbf{q} + f = 0 \quad (10.3.3.8)$$

yielding

$$\begin{pmatrix} 1 & -1 \end{pmatrix} \mathbf{x} + 1 = 0 \quad (10.3.3.9)$$

$$\begin{pmatrix} 1 & -1 \end{pmatrix} \mathbf{x} - 3 = 0 \quad (10.3.3.10)$$

$$(10.3.3.11)$$

See Fig. 10.3.3.1.

10.3.4 Find the equation of all lines having slope 2 which are tangents to the curve

$$y = \frac{1}{x-3}, x \neq 3 \quad (10.3.4.1)$$

**Solution:**

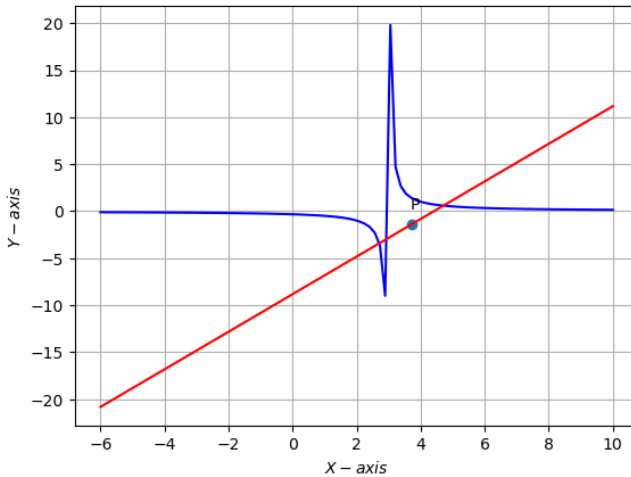


Fig. 10.3.4.1

From the given information

$$\mathbf{V} = \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -\frac{3}{2} \end{pmatrix}, f = -1, m = 2 \quad (10.3.4.2)$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} -m \\ 1 \end{pmatrix} = \begin{pmatrix} -2 \\ 1 \end{pmatrix} \quad (10.3.4.3)$$

$$(10.3.4.4)$$

Hence, the given curve is a hyperbola. Substituting numerical values, we obtain the condition in (10.1.6), which implies that the line with slope 2 is not a tangent. This can be verified from Fig. 10.3.4.1.

10.3.5 Find points on the curve  $\frac{x^2}{9} + \frac{y^2}{16} = 1$  at which the tangents are

a) parallel to x-axis

b) parallel to y-axis

**Solution:**

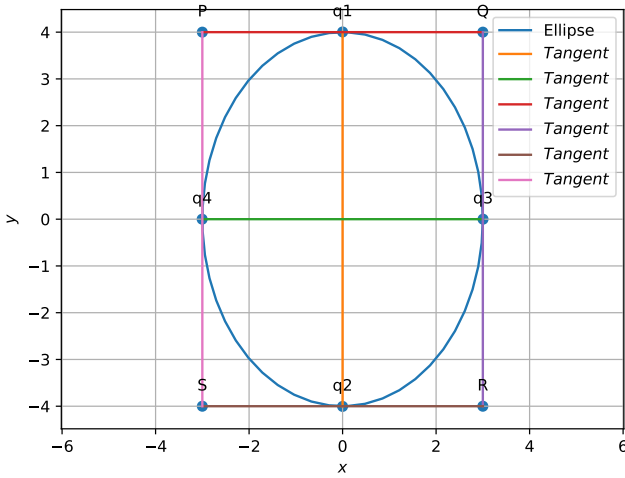


Fig. 10.3.5.1

The parameters of the given conic are

$$\lambda_1 = 16, \lambda_2 = 9 \quad (10.3.5.1)$$

$$\mathbf{V} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, f = -144 \quad (10.3.5.2)$$

a) The normal vector in this case is

$$\mathbf{n}_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (10.3.5.3)$$

which can be used along with the parameters in (10.3.5.2) to obtain

$$\mathbf{q}_1 = \begin{pmatrix} 0 \\ 4 \end{pmatrix}, \mathbf{q}_2 = \begin{pmatrix} 0 \\ -4 \end{pmatrix} \quad (10.3.5.4)$$

using (10.1.4.1).

b) Similarly, choosing

$$\mathbf{n}_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad (10.3.5.5)$$

$$\mathbf{q}_3 = \begin{pmatrix} 3 \\ 0 \end{pmatrix}, \mathbf{q}_4 = \begin{pmatrix} -3 \\ 0 \end{pmatrix} \quad (10.3.5.6)$$

See Fig. 10.3.5.1.

10.3.6 Find the equation of the tangent line to the curve

$$y = x^2 - 2x + 7 \quad (10.3.6.1)$$

- a) parallel to the line  $2x - y + 9 = 0$ .  
 b) perpendicular to the line  $5y - 15x = 13$ .

**Solution:**

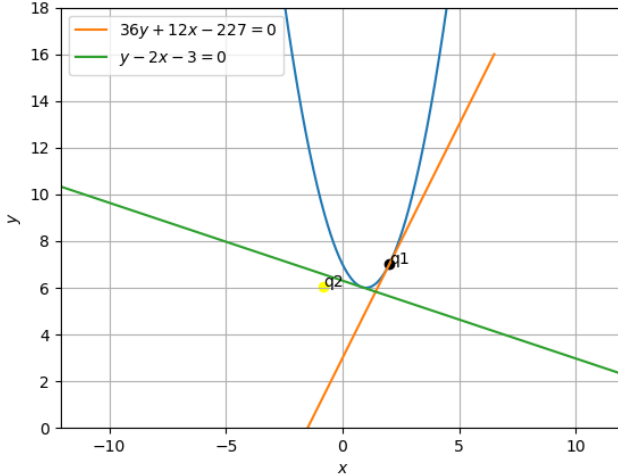


Fig. 10.3.6.1

The parameters of the given conic are

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = -\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix}, f = 7 \quad (10.3.6.2)$$

- a) In this case, the normal vector

$$\mathbf{n}_1 = \begin{pmatrix} 2 \\ -1 \end{pmatrix} \quad (10.3.6.3)$$

Since  $\mathbf{V}$  is not invertible, the point of contact is given by (10.1.5.1) resulting in

$$\begin{pmatrix} \begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 2 \\ -1 \end{pmatrix} \\ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \mathbf{q}_1 = \begin{pmatrix} -7 \\ \frac{1}{2} \begin{pmatrix} 2 \\ -1 \end{pmatrix} - \begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} \end{pmatrix} \quad (10.3.6.4)$$

By solving the above equation, we can get the point of contact as

$$\mathbf{q}_1 = \begin{pmatrix} 2 \\ 7 \end{pmatrix} \quad (10.3.6.5)$$

The tangent equation is then obtained as

$$\mathbf{n}_1^\top (\mathbf{x} - \mathbf{q}_1) = 0 \quad (10.3.6.6)$$

$$\Rightarrow \begin{pmatrix} 2 & -1 \end{pmatrix} \mathbf{x} + 3 = 0 \quad (10.3.6.7)$$

b) In this case,

$$\mathbf{n}_2 = \begin{pmatrix} 1 \\ 3 \end{pmatrix} \quad (10.3.6.8)$$

resulting in

$$\left( \begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} + -\frac{1}{6} \begin{pmatrix} 1 \\ 3 \end{pmatrix}^\top \right) \mathbf{q}_2 = \begin{pmatrix} -7 \\ -\frac{1}{6} \begin{pmatrix} 1 \\ 3 \end{pmatrix} - \begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} \end{pmatrix} \quad (10.3.6.9)$$

$$\text{or, } \mathbf{q}_2 = \begin{pmatrix} \frac{5}{6} \\ \frac{217}{36} \end{pmatrix} \quad (10.3.6.10)$$

The tangent equation is

$$\mathbf{n}_2^\top (\mathbf{x} - \mathbf{q}_2) = 0 \quad (10.3.6.11)$$

$$\text{or, } \begin{pmatrix} 1 & 3 \end{pmatrix} \mathbf{x} = \frac{227}{12} \quad (10.3.6.12)$$

See Fig. 10.3.6.1.

10.3.7 Find the equation of the tangent to the curve

$$y = \sqrt{3x - 2} \quad (10.3.7.1)$$

which is parallel to the line

$$4x - 2y + 5 = 0 \quad (10.3.7.2)$$

**Solution:** The parameters for the given conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \quad (10.3.7.3)$$

$$\mathbf{u} = \begin{pmatrix} -3/2 \\ 0 \end{pmatrix}, \quad (10.3.7.4)$$

$$f = 2 \quad (10.3.7.5)$$

which represent a parabola. Following the approach in Problem 10.3.6,

$$\mathbf{p}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \quad \mathbf{n} = \begin{pmatrix} -2 \\ 1 \end{pmatrix}, \quad (10.3.7.6)$$

yielding the matrix equation

$$\begin{pmatrix} -3 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{q} = \begin{pmatrix} -41/16 \\ 0 \\ 3/4 \end{pmatrix} \quad (10.3.7.7)$$

$$(10.3.7.8)$$

The augmented matrix for (10.3.7.7) can be expressed as

$$\begin{aligned} \xleftrightarrow{R_2 \leftrightarrow R_3} \left( \begin{array}{cc|c} -3 & 0 & -41/16 \\ 0 & 1 & 0 \\ 0 & 0 & 3/4 \end{array} \right) & \xleftrightarrow{-R_1 \leftarrow R_2} \left( \begin{array}{cc|c} 1 & 0 & 41/48 \\ 0 & 1 & 0 \\ 0 & 0 & 3/4 \end{array} \right) \\ & \Rightarrow \mathbf{q} = \begin{pmatrix} \frac{41}{48} \\ \frac{3}{4} \end{pmatrix} \end{aligned}$$

The equation of tangent is then obtained as

$$(-2 \quad 1)\mathbf{x} + \frac{23}{24} = 0 \quad (10.3.7.9)$$

See Fig. 10.3.7.1.

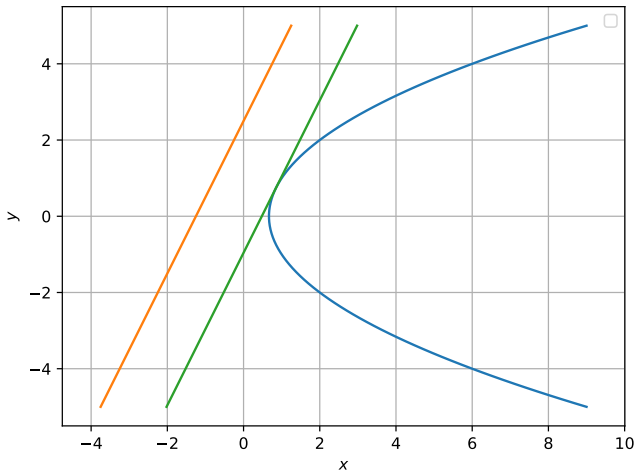


Fig. 10.3.7.1

10.3.8 Find the point at which the line  $y = x + 1$  is a tangent to the curve  $y^2 = 4x$ .

**Solution:**

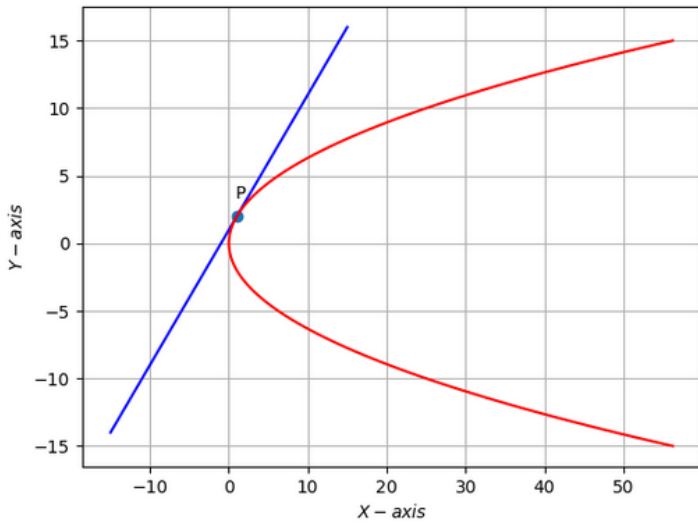


Fig. 10.3.8.1

The parameters of the conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} -2 & 0 \end{pmatrix}, f = 0 \quad (10.3.8.1)$$

Following the approach in Problem 10.3.6, since

$$\mathbf{n} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (10.3.8.2)$$

we obtain

$$\mathbf{q} = \begin{pmatrix} 1 \\ 2 \end{pmatrix} \quad (10.3.8.3)$$

See Fig. 10.3.8.1.

10.3.9 The point on the curve

$$x^2 = 2y \quad (10.3.9.1)$$

which is nearest to the point  $\mathbf{P} = \begin{pmatrix} 0 \\ 5 \end{pmatrix}$  is

- a)  $\begin{pmatrix} 2\sqrt{2} \\ 4 \end{pmatrix}$
- b)  $\begin{pmatrix} 2\sqrt{2} \\ 0 \end{pmatrix}$
- c)  $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$

d)  $\begin{pmatrix} 2 \\ 2 \end{pmatrix}$

**Solution:** We rewrite the conic (10.3.9.1) in matrix form.

$$\mathbf{x}^\top \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{x} + 2 \begin{pmatrix} 0 & -1 \end{pmatrix} \mathbf{x} = 0 \quad (10.3.9.2)$$

Comparing with the general equation of the conic,

$$\mathbf{V}_0 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad \mathbf{u}_0 = \begin{pmatrix} 0 \\ -1 \end{pmatrix}, \quad f_0 = 0 \quad (10.3.9.3)$$

Therefore, the equation of the normal where  $\mathbf{q}$  is the point of contact and

$$\mathbf{R} \triangleq \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} \quad (10.3.9.4)$$

is

$$(\mathbf{V}_0 \mathbf{q} + \mathbf{u}_0)^\top \mathbf{R} \begin{pmatrix} 0 \\ 5 \end{pmatrix} - \mathbf{q} = 0 \quad (10.3.9.5)$$

Substituting appropriate values and simplifying, we get

$$\mathbf{q}^\top \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \mathbf{q} + 2 \begin{pmatrix} -2 & 0 \end{pmatrix} \mathbf{q} = 0 \quad (10.3.9.6)$$

which can be expressed as

$$\begin{aligned} \frac{1}{2} \left\{ \mathbf{q}^\top \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \mathbf{q} + 2 \begin{pmatrix} -2 & 0 \end{pmatrix} \mathbf{q} \right. \\ \left. + \mathbf{q}^\top \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}^\top \mathbf{q} + 2 \begin{pmatrix} -2 & 0 \end{pmatrix} \mathbf{q} \right\} = 0 \end{aligned} \quad (10.3.9.7)$$

yielding

$$\mathbf{q}^\top \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix} \mathbf{q} + 2 \begin{pmatrix} -2 & 0 \end{pmatrix} \mathbf{q} = 0 \quad (10.3.9.8)$$

(10.3.9.8) also looks like a conic with parameters

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \quad \mathbf{u} = \begin{pmatrix} 0 \\ -1 \end{pmatrix}, \quad f = 0 \quad (10.3.9.9)$$

The eigenparameters of  $\mathbf{V}$  are

$$\mathbf{P} = \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}, \quad \mathbf{D} = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \quad (10.3.9.10)$$



Applying the affine transformation

$$\mathbf{q} = \mathbf{P}\mathbf{y} + \mathbf{c} \quad (10.3.9.11)$$

$$\mathbf{c} = -\mathbf{V}^{-1}\mathbf{u} = \begin{pmatrix} 0 \\ 4 \end{pmatrix} \quad (10.3.9.12)$$

$$f_0 = \mathbf{u}^\top \mathbf{V}^{-1}\mathbf{u} - f = 0 \quad (10.3.9.13)$$

$\because \det V = -\frac{1}{4} \neq 0$ , using (B.4.9.1), (10.3.9.8) represents a pair of straight lines. From (B.4.8.2), (10.3.9.10), (A.8.3.4) and (A.8.3.7),

$$\mathbf{y} = \kappa \begin{pmatrix} 1 \\ \pm 1 \end{pmatrix}. \quad (10.3.9.14)$$

Hence, using (10.3.9.11),

$$\mathbf{q} = \begin{pmatrix} 0 \\ 4 \end{pmatrix} + \kappa \begin{pmatrix} 1 \\ \pm 1 \end{pmatrix}, \quad (10.3.9.15)$$

which, upon substituting in (10.3.9.2) and solving for  $\kappa$  yields

$$\kappa = \pm \sqrt{2}, -2. \quad (10.3.9.16)$$

Thus, the points of contact are

$$\mathbf{q} = \left\{ \begin{pmatrix} \pm 2\sqrt{2} \\ 4 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \end{pmatrix} \right\} \quad (10.3.9.17)$$

The nearest point out of these three candidates for  $\mathbf{q}$  is  $\begin{pmatrix} \pm 2\sqrt{2} \\ 4 \end{pmatrix}$ . See Fig. 10.3.9.1.

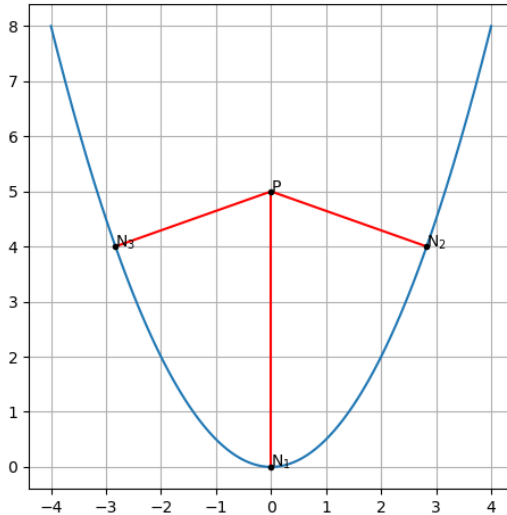


Fig. 10.3.9.1

10.3.10 Find the equation of the normal to curve  $x^2 = 4y$  which passes through the point (1, 2).

**Solution:**

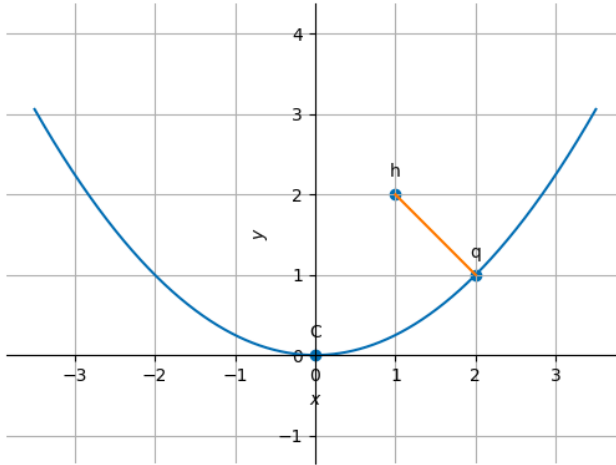


Fig. 10.3.10.1

The conic parameters are

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0 \quad (10.3.10.1)$$

Choosing the direction and normal vectors as

$$\mathbf{m} = \begin{pmatrix} 1 \\ m \end{pmatrix}, \mathbf{n} = \begin{pmatrix} -m \\ 1 \end{pmatrix}, \quad (10.3.10.2)$$

and substituting these values in (10.1.8.1), we obtain

$$m = 1 \quad (10.3.10.3)$$

as the only real solution. Thus,

$$\mathbf{m} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \quad (10.3.10.4)$$

and the equation of the normal is then obtained as

$$\mathbf{m}^T (\mathbf{x} - \mathbf{h}) = 0 \quad (10.3.10.5)$$

$$\Rightarrow \begin{pmatrix} 1 & 1 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 1 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ 2 \end{pmatrix} \quad (10.3.10.6)$$

$$= 3 \quad (10.3.10.7)$$

See Fig. 10.3.10.1.

10.3.11 The line  $y = mx + 1$  is a tangent to the curve  $y^2 = 4x$ , find the value of  $m$ .

**Solution:**

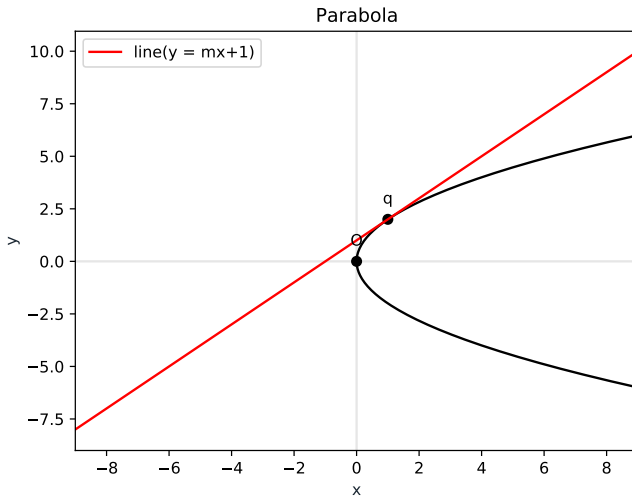


Fig. 10.3.11.1

The parameters for the given conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} -2 \\ 0 \end{pmatrix}, f = 0 \quad (10.3.11.1)$$

The given tangent can be expressed in parametric form as

$$\mathbf{x} = \mathbf{e}_2 + \mu \mathbf{m} \quad (10.3.11.2)$$

Substituting from (10.3.11.2) and (10.3.11.1) in (10.1.9.1) and solving, we obtain

$$m = 1. \quad (10.3.11.3)$$

See Fig. 10.3.11.1.

10.3.12 Find the normal at the point (1,1) on the curve

$$2y + x^2 = 3 \quad (10.3.12.1)$$

**Solution:** Use (10.1.1.1) with

$$\mathbf{m} = \begin{pmatrix} 1 \\ m \end{pmatrix} \quad (10.3.12.2)$$

10.3.13 If the line  $y = \sqrt{3}x + K$  touches the parabola  $x^2 = 16y$ , then find the value of  $K$ .

10.3.14 If the line  $y = mx + 1$  is tangent to the parabola  $y^2 = 4x$  then find the value of  $m$ .

10.3.15 Find the condition that the curves  $2x = y^2$  and  $2xy = k$  intersect orthogonally.

- 10.3.16 Prove that the curves  $xy = 4$  and  $x^2 + y^2 = 8$  touch each other.
- 10.3.17 Find the angle of intersection of the curves  $y = 4 - x^2$  and  $y = x^2$ .
- 10.3.18 Prove that the curves  $y^2 = 4x$  and  $x^2 + y^2 - 6x + 1 = 0$  touch each other at the point (1,2).
- 10.3.19 Find the equation of the normal lines to the curve  $3x^2 - y^2 = 8$  which are parallel to the line  $x + 3y = 4$ .
- 10.3.20 The equation of the normal to the curve  $3x^2 - y^2 = 8$  which is parallel to the line  $x + 3y = 8$  is
- $3x - y = 8$
  - $3x + y + 8 = 0$
  - $x + 3y + 8 = 0$
  - $x + 3y = 0$
- 10.3.21 The equation of the tangent to the curve  $(1 + y^2) = 2 - x$ , where it crosses the x-axis is
- $x + 5y = 2$
  - $x - 5y = 2$
  - $5x - y = 2$
  - $5x + y = 2$

State whether the statements are True or False

- 10.22 The line  $lx + my + n = 0$  will touch the parabola  $y^2 = 4ax$  if  $ln = am^2$ ,
- 10.23 The line  $2x + 3y = 12$  touches the ellipse  $\frac{x^2}{9} + \frac{y^2}{4} = 2$  at the point (3,2).

#### 10.4 Construction

- 10.4.1 Let  $ABC$  be a right triangle in which  $AB = 6\text{cm}$ ,  $BC = 8\text{cm}$  and  $\angle B = 90^\circ$ .  $BD$  is the perpendicular from  $B$  on  $AC$ . The circle through  $B, C, D$  is drawn. Construct the tangents from  $A$  to this circle.
- 10.4.2 Draw a line segment  $AB$  of length 8cm. Taking  $A$  as centre, draw a circle of radius 4cm and taking  $B$  as centre, draw another circle of radius 3cm. Construct tangents to each circle from the centre of the circle.
- 10.4.3 Draw a pair of tangents to a circle of radius 5 cm which are inclined to each other at an angle of  $60^\circ$ .
- 10.4.4 Draw a circle of radius 3 cm. Take two points  $P$  and  $Q$  on one of its extended diameter each at a distance of 7 cm from its centre. Draw tangents to the circle from these two points  $P$  and  $Q$ .
- 10.4.5 Construct a tangent to a circle of radius 4cm from a point on the concentric circle of radius 6cm and measure its length. Also verify the measurement by actual calculation.
- 10.4.6 From a point  $Q$ , the length of the tangent to a circle is 24cm and the distance of  $Q$  from the centre is 25cm. Find the radius of the circle. Draw the circle and the tangents.
- 10.4.7 To draw a pair of tangents to a circle which are inclined to each other at an angle of  $60^\circ$ , it is required to draw tangents at end points of those two radii of the circle, the angle between them should be

- a)  $135^\circ$
- b)  $90^\circ$
- c)  $60^\circ$
- d)  $120^\circ$

10.4.8 Draw two concentric circles of radii 3 cm and 5 cm. Taking a point on outer circle construct the pair of tangents to the other. Measure the length of a tangent and verify it by actual calculation.

10.4.9 Draw a circle of radius 4 cm. Construct a pair of tangents to it, the angle between which is  $60^\circ$ . Also justify the construction. Measure the distance between the centre of the circle and the point of intersection of tangents.

10.4.10 Construct a tangent to a circle of radius 4 cm from a point which is at a distance of 6 cm from its centre.

Write True or False and give reasons for your answer in each of the following

10.4.11 A pair of tangents can be constructed from a point **h** to a circle of radius 3.5 cm situated at a distance of 3 cm from the centre.

10.4.12 A pair of tangents can be constructed to a circle inclined at an angle of  $170^\circ$ .

## APPENDIX A

### TRIANGLE

Consider a triangle with vertices

$$\mathbf{A} = \begin{pmatrix} 1 \\ -1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} -4 \\ 6 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} -3 \\ -5 \end{pmatrix} \quad (12.1)$$

#### A.1 Sides

A.1.1. The direction vector of  $AB$  is defined as

$$\mathbf{B} - \mathbf{A} \quad (\text{A.1.1.1})$$

Find the direction vectors of  $AB$ ,  $BC$  and  $CA$ .

**Solution:**

a) The Direction vector of  $AB$  is

$$\mathbf{B} - \mathbf{A} = \begin{pmatrix} -4 \\ 6 \end{pmatrix} - \begin{pmatrix} 1 \\ -1 \end{pmatrix} = \begin{pmatrix} -4 - 1 \\ 6 - (-1) \end{pmatrix} = \begin{pmatrix} -5 \\ 7 \end{pmatrix} \quad (\text{A.1.1.2})$$

b) The Direction vector of  $BC$  is

$$\mathbf{C} - \mathbf{B} = \begin{pmatrix} -3 \\ -5 \end{pmatrix} - \begin{pmatrix} -4 \\ 6 \end{pmatrix} = \begin{pmatrix} -3 - (-4) \\ -5 - 6 \end{pmatrix} = \begin{pmatrix} 1 \\ -11 \end{pmatrix} \quad (\text{A.1.1.3})$$

c) The Direction vector of  $CA$  is

$$\mathbf{A} - \mathbf{C} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} - \begin{pmatrix} -3 \\ -5 \end{pmatrix} = \begin{pmatrix} 1 - (-3) \\ -1 - (-5) \end{pmatrix} = \begin{pmatrix} 4 \\ 4 \end{pmatrix} \quad (\text{A.1.1.4})$$

A.1.2. The length of side  $BC$  is

$$c = \|\mathbf{B} - \mathbf{A}\| \triangleq \sqrt{(\mathbf{B} - \mathbf{A})^\top (\mathbf{B} - \mathbf{A})} \quad (\text{A.1.2.1})$$

where

$$\mathbf{A}^T \triangleq \begin{pmatrix} 1 & -1 \end{pmatrix} \quad (\text{A.1.2.2})$$

Similarly,

$$b = \|\mathbf{C} - \mathbf{B}\|, \quad a = \|\mathbf{A} - \mathbf{C}\| \quad (\text{A.1.2.3})$$

Find  $a, b, c$ .

a) From (A.1.1.2),

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} 5 \\ -7 \end{pmatrix}, \quad (\text{A.1.2.4})$$

$$\implies c = \|\mathbf{B} - \mathbf{A}\| = \|\mathbf{A} - \mathbf{B}\| \quad (\text{A.1.2.5})$$

$$= \sqrt{\begin{pmatrix} 5 & -7 \end{pmatrix} \begin{pmatrix} 5 \\ -7 \end{pmatrix}} = \sqrt{(5)^2 + (7)^2} \quad (\text{A.1.2.6})$$

$$= \sqrt{74} \quad (\text{A.1.2.7})$$

b) Similarly, from (A.1.1.3),

$$a = \|\mathbf{B} - \mathbf{C}\| = \sqrt{\begin{pmatrix} -1 & 11 \end{pmatrix} \begin{pmatrix} -1 \\ 11 \end{pmatrix}} \quad (\text{A.1.2.8})$$

$$= \sqrt{(1)^2 + (11)^2} = \sqrt{122} \quad (\text{A.1.2.9})$$

and from (A.1.1.4),

c)

$$b = \|\mathbf{A} - \mathbf{C}\| = \sqrt{\begin{pmatrix} 4 & 4 \end{pmatrix} \begin{pmatrix} 4 \\ 4 \end{pmatrix}} \quad (\text{A.1.2.10})$$

$$= \sqrt{(4)^2 + (4)^2} = \sqrt{32} \quad (\text{A.1.2.11})$$

A.1.3. Points  $\mathbf{A}, \mathbf{B}, \mathbf{C}$  are defined to be collinear if

$$\text{rank} \begin{pmatrix} 1 & 1 & 1 \\ \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix} = 2 \quad (\text{A.1.3.1})$$

Are the given points in (12.1) collinear?

**Solution:** From (12.1),

$$\begin{pmatrix} 1 & 1 & 1 \\ \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & -4 & -3 \\ -1 & 6 & -5 \end{pmatrix} \xrightarrow{R_3 \leftarrow R_3 + R_2} \begin{pmatrix} 1 & 1 & 1 \\ 1 & -4 & -3 \\ 0 & 2 & -8 \end{pmatrix} \quad (\text{A.1.3.2})$$

$$\xrightarrow{R_2 \leftarrow R_1 - R_2} \begin{pmatrix} 1 & 1 & 1 \\ 0 & 5 & 4 \\ 0 & 2 & -8 \end{pmatrix} \xrightarrow{R_3 \leftarrow R_3 - \frac{2}{5}R_2} \begin{pmatrix} 1 & 1 & 1 \\ 0 & 5 & 4 \\ 0 & 0 & -\frac{48}{5} \end{pmatrix} \quad (\text{A.1.3.3})$$

There are no zero rows. So,

$$\text{rank} \begin{pmatrix} 1 & 1 & 1 \\ \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix} = 3 \quad (\text{A.1.3.4})$$

Hence, the points **A, B, C** are not collinear. This is visible in Fig. A.1.3.1.

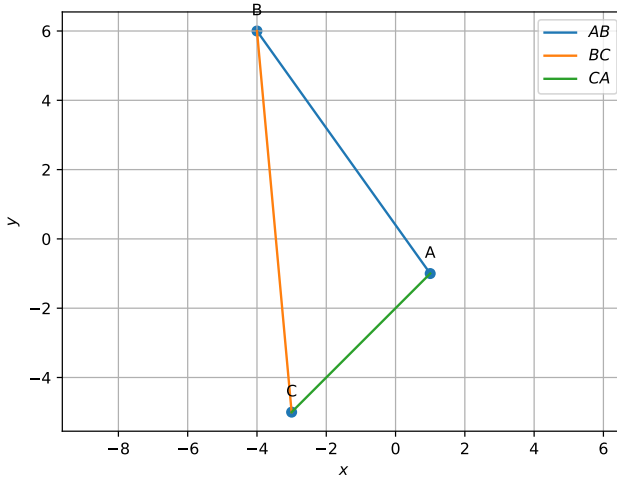


Fig. A.1.3.1:  $\triangle ABC$

A.1.4. The parametric form of the equation of  $AB$  is

$$\mathbf{x} = \mathbf{A} + k\mathbf{m} \quad k \neq 0, \quad (\text{A.1.4.1})$$

where

$$\mathbf{m} = \mathbf{B} - \mathbf{A} \quad (\text{A.1.4.2})$$

is the direction vector of  $AB$ . Find the parametric equations of  $AB, BC$  and  $CA$ .

**Solution:** From (A.1.4.1) and (A.1.1.2), the parametric equation for  $AB$  is given by

$$AB : \mathbf{x} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} + k \begin{pmatrix} -5 \\ 7 \end{pmatrix} \quad (\text{A.1.4.3})$$

Similarly, from (A.1.1.3) and (A.1.1.4),

$$BC : \mathbf{x} = \begin{pmatrix} -4 \\ 6 \end{pmatrix} + k \begin{pmatrix} 1 \\ -11 \end{pmatrix} \quad (\text{A.1.4.4})$$

$$CA : \mathbf{x} = \begin{pmatrix} -3 \\ -5 \end{pmatrix} + k \begin{pmatrix} 4 \\ 4 \end{pmatrix} \quad (\text{A.1.4.5})$$

A.1.5. The normal form of the equation of  $AB$  is

$$\mathbf{n}^\top (\mathbf{x} - \mathbf{A}) = 0 \quad (\text{A.1.5.1})$$

where

$$\mathbf{n}^\top \mathbf{m} = \mathbf{n}^\top (\mathbf{B} - \mathbf{A}) = 0 \quad (\text{A.1.5.2})$$

$$\text{or, } \mathbf{n} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \mathbf{m} \quad (\text{A.1.5.3})$$

Find the normal form of the equations of  $AB$ ,  $BC$  and  $CA$ .

**Solution:**

a) From (A.1.1.3), the direction vector of side  $BC$  is

$$\mathbf{m} = \begin{pmatrix} 1 \\ -11 \end{pmatrix} \quad (\text{A.1.5.4})$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ -11 \end{pmatrix} = \begin{pmatrix} -11 \\ -1 \end{pmatrix} \quad (\text{A.1.5.5})$$

from (A.1.5.3). Hence, from (A.1.5.1), the normal equation of side  $BC$  is

$$\mathbf{n}^\top (\mathbf{x} - \mathbf{B}) = 0 \quad (\text{A.1.5.6})$$

$$\Rightarrow \begin{pmatrix} -11 & -1 \end{pmatrix} \mathbf{x} = \begin{pmatrix} -11 & -1 \end{pmatrix} \begin{pmatrix} -4 \\ 6 \end{pmatrix} \quad (\text{A.1.5.7})$$

$$\Rightarrow BC : \begin{pmatrix} 11 & 1 \end{pmatrix} \mathbf{x} = -38 \quad (\text{A.1.5.8})$$

b) Similarly, for  $AB$ , from (A.1.1.2),

$$\mathbf{m} = \begin{pmatrix} -5 \\ 7 \end{pmatrix} \quad (\text{A.1.5.9})$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} -5 \\ 7 \end{pmatrix} = \begin{pmatrix} 7 \\ 5 \end{pmatrix} \quad (\text{A.1.5.10})$$

and

$$\mathbf{n}^\top (\mathbf{x} - \mathbf{A}) = 0 \quad (\text{A.1.5.11})$$

$$\Rightarrow AB : \mathbf{n}^\top \mathbf{x} = \begin{pmatrix} 7 & 5 \end{pmatrix} \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (\text{A.1.5.12})$$

$$\Rightarrow \begin{pmatrix} 7 & 5 \end{pmatrix} \mathbf{x} = 2 \quad (\text{A.1.5.13})$$



c) For  $CA$ , from (A.1.1.4),

$$\mathbf{m} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (\text{A.1.5.14})$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \quad (\text{A.1.5.15})$$

$$(\text{A.1.5.16})$$

$$\Rightarrow \mathbf{n}^\top (\mathbf{x} - \mathbf{C}) = 0 \quad (\text{A.1.5.17})$$

$$\Rightarrow \begin{pmatrix} 1 & -1 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 1 & -1 \end{pmatrix} \begin{pmatrix} -3 \\ -5 \end{pmatrix} = 2 \quad (\text{A.1.5.18})$$

A.1.6. The area of  $\triangle ABC$  is defined as

$$\frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C})\| \quad (\text{A.1.6.1})$$

where

$$\mathbf{A} \times \mathbf{B} \triangleq \begin{vmatrix} 1 & -4 \\ -1 & 6 \end{vmatrix} \quad (\text{A.1.6.2})$$

Find the area of  $\triangle ABC$ .

**Solution:** From (A.1.1.2) and (A.1.1.4),

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} 5 \\ -7 \end{pmatrix}, \mathbf{A} - \mathbf{C} = \begin{pmatrix} 4 \\ 4 \end{pmatrix} \quad (\text{A.1.6.3})$$

$$\Rightarrow (\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C}) = \begin{vmatrix} 5 & 4 \\ -7 & 4 \end{vmatrix} \quad (\text{A.1.6.4})$$

$$= 5 \times 4 - 4 \times (-7) \quad (\text{A.1.6.5})$$

$$= 48 \quad (\text{A.1.6.6})$$

$$\Rightarrow \frac{1}{2} \|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C})\| = \frac{48}{2} = 24 \quad (\text{A.1.6.7})$$

which is the desired area.

A.1.7. Find the angles  $A, B, C$  if

$$\cos A \triangleq \frac{(\mathbf{B} - \mathbf{A})^\top \mathbf{C} - \mathbf{A}}{\|\mathbf{B} - \mathbf{A}\| \|\mathbf{C} - \mathbf{A}\|} \quad (\text{A.1.7.1})$$

**Solution:**

a) From (A.1.1.2), (A.1.1.4), (A.1.2.7) and (A.1.2.11)

$$(\mathbf{B} - \mathbf{A})^\top (\mathbf{C} - \mathbf{A}) = \begin{pmatrix} -5 & 7 \end{pmatrix} \begin{pmatrix} -4 \\ -4 \end{pmatrix} \quad (\text{A.1.7.2})$$

$$= -8 \quad (\text{A.1.7.3})$$

$$\Rightarrow \cos A = \frac{-8}{\sqrt{74} \sqrt{32}} = \frac{-1}{\sqrt{37}} \quad (\text{A.1.7.4})$$

$$\Rightarrow A = \cos^{-1} \frac{-1}{\sqrt{37}} \quad (\text{A.1.7.5})$$

b) From (A.1.1.2), (A.1.1.3), (A.1.2.7) and (A.1.2.9)

$$(\mathbf{C} - \mathbf{B})^\top (\mathbf{A} - \mathbf{B}) = \begin{pmatrix} 1 & -11 \end{pmatrix} \begin{pmatrix} 5 \\ -7 \end{pmatrix} \quad (\text{A.1.7.6})$$

$$= 82 \quad (\text{A.1.7.7})$$

$$\Rightarrow \cos B = \frac{82}{\sqrt{74} \sqrt{122}} = \frac{41}{\sqrt{2257}} \quad (\text{A.1.7.8})$$

$$\Rightarrow B = \cos^{-1} \frac{41}{\sqrt{2257}} \quad (\text{A.1.7.9})$$

c) From (A.1.1.3), (A.1.1.4), (A.1.2.9) and (A.1.2.11)

$$(\mathbf{A} - \mathbf{C})^\top (\mathbf{B} - \mathbf{C}) = \begin{pmatrix} 4 & 4 \end{pmatrix} \begin{pmatrix} -1 \\ 11 \end{pmatrix} \quad (\text{A.1.7.10})$$

$$= 40 \quad (\text{A.1.7.11})$$

$$\Rightarrow \cos C = \frac{40}{\sqrt{32} \sqrt{122}} = \frac{5}{\sqrt{61}} \quad (\text{A.1.7.12})$$

$$\Rightarrow C = \cos^{-1} \frac{5}{\sqrt{61}} \quad (\text{A.1.7.13})$$

All codes for this section are available at

codes/triangle/sides.py

## A.2 Formulae

A.1. The equation of a line is given by

$$y = mx + c \quad (\text{A.1.1})$$

$$\Rightarrow \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x \\ mx + c \end{pmatrix} = \begin{pmatrix} 0 \\ c \end{pmatrix} + x \begin{pmatrix} 1 \\ m \end{pmatrix} \quad (\text{A.1.2})$$

yielding (4.1.1.3).

A.2. (A.1.1) can also be expressed as

$$y - mx = c \quad (\text{A.2.1})$$

$$\Rightarrow \begin{pmatrix} -m & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} = c \quad (\text{A.2.2})$$

yielding (4.1.2.3).

A.3. The direction vector is

$$\mathbf{m} = \begin{pmatrix} 1 \\ m \end{pmatrix} \quad (\text{A.3.1})$$

and the normal vector is

$$\mathbf{n} = \begin{pmatrix} -m \\ 1 \end{pmatrix} \quad (\text{A.3.2})$$

A.4. From (4.1.1.3), if  $\mathbf{A}, \mathbf{D}$  and  $\mathbf{C}$  are on the same line,

$$\mathbf{D} = \mathbf{A} + q\mathbf{m} \quad (\text{A.4.1})$$

$$\mathbf{C} = \mathbf{D} + p\mathbf{m} \quad (\text{A.4.2})$$

$$\Rightarrow p(\mathbf{D} - \mathbf{A}) + q(\mathbf{D} - \mathbf{C}) = \mathbf{0}, \quad p, q \neq 0 \quad (\text{A.4.3})$$

$$\Rightarrow \mathbf{D} = \frac{p\mathbf{A} + q\mathbf{C}}{p + q} \quad (\text{A.4.4})$$

yielding (1.1.4.1) upon substituting

$$k = \frac{p}{q}. \quad (\text{A.4.5})$$

$(\mathbf{D} - \mathbf{A}), (\mathbf{D} - \mathbf{C})$  are then said to be *linearly dependent*.

A.5. If  $\mathbf{A}, \mathbf{B}, \mathbf{C}$  are collinear, from (4.1.2.3),

$$\mathbf{n}^\top \mathbf{A} = c \quad (\text{A.5.1})$$

$$\mathbf{n}^\top \mathbf{B} = c \quad (\text{A.5.2})$$

$$\mathbf{n}^\top \mathbf{C} = c \quad (\text{A.5.3})$$

which can be expressed as

$$\begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix}^\top \mathbf{n} = c \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} \quad (\text{A.5.4})$$

$$\equiv \begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix}^\top \mathbf{n} = \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}, \quad (\text{A.5.5})$$

$$\Rightarrow \begin{pmatrix} 1 & 1 & 1 \\ \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix}^\top \begin{pmatrix} \mathbf{n} \\ -1 \end{pmatrix} = \mathbf{0} \quad (\text{A.5.6})$$

yielding

$$\text{rank} \begin{pmatrix} 1 & 1 & 1 \\ \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix} = 2 \quad (\text{A.5.7})$$

Rank is defined to be the number of linearly independent rows or columns of a matrix.

A.6. The equation of a line can also be expressed as

$$\mathbf{n}^\top \mathbf{x} = 1 \quad (\text{A.6.1})$$

### A.3 Median

A.3.1. If **D** divides  $BC$  in the ratio  $k : 1$ ,

$$\mathbf{D} = \frac{k\mathbf{C} + \mathbf{B}}{k + 1} \quad (\text{A.3.1.1})$$

Find the mid points **D**, **E**, **F** of the sides  $BC$ ,  $CA$  and  $AB$  respectively.

**Solution:** Since **D** is the midpoint of  $BC$ ,

$$k = 1, \quad (\text{A.3.1.2})$$

$$\Rightarrow \mathbf{D} = \frac{\mathbf{C} + \mathbf{B}}{2} = \frac{1}{2} \begin{pmatrix} -7 \\ 1 \end{pmatrix} \quad (\text{A.3.1.3})$$

Similarly,

$$\mathbf{E} = \frac{\mathbf{A} + \mathbf{C}}{2} = \begin{pmatrix} -1 \\ -3 \end{pmatrix} \quad (\text{A.3.1.4})$$

$$\mathbf{F} = \frac{\mathbf{A} + \mathbf{B}}{2} = \frac{1}{2} \begin{pmatrix} -3 \\ 5 \end{pmatrix} \quad (\text{A.3.1.5})$$

A.3.2. Find the equations of  $AD$ ,  $BE$  and  $CF$ .

**Solution:** :

a) The direction vector of  $AD$  is

$$\mathbf{m} = \mathbf{D} - \mathbf{A} = \begin{pmatrix} -7/2 \\ 1/2 \end{pmatrix} - \begin{pmatrix} 1 \\ -1 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} -9 \\ 3 \end{pmatrix} \equiv \begin{pmatrix} -3 \\ 1 \end{pmatrix} \quad (\text{A.3.2.1})$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 1 \\ 3 \end{pmatrix} \quad (\text{A.3.2.2})$$

Hence the normal equation of median  $AD$  is

$$\mathbf{n}^T (\mathbf{x} - \mathbf{A}) = 0 \quad (\text{A.3.2.3})$$

$$\Rightarrow \begin{pmatrix} 1 & 3 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 1 & 3 \end{pmatrix} \begin{pmatrix} 1 \\ -1 \end{pmatrix} = -2 \quad (\text{A.3.2.4})$$

b) For  $BE$ ,

$$\mathbf{m} = \mathbf{E} - \mathbf{B} = \begin{pmatrix} -1 \\ -3 \end{pmatrix} - \begin{pmatrix} -4 \\ 6 \end{pmatrix} = \begin{pmatrix} 3 \\ -9 \end{pmatrix} \equiv \begin{pmatrix} 1 \\ -3 \end{pmatrix} \quad (\text{A.3.2.5})$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 3 \\ 1 \end{pmatrix} \quad (\text{A.3.2.6})$$

Hence the normal equation of median  $BE$  is

$$\mathbf{n}^T (\mathbf{x} - \mathbf{B}) = 0 \quad (\text{A.3.2.7})$$

$$\Rightarrow \begin{pmatrix} 3 & 1 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 3 & 1 \end{pmatrix} \begin{pmatrix} -4 \\ 6 \end{pmatrix} = -6 \quad (\text{A.3.2.8})$$

c) For median  $CF$ ,

$$\mathbf{m} = \mathbf{F} - \mathbf{C} = \begin{pmatrix} \frac{-3}{2} \\ \frac{5}{2} \end{pmatrix} - \begin{pmatrix} -3 \\ -5 \end{pmatrix} = \begin{pmatrix} \frac{3}{2} \\ \frac{15}{2} \end{pmatrix} \equiv \begin{pmatrix} 1 \\ 5 \end{pmatrix} \quad (\text{A.3.2.9})$$

$$\Rightarrow \mathbf{n} = \begin{pmatrix} 5 \\ -1 \end{pmatrix} \quad (\text{A.3.2.10})$$

Hence the normal equation of median  $CF$  is

$$\mathbf{n}^\top (\mathbf{x} - \mathbf{C}) = 0 \quad (\text{A.3.2.11})$$

$$\Rightarrow \begin{pmatrix} 5 & -1 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 5 & -1 \end{pmatrix} \begin{pmatrix} -3 \\ -5 \end{pmatrix} = -10 \quad (\text{A.3.2.12})$$

A.3.3. Find the intersection  $\mathbf{G}$  of  $BE$  and  $CF$ .

**Solution:** From (A.3.2.8) and (A.3.2.12), the equations of  $BE$  and  $CF$  are, respectively,

$$\begin{pmatrix} 3 & 1 \end{pmatrix} \mathbf{x} = (-6) \quad (\text{A.3.3.1})$$

$$\begin{pmatrix} 5 & -1 \end{pmatrix} \mathbf{x} = (-10) \quad (\text{A.3.3.2})$$

From (A.3.3.1) and (A.3.3.2) the augmented matrix is

$$\begin{pmatrix} 3 & 1 & -6 \\ 5 & -1 & -10 \end{pmatrix} \xleftrightarrow{R_1 \leftarrow R_1 + R_2} \begin{pmatrix} 8 & 0 & -16 \\ 5 & -1 & -10 \end{pmatrix} \quad (\text{A.3.3.3})$$

$$\xleftrightarrow{R_1 \leftarrow R_1 / 8} \begin{pmatrix} 1 & 0 & -2 \\ 5 & -1 & -10 \end{pmatrix} \xleftrightarrow{R_2 \leftarrow R_2 - 5R_1} \begin{pmatrix} 1 & 0 & -2 \\ 0 & -1 & 0 \end{pmatrix} \quad (\text{A.3.3.4})$$

$$\xleftrightarrow{R_2 \leftarrow -R_2} \begin{pmatrix} 1 & 0 & -2 \\ 0 & 1 & 0 \end{pmatrix} \quad (\text{A.3.3.5})$$

using Gauss elimination. Therefore,

$$\mathbf{G} = \begin{pmatrix} -2 \\ 0 \end{pmatrix} \quad (\text{A.3.3.6})$$

A.3.4. Verify that

$$\frac{BG}{GE} = \frac{CG}{GF} = \frac{AG}{GD} = 2 \quad (\text{A.3.4.1})$$

**Solution:**

a) From (A.3.1.4) and (A.3.3.6),

$$\mathbf{G} - \mathbf{B} = \begin{pmatrix} 2 \\ -6 \end{pmatrix}, \mathbf{E} - \mathbf{G} = \begin{pmatrix} 1 \\ -3 \end{pmatrix} \quad (\text{A.3.4.2})$$

$$\Rightarrow \mathbf{G} - \mathbf{B} = 2(\mathbf{E} - \mathbf{G}) \quad (\text{A.3.4.3})$$

$$\Rightarrow \|\mathbf{G} - \mathbf{B}\| = 2\|\mathbf{E} - \mathbf{G}\| \quad (\text{A.3.4.4})$$

$$\text{or, } \frac{BG}{GE} = 2 \quad (\text{A.3.4.5})$$

b) From (A.3.1.5) and (A.3.3.6),

$$\mathbf{F} - \mathbf{G} = \frac{1}{2} \begin{pmatrix} 1 \\ 5 \end{pmatrix}, \mathbf{G} - \mathbf{C} = \begin{pmatrix} 1 \\ 5 \end{pmatrix} \quad (\text{A.3.4.6})$$

$$\Rightarrow \mathbf{G} - \mathbf{C} = 2(\mathbf{F} - \mathbf{G}) \quad (\text{A.3.4.7})$$

$$\Rightarrow \|\mathbf{G} - \mathbf{C}\| = 2\|\mathbf{F} - \mathbf{G}\| \quad (\text{A.3.4.8})$$

$$\text{or, } \frac{CG}{GF} = 2 \quad (\text{A.3.4.9})$$

c) From (A.3.1.3) and (A.3.3.6),

$$\mathbf{G} - \mathbf{A} = \begin{pmatrix} -3 \\ 1 \end{pmatrix}, \mathbf{D} - \mathbf{G} = \frac{1}{2} \begin{pmatrix} -3 \\ 1 \end{pmatrix} \quad (\text{A.3.4.10})$$

$$\mathbf{G} - \mathbf{A} = 2(\mathbf{D} - \mathbf{G}) \quad (\text{A.3.4.11})$$

$$\Rightarrow \|\mathbf{G} - \mathbf{A}\| = 2\|\mathbf{D} - \mathbf{G}\| \quad (\text{A.3.4.12})$$

$$\text{or, } \frac{AG}{GD} = 2 \quad (\text{A.3.4.13})$$

From (A.3.4.5), (A.3.4.9), (A.3.4.13)

$$\frac{BG}{GE} = \frac{CG}{GF} = \frac{AG}{GD} = 2 \quad (\text{A.3.4.14})$$

A.3.5. Show that  $\mathbf{A}$ ,  $\mathbf{G}$  and  $\mathbf{D}$  are collinear.

**Solution:** Points  $\mathbf{A}$ ,  $\mathbf{D}$ ,  $\mathbf{G}$  are defined to be collinear if

$$\text{rank} \begin{pmatrix} 1 & 1 & 1 \\ \mathbf{A} & \mathbf{D} & \mathbf{G} \end{pmatrix} = 2 \quad (\text{A.3.5.1})$$

$$\Rightarrow \begin{pmatrix} 1 & 1 & 1 \\ 1 & -\frac{7}{2} & -2 \\ -1 & \frac{1}{2} & 0 \end{pmatrix} \xleftrightarrow{R_3 \leftarrow R_3 + R_2} \begin{pmatrix} 1 & 1 & 1 \\ 1 & -\frac{7}{2} & -2 \\ 0 & -3 & -2 \end{pmatrix} \quad (\text{A.3.5.2})$$

$$\xleftrightarrow{R_2 \leftarrow R_2 - R_1} \begin{pmatrix} 1 & 1 & 1 \\ 0 & -\frac{9}{2} & -3 \\ 0 & -3 & -2 \end{pmatrix} \xleftrightarrow{R_3 \leftarrow R_3 - \frac{2}{3}R_2} \begin{pmatrix} 1 & 1 & 1 \\ 0 & -\frac{9}{2} & -3 \\ 0 & 0 & 0 \end{pmatrix} \quad (\text{A.3.5.3})$$

Thus, the matrix (A.3.5.1) has rank 2 and the points are collinear. Thus, the medians of a triangle meet at the point  $\mathbf{G}$ . See Fig. A.3.5.1.

A.3.6. Verify that

$$\mathbf{G} = \frac{\mathbf{A} + \mathbf{B} + \mathbf{C}}{3} \quad (\text{A.3.6.1})$$

$\mathbf{G}$  is known as the *centroid* of  $\triangle ABC$ .

**Solution:**

$$\begin{aligned} \mathbf{G} &= \frac{\begin{pmatrix} 1 \\ -1 \end{pmatrix} + \begin{pmatrix} -4 \\ 6 \end{pmatrix} + \begin{pmatrix} -3 \\ -5 \end{pmatrix}}{3} \\ &= \begin{pmatrix} -2 \\ 0 \end{pmatrix} \end{aligned} \quad (\text{A.3.6.2})$$

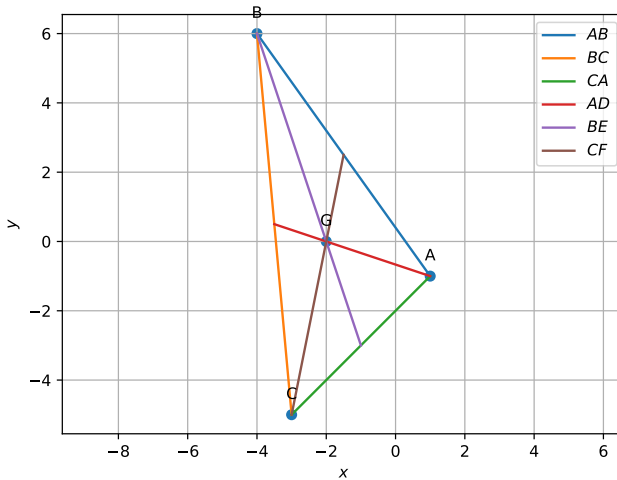


Fig. A.3.5.1: Medians of  $\triangle ABC$  meet at  $G$ .

A.3.7. Verify that

$$\mathbf{A} - \mathbf{F} = \mathbf{E} - \mathbf{D} \quad (\text{A.3.7.1})$$

The quadrilateral  $AFDE$  is defined to be a parallelogram.

**Solution:**

$$\mathbf{A} - \mathbf{F} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} - \begin{pmatrix} -3 \\ 5 \\ 2 \end{pmatrix} = \begin{pmatrix} 5 \\ 2 \\ -7 \end{pmatrix} \quad (\text{A.3.7.2})$$

$$\mathbf{E} - \mathbf{D} = \begin{pmatrix} -1 \\ -3 \end{pmatrix} - \begin{pmatrix} -7 \\ 2 \\ 1 \end{pmatrix} = \begin{pmatrix} 5 \\ 2 \\ -7 \end{pmatrix} \quad (\text{A.3.7.3})$$

$$\Rightarrow \mathbf{A} - \mathbf{F} = \mathbf{E} - \mathbf{D} \quad (\text{A.3.7.4})$$

See Fig. A.3.7.1,

All codes for this section are available in

codes/triangle/medians.py  
codes/triangle/pgm.py

#### A.4 Altitude

A.4.1.  $D_1$  is a point on  $BC$  such that

$$AD_1 \perp BC \quad (\text{A.4.1.1})$$

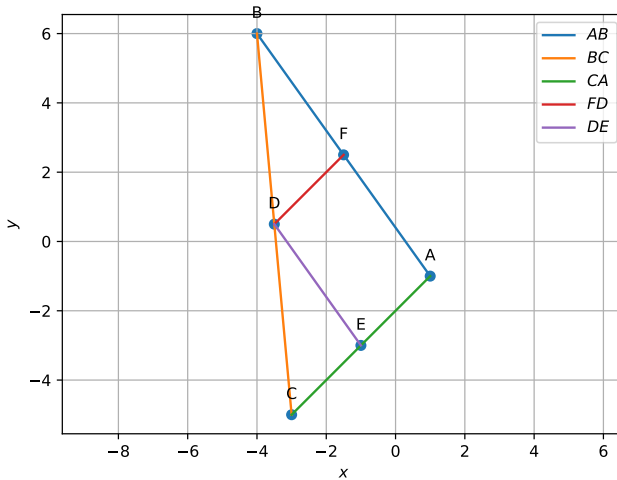


Fig. A.3.7.1:  $AFDE$  forms a parallelogram in triangle  $ABC$

and  $AD_1$  is defined to be the altitude. Find the normal vector of  $AD_1$ .

**Solution:** The normal vector of  $AD_1$  is the direction vector  $BC$  and is obtained from (A.1.1.3) as

$$\mathbf{n} = \begin{pmatrix} 1 \\ -11 \end{pmatrix} \quad (\text{A.4.1.2})$$

A.4.2. Find the equation of  $AD_1$ .

**Solution:** The equation of  $AD_1$  is

$$\mathbf{n}^T(\mathbf{x} - \mathbf{A}) = 0 \quad (\text{A.4.2.1})$$

$$\Rightarrow \begin{pmatrix} -1 & 11 \end{pmatrix} \mathbf{x} = \begin{pmatrix} -1 & 11 \end{pmatrix} \begin{pmatrix} 1 \\ -1 \end{pmatrix} = -12 \quad (\text{A.4.2.2})$$

A.4.3. Find the equations of the altitudes  $BE_1$  and  $CF_1$  to the sides  $AC$  and  $AB$  respectively.

**Solution:**

a) From (A.1.1.4), the normal vector of  $CF_1$  is

$$\mathbf{n} = \begin{pmatrix} -5 \\ 7 \end{pmatrix} \quad (\text{A.4.3.1})$$



and the equation of  $CF_1$  is

$$\mathbf{n}^\top (\mathbf{x} - \mathbf{C}) = 0 \quad (\text{A.4.3.2})$$

$$\Rightarrow (-5 \ 7) \left( \mathbf{x} - \begin{pmatrix} -3 \\ -5 \end{pmatrix} \right) = 0 \quad (\text{A.4.3.3})$$

$$\Rightarrow (5 \ -7) \mathbf{x} = 20, \quad (\text{A.4.3.4})$$

b) Similarly, from (A.1.1.2), the normal vector of  $BE_1$  is

$$\mathbf{n} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (\text{A.4.3.5})$$

and the equation of  $BE_1$  is

$$\mathbf{n}^\top (\mathbf{x} - \mathbf{B}) = 0 \quad (\text{A.4.3.6})$$

$$\Rightarrow (1 \ 1) \left( \mathbf{x} - \begin{pmatrix} -4 \\ 6 \end{pmatrix} \right) = 0 \quad (\text{A.4.3.7})$$

$$\Rightarrow (1 \ 1) \mathbf{x} = 2, \quad (\text{A.4.3.8})$$

A.4.4. Find the intersection  $\mathbf{H}$  of  $BE_1$  and  $CF_1$ .

**Solution:** The intersection of (A.4.3.8) and (A.4.3.4), is obtained from the matrix equation

$$\begin{pmatrix} 1 & 1 \\ 5 & -7 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 2 \\ 20 \end{pmatrix} \quad (\text{A.4.4.1})$$

which can be solved as

$$\begin{pmatrix} 1 & 1 & 2 \\ 5 & -7 & 20 \end{pmatrix} \xrightarrow{R_2 \leftarrow R_2 - 5R_1} \begin{pmatrix} 1 & 1 & 2 \\ 0 & -12 & 10 \end{pmatrix} \quad (\text{A.4.4.2})$$

$$\xleftrightarrow{R_2 \leftarrow \frac{R_2}{-12}} \begin{pmatrix} 1 & 1 & 2 \\ 0 & 1 & -\frac{5}{6} \end{pmatrix} \xrightarrow{R_1 \leftarrow R_1 - R_2} \begin{pmatrix} 1 & 0 & \frac{17}{6} \\ 0 & 1 & -\frac{5}{6} \end{pmatrix} \quad (\text{A.4.4.3})$$

yielding

$$\mathbf{H} = \frac{1}{6} \begin{pmatrix} 17 \\ -5 \end{pmatrix}, \quad (\text{A.4.4.4})$$

See Fig. A.4.4.1

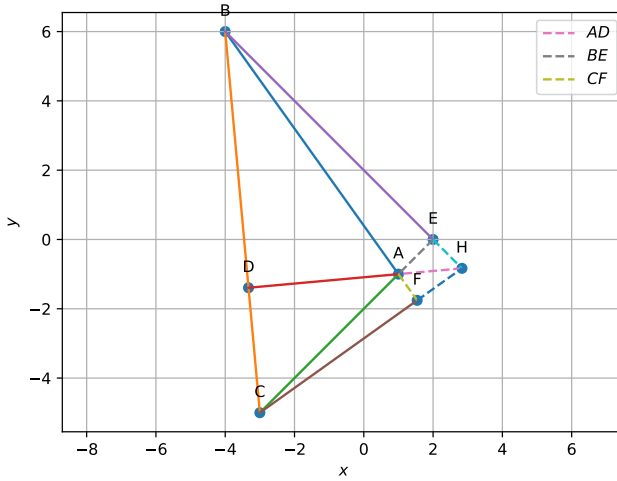


Fig. A.4.4.1: Altitudes  $BE_1$  and  $CF_1$  intersect at  $\mathbf{H}$

A.4.5. Verify that

$$(\mathbf{A} - \mathbf{H})^\top (\mathbf{B} - \mathbf{C}) = 0 \quad (\text{A.4.5.1})$$

**Solution:** From (A.4.4.4),

$$\mathbf{A} - \mathbf{H} = -\frac{1}{6} \begin{pmatrix} 11 \\ 1 \end{pmatrix}, \quad \mathbf{B} - \mathbf{C} = \begin{pmatrix} -1 \\ 11 \end{pmatrix} \quad (\text{A.4.5.2})$$

$$\Rightarrow (\mathbf{A} - \mathbf{H})^\top (\mathbf{B} - \mathbf{C}) = \frac{1}{6} \begin{pmatrix} 11 & 1 \end{pmatrix} \begin{pmatrix} -1 \\ 11 \end{pmatrix} = 0 \quad (\text{A.4.5.3})$$

All codes for this section are available at

codes/triangle/altitude.py

## A.5 Perpendicular Bisector

A.5.1. The equation of the perpendicular bisector of  $BC$  is

$$\left( \mathbf{x} - \frac{\mathbf{B} + \mathbf{C}}{2} \right) (\mathbf{B} - \mathbf{C}) = 0 \quad (\text{A.5.1.1})$$

Substitute numerical values and find the equations of the perpendicular bisectors of  $AB$ ,  $BC$  and  $CA$ .

**Solution:** From (A.1.1.2), (A.1.1.3), (A.1.1.4), (A.3.1.3), (A.3.1.4) and (A.3.1.5),

$$\frac{\mathbf{B} + \mathbf{C}}{2} = \frac{1}{2} \begin{pmatrix} -7 \\ 1 \end{pmatrix}, \mathbf{B} - \mathbf{C} = \begin{pmatrix} -1 \\ 11 \end{pmatrix} \quad (\text{A.5.1.2})$$

$$\frac{\mathbf{A} + \mathbf{B}}{2} = \frac{1}{2} \begin{pmatrix} -3 \\ 5 \end{pmatrix}, \mathbf{A} - \mathbf{B} = \begin{pmatrix} 5 \\ -7 \end{pmatrix} \quad (\text{A.5.1.3})$$

$$\frac{\mathbf{C} + \mathbf{A}}{2} = \begin{pmatrix} -1 \\ -3 \end{pmatrix}, \mathbf{C} - \mathbf{A} = \begin{pmatrix} -4 \\ -4 \end{pmatrix} \quad (\text{A.5.1.4})$$

yielding

$$(\mathbf{B} - \mathbf{C})^\top \left( \frac{\mathbf{B} + \mathbf{C}}{2} \right) = \begin{pmatrix} -1 & 11 \end{pmatrix} \begin{pmatrix} -\frac{7}{2} \\ \frac{1}{2} \end{pmatrix} = 9 \quad (\text{A.5.1.5})$$

$$(\mathbf{A} - \mathbf{B})^\top \left( \frac{\mathbf{A} + \mathbf{B}}{2} \right) = \begin{pmatrix} 5 & -7 \end{pmatrix} \begin{pmatrix} -\frac{3}{2} \\ \frac{5}{2} \end{pmatrix} = -25 \quad (\text{A.5.1.6})$$

$$(\mathbf{C} - \mathbf{A})^\top \left( \frac{\mathbf{C} + \mathbf{A}}{2} \right) = \begin{pmatrix} -4 & -4 \end{pmatrix} \begin{pmatrix} -1 \\ -3 \end{pmatrix} = 16 \quad (\text{A.5.1.7})$$

Thus, the perpendicular bisectors are obtained from (A.5.1.1) as

$$BC : \begin{pmatrix} -1 & 11 \end{pmatrix} \mathbf{x} = 9 \quad (\text{A.5.1.8})$$

$$CA : \begin{pmatrix} 5 & -7 \end{pmatrix} \mathbf{x} = -25 \quad (\text{A.5.1.9})$$

$$AB : \begin{pmatrix} 1 & 1 \end{pmatrix} \mathbf{x} = -4 \quad (\text{A.5.1.10})$$

A.5.2. Find the intersection  $\mathbf{O}$  of the perpendicular bisectors of  $AB$  and  $AC$ .

**Solution:**

The intersection of (A.5.1.9) and (A.5.1.10), can be obtained as

$$\begin{pmatrix} 5 & -7 & -25 \\ 1 & 1 & -4 \end{pmatrix} \xrightarrow{R_2 \leftarrow 5R_2 - R_1} \begin{pmatrix} 5 & -7 & -25 \\ 0 & 12 & 5 \end{pmatrix} \quad (\text{A.5.2.1})$$

$$\xrightarrow{R_1 \leftarrow \frac{1}{7}R_1 + R_2} \begin{pmatrix} \frac{60}{7} & 0 & \frac{-265}{7} \\ 0 & 12 & 5 \end{pmatrix} \xrightarrow{\begin{matrix} R_2 \leftarrow \frac{1}{12}R_2 \\ R_1 \leftarrow \frac{7}{60}R_1 \end{matrix}} \begin{pmatrix} 1 & 0 & \frac{-53}{12} \\ 0 & 1 & \frac{5}{12} \end{pmatrix} \quad (\text{A.5.2.2})$$

$$\Rightarrow \mathbf{O} = \begin{pmatrix} -\frac{53}{12} \\ \frac{5}{12} \end{pmatrix} \quad (\text{A.5.2.3})$$

A.5.3. Verify that  $\mathbf{O}$  satisfies (A.5.1.1).  $\mathbf{O}$  is known as the circumcentre.

**Solution:** Substituting from (A.5.2.3) in (A.5.1.1),

$$\begin{aligned} \left( \mathbf{O} - \frac{\mathbf{B} + \mathbf{C}}{2} \right)^\top (\mathbf{B} - \mathbf{C}) &= \left( \frac{1}{12} \begin{pmatrix} -53 \\ 5 \end{pmatrix} - \frac{1}{2} \begin{pmatrix} -7 \\ 1 \end{pmatrix} \right)^\top \begin{pmatrix} -1 \\ 11 \end{pmatrix} \\ &= \frac{1}{12} \begin{pmatrix} -11 & -1 \end{pmatrix} \begin{pmatrix} -1 \\ 11 \end{pmatrix} = 0 \quad (\text{A.5.3.1}) \end{aligned}$$

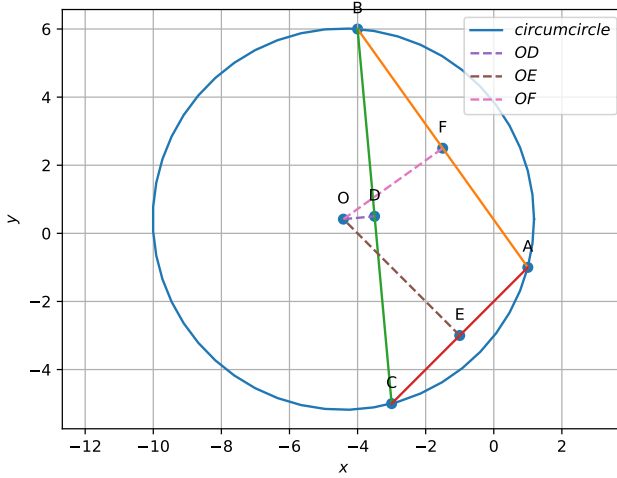


Fig. A.5.5.1: Circumcircle of  $\triangle ABC$  with centre  $\mathbf{O}$ .

A.5.4. Verify that

$$OA = OB = OC \quad (\text{A.5.4.1})$$

A.5.5. Draw the circle with centre at  $\mathbf{O}$  and radius

$$R = OA \quad (\text{A.5.5.1})$$

This is known as the *circumradius*.

**Solution:** See Fig. A.5.5.1.

A.5.6. Verify that

$$\angle BOC = 2\angle BAC. \quad (\text{A.5.6.1})$$

**Solution:**

a) To find the value of  $\angle BOC$  :

$$\mathbf{B} - \mathbf{O} = \begin{pmatrix} \frac{5}{12} \\ \frac{67}{12} \end{pmatrix}, \mathbf{C} - \mathbf{O} = \begin{pmatrix} \frac{17}{12} \\ \frac{-65}{12} \end{pmatrix} \quad (\text{A.5.6.2})$$

$$\Rightarrow (\mathbf{B} - \mathbf{O})^\top (\mathbf{C} - \mathbf{O}) = \frac{-4270}{144} \quad (\text{A.5.6.3})$$

$$\Rightarrow \|\mathbf{B} - \mathbf{O}\| = \frac{\sqrt{4514}}{12}, \|\mathbf{C} - \mathbf{O}\| = \frac{\sqrt{4514}}{12} \quad (\text{A.5.6.4})$$

Thus,

$$\cos BOC = \frac{(\mathbf{B} - \mathbf{O})^\top (\mathbf{C} - \mathbf{O})}{\|\mathbf{B} - \mathbf{O}\| \|\mathbf{C} - \mathbf{O}\|} = \frac{-4270}{4514} \quad (\text{A.5.6.5})$$

$$\Rightarrow \angle BOC = \cos^{-1} \left( \frac{-4270}{4514} \right) \quad (\text{A.5.6.6})$$

$$= 161.07536^\circ \text{ or } 198.92464^\circ \quad (\text{A.5.6.7})$$

b) To find the value of  $\angle BAC$  :

$$\mathbf{B} - \mathbf{A} = \begin{pmatrix} -5 \\ 7 \end{pmatrix}, \mathbf{C} - \mathbf{A} = \begin{pmatrix} -4 \\ -4 \end{pmatrix} \quad (\text{A.5.6.8})$$

$$\Rightarrow (\mathbf{B} - \mathbf{A})^\top (\mathbf{C} - \mathbf{A}) = -8 \quad (\text{A.5.6.9})$$

$$\|\mathbf{B} - \mathbf{A}\| = \sqrt{74} \|\mathbf{C} - \mathbf{A}\| = 4\sqrt{2} \quad (\text{A.5.6.10})$$

Thus,

$$\cos BAC = \frac{(\mathbf{B} - \mathbf{A})^\top (\mathbf{C} - \mathbf{A})}{\|\mathbf{B} - \mathbf{A}\| \|\mathbf{C} - \mathbf{A}\|} = \frac{-8}{4\sqrt{148}} \quad (\text{A.5.6.11})$$

$$\Rightarrow \angle BAC = \cos^{-1} \left( \frac{-8}{4\sqrt{148}} \right) \quad (\text{A.5.6.12})$$

$$= 99.46232^\circ \quad (\text{A.5.6.13})$$

From (A.5.6.13) and (A.5.6.7),

$$2 \times \angle BAC = \angle BOC \quad (\text{A.5.6.14})$$

A.5.7. Let

$$\mathbf{P} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} \quad (\text{A.5.7.1})$$

where

$$\theta = \angle BOC \quad (\text{A.5.7.2})$$

Verify that

$$\mathbf{B} - \mathbf{O} = \mathbf{P}(\mathbf{C} - \mathbf{O}) \quad (\text{A.5.7.3})$$

All codes for this section are available at

codes/triangle/perp-bisect.py

## A.6 Angle Bisector

A.6.1. Let  $\mathbf{D}_3, \mathbf{E}_3, \mathbf{F}_3$ , be points on  $AB, BC$  and  $CA$  respectively such that

$$BD_3 = BF_3 = m, CD_3 = CE_3 = n, AE_3 = AF_3 = p. \quad (\text{A.6.1.1})$$

Obtain  $m, n, p$  in terms of  $a, b, c$  obtained in Problem A.1.2.

**Solution:** From the given information,

$$a = m + n, \quad (\text{A.6.1.2})$$

$$b = n + p, \quad (\text{A.6.1.3})$$

$$c = m + p \quad (\text{A.6.1.4})$$

which can be expressed as

$$\begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{pmatrix} \begin{pmatrix} m \\ n \\ p \end{pmatrix} = \begin{pmatrix} a \\ b \\ c \end{pmatrix} \quad (\text{A.6.1.5})$$

$$\Rightarrow \begin{pmatrix} m \\ n \\ p \end{pmatrix} = \begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{pmatrix}^{-1} \begin{pmatrix} a \\ b \\ c \end{pmatrix} \quad (\text{A.6.1.6})$$

Using row reduction,

$$\left( \begin{array}{ccc|ccc} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 1 \end{array} \right) \quad (\text{A.6.1.7})$$

$$\xleftrightarrow{R_3 \leftarrow R_3 - R_1} \left( \begin{array}{ccc|ccc} 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & -1 & 1 & -1 & 0 & 1 \end{array} \right) \quad (\text{A.6.1.8})$$

$$\xleftrightarrow{\begin{matrix} R_3 \leftarrow R_3 + R_2 \\ R_1 \leftarrow R_1 - R_2 \end{matrix}} \left( \begin{array}{ccc|ccc} 1 & 0 & -1 & 1 & -1 & 0 \\ 0 & 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 2 & -1 & 1 & 1 \end{array} \right) \quad (\text{A.6.1.9})$$

$$\xleftrightarrow{\begin{matrix} R_2 \leftarrow 2R_2 - R_3 \\ R_1 \leftarrow 2R_1 + R_3 \end{matrix}} \left( \begin{array}{ccc|ccc} 2 & 0 & 0 & 1 & -1 & 1 \\ 0 & 2 & 0 & 1 & 1 & -1 \\ 0 & 0 & 2 & -1 & 1 & 1 \end{array} \right) \quad (\text{A.6.1.10})$$

yielding

$$\begin{pmatrix} 1 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 1 \end{pmatrix}^{-1} = \frac{1}{2} \begin{pmatrix} 1 & -1 & 1 \\ 1 & 1 & -1 \\ -1 & 1 & 1 \end{pmatrix} \quad (\text{A.6.1.11})$$

Therefore,

$$\begin{aligned} p &= \frac{c + b - a}{2} = \frac{\sqrt{74} + \sqrt{32} - \sqrt{122}}{2} \\ m &= \frac{a + c - b}{2} = \frac{\sqrt{74} + \sqrt{122} - \sqrt{32}}{2} \\ n &= \frac{a + b - c}{2} = \frac{\sqrt{122} + \sqrt{32} - \sqrt{74}}{2} \end{aligned} \quad (\text{A.6.1.12})$$

upon substituting from (A.1.2.7), (A.1.2.9) and (A.1.2.11).

A.6.2. Using section formula, find

$$\mathbf{D}_3 = \frac{m\mathbf{C} + n\mathbf{B}}{m + n}, \mathbf{E}_3 = \frac{n\mathbf{A} + p\mathbf{C}}{n + p}, \mathbf{F}_3 = \frac{p\mathbf{B} + m\mathbf{A}}{p + m} \quad (\text{A.6.2.1})$$

A.6.3. Find the circumcentre and circumradius of  $\triangle D_3E_3F_3$ . These are the *incentre* and *inradius* of  $\triangle ABC$ .

A.6.4. Draw the circumcircle of  $\triangle D_3E_3F_3$ . This is known as the *incircle* of  $\triangle ABC$ .

**Solution:** See Fig. A.6.4.1

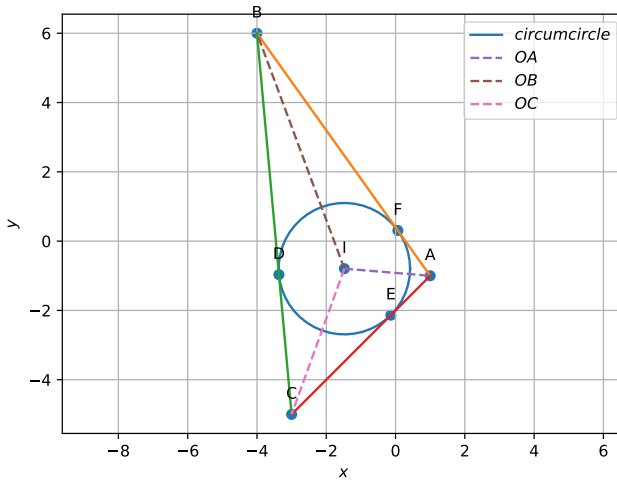


Fig. A.6.4.1: Incircle of  $\triangle ABC$

A.6.5. Using (A.1.7.1) verify that

$$\angle BAI = \angle CAI. \quad (\text{A.6.5.1})$$

$AI$  is the bisector of  $\angle A$ .

A.6.6. Verify that  $BI, CI$  are also the angle bisectors of  $\triangle ABC$ . All codes for this section are available at

codes/triangle/ang-bisect.py

## A.7 Eigenvalues and Eigenvectors

A.7.1. The equation of a circle is given by

$$\|\mathbf{x}\|^2 + 2\mathbf{u}^\top \mathbf{x} + f = 0 \quad (\text{A.7.1.1})$$

for

$$\mathbf{u} = -\mathbf{O}, f = \|\mathbf{O}\|^2 - r^2, \quad (\text{A.7.1.2})$$

**O** being the incentre and  $r$  the inradius.

A.7.2. Compute

$$\Sigma = (\mathbf{V}\mathbf{h} + \mathbf{u})(\mathbf{V}\mathbf{h} + \mathbf{u})^\top - g(\mathbf{h})\mathbf{V} \quad (\text{A.7.2.1})$$

for  $\mathbf{h} = \mathbf{A}$ .

A.7.3. Find the roots of the equation

$$|\lambda\mathbf{I} - \Sigma| = 0 \quad (\text{A.7.3.1})$$

These are known as the eigenvalues of  $\Sigma$ .

A.7.4. Find  $\mathbf{p}$  such that

$$\Sigma\mathbf{p} = \lambda\mathbf{p} \quad (\text{A.7.4.1})$$

using row reduction. These are known as the eigenvectors of  $\Sigma$ .

A.7.5. Define

$$\mathbf{D} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}, \quad (\text{A.7.5.1})$$

$$\mathbf{P} = \begin{pmatrix} \frac{\mathbf{p}_1}{\|\mathbf{p}_1\|} & \frac{\mathbf{p}_2}{\|\mathbf{p}_2\|} \end{pmatrix} \quad (\text{A.7.5.2})$$

A.7.6. Verify that

$$\mathbf{P}^\top = \mathbf{P}^{-1}. \quad (\text{A.7.6.1})$$

$\mathbf{P}$  is defined to be an orthogonal matrix.

A.7.7. Verify that

$$\mathbf{P}^\top \Sigma \mathbf{P} = \mathbf{D}, \quad (\text{A.7.7.1})$$

This is known as the spectral (eigenvalue ) decomposition of a symmetric matrix

A.7.8. The direction vectors of the tangents from a point  $\mathbf{h}$  to the circle in (8.1.1.1) are given by

$$\mathbf{m} = \mathbf{P} \begin{pmatrix} \sqrt{|\lambda_2|} \\ \pm \sqrt{|\lambda_1|} \end{pmatrix} \quad (\text{A.7.8.1})$$

A.7.9. The points of contact of the pair of tangents to the circle in (8.1.1.1) from a point  $\mathbf{h}$  are given by

$$\mathbf{x} = \mathbf{h} + \mu\mathbf{m} \quad (\text{A.7.9.1})$$

where

$$\mu = -\frac{\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})}{\mathbf{m}^\top \mathbf{V}\mathbf{m}} \quad (\text{A.7.9.2})$$

for  $\mathbf{m}$  in (A.7.8.1). Compute the points of contact. You should get the same points that you obtained in the previous section.

All codes for this section are available at

codes/triangle/tangpair.py



### A.8 Formulae

A.8.1 The equation of the *incircle* is given by

$$\|\mathbf{x} - \mathbf{O}\|^2 = r^2 \quad (\text{A.8.1.1})$$

which can be expressed as (8.1.1.1) using (A.7.1.2).

A.8.2 In Fig. A.6.4.1, let (A.7.9.1) be the equation of  $AB$ . Then, the intersection of (A.7.9.1) and (8.1.1.1) can be expressed as

$$(\mathbf{h} + \mu\mathbf{m})^\top \mathbf{V}(\mathbf{h} + \mu\mathbf{m}) + 2\mathbf{u}^\top (\mathbf{h} + \mu\mathbf{m}) + f = 0 \quad (\text{A.8.2.1})$$

$$\implies \mu^2 \mathbf{m}^\top \mathbf{V} \mathbf{m} + 2\mu \mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u}) + g(\mathbf{h}) = 0 \quad (\text{A.8.2.2})$$

For (A.8.2.2) to have exactly one root, the discriminant

$$\{\mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u})\}^2 - g(\mathbf{h}) \mathbf{m}^\top \mathbf{V} \mathbf{m} = 0 \quad (\text{A.8.2.3})$$

and (A.7.9.2) is obtained.

A.8.3 (A.8.2.3) can be expressed as

$$\mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u})^\top (\mathbf{V} \mathbf{h} + \mathbf{u}) \mathbf{m} - g(\mathbf{h}) \mathbf{m}^\top \mathbf{V} \mathbf{m} = 0 \quad (\text{A.8.3.1})$$

$$\implies \mathbf{m}^\top \Sigma \mathbf{m} = 0 \quad (\text{A.8.3.2})$$

for  $\Sigma$  defined in (A.8.3.2). Substituting (A.7.7.1) in (A.8.3.2),

$$\mathbf{m}^\top \mathbf{P} \mathbf{D} \mathbf{P}^\top \mathbf{m} = 0 \quad (\text{A.8.3.3})$$

$$\implies \mathbf{v}^\top \mathbf{D} \mathbf{v} = 0 \quad (\text{A.8.3.4})$$

where

$$\mathbf{v} = \mathbf{P}^\top \mathbf{m} \quad (\text{A.8.3.5})$$

(A.8.3.4) can be expressed as

$$\lambda_1 v_1^2 + \lambda_2 v_2^2 = 0 \quad (\text{A.8.3.6})$$

$$\implies \mathbf{v} = \begin{pmatrix} \sqrt{|\lambda_2|} \\ \pm \sqrt{|\lambda_1|} \end{pmatrix} \quad (\text{A.8.3.7})$$

after some algebra. From (A.8.3.7) and (A.8.3.5) we obtain (A.7.8.1).

### A.9 Matrices

A.9.1. The matrix of the vertices of the triangle is defined as

$$\mathbf{P} = (\mathbf{A} \quad \mathbf{B} \quad \mathbf{C}) \quad (\text{A.9.1.1})$$

A.9.2. Obtain the direction matrix of the sides of  $\triangle ABC$  defined as

$$\mathbf{M} = (\mathbf{A} - \mathbf{B} \quad \mathbf{B} - \mathbf{C} \quad \mathbf{C} - \mathbf{A}) \quad (\text{A.9.2.1})$$

**Solution:**

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} - \mathbf{B} & \mathbf{B} - \mathbf{C} & \mathbf{C} - \mathbf{A} \end{pmatrix} \quad (\text{A.9.2.2})$$

$$= \begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix} \begin{pmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{pmatrix} \quad (\text{A.9.2.3})$$

where the second matrix above is known as a *circulant* matrix. Note that the 2nd and 3rd row of the above matrix are circular shifts of the 1st row.

A.9.3. Obtain the normal matrix of the sides of  $\triangle ABC$

**Solution:** Considering the rotation matrix

$$\mathbf{R} = \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}, \quad (\text{A.9.3.1})$$

the normal matrix is obtained as

$$\mathbf{N} = \mathbf{R}\mathbf{M} \quad (\text{A.9.3.2})$$

A.9.4. Obtain  $a, b, c$ .

**Solution:** The sides vector is obtained as

$$\mathbf{d} = \sqrt{\text{diag}(\mathbf{M}^T \mathbf{M})} \quad (\text{A.9.4.1})$$

A.9.5. Obtain the constant terms in the equations of the sides of the triangle.

**Solution:** The constants for the lines can be expressed in vector form as

$$\mathbf{c} = \text{diag} \{ (\mathbf{N}^T \mathbf{P}) \} \quad (\text{A.9.5.1})$$

A.9.6. Obtain the mid point matrix for the sides of the triangle

**Solution:**

$$\begin{pmatrix} \mathbf{D} & \mathbf{E} & \mathbf{F} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \quad (\text{A.9.6.1})$$

A.9.7. Obtain the median direction matrix.

**Solution:** The median direction matrix is given by

$$\mathbf{M}_1 = \begin{pmatrix} \mathbf{A} - \mathbf{D} & \mathbf{B} - \mathbf{E} & \mathbf{C} - \mathbf{F} \end{pmatrix} \quad (\text{A.9.7.1})$$

$$= \begin{pmatrix} \mathbf{A} - \frac{\mathbf{B} + \mathbf{C}}{2} & \mathbf{B} - \frac{\mathbf{C} + \mathbf{A}}{2} & \mathbf{C} - \frac{\mathbf{A} + \mathbf{B}}{2} \end{pmatrix} \quad (\text{A.9.7.2})$$

$$= \begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{C} \end{pmatrix} \begin{pmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ -\frac{1}{2} & 1 & -\frac{1}{2} \\ -\frac{1}{2} & -\frac{1}{2} & 1 \end{pmatrix} \quad (\text{A.9.7.3})$$

A.9.8. Obtain the median normal matrix.

A.9.9. Obtain the median equation constants.

A.9.10. Obtain the centroid by finding the intersection of the medians.

A.9.11. Find the normal matrix for the altitudes

**Solution:** The desired matrix is

$$\mathbf{M}_2 = (\mathbf{B} - \mathbf{C} \quad \mathbf{C} - \mathbf{A} \quad \mathbf{A} - \mathbf{B}) \quad (\text{A.9.11.1})$$

$$= (\mathbf{A} \quad \mathbf{B} \quad \mathbf{C}) \begin{pmatrix} 0 & -1 & 1 \\ 1 & 0 & -1 \\ -1 & 1 & 0 \end{pmatrix} \quad (\text{A.9.11.2})$$

A.9.12. Find the constants vector for the altitudes.

**Solution:** The desired vector is

$$\mathbf{c}_2 = \text{diag} \{ (\mathbf{M}^\top \mathbf{P}) \} \quad (\text{A.9.12.1})$$

A.9.13. Find the normal matrix for the perpendicular bisectors

**Solution:** The normal matrix is  $\mathbf{M}_2$

A.9.14. Find the constants vector for the perpendicular bisectors.

**Solution:** The desired vector is

$$\mathbf{c}_3 = \text{diag} \{ \mathbf{M}_2^\top (\mathbf{D} \quad \mathbf{E} \quad \mathbf{F}) \} \quad (\text{A.9.14.1})$$

A.9.15. Find the points of contact.

**Solution:** The points of contact are given by

$$\begin{pmatrix} \frac{m\mathbf{C}+n\mathbf{B}}{m+n} & \frac{n\mathbf{A}+p\mathbf{C}}{n+p} & \frac{p\mathbf{B}+m\mathbf{A}}{p+m} \end{pmatrix} = (\mathbf{A} \quad \mathbf{B} \quad \mathbf{C}) \begin{pmatrix} 0 & \frac{n}{b} & \frac{m}{c} \\ \frac{n}{a} & 0 & \frac{p}{c} \\ \frac{m}{a} & \frac{p}{b} & 0 \end{pmatrix} \quad (\text{A.9.15.1})$$

All codes for this section are available at

codes/triangle/mat-alg.py

## APPENDIX B

### CONIC SECTION

#### B.1 Equation

B.1.1. Let  $\mathbf{q}$  be a point such that the ratio of its distance from a fixed point  $\mathbf{F}$  and the distance ( $d$ ) from a fixed line

$$L : \mathbf{n}^\top \mathbf{x} = c \quad (\text{B.1.1.1})$$

is constant, given by

$$\frac{\|\mathbf{q} - \mathbf{F}\|}{d} = e \quad (\text{B.1.1.2})$$

The locus of  $\mathbf{q}$  is known as a conic section. The line  $L$  is known as the directrix and the point  $\mathbf{F}$  is the focus.  $e$  is defined to be the eccentricity of the conic.

- a) For  $e = 1$ , the conic is a parabola
- b) For  $e < 1$ , the conic is an ellipse
- c) For  $e > 1$ , the conic is a hyperbola

B.1.2. The equation of a conic with directrix  $\mathbf{n}^\top \mathbf{x} = c$ , eccentricity  $e$  and focus  $\mathbf{F}$  is given by

$$\mathbf{g}(\mathbf{x}) = \mathbf{x}^\top \mathbf{V} \mathbf{x} + 2\mathbf{u}^\top \mathbf{x} + f = 0 \quad (\text{B.1.2.1})$$

where

$$\mathbf{V} = \|\mathbf{n}\|^2 \mathbf{I} - e^2 \mathbf{n} \mathbf{n}^\top, \quad (\text{B.1.2.2})$$

$$\mathbf{u} = ce^2 \mathbf{n} - \|\mathbf{n}\|^2 \mathbf{F}, \quad (\text{B.1.2.3})$$

$$f = \|\mathbf{n}\|^2 \|\mathbf{F}\|^2 - c^2 e^2 \quad (\text{B.1.2.4})$$

**Solution:** Using Definition B.1.1 and (4.1.6.6), for any point  $\mathbf{x}$  on the conic,

$$\|\mathbf{x} - \mathbf{F}\|^2 = e^2 \frac{(\mathbf{n}^\top \mathbf{x} - c)^2}{\|\mathbf{n}\|^2} \quad (\text{B.1.2.5})$$

$$\implies \|\mathbf{n}\|^2 (\mathbf{x} - \mathbf{F})^\top (\mathbf{x} - \mathbf{F}) = e^2 (\mathbf{n}^\top \mathbf{x} - c)^2 \quad (\text{B.1.2.6})$$

$$\implies \|\mathbf{n}\|^2 (\mathbf{x}^\top \mathbf{x} - 2\mathbf{F}^\top \mathbf{x} + \|\mathbf{F}\|^2) = e^2 (c^2 + (\mathbf{n}^\top \mathbf{x})^2 - 2c\mathbf{n}^\top \mathbf{x}) \quad (\text{B.1.2.7})$$

$$= e^2 (c^2 + (\mathbf{x}^\top \mathbf{n} \mathbf{n}^\top \mathbf{x}) - 2c\mathbf{n}^\top \mathbf{x}) \quad (\text{B.1.2.8})$$

which can be expressed as (B.1.2.1) after simplification.

B.1.3. The eccentricity, directrices and foci of (B.1.2.1) are given by

$$e = \sqrt{1 - \frac{\lambda_1}{\lambda_2}} \quad (\text{B.1.3.1})$$

$$\mathbf{n} = \sqrt{\lambda_2} \mathbf{p}_1,$$

$$c = \begin{cases} \frac{e \mathbf{u}^\top \mathbf{n} \pm \sqrt{e^2 (\mathbf{u}^\top \mathbf{n})^2 - \lambda_2 (e^2 - 1) (\|\mathbf{u}\|^2 - \lambda_2 f)}}{\lambda_2 e (e^2 - 1)} & e \neq 1 \\ \frac{\|\mathbf{u}\|^2 - \lambda_2 f}{2 \mathbf{u}^\top \mathbf{n}} & e = 1 \end{cases} \quad (\text{B.1.3.2})$$

$$\mathbf{F} = \frac{ce^2 \mathbf{n} - \mathbf{u}}{\lambda_2} \quad (\text{B.1.3.3})$$

**Solution:** From (B.1.2.2), using the fact that  $\mathbf{V}$  is symmetric with  $\mathbf{V} = \mathbf{V}^\top$ ,

$$\mathbf{V}^\top \mathbf{V} = (\|\mathbf{n}\|^2 \mathbf{I} - e^2 \mathbf{n} \mathbf{n}^\top)^\top (\|\mathbf{n}\|^2 \mathbf{I} - e^2 \mathbf{n} \mathbf{n}^\top) \quad (\text{B.1.3.4})$$

$$\Rightarrow \mathbf{V}^2 = \|\mathbf{n}\|^4 \mathbf{I} + e^4 \mathbf{n} \mathbf{n}^\top \mathbf{n} \mathbf{n}^\top - 2e^2 \|\mathbf{n}\|^2 \mathbf{n} \mathbf{n}^\top \quad (\text{B.1.3.5})$$

$$= \|\mathbf{n}\|^4 \mathbf{I} + e^4 \|\mathbf{n}\|^2 \mathbf{n} \mathbf{n}^\top - 2e^2 \|\mathbf{n}\|^2 \mathbf{n} \mathbf{n}^\top \quad (\text{B.1.3.6})$$

$$= \|\mathbf{n}\|^4 \mathbf{I} + e^2 (e^2 - 2) \|\mathbf{n}\|^2 \mathbf{n} \mathbf{n}^\top \quad (\text{B.1.3.7})$$

$$= \|\mathbf{n}\|^4 \mathbf{I} + (e^2 - 2) \|\mathbf{n}\|^2 (\|\mathbf{n}\|^2 \mathbf{I} - \mathbf{V}) \quad (\text{B.1.3.8})$$

which can be expressed as

$$\mathbf{V}^2 + (e^2 - 2) \|\mathbf{n}\|^2 \mathbf{V} - (e^2 - 1) \|\mathbf{n}\|^4 \mathbf{I} = 0 \quad (\text{B.1.3.9})$$

Using the Cayley-Hamilton theorem, (B.1.3.9) results in the characteristic equation,

$$\lambda^2 - (2 - e^2) \|\mathbf{n}\|^2 \lambda + (1 - e^2) \|\mathbf{n}\|^4 = 0 \quad (\text{B.1.3.10})$$

which can be expressed as

$$\left( \frac{\lambda}{\|\mathbf{n}\|^2} \right)^2 - (2 - e^2) \left( \frac{\lambda}{\|\mathbf{n}\|^2} \right) + (1 - e^2) = 0 \quad (\text{B.1.3.11})$$

$$\Rightarrow \frac{\lambda}{\|\mathbf{n}\|^2} = 1 - e^2, 1 \quad (\text{B.1.3.12})$$

$$\text{or, } \lambda_2 = \|\mathbf{n}\|^2, \lambda_1 = (1 - e^2) \lambda_2 \quad (\text{B.1.3.13})$$

From (B.1.3.13), the eccentricity of (B.1.2.1) is given by (B.1.3.1). Multiplying both sides of (B.1.2.2) by  $\mathbf{n}$ ,

$$\mathbf{V} \mathbf{n} = \|\mathbf{n}\|^2 \mathbf{n} - e^2 \mathbf{n} \mathbf{n}^\top \mathbf{n} \quad (\text{B.1.3.14})$$

$$= \|\mathbf{n}\|^2 (1 - e^2) \mathbf{n} \quad (\text{B.1.3.15})$$

$$= \lambda_1 \mathbf{n} \quad (\text{B.1.3.16})$$

$$(\text{B.1.3.17})$$

from (B.1.3.13). Thus,  $\lambda_1$  is the corresponding eigenvalue for  $\mathbf{n}$ . From (A.7.5.2) and

(B.1.3.17), this implies that

$$\mathbf{p}_1 = \frac{\mathbf{n}}{\|\mathbf{n}\|} \quad (\text{B.1.3.18})$$

$$\text{or, } \mathbf{n} = \|\mathbf{n}\| \mathbf{p}_1 = \sqrt{\lambda_2} \mathbf{p}_1 \quad (\text{B.1.3.19})$$

from (B.1.3.13) . From (B.1.2.3) and (B.1.3.13),

$$\mathbf{F} = \frac{ce^2 \mathbf{n} - \mathbf{u}}{\lambda_2} \quad (\text{B.1.3.20})$$

$$\Rightarrow \|\mathbf{F}\|^2 = \frac{(ce^2 \mathbf{n} - \mathbf{u})^\top (ce^2 \mathbf{n} - \mathbf{u})}{\lambda_2^2} \quad (\text{B.1.3.21})$$

$$\Rightarrow \lambda_2^2 \|\mathbf{F}\|^2 = c^2 e^4 \lambda_2 - 2ce^2 \mathbf{u}^\top \mathbf{n} + \|\mathbf{u}\|^2 \quad (\text{B.1.3.22})$$

Also, (B.1.2.4) can be expressed as

$$\lambda_2 \|\mathbf{F}\|^2 = f + c^2 e^2 \quad (\text{B.1.3.23})$$

From (B.1.3.22) and (B.1.3.23),

$$c^2 e^4 \lambda_2 - 2ce^2 \mathbf{u}^\top \mathbf{n} + \|\mathbf{u}\|^2 = \lambda_2 (f + c^2 e^2) \quad (\text{B.1.3.24})$$

$$\Rightarrow \lambda_2 e^2 (e^2 - 1) c^2 - 2ce^2 \mathbf{u}^\top \mathbf{n} + \|\mathbf{u}\|^2 - \lambda_2 f = 0 \quad (\text{B.1.3.25})$$

yielding (B.1.3.3).

B.1.4. (B.1.2.1) represents

- a) a parabola for  $|\mathbf{V}| = 0$ ,
- b) ellipse for  $|\mathbf{V}| > 0$  and
- c) hyperbola for  $|\mathbf{V}| < 0$ .

**Solution:** From (B.1.3.1),

$$\frac{\lambda_1}{\lambda_2} = 1 - e^2 \quad (\text{B.1.4.1})$$

Also,

$$|\mathbf{V}| = \lambda_1 \lambda_2 \quad (\text{B.1.4.2})$$

yielding Table B.1.4.

Eccentricity	Conic	Eigenvalue	Determinant
$e = 1$	Parabola	$\lambda_1 = 0$	$ \mathbf{V}  = 0$
$e < 1$	Ellipse	$\lambda_1 > 0, \lambda_2 > 0$	$ \mathbf{V}  > 0$
$e > 1$	Hyperbola	$\lambda_1 < 0, \lambda_2 > 0$	$ \mathbf{V}  < 0$

TABLE B.1.4

B.1.5. Using the affine transformation in (2.1.15.1), the conic in (B.1.2.1) can be expressed

in standard form as

$$\mathbf{y}^\top \left( \frac{\mathbf{D}}{f_0} \right) \mathbf{y} = 1 \quad |\mathbf{V}| \neq 0 \quad (\text{B.1.5.1})$$

$$\mathbf{y}^\top \mathbf{D} \mathbf{y} = -\eta \mathbf{e}_1^\top \mathbf{y} \quad |\mathbf{V}| = 0 \quad (\text{B.1.5.2})$$

where

$$f_0 = \mathbf{u}^\top \mathbf{V}^{-1} \mathbf{u} - f \neq 0 \quad (\text{B.1.5.3})$$

$$\eta = 2\mathbf{u}^\top \mathbf{p}_1 \quad (\text{B.1.5.4})$$

$$\mathbf{e}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (\text{B.1.5.5})$$

**Solution:** Using (2.1.15.1), (B.1.2.1) can be expressed as

$$(\mathbf{P} \mathbf{y} + \mathbf{c})^\top \mathbf{V} (\mathbf{P} \mathbf{y} + \mathbf{c}) + 2\mathbf{u}^\top (\mathbf{P} \mathbf{y} + \mathbf{c}) + f = 0, \quad (\text{B.1.5.6})$$

yielding

$$\mathbf{y}^\top \mathbf{P}^\top \mathbf{V} \mathbf{P} \mathbf{y} + 2(\mathbf{V} \mathbf{c} + \mathbf{u})^\top \mathbf{P} \mathbf{y} + \mathbf{c}^\top \mathbf{V} \mathbf{c} + 2\mathbf{u}^\top \mathbf{c} + f = 0 \quad (\text{B.1.5.7})$$

From (B.1.5.7) and (A.7.7.1),

$$\mathbf{y}^\top \mathbf{D} \mathbf{y} + 2(\mathbf{V} \mathbf{c} + \mathbf{u})^\top \mathbf{P} \mathbf{y} + \mathbf{c}^\top (\mathbf{V} \mathbf{c} + \mathbf{u}) + \mathbf{u}^\top \mathbf{c} + f = 0 \quad (\text{B.1.5.8})$$

When  $\mathbf{V}^{-1}$  exists, choosing

$$\mathbf{V} \mathbf{c} + \mathbf{u} = \mathbf{0}, \quad \text{or, } \mathbf{c} = -\mathbf{V}^{-1} \mathbf{u}, \quad (\text{B.1.5.9})$$

and substituting (B.1.5.9) in (B.1.5.8) yields (B.1.5.1). When  $|\mathbf{V}| = 0, \lambda_1 = 0$  and

$$\mathbf{V} \mathbf{p}_1 = \mathbf{0}, \mathbf{V} \mathbf{p}_2 = \lambda_2 \mathbf{p}_2. \quad (\text{B.1.5.10})$$

Substituting (8.1.3.2) in (B.1.5.8),

$$\begin{aligned} & \mathbf{y}^\top \mathbf{D} \mathbf{y} + 2(\mathbf{c}^\top \mathbf{V} + \mathbf{u}^\top) (\mathbf{p}_1 \quad \mathbf{p}_2) \mathbf{y} + \mathbf{c}^\top (\mathbf{V} \mathbf{c} + \mathbf{u}) + \mathbf{u}^\top \mathbf{c} + f = 0 \\ \implies & \mathbf{y}^\top \mathbf{D} \mathbf{y} + 2((\mathbf{c}^\top \mathbf{V} + \mathbf{u}^\top) \mathbf{p}_1 \quad (\mathbf{c}^\top \mathbf{V} + \mathbf{u}^\top) \mathbf{p}_2) \mathbf{y} + \mathbf{c}^\top (\mathbf{V} \mathbf{c} + \mathbf{u}) + \mathbf{u}^\top \mathbf{c} + f = 0 \\ \implies & \mathbf{y}^\top \mathbf{D} \mathbf{y} + 2(\mathbf{u}^\top \mathbf{p}_1 \quad (\lambda_2 \mathbf{c}^\top + \mathbf{u}^\top) \mathbf{p}_2) \mathbf{y} + \mathbf{c}^\top (\mathbf{V} \mathbf{c} + \mathbf{u}) + \mathbf{u}^\top \mathbf{c} + f = 0 \end{aligned}$$

upon substituting from (B.1.5.10), yielding

$$\lambda_2 y_2^2 + 2(\mathbf{u}^\top \mathbf{p}_1) y_1 + 2y_2 (\lambda_2 \mathbf{c} + \mathbf{u})^\top \mathbf{p}_2 + \mathbf{c}^\top (\mathbf{V} \mathbf{c} + \mathbf{u}) + \mathbf{u}^\top \mathbf{c} + f = 0 \quad (\text{B.1.5.11})$$

Thus, (B.1.5.11) can be expressed as (B.1.5.2) by choosing

$$\eta = 2\mathbf{u}^\top \mathbf{p}_1 \quad (\text{B.1.5.12})$$

and  $\mathbf{c}$  in (B.1.5.8) such that

$$2\mathbf{P}^\top (\mathbf{V} \mathbf{c} + \mathbf{u}) = \eta \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad (\text{B.1.5.13})$$

$$\mathbf{c}^\top (\mathbf{V} \mathbf{c} + \mathbf{u}) + \mathbf{u}^\top \mathbf{c} + f = 0 \quad (\text{B.1.5.14})$$

B.1.6. The center/vertex of a conic section are given by

$$\mathbf{c} = -\mathbf{V}^{-1}\mathbf{u} \quad |\mathbf{V}| \neq 0 \quad (\text{B.1.6.1})$$

$$\begin{pmatrix} \mathbf{u}^\top + \frac{\eta}{2}\mathbf{p}_1^\top \\ \mathbf{v} \end{pmatrix} \mathbf{c} = \begin{pmatrix} -f \\ \frac{\eta}{2}\mathbf{p}_1 - \mathbf{u} \end{pmatrix} \quad |\mathbf{V}| = 0 \quad (\text{B.1.6.2})$$

**Solution:**  $\because \mathbf{P}^\top \mathbf{P} = \mathbf{I}$ , multiplying (B.1.5.13) by  $\mathbf{P}$  yields

$$(\mathbf{V}\mathbf{c} + \mathbf{u}) = \frac{\eta}{2}\mathbf{p}_1, \quad (\text{B.1.6.3})$$

which, upon substituting in (B.1.5.14) results in

$$\frac{\eta}{2}\mathbf{c}^\top \mathbf{p}_1 + \mathbf{u}^\top \mathbf{c} + f = 0 \quad (\text{B.1.6.4})$$

(B.1.6.3) and (B.1.6.4) can be clubbed together to obtain (B.1.6.2).

B.1.7. In (2.1.15.1), substituting  $\mathbf{y} = \mathbf{0}$ , the center/vertex for the quadratic form is obtained as

$$\mathbf{x} = \mathbf{c}, \quad (\text{B.1.7.1})$$

where  $\mathbf{c}$  is derived as (B.1.6.1) and (B.1.6.2) in Appendix B.1.5.

## B.2 Standard Conic

B.2.1. For the standard conic,

$$\mathbf{P} = \mathbf{I} \quad (\text{B.2.1.1})$$

$$\mathbf{u} = \begin{cases} 0 & e \neq 1 \\ \frac{\eta}{2}\mathbf{e}_1 & e = 1 \end{cases} \quad (\text{B.2.1.2})$$

$$\lambda_1 \begin{cases} = 0 & e = 1 \\ \neq 0 & e \neq 1 \end{cases} \quad (\text{B.2.1.3})$$

where

$$\mathbf{I} = (\mathbf{e}_1 \quad \mathbf{e}_2) \quad (\text{B.2.1.4})$$

is the identity matrix.

B.2.2. The center of the standard ellipse/hyperbola, defined to be the mid point of the line joining the foci, is the origin.

B.2.3. The principal (major) axis of the standard ellipse/hyperbola, defined to be the line joining the two foci is the  $x$ -axis.

*Proof.* From (B.2.7.3), it is obvious that the line joining the foci passes through the origin. Also, the direction vector of this line is  $\mathbf{e}_1$ . Thus, the principal axis is the  $x$ -axis.  $\square$

B.2.4. The minor axis of the standard ellipse/hyperbola, defined to be the line orthogonal to the  $x$ -axis is the  $y$ -axis.

B.2.5. The axis of symmetry of the standard parabola, defined to be the line perpendicular to the directrix and passing through the focus, is the  $x$ -axis.



*Proof.* From (B.2.7.7) and (B.2.7.3), the axis of the parabola can be expressed as

$$\mathbf{e}_2^\top \left( \mathbf{y} + \frac{\eta}{4\lambda_2} \mathbf{e}_1 \right) = 0 \quad (\text{B.2.5.1})$$

$$\implies \mathbf{e}_2^\top \mathbf{y} = 0, \quad (\text{B.2.5.2})$$

which is the equation of the  $x$ -axis.  $\square$

B.2.6. The point where the parabola intersects its axis of symmetry is called the vertex. For the standard parabola, the vertex is the origin.

*Proof.* (B.2.5.2) can be expressed as

$$\mathbf{y} = \alpha \mathbf{e}_1. \quad (\text{B.2.6.1})$$

Substituting (B.2.6.1) in (B.1.5.2),

$$\alpha^2 \mathbf{e}_1^\top \mathbf{D} \mathbf{e}_1 = -\eta \alpha \mathbf{e}_1^\top \mathbf{e}_1 \quad (\text{B.2.6.2})$$

$$\implies \alpha = 0, \text{ or, } \mathbf{y} = \mathbf{0}. \quad (\text{B.2.6.3})$$

$\square$

B.2.7.

a) The directrices for the standard conic are given by

$$\mathbf{e}_1^\top \mathbf{y} = \pm \frac{1}{e} \sqrt{\frac{|f_0|}{\lambda_2(1-e^2)}} \quad e \neq 1 \quad (\text{B.2.7.1})$$

$$\mathbf{e}_1^\top \mathbf{y} = \frac{\eta}{2\lambda_2} \quad e = 1 \quad (\text{B.2.7.2})$$

b) The foci of the standard ellipse and hyperbola are given by

$$\mathbf{F} = \begin{cases} \pm e \sqrt{\frac{|f_0|}{\lambda_2(1-e^2)}} \mathbf{e}_1 & e \neq 1 \\ -\frac{\eta}{4\lambda_2} \mathbf{e}_1 & e = 1 \end{cases} \quad (\text{B.2.7.3})$$

*Proof.* a) For the standard hyperbola/ellipse in (B.1.5.1), from (B.2.1.1), (B.1.3.2) and (B.2.1.2),

$$\mathbf{n} = \sqrt{\frac{\lambda_2}{f_0}} \mathbf{e}_1 \quad (\text{B.2.7.4})$$

$$c = \pm \frac{\sqrt{-\frac{\lambda_2}{f_0} (e^2 - 1) \left(\frac{\lambda_2}{f_0}\right)}}{\frac{\lambda_2}{f_0} e (e^2 - 1)} \quad (\text{B.2.7.5})$$

$$= \pm \frac{1}{e \sqrt{1 - e^2}} \quad (\text{B.2.7.6})$$

yielding (B.2.7.1) upon substituting from (B.1.3.1) and simplifying. For the standard parabola in (B.1.5.2), from (B.2.1.1), (B.1.3.2) and (B.2.1.2), noting that  $f = 0$ ,

$$\mathbf{n} = \sqrt{\lambda_2} \mathbf{e}_1 \quad (\text{B.2.7.7})$$

$$c = \frac{\left\| \frac{\eta}{2} \mathbf{e}_1 \right\|^2}{2 \left( \frac{\eta}{2} \right) (\mathbf{e}_1)^\top \mathbf{n}} \quad (\text{B.2.7.8})$$

$$(\text{B.2.7.9})$$

$$= \frac{\eta}{4 \sqrt{\lambda_2}} \quad (\text{B.2.7.10})$$

yielding (B.2.7.2).

- b) For the standard ellipse/hyperbola, substituting from (B.2.7.6), (B.2.7.4), (B.2.1.2) and (B.1.3.1) in (B.1.3.3),

$$\mathbf{F} = \pm \frac{\left( \frac{1}{e \sqrt{1-e^2}} \right) (e^2) \sqrt{\frac{\lambda_2}{f_0}} \mathbf{e}_1}{\frac{\lambda_2}{f_0}} \quad (\text{B.2.7.11})$$

yielding (B.2.7.3) after simplification. For the standard parabola, substituting from (B.2.7.10), (B.2.7.7), (B.2.1.2) and (B.1.3.1) in (B.1.3.3),

$$\mathbf{F} = \frac{\left( \frac{\eta}{4 \sqrt{\lambda_2}} \right) \sqrt{\lambda_2} \mathbf{e}_1 - \frac{\eta}{2} \mathbf{e}_1}{\lambda_2} \quad (\text{B.2.7.12})$$

$$(\text{B.2.7.13})$$

yielding (B.2.7.3) after simplification.

□

B.2.8. The *focal length* of the standard parabola, , defined to be the distance between the vertex and the focus, measured along the axis of symmetry, is  $\left| \frac{\eta}{4\lambda_2} \right|$

### B.3 Conic Lines

B.3.1. The points of intersection of the line

$$L : \quad \mathbf{x} = \mathbf{h} + \kappa \mathbf{m} \quad \kappa \in \mathbb{R} \quad (\text{B.3.1.1})$$

with the conic section in (B.1.2.1) are given by

$$\mathbf{x}_i = \mathbf{h} + \kappa_i \mathbf{m} \quad (\text{B.3.1.2})$$

where

$$\kappa_i = \frac{1}{\mathbf{m}^\top \mathbf{V} \mathbf{m}} \left( -\mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u}) \pm \sqrt{[\mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u})]^2 - g(\mathbf{h}) (\mathbf{m}^\top \mathbf{V} \mathbf{m})} \right) \quad (\text{B.3.1.3})$$

**Solution:** Substituting (B.3.1.1) in (B.1.2.1),

$$(\mathbf{h} + \kappa \mathbf{m})^\top \mathbf{V} (\mathbf{h} + \kappa \mathbf{m}) + 2\mathbf{u}^\top (\mathbf{h} + \kappa \mathbf{m}) + f = 0 \quad (\text{B.3.1.4})$$

$$\implies \kappa^2 \mathbf{m}^\top \mathbf{V} \mathbf{m} + 2\kappa \mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u}) + \mathbf{h}^\top \mathbf{V} \mathbf{h} + 2\mathbf{u}^\top \mathbf{h} + f = 0 \quad (\text{B.3.1.5})$$

$$\text{or, } \kappa^2 \mathbf{m}^\top \mathbf{V} \mathbf{m} + 2\kappa \mathbf{m}^\top (\mathbf{V} \mathbf{h} + \mathbf{u}) + g(\mathbf{h}) = 0 \quad (\text{B.3.1.6})$$

for  $g$  defined in (B.1.2.1). Solving the above quadratic in (B.3.1.6) yields (B.3.1.3).

B.3.2. The length of the chord in (B.3.1.1) is given by

$$\frac{2 \sqrt{[\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})]^2 - (\mathbf{h}^\top \mathbf{V}\mathbf{h} + 2\mathbf{u}^\top \mathbf{h} + f) (\mathbf{m}^\top \mathbf{V}\mathbf{m})}}{\mathbf{m}^\top \mathbf{V}\mathbf{m}} \|\mathbf{m}\| \quad (\text{B.3.2.1})$$

*Proof.* The distance between the points in (B.3.1.2) is given by

$$\|\mathbf{x}_1 - \mathbf{x}_2\| = |\kappa_1 - \kappa_2| \|\mathbf{m}\| \quad (\text{B.3.2.2})$$

Substituting  $\kappa_i$  from (B.3.1.3) in (B.3.2.2) yields (B.3.2.1).  $\square$

B.3.3. The affine transform for the conic section, preserves the norm. This implies that the length of any chord of a conic is invariant to translation and/or rotation.

*Proof.* Let

$$\mathbf{x}_i = \mathbf{P}\mathbf{y}_i + \mathbf{c} \quad (\text{B.3.3.1})$$

be any two points on the conic. Then the distance between the points is given by

$$\|\mathbf{x}_1 - \mathbf{x}_2\| = \|\mathbf{P}(\mathbf{y}_1 - \mathbf{y}_2)\| \quad (\text{B.3.3.2})$$

which can be expressed as

$$\|\mathbf{x}_1 - \mathbf{x}_2\|^2 = (\mathbf{y}_1 - \mathbf{y}_2)^\top \mathbf{P}^\top \mathbf{P} (\mathbf{y}_1 - \mathbf{y}_2) \quad (\text{B.3.3.3})$$

$$= \|\mathbf{y}_1 - \mathbf{y}_2\|^2 \quad (\text{B.3.3.4})$$

since

$$\mathbf{P}^\top \mathbf{P} = \mathbf{I} \quad (\text{B.3.3.5})$$

$\square$

B.3.4. For the standard hyperbola/ellipse, the length of the major axis is

$$2 \sqrt{\left| \frac{f_0}{\lambda_1} \right|} \quad (\text{B.3.4.1})$$

and the minor axis is

$$2 \sqrt{\left| \frac{f_0}{\lambda_2} \right|} \quad (\text{B.3.4.2})$$

**Solution:** Since the major axis passes through the origin,

$$\mathbf{q} = \mathbf{0} \quad (\text{B.3.4.3})$$

Further, from Corollary (B.2.3),

$$\mathbf{m} = \mathbf{e}_2, \quad (\text{B.3.4.4})$$

and from (B.1.5.1),

$$\mathbf{V} = \frac{\mathbf{D}}{f_0}, \mathbf{u} = \mathbf{0}, f = -1 \quad (\text{B.3.4.5})$$

Substituting the above in (B.3.2.1),

$$\frac{2\sqrt{\mathbf{e}_1^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_1}}{\mathbf{e}_1^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_1} \|\mathbf{e}_1\| \quad (\text{B.3.4.6})$$

yielding (B.3.4.1). Similarly, for the minor axis, the only different parameter is

$$\mathbf{m} = \mathbf{e}_2, \quad (\text{B.3.4.7})$$

Substituting the above in (B.3.2.1),

$$\frac{2\sqrt{\mathbf{e}_2^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_2}}{\mathbf{e}_2^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_2} \|\mathbf{e}_2\| \quad (\text{B.3.4.8})$$

yielding (B.3.4.2).

B.3.5. The equation of the minor and major axes for the ellipse/hyperbola are respectively given by

$$\mathbf{p}_i^\top (\mathbf{x} - \mathbf{c}) = 0, i = 1, 2 \quad (\text{B.3.5.1})$$

The axis of symmetry for the parabola is also given by (B.3.5.1).

*Proof.* From (B.2.3), the major/symmetry axis for the hyperbola/ellipse/parabola can be expressed using (2.1.15.1) as

$$\mathbf{e}_2^\top \mathbf{P}^\top (\mathbf{x} - \mathbf{c}) = 0 \quad (\text{B.3.5.2})$$

$$\implies (\mathbf{P}\mathbf{e}_2)^\top (\mathbf{x} - \mathbf{c}) = 0 \quad (\text{B.3.5.3})$$

yielding (B.3.5.1), and the proof for the minor axis is similar.  $\square$

B.3.6. The latus rectum of a conic section is the chord that passes through the focus and is perpendicular to the major axis. The length of the latus rectum for a conic is given by

$$l = \begin{cases} 2\frac{\sqrt{|f_0\lambda_1|}}{\lambda_2} & e \neq 1 \\ \frac{\eta}{\lambda_2} & e = 1 \end{cases} \quad (\text{B.3.6.1})$$

**Solution:** The latus rectum is perpendicular to the major axis for the standard conic. Hence, from Corollary (B.2.3),

$$\mathbf{m} = \mathbf{e}_2, \quad (\text{B.3.6.2})$$

Since it passes through the focus, from (B.2.7.3)

$$\mathbf{q} = \mathbf{F} = \pm e \sqrt{\frac{f_0}{\lambda_2(1-e^2)}} \mathbf{e}_1 \quad (\text{B.3.6.3})$$

for the standard hyperbola/ellipse. Also, from (B.1.5.1),

$$\mathbf{v} = \frac{\mathbf{D}}{f_0}, \mathbf{u} = 0, f = -1 \quad (\text{B.3.6.4})$$

Substituting the above in (B.3.2.1), we obtain

$$\frac{2\sqrt{\left[\mathbf{e}_2^\top \left(\frac{\mathbf{D}}{f_0} e \sqrt{\frac{f_0}{\lambda_2(1-e^2)}} \mathbf{e}_1\right)\right]^2 - \left(e \sqrt{\frac{f_0}{\lambda_2(1-e^2)}} \mathbf{e}_1^\top \frac{\mathbf{D}}{f_0} e \sqrt{\frac{f_0}{\lambda_2(1-e^2)}} \mathbf{e}_1 - 1\right) \left(\mathbf{e}_2^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_2\right)}}{\mathbf{e}_2^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_2} \|\mathbf{e}_2\| \quad (\text{B.3.6.5})$$

Since

$$\mathbf{e}_2^\top \mathbf{D} \mathbf{e}_1 = 0, \mathbf{e}_1^\top \mathbf{D} \mathbf{e}_1 = \lambda_1, \mathbf{e}_1^\top \mathbf{e}_1 = 1, \|\mathbf{e}_2\| = 1, \mathbf{e}_2^\top \mathbf{D} \mathbf{e}_2 = \lambda_2, \quad (\text{B.3.6.6})$$

(B.3.6.5) can be expressed as

$$\frac{2\sqrt{\left(1 - \frac{\lambda_1 e^2}{\lambda_2(1-e^2)}\right) \left(\frac{\lambda_2}{f_0}\right)}}{\frac{\lambda_2}{f_0}} \quad (\text{B.3.6.7})$$

$$= 2 \frac{\sqrt{f_0 \lambda_1}}{\lambda_2} \quad \left(\because e^2 = 1 - \frac{\lambda_1}{\lambda_2}\right) \quad (\text{B.3.6.8})$$

For the standard parabola, the parameters in (B.3.2.1) are

$$\mathbf{q} = \mathbf{F} = -\frac{\eta}{4\lambda_2} \mathbf{e}_1, \mathbf{m} = \mathbf{e}_1, \mathbf{V} = \mathbf{D}, \mathbf{u} = \frac{\eta}{2} \mathbf{e}_1^\top, f = 0 \quad (\text{B.3.6.9})$$

Substituting the above in (B.3.2.1), the length of the latus rectum can be expressed as

$$\frac{2\sqrt{\left[\mathbf{e}_2^\top \left(\mathbf{D} \left(-\frac{\eta}{4\lambda_2} \mathbf{e}_1\right) + \frac{\eta}{2} \mathbf{e}_1\right)\right]^2 - \left(\left(-\frac{\eta}{4\lambda_2} \mathbf{e}_1\right)^\top \mathbf{D} \left(-\frac{\eta}{4\lambda_2} \mathbf{e}_1\right) + 2\frac{\eta}{2} \mathbf{e}_1^\top \left(-\frac{\eta}{4\lambda_2} \mathbf{e}_1\right)\right) \left(\mathbf{e}_2^\top \mathbf{D} \mathbf{e}_2\right)}}{\mathbf{e}_2^\top \mathbf{D} \mathbf{e}_2} \|\mathbf{e}_2\| \quad (\text{B.3.6.10})$$

Since

$$\mathbf{e}_2^\top \mathbf{D} \mathbf{e}_1 = 0, \mathbf{e}_2^\top \mathbf{e}_2 = 0, \mathbf{e}_1^\top \mathbf{D} \mathbf{e}_1 = 0, \quad (\text{B.3.6.11})$$

$$\mathbf{e}_1^\top \mathbf{e}_1 = 1, \|\mathbf{e}_1\| = 1, \mathbf{e}_2^\top \mathbf{D} \mathbf{e}_2 = \lambda_2, \quad (\text{B.3.6.12})$$

(B.3.6.10) can be expressed as

$$2 \frac{\sqrt{\frac{\eta^2}{4\lambda_2} \lambda_2}}{\lambda_2} = \frac{\eta}{\lambda_2} \quad (\text{B.3.6.13})$$

#### B.4 Tangent and Normal

B.4.1. If  $L$  in (B.3.1.1) touches (B.1.2.1) at exactly one point  $\mathbf{q}$ ,

$$\mathbf{m}^\top (\mathbf{V} \mathbf{q} + \mathbf{u}) = 0 \quad (\text{B.4.1.1})$$

*Proof.* In this case, (B.3.1.6) has exactly one root. Hence, in (B.3.1.3)

$$\left[\mathbf{m}^\top (\mathbf{V} \mathbf{q} + \mathbf{u})\right]^2 - \left(\mathbf{m}^\top \mathbf{V} \mathbf{m}\right) \mathbf{g}(\mathbf{q}) = 0 \quad (\text{B.4.1.2})$$

$\therefore \mathbf{q}$  is the point of contact,

$$g(\mathbf{q}) = 0 \quad (\text{B.4.1.3})$$

Substituting (B.4.1.3) in (B.4.1.2) and simplifying, we obtain (B.4.1.1).  $\square$

B.4.2. Given the point of contact  $\mathbf{q}$ , the equation of a tangent to (B.1.2.1) is

$$(\mathbf{V}\mathbf{q} + \mathbf{u})^\top \mathbf{x} + \mathbf{u}^\top \mathbf{q} + f = 0 \quad (\text{B.4.2.1})$$

*Proof.* The normal vector is obtained from (B.4.1.1) as

$$\kappa \mathbf{n} = \mathbf{V}\mathbf{q} + \mathbf{u}, \kappa \in \mathbb{R} \quad (\text{B.4.2.2})$$

From (B.4.2.2), the equation of the tangent is

$$(\mathbf{V}\mathbf{q} + \mathbf{u})^\top (\mathbf{x} - \mathbf{q}) = 0 \quad (\text{B.4.2.3})$$

$$\implies (\mathbf{V}\mathbf{q} + \mathbf{u})^\top \mathbf{x} - \mathbf{q}^\top \mathbf{V}\mathbf{q} - \mathbf{u}^\top \mathbf{q} = 0 \quad (\text{B.4.2.4})$$

which, upon substituting from (B.4.1.3) and simplifying yields (B.4.2.1)  $\square$

B.4.3. Given the point of contact  $\mathbf{q}$ , the equation of the normal to (B.1.2.1) is

$$(\mathbf{V}\mathbf{q} + \mathbf{u})^\top \mathbf{R}(\mathbf{x} - \mathbf{q}) = 0 \quad (\text{B.4.3.1})$$

*Proof.* The direction vector of the tangent is obtained from (B.4.2.2) as

$$\mathbf{m} = \mathbf{R}(\mathbf{V}\mathbf{q} + \mathbf{u}), \quad (\text{B.4.3.2})$$

where  $\mathbf{R}$  is the rotation matrix. From (B.4.3.2), the equation of the normal is given by (10.1.3.1)  $\square$

B.4.4. Given the tangent

$$\mathbf{n}^\top \mathbf{x} = c, \quad (\text{B.4.4.1})$$

the point of contact to the conic in (B.1.2.1) is given by

$$\begin{pmatrix} \mathbf{n}^\top \\ \mathbf{m}^\top \mathbf{V} \end{pmatrix} \mathbf{q} = \begin{pmatrix} c \\ -\mathbf{m}^\top \mathbf{u} \end{pmatrix} \quad (\text{B.4.4.2})$$

*Proof.* From (B.4.1.1),

$$\mathbf{m}^\top (\mathbf{V}\mathbf{q} + \mathbf{u}) = 0 \quad (\text{B.4.4.3})$$

$$\implies \mathbf{m}^\top \mathbf{V}\mathbf{q} = -\mathbf{m}^\top \mathbf{u} \quad (\text{B.4.4.4})$$

Combining (B.4.4.1) and (B.4.4.4), (B.4.4.2) is obtained.  $\square$

B.4.5. If  $\mathbf{V}^{-1}$  exists, given the normal vector  $\mathbf{n}$ , the tangent points of contact to (B.1.2.1) are given by

$$\mathbf{q}_i = \mathbf{V}^{-1}(\kappa_i \mathbf{n} - \mathbf{u}), i = 1, 2$$

$$\text{where } \kappa_i = \pm \sqrt{\frac{f_0}{\mathbf{n}^\top \mathbf{V}^{-1} \mathbf{n}}} \quad (\text{B.4.5.1})$$

*Proof.* From (B.4.2.2),

$$\mathbf{q} = \mathbf{V}^{-1}(\kappa \mathbf{n} - \mathbf{u}), \quad \kappa \in \mathbb{R} \quad (\text{B.4.5.2})$$

Substituting (B.4.5.2) in (B.4.1.3),

$$(\kappa \mathbf{n} - \mathbf{u})^\top \mathbf{V}^{-1}(\kappa \mathbf{n} - \mathbf{u}) + 2\mathbf{u}^\top \mathbf{V}^{-1}(\kappa \mathbf{n} - \mathbf{u}) + f = 0 \quad (\text{B.4.5.3})$$

$$\implies \kappa^2 \mathbf{n}^\top \mathbf{V}^{-1} \mathbf{n} - \mathbf{u}^\top \mathbf{V}^{-1} \mathbf{u} + f = 0 \quad (\text{B.4.5.4})$$

$$\text{or, } \kappa = \pm \sqrt{\frac{f_0}{\mathbf{n}^\top \mathbf{V}^{-1} \mathbf{n}}} \quad (\text{B.4.5.5})$$

Substituting (B.4.5.5) in (B.4.5.2) yields (B.4.5.1).  $\square$

B.4.6. For a conic/hyperbola, a line with normal vector  $\mathbf{n}$  cannot be a tangent if

$$\frac{\mathbf{u}^\top \mathbf{V}^{-1} \mathbf{u} - f}{\mathbf{n}^\top \mathbf{V}^{-1} \mathbf{n}} < 0 \quad (\text{B.4.6.1})$$

B.4.7. If  $\mathbf{V}$  is not invertible, given the normal vector  $\mathbf{n}$ , the point of contact to (B.1.2.1) is given by the matrix equation

$$\begin{pmatrix} (\mathbf{u} + \kappa \mathbf{n})^\top \\ \mathbf{V} \end{pmatrix} \mathbf{q} = \begin{pmatrix} -f \\ \kappa \mathbf{n} - \mathbf{u} \end{pmatrix} \quad (\text{B.4.7.1})$$

$$\text{where } \kappa = \frac{\mathbf{p}_1^\top \mathbf{u}}{\mathbf{p}_1^\top \mathbf{n}}, \quad \mathbf{V} \mathbf{p}_1 = 0 \quad (\text{B.4.7.2})$$

*Proof.* If  $\mathbf{V}$  is non-invertible, it has a zero eigenvalue. If the corresponding eigenvector is  $\mathbf{p}_1$ , then,

$$\mathbf{V} \mathbf{p}_1 = 0 \quad (\text{B.4.7.3})$$

From (B.4.2.2),

$$\kappa \mathbf{n} = \mathbf{V} \mathbf{q} + \mathbf{u}, \quad \kappa \in \mathbb{R} \quad (\text{B.4.7.4})$$

$$\implies \kappa \mathbf{p}_1^\top \mathbf{n} = \mathbf{p}_1^\top \mathbf{V} \mathbf{q} + \mathbf{p}_1^\top \mathbf{u} \quad (\text{B.4.7.5})$$

$$\text{or, } \kappa \mathbf{p}_1^\top \mathbf{n} = \mathbf{p}_1^\top \mathbf{u}, \quad \because \mathbf{p}_1^\top \mathbf{V} = 0, \quad (\text{from (B.4.7.3)}) \quad (\text{B.4.7.6})$$

yielding  $\kappa$  in (B.4.7.2). From (B.4.7.4),

$$\kappa \mathbf{q}^\top \mathbf{n} = \mathbf{q}^\top \mathbf{V} \mathbf{q} + \mathbf{q}^\top \mathbf{u} \quad (\text{B.4.7.7})$$

$$\implies \kappa \mathbf{q}^\top \mathbf{n} = -f - \mathbf{q}^\top \mathbf{u} \quad \text{from (B.4.1.3)}, \quad (\text{B.4.7.8})$$

$$\text{or, } (\kappa \mathbf{n} + \mathbf{u})^\top \mathbf{q} = -f \quad (\text{B.4.7.9})$$

(B.4.7.4) can be expressed as

$$\mathbf{V} \mathbf{q} = \kappa \mathbf{n} - \mathbf{u}. \quad (\text{B.4.7.10})$$

(B.4.7.9) and (B.4.7.10) clubbed together result in (B.4.7.1).  $\square$

B.4.8. The asymptotes of the hyperbola in (B.1.5.1), defined to be the lines that do not

intersect the hyperbola, are given by

$$\left( \sqrt{|\lambda_1|} \pm \sqrt{|\lambda_2|} \right) \mathbf{y} = 0 \quad (\text{B.4.8.1})$$

*Proof.* From (B.1.5.1), it is obvious that the pair of lines represented by

$$\mathbf{y}^\top \mathbf{D} \mathbf{y} = 0 \quad (\text{B.4.8.2})$$

do not intersect the conic

$$\mathbf{y}^\top \mathbf{D} \mathbf{y} = f_0 \quad (\text{B.4.8.3})$$

Thus, (B.4.8.2) represents the asymptotes of the hyperbola in (B.1.5.1) and can be expressed as

$$\lambda_1 y_1^2 + \lambda_2 y_1^2 = 0, \quad (\text{B.4.8.4})$$

which can then be simplified using the steps in (A.8.3.4)- (A.8.3.7) to obtain (B.4.8.1).  $\square$

B.4.9. (B.1.2.1) represents a pair of straight lines if

$$\mathbf{u}^\top \mathbf{V}^{-1} \mathbf{u} - f = 0 \quad (\text{B.4.9.1})$$

B.4.10. (B.1.2.1) represents a pair of straight lines if the matrix

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u}^\top & f \end{pmatrix} \quad (\text{B.4.10.1})$$

is singular.

*Proof.* Let

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u}^\top & f \end{pmatrix} \mathbf{x} = \mathbf{0} \quad (\text{B.4.10.2})$$

Expressing

$$\mathbf{x} = \begin{pmatrix} \mathbf{y} \\ y_3 \end{pmatrix}, \quad (\text{B.4.10.3})$$

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u}^\top & f \end{pmatrix} \begin{pmatrix} \mathbf{y} \\ y_3 \end{pmatrix} = \mathbf{0} \quad (\text{B.4.10.4})$$

$$\implies \mathbf{V} \mathbf{y} + y_3 \mathbf{u} = \mathbf{0} \quad \text{and} \quad (\text{B.4.10.5})$$

$$\mathbf{u}^\top \mathbf{y} + f y_3 = 0 \quad (\text{B.4.10.6})$$

From (B.4.10.5) we obtain,

$$\mathbf{y}^\top \mathbf{V} \mathbf{y} + y_3 \mathbf{y}^\top \mathbf{u} = 0 \quad (\text{B.4.10.7})$$

$$\implies \mathbf{y}^\top \mathbf{V} \mathbf{y} + y_3 \mathbf{u}^\top \mathbf{y} = 0 \quad (\text{B.4.10.8})$$

yielding (B.4.9.1) upon substituting from (B.4.10.6).  $\square$



B.4.11. Using the affine transformation, (B.4.8.1) can be expressed as the lines

$$\left( \sqrt{|\lambda_1|} \pm \sqrt{|\lambda_2|} \right) \mathbf{P}^\top (\mathbf{x} - \mathbf{c}) = 0 \quad (\text{B.4.11.1})$$

B.4.12. The angle between the asymptotes can be expressed as

$$\cos \theta = \frac{|\lambda_1| - |\lambda_2|}{|\lambda_1| + |\lambda_2|} \quad (\text{B.4.12.1})$$

*Proof.* The normal vectors of the lines in (B.4.11.1) are

$$\begin{aligned} \mathbf{n}_1 &= \mathbf{P} \begin{pmatrix} \sqrt{|\lambda_1|} \\ \sqrt{|\lambda_2|} \end{pmatrix} \\ \mathbf{n}_2 &= \mathbf{P} \begin{pmatrix} \sqrt{|\lambda_1|} \\ -\sqrt{|\lambda_2|} \end{pmatrix} \end{aligned} \quad (\text{B.4.12.2})$$

The angle between the asymptotes is given by

$$\cos \theta = \frac{\mathbf{n}_1^\top \mathbf{n}_2}{\|\mathbf{n}_1\| \|\mathbf{n}_2\|} \quad (\text{B.4.12.3})$$

The orthogonal matrix  $\mathbf{P}$  preserves the norm, i.e.

$$\|\mathbf{n}_1\| = \left\| \mathbf{P} \begin{pmatrix} \sqrt{|\lambda_1|} \\ \sqrt{|\lambda_2|} \end{pmatrix} \right\| = \left\| \begin{pmatrix} \sqrt{|\lambda_1|} \\ \sqrt{|\lambda_2|} \end{pmatrix} \right\| \quad (\text{B.4.12.4})$$

$$= \sqrt{|\lambda_1| + |\lambda_2|} = \|\mathbf{n}_2\| \quad (\text{B.4.12.5})$$

It is easy to verify that

$$\mathbf{n}_1^\top \mathbf{n}_2 = |\lambda_1| - |\lambda_2| \quad (\text{B.4.12.6})$$

Thus, the angle between the asymptotes is obtained from (B.4.12.3) as (B.4.12.1).  $\square$

B.4.13. For a circle, the points of contact are

$$\mathbf{q}_{ij} = \left( \pm r \frac{\mathbf{n}_j}{\|\mathbf{n}_j\|} - \mathbf{u} \right), \quad i, j = 1, 2 \quad (\text{B.4.13.1})$$

*Proof.* From (B.4.5.1), and (7.1.1.1),

$$\kappa_{ij} = \pm \frac{r}{\|\mathbf{n}_j\|} \quad (\text{B.4.13.2})$$

$\square$

B.4.14. A point  $\mathbf{h}$  lies on a normal to the conic in (B.1.2.1) if

$$\left( \mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) \right)^2 \left( \mathbf{n}^\top \mathbf{V}\mathbf{n} \right) - 2 \left( \mathbf{m}^\top \mathbf{V}\mathbf{n} \right) \left( \mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) \mathbf{n}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) \right) + g(\mathbf{h}) \left( \mathbf{m}^\top \mathbf{V}\mathbf{n} \right)^2 = 0 \quad (\text{B.4.14.1})$$

*Proof.* The point of contact for the normal passing through a point  $\mathbf{h}$  is given by

$$\mathbf{q} = \mathbf{h} + \mu \mathbf{n} \quad (\text{B.4.14.2})$$

From (B.4.1.1), the tangent at  $\mathbf{q}$  satisfies

$$\mathbf{m}^\top (\mathbf{V}\mathbf{q} + \mathbf{u}) = 0 \quad (\text{B.4.14.3})$$

Substituting (B.4.14.2) in (B.4.14.3),

$$\mathbf{m}^\top (\mathbf{V}(\mathbf{h} + \mu\mathbf{n}) + \mathbf{u}) = 0 \quad (\text{B.4.14.4})$$

$$\implies \mu \mathbf{m}^\top \mathbf{V}\mathbf{n} = -\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) \quad (\text{B.4.14.5})$$

yielding

$$\mu = -\frac{\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})}{\mathbf{m}^\top \mathbf{V}\mathbf{n}}, \quad (\text{B.4.14.6})$$

From (B.3.1.6),

$$\mu^2 \mathbf{n}^\top \mathbf{V}\mathbf{n} + 2\mu \mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) + g(\mathbf{h}) = 0 \quad (\text{B.4.14.7})$$

From (B.4.14.6), (B.4.14.7) can be expressed as

$$\left(-\frac{\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})}{\mathbf{m}^\top \mathbf{V}\mathbf{n}}\right)^2 \mathbf{n}^\top \mathbf{V}\mathbf{n} + 2\left(-\frac{\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})}{\mathbf{m}^\top \mathbf{V}\mathbf{n}}\right) \mathbf{n}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) + g(\mathbf{h}) = 0 \quad (\text{B.4.14.8})$$

yielding (B.4.14.1).  $\square$

B.4.15. A point  $\mathbf{h}$  lies on a tangent to the conic in (B.1.2.1) if

$$\mathbf{m}^\top [(\mathbf{V}\mathbf{h} + \mathbf{u})(\mathbf{V}\mathbf{h} + \mathbf{u})^\top - \mathbf{V}g(\mathbf{h})] \mathbf{m} = 0 \quad (\text{B.4.15.1})$$

*Proof.* From (B.3.1.3) and (B.4.1.2)

$$[\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})]^2 - (\mathbf{m}^\top \mathbf{V}\mathbf{m}) g(\mathbf{h}) = 0 \quad (\text{B.4.15.2})$$

yielding (B.4.15.1).  $\square$

B.4.16. The normal vectors of the tangents to the conic in (B.1.2.1) from a point  $\mathbf{h}$  are given by

$$\begin{aligned} \mathbf{n}_1 &= \mathbf{P} \begin{pmatrix} \sqrt{|\lambda_1|} \\ \sqrt{|\lambda_2|} \end{pmatrix} \\ \mathbf{n}_2 &= \mathbf{P} \begin{pmatrix} \sqrt{|\lambda_1|} \\ -\sqrt{|\lambda_2|} \end{pmatrix} \end{aligned} \quad (\text{B.4.16.1})$$

where  $\lambda_i, \mathbf{P}$  are the eigenparameters of

$$\Sigma = (\mathbf{V}\mathbf{h} + \mathbf{u})(\mathbf{V}\mathbf{h} + \mathbf{u})^\top - (g(\mathbf{h})) \mathbf{V}. \quad (\text{B.4.16.2})$$

*Proof.* From (B.4.15.1) we obtain (B.4.16.2). Consequently, from (B.4.12.2), (B.4.16.1) can be obtained.  $\square$

B.4.17. (B.1.2.1) represents a pair of straight lines if the matrix

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u}^\top & f \end{pmatrix} \quad (\text{B.4.17.1})$$

is singular.

B.4.18. The intersection of two conics with parameters  $\mathbf{V}_i, \mathbf{u}_i, f_i, i = 1, 2$  is defined as

$$\mathbf{x}^\top (\mathbf{V}_1 + \mu \mathbf{V}_2) \mathbf{x} + 2(\mathbf{u}_1 + \mu \mathbf{u}_2)^\top \mathbf{x} + (f_1 + \mu f_2) = 0 \quad (\text{B.4.18.1})$$

B.4.19. From (B.4.17.1), (B.4.18.1) represents a pair of straight lines if

$$\begin{vmatrix} \mathbf{V}_1 + \mu \mathbf{V}_2 & \mathbf{u}_1 + \mu \mathbf{u}_2 \\ (\mathbf{u}_1 + \mu \mathbf{u}_2)^\top & f_1 + \mu f_2 \end{vmatrix} = 0 \quad (\text{B.4.19.1})$$