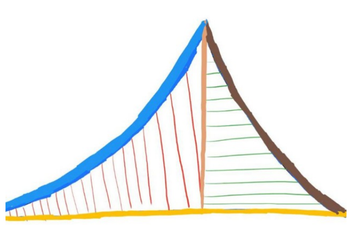
MATRIX ANALYSIS

Through Coordinate Geometry

G. V. V. Sharma



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Introduction

This book links high school coordinate geometry to linear algebra and matrix analysis through solved problems.

Chapter 1

Vectors

1.1. Distance Formula

1.2. Section Formula

1.3. Scalar Product

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

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

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

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

1.3.5 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.

1.3.6 Find $|\overrightarrow{a}|$ and $\left|\overrightarrow{b}\right|$,if $(\overrightarrow{a} + \overrightarrow{b}).(\overrightarrow{a} - \overrightarrow{b}) = 8$ and $|\overrightarrow{a}| = 8\left|\overrightarrow{b}\right|$.

1.3.7 Evaluate the product$(3\overrightarrow{a} - 5\overrightarrow{b}).(2\overrightarrow{a} + 7\overrightarrow{b})$.

1.3.8 Find the magnitude of two vectors $\overrightarrow{a}$ and $\overrightarrow{b}$, having the same magnitude and such that the angle between them is $60°$ and their scalar product is $\frac{1}{2}$

1.3.9 Find $|\overrightarrow{x}|$,if for a unit vector $\overrightarrow{a}$, $(\overrightarrow{x} - \overrightarrow{a}).(\overrightarrow{x} + \overrightarrow{a})$=12.

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

1.3.11 Show that $|\overrightarrow{a}|\overrightarrow{b} + \left|\overrightarrow{b}\right|\overrightarrow{a}$ is perpendicular to $|\overrightarrow{a}|\overrightarrow{b} - \left|\overrightarrow{b}\right|\overrightarrow{a}$, for any two nonzero vectors $\overrightarrow{a}$ and $\overrightarrow{b}$.

1.3.12 If $\overrightarrow{a}.\overrightarrow{a}$=0 and $\overrightarrow{a}.\overrightarrow{b}$=0, then what can be conculded about the vector $\overrightarrow{b}$?

1.3.13 If $\overrightarrow{a}, \overrightarrow{b}, \overrightarrow{c}$ are unit vectors such that $\overrightarrow{a} + \overrightarrow{b} + \overrightarrow{c} = \overrightarrow{0}$, find the value of $\overrightarrow{a}.\overrightarrow{b} + \overrightarrow{b}.\overrightarrow{c} + \overrightarrow{c}.\overrightarrow{a}$.

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

1.3.15 If the vertices A,B,C of a triangle ABC are (1,2,3),(-1,0,0)(0,1,2), respectively , then find $\angle ABC$.[$\angle ABC$ is the angle between the vectors $\overrightarrow{BA}$ and $\overrightarrow{BC}$].

1.3.16 show that the points A(1,2,7),B(2,6,3)and C(3,10,-1) are collinear.

1.3.17 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.

1.3.18 If $\overrightarrow{a}$ is a nonzero vector of magnitude 'a' and λ a nonzero scalar , then $\lambda\overrightarrow{a}$ is unit vector if

1. $\lambda = 1$

2. $\lambda = -1$

3. $a = |\lambda|$

4. $a = 1/|\lambda|$

1.4. Area of a Triangle

1.4.1 Find the area of the triangle whose vertices are

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

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

Solution:

(a) In this case, the area is given by

$$\frac{1}{2}\left\|(\mathbf{A}-\mathbf{B})\times(\mathbf{A}-\mathbf{C})\right\| \tag{1.4.1.1}$$

$$\tag{1.4.1.2}$$

Since

$$\mathbf{A}-\mathbf{B} = \begin{pmatrix} 2 \\ 3 \end{pmatrix} - \begin{pmatrix} -1 \\ 0 \end{pmatrix} = \begin{pmatrix} 3 \\ 3 \end{pmatrix} \tag{1.4.1.3}$$

$$\mathbf{A}-\mathbf{C} = \begin{pmatrix} 2 \\ 3 \end{pmatrix} - \begin{pmatrix} 2 \\ -4 \end{pmatrix} = \begin{pmatrix} 0 \\ 7 \end{pmatrix} \tag{1.4.1.4}$$

the desired area is given by

$$\frac{1}{2}\begin{vmatrix}3 & 0\\ 3 & 7\end{vmatrix} = \frac{21}{2} \tag{1.4.1.5}$$

(b) In this case,

$$\mathbf{A}-\mathbf{B} = \begin{pmatrix}-5\\-1\end{pmatrix} - \begin{pmatrix}3\\-5\end{pmatrix} = \begin{pmatrix}-8\\4\end{pmatrix} \tag{1.4.1.6}$$

$$\mathbf{A}-\mathbf{C} = \begin{pmatrix}-5\\-1\end{pmatrix} - \begin{pmatrix}5\\2\end{pmatrix} = \begin{pmatrix}-10\\-3\end{pmatrix} \tag{1.4.1.7}$$

$$\implies \text{Area} = \frac{1}{2}\begin{vmatrix}-8 & -10\\ 4 & -3\end{vmatrix} = 32 \tag{1.4.1.8}$$

1.4.2 In each of the following, find the value of 'k', for which the points are collinear.

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

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

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

1.4.4 Find the area of the quadrilateral whose vertices, taken in order, are $(-4,-2),(-3,-5),(3,-2)$ and $(2,3)$.

1.4.5 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 $\mathbf{C}(5,2)$.

1.4.6 Find the area of region bounded by the triangle whose vertices are $(1,0),(2,2)$ and $(3,1)$.

1.4.7 Find the area of region bounded by the triangle whose vertices are $(-1,0),(1,3)$ and $(3,2)$.

1.4.8 Find the area of the $\triangle ABC$, coordinates of whose vertices are $\mathbf{A}(2,0),\mathbf{B}(4,5),$ and $\mathbf{C}(6,3)$.

1.5. Miscellaneous Exercises

1.5.1 Determine the ratio in which the line $2x+y-4=0$ divides the line segment joining the points $\mathbf{A}(2,-2)$ and $\mathbf{B}(3,7)$.

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

1.5.3 Find the centre of a circle passing through the points $(6,-6),(3,-7)$ and $(3,3)$.

1.5.4 The two opposite vertices of a square are $(-1,2)$ and $(3,2)$. Find the coordinates of the other two vertices.

1.5.5 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 $\triangle ABC$.

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

(a) The median from $\mathbf{A}$ meets BC at $\mathbf{D}$. Find the coordinates of the point $\mathbf{D}$.

(b) Find the coordinates of the point $\mathbf{P}$ on AD such that $AP:PD=2:1$.

(c) Find the coordinates of points $\mathbf{Q}$ and $\mathbf{R}$ on medians BE and CF respectively such that $BQ:QE=2:1$ and $CR:RF=2:1$.

(d) What do you observe?

(e) If $\mathbf{A}, \mathbf{B}$ and $\mathbf{C}$ are the vertices of $\triangle ABC$, find the coordinates of the centroid of the triangle.

1.5.7 $ABCD$ 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. 1.5.7.1.

$$\mathbf{P} = \frac{1}{2}(\mathbf{A}+\mathbf{B}) = \frac{1}{2}\left(\begin{pmatrix}-1\\-1\end{pmatrix}+\begin{pmatrix}-1\\4\end{pmatrix}\right) = \begin{pmatrix}-1\\\frac{3}{2}\end{pmatrix} \tag{1.5.7.1}$$

$$\mathbf{Q} = \frac{1}{2}(\mathbf{B}+\mathbf{C}) = \frac{1}{2}\left(\begin{pmatrix}-1\\4\end{pmatrix}+\begin{pmatrix}5\\4\end{pmatrix}\right) = \begin{pmatrix}2\\4\end{pmatrix} \tag{1.5.7.2}$$

$$\mathbf{R} = \frac{1}{2}(\mathbf{C}+\mathbf{D}) = \frac{1}{2}\left(\begin{pmatrix}5\\4\end{pmatrix}+\begin{pmatrix}5\\-1\end{pmatrix}\right) = \begin{pmatrix}5\\\frac{3}{2}\end{pmatrix} \tag{1.5.7.3}$$

$$\mathbf{S} = \frac{1}{2}(\mathbf{D}+\mathbf{A}) = \frac{1}{2}\left(\begin{pmatrix}5\\-1\end{pmatrix}+\begin{pmatrix}-1\\-1\end{pmatrix}\right) = \begin{pmatrix}2\\-1\end{pmatrix} \tag{1.5.7.4}$$

We know that PQRS is a parallelogram. To know, if it is a rectangle, we need to ascertain whether any of the two adjacent sides are perpendicular. That means

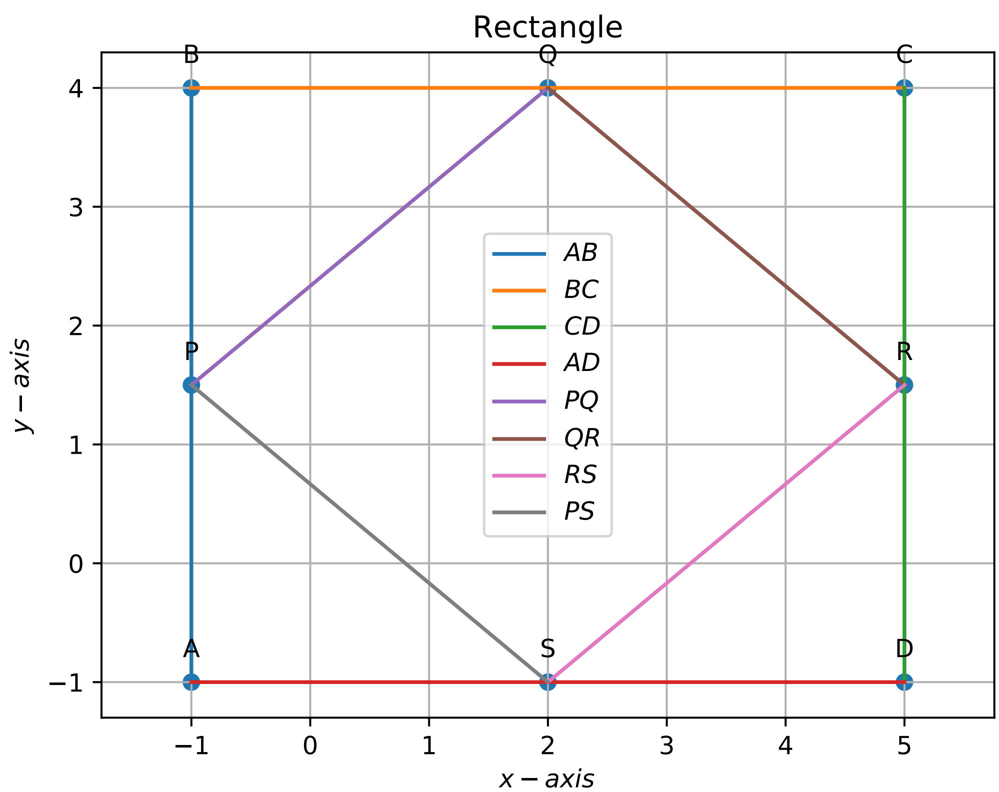


Figure 1.5.7.1:

$(\mathbf{Q}-\mathbf{P})^\top(\mathbf{R}-\mathbf{Q})$ should be equal to zero.

$$\mathbf{Q}-\mathbf{P} = \begin{pmatrix} 2 \\ 4 \end{pmatrix} - \begin{pmatrix} -1 \\ \frac{3}{2} \end{pmatrix} = \begin{pmatrix} 3 \\ \frac{5}{2} \end{pmatrix} \tag{1.5.7.5}$$

$$\mathbf{R}-\mathbf{Q} = \begin{pmatrix} 5 \\ \frac{3}{2} \end{pmatrix} - \begin{pmatrix} 2 \\ 4 \end{pmatrix} = \begin{pmatrix} 3 \\ -\frac{5}{2} \end{pmatrix} \tag{1.5.7.6}$$

$$(\mathbf{Q}-\mathbf{P})^\top(\mathbf{R}-\mathbf{Q}) = \begin{pmatrix} 3 & \frac{5}{2} \end{pmatrix} \begin{pmatrix} 3 \\ -\frac{5}{2} \end{pmatrix} \neq 0 \tag{1.5.7.7}$$

Therefore PQRS is not a rectangle. Let us check if it is a rhombus. For a rhombus, the diagonals bisect perpendicularly. That means $(\mathbf{R}-\mathbf{P})^\top(\mathbf{S}-\mathbf{Q})$ should be equal to zero.

$$\mathbf{R}-\mathbf{P} = \begin{pmatrix} 5 \\ \frac{3}{2} \end{pmatrix} - \begin{pmatrix} -1 \\ \frac{3}{2} \end{pmatrix} = \begin{pmatrix} 6 \\ 0 \end{pmatrix} \tag{1.5.7.8}$$

$$\mathbf{S}-\mathbf{Q} = \begin{pmatrix} 2 \\ -1 \end{pmatrix} - \begin{pmatrix} 2 \\ 4 \end{pmatrix} = \begin{pmatrix} 0 \\ -5 \end{pmatrix} \tag{1.5.7.9}$$

$$(\mathbf{R}-\mathbf{P})^\top(\mathbf{S}-\mathbf{Q}) = \begin{pmatrix} 6 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ -5 \end{pmatrix} = 0 \tag{1.5.7.10}$$

Therefore $PQRS$ is a rhombus.

1.6. Line Preliminaries

1.6.1 Draw a quadrilateral in the Cartesian plane, whose vertices are (-4,5), (0,7), (5,-5), (-4,-2). Also, find its area.

Solution: See Fig. 1.6.1.1.

$$ar(\triangle ABC) = \frac{1}{2}\left\|(\mathbf{B}-\mathbf{A})\times(\mathbf{B}-\mathbf{C})\right\| \tag{1.6.1.1}$$

$$= \frac{1}{2}\begin{vmatrix} 4 & 2 \\ -5 & 12 \end{vmatrix} = 29 \tag{1.6.1.2}$$

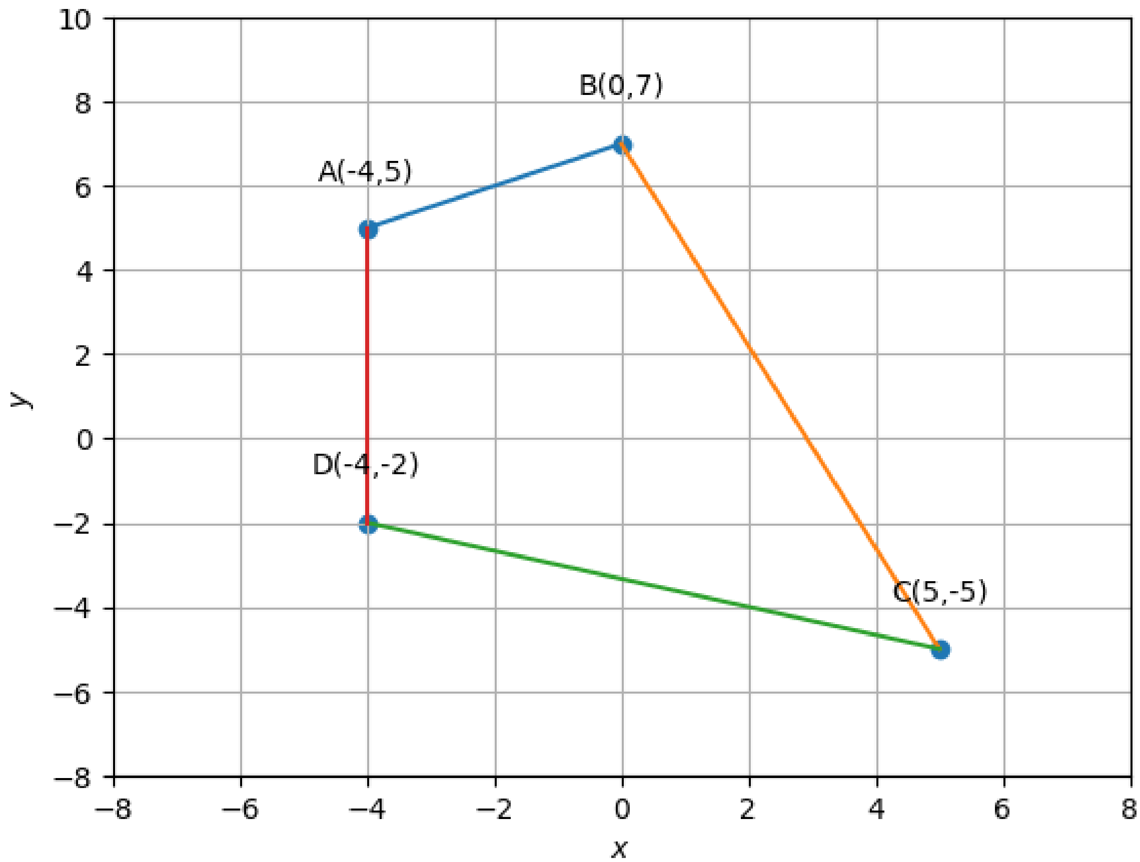


Figure 1.6.1.1:

Similarly,

$$ar(\triangle ADC) = \frac{1}{2} \left\| (\mathbf{D} - \mathbf{A}) \times (\mathbf{D} - \mathbf{C}) \right\| \tag{1.6.1.3}$$

$$= \frac{1}{2} \begin{vmatrix} 0 & -7 \\ -9 & 3 \end{vmatrix} = 31.5 \tag{1.6.1.4}$$

Thus,

$$ar(ABCD) = ar(\triangle ABC) + ar(\triangle ADC) = 60.5 \tag{1.6.1.5}$$

1.6.2 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 vertices of the triangle.

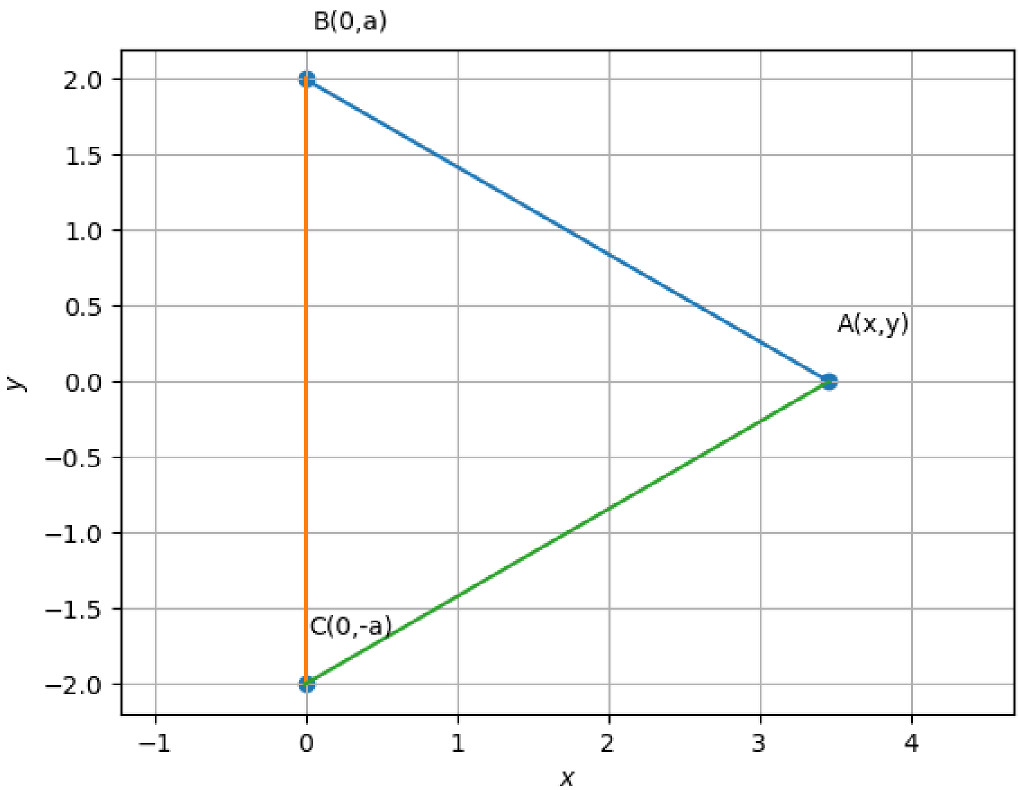


Figure 1.6.2.1:

Solution: Let the base be BC. From the given information,

$$\mathbf{B} = a\mathbf{e}_2, \mathbf{C} = -a\mathbf{e}_2 \tag{1.6.2.1}$$

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

$$\mathbf{A} = k\mathbf{e}_1 \tag{1.6.2.2}$$

and

$$\|\mathbf{A} - \mathbf{C}\|^2 = (2a)^2 \tag{1.6.2.3}$$

$$\implies \|\mathbf{A}\|^2 + \|\mathbf{C}\|^2 - 2\mathbf{A}^\top\mathbf{C} = 4a^2 \tag{1.6.2.4}$$

$$\implies k^2 + a^2 = 4a^2 \tag{1.6.2.5}$$

$$\text{or, } k = \pm a\sqrt{3} \tag{1.6.2.6}$$

Thus,

$$\mathbf{A} = \pm\sqrt{3}a\mathbf{e}_1 \tag{1.6.2.7}$$

Fig. 1.6.2.1 is plotted for $a = 2$.

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

Solution: From the given information

$$\|\mathbf{x} - \mathbf{A}\|^2 = \|\mathbf{x} - \mathbf{B}\|^2 \tag{1.6.3.1}$$

$$\implies (\mathbf{x} - \mathbf{A})^\top (\mathbf{x} - \mathbf{A}) = (\mathbf{x} - \mathbf{B})^\top (\mathbf{x} - \mathbf{B}) \tag{1.6.3.2}$$

$$\implies \|\mathbf{x}\|^2 - 2\mathbf{A}^\top\mathbf{x} + \|\mathbf{A}\|^2 = \|\mathbf{x}\|^2 - 2\mathbf{B}^\top\mathbf{x} + \|\mathbf{B}\|^2 \tag{1.6.3.3}$$

$$\text{or, } (\mathbf{A} - \mathbf{B})^\top \mathbf{x} = \frac{\|\mathbf{A}\|^2 - \|\mathbf{B}\|^2}{2} \tag{1.6.3.4}$$

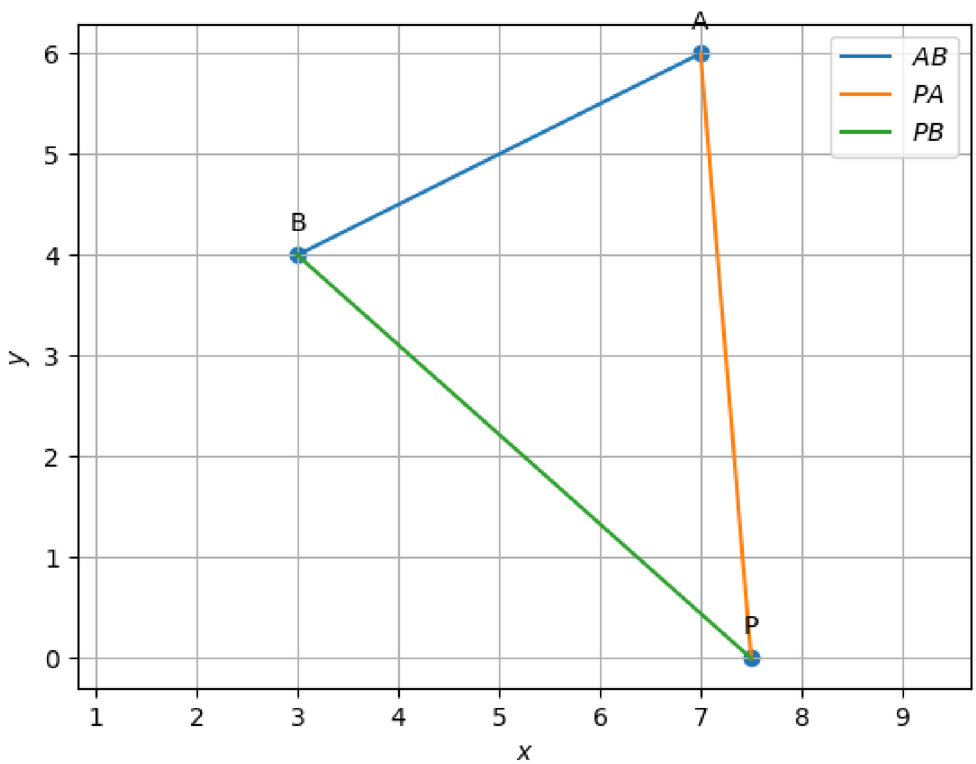


Figure 1.6.3.1:

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

$$\mathbf{x} = k\mathbf{e}_1 \tag{1.6.3.5}$$

which, upon substituting in (1.6.3.4) yields

$$k = \frac{15}{2} \tag{1.6.3.6}$$

1.6.4

1.6.5 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).

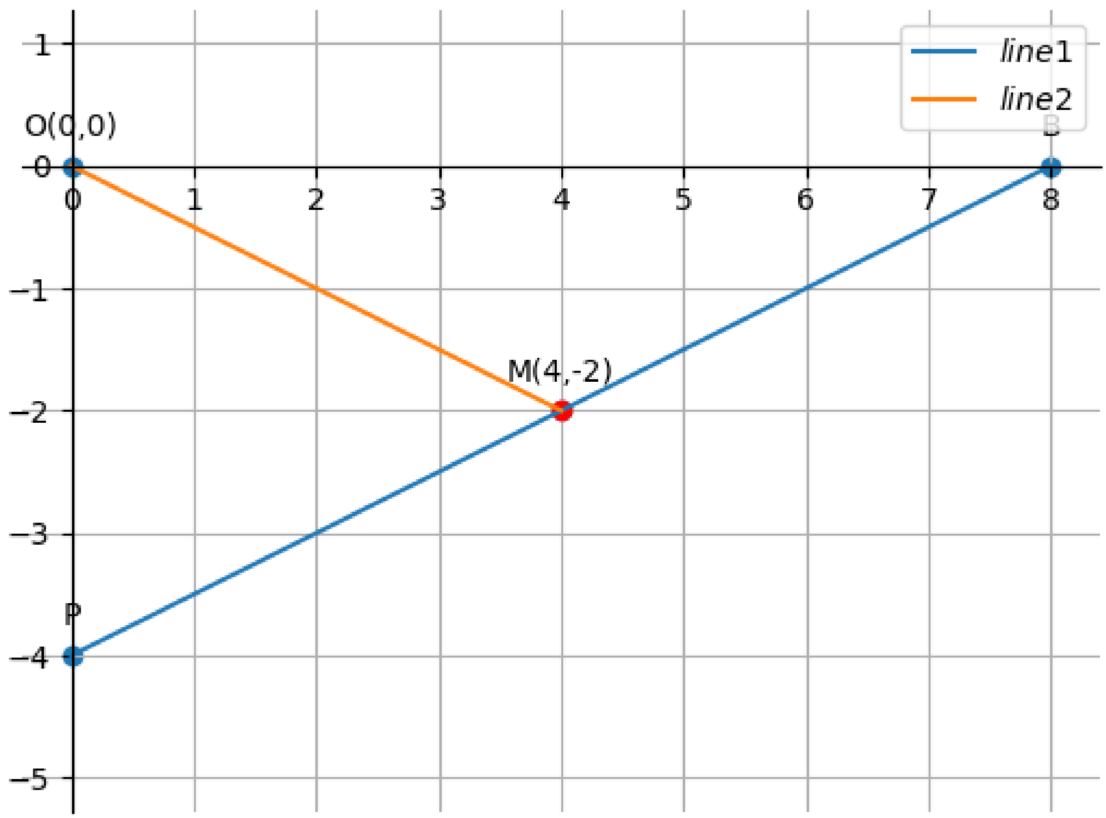


Figure 1.6.5.1:

Solution: The mid point of PB is

$$\mathbf{M} = \frac{1}{2}(\mathbf{P}+\mathbf{B}) = \begin{pmatrix} 4 \\ -2 \end{pmatrix} \tag{1.6.5.1}$$

The direction vector of line joining $\mathbf{O}, \mathbf{M}$ is

$$\mathbf{m} = \mathbf{O} - \mathbf{M} = -\mathbf{M} \tag{1.6.5.2}$$

which can be expressed as

$$\begin{pmatrix} 1 \\ -\frac{1}{2} \end{pmatrix} \tag{1.6.5.3}$$

Thus the slope is

$$m = -\frac{1}{2} \tag{1.6.5.4}$$

1.6.6 Without using the Baudhayana theorem, show that the points $(4, 4), (3, 5)$ and $(-1, -1)$ are the vertices of a right angled triangle.

$$\mathbf{C} - \mathbf{A} = \begin{pmatrix} -5 \\ -5 \end{pmatrix}, \tag{1.6.6.1}$$

$$\mathbf{A} - \mathbf{B} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \tag{1.6.6.2}$$

$$\implies (\mathbf{C} - \mathbf{A})^\top (\mathbf{A} - \mathbf{B}) = 0 \tag{1.6.6.3}$$

Thus, $AB \perp AC$.

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

Solution: Let

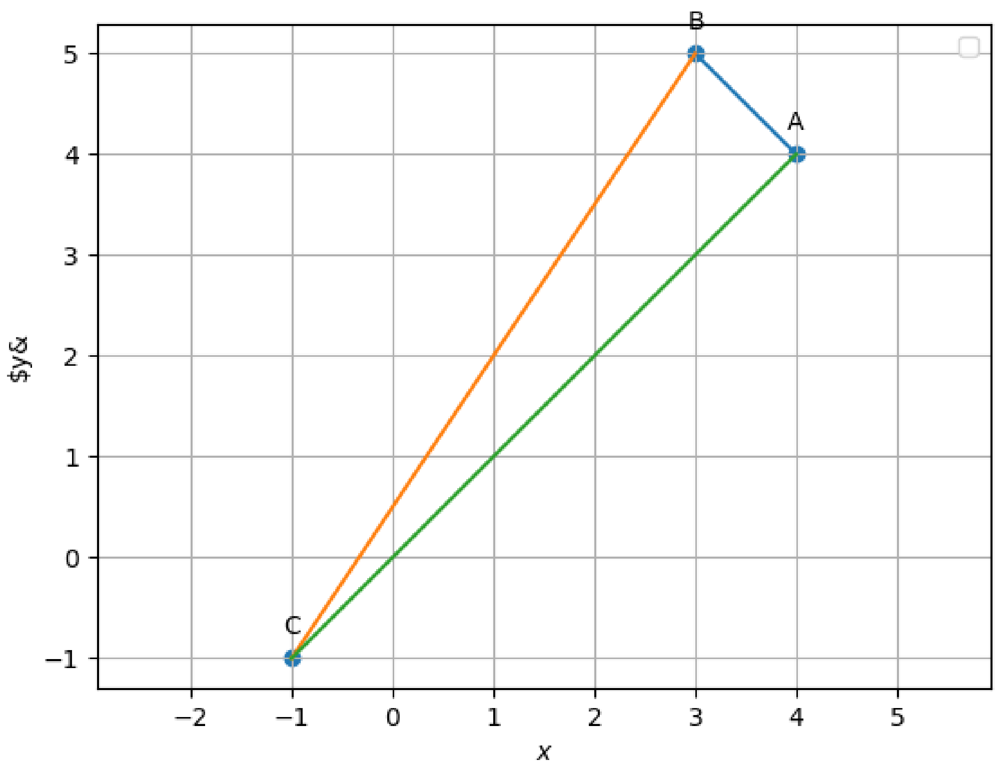


Figure 1.6.6.1:

$$\mathbf{A} = \begin{pmatrix} x \\ -1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 2 \\ 1 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} 4 \\ 5 \end{pmatrix}. \tag{1.6.7.1}$$

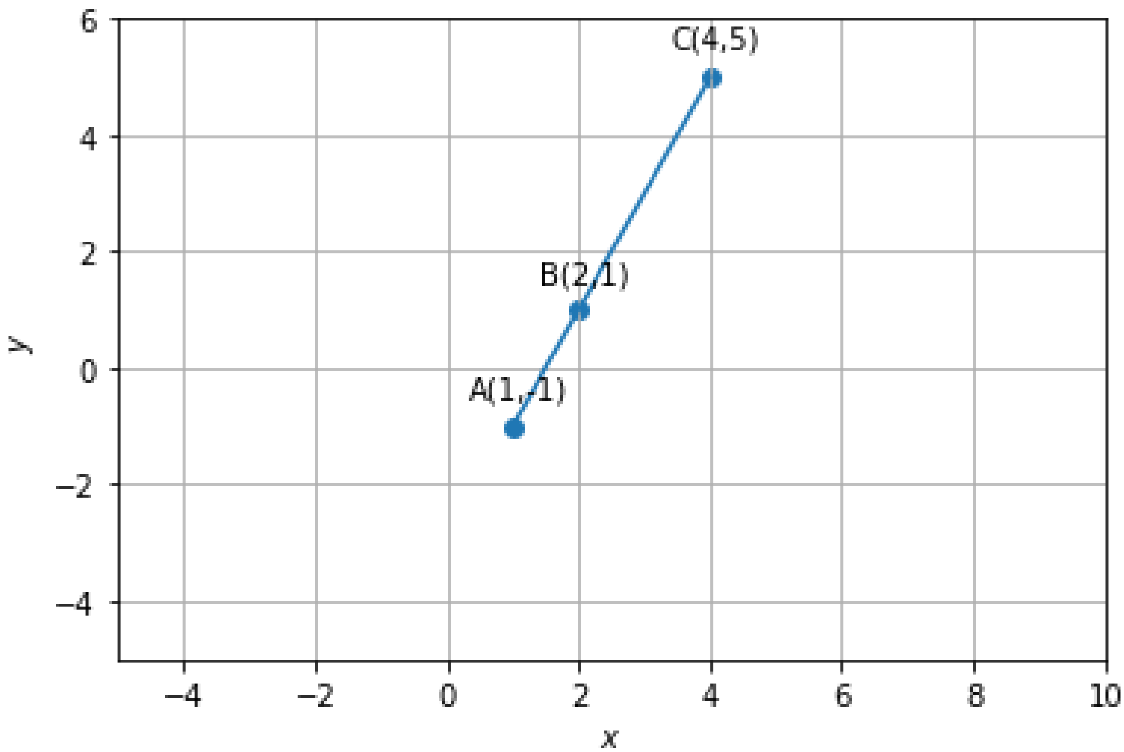


Figure 1.6.7.1:

Then

$$\mathbf{A}-\mathbf{B}=\begin{pmatrix} x-2 \\ -2 \end{pmatrix} \tag{1.6.7.2}$$

$$\mathbf{A}-\mathbf{C}=\begin{pmatrix} 4-x \\ 6 \end{pmatrix} \tag{1.6.7.3}$$

Forming the collinearity matrix using (C.1.4.1),

$$\begin{pmatrix} x-2 & -2 \\ 4-x & 6 \end{pmatrix} \xleftrightarrow{R_1=3R_1+R-2} = \begin{pmatrix} 2x-2 & 0 \\ 4-x & 6 \end{pmatrix} \tag{1.6.7.4}$$

If the rank of the matrix is 1, any one of the rows must be zero. So, making the first element in the above matrix 0,

$$x = 1 \tag{1.6.7.5}$$

1.6.8 Without using distance formula, show that points (– 2, – 1), (4, 0), (3, 3) and (–3, 2) are the vertices of a parallelogram.

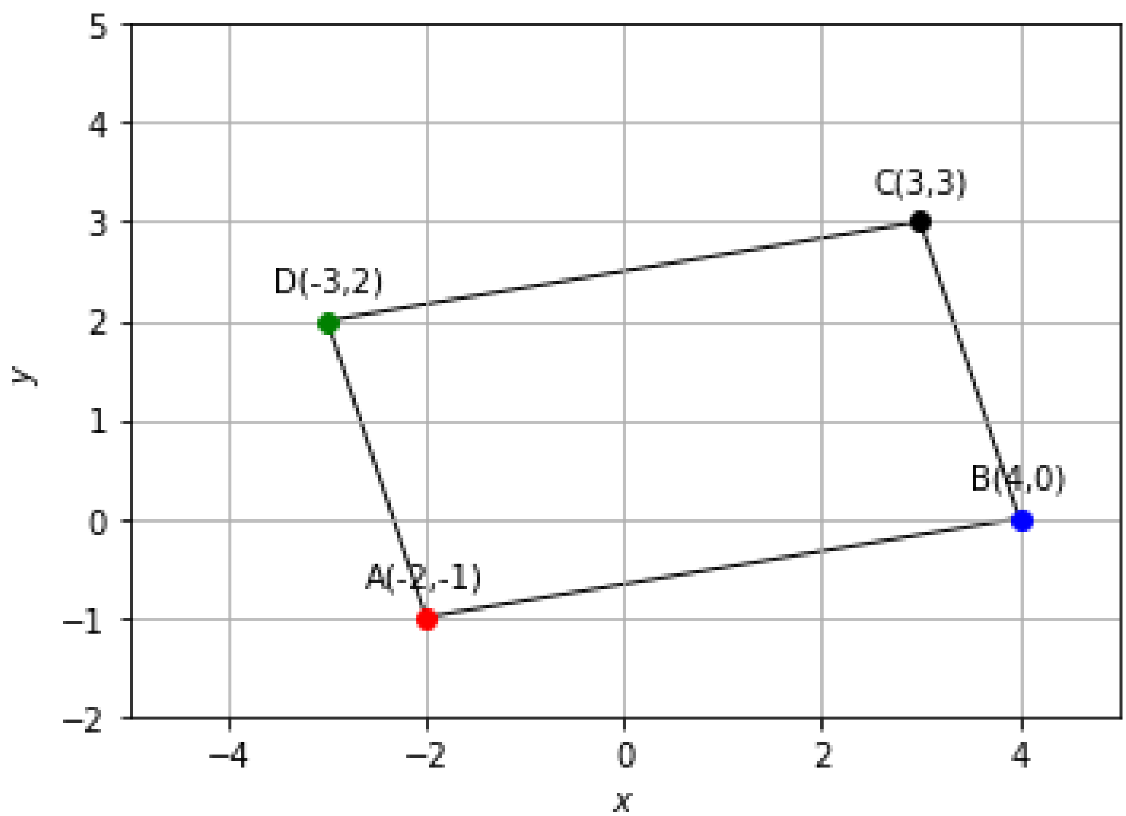


Figure 1.6.8.1:

Solution: See Fig. 1.6.8.1.

$$\mathbf{A} = \begin{pmatrix} -2 \\ -1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} 3 \\ 3 \end{pmatrix}, \mathbf{D} = \begin{pmatrix} -3 \\ 2 \end{pmatrix} \tag{1.6.8.1}$$

and

$$\mathbf{P} = \mathbf{B} - \mathbf{A} = \begin{pmatrix} 6 \\ 1 \end{pmatrix} \tag{1.6.8.2}$$

$$\mathbf{Q} = \mathbf{C} - \mathbf{D} = \begin{pmatrix} 6 \\ 1 \end{pmatrix} \tag{1.6.8.3}$$

$$\mathbf{R} = \mathbf{A} - \mathbf{C} = \begin{pmatrix} 1 \\ -3 \end{pmatrix} \tag{1.6.8.4}$$

$$\mathbf{S} = \mathbf{A} - \mathbf{D} = \begin{pmatrix} 1 \\ -3 \end{pmatrix} \tag{1.6.8.5}$$

Since $\mathbf{P} = \mathbf{Q}$ and $\mathbf{R} = \mathbf{S}$, from (A.1.24.1), $ABCD$ is a parallelogram

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

Solution: See Fig. 1.6.9.1.

Let

$$\mathbf{P} = \begin{pmatrix} 3 \\ -1 \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} 4 \\ -2 \end{pmatrix} \tag{1.6.9.1}$$

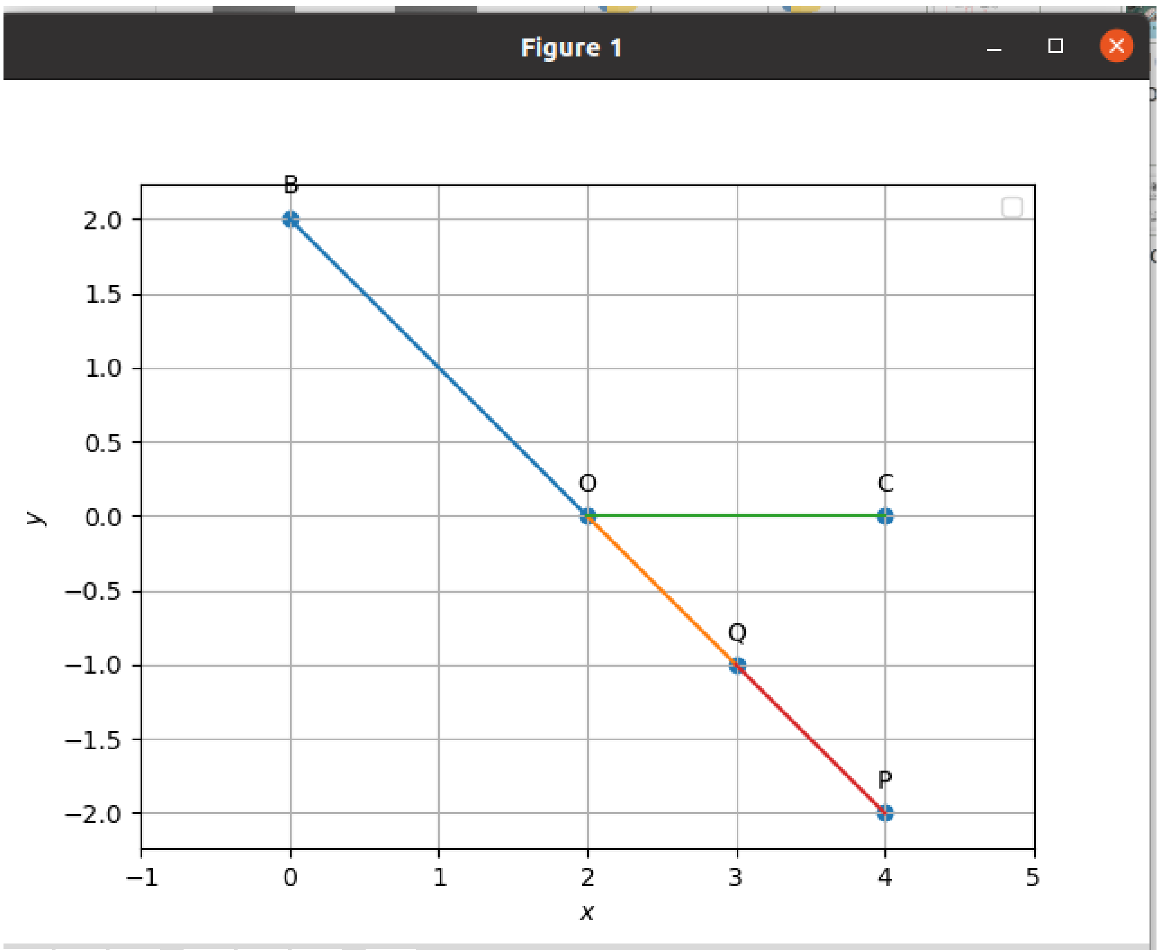


Figure 1.6.9.1:

Then

$$\mathbf{C} = \mathbf{P} - \mathbf{Q} = \begin{pmatrix} -1 \\ 1 \end{pmatrix} \tag{1.6.9.2}$$

The desired angle is given by

$$\cos\theta = \frac{\mathbf{C}^T\mathbf{e}_1}{\|\mathbf{C}\|\,\|\mathbf{e}_1\|} \tag{1.6.9.3}$$

$$= -\frac{1}{\sqrt{2}} \tag{1.6.9.4}$$

$$\implies \theta = 135^\circ \tag{1.6.9.5}$$

1.6.10 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.

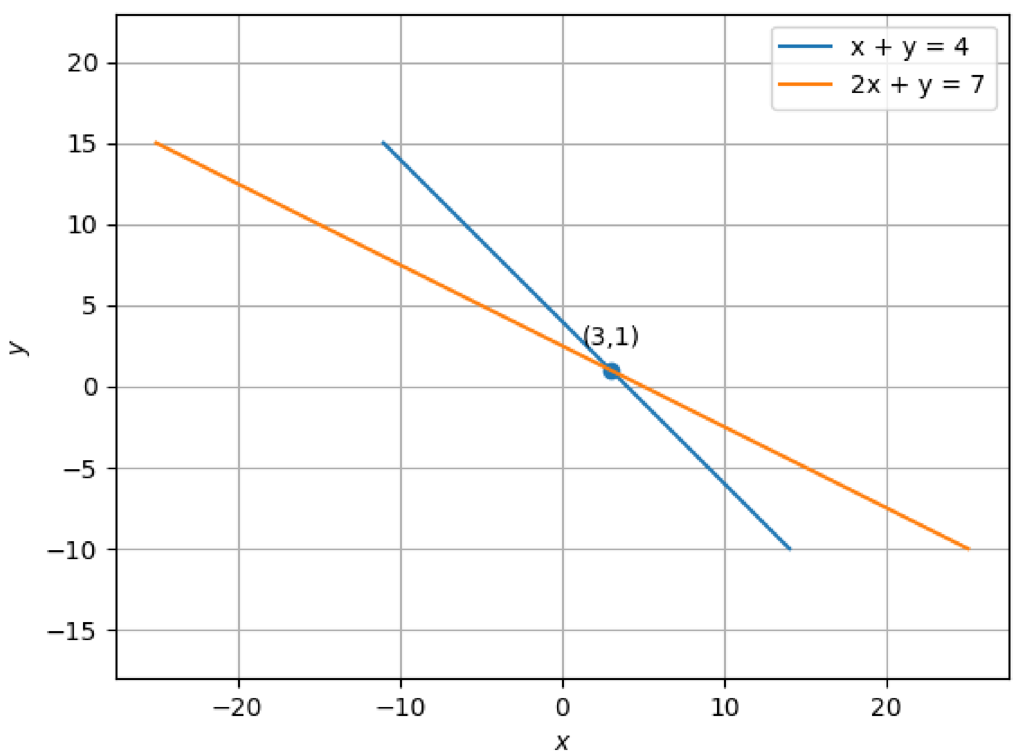


Figure 1.6.10.1:

Solution: The direction vector of a line is expressed as

$$\mathbf{m} = \begin{pmatrix} 1 \\ m \end{pmatrix} \tag{1.6.10.1}$$

where m is defined to be the slope of the line. If the angle between the lines be θ,

$$\tan\theta = \frac{1}{3} \implies \cos\theta = \frac{3}{\sqrt{10}} \tag{1.6.10.2}$$

The angle between two vectors is then expressed as

$$\frac{3}{\sqrt{10}} = \frac{\mathbf{m}_1^\top \mathbf{m}_2}{\|\mathbf{m}_1\| \|\mathbf{m}_2\|} \tag{1.6.10.3}$$

$$= \frac{\begin{pmatrix} 1 & m \end{pmatrix} \begin{pmatrix} 1 \\ 2m \end{pmatrix}}{\left\| \begin{pmatrix} 1 \\ m \end{pmatrix} \right\| \left\| \begin{pmatrix} 1 \\ 2m \end{pmatrix} \right\|} \tag{1.6.10.4}$$

$$= \frac{2m^2 + 1}{\sqrt{m^2+1}\sqrt{4m^2+1}} \tag{1.6.10.5}$$

$$\implies \frac{9}{10} = \frac{4m^4 + 4m^2 + 1}{4m^4 + 5m^2 + 1} \tag{1.6.10.6}$$

$$\text{or, } 4m^4 - 5m^2 + 1 = 0 \tag{1.6.10.7}$$

yielding

$$m = \pm\frac{1}{2}, \pm 1 \tag{1.6.10.8}$$

1.6.11 A line passes through (x_1, y_1) and (h, k). If slope of the line is m show that

$(k - y_1) = m(h - x_1)$.

Solution: Given

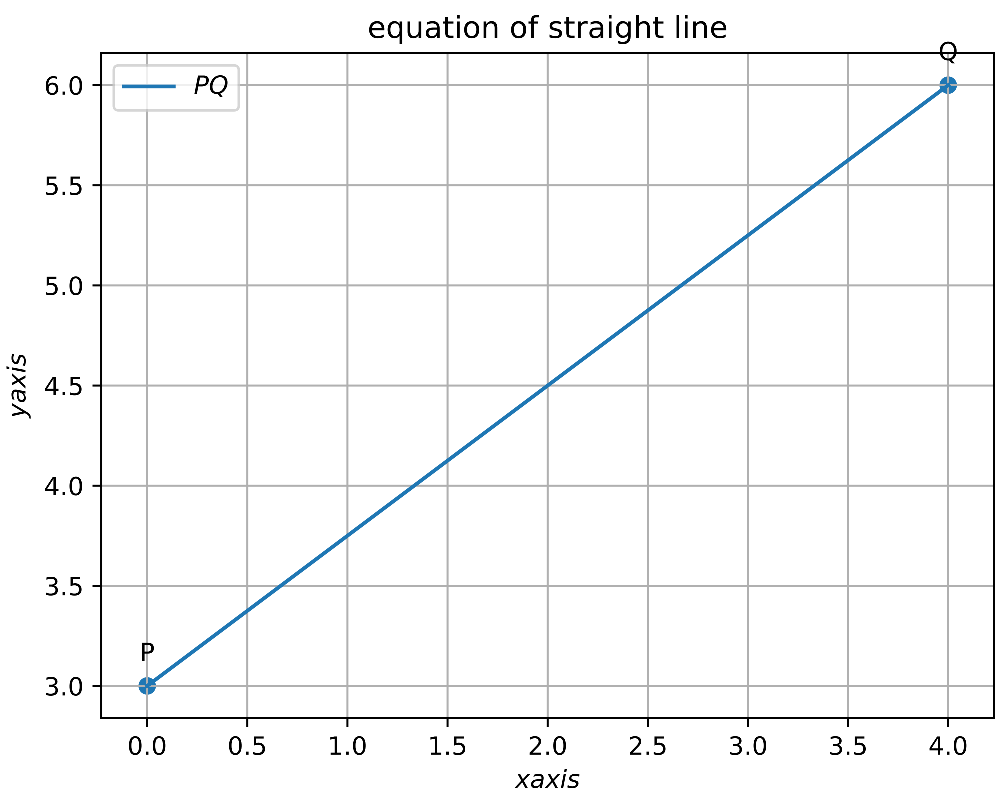


Figure 1.6.11.1:

$$\mathbf{A} = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} h \\ k \end{pmatrix} \tag{1.6.11.1}$$

The direction vector

$$\mathbf{m} = \mathbf{B} - \mathbf{A} \tag{1.6.11.2}$$

$$= \begin{pmatrix} h - x_1 \\ k - y_1 \end{pmatrix} \equiv \begin{pmatrix} 1 \\ \frac{k-y_1}{h-x_1} \end{pmatrix} \tag{1.6.11.3}$$

which yields the desired relation from (A.1.18.1).

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

$$\frac{a}{h} + \frac{b}{k} = 1 \tag{1.6.12.1}$$

Solution: Let

$$\mathbf{A} = \begin{pmatrix} h \\ 0 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} a \\ b \end{pmatrix}, \mathbf{C} = \begin{pmatrix} 0 \\ k \end{pmatrix} \tag{1.6.12.2}$$

Forming the matrix in (C.1.4.1), we obtain, upon row reduction

$$\begin{pmatrix} h - a & -b \\ h & -k \end{pmatrix} \xleftrightarrow{\frac{R_1}{h-a}} \begin{pmatrix} 1 & \frac{-b}{h-a} \\ h & -k \end{pmatrix} \tag{1.6.12.3}$$

$$\xleftrightarrow{R_2 \to R_2 - hR_1} \begin{pmatrix} 1 & \frac{-b}{h-a} \\ 0 & -k + \frac{bh}{h-a} \end{pmatrix} \tag{1.6.12.4}$$

For obtaining a rank 1 matrix,

$$-k + \frac{bh}{h-a} = 0 \tag{1.6.12.5}$$

$$\implies \frac{a}{h} + \frac{b}{k} = 1 \tag{1.6.12.6}$$

upon simplification.

Chapter 2

Line

2.1. Equation of a Line

2.1.1

2.1.2

2.1.3

2.1.4

2.1.5

2.1.6

2.1.7

2.1.8

2.1.9 The Vertices of Triangle PQR is $\mathbf{P}(2,1), \mathbf{Q}(-2,3), \mathbf{R}(4,5)$. Find the equation of the Median Through $\mathbf{R}$.

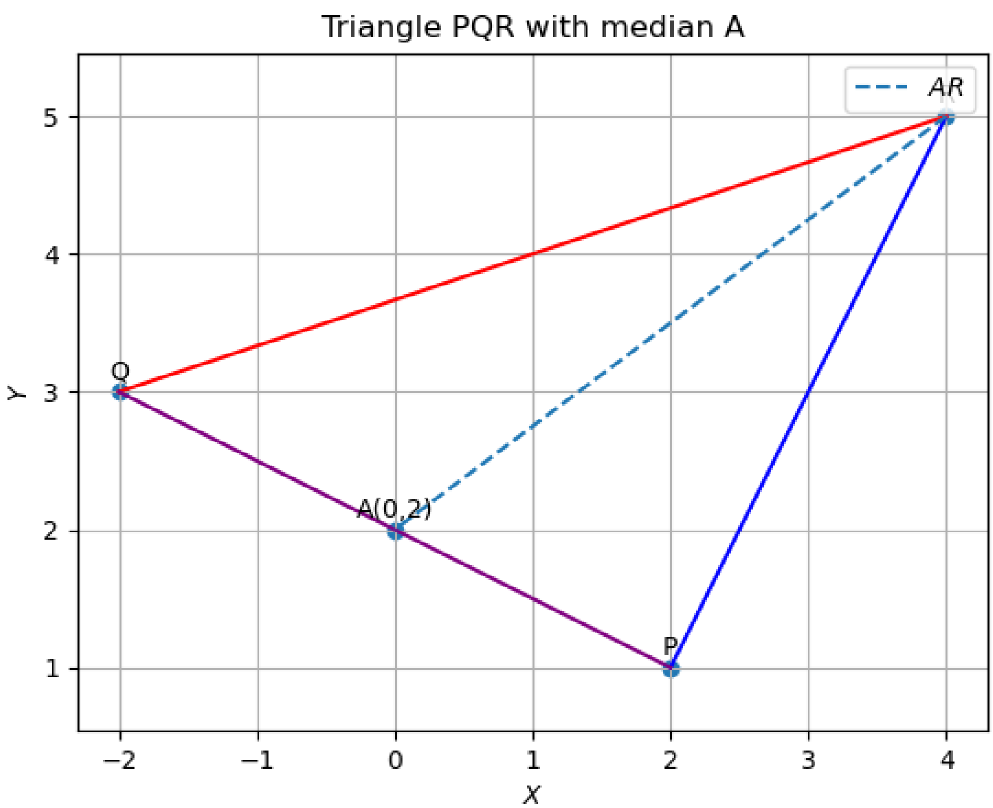


Figure 2.1.9.1:

Solution: See Fig. 2.1.9.1. Using Section Formula,

$$\mathbf{A} = \frac{\mathbf{P}+\mathbf{Q}}{2} \tag{2.1.9.1}$$

$$= \begin{pmatrix} 0 \\ 2 \end{pmatrix} \tag{2.1.9.2}$$

So , the Direction Vector of AR is

$$\mathbf{m} = \mathbf{R} - \mathbf{A} = \begin{pmatrix} 4 \\ 3 \end{pmatrix} \tag{2.1.9.3}$$

$$\implies \mathbf{n} = \begin{pmatrix} 3 \\ -4 \end{pmatrix} \tag{2.1.9.4}$$

which is the normal vector. Thus, from (C.1.2.1), the equation of the line is

$$\begin{pmatrix} 3 & -4 \end{pmatrix} (\mathbf{x} - \mathbf{R}) = 0 \tag{2.1.9.5}$$

$$\implies \begin{pmatrix} 3 & -4 \end{pmatrix} \mathbf{x} = 8 \tag{2.1.9.6}$$

2.1.10 Find the equation of the line passing through (-3,5) and perpendicular to the line through the points (2,5) and (-3,6).

Solution: Let

$$\mathbf{A} = \begin{pmatrix} 2 \\ 5 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} -3 \\ 6 \end{pmatrix}, \mathbf{P} = \begin{pmatrix} -3 \\ 5 \end{pmatrix} \tag{2.1.10.1}$$

The normal vector of the desired line is then given by

$$\mathbf{n} = \mathbf{B} - \mathbf{A} = \begin{pmatrix} 5 \\ -1 \end{pmatrix} \tag{2.1.10.2}$$

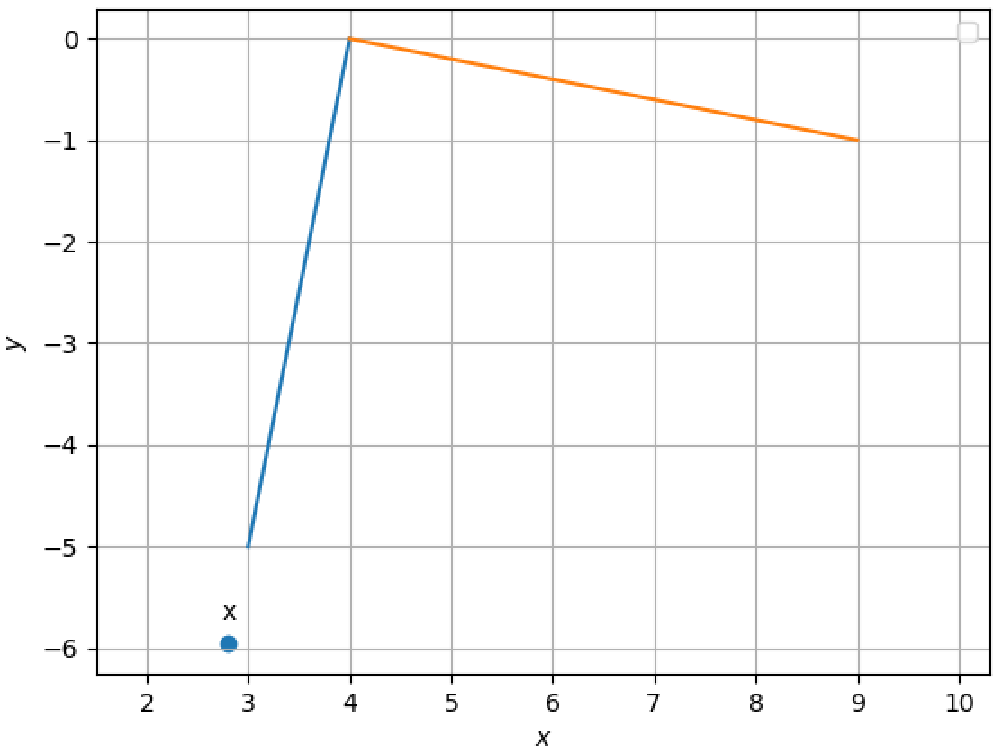


Figure 2.1.10.1:

Thus, the equation of the line is

$$\begin{pmatrix} 5 & -1 \end{pmatrix} \left(\mathbf{x} - \begin{pmatrix} -3 \\ 5 \end{pmatrix} \right) = 0 \tag{2.1.10.3}$$

$$\implies \begin{pmatrix} 5 & -1 \end{pmatrix} \mathbf{x} = -20 \tag{2.1.10.4}$$

2.1.11 A line perpendicular to the line segement joining the points (1,0) and (2,3) divides it in the ratio $1 : n$. Find the equation of the line.

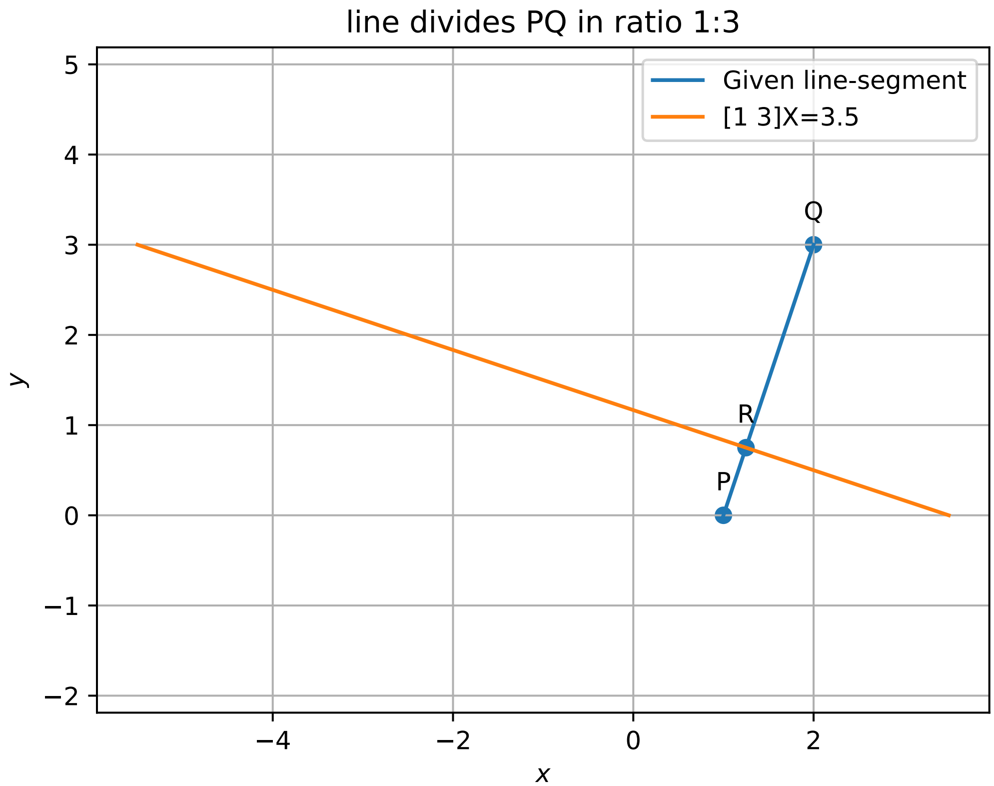


Figure 2.1.11.1:

Solution: Let

$$\mathbf{P} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} 2 \\ 3 \end{pmatrix} \tag{2.1.11.1}$$

The direction vector of PQ is

$$\mathbf{m} = \mathbf{Q} - \mathbf{P} = \begin{pmatrix} 1 \\ 3 \end{pmatrix} \tag{2.1.11.2}$$

Also, using section formula,

$$\mathbf{R} = \frac{\mathbf{Q} + n\mathbf{P}}{1+n} \tag{2.1.11.3}$$

and the equation of line passing through $\mathbf{R}$ is

$$\mathbf{m}^\top (\mathbf{x} - \mathbf{R}) = 0 \tag{2.1.11.4}$$

$$\implies \begin{pmatrix} 1 & 3 \end{pmatrix} \mathbf{x} = \begin{pmatrix} 1 \ 3 \end{pmatrix} \begin{pmatrix} \frac{2+n}{1+n} \\ \frac{3}{1+n} \end{pmatrix} \tag{2.1.11.5}$$

$$= \frac{11+n}{1+n} \tag{2.1.11.6}$$

2.1.12

2.1.13 Find equation of a line passing trough a point (2,2) and cutting off intercepts on the axes whose sum is 9.

Solution: Let the x intercept be a and the y intercept be b. Then

$$a + b = 9 \tag{2.1.13.1}$$

Let

$$\mathbf{P} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} 0 \\ b \end{pmatrix}, \mathbf{R} = \begin{pmatrix} 2 \\ 2 \end{pmatrix} \tag{2.1.13.2}$$

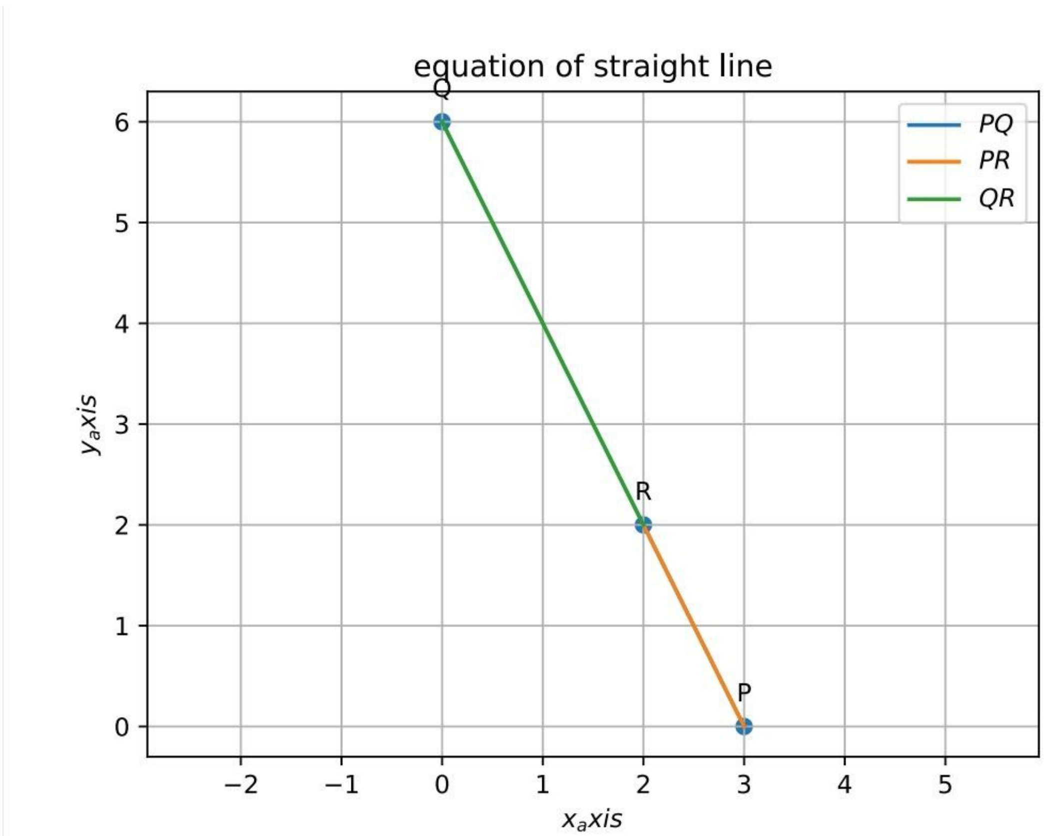


Figure 2.1.13.1:

Since the points are collinear, from (C.1.4.1), we obtain the matrix

$$\begin{pmatrix} \mathbf{P}-\mathbf{Q} & \mathbf{P}-\mathbf{R} \end{pmatrix} = \begin{pmatrix} a & a-2 \\ -b & -2 \end{pmatrix} \tag{2.1.13.3}$$

which is singular if the determinant

$$-2a + b(a-2) = ab - 2\,(a+b) = 0 \tag{2.1.13.4}$$

yielding

$$ab = 18 \tag{2.1.13.5}$$

upon substituting from (2.1.13.1). (2.1.13.5) and (2.1.13.1) form

$$x^2 - 9x + 18 = 0 \tag{2.1.13.6}$$

with roots

$$x = 6, 3 \tag{2.1.13.7}$$

$$\text{or, } \begin{pmatrix} a \\ b \end{pmatrix} = \begin{pmatrix} 6 \\ 3 \end{pmatrix}, \begin{pmatrix} 3 \\ 6 \end{pmatrix} \tag{2.1.13.8}$$

Since the direction vector of the line is

$$\mathbf{P} - \mathbf{Q} = \begin{pmatrix} a \\ -b \end{pmatrix}, \tag{2.1.13.9}$$

the normal vector is

$$\mathbf{n} = \begin{pmatrix} b \\ a \end{pmatrix} \equiv \begin{pmatrix} 1 \\ 2 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \end{pmatrix} \tag{2.1.13.10}$$

Thus, the possible equations of the line are

$$\begin{pmatrix} 1 & 2 \end{pmatrix} \mathbf{x} = 6 \tag{2.1.13.11}$$

$$\begin{pmatrix} 2 & 1 \end{pmatrix} \mathbf{x} = 6 \tag{2.1.13.12}$$

2.1.14 Find the equation of the line through the point (0,2) making an angle

$$2\pi/3 \tag{2.1.14.1}$$

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

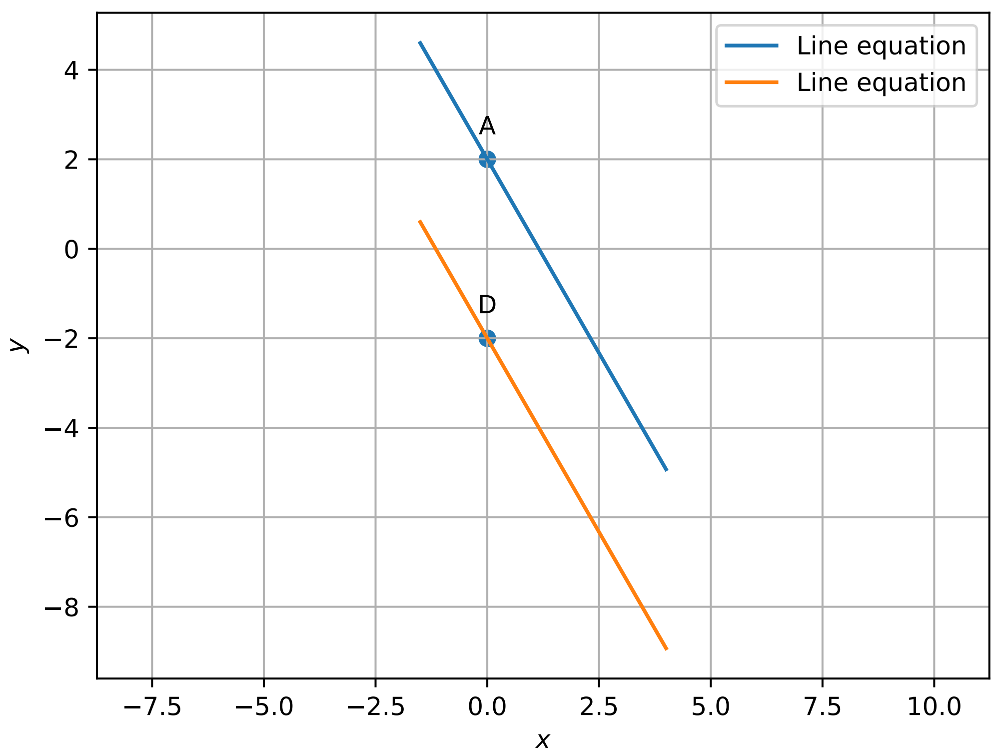


Figure 2.1.14.1:

Solution: From the given information, the direction vector is

$$\mathbf{m} = \begin{pmatrix} 1 \\ -\sqrt{3} \end{pmatrix} \tag{2.1.14.2}$$

Thus, the normal vector is

$$\mathbf{n} = \begin{pmatrix} \sqrt{3} \\ 1 \end{pmatrix} \tag{2.1.14.3}$$

and the equation of the line is

$$\begin{pmatrix} \sqrt{3} & 1 \end{pmatrix} \left(\mathbf{x} - \begin{pmatrix} 0 \\ 2 \end{pmatrix} \right) = 0 \tag{2.1.14.4}$$

$$\implies \begin{pmatrix} \sqrt{3} & 1 \end{pmatrix} \mathbf{x} = 2 \tag{2.1.14.5}$$

The equation of the parallel crossing the Y-axis at a distance of 2 units below the origin is given by

$$\begin{pmatrix} \sqrt{3} & 1 \end{pmatrix} \left(\mathbf{x} - \begin{pmatrix} 0 \\ -2 \end{pmatrix} \right) = 0 \tag{2.1.14.6}$$

$$\implies \begin{pmatrix} \sqrt{3} & 1 \end{pmatrix} \mathbf{x} = -2 \tag{2.1.14.7}$$

2.1.15 The perpendicular from the origin to a line meets it at the point (-2,9). Find the equation of the line.

Solution:

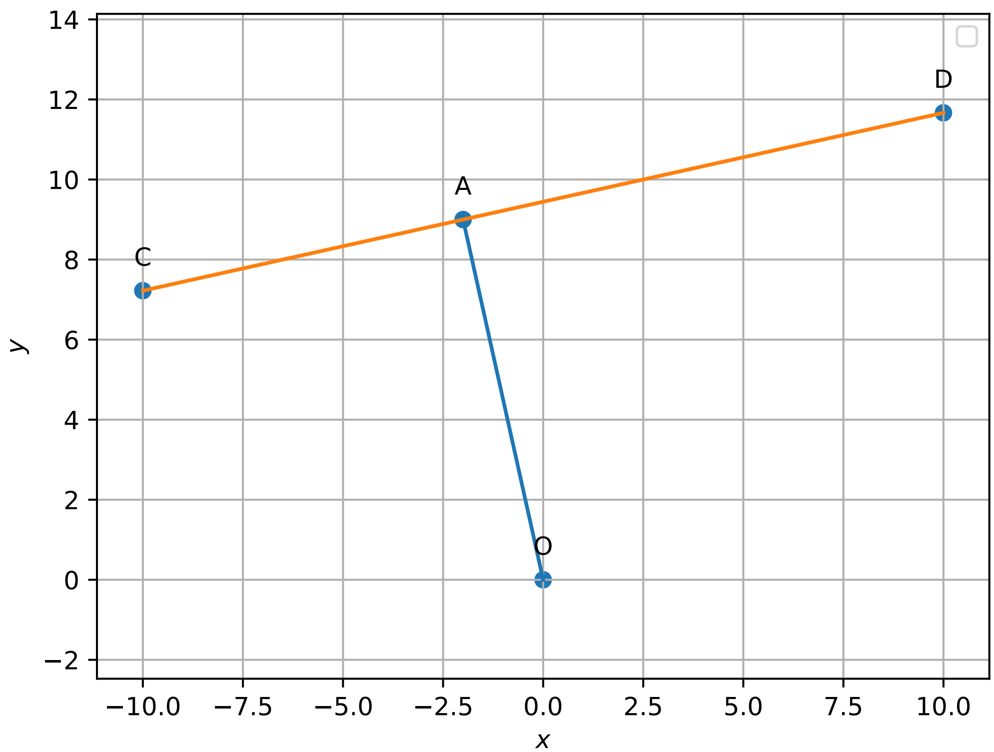


Figure 2.1.15.1:

Given

$$\mathbf{0} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \mathbf{A} = \begin{pmatrix} -2 \\ 9 \end{pmatrix} \tag{2.1.15.1}$$

The normal vector is

$$\mathbf{n} = \mathbf{O} - \mathbf{A} \tag{2.1.15.2}$$

$$= \begin{pmatrix} 2 \\ -9 \end{pmatrix} \tag{2.1.15.3}$$

yielding the equation of the line as

$$\begin{pmatrix} 2 & -9 \end{pmatrix} \left(\mathbf{x} - \begin{pmatrix} 2 \\ -9 \end{pmatrix} \right) = 0 \tag{2.1.15.4}$$

$$\implies \begin{pmatrix} 2 & -9 \end{pmatrix} \mathbf{x} = 85 \tag{2.1.15.5}$$

2.1.16

2.1.17

2.1.18

2.1.19

2.1.20 By using the concept of equation of a line, prove that the three points (3, 0), (– 2, – 2) and (8, 2) are collinear.

Solution: The collinearity matrix can be expressed as

$$\begin{pmatrix} -5 & -2 \\ 5 & 2 \end{pmatrix} \xleftrightarrow{R_2 \leftarrow R_1 + R_2} = \begin{pmatrix} -5 & -2 \\ 0 & 0 \end{pmatrix} \tag{2.1.20.1}$$

which is a rank 1 matrix.

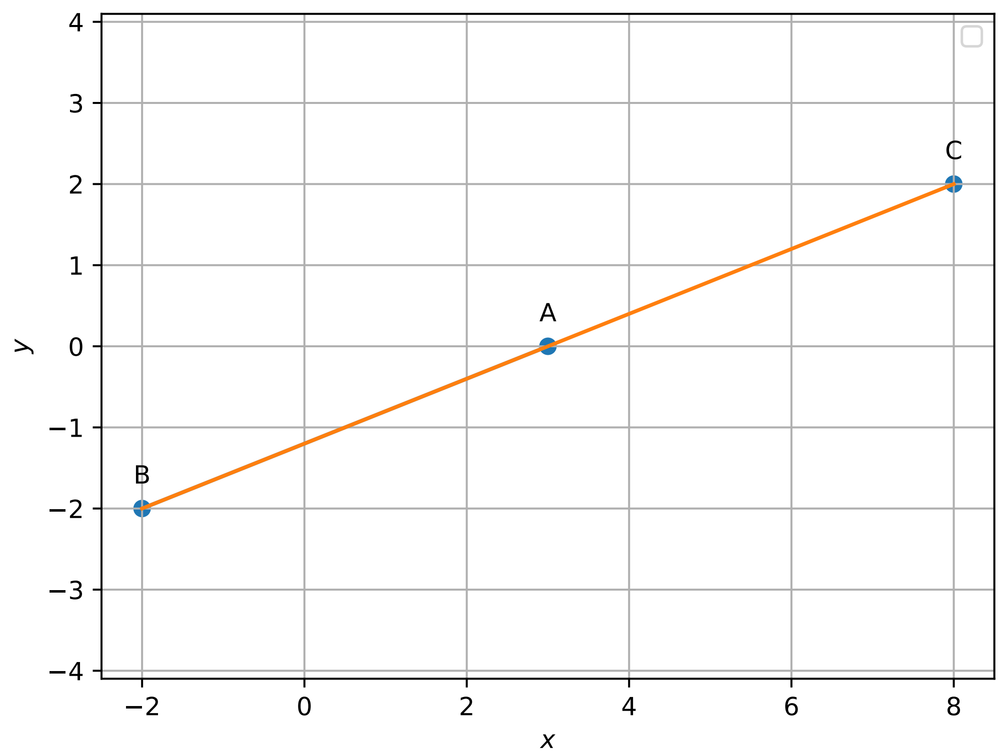


Figure 2.1.20.1:

2.2. General Equation of a Line

2.2.1

2.2.2

2.2.3

2.2.4

2.2.5

2.2.6

2.2.7 Find the equation of the line parallel to the line 3x-4y+2=0 and passing through the point (-2,3).

Solution: From the given information,

$$\mathbf{n} = \begin{pmatrix} 3 \\ -4 \end{pmatrix} \tag{2.2.7.1}$$

$$\implies \begin{pmatrix} 3 & -4 \end{pmatrix} \left\{ \mathbf{x} - \begin{pmatrix} -2 \\ 3 \end{pmatrix} \right\} = 0 \tag{2.2.7.2}$$

$$= -18 \tag{2.2.7.3}$$

which is the required equation of the line.

2.2.8

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

Solution: From the given equations, the normal vectors can be expressed as

$$\mathbf{n}_1 = \begin{pmatrix} \sqrt{3} \\ 1 \end{pmatrix}, \mathbf{n}_2 = \begin{pmatrix} 1 \\ \sqrt{3} \end{pmatrix} \tag{2.2.9.1}$$

The angle between the lines can then be expressed as

$$cos\theta = \frac{\mathbf{n}_1^T \mathbf{n}_2}{\|\mathbf{n}_1\| \|\mathbf{n}_2\|} \tag{2.2.9.2}$$

$$= \frac{\sqrt{3}}{2} \tag{2.2.9.3}$$

$$\text{or, } \theta = 30^\circ \tag{2.2.9.4}$$

2.2.10

2.2.11

2.2.12

2.2.13

2.2.14

2.2.15

2.2.16

2.2.17

2.2.18

2.3. Miscellaneous Exercises

Chapter 3

Circles

3.1. Equation

3.1.1

3.1.2

3.1.3

3.1.4

3.1.5

3.1.6

3.1.7

3.1.8

3.1.9

3.1.10

3.1.11 Find the equation of the circle passing through the points (2,3) and (-1,1) and whose centre is on the line $x - 3y - 11 = 0$

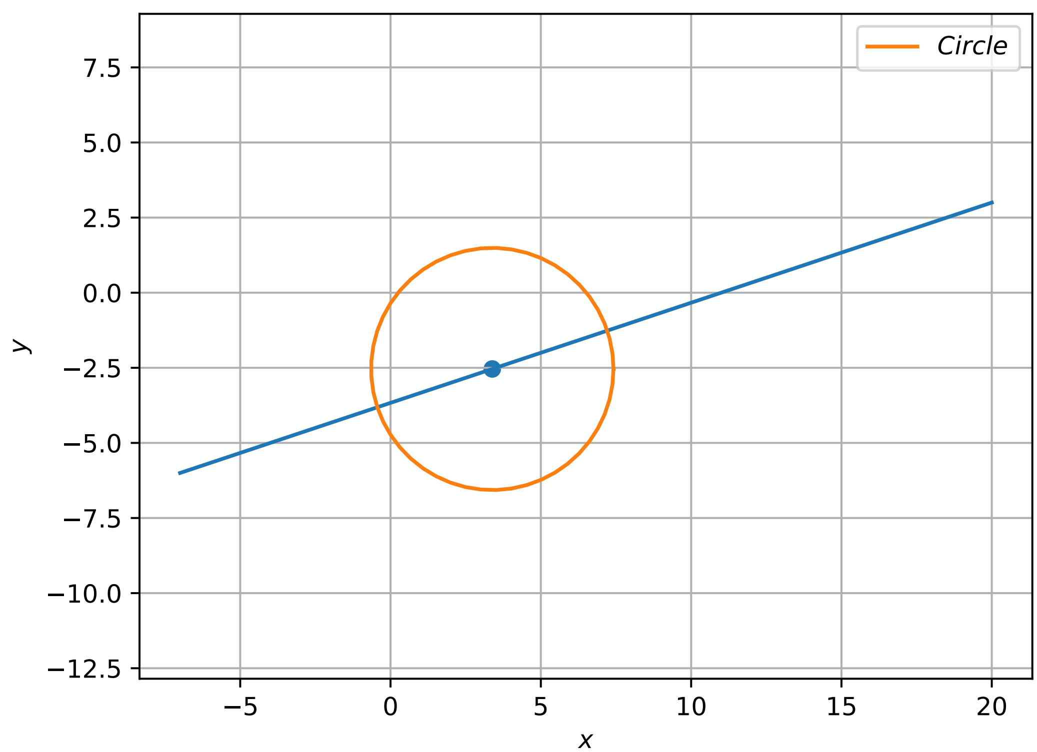


Figure 3.1.11.1:

Solution: See Fig. From (D.2.1.1), and the given information,

$$\|\mathbf{P}\|^2 + 2\mathbf{u}^\top \mathbf{P} + f = 0 \tag{3.1.11.1}$$

$$\|\mathbf{Q}\|^2 + 2\mathbf{u}^\top \mathbf{Q} + f = 0 \tag{3.1.11.2}$$

$$-\mathbf{n}^\top \mathbf{u} = c \tag{3.1.11.3}$$

by noting that the centre of the circle is $-\mathbf{u}$. Substituting numerical values, we obtain the matrix equation

$$\begin{pmatrix} 4 & 6 & 1 \\ -2 & 2 & 1 \\ -1 & 3 & 0 \end{pmatrix} \begin{pmatrix} \mathbf{u} \\ f \end{pmatrix} = \begin{pmatrix} -13 \\ -2 \\ 11 \end{pmatrix} \tag{3.1.11.4}$$

$$\tag{3.1.11.5}$$

The augmented matrix for (3.1.11.4) can be expressed as

$$\xleftrightarrow{1/4R_1 \leftrightarrow R_1} \left(\begin{array}{ccc|c} 1 & 3/2 & .1/4 & -13/4 \\ -2 & 2 & 1 & -2 \\ -1 & 3 & 0 & 11 \end{array}\right) \tag{3.1.11.6}$$

which can be reduced to echelon form using row operations to obtain

$$\mathbf{u} = \begin{pmatrix} -7/2 \\ 5/2 \end{pmatrix}, f = -14 \tag{3.1.11.7}$$

3.1.12 Find the equation of circle with radius 5 whose center lies on x-axis and passes through point $(2, 3)$.

Solution: See Fig. 3.1.12.1. From the given information, the following equations can be formulated using (D.2.1.1).

$$\|\mathbf{P}\|^2 + 2\mathbf{u}^\top \mathbf{P} + f = 0 \tag{3.1.12.1}$$

$$\mathbf{u} = k\mathbf{e}_1 \tag{3.1.12.2}$$

$$\|\mathbf{u}\|^2 - f = r^2 \tag{3.1.12.3}$$

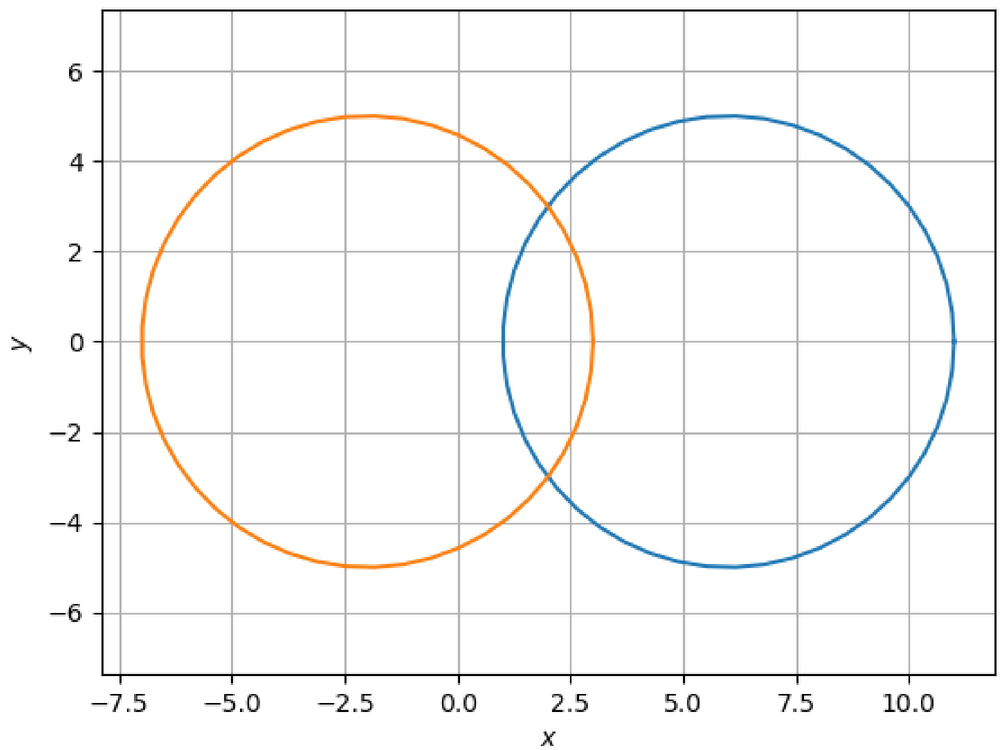


Figure 3.1.12.1:

where

$$\mathbf{P} = \begin{pmatrix} 2 \\ 3 \end{pmatrix} \text{ and } r = 5 \tag{3.1.12.4}$$

From (3.1.12.1) and (3.1.12.3),

$$\|\mathbf{P}\|^2 + 2\mathbf{u}^\top \mathbf{P} + \|\mathbf{u}\|^2 = r^2 \tag{3.1.12.5}$$

Substituting from (3.1.12.2) in the above,

$$k^2 + 2k\mathbf{e}_1^\top \mathbf{P} + \|\mathbf{P}\|^2 - r^2 = 0 \tag{3.1.12.6}$$

resulting in

$$k = -\mathbf{e}_1^\top \mathbf{P} \pm \sqrt{\left(\mathbf{e}_1^\top \mathbf{P}\right)^2 + r^2 - \|\mathbf{P}\|^2} \tag{3.1.12.7}$$

Substituting numerical values,

$$k = 2, -6 \tag{3.1.12.8}$$

resulting in circles with centre

$$-\mathbf{u} = \begin{pmatrix} -2 \\ 0 \end{pmatrix} \text{ or } \begin{pmatrix} 6 \\ 0 \end{pmatrix}. \tag{3.1.12.9}$$

This is verified in Fig. (3.1.12.1).

3.2. Construction of Tangents to a Circle

3.2.1 Draw a circle of radius 6 cm. From a point 10 cm away from its centre, construct the pair of tangents to the circle and measure their lengths.

Solution: Follow the approach in Problem 6.4.6.

3.2.2 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.

Solution: See Fig. 3.2.2.1.

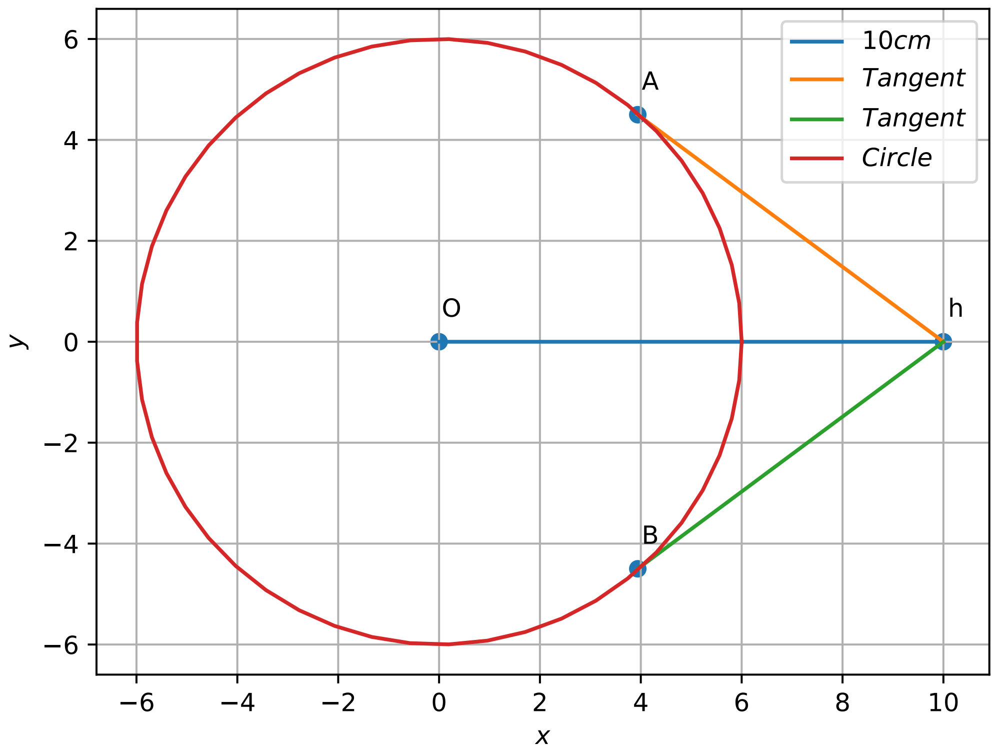


Figure 3.2.1.1:

3.2.3 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**.

Solution: See Fig. 3.2.3.1.

3.2.4 Draw a pair of tangents to a circle of radius 5 cm which are inclined to each other at an angle of 60°.

Solution: See Fig. 3.2.4.1.

3.2.5 Draw a line segment AB of length 8cm. Taking **A** as centre, draw a circle of radius

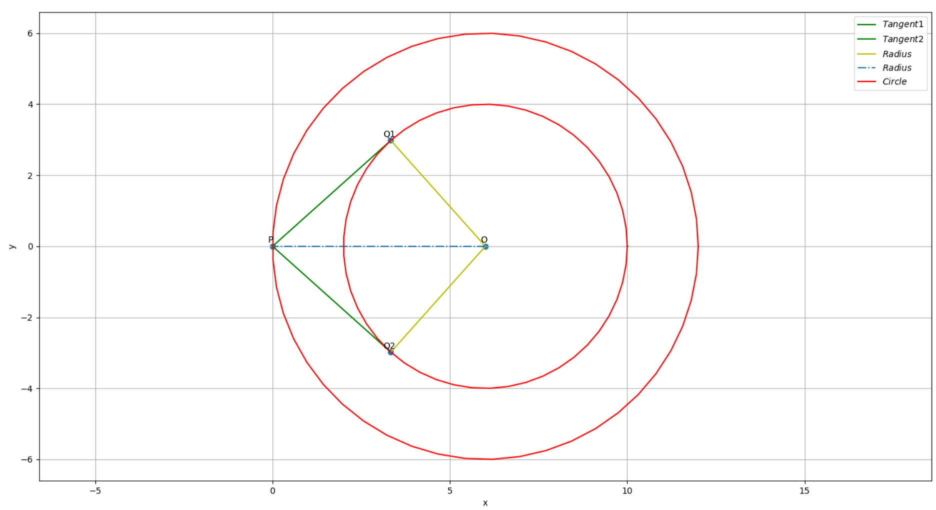


Figure 3.2.2.1:

4cm and taking $\mathbf{B}$ as centre, draw another circle of radius 3cm. Construct tangents to each circle from the centre of the circle.

Solution: See Fig. 3.2.5.1.

3.2.6 Let ABC be a right triangle in which $AB = 6cm, BC = 8cm$ and $\angle B = 90°$. BD is the perpendicular from $\mathbf{B}$ on AC. The circle through $\mathbf{B}, \mathbf{C}, \mathbf{D}$ is drawn. Construct the tangents from $\mathbf{A}$ to this circle.

Solution: See Fig. 3.2.6.1.

$$BD \perp AC \implies \mathbf{O} = \frac{\mathbf{B}+\mathbf{C}}{2} \tag{3.2.6.1}$$

From (C.1.11.1), the coordinates of $\mathbf{D}$ can be obtained.

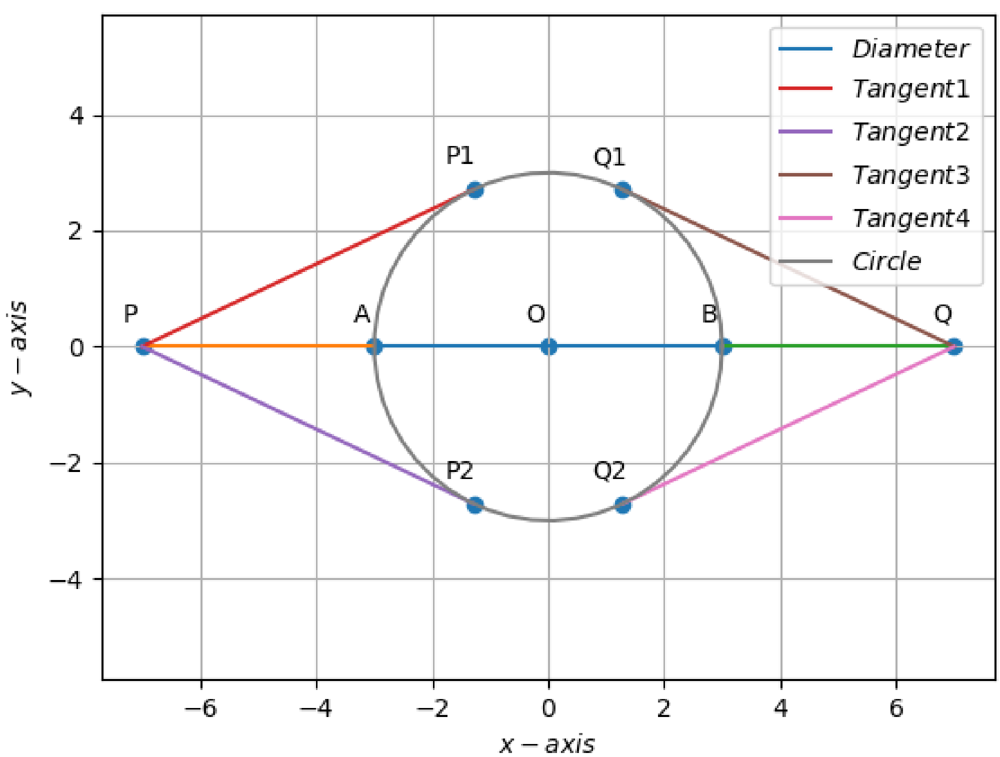

Diameter
Tangent1
Tangent2
Tangent3
Tangent4
Circle
P
A
O
B
Q
P1
Q1
P2
Q2
x − axis
y − axis
−6
−4
−2
0
2
4
6
−4
−2
0
2
4

Figure 3.2.3.1:

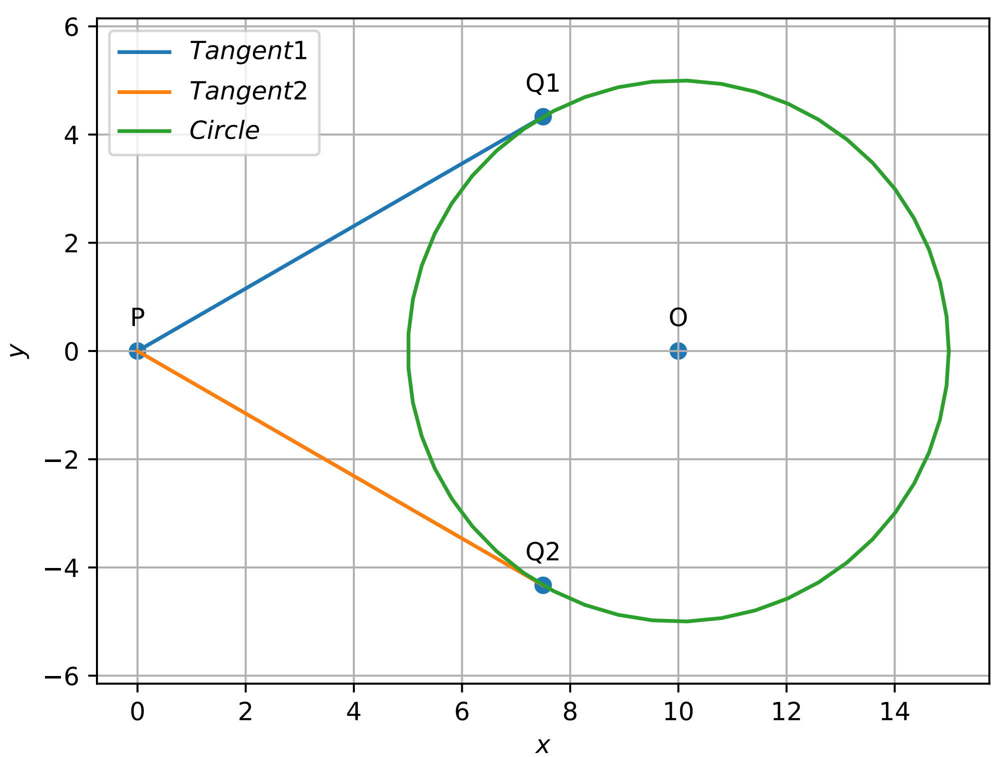


Figure 3.2.4.1:

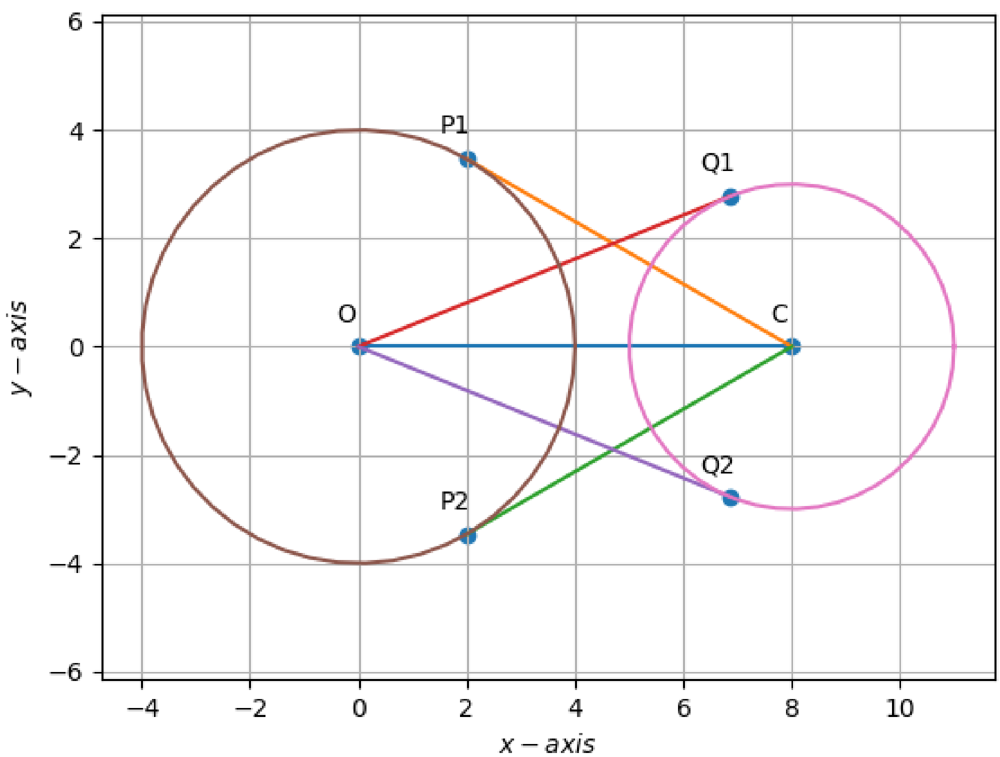


Figure 3.2.5.1:

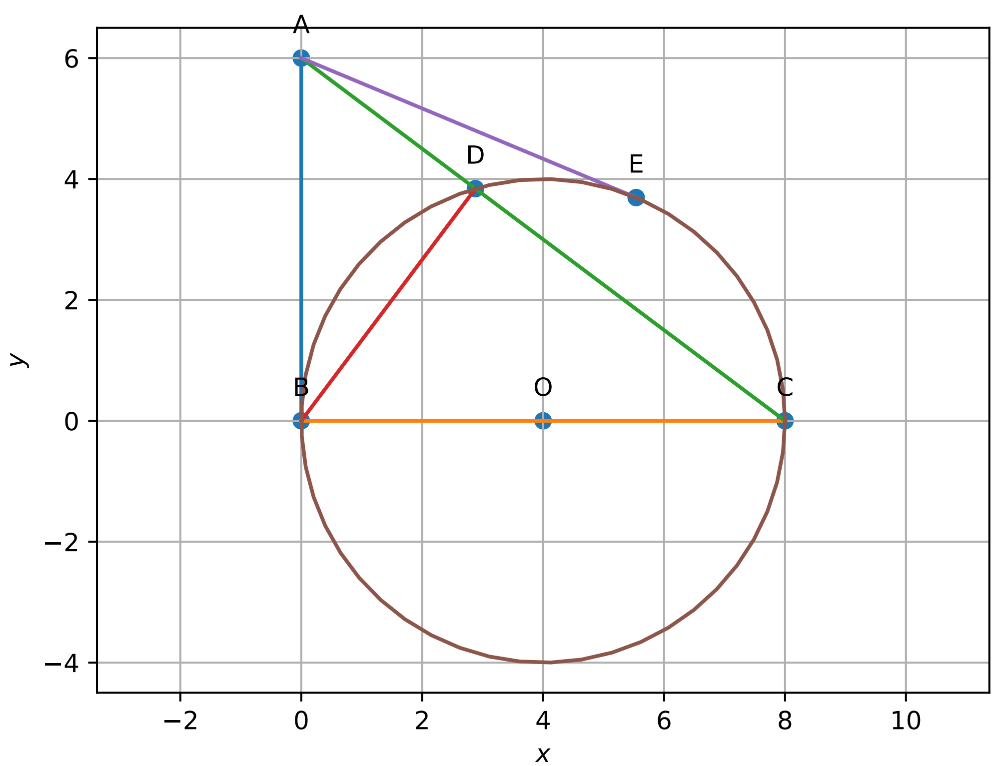


Figure 3.2.6.1:

Chapter 4

Triangle Constructions

4.1. Introduction

4.1.1 Construct a triangle ABC in which $BC = 7cm, \angle B = 75°$ and $AB + AC = 13cm$.

Solution: See Fig. 4.1.1.1.

Using the cosine formula in $\triangle ABC$,

$$b^2 = a^2 + c^2 - 2ac \cos B \tag{4.1.1.1}$$

$$\implies (b + c)(b - c) = a^2 - 2ac \cos B \tag{4.1.1.2}$$

$$\text{or, } K(b - c) = a^2 - 2ac \cos B \tag{4.1.1.3}$$

where

$$K = b + c \tag{4.1.1.4}$$

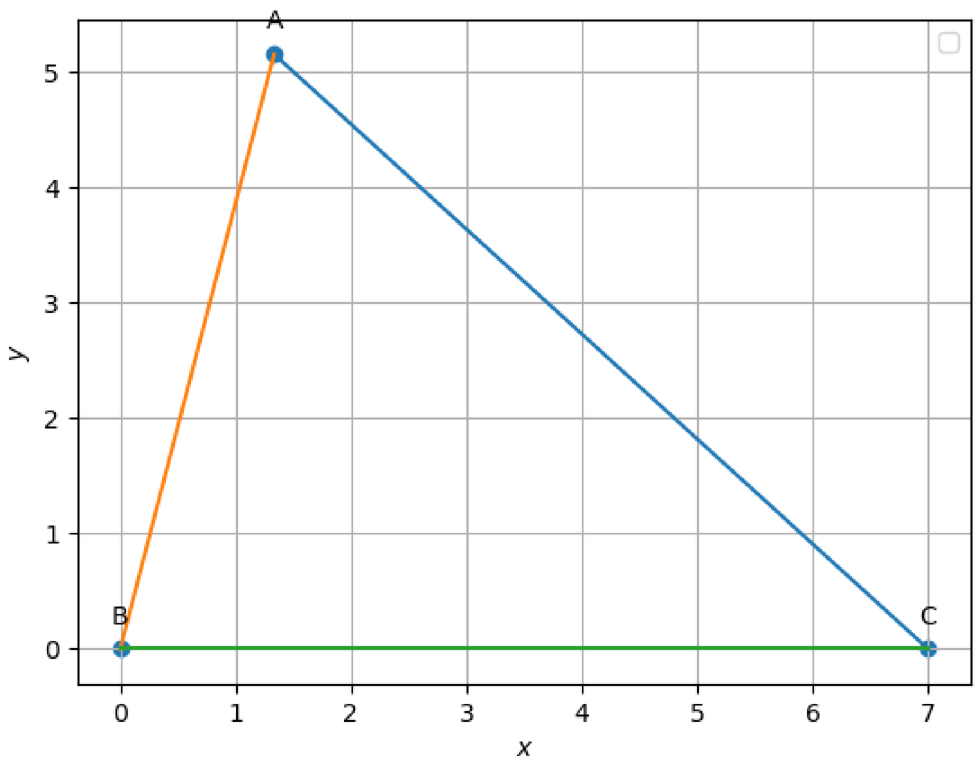


Figure 4.1.1.1:

From (4.1.1.3) and (4.1.1.4),

$$\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} b \\ c \end{pmatrix} = \begin{pmatrix} \frac{a^2 - 2ac\cos B}{K} \\ K \end{pmatrix} \tag{4.1.1.5}$$

$$\implies \begin{pmatrix} b \\ c \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{a^2 - 2ac\cos B}{K} \\ K \end{pmatrix} \tag{4.1.1.6}$$

$$\because \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} = 2\mathbf{I} \tag{4.1.1.7}$$

From (4.1.1.6)

$$c = \frac{1}{2}\mathbf{e}_2^\top \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{a^2}{K} \\ K \end{pmatrix} - \frac{2ac\cos B}{K} \tag{4.1.1.8}$$

$$\implies c = \frac{1}{2\left(1 + \frac{2a\cos B}{K}\right)}\mathbf{e}_2^\top \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{a^2}{K} \\ K \end{pmatrix} \tag{4.1.1.9}$$

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

$$\mathbf{A} = c\begin{pmatrix} \cos B \\ \sin B \end{pmatrix}, \mathbf{B} = \mathbf{0}, \mathbf{C} = \begin{pmatrix} a \\ 0 \end{pmatrix}. \tag{4.1.1.10}$$

4.1.2 Construct a triangle ABC in which $BC = 8cm, \angle B = 45°$ and $AB - AC = 3.5cm$.

Solution: See Fig. 4.1.2.1. Using the cosine formula in $\triangle ABC$,

$$b^2 = a^2 + c^2 - 2ac\cos B \tag{4.1.2.1}$$

$$\implies (b+c)(b-c) = a^2 - 2ac\cos B \tag{4.1.2.2}$$

$$\text{or, } K(b+c) = a^2 - 2ac\cos B \tag{4.1.2.3}$$

where

$$-K = b - c \tag{4.1.2.4}$$

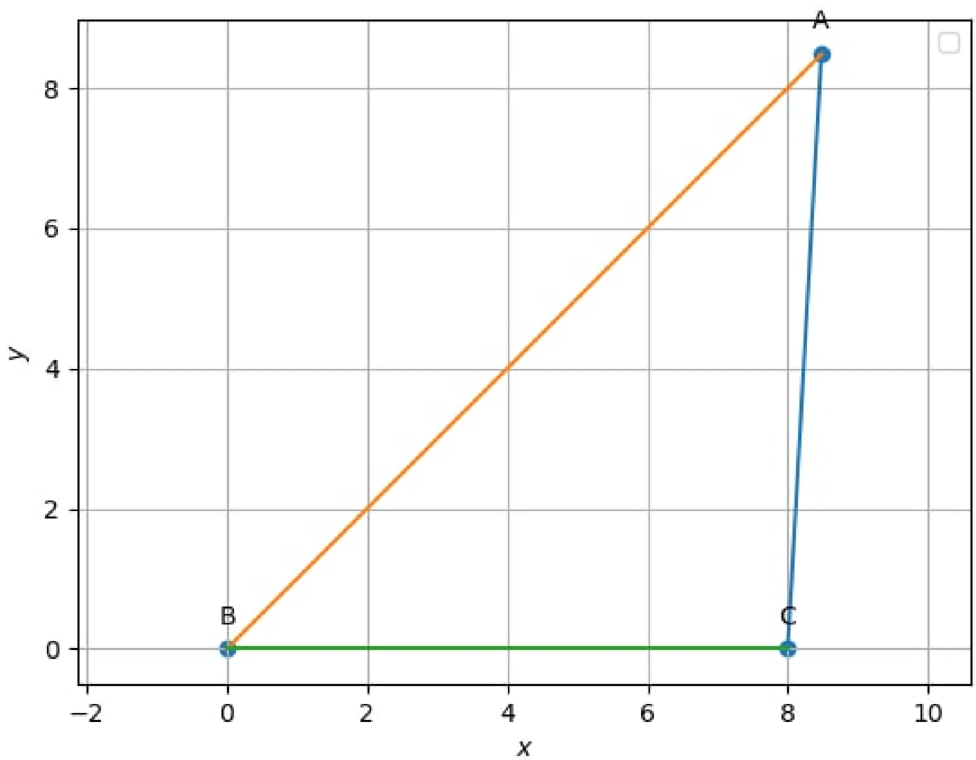


Figure 4.1.2.1:

From (4.1.2.3) and (4.1.2.4),

$$\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} b \\ c \end{pmatrix} = \begin{pmatrix} \frac{a^2-2ac\cos B}{K} \\ -K \end{pmatrix} \tag{4.1.2.5}$$

$$\implies \begin{pmatrix} b \\ c \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{a^2-2ac\cos B}{K} \\ -K \end{pmatrix} \tag{4.1.2.6}$$

$$\because \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} = 2\mathbf{I} \tag{4.1.2.7}$$

From (4.1.2.6)

$$c = \frac{1}{2}\mathbf{e}_2^\top \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{a^2}{K} \\ -K \end{pmatrix} - \frac{2ac\cos B}{K} \tag{4.1.2.8}$$

$$\implies c = \frac{1}{2\left(1 + \frac{2a\cos B}{K}\right)}\mathbf{e}_2^\top \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} \frac{a^2}{K} \\ -K \end{pmatrix} \tag{4.1.2.9}$$

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

$$\mathbf{A} = c\begin{pmatrix} \cos B \\ \sin B \end{pmatrix}, \mathbf{B} = \mathbf{0}, \mathbf{C} = \begin{pmatrix} a \\ 0 \end{pmatrix}. \tag{4.1.2.10}$$

4.1.3 Construct a triangle PQR in which $QR = 6cm, \angle Q = 60°$ and $PR - PQ = 2cm$.

Solution: Same as Problem 4.1.1 with

$$\angle Q = \angle B, QR = a, PR = b, PQ = c \tag{4.1.3.1}$$

4.1.4 Construct a triangle XYZ in which $\angle Y = 30°, \angle Z = 90°$ and $XY + YZ + ZX = 11cm$.

Solution: From the given information,

$$x + y + z = K \tag{4.1.4.1}$$

$$y\cos Z + z\cos Y - x = 0 \tag{4.1.4.2}$$

$$y\sin Z - z\sin Y = 0 \tag{4.1.4.3}$$

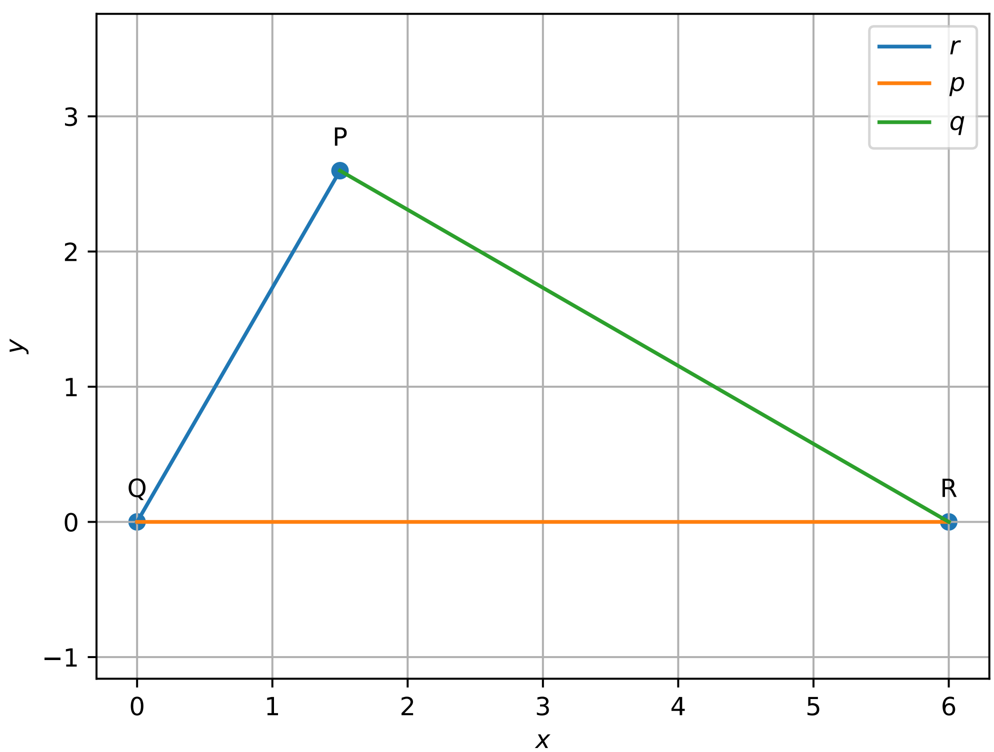


Figure 4.1.3.1:

resulting in the matrix equation

$$\begin{pmatrix} 1 & 1 & 1 \\ \cos Z & \cos Y & -1 \\ \sin Z & -\sin Y & 0 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix} = K\mathbf{e}_1 \tag{4.1.4.4}$$

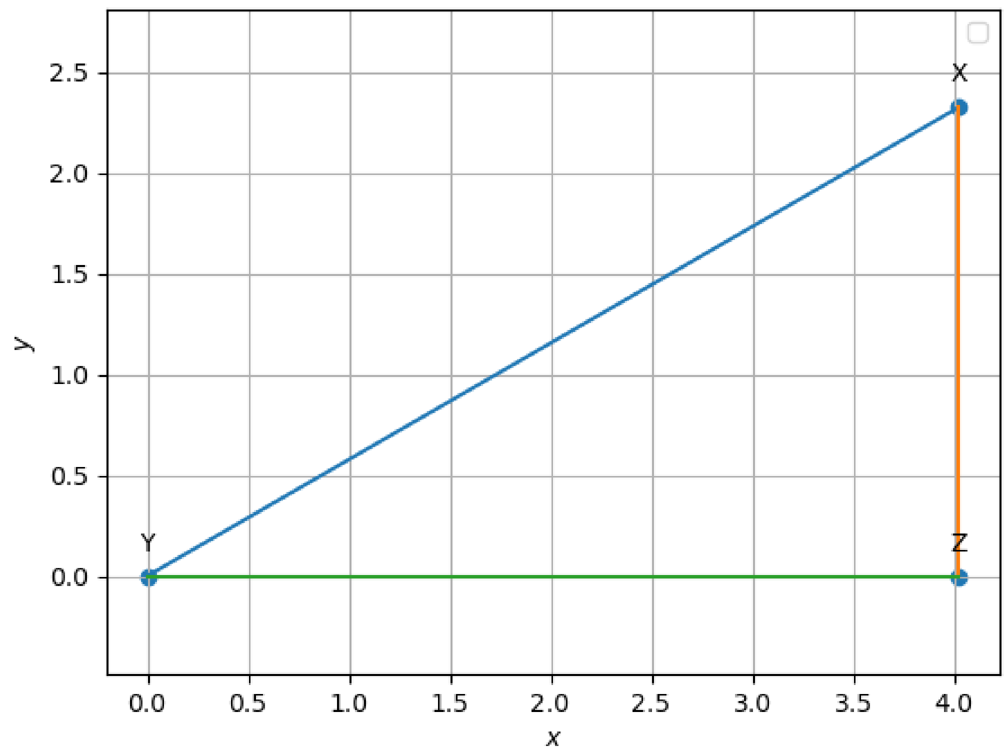


Figure 4.1.4.1:

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

$$\mathbf{X} = \begin{pmatrix} x \\ y \end{pmatrix}, \mathbf{Y} = \mathbf{0}, \mathbf{Z} = \begin{pmatrix} x \\ 0 \end{pmatrix} \tag{4.1.4.5}$$

4.1.5 Construct a right triangle whose base is 12cm and sum of its hypotenuse and other side is 18cm.

Solution: From the given information, let

$$a = 12, \angle B = 90^\circ, b + c = 18 \tag{4.1.5.1}$$

We need to find b. This is similar to Problem 4.1.1.

4.2. Properties

4.2.1 In the Figure 4.2.1.1, $\mathbf{E}$ is any point on median AD of a $\triangle ABC$. Show that

$$ar(ABE) = ar(ACE). \tag{4.2.1.1}$$

Proof. From (A.1.3.1)

$$ar\,(BDE) = \frac{1}{2}\left\|\mathbf{B}\times\mathbf{D} + \mathbf{D}\times\mathbf{E} + \mathbf{E}\times\mathbf{B}\right\| \tag{4.2.1.2}$$

$$= \frac{1}{2}\left\|\mathbf{B}\times\left(\frac{\mathbf{B}+\mathbf{C}}{2}\right) + \left(\frac{\mathbf{B}+\mathbf{C}}{2}\right)\times\mathbf{E} + \mathbf{E}\times\mathbf{B}\right\| \tag{4.2.1.3}$$

$$= \frac{1}{4}\left\|\mathbf{B}\times\mathbf{C} + \mathbf{C}\times\mathbf{E} + \mathbf{E}\times\mathbf{B}\right\| \tag{4.2.1.4}$$

after simplification. Similarly, it can be shown that

$$ar\,(EDC) = \frac{1}{4}\left\|\mathbf{B}\times\mathbf{C} + \mathbf{C}\times\mathbf{E} + \mathbf{E}\times\mathbf{B}\right\| \tag{4.2.1.5}$$

$$= ar\,(BDE) \tag{4.2.1.6}$$

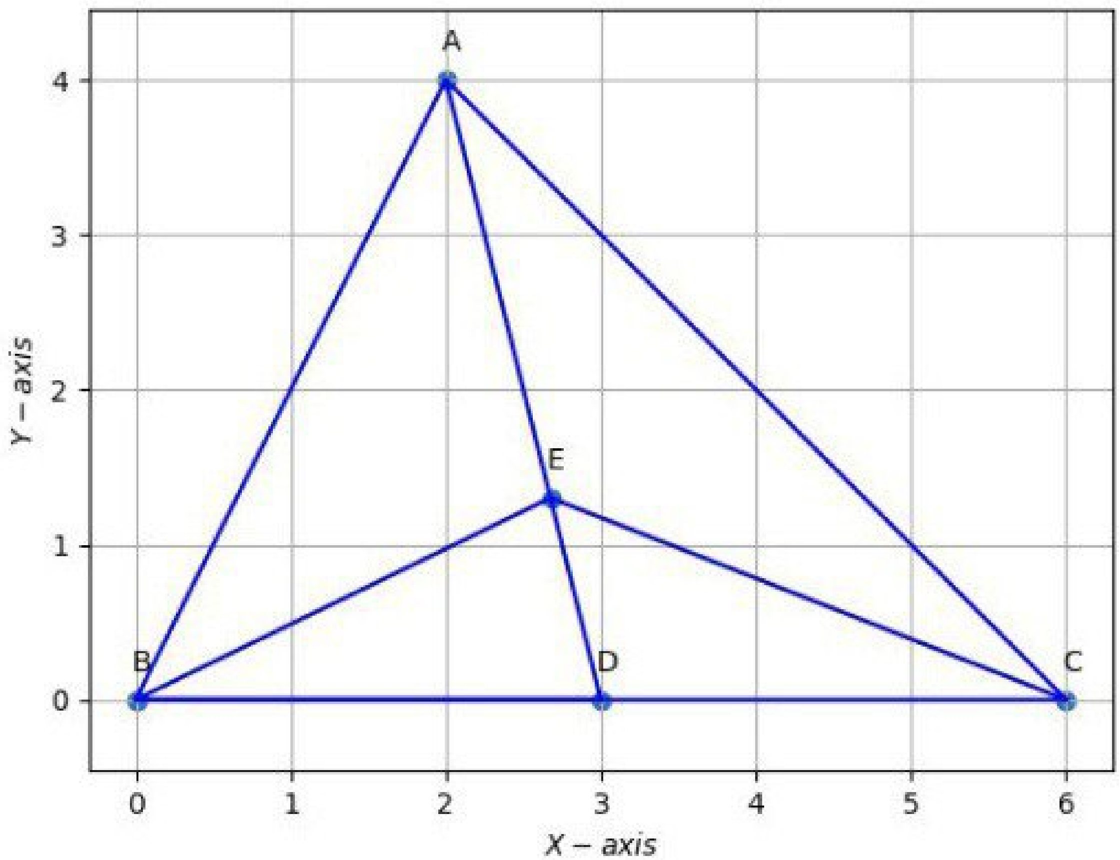


Figure 4.2.1.1:

The same approach can be used to show that

$$ar(ADB) = ar(ADC) \tag{4.2.1.7}$$

Subtracting (4.2.1.6) from (4.2.1.7) yields (4.2.1.1)

$\square$

4.2.2 In $\triangle ABC$, $\mathbf{E}$ is the mid-point of median AD. Show that

$$ar(\triangle BED) = \frac{1}{4} ar(\triangle ABC) \tag{4.2.2.1}$$

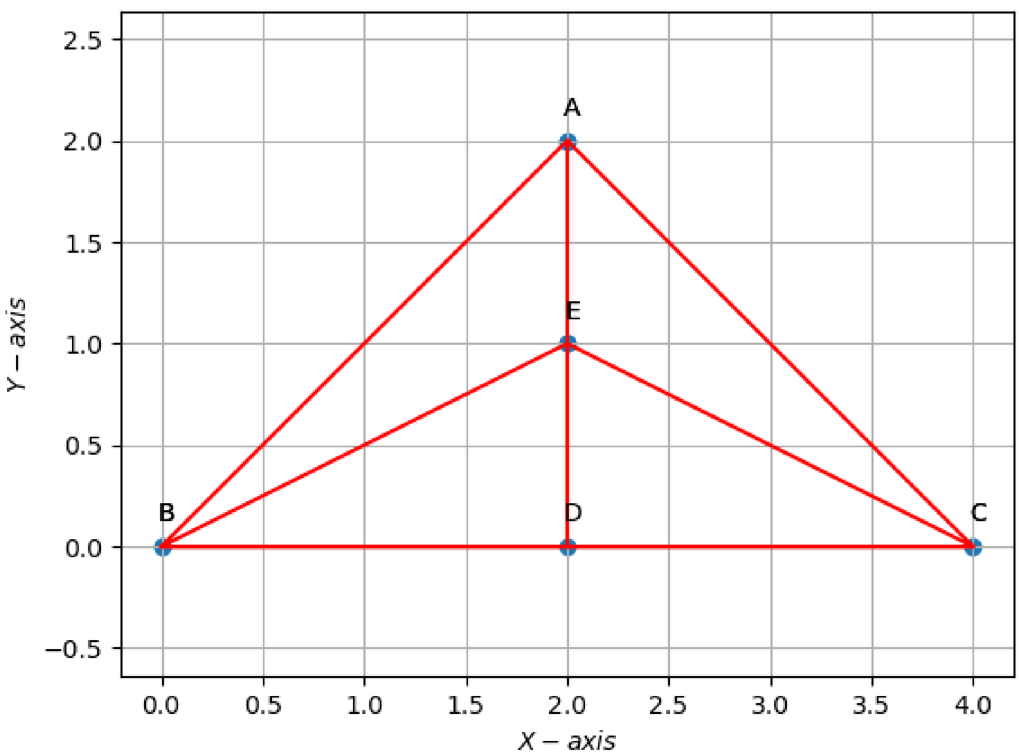


Figure 4.2.2.1:

Proof. From Problem 4.2.2,

$$ar(\triangle BED) = \frac{1}{4} \left\| \mathbf{B} \times \mathbf{C} + \mathbf{C} \times \mathbf{E} + \mathbf{E} \times \mathbf{B} \right\| \tag{4.2.2.2}$$

Since

$$\mathbf{E} = \frac{\mathbf{A}+\mathbf{D}}{2} \tag{4.2.2.3}$$
$$= \frac{2\mathbf{A}+\mathbf{B}+\mathbf{C}}{4}, \tag{4.2.2.4}$$

substituting the above in (4.2.2.2) yields

$$ar(\triangle BED) = \frac{1}{4}\left\|\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\frac{2\mathbf{A}+\mathbf{B}+\mathbf{C}}{4}+\frac{2\mathbf{A}+\mathbf{B}+\mathbf{C}}{4}\times\mathbf{B}\right\| \tag{4.2.2.5}$$
$$= \frac{1}{8}\left\|\mathbf{A}\times\mathbf{B}+\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\mathbf{A}\right\| \tag{4.2.2.6}$$

resulting in (4.2.2.1). □

4.2.3 Show that the diagonals of a parallelogram divide it into four triangles of equal area.

Proof. See Fig. 4.2.3.1. From Appendix A.1.25 and A.1.3

$$ar\,(AOB) = \frac{1}{2}\left\|\mathbf{A}\times\mathbf{O}+\mathbf{O}\times\mathbf{B}+\mathbf{B}\times\mathbf{A}\right\| \tag{4.2.3.1}$$
$$= \frac{1}{2}\left\|\mathbf{A}\times\left(\frac{\mathbf{A}+\mathbf{C}}{2}\right)+\left(\frac{\mathbf{A}+\mathbf{C}}{2}\right)\times\mathbf{B}+\mathbf{B}\times\mathbf{A}\right\| \tag{4.2.3.2}$$
$$= \frac{1}{4}\left\|\mathbf{A}\times\mathbf{C}+\mathbf{C}\times\mathbf{B}+\mathbf{B}\times\mathbf{A}\right\| \tag{4.2.3.3}$$

yielding the desired result from Appendix A.1.26 □

4.2.4 ABC, ABD are 2 triangles on same base AB, if line segment CD is bisected by AB at $\mathbf{O}$, show that

$$ar(ABC) = ar(ABD) \tag{4.2.4.1}$$

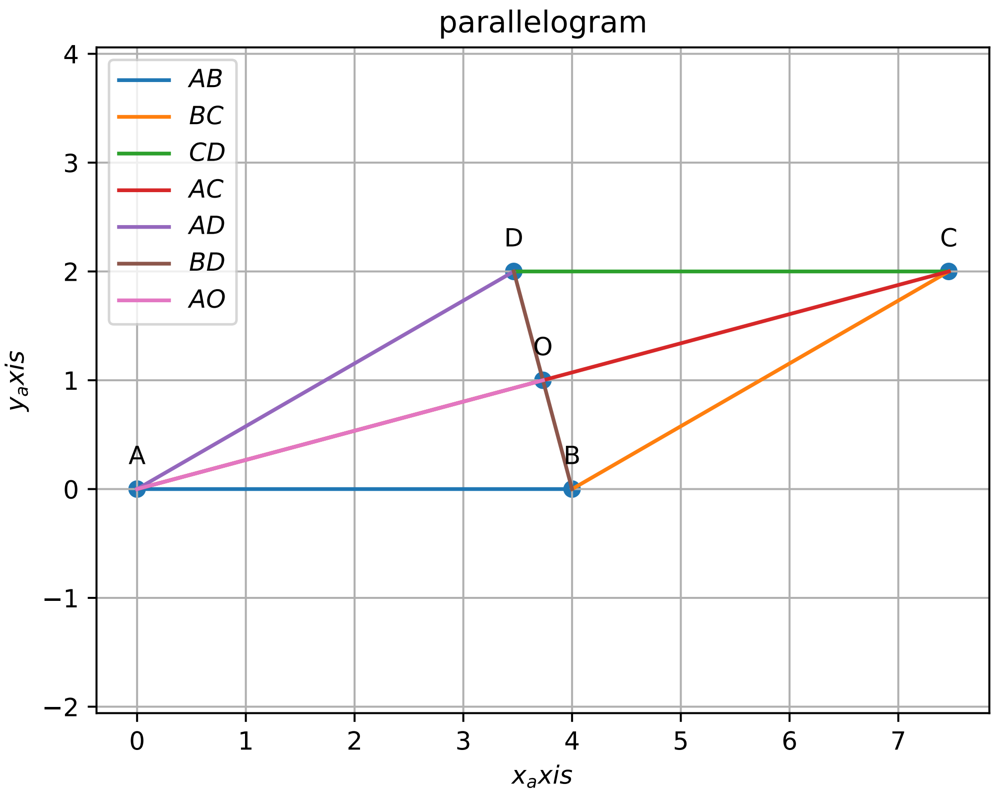


Figure 4.2.3.1:

Proof. See Fig. 4.2.4.1. AO and OB are medians of triangles ADC and BDC. From Appendix A.1.5, (4.2.4.1) is trivial. □

4.2.5

4.2.6

4.2.7

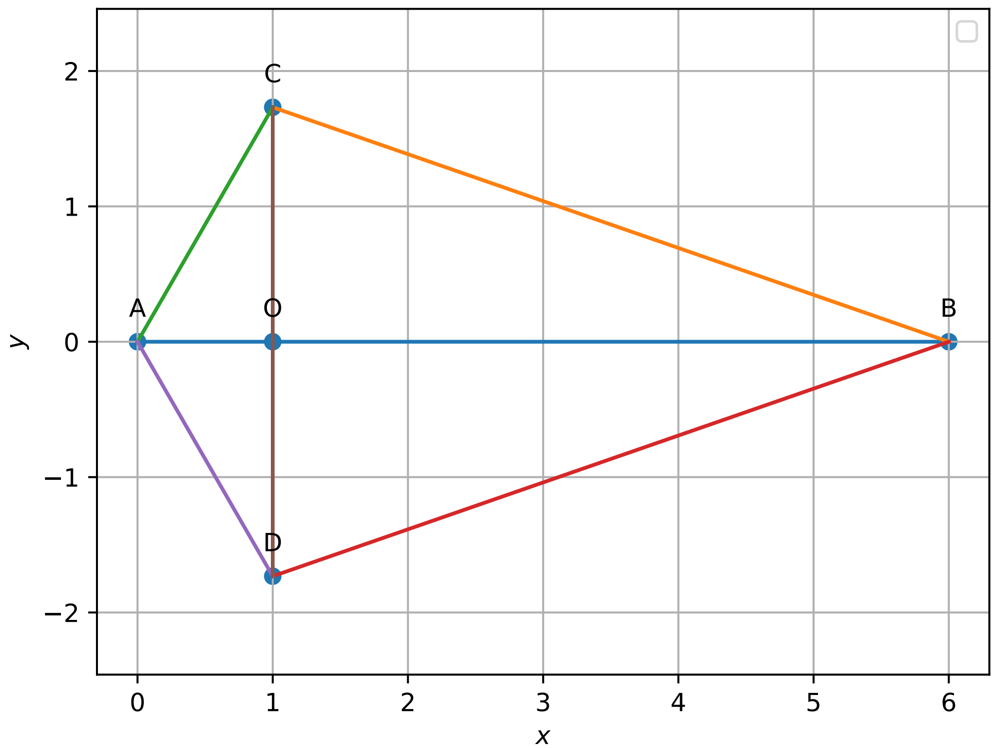


Figure 4.2.4.1:

4.2.8

4.2.9 The side AB of a parallelogram $ABCD$ is produced to any point $\mathbf{P}$. A line through $\mathbf{A}$ and parallel to CP meets CB produced at $\mathbf{Q}$ and then parallelogram $PBQR$ is completed. Show that

$$ar(ABCD) = ar(PBQR) \tag{4.2.9.1}$$

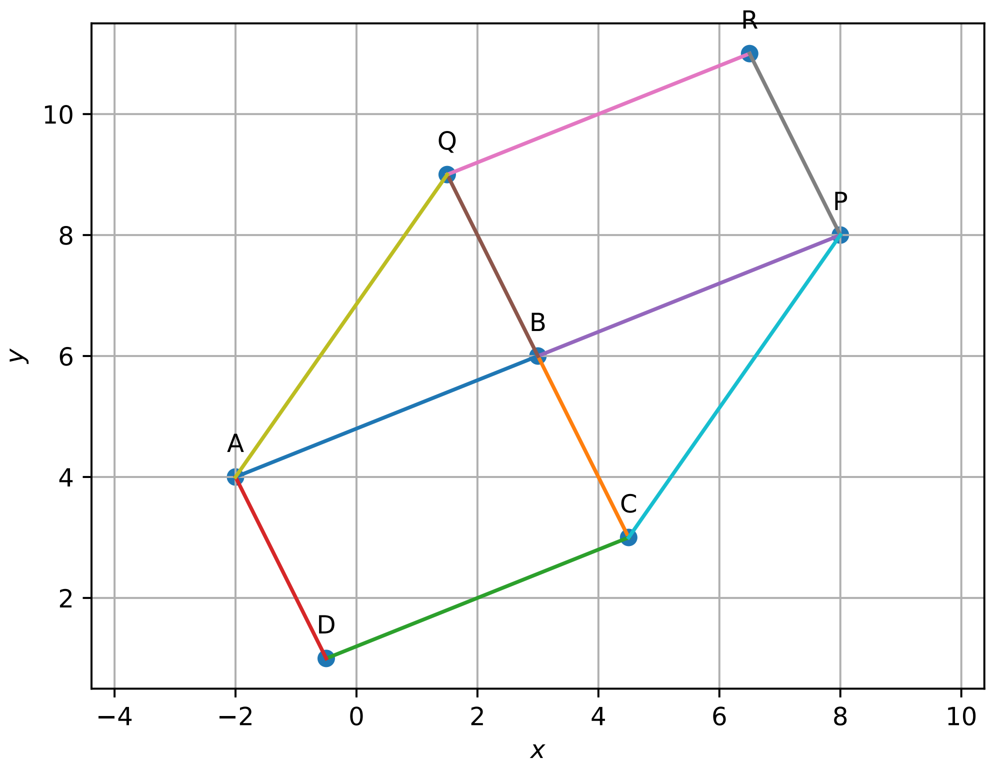


Figure 4.2.9.1:

Proof. From the given information, using section formula,

$$\mathbf{Q} = \frac{k_1\mathbf{C} + \mathbf{B}}{k_1 + 1} \tag{4.2.9.2}$$

$$\mathbf{P} = \frac{k_2\mathbf{A} + \mathbf{B}}{k_2 + 1} \tag{4.2.9.3}$$

Also, since $AQ \parallel CP$,

$$\mathbf{A} - \mathbf{Q} = k\left(\mathbf{C} - \mathbf{P}\right) \tag{4.2.9.4}$$

Substituting from (4.2.9.2) and (4.2.9.3) in the above,

$$\mathbf{A} - \frac{k_1\mathbf{C} + \mathbf{B}}{k_1 + 1} = k\left(\mathbf{C} - \frac{k_2\mathbf{A} + \mathbf{B}}{k_2 + 1}\right) \tag{4.2.9.5}$$

which, after some algebra, yields

$$\left(1 + \frac{kk_2}{k_2 + 1}\right)\mathbf{A} + \left(\frac{k}{k_2 + 1} - \frac{1}{k_1 + 1}\right)\mathbf{B} - \left(\frac{k_1}{k_1 + 1} + k\right)\mathbf{C} = \mathbf{0} \tag{4.2.9.6}$$

From Appendix A.1.27, (4.2.9.6) results in

$$\left(\frac{k}{k_2 + 1} - \frac{1}{k_1 + 1}\right) = \left(\frac{k_1}{k_1 + 1} + k\right) = 0 \tag{4.2.9.7}$$

$$\text{or, } k_1 + k_2 = -1 \tag{4.2.9.8}$$

From Appendix A.1.26

$$ar\left(PBQR\right) = \left\|\mathbf{P} \times \mathbf{B} + \mathbf{B} \times \mathbf{Q} + \mathbf{Q} \times \mathbf{P}\right\| \tag{4.2.9.9}$$

The R.H.S. in the above can be expressed as

$$\frac{k_2\mathbf{A} + \mathbf{B}}{k_2 + 1} \times \mathbf{B} + \mathbf{B} \times \frac{k_1\mathbf{C} + \mathbf{B}}{k_1 + 1} + \frac{k_1\mathbf{C} + \mathbf{B}}{k_1 + 1} \times \frac{k_2\mathbf{A} + \mathbf{B}}{k_2 + 1} \tag{4.2.9.10}$$

leading to

$$\begin{aligned}\left(\frac{k_2}{k_2 + 1} - \frac{k_2}{\left(k_1 + 1\right)\left(k_2 + 1\right)}\right)\mathbf{A} \times \mathbf{B} \\ + \mathbf{B} \times \mathbf{C}\left(\frac{k_1}{k_1 + 1} - \frac{k_1}{\left(k_1 + 1\right)\left(k_2 + 1\right)}\right) \\ + \frac{k_1k_2}{\left(k_1 + 1\right)\left(k_2 + 1\right)}\mathbf{C} \times \mathbf{A}\end{aligned} \tag{4.2.9.11}$$

that can be simplified to obtain

$$ar\left(PBQR\right) = \frac{k_1 k_2}{\left(k_1+1\right)\left(k_2+1\right)} \left\|\left(\mathbf{A}\times\mathbf{B}+\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\mathbf{A}\right)\right\| \tag{4.2.9.12}$$

$$= \left\|\left(\mathbf{A}\times\mathbf{B}+\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\mathbf{A}\right)\right\| \tag{4.2.9.13}$$

using the fact that

$$\frac{k_1 k_2}{\left(k_1+1\right)\left(k_2+1\right)} = 1 \tag{4.2.9.14}$$

from (4.2.9.8). Also, from Appendix A.1.26,

$$ar\left(ABCD\right) = \left\|\left(\mathbf{A}\times\mathbf{B}+\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\mathbf{A}\right)\right\| \tag{4.2.9.15}$$

yielding (4.2.9.1) from (4.2.9.13). □

4.2.10

4.2.11 $ABCDE$ is a pentagon. A line through $\mathbf{B}$ parallel to AC meets DC produced at F. Show that

$$ar(ACB) = ar(ACF) \tag{4.2.11.1}$$

$$ar(AEDF) = ar(ABCDE) \tag{4.2.11.2}$$

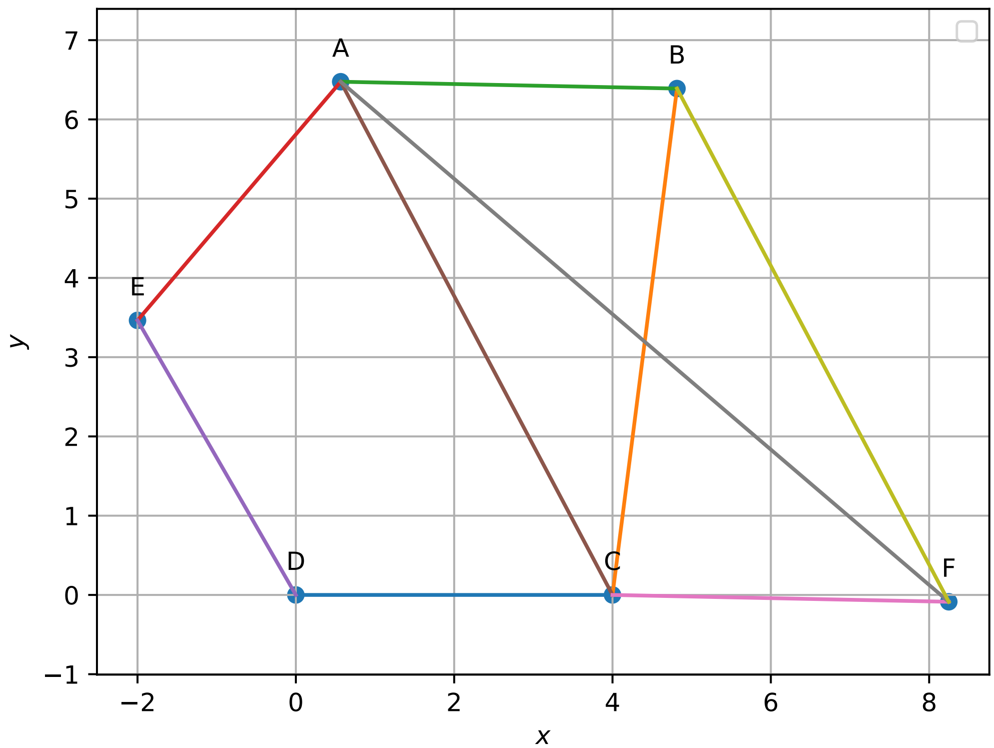


Figure 4.2.11.1:

Proof. Since $BF \parallel AC$,

$$\mathbf{F} - \mathbf{B} = k\left(\mathbf{C} - \mathbf{A}\right) \tag{4.2.11.3}$$

$$\implies \mathbf{F} = \mathbf{B} + k\left(\mathbf{C} - \mathbf{A}\right) \tag{4.2.11.4}$$

Thus, from Appendix A.1.3,

$$ar(ACF) = \frac{1}{2}\left\|\mathbf{F} \times \mathbf{A} + \mathbf{A} \times \mathbf{C} + \mathbf{C} \times \mathbf{F}\right\| \tag{4.2.11.5}$$

Substituting from (4.2.11.4) in (4.2.11.5),

$$ar(ACF) = \frac{1}{2}\left\|\{\mathbf{B} + k(\mathbf{C} - \mathbf{A})\} \times \mathbf{A} + \mathbf{A} \times \mathbf{C} + \mathbf{C} \times \{\mathbf{B} + k(\mathbf{C} - \mathbf{A})\}\right\| \tag{4.2.11.6}$$

$$= \frac{1}{2}\left\|\mathbf{B} \times \mathbf{A} + \mathbf{A} \times \mathbf{C} + \mathbf{C} \times \mathbf{B}\right\| \tag{4.2.11.7}$$

$$= ar(ACB) \tag{4.2.11.8}$$

upon substituting from from Appendix A.1.3. (4.2.11.2) follows from (4.2.11.1).

□

4.2.12

4.2.13

4.2.14

4.2.15

4.2.16 In the Figure 4.2.16.1,

$$ar(DRC) = ar(DPC) \tag{4.2.16.1}$$

$$ar(BDP) = ar(ARC). \tag{4.2.16.2}$$

Show that the quadrilaterals $ABCD$ and $DCPR$ are trapeziums.

Proof. From Appendix A.1.4 and (4.2.16.1),

$$\frac{1}{2}\left\|(\mathbf{D} - \mathbf{R}) \times (\mathbf{D} - \mathbf{C})\right\| = \frac{1}{2}\left\|(\mathbf{C} - \mathbf{D}) \times (\mathbf{C} - \mathbf{P})\right\| \tag{4.2.16.3}$$

$$\implies (\mathbf{D} - \mathbf{R}) \times (\mathbf{D} - \mathbf{C}) = (\mathbf{C} - \mathbf{D}) \times (\mathbf{C} - \mathbf{P}) \tag{4.2.16.4}$$

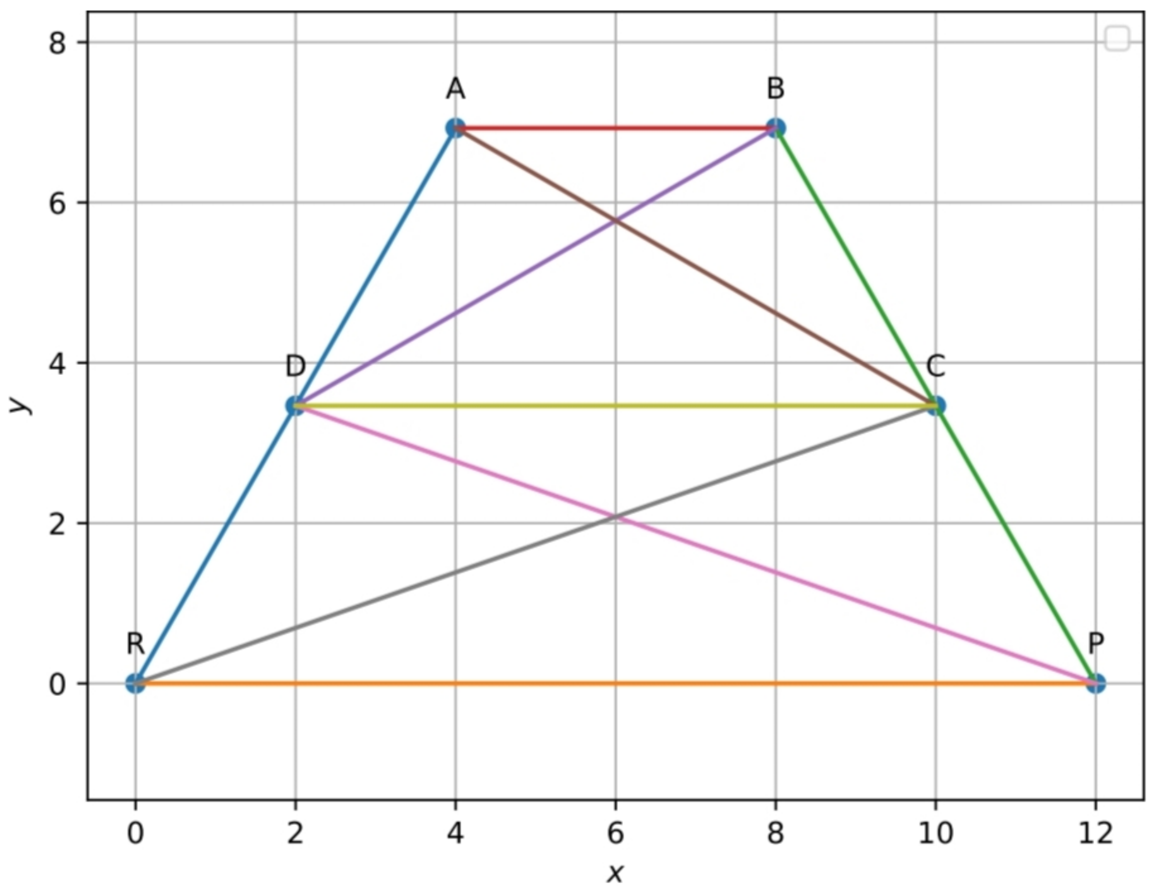


Figure 4.2.16.1:

which can be expressed as

$$(\mathbf{C} - \mathbf{D}) \times (\mathbf{C} - \mathbf{D} + \mathbf{R} - \mathbf{P}) = \mathbf{0} \tag{4.2.16.5}$$

$$\implies (\mathbf{C} - \mathbf{D}) \times (\mathbf{R} - \mathbf{P}) = \mathbf{0} \tag{4.2.16.6}$$

$$\text{or, } CD \parallel RP \tag{4.2.16.7}$$

Hence, $DCPR$ is a trapezium. Similarly, it can be shown that $ABCD$ is also a trapezium.

$\square$

Chapter 5

Quadrilateral Construction

5.1. Properties

5.1.1 The angles of quadrilateral are in the ratio 3:5:9:13. Find all the angles of the quadrilateral.

5.1.2 If diagonals of a parallelogram are equal then show that it is a rectangle.

Solution: See Fig. 5.1.2.1. From (A.1.24.1),

$$\mathbf{B} - \mathbf{A} = \mathbf{C} - \mathbf{D} \tag{5.1.2.1}$$

$$\implies \mathbf{B} - \mathbf{C} = \mathbf{A} - \mathbf{D} \tag{5.1.2.2}$$

Also, it is given that the diagonals of $ABCD$ are equal. Hence,

$$\|\mathbf{C} - \mathbf{A}\|^2 = \|\mathbf{D} - \mathbf{B}\|^2 \tag{5.1.2.3}$$

$$\implies \|(\mathbf{C} - \mathbf{B}) + (\mathbf{B} - \mathbf{A})\|^2 = \|(\mathbf{D} - \mathbf{C}) + (\mathbf{C} - \mathbf{B}\|^2 \tag{5.1.2.4}$$

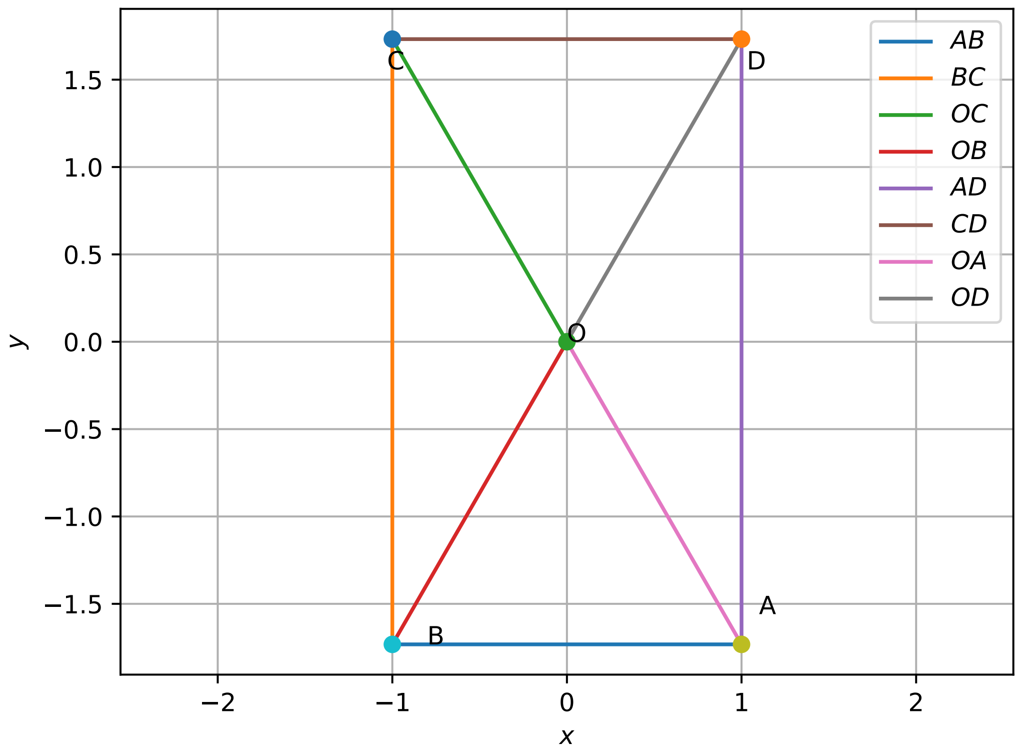


Figure 5.1.2.1:

which can be expressed as

$$\|\mathbf{C}-\mathbf{B}\|^2+\|\mathbf{B}-\mathbf{A}\|^2+2(\mathbf{C}-\mathbf{B})^\top(\mathbf{B}-\mathbf{A})$$
$$=\|\mathbf{D}-\mathbf{C}\|^2+\|\mathbf{C}-\mathbf{B}\|^2+2(\mathbf{D}-\mathbf{C})^\top(\mathbf{C}-\mathbf{B}) \quad (5.1.2.5)$$

which, can be simplified to obtain

$$(\mathbf{C}-\mathbf{B})^\top(\mathbf{B}-\mathbf{A})=(\mathbf{D}-\mathbf{C})^\top(\mathbf{C}-\mathbf{B}) \quad (5.1.2.6)$$

since

$$\|\mathbf{D}-\mathbf{C}\| = \|\mathbf{B}-\mathbf{A}\| \tag{5.1.2.7}$$

yielding

$$(\mathbf{A}-\mathbf{B})^\top(\mathbf{B}-\mathbf{C}) = \mathbf{0} \tag{5.1.2.8}$$

from (5.1.2.1).

5.1.3 Show that if the diagonals of a quadrilateral bisect each other at right angles, then it is a rhombus.

Solution: See Fig. 5.1.3.1. From the given information,

$$\frac{\mathbf{B}+\mathbf{D}}{2} = \frac{\mathbf{A}+\mathbf{C}}{2} \tag{5.1.3.1}$$

$$(\mathbf{B}-\mathbf{D})^\top(\mathbf{A}-\mathbf{C}) = 0 \tag{5.1.3.2}$$

From (5.1.3.1),

$$\mathbf{B}-\mathbf{A} = \mathbf{C}-\mathbf{D} \tag{5.1.3.3}$$

which, from (A.1.24.1), is the definition of a parallelogram. Further, substituting

$$\mathbf{B}-\mathbf{D} = (\mathbf{B}-\mathbf{A}) + (\mathbf{A}-\mathbf{D}) \tag{5.1.3.4}$$

$$\mathbf{A}-\mathbf{C} = (\mathbf{A}-\mathbf{B}) + (\mathbf{B}-\mathbf{C}) \tag{5.1.3.5}$$

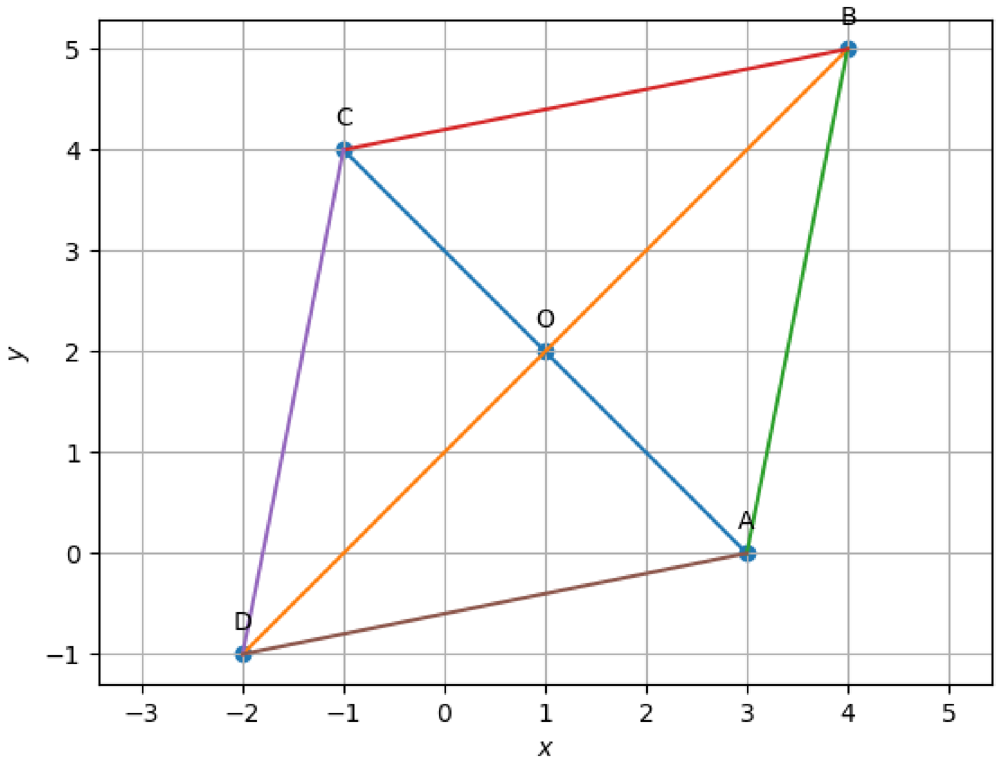


Figure 5.1.3.1: Rhombus

in (5.1.3.2),

$$[(\mathbf{B}-\mathbf{A})+(\mathbf{A}-\mathbf{D})]^\top [(\mathbf{A}-\mathbf{B})+(\mathbf{B}-\mathbf{C})] = 0$$

$$\implies -\|\mathbf{B}-\mathbf{A}\|^2 + (\mathbf{B}-\mathbf{A})^\top (\mathbf{B}-\mathbf{C}) +$$

$$(\mathbf{A}-\mathbf{D})^\top (\mathbf{A}-\mathbf{B}) + (\mathbf{A}-\mathbf{D})^\top (\mathbf{B}-\mathbf{C}) = 0 \quad (5.1.3.6)$$

From (5.1.3.3),

$$\mathbf{B} - \mathbf{C} = \mathbf{A} - \mathbf{D} \tag{5.1.3.7}$$

$$\implies (\mathbf{B} - \mathbf{A})^\top (\mathbf{B} - \mathbf{C}) + (\mathbf{A} - \mathbf{D})^\top (\mathbf{A} - \mathbf{B}) = \mathbf{0} \tag{5.1.3.8}$$

and

$$(\mathbf{A} - \mathbf{D})^\top (\mathbf{B} - \mathbf{C}) = \|\mathbf{B} - \mathbf{C}\|^2 \tag{5.1.3.9}$$

Substituting from

(5.1.3.8) and (5.1.3.9) in (5.1.3.6),

$$\|\mathbf{A} - \mathbf{B}\|^2 = \|\mathbf{B} - \mathbf{C}\|^2 \tag{5.1.3.10}$$

which means that the adjacent sides of the parallelogram are equal. Thus, the quadrilateral is a rhombus

5.1.4 Show that the diagonals of a square are equal and bisect each other at right angles.

Solution: This is obvious from Problems (5.1.2) and (5.1.3).

5.1.5

5.1.6 Diagonal AC of a parallelogram ABCD bisects $\angle A$ in Fig (5.1.6.1). Show that

(a) it bisects $\angle C$ also

(b) $ABCD$ is a rhombus

Solution:

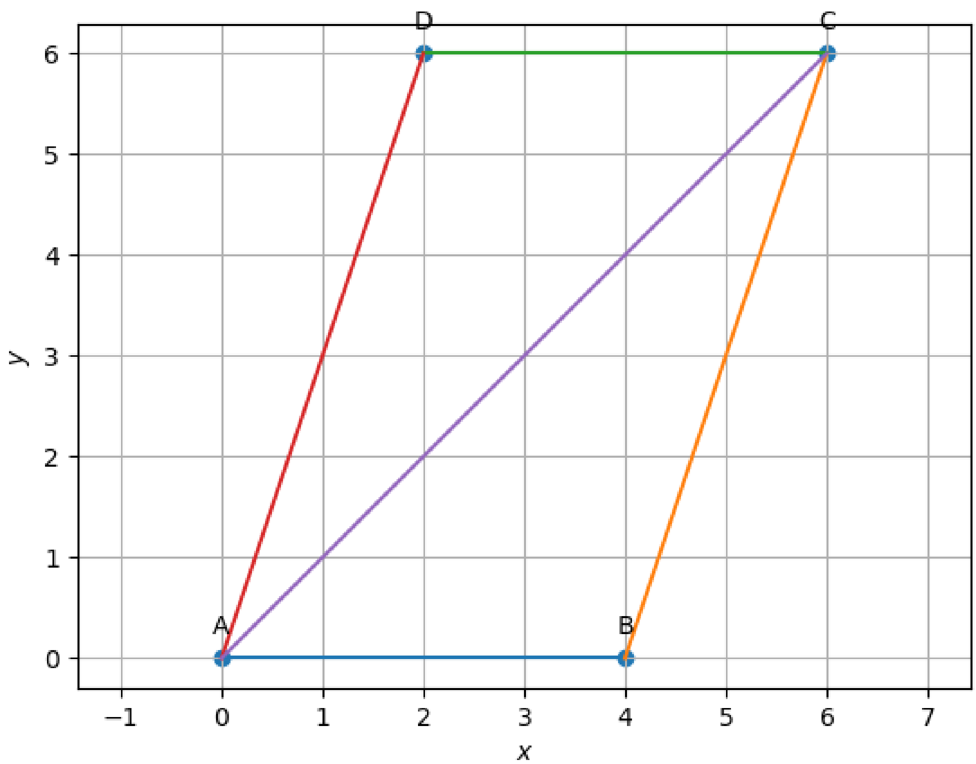


Figure 5.1.6.1:

(a) From (A.1.12.1),

$$\angle BAC = \angle DAC \tag{5.1.6.1}$$

$$\implies \frac{(\mathbf{A}-\mathbf{B})^T(\mathbf{A}-\mathbf{C})}{\|\mathbf{A}-\mathbf{B}\|\,\|\mathbf{A}-\mathbf{C}\|} = \frac{(\mathbf{A}-\mathbf{D})^T(\mathbf{A}-\mathbf{C})}{\|\mathbf{A}-\mathbf{D}\|\,\|\mathbf{A}-\mathbf{C}\|} \tag{5.1.6.2}$$

Also,

$$\cos\angle ACD = \frac{(\mathbf{C}-\mathbf{D})^T(\mathbf{C}-\mathbf{A})}{\|\mathbf{C}-\mathbf{D}\|\,\|\mathbf{C}-\mathbf{A}\|} \tag{5.1.6.3}$$

From Appendix A.1.24.1,

$$\mathbf{B} - \mathbf{A} = \mathbf{C} - \mathbf{D} \tag{5.1.6.4}$$

$$\implies \frac{(\mathbf{C} - \mathbf{D})^T(\mathbf{C} - \mathbf{A})}{\|\mathbf{C} - \mathbf{D}\| \, \|\mathbf{C} - \mathbf{A}\|} = \frac{(\mathbf{B} - \mathbf{A})^T(\mathbf{C} - \mathbf{A})}{\|\mathbf{B} - \mathbf{A}\| \, \|\mathbf{C} - \mathbf{A}\|} \tag{5.1.6.5}$$

upon substituting in (5.1.6.3). Thus, from (5.1.6.3) and (5.1.6.1),

$$\angle BAC = \angle DAC = \angle ACD \tag{5.1.6.6}$$

Similarly, it can be shown that

$$\angle ACD = \angle ACB \tag{5.1.6.7}$$

(b)

5.1.7 $ABCD$ is a rhombus. Show that the diagonal AC bisects angle A as well as angle C and diagonal BD bisects angle B as well as angle D.

Solution: For the rhombus in Fig. 5.1.7.1,

$$\begin{aligned} \|\mathbf{A} - \mathbf{B}\| &= \|\mathbf{A} - \mathbf{D}\| \\ \mathbf{A} - \mathbf{B} &= \mathbf{D} - \mathbf{C} \end{aligned} \tag{5.1.7.1}$$

From (A.1.12.1),

$$\begin{aligned} \cos\angle BAC &= \frac{(\mathbf{A} - \mathbf{B})^T(\mathbf{A} - \mathbf{C})}{\|\mathbf{A} - \mathbf{B}\| \, \|\mathbf{A} - \mathbf{C}\|} \\ \cos\angle DAC &= \frac{(\mathbf{C} - \mathbf{D})^T(\mathbf{C} - \mathbf{A})}{\|\mathbf{C} - \mathbf{D}\| \, \|\mathbf{C} - \mathbf{A}\|} \end{aligned} \tag{5.1.7.2}$$

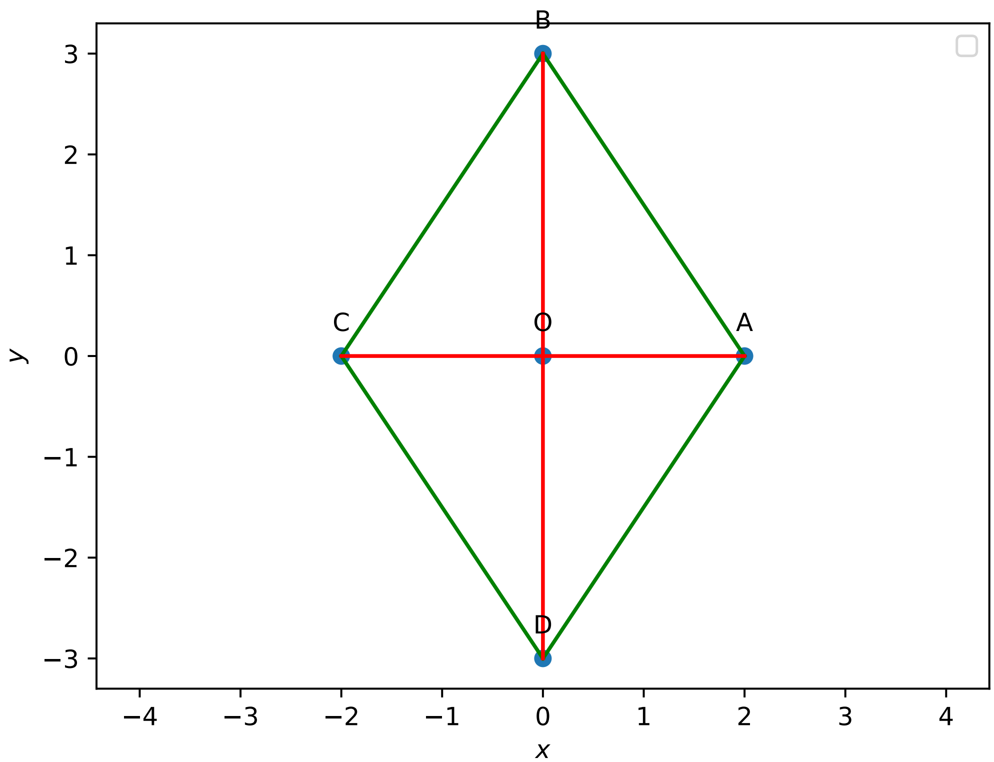


Figure 5.1.7.1:

From (5.1.7.1) and (5.1.7.2), we obtain

$$\cos\angle BAC = \cos\angle DAC \tag{5.1.7.3}$$

Thus, AC bisects $\angle A$. Similarly, the remaining results can be proved.

5.1.8

5.1.9 In parallelogram $ABCD$, two points $\mathbf{P}$ and $\mathbf{Q}$ are taken on diagonal BD such that $DP = BQ$. Show that

(a) $\triangle APD \cong \triangle CQB$

(b) $AP = CQ$

(c) $\triangle AQB \cong \triangle CPD$

(d) $AQ = CP$

(e) $APCQ$ is a parallelogram

Solution: See Fig. 5.1.9.1.

From (A.1.12.1) and the given information,

$$\mathbf{A} - \mathbf{B} = \mathbf{D} - \mathbf{C} \tag{5.1.9.1}$$

$$\implies \mathbf{A} - \mathbf{D} = \mathbf{B} - \mathbf{C} \tag{5.1.9.2}$$

$$\mathbf{B} - \mathbf{Q} = \mathbf{P} - \mathbf{D} \quad \text{(given)} \tag{5.1.9.3}$$

From (5.1.9.1) and (5.1.9.3)

$$\mathbf{A} - \mathbf{P} = \mathbf{Q} - \mathbf{C} \tag{5.1.9.4}$$

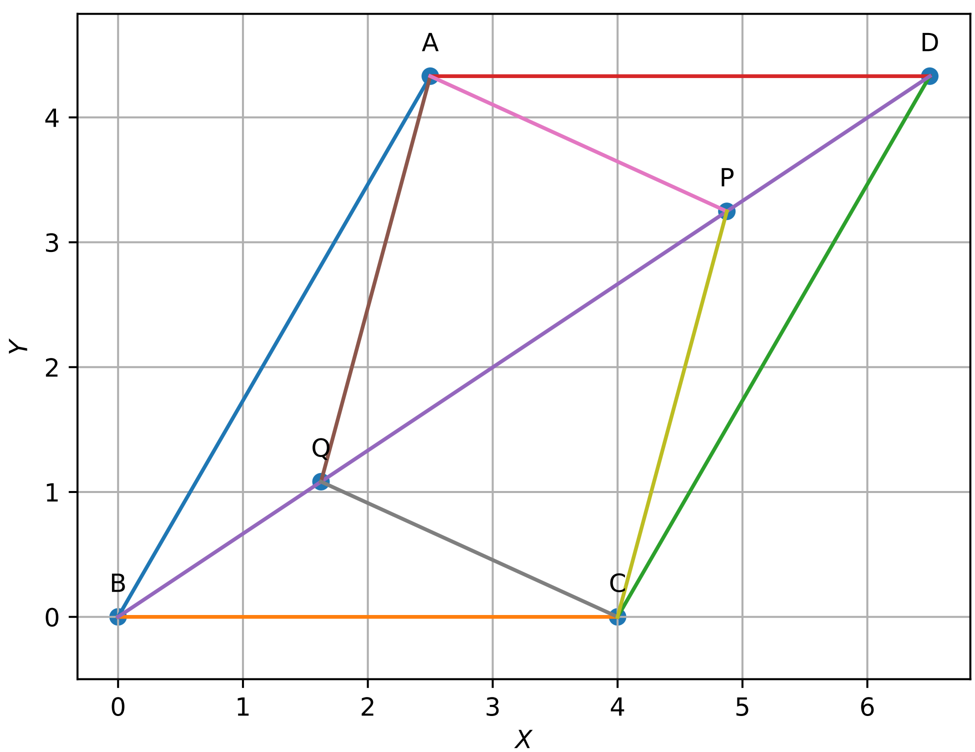


Figure 5.1.9.1:

(a) From (5.1.9.1), (5.1.9.3) and (5.1.9.4) taking the norms of the respective sides,

$$\triangle APD \cong \triangle CQB \tag{5.1.9.5}$$

(b) From (5.1.9.4), taking the norm,

$$AP = CQ \tag{5.1.9.6}$$

(c) From (5.1.9.1), (5.1.9.3) and (5.1.9.4) taking the norms of the respective sides,

$$\triangle AQB \cong \triangle CPD \tag{5.1.9.7}$$

(d) From (5.1.9.4),

$$AQ = CP \tag{5.1.9.8}$$

5.1.10 $ABCD$ is a parallelogram and AP and CQ are perpendiculars from vertices $\mathbf{A}$ and $\mathbf{C}$ on diagonal BD . Show that

(a) $\triangle APB \cong \triangle CQD$

(b) $AP = CQ$

Solution: From Fig. 5.1.10.1, and (A.1.12.1),

$$\begin{aligned}\cos\angle ABD &= \frac{(\mathbf{A}-\mathbf{B})^T(\mathbf{D}-\mathbf{B})}{\|\mathbf{A}-\mathbf{B}\|\,\|\mathbf{D}-\mathbf{B}\|}\\ \cos\angle CDB &= \frac{(\mathbf{C}-\mathbf{D})^T(\mathbf{B}-\mathbf{D})}{\|\mathbf{C}-\mathbf{D}\|\,\|\mathbf{B}-\mathbf{D}\|}\end{aligned} \tag{5.1.10.1}$$

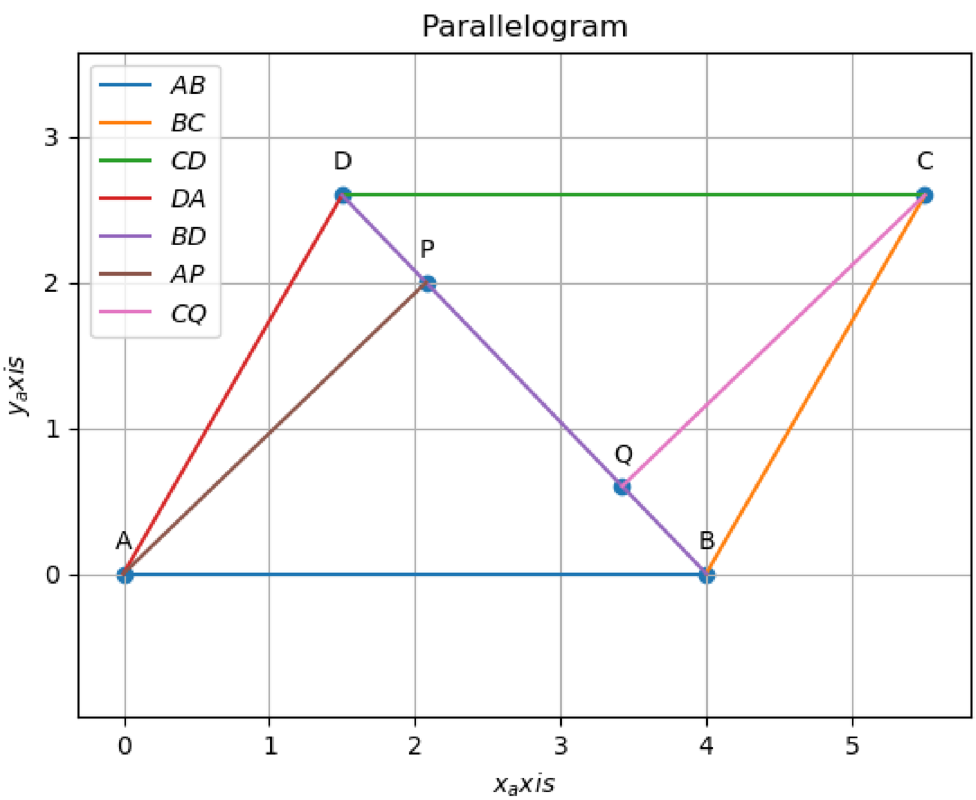


Figure 5.1.10.1:

From Appendix A.1.24.1,

$$\mathbf{A} - \mathbf{B} = \mathbf{D} - \mathbf{C} \tag{5.1.10.2}$$

Substituting in (5.1.10.1),

$$\cos \angle ABD = \cos \angle CDB \tag{5.1.10.3}$$

Using SAS congruence, 5.1.10a is proved. 5.1.10b follows from 5.1.10a.

5.1.11 In $\triangle ABC$ and $\triangle DEF$, $AB = DE$, $AB \parallel DE$, $BC = EF$ and $BC \parallel EF$. Vertices $\mathbf{A}, \mathbf{B}$ and $\mathbf{C}$ are joined to vertices $\mathbf{D}, \mathbf{E}$ and $\mathbf{F}$ respectively (see Figure 5.1.11.1). Show that

(a) quadrilateral $ABED$ is a parallelogram

(b) quadrilateral $BEFC$ is a parallelogram

(c) $AD \parallel CF$ and $AD = CF$

(d) quadrilateral $ACFD$ is a parallelogram

(e) $AC = DF$

(f) $\triangle ABC \cong \triangle DEF$.

Solution: From the given information

$$\mathbf{A} - \mathbf{B} = \mathbf{D} - \mathbf{E} \tag{5.1.11.1}$$

$$\mathbf{B} - \mathbf{E} = \mathbf{C} - \mathbf{F} \tag{5.1.11.2}$$

(a) From Appendix A.1.24.1, (5.1.11.1) defines the parallelogram $ABED$.

(b) Similarly, (5.1.11.2) defines the parallelogram $BEFC$.

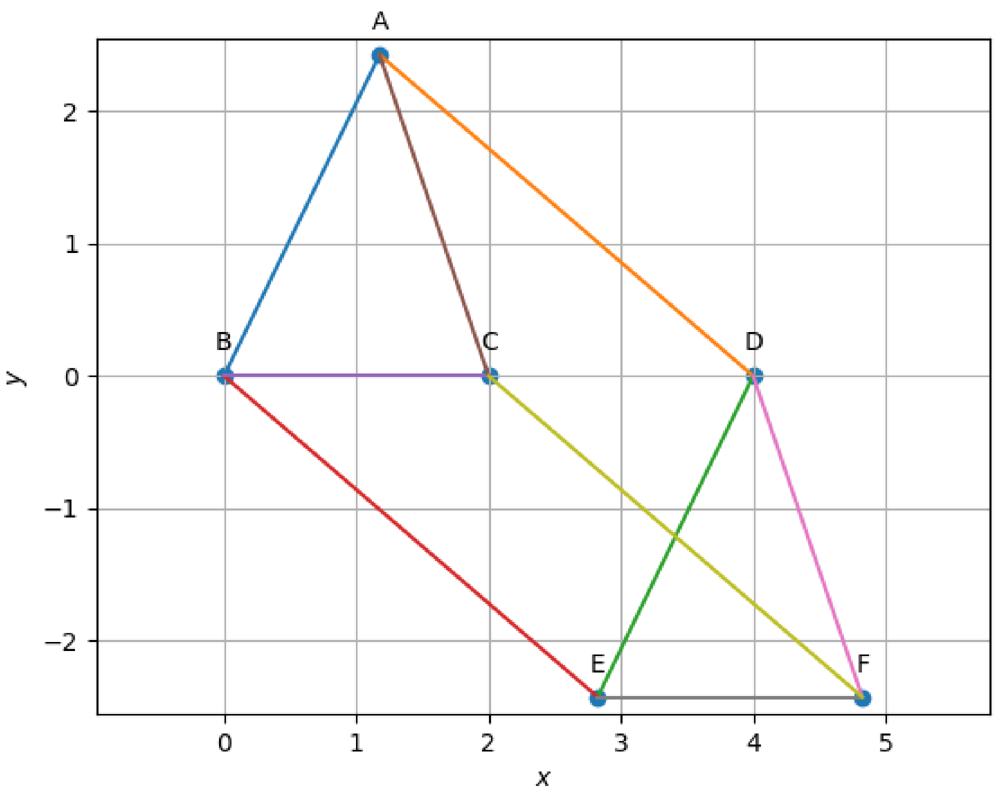


Figure 5.1.11.1:

(c) From (5.1.11.1) and (5.1.11.2),

$$\mathbf{A} - \mathbf{D} = \mathbf{C} - \mathbf{F} \tag{5.1.11.3}$$

which yields 5.1.11c.

(d) (5.1.11.3) implies that $ACFD$ is a parallelogram.

(e) (5.1.11.3) implies $AC = DF$.

(f) Obvious from the fact the $ABCD, BEFC$ and $ACFD$ are parallelograms.

5.1.12 $ABCD$ is trapezium in which $AB \parallel CD$ and $AD = BC$. Show that,

(a) $\angle A = \angle B$

(b) $\angle C = \angle D$

(c) Diagonal AC = Diagonal BD

(d) $\triangle ABC = \triangle BAD$

5.2. Mid Point Theorem

5.2.1 ABCD is a quadrilateral in which $\mathbf{P}, \mathbf{Q}, \mathbf{R}$ and $\mathbf{S}$ are mid-points of the sides AB, BC, CD and DA (see Fig 5.2.1.1). AC is a diagonal.

Show that

(a) $SR \parallel AC$ and $SR = \frac{1}{2}AC$

(b) $PQ = SR$

(c) $PQRS$ is a parallelogram.

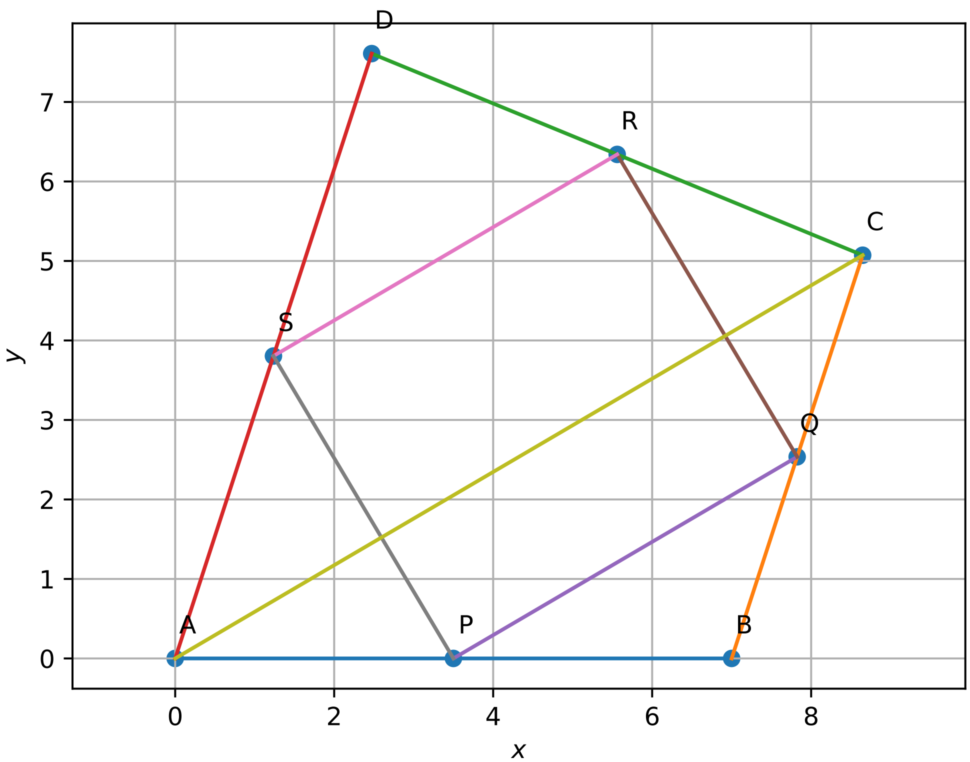


Figure 5.2.1.1:

Solution: Using (A.1.22.1),

$$\mathbf{P} = \frac{\mathbf{A}+\mathbf{B}}{2}$$
$$\mathbf{Q} = \frac{\mathbf{C}+\mathbf{B}}{2}$$
$$\mathbf{R} = \frac{\mathbf{C}+\mathbf{D}}{2} \tag{5.2.1.1}$$
$$\mathbf{S} = \frac{\mathbf{D}+\mathbf{A}}{2}$$

(a) Consequently,

$$\mathbf{R}-\mathbf{S} = \frac{\mathbf{C}-\mathbf{A}}{2} \tag{5.2.1.2}$$
$$\implies SR \parallel AC \tag{5.2.1.3}$$

Also,

$$\left\|\mathbf{R}-\mathbf{S}\right\| = \frac{\left\|\mathbf{C}-\mathbf{A}\right\|}{2} \tag{5.2.1.4}$$
$$\implies SR = \frac{1}{2}AC \tag{5.2.1.5}$$

(b) From (5.2.1.1),

$$\mathbf{R}-\mathbf{S} = \mathbf{Q}-\mathbf{P} \tag{5.2.1.6}$$

which means that $PQRS$ is a parallelogram and $PQ = SR$.

5.2.2

5.2.3 $ABCD$ is a rectangle and $\mathbf{P}, \mathbf{Q}, \mathbf{R}$ and $\mathbf{S}$ are mid-points of the sides AB, BC, CD and DA respectively. Show that the quadrilateral $PQRS$ is a rhombus.

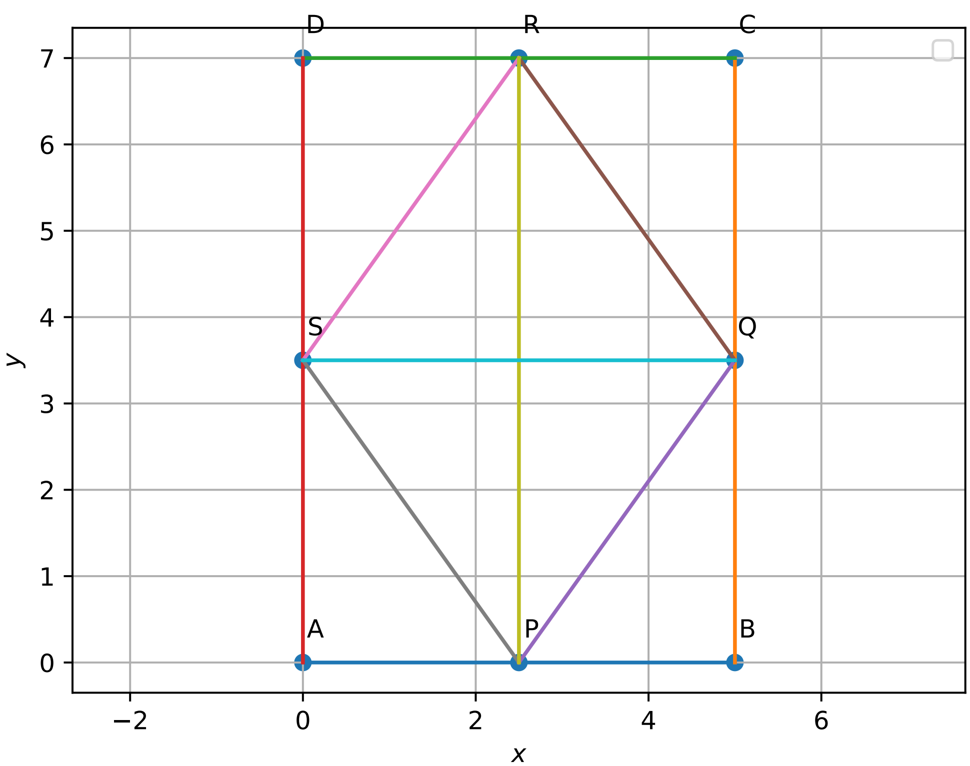


Figure 5.2.3.1:

Solution: From Problem 5.2.1, it is obvious that $PQRS$ is a parallelogram. Further, from (5.2.1.1),

$$(\mathbf{P}-\mathbf{R})^{\top}(\mathbf{S}-\mathbf{Q}) = (\mathbf{A}+\mathbf{B}-\mathbf{C}-\mathbf{D})^{\top}(\mathbf{A}+\mathbf{D}-\mathbf{B}-\mathbf{C}) \tag{5.2.3.1}$$

$$= \mathbf{0} \tag{5.2.3.2}$$

since

$$(\mathbf{A}-\mathbf{D})^{\top}(\mathbf{A}-\mathbf{B}) = \mathbf{0} \tag{5.2.3.3}$$

$$\|\mathbf{A}-\mathbf{D}\| = \|\mathbf{A}-\mathbf{B}\| \tag{5.2.3.4}$$

as $ABCD$ is a rectangle. Thus, the diagonals PR and SQ bisect each other proving that $PQRS$ is a rhombus.

5.2.4

5.2.5 In a parallelogram ABCD, **E** and **F** are the mid-points of sides AB and CD respectively (see Fig. 5.2.5.1) Show that the line segments AF and EC trisect the diagonal BD.

Proof. From the given information,

$$\mathbf{E} = \frac{\mathbf{A}+\mathbf{B}}{2} \tag{5.2.5.1}$$

$$\mathbf{F} = \frac{\mathbf{C}+\mathbf{D}}{2} \tag{5.2.5.2}$$

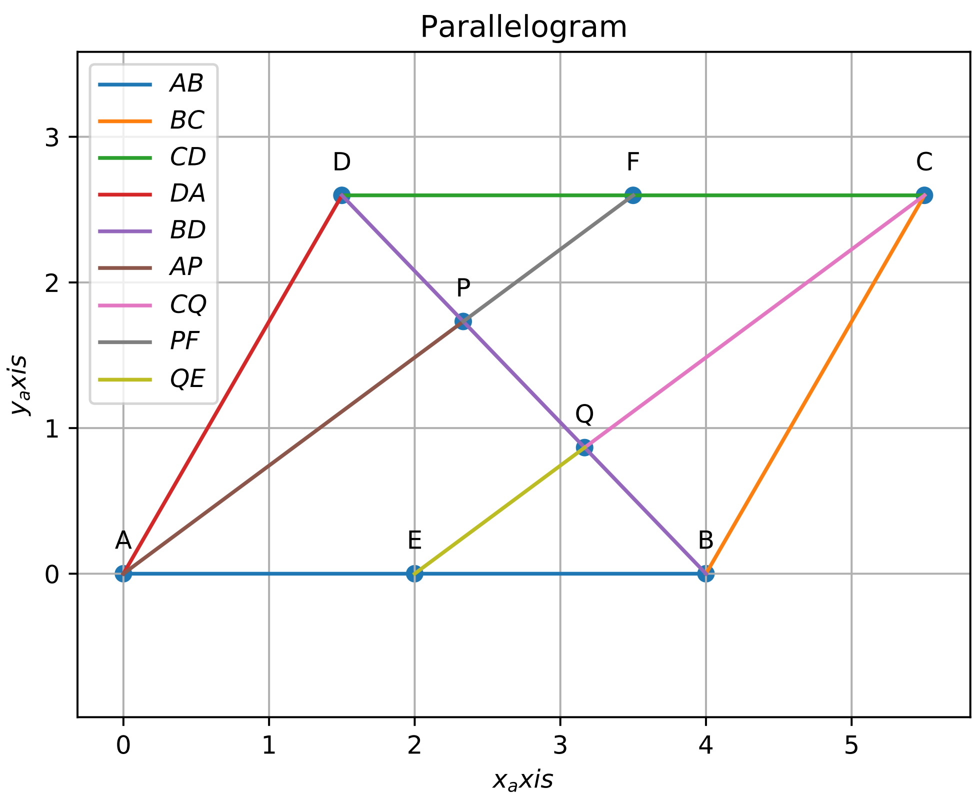

Parallelogram
AB
BC
CD
DA
BD
AP
CQ
PF
QE
D
F
C
P
Q
A
E
B
0
1
2
3
4
5
y_axis
x_axis

Figure 5.2.5.1:

Hence,

$$\mathbf{E} - \mathbf{C} = \frac{\mathbf{A} - \mathbf{C} + \mathbf{B} - \mathbf{C}}{2} \tag{5.2.5.3}$$

$$\mathbf{A} - \mathbf{F} = \frac{\mathbf{A} - \mathbf{C} + \mathbf{A} - \mathbf{D}}{2} \tag{5.2.5.4}$$

Since $ABCD$ is a parallelogram,

$$\mathbf{B} - \mathbf{C} = \mathbf{A} - \mathbf{D} \tag{5.2.5.5}$$

$$\implies \mathbf{E} - \mathbf{C} = \mathbf{A} - \mathbf{F} \tag{5.2.5.6}$$

Thus, $AF \parallel EC$. From Appendix A.1.29, using the fact that $\mathbf{F}$ is the mid point of CD, we conclude that $\mathbf{P}$ is the mid point of DQ. Similarly, it can be shown that $\mathbf{Q}$ is the mid point of BP. □

5.2.6

5.2.7 ABC is a triangle right angled at $\mathbf{C}$. A line through the mid-point $\mathbf{M}$ of hypotenuse AB and parallel to BC intersects AC at D (see Fig. 5.2.7.1). Show that

(a) D is the mid-point of AC

(b) $MD \perp AC$

(c) $CM = MA = \frac{1}{2}AB$

Solution:

(a) Trivial from Appendix A.1.29.

(b) Since ABC is right angled at C,

$$(\mathbf{C} - \mathbf{A})^\top (\mathbf{C} - \mathbf{B}) = 0 \tag{5.2.7.1}$$

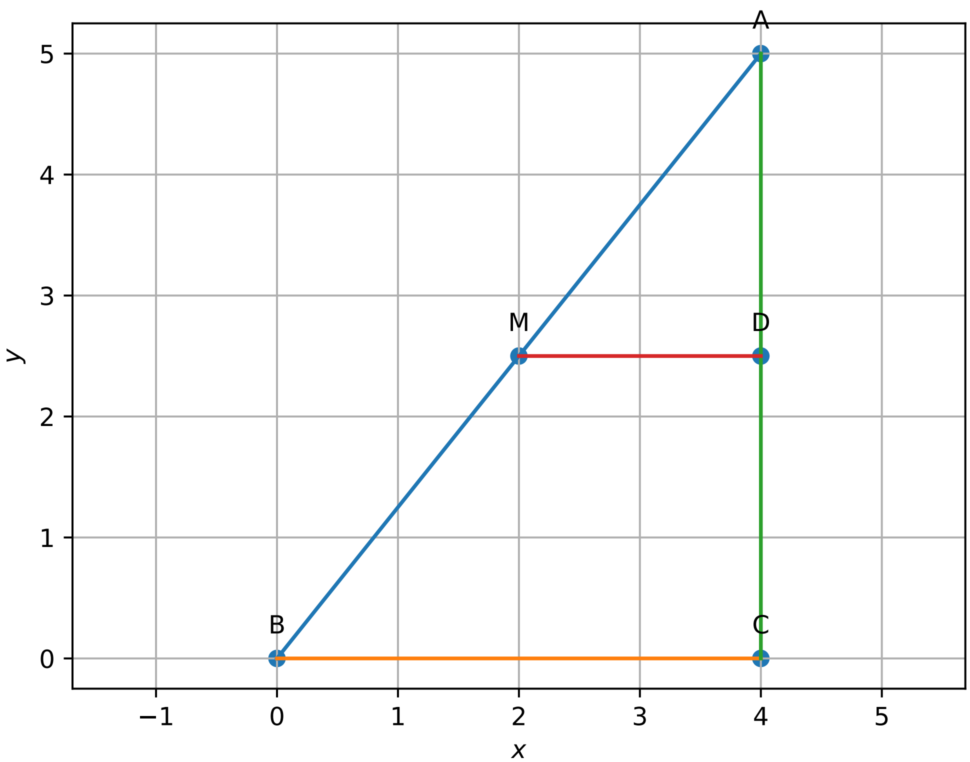


Figure 5.2.7.1:

Given that MD is parallel to BC, so

$$(\mathbf{C} - \mathbf{B}) = \lambda(\mathbf{M} - \mathbf{D}) \tag{5.2.7.2}$$

Substituting (5.2.7.2) in (5.2.7.1) and dividing by λ, we get

$$(\mathbf{C} - \mathbf{A})^\top(\mathbf{M} - \mathbf{D}) = 0 \tag{5.2.7.3}$$

From (5.2.7.3) it can be concluded that $MD \perp AC$.

(c) Since

$$\|\mathbf{C}-\mathbf{M}\|^2 - \|\mathbf{A}-\mathbf{M}\|^2 = \|\mathbf{C}\|^2 - \|\mathbf{A}\|^2 - 2\left(\mathbf{C}-\mathbf{A}\right)^\top \mathbf{M} \tag{5.2.7.4}$$

$$= \left(\mathbf{C}-\mathbf{A}\right)^\top \left(\mathbf{C}+\mathbf{A}-2\mathbf{M}\right) \tag{5.2.7.5}$$

$$= \left(\mathbf{C}-\mathbf{A}\right)^\top \left(\mathbf{C}-\mathbf{B}\right) = \mathbf{0} \tag{5.2.7.6}$$

upon substituting from Property 5.2.7a and (5.2.7.1). Thus, $CM = AM$.

5.3. Parallelograms

5.3.1 In the Figure 5.3.1.1, $ABCD$ is a parallelogram, $AE \perp DC$ and $CF \perp AD$. If $AB = 16cm$, $AE = 8cm$, and $CF = 10cm$, find AD.

5.3.2 If $\mathbf{E}, \mathbf{F}, \mathbf{G}$ and $\mathbf{H}$ are respectively the mid-points of the sides of a parallelogram $ABCD$, show that

$$ar(EFGH) = \frac{1}{2}ar(ABCD) \tag{5.3.2.1}$$

Proof. From Problem 5.2.1, $EFGH$ is also a parallelogram and

$$\mathbf{E}-\mathbf{F} = \frac{\mathbf{A}-\mathbf{C}}{2} \tag{5.3.2.2}$$

$$\mathbf{E}-\mathbf{H} = \frac{\mathbf{A}-\mathbf{D}}{2} \tag{5.3.2.3}$$

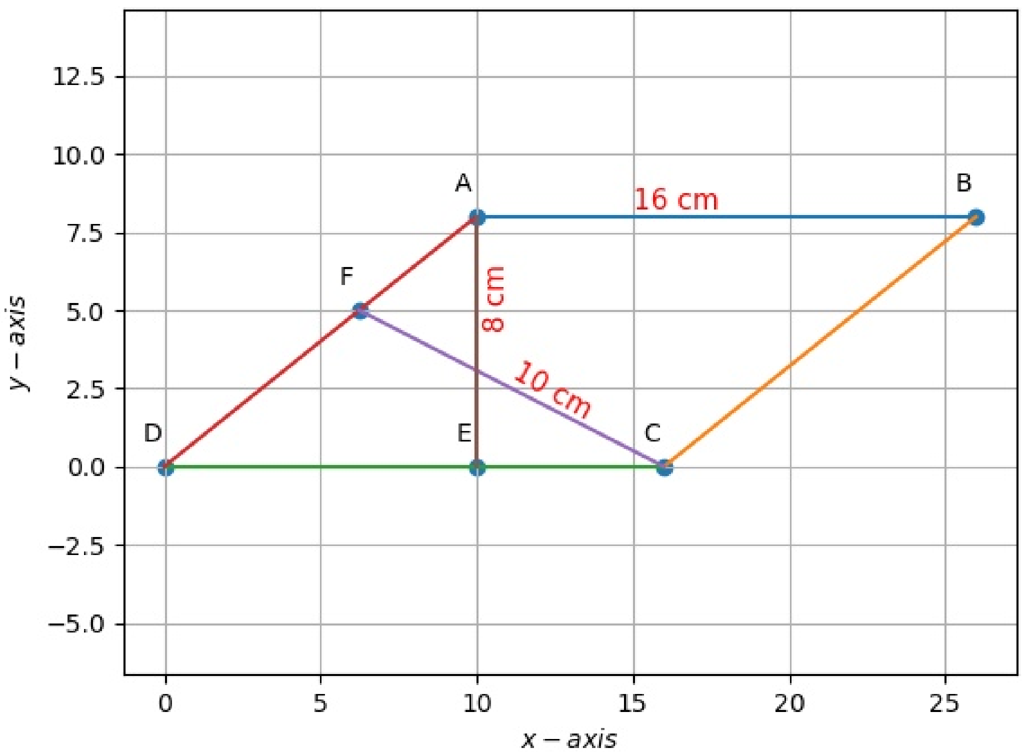


Figure 5.3.1.1:

Thus, the area off $EFGH$ is obtained from (A.1.26.1) as

$$\|(\mathbf{E}-\mathbf{F})\times(\mathbf{E}-\mathbf{H})\| = \frac{1}{4}\|(\mathbf{A}-\mathbf{C})\times(\mathbf{B}-\mathbf{D})\| \tag{5.3.2.4}$$

From Appendix A.1.24.1,

$$\mathbf{D} = \mathbf{C}-\mathbf{B}+\mathbf{A} \tag{5.3.2.5}$$

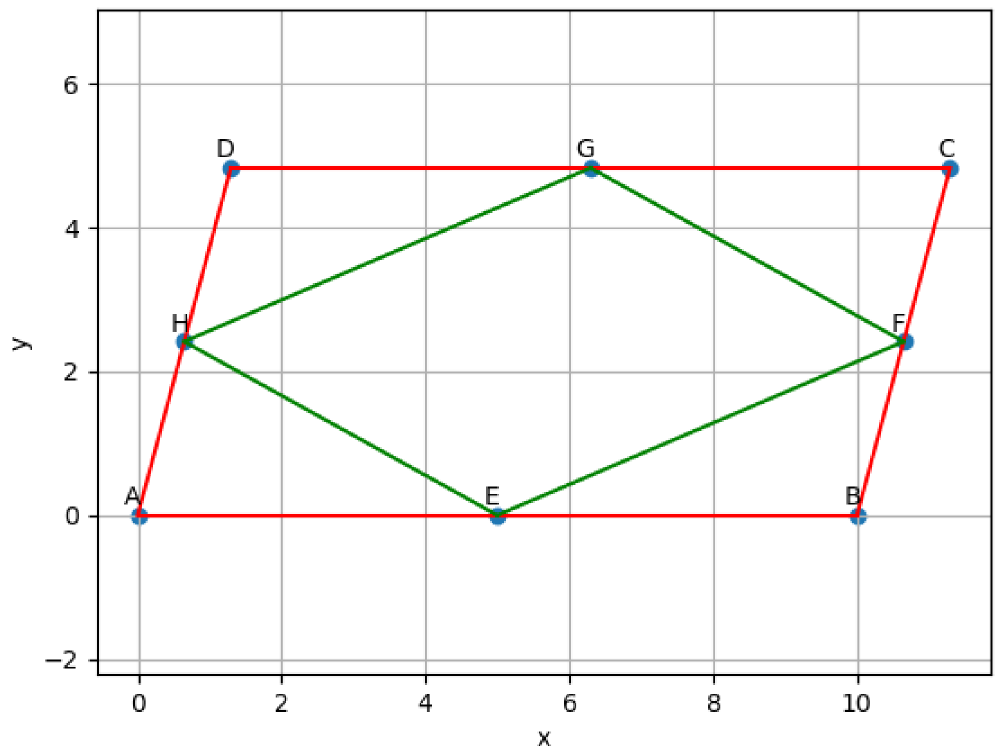


Figure 5.3.2.1:

which,

$$(\mathbf{A}-\mathbf{C})\times(\mathbf{B}-\mathbf{D}) = (\mathbf{A}-\mathbf{C})\times(2\mathbf{B}-\mathbf{C}-\mathbf{A}) \tag{5.3.2.6}$$

$$= 2\left(\mathbf{A}\times\mathbf{B}+\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\mathbf{A}\right) \tag{5.3.2.7}$$

Substituting (5.3.2.7) in (5.3.2.4) yields

$$\left\|(\mathbf{E}-\mathbf{F})\times(\mathbf{E}-\mathbf{H})\right\| = \frac{1}{2}\left\|\mathbf{A}\times\mathbf{B}+\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\mathbf{A}\right\| \tag{5.3.2.8}$$

The area of $ABCD$ is

$$\|(\mathbf{A}-\mathbf{B})\times(\mathbf{A}-\mathbf{D})\| = \|\mathbf{A}\times\mathbf{B}+\mathbf{B}\times\mathbf{C}+\mathbf{C}\times\mathbf{A}\| \tag{5.3.2.9}$$

upon substituting from Appendix A.1.24.1 and simplifying. From (5.3.2.8) and (5.3.2.9) we obtain (5.3.2.1). □

5.3.3

5.3.4 For a given Parallelogram $ABCD$, show that for any point $\mathbf{P}$ inside the parallelogram,

(a) $Ar(APD) + Ar(PBC) = \frac{1}{2}Ar(ABCD)$

(b) $Ar(APD) + Ar(PBC) = Ar(APB) + Ar(PCD)$

5.3.5 In Fig.1, $PQRS$ and $ABRS$ are parallelograms and $\mathbf{X}$ is any point on side BR. Show that

(a) $ar(PQRS) = ar(ABRS)$

(b) $ar(AXS) = \frac{1}{2}ar(PQRS)$

Proof. (a) From Appendix A.1.24.1,

$$\mathbf{A}-\mathbf{B} = \mathbf{S}-\mathbf{R} = \mathbf{P}-\mathbf{Q} \tag{5.3.5.1}$$

and from Appendix A.1.26, using (5.3.5.1), we obtain Property 5.3.5a.

(b) Using section formula, let

$$\mathbf{X} = \frac{\mathbf{R}+k\mathbf{B}}{1+k}. \tag{5.3.5.2}$$

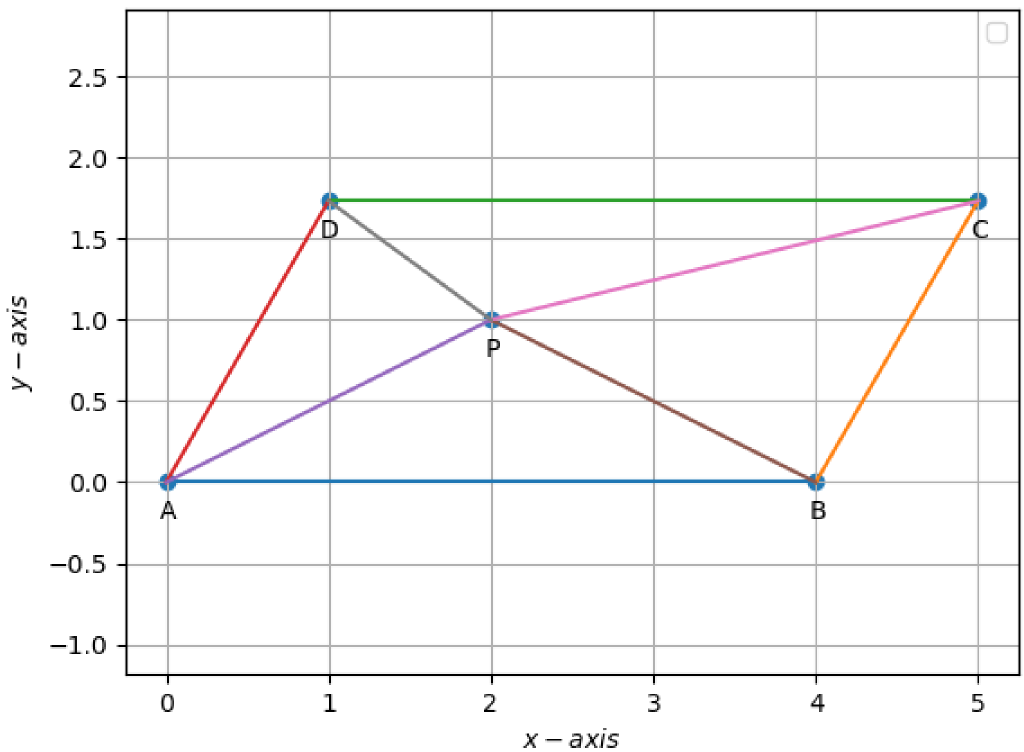


Figure 5.3.4.1:

Then,

$$ar(AXS) = \frac{1}{2}\left\|\mathbf{S}\times\mathbf{X}+\mathbf{X}\times\mathbf{A}+\mathbf{A}\times\mathbf{S}\right\| \tag{5.3.5.3}$$

$$= \frac{1}{2}\left\|\frac{\mathbf{S}\times\mathbf{R}+k\mathbf{S}\times\mathbf{B}+\mathbf{R}\times\mathbf{A}+k\mathbf{B}\times\mathbf{A}}{k+1}+\mathbf{A}\times\mathbf{S}\right\| \tag{5.3.5.4}$$

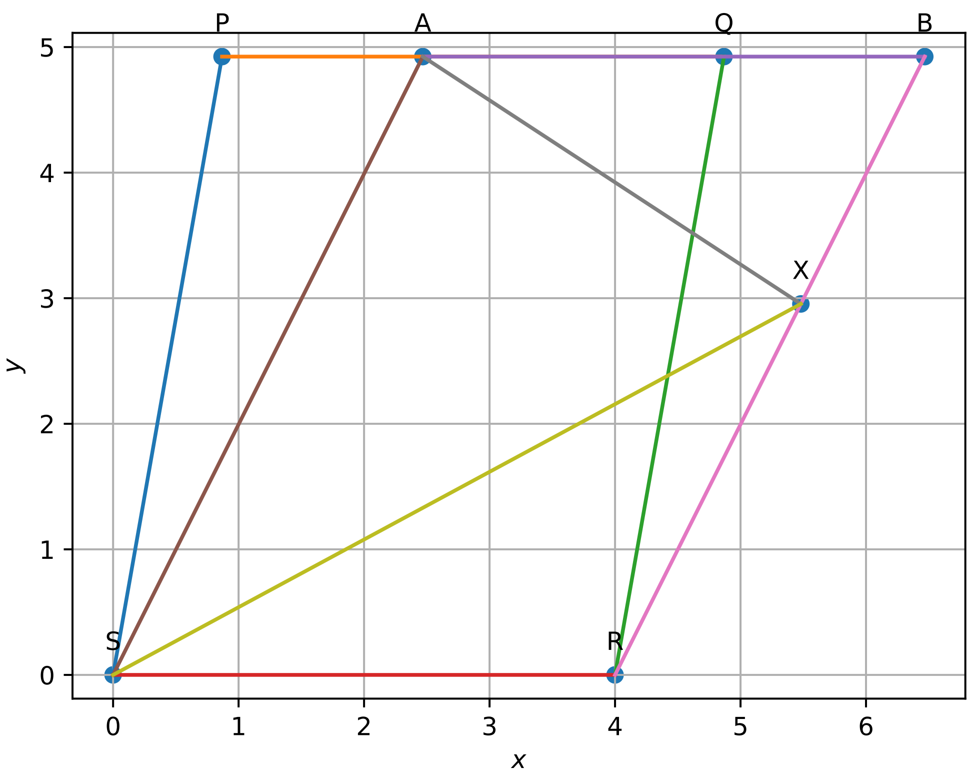


Figure 5.3.5.1:

Substituting for $\mathbf{B}$ from (5.3.5.1) in the above,

$$ar\left(AXS\right) = \frac{1}{2}\left\|\frac{\mathbf{S}\times\mathbf{R}+\mathbf{R}\times\mathbf{A}+k\left(\mathbf{S}-\mathbf{A}\right)\times\left(\mathbf{A}-\mathbf{S}+\mathbf{R}\right)}{k+1}+\mathbf{A}\times\mathbf{S}\right\| \tag{5.3.5.5}$$

$$= \frac{1}{2}\left\|\frac{\mathbf{S}\times\mathbf{R}+\mathbf{R}\times\mathbf{A}+k\left(\mathbf{S}-\mathbf{A}\right)\times\mathbf{R}}{k+1}+\mathbf{A}\times\mathbf{S}\right\| \tag{5.3.5.6}$$

$$= \frac{1}{2}\left\|\mathbf{S}\times\mathbf{R}+\mathbf{R}\times\mathbf{A}+\mathbf{A}\times\mathbf{S}\right\| \tag{5.3.5.7}$$

$$= \frac{1}{2}ar\left(ABRS\right) \tag{5.3.5.8}$$

□

5.4. Triangles and Parallelograms

5.4.1

5.4.2

5.4.3 In Fig. 5.4.3.1 $ABCD, DCFE$ and $ABFE$ are parallelograms. Show that

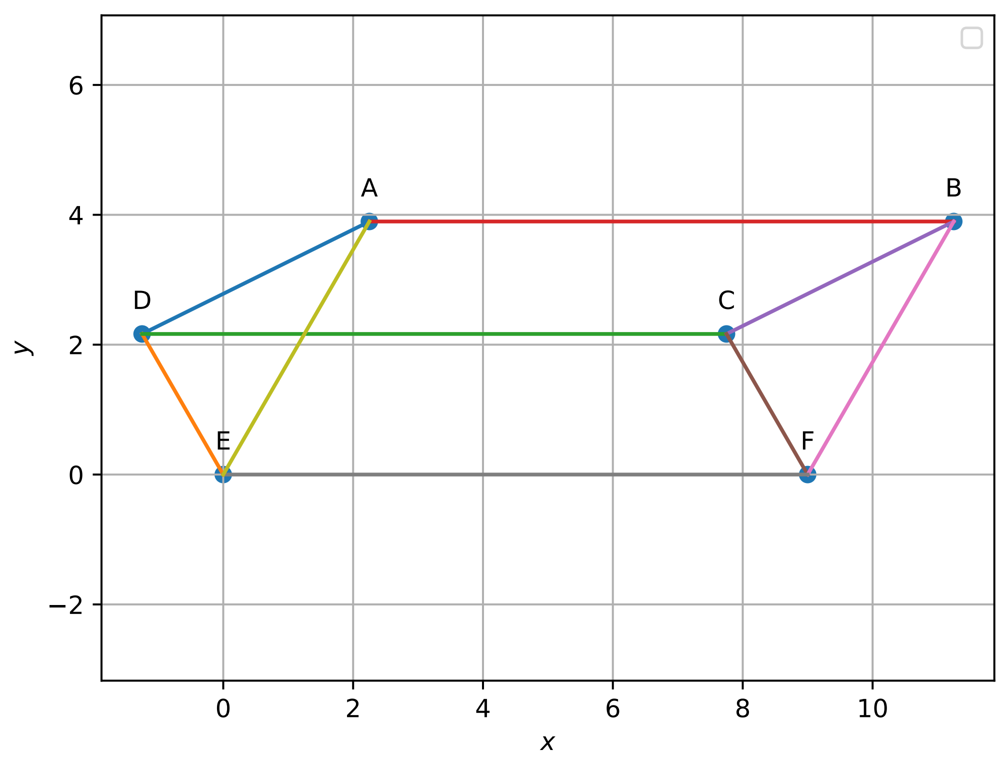


Figure 5.4.3.1:

$$ar(ADE) = ar(BCF) \tag{5.4.3.1}$$

Proof. From the given information and Appendix A.1.24.1,

$$\mathbf{B} - \mathbf{A} = \mathbf{C} - \mathbf{D} \tag{5.4.3.2}$$

$$\mathbf{C} - \mathbf{D} = \mathbf{F} - \mathbf{E} \tag{5.4.3.3}$$

$$\mathbf{B} - \mathbf{A} = \mathbf{F} - \mathbf{E} \tag{5.4.3.4}$$

Thus, from Appendix A.1.26,

$$ar(ADE) = \|(\mathbf{D} - \mathbf{E}) \times (\mathbf{D} - \mathbf{A})\| \tag{5.4.3.5}$$

$$= \|(\mathbf{C} - \mathbf{F}) \times (\mathbf{C} - \mathbf{B})\| \tag{5.4.3.6}$$

$$= ar(ADE) \tag{5.4.3.7}$$

upon substituting from (5.4.3.2) and (5.4.3.3). □

5.4.4 In figure below, $ABCD$ is a parallelogram and BC is produced to a point $\mathbf{Q}$ such that $AD = CQ$. If AQ intersect DC at $\mathbf{P}$, show that

$$ar(BPC) = ar(DPQ). \tag{5.4.4.1}$$

5.4.5 In Fig. 5.4.5.1, ABC and BDE are two equilateral triangles such that $\mathbf{D}$ is the mid-

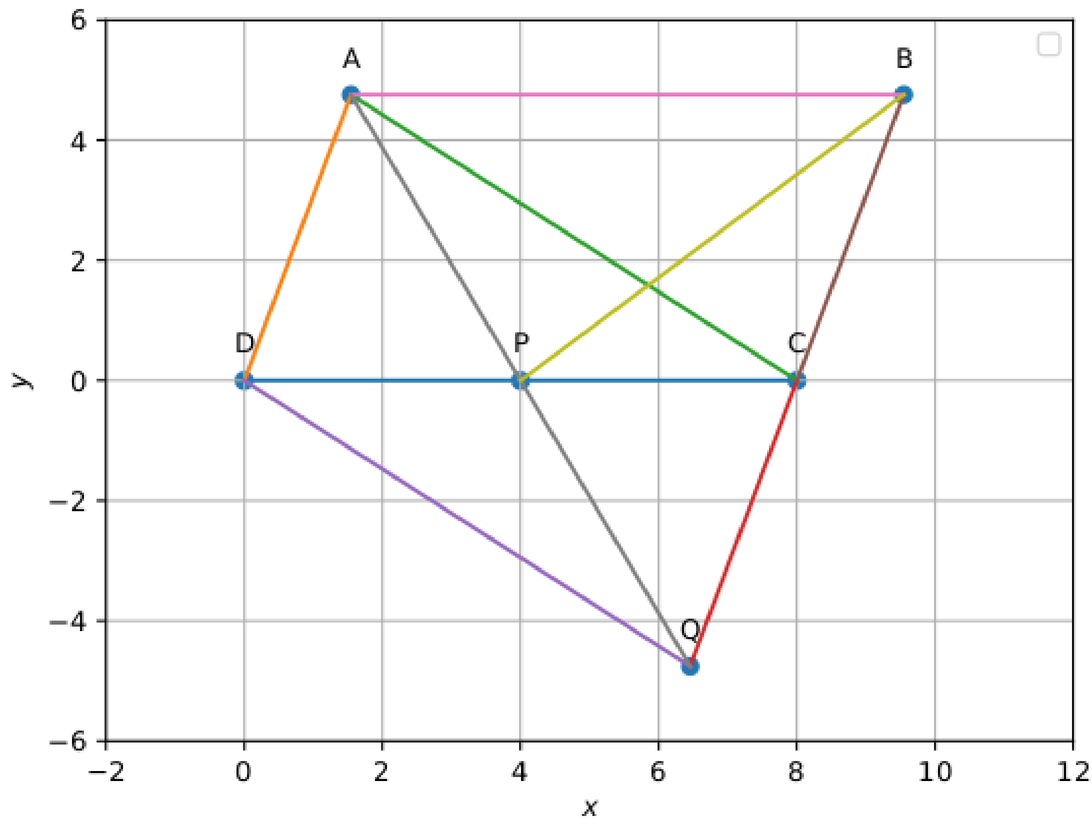


Figure 5.4.4.1:

point of BC. If AE intersects BC at $\mathbf{F}$, show that

$$ar(BDE) = \frac{1}{4}ar(ABC) \tag{5.4.5.1}$$

$$ar(BDE) = \frac{1}{2}ar(BAE) \tag{5.4.5.2}$$

$$ar(ABC) = 2ar(BEC) \tag{5.4.5.3}$$

$$ar(BFE) = ar(AFD) \tag{5.4.5.4}$$

$$ar(BFE) = 2ar(FED) \tag{5.4.5.5}$$

$$ar(FED) = \frac{1}{8}ar(AFC) \tag{5.4.5.6}$$

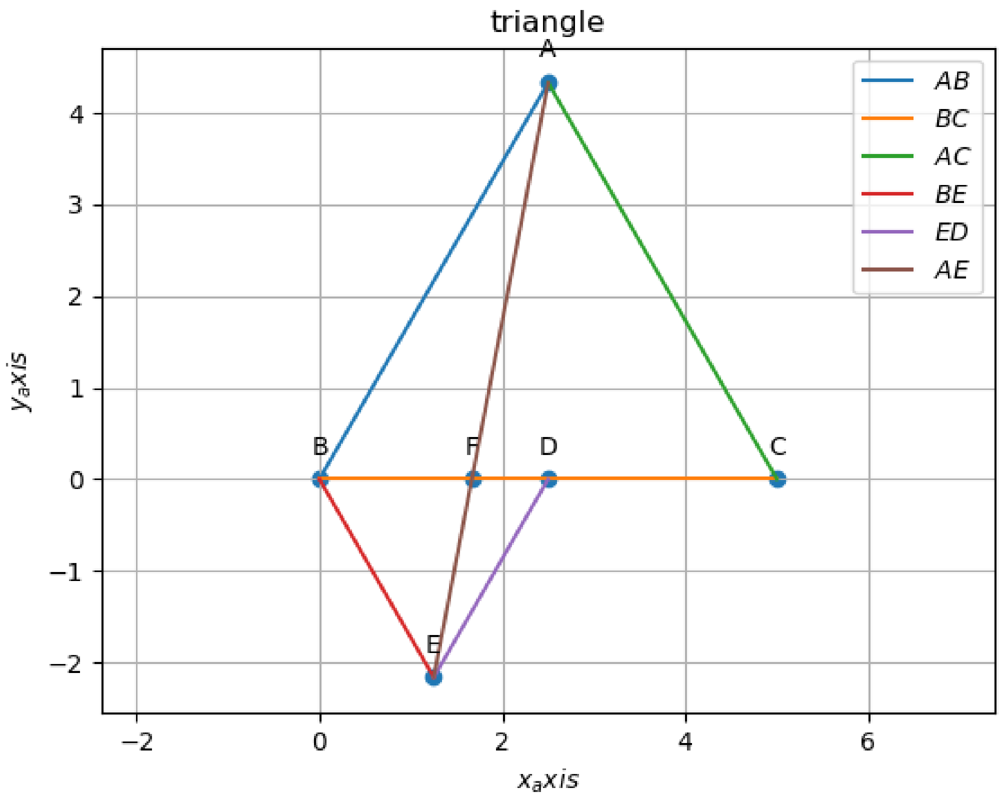


Figure 5.4.5.1:

5.4.6

5.4.7

5.4.8

Chapter 6

Circle Construction

6.1. Equal Chords

6.1.1 Two circles of radii 5cm and 3cm intersect at two points and the distance between their center is 4cm. Find the length of the common chord.

Solution: See Fig. 6.1.1.1. and

Parameter	Value	Description
$\mathbf{c}_1$	$\mathbf{0}$	Center of Circle 1
$\mathbf{c}_2$	$4\mathbf{e}_1$	Center of Circle 2
r_1	5	Radius of Circle 1
r_2	3	Radius of Circle 2

Table 6.1.1.2:

From Table 6.1.1.2, (D.2.1.1) and (D.2.2.1), the equations of the two circles are

$$\|\mathbf{x}\|^2 - 25 = 0$$
$$\|\mathbf{x}\|^2 - 8\mathbf{e}_1^\top \mathbf{x} + 7 = 0 \tag{6.1.1.1}$$

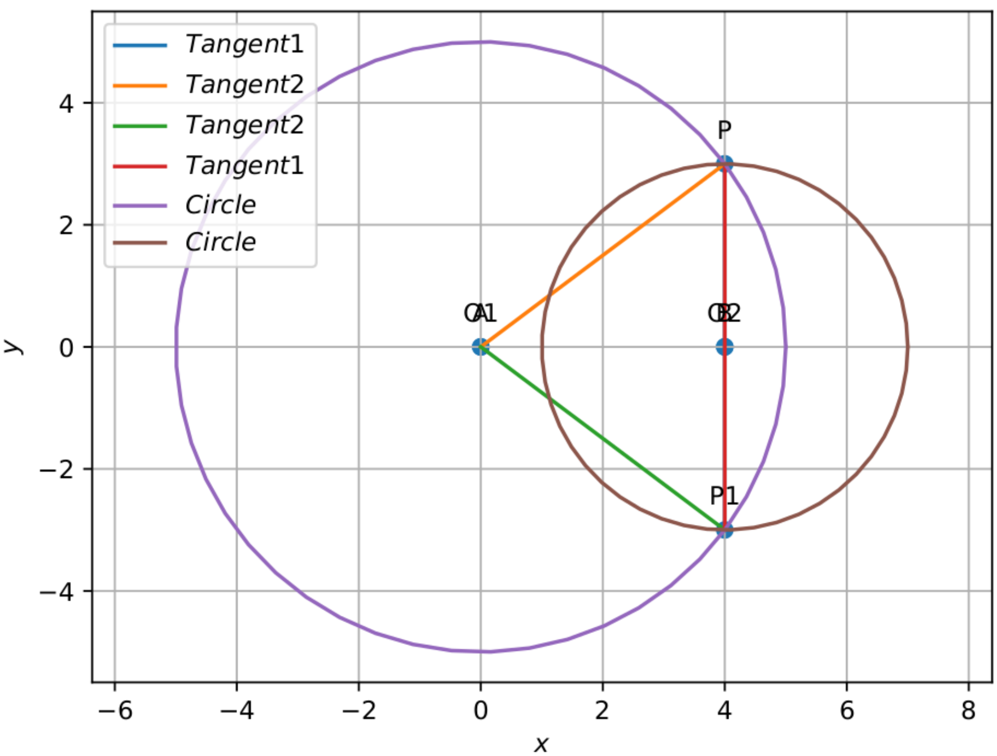


Figure 6.1.1.1:

From (6.1.1.1) and (D.2.4.1) the equation of the common chord is

$$\mathbf{e}_1^\top \mathbf{x} = 4 \tag{6.1.1.2}$$

It is easy to verify that

$$\mathbf{q} = 4\mathbf{e}_1 \tag{6.1.1.3}$$

is a point on (6.1.1.2). Substituting

$$\mathbf{m} = \mathbf{e}_2, \mathbf{q} = 4\mathbf{e}_1, \mathbf{V} = \mathbf{I}, \mathbf{u} = \mathbf{0}, f = -25 \tag{6.1.1.4}$$

in (F.3.3.1), the length of the chord in (F.3.1.1) is given by

$$\frac{2\sqrt{\left[\mathbf{e}_2^\top\left(4\mathbf{e}_1\right)\right]^2-\left(16\mathbf{e}_1^\top\mathbf{e}_1-25\right)\left(\mathbf{e}_2^\top\mathbf{e}_2\right)}}{\mathbf{e}_2^\top\mathbf{e}_2}\left\|\mathbf{e}_2\right\|=6 \tag{6.1.1.5}$$

6.1.2

6.1.3

6.1.4

6.1.5

6.1.6

6.2. Inscribed Polygons

6.2.1 In Fig. 6.2.1.1, $\mathbf{A}, \mathbf{B}$ and $\mathbf{C}$ are three points with centre $\mathbf{O}$ such that $\angle BOC = 30°$ and $\angle AOB = 60°$. If $\mathbf{D}$ is a point on the circle other than the arc ABC, find $\angle ADC$.

Solution: See Fig. (6.2.1.1).

$$\mathbf{A}=\mathbf{e}_2, \mathbf{B}=\begin{pmatrix}\cos 30\\ \sin 30\end{pmatrix}, \mathbf{C}=\mathbf{e}_1 \text{ and } \mathbf{D}=\begin{pmatrix}\cos\theta\\ \sin\theta\end{pmatrix}. \tag{6.2.1.1}$$

6.2.2

6.2.3 Let $\angle PQR = 100°$ where $\mathbf{PQ}, \mathbf{R}$ are points on a circle with centre $\mathbf{O}$. Find $\angle OPR$.

Solution: In Fig. 6.2.3.1,

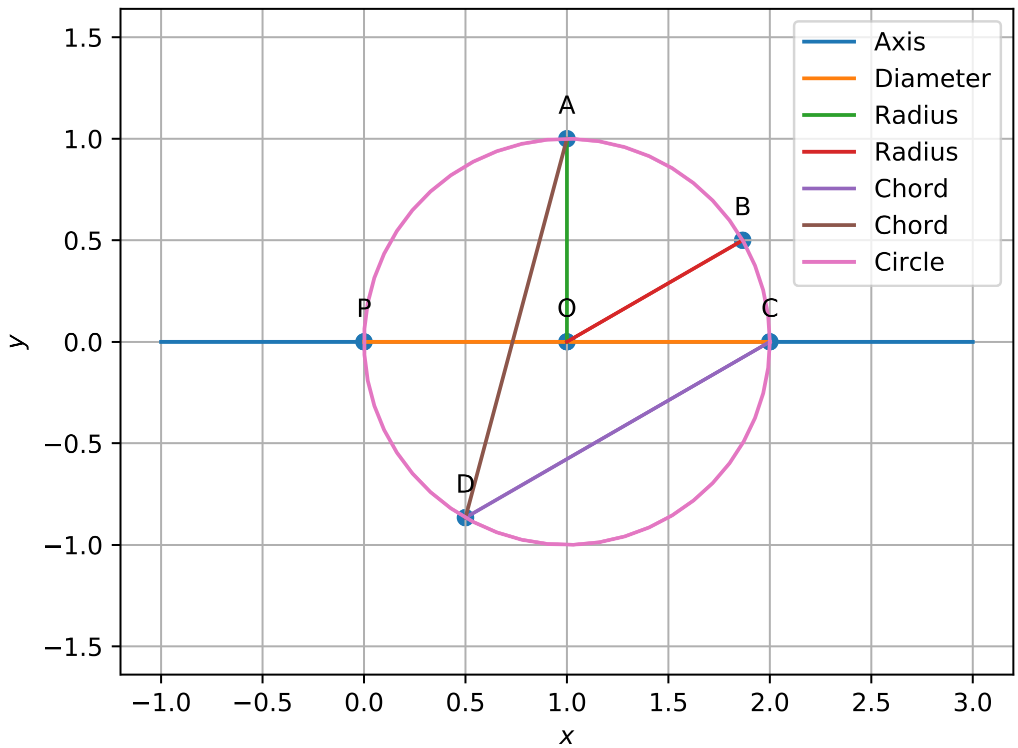


Figure 6.2.1.1:

$$\mathbf{P} = \begin{pmatrix} \cos(\theta + 160) \\ \sin(\theta + 160) \end{pmatrix}, \mathbf{Q} = \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix}, \mathbf{R} = \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}. \tag{6.2.3.1}$$

6.3. Tangent to a Circle

6.3.1

6.3.2 Draw a circle and two lines parallel to a given line such that one is a tangent and the other is a secant to the circle

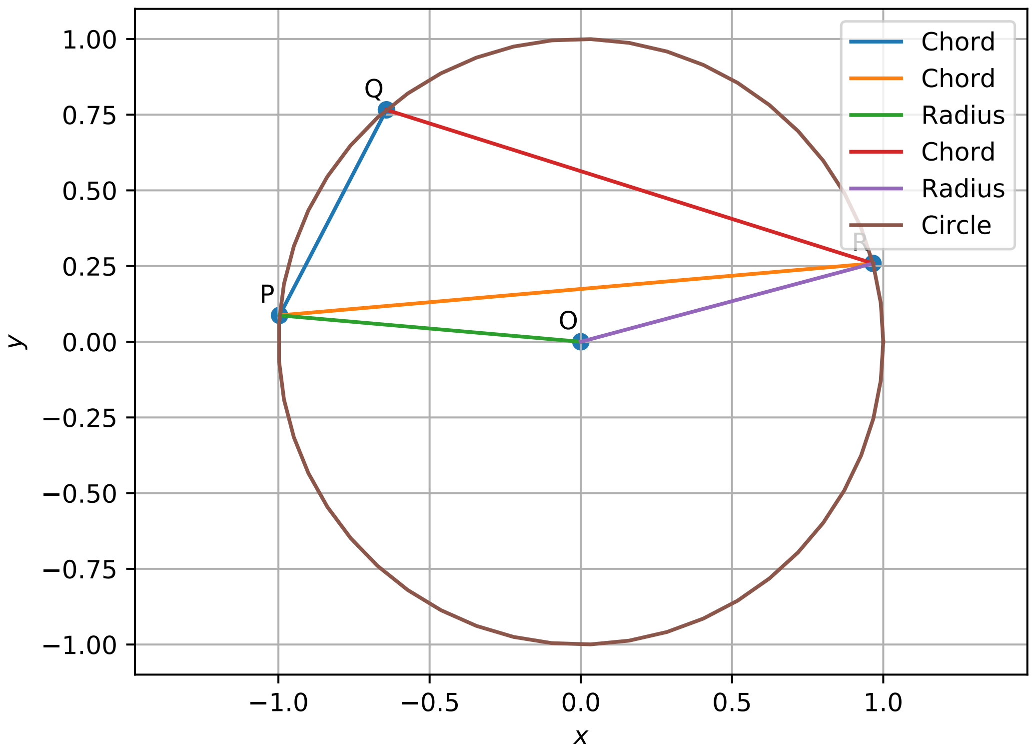


Figure 6.2.3.1:

Solution: The parameters of the circle in Fig. 6.3.2.1 are

$$\mathbf{u} = \mathbf{0}, f = -16 \tag{6.3.2.1}$$

Considering the given line to be

$$\mathbf{e}_1^\top \mathbf{x} = 5 \tag{6.3.2.2}$$

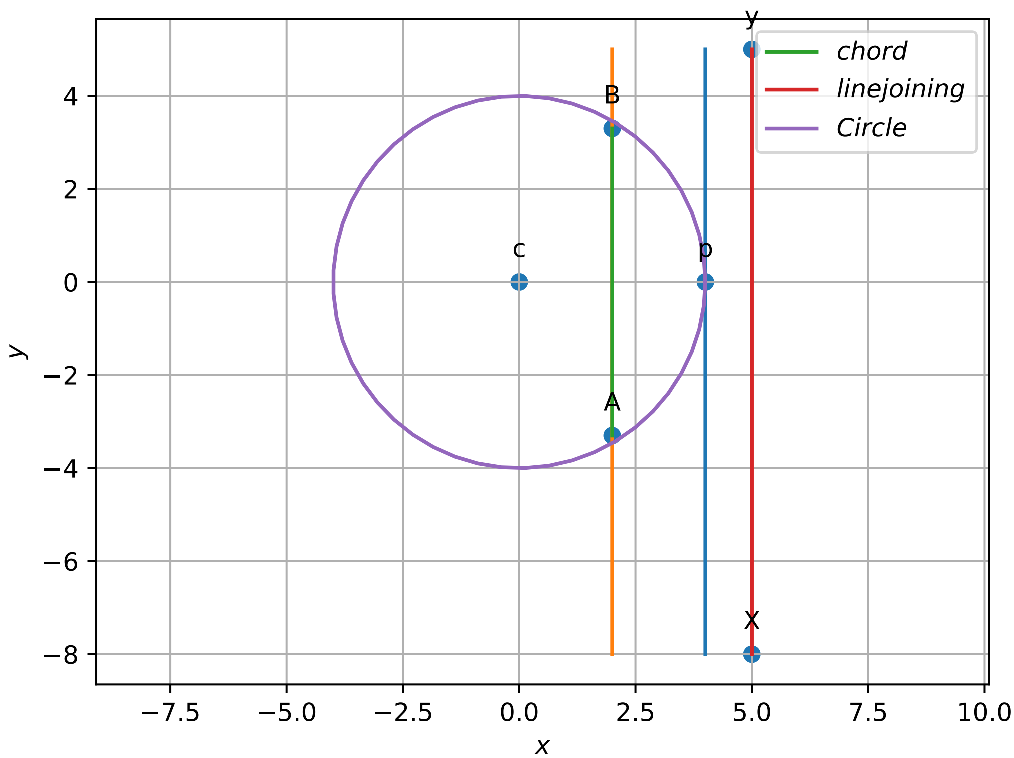


Figure 6.3.2.1:

the tangent to the circle will be

$$\mathbf{e}_1^\top \mathbf{x} = 4 \tag{6.3.2.3}$$

and the secant will be

$$\mathbf{e}_1^\top \mathbf{x} = c \tag{6.3.2.4}$$

where

$$|c| < 4 \tag{6.3.2.5}$$

6.4. Tangents from a Point

6.4.1

6.4.2

6.4.3

6.4.4 Show that the tangents of circle drawn at the ends of diameter are parallel.

Solution: See Fig. 6.4.4.1. Let $\mathbf{A}, \mathbf{B}$ be the end points of the diameter of the circle through which the tangents are drawn. From (D.2.2.1),

$$\frac{\mathbf{A}+\mathbf{B}}{2} = -\mathbf{u} \tag{6.4.4.1}$$

$$\implies \mathbf{A}+\mathbf{B} = -2\mathbf{u} \tag{6.4.4.2}$$

From (F.3.2.1),

$$\mathbf{m_1}^\top (\mathbf{A}+\mathbf{u}) = 0 \tag{6.4.4.3}$$

$$\mathbf{m_2}^\top (\mathbf{B}+\mathbf{u}) = 0 \tag{6.4.4.4}$$

where $\mathbf{m_1}, \mathbf{m_2}$ are the direction vectors of the tangents at $\mathbf{A}, \mathbf{B}$ respectively. Then,

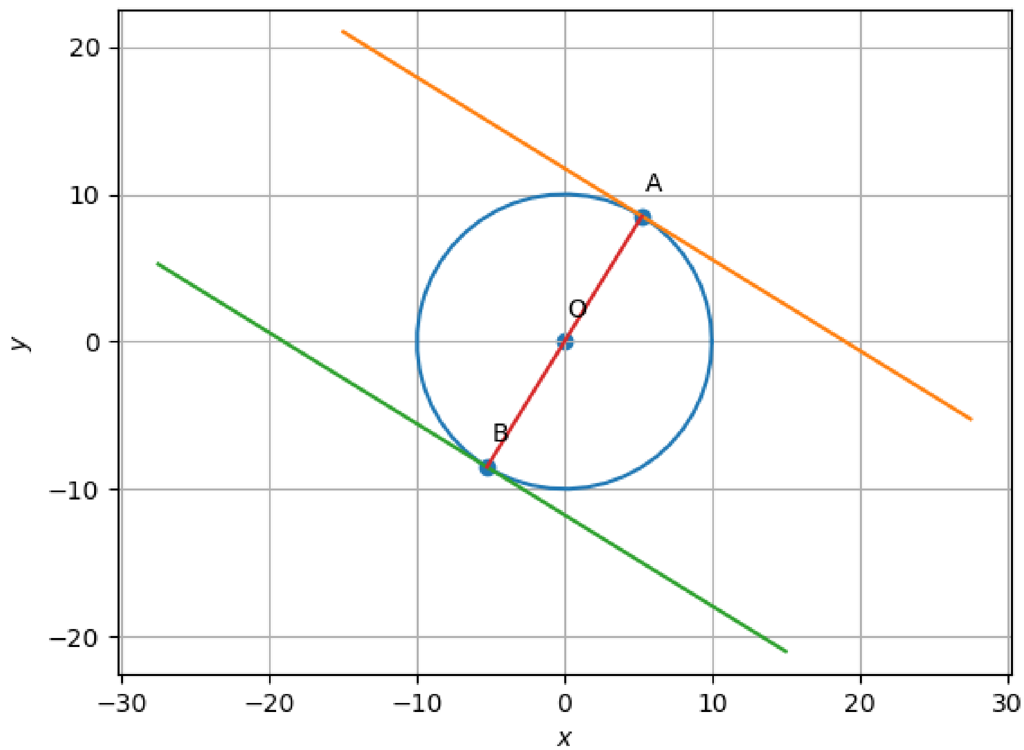


Figure 6.4.4.1:

the normal vectors at the point of contact of tangets are

$$\mathbf{A} + \mathbf{u} = k_1 \mathbf{n_1} \tag{6.4.4.5}$$

$$\mathbf{B} + \mathbf{u} = k_2 \mathbf{n_2} \tag{6.4.4.6}$$

Adding (6.4.4.5) and (6.4.4.6),

$$k_1\mathbf{n_1} + k_2\mathbf{n_2} = \mathbf{A} + \mathbf{B} + 2\mathbf{u} \tag{6.4.4.7}$$

$$= \mathbf{0} \tag{6.4.4.8}$$

from (6.4.4.2), (6.4.4.8) can be expressed as

$$k_1\mathbf{n_1} + k_2\mathbf{n_2} = 0 \tag{6.4.4.9}$$

$$k_1\mathbf{n_1} = -k_2\mathbf{n_2} \tag{6.4.4.10}$$

Since

$$\mathbf{n_1} \times \mathbf{n_2} = \mathbf{0}, \tag{6.4.4.11}$$

$$\mathbf{n_1} \parallel \mathbf{n_2} \implies \mathbf{m_1} \parallel \mathbf{m_2} \tag{6.4.4.12}$$

6.4.5

6.4.6 The length of a tangent from a point $\mathbf{A}$ at distance 5 cm from the centre of the circle is 4 cm. Find the radius of the circle.

Solution: From the Baudhayana theorem, the radius

$$r = 3 \tag{6.4.6.1}$$

Let

$$\mathbf{A} = \mathbf{O} \text{ and } \mathbf{O} = \begin{pmatrix} 5 \\ 0 \end{pmatrix} \tag{6.4.6.2}$$

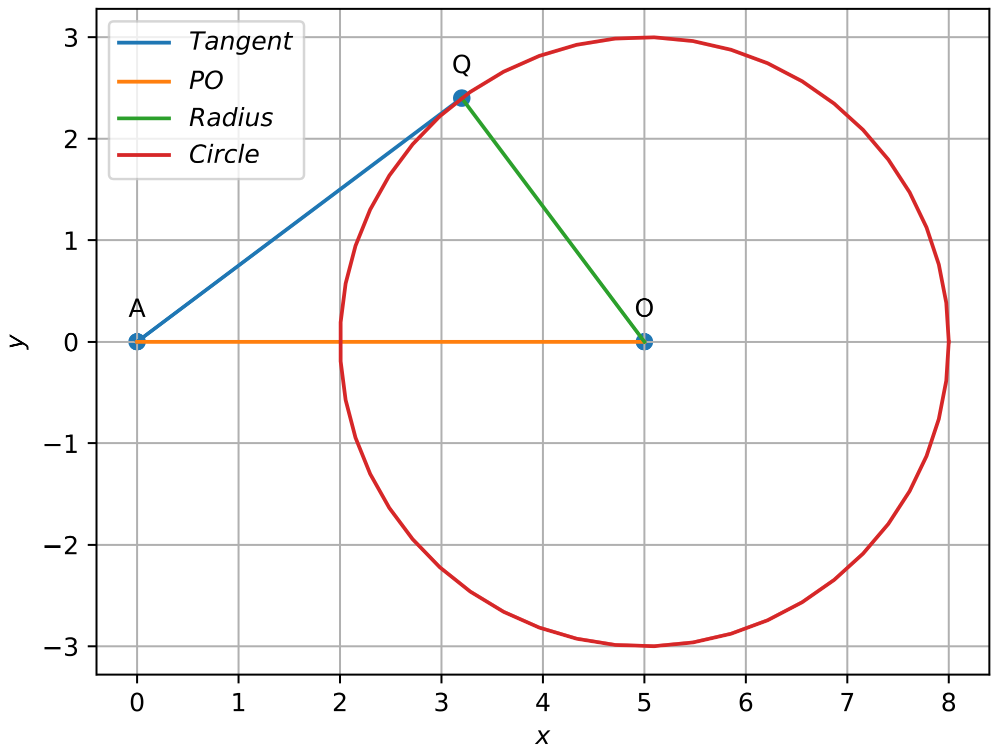


Figure 6.4.6.1:

The equation of the circle can then be expressed as

$$\|\mathbf{x}\|^2 + 2\mathbf{u}^\top \mathbf{x} + f = 0 \tag{6.4.6.3}$$

where

$$\mathbf{u} = -\mathbf{O} = -\begin{pmatrix} 5 \\ 0 \end{pmatrix} \tag{6.4.6.4}$$

$$f = \|\mathbf{u}\|^2 - r^2 = 16 \tag{6.4.6.5}$$

From (F.4.9.2),

$$\mathbf{\Sigma} = (\mathbf{A} + \mathbf{u})(\mathbf{A} + \mathbf{u})^\top - \left(\mathbf{A}^\top\mathbf{A} + 2\mathbf{u}^\top\mathbf{A} + f\right)\mathbf{I} \tag{6.4.6.6}$$

$$= \begin{pmatrix} 9 & 0 \\ 0 & -16 \end{pmatrix} \tag{6.4.6.7}$$

Thus, from (F.4.9.1),

$$\mathbf{P} = \mathbf{I}, \lambda_1 = 9, \lambda_2 = -16 \tag{6.4.6.8}$$

$$\implies \mathbf{n}_1 = \begin{pmatrix} 3 \\ 4 \end{pmatrix} \quad \text{and } \mathbf{n}_2 = \begin{pmatrix} 3 \\ -4 \end{pmatrix} \tag{6.4.6.9}$$

Substituting from the above in (F.4.6.1),

$$\mathbf{q}_{22} = \frac{1}{5}\begin{pmatrix} 16 \\ 12 \end{pmatrix} = \mathbf{Q} \tag{6.4.6.10}$$

in Fig. 6.4.6.1.

6.4.7 Two concentric circles are of radii 5cm and 3cm. Find the length of the chord of the larger circle which touches the smaller circle.

Solution: See Fig. 6.4.7.1. Let

$$\mathbf{O} = \mathbf{0} \tag{6.4.7.1}$$

$$r_1 = 5, r_2 = 3. \tag{6.4.7.2}$$

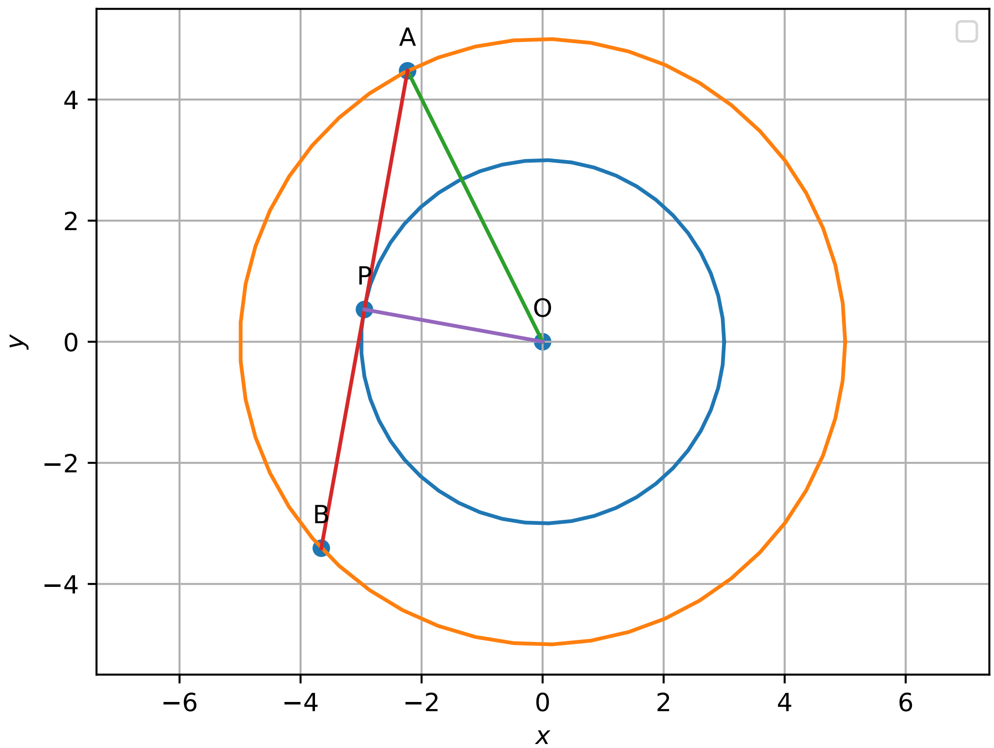


Figure 6.4.7.1:

Choosing

$$\mathbf{A} = r_1 \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}, \tag{6.4.7.3}$$

$\mathbf{P}$ can be obtained following the approach in Problem 6.4.7. From Appendix D.2.5, $\mathbf{P}$ is the mid point of AB. This can be used to obtain $\mathbf{B}$.

6.4.8 A quadrilateral $ABCD$ is drawn to circumscribe a circle. Show that $AB+CD$ is equal to $BC+AD$

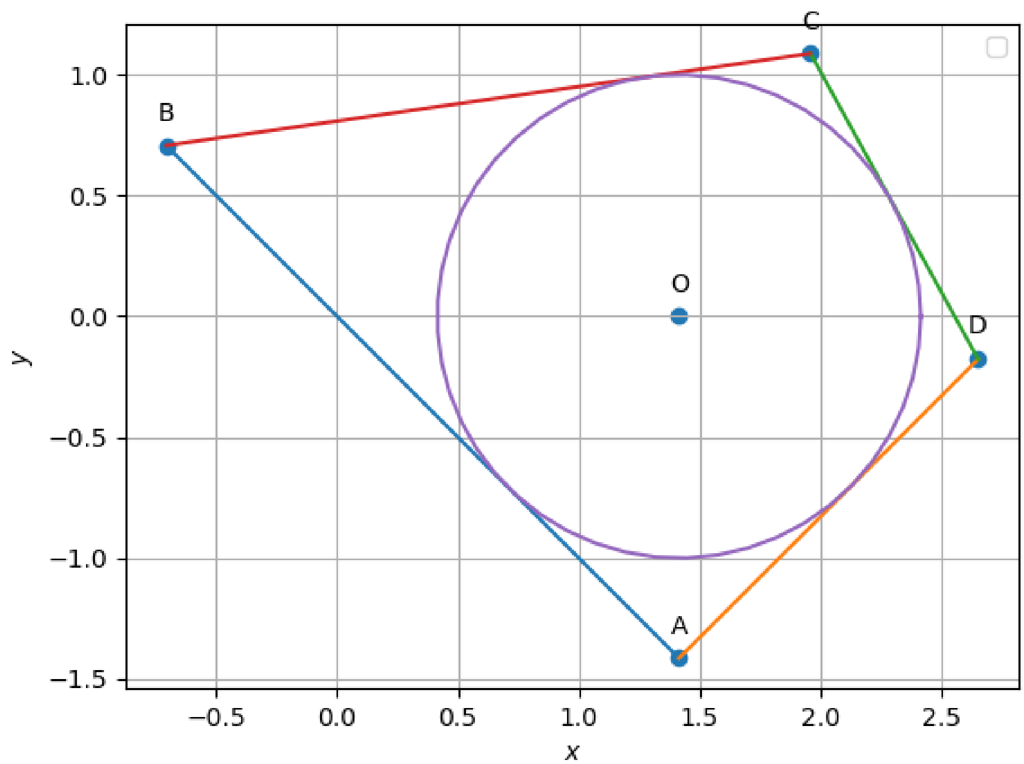


Figure 6.4.8.1:

Solution:

(a) Draw the circle.

(b) Choose the point $\mathbf{A}$.

(c) Draw the tangents from $\mathbf{A}$ to the circle.

(d) Choose points $\mathbf{B}, \mathbf{D}$ on the tangents.

(e) From $\mathbf{B}, \mathbf{D}$, draw tangents to the circle intersecting at $\mathbf{C}$.

6.4.9 In Fig. 6.4.9.1, XY and EF are two parallel tangents to a circle with centre $\mathbf{O}$ and another tangent AB with point of contact **C** intersecting XY at **A** and EF at **B**. Prove that $\angle AOB = 90°$.

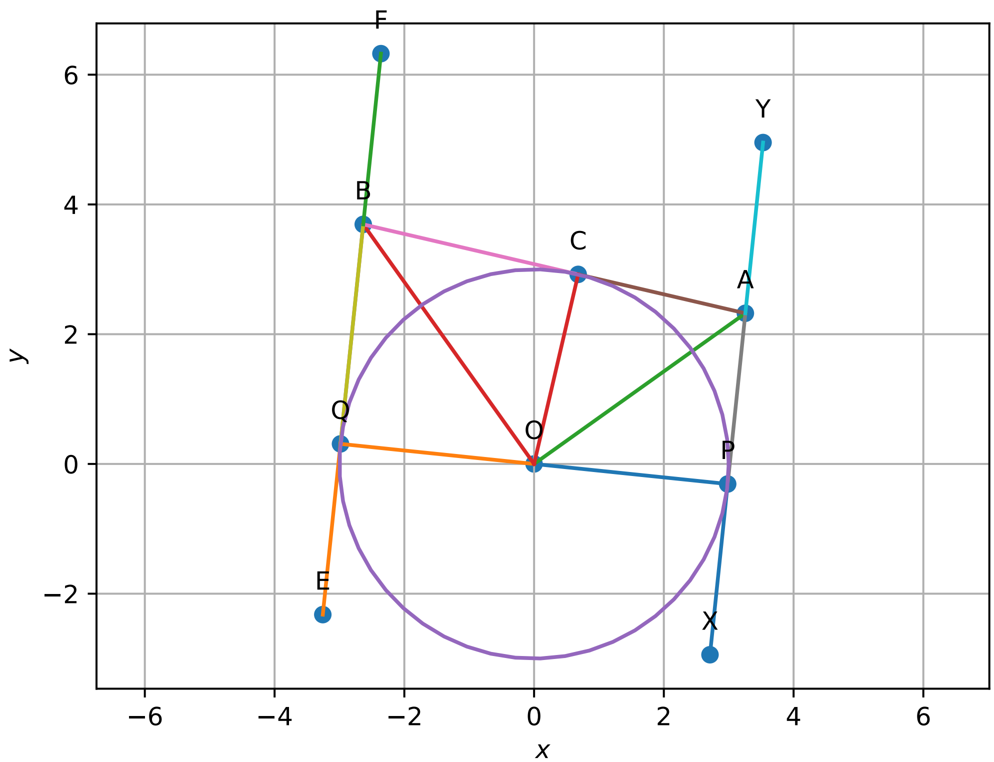


Figure 6.4.9.1:

Solution:

6.4.10 Prove that the angle between the two tangents drawn from an external point to a circle is supplementary to the angle subtended by the line-segment joining the points of contact at the centre.

Solution: Follow the approach in Problem 6.4.6 for constructing the tangents to the circle.

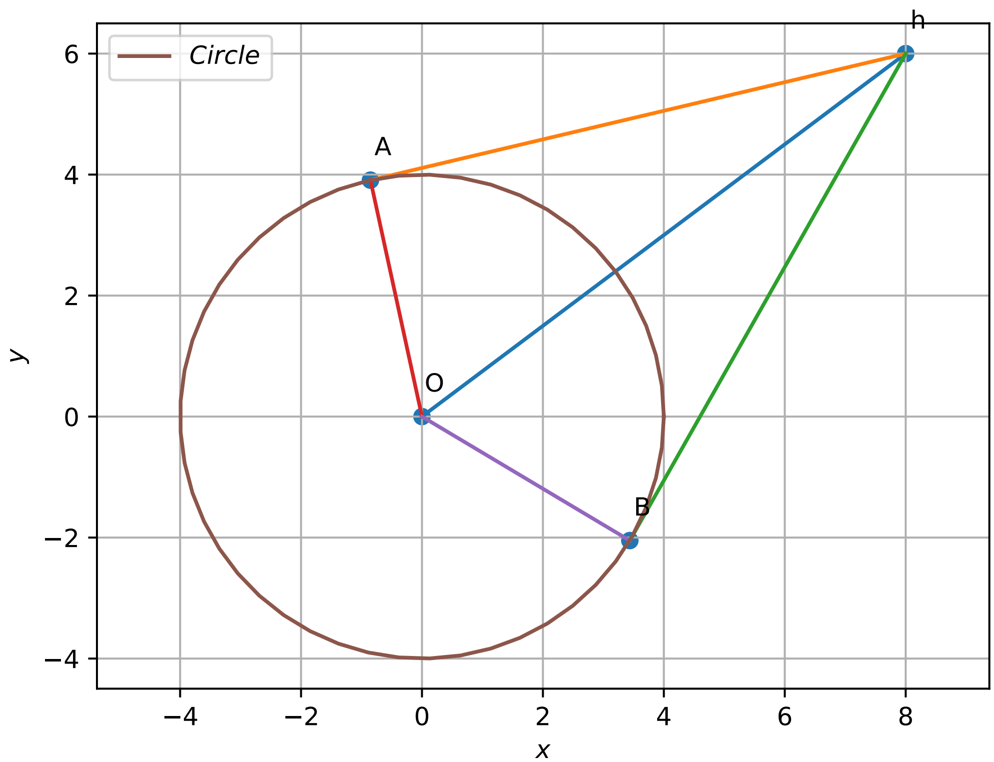


Figure 6.4.10.1:

6.4.11

6.4.12 A triangle ABC is drawn to circumscribe a circle of radius 4cm such that the segments BD and DC into which BC is divided by the point of contact D are of lengths 8cm and 6cm respectively. Find the sides AB and AC.

6.4.13

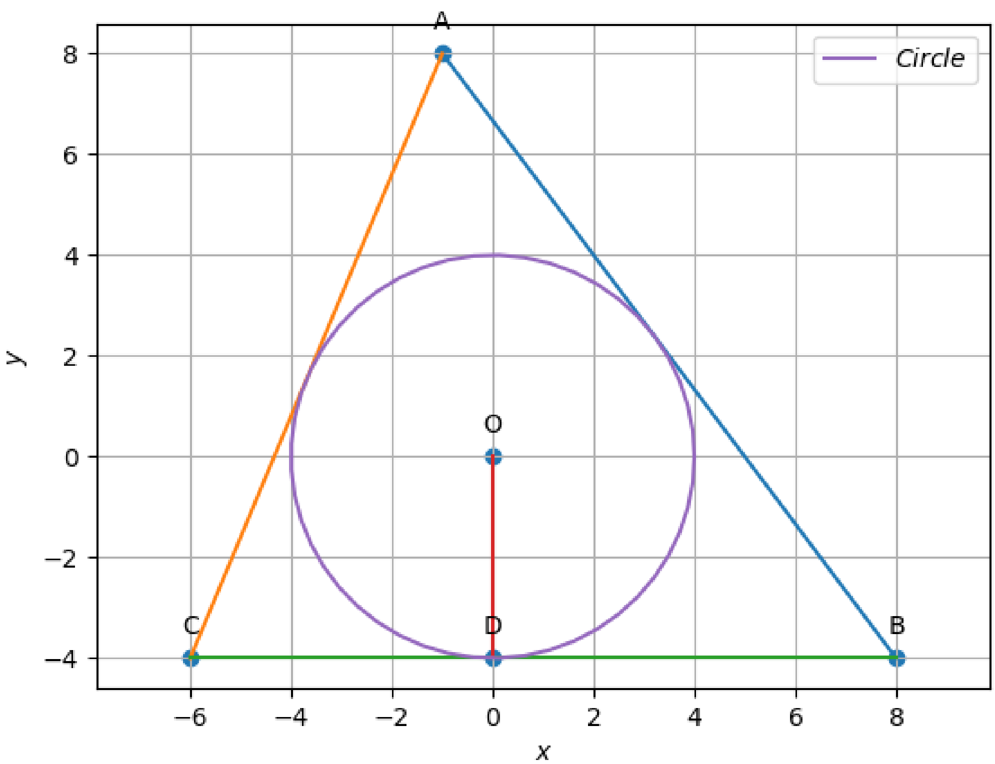


Figure 6.4.12.1:

Chapter 7

Conics

7.1. Parabola

7.2. Ellipse

7.3. Hyperbola

7.4. Miscellaneous

7.4.1

7.4.2 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?

Solution:

7.4.3

7.4.4 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.

Solution:

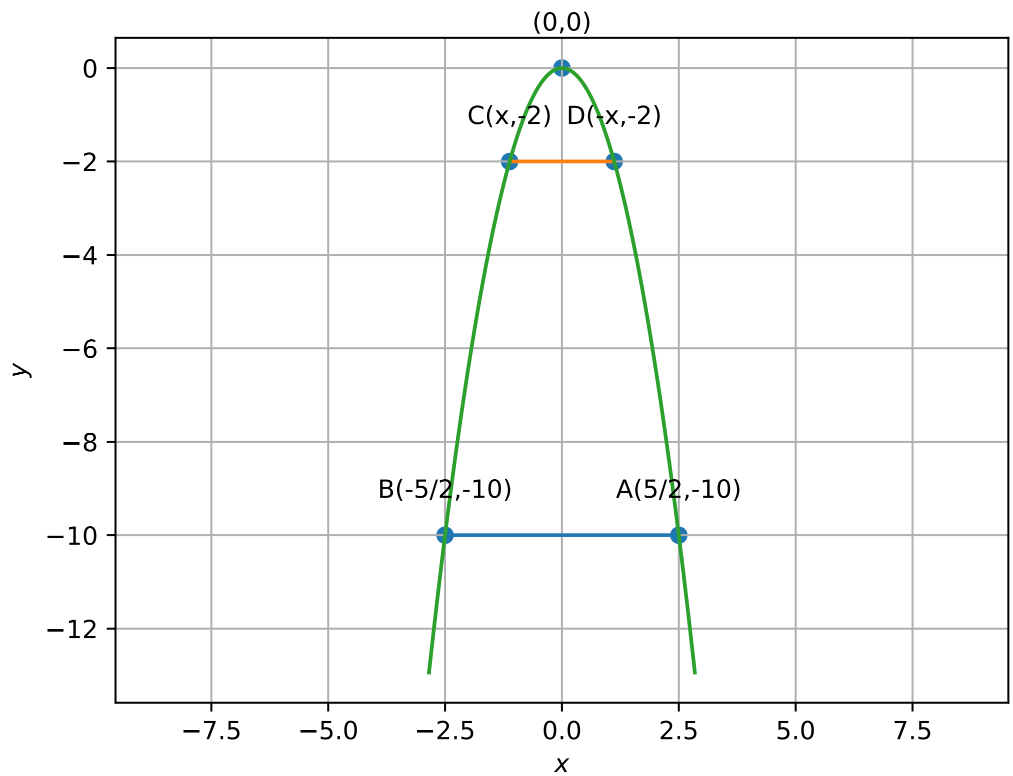


Figure 7.4.2.1:

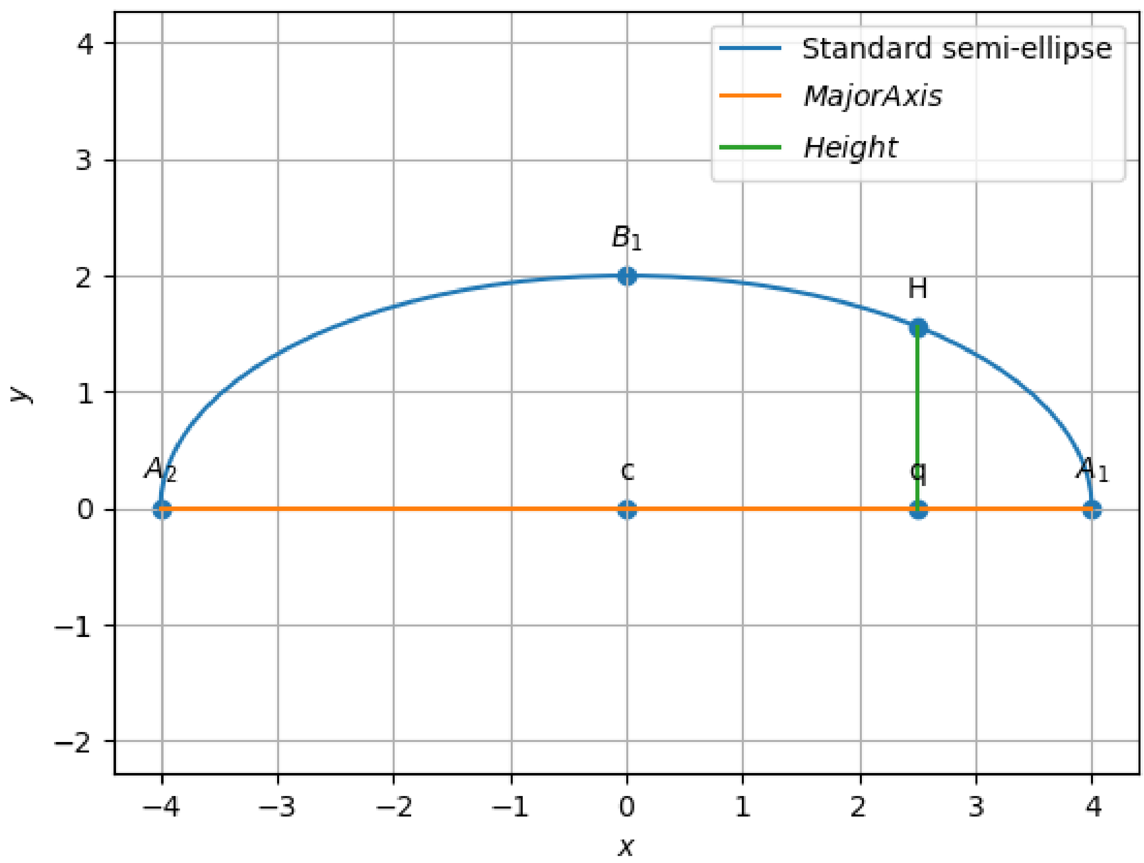
7.4.5

7.4.6 Find the area of the triangle formed by the lines joining the vertex of the parabola $x^2 = 12y$ to the ends of its latus rectum.

7.4.7

7.4.8 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.

Solution:



Standard semi-ellipse
MajorAxis
Height
B_1
H
A_2
c
q
A_1
4
3
2
1
0
−1
−2
y
−4
−3
−2
−1
0
1
2
3
4
x

Figure 7.4.4.1:

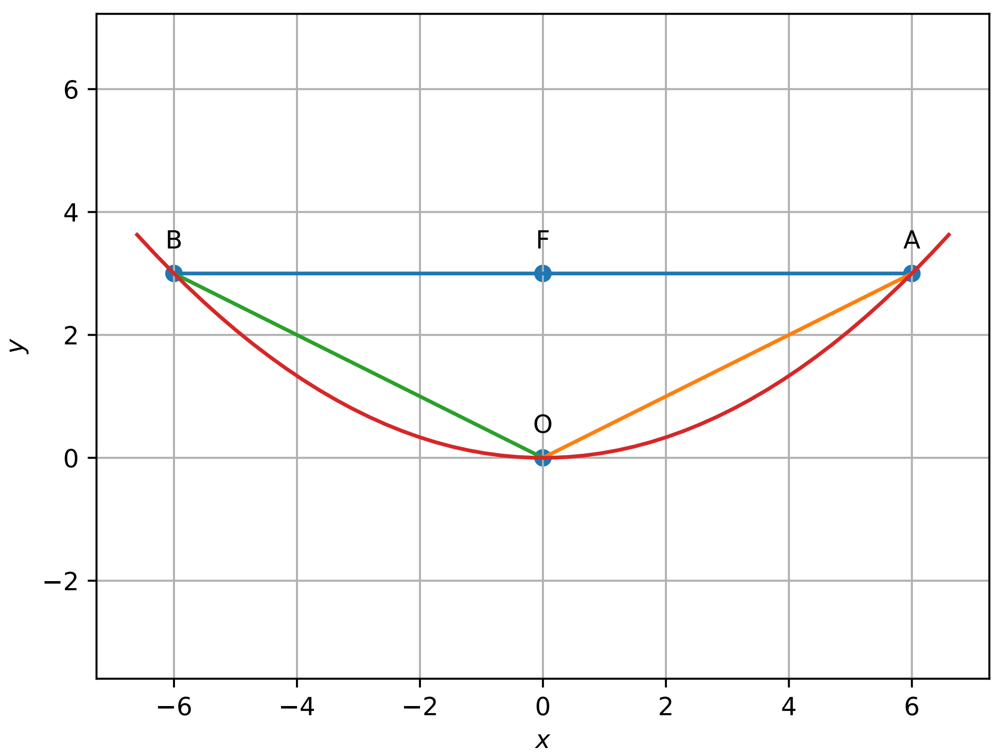


Figure 7.4.6.1:

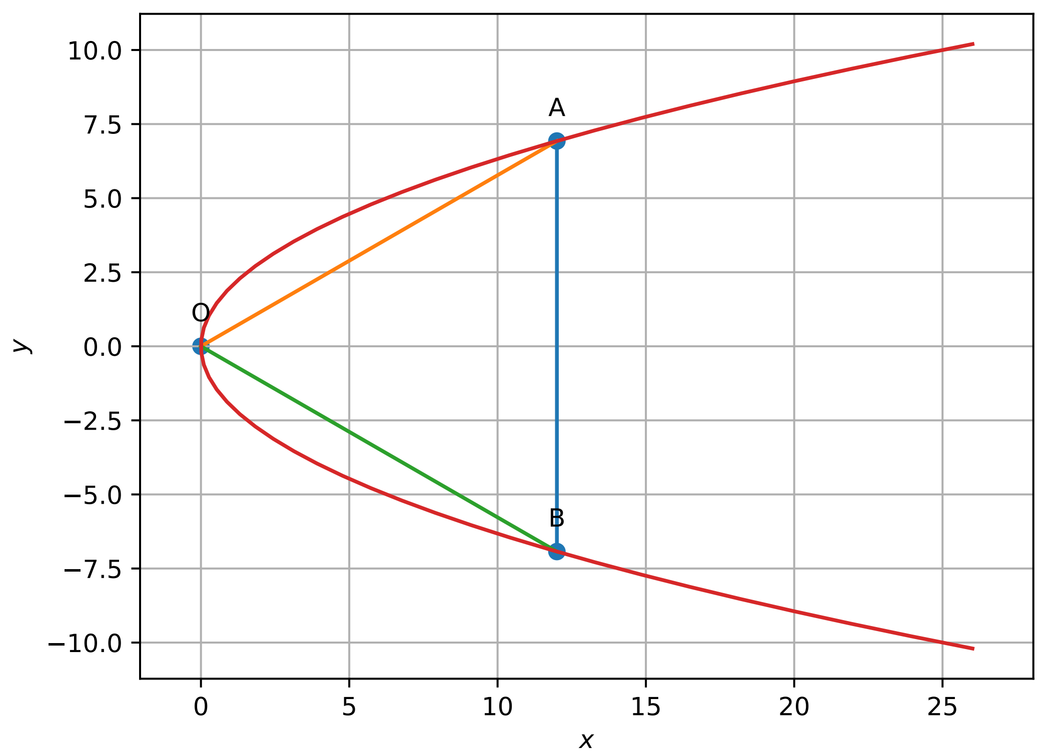


Figure 7.4.8.1:

Chapter 8

Intersection of Conics

8.1. Chords

8.1.1 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:

The parameters of the conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = -\frac{1}{2}\begin{pmatrix} 1 \\ 0 \end{pmatrix}, f = 0 \tag{8.1.1.1}$$

For the line $x - 1 = 0$, the parameters are

$$\mathbf{q}_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{8.1.1.2}$$

Substituting from the above in (F.3.1.3),

$$\mu_i = 1, -1 \tag{8.1.1.3}$$

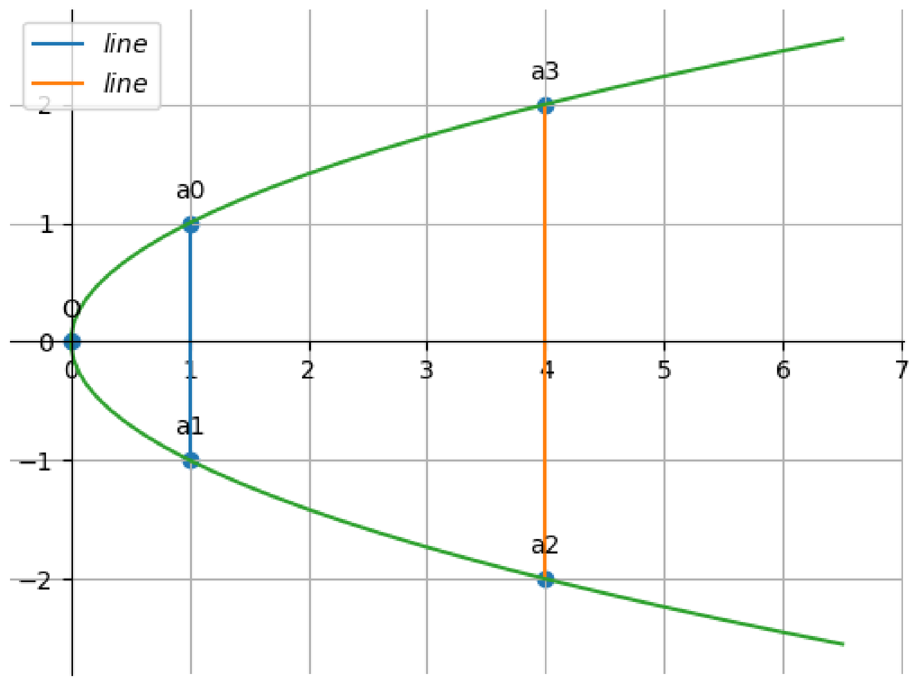


Figure 8.1.1.1:

yilelding the points of intersection

$$\mathbf{a}_0 = \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \mathbf{a}_1 = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \tag{8.1.1.4}$$

Similarly, for the line $x - 4 = 0$

$$\mathbf{q_1} = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \mathbf{m_1} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{8.1.1.5}$$

yielding

$$\mu_i = 2, -2 \tag{8.1.1.6}$$

from which, the points of intersection are

$$\mathbf{a_3} = \begin{pmatrix} 4 \\ 2 \end{pmatrix}, \mathbf{a_2} = \begin{pmatrix} 4 \\ -2 \end{pmatrix} \tag{8.1.1.7}$$

Thus, the area of the parabola in between the lines $x = 1$ and $x = 4$ is given by

$$\int_0^4 \sqrt{x}\,dx - \int_0^1 \sqrt{x}\,dx = 14/3 \tag{8.1.1.8}$$

8.1.2 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: The parameters of the conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = \frac{9}{2}\begin{pmatrix} 1 \\ 0 \end{pmatrix}, f = 0. \tag{8.1.2.1}$$

The parameters of the line $x - 2 = 0$ are

$$\mathbf{q_2} = \begin{pmatrix} 2 \\ 0 \end{pmatrix}, \mathbf{m_2} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{8.1.2.2}$$

Substituting in (F.3.1.3),

$$\mu_i = \pm 3\sqrt{2} \tag{8.1.2.3}$$

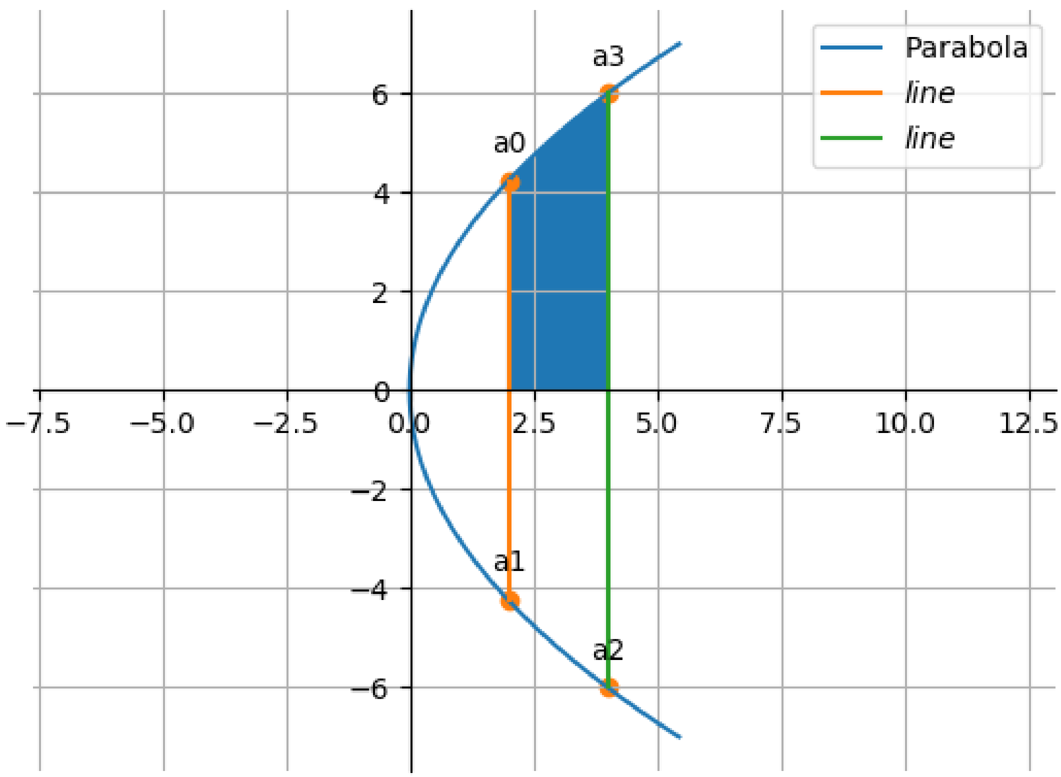


Figure 8.1.2.1:

yielding

$$\mathbf{a_0} = \begin{pmatrix} 2 \\ 3\sqrt{2} \end{pmatrix}, \mathbf{a_1} = \begin{pmatrix} 2 \\ -3\sqrt{2} \end{pmatrix}. \tag{8.1.2.4}$$

Similarly, for the line $x - 4 = 0$,

$$\mathbf{q_1} = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \mathbf{m_1} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{8.1.2.5}$$

yielding

$$\mu_i = \pm 6. \tag{8.1.2.6}$$

Thus,

$$\mathbf{a_3} = \begin{pmatrix} 4 \\ 6 \end{pmatrix}, \mathbf{a_2} = \begin{pmatrix} 4 \\ -6 \end{pmatrix} \tag{8.1.2.7}$$

and the desired area of the parabola is

$$\int_0^4 3\sqrt{x}\, dx - \int_0^2 3\sqrt{x}\, dx = 16 - 4\sqrt{2} \tag{8.1.2.8}$$

8.1.3

8.1.4 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: From the given information, the parameters of the circle and line are

$$f = -4, \mathbf{u} = \mathbf{0}, \mathbf{V} = \mathbf{I}, \mathbf{m} = \begin{pmatrix} 1 \\ \sqrt{3} \end{pmatrix}, \mathbf{h} = \mathbf{0} \tag{8.1.4.1}$$

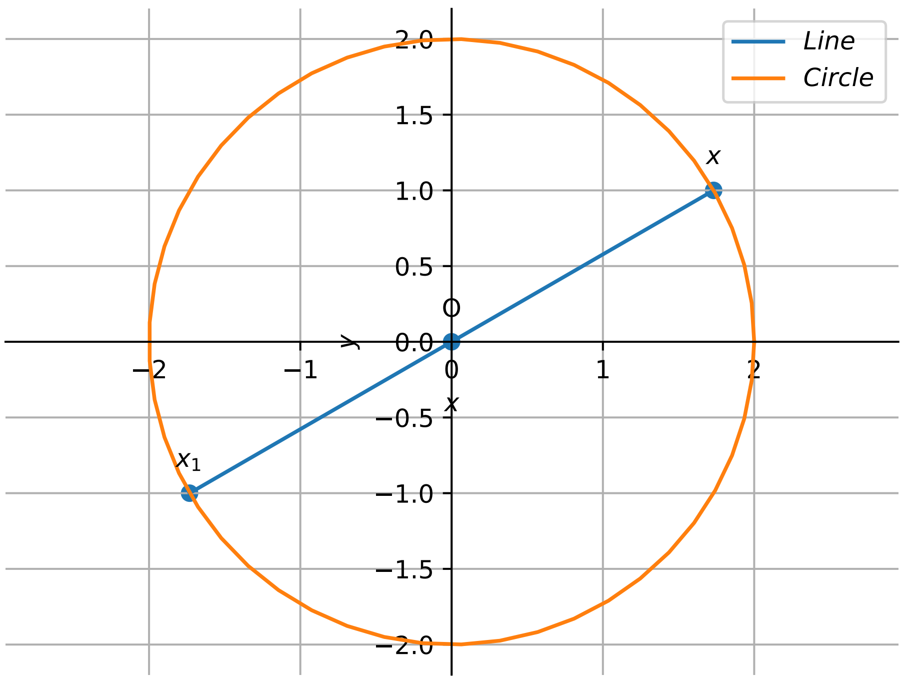


Figure 8.1.4.1:

Substituting the above parameters in (F.3.1.3),

$$\mu = \sqrt{3} \tag{8.1.4.2}$$

yielding the desired point of intersection as

$$\mathbf{x} = \begin{pmatrix} \sqrt{3} \\ 1 \end{pmatrix} \tag{8.1.4.3}$$

From (8.1.4.1), the angle between the given line and the x axis is

$$\theta = 30^\circ \tag{8.1.4.4}$$

and the area of the sector is

$$\frac{\theta}{360}\pi r^2 = \frac{\pi}{3} \tag{8.1.4.5}$$

8.1.5 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: The given circle can be expressed as a conic with parameters

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = 0, f = -a^2 \tag{8.1.5.1}$$

The given line parameters are

$$\mathbf{h} = \begin{pmatrix} \frac{a}{\sqrt{2}} \\ 0 \end{pmatrix}, \mathbf{m} = \mathbf{e}_2. \tag{8.1.5.2}$$

Substituting the above in (F.3.1.3),

$$\mu = \pm\frac{a}{\sqrt{2}} \tag{8.1.5.3}$$

yielding the points of intersection of the line with circle as

$$\mathbf{A} = \begin{pmatrix} \frac{a}{\sqrt{2}} \\ -\frac{a}{\sqrt{2}} \end{pmatrix}, \mathbf{B} = \begin{pmatrix} \frac{a}{\sqrt{2}} \\ \frac{a}{\sqrt{2}} \end{pmatrix} \tag{8.1.5.4}$$

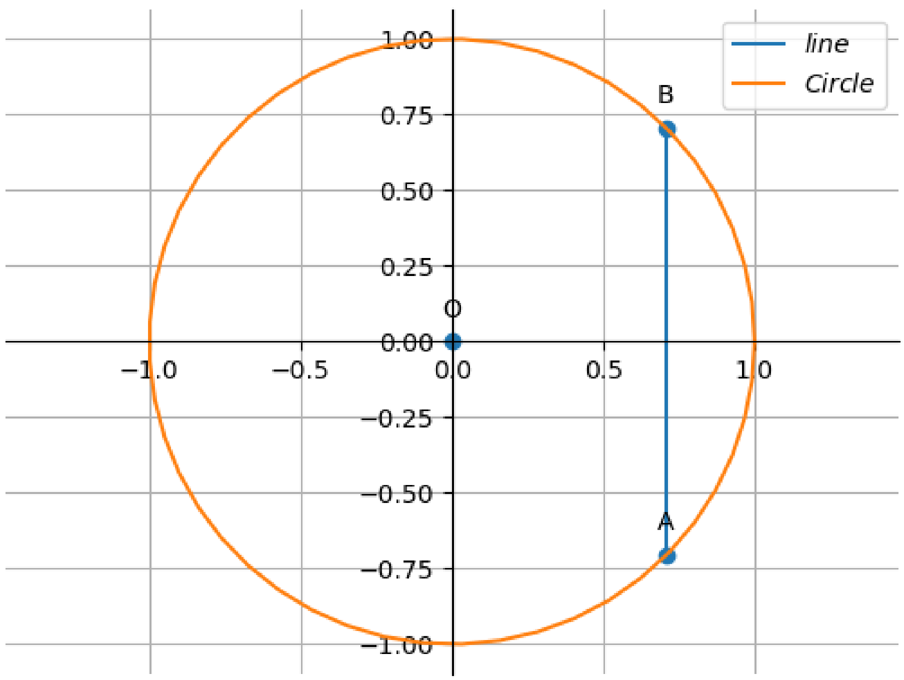


Figure 8.1.5.1:

From Fig. 8.1.5.1, the total area of the portion is given by

$$ar(APQ) = 2ar(APR) \tag{8.1.5.5}$$

$$= 2\int_0^{\frac{a}{\sqrt{2}}} \sqrt{a^2 - x^2}\, dx \tag{8.1.5.6}$$

$$= \frac{a^2}{2}\left(1 + \frac{\pi}{2}\right) \tag{8.1.5.7}$$

8.1.6 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: The given conic parameters are

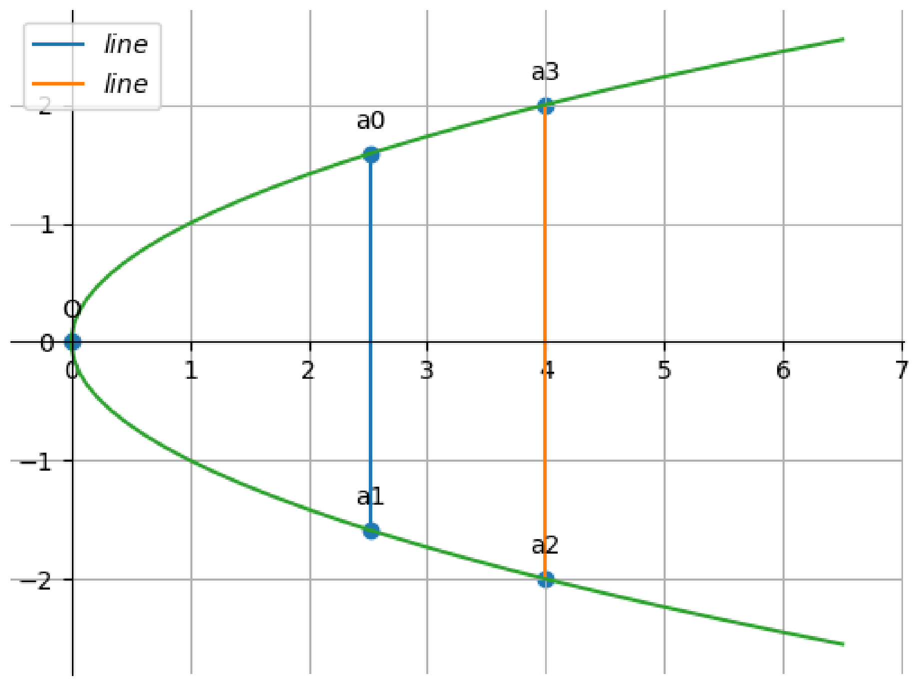


Figure 8.1.6.1:

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = -\frac{1}{2}\mathbf{e}_1 f = 0 \tag{8.1.6.1}$$

The parameters of the lines are

$$\mathbf{q}_2 = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{m}_2 = \mathbf{e}_2 \tag{8.1.6.2}$$

Substituting the above values in (F.3.1.3),

$$\mu_i = a, -a \tag{8.1.6.3}$$

yielding the points of intersection as

$$\mathbf{a_0} = \begin{pmatrix} a \\ a \end{pmatrix}, \mathbf{a_1} = \begin{pmatrix} a \\ -a \end{pmatrix} \tag{8.1.6.4}$$

Similarly, for the line $x - 4 = 0$,

$$\mathbf{q_1} = \begin{pmatrix} 4 \\ 0 \end{pmatrix}, \mathbf{m_1} = \mathbf{e}_2 \tag{8.1.6.5}$$

yielding

$$\mu_i = 2, -2 \tag{8.1.6.6}$$

and

$$\mathbf{a}_3 = \begin{pmatrix} 4 \\ 2 \end{pmatrix}, \mathbf{a}_2 = \begin{pmatrix} 4 \\ -2 \end{pmatrix}. \tag{8.1.6.7}$$

Area between parabola and the line $x = 4$ is divided equally by the line $x = a$. Thus,

$$A_1 = \int_0^a \sqrt{x}\, dx \tag{8.1.6.8}$$

$$A_2 = \int_a^4 \sqrt{x}\, dx \tag{8.1.6.9}$$

$$\text{and } A_1 = A_2 \tag{8.1.6.10}$$

$$\implies a = 4^{\frac{2}{3}} \tag{8.1.6.11}$$

8.1.7 Find the area of the region bounded by the parabola $y = x^2$ and $y = |x|$.

Solution:

8.1.8 Find the area bounded by the curve $x^2 = 4y$ and the line $x = 4y - 2$.

Solution: The given curve can be expressed as a conic with parameters

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0 \tag{8.1.8.1}$$

The parameters of the given line are

$$\mathbf{q} = \begin{pmatrix} -2 \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} 4 \\ 1 \end{pmatrix} \tag{8.1.8.2}$$

The points of intersection can then be obtained from (F.3.1.3) as

$$\therefore \mathbf{x}_1 = \begin{pmatrix} 2 \\ 1 \end{pmatrix}, \mathbf{x}_2 = \begin{pmatrix} -1 \\ \frac{1}{4} \end{pmatrix} \tag{8.1.8.3}$$

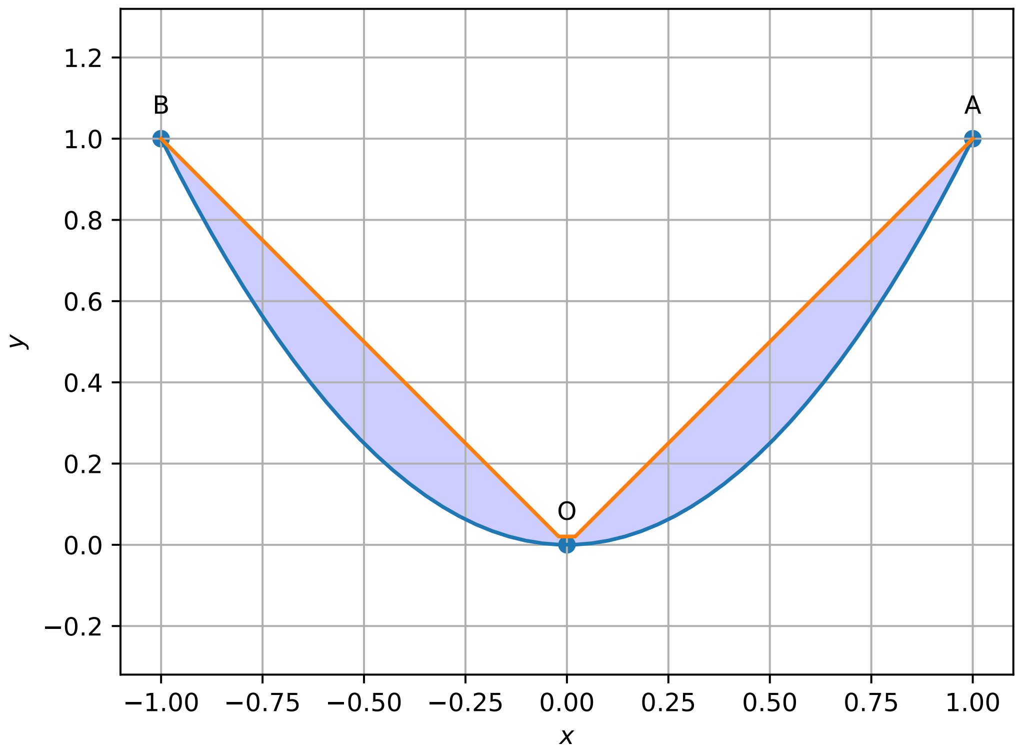


Figure 8.1.7.1:

The desired area is then obtained as

$$A = \int_{x_2}^{x_1} [f(x) - g(x)]\, dx \tag{8.1.8.4}$$

$$= \int_{-1}^{2} \left(\frac{x+2}{4} - \frac{x^2}{4} \right) dx \tag{8.1.8.5}$$

$$= \frac{9}{8} \tag{8.1.8.6}$$

8.1.9

8.1.10

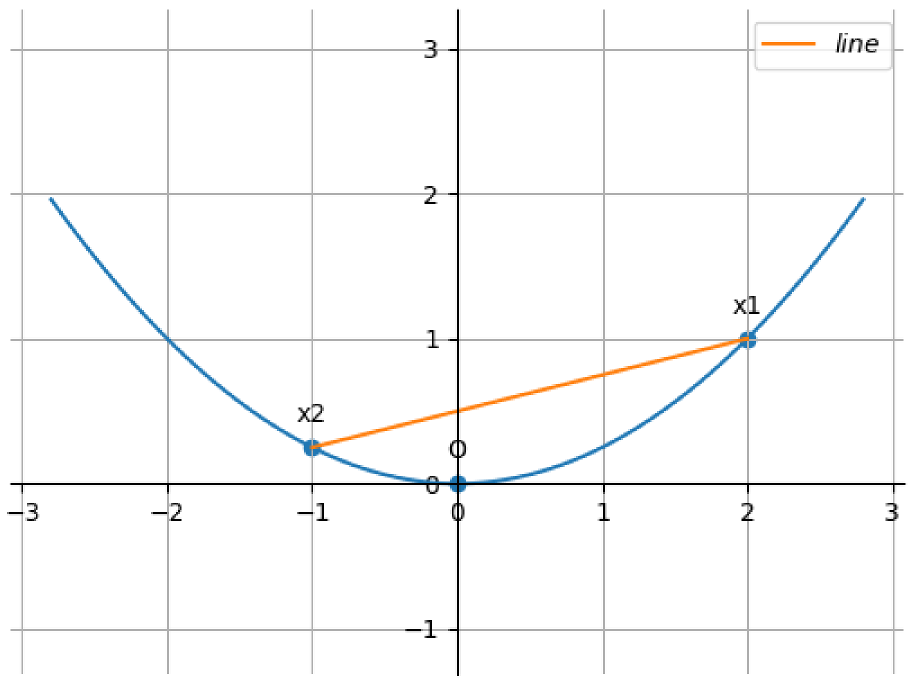


Figure 8.1.8.1:

8.1.11

8.2. Curves

8.2.1 Find the area of the circle $4x^2 + 4y^2 = 9$ which is interior to the parabola $x^2 = 4y$.

Solution: The given circle and parabola can be expressed as conics with parameters

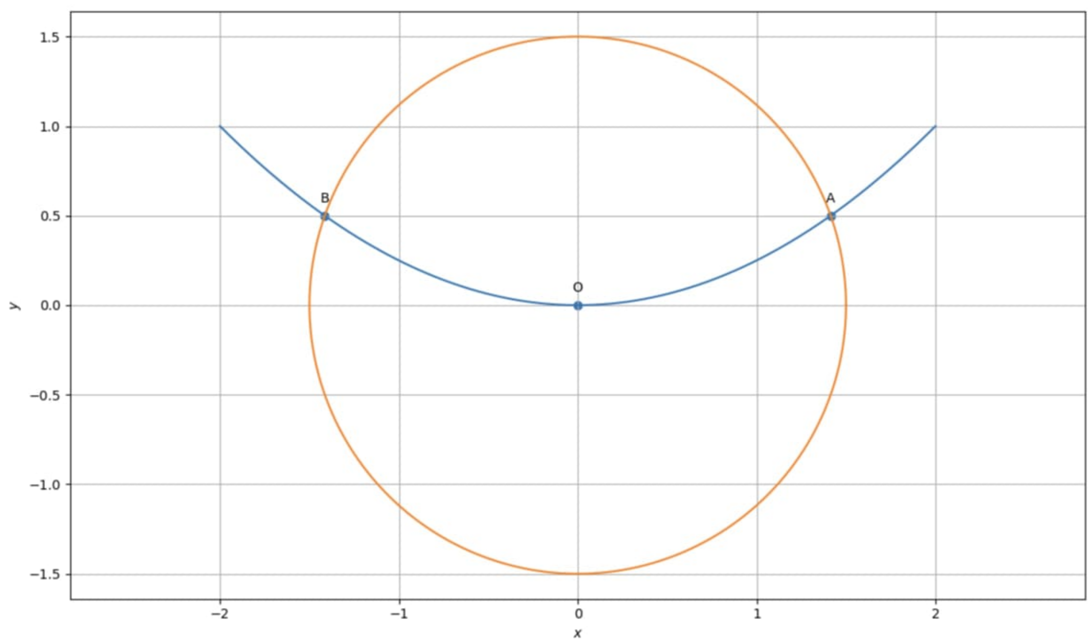


Figure 8.2.1.1:

$$\mathbf{V}_1 = 4\mathbf{I}, \mathbf{u_1} = \mathbf{0}, f_1 = -9 \tag{8.2.1.1}$$

$$\mathbf{V}_2 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u_2} = -\begin{pmatrix} 0 \\ 2 \end{pmatrix}, f_2 = 0 \tag{8.2.1.2}$$

The intersection of the given conics is obtained as

$$\mathbf{x}^\top \left(\mathbf{V}_1 + \mu \mathbf{V}_2\right) \mathbf{x} + 2\left(\mathbf{u}_1 + \mu \mathbf{u}_2\right)^\top \mathbf{x} + \left(f_1 + \mu f_2\right) = 0 \tag{8.2.1.3}$$

This conic represents a pair of straight lines if

$$\begin{vmatrix} \mathbf{V}_1 + \mu \mathbf{V}_2 & \mathbf{u}_1 + \mu \mathbf{u}_2 \\ \left(\mathbf{u}_1 + \mu \mathbf{u}_2\right)^\top & f_1 + \mu f_2 \end{vmatrix} = 0 \tag{8.2.1.4}$$

which can be expressed as

$$\implies \begin{vmatrix} \mu + 4 & 0 & 0 \\ 0 & 4 & -2\mu \\ 0 & -2\mu & -9 \end{vmatrix} = 0 \tag{8.2.1.5}$$

Solving the above equation we get,

$$\mu^3 + 4\mu^2 + 9\mu + 36 = 0 \tag{8.2.1.6}$$

yielding

$$\mu = -4. \tag{8.2.1.7}$$

Thus, the parameters for the pair of straight lines can be expressed as

$$\mathbf{V} = \mathbf{V}_1 + \mu\mathbf{V}_2 = \begin{pmatrix} 0 & 0 \\ 0 & 4 \end{pmatrix}, \tag{8.2.1.8}$$

$$\mathbf{u} = \mathbf{u}_1 + \mu\mathbf{u}_2 = \begin{pmatrix} 0 \\ 8 \end{pmatrix} \tag{8.2.1.9}$$

$$f = -9, \tag{8.2.1.10}$$

$$\implies \mathbf{D} = \mathbf{V}, \mathbf{P} = \mathbf{I} \tag{8.2.1.11}$$

8.2.2

8.2.3 Find the area of the region bounded by the curves $y = x^2 + 2$, $y = x$, $x = 0$ and $x = 3$.

Solution: The conic parameters are

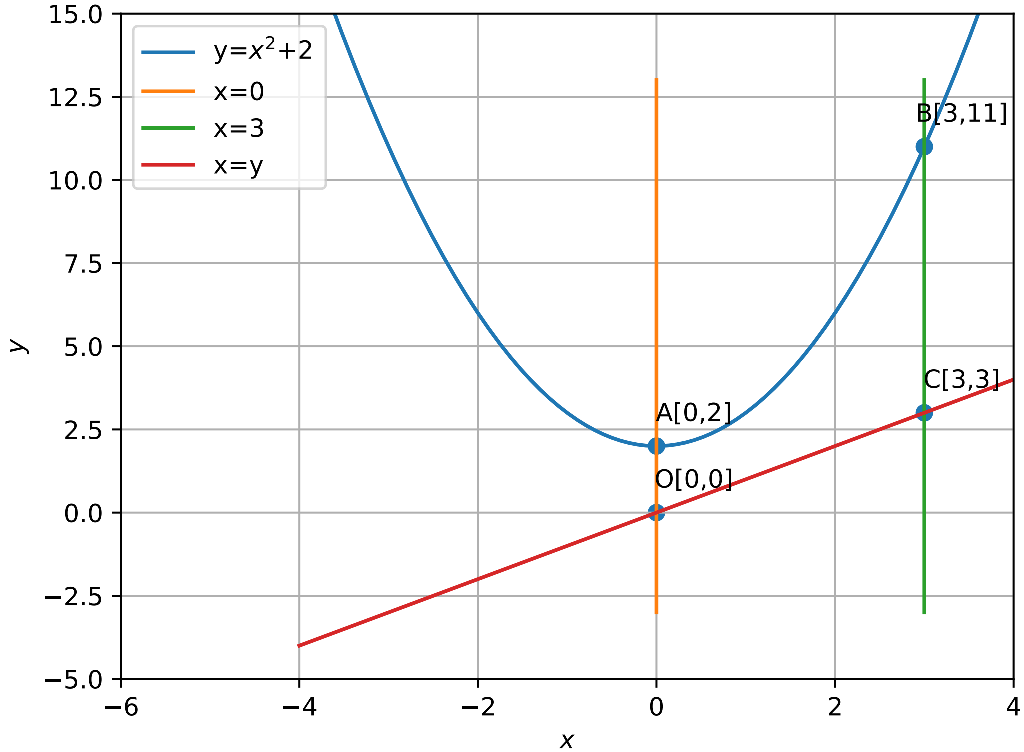


Figure 8.2.3.1:

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -1/2 \end{pmatrix}, f = 2. \tag{8.2.3.1}$$

8.2.4

8.2.5

8.2.6 Find the smaller area enclosed by the circle $x^2 + y^2 = 4$ and the line $x + y = 2$.

Solution: The given circle can be expressed as conics with parameters,

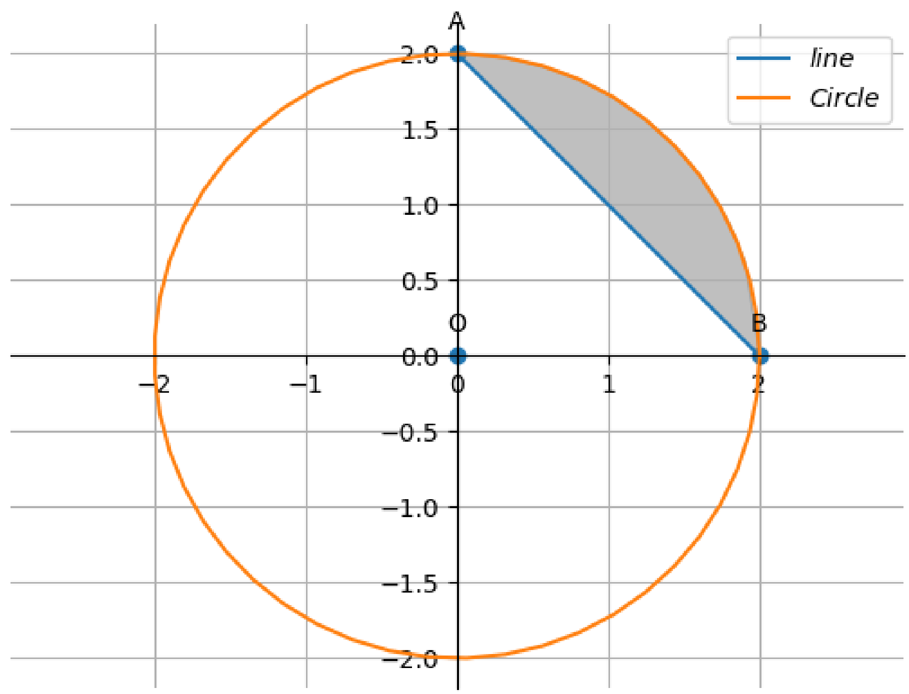


Figure 8.2.6.1:

$$\mathbf{V} = \begin{pmatrix} 4 & 0 \\ 0 & 4 \end{pmatrix}, \mathbf{u} = 0, f = -16 \tag{8.2.6.1}$$

The line parameters are

$$\mathbf{h} = \begin{pmatrix} 2 \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix} \tag{8.2.6.2}$$

Substituting the parameters in (F.3.1.3),

$$\mu = 0, -4 \tag{8.2.6.3}$$

yielding the points of intersection as

$$\mathbf{A} = \begin{pmatrix} 0 \\ 2 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 2 \\ 0 \end{pmatrix} \tag{8.2.6.4}$$

From Fig. 8.2.6.1, the desired area is

$$\int_0^2 \sqrt{4 - x^2}\, dx - \int_0^2 (2 - x)\, dx = \pi - 2 \tag{8.2.6.5}$$

8.2.7

8.3. Miscellaneous

8.3.1

8.3.2 Find the area between the curves $y = x$ and $y = x^2$.

Solution: The given curve can be expressed as a conic with parameters

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -\frac{1}{2} \end{pmatrix}, f = 0 \tag{8.3.2.1}$$

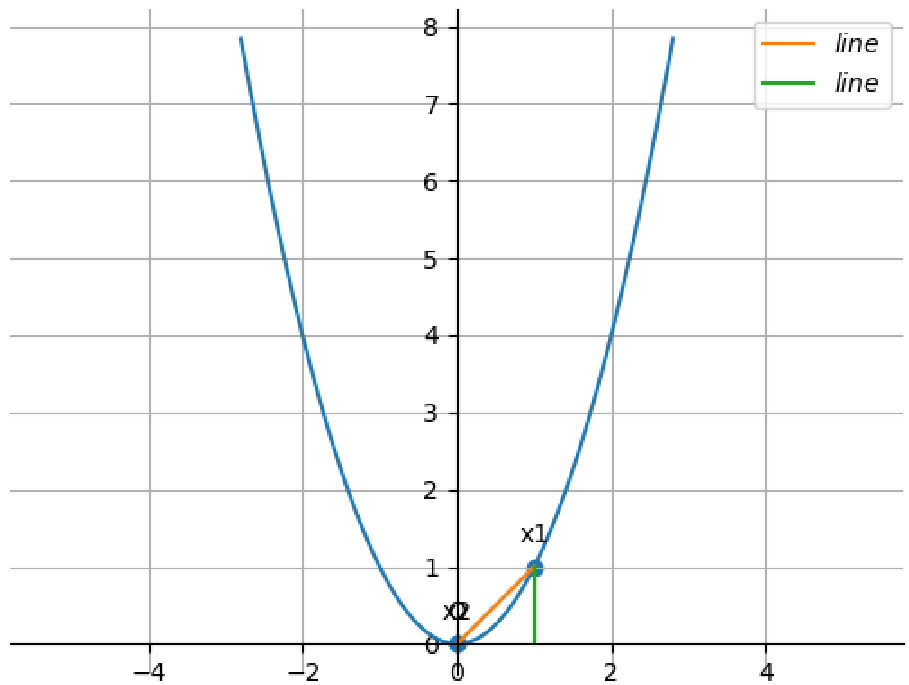


Figure 8.3.2.1:

The given line parameters are

$$\mathbf{h} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \tag{8.3.2.2}$$

Substituting the given parameters in (F.3.1.3),

$$\mathbf{x_1} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, \mathbf{x_2} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}. \tag{8.3.2.3}$$

From Fig. 8.3.2.1, the area bounded by the curve $y = x^2$ and line $y = x$ is given by

$$\int_0^1 \left(x - \frac{x^2}{2} \right) dx = \frac{1}{6} \tag{8.3.2.4}$$

8.3.3 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: The conic parameters are

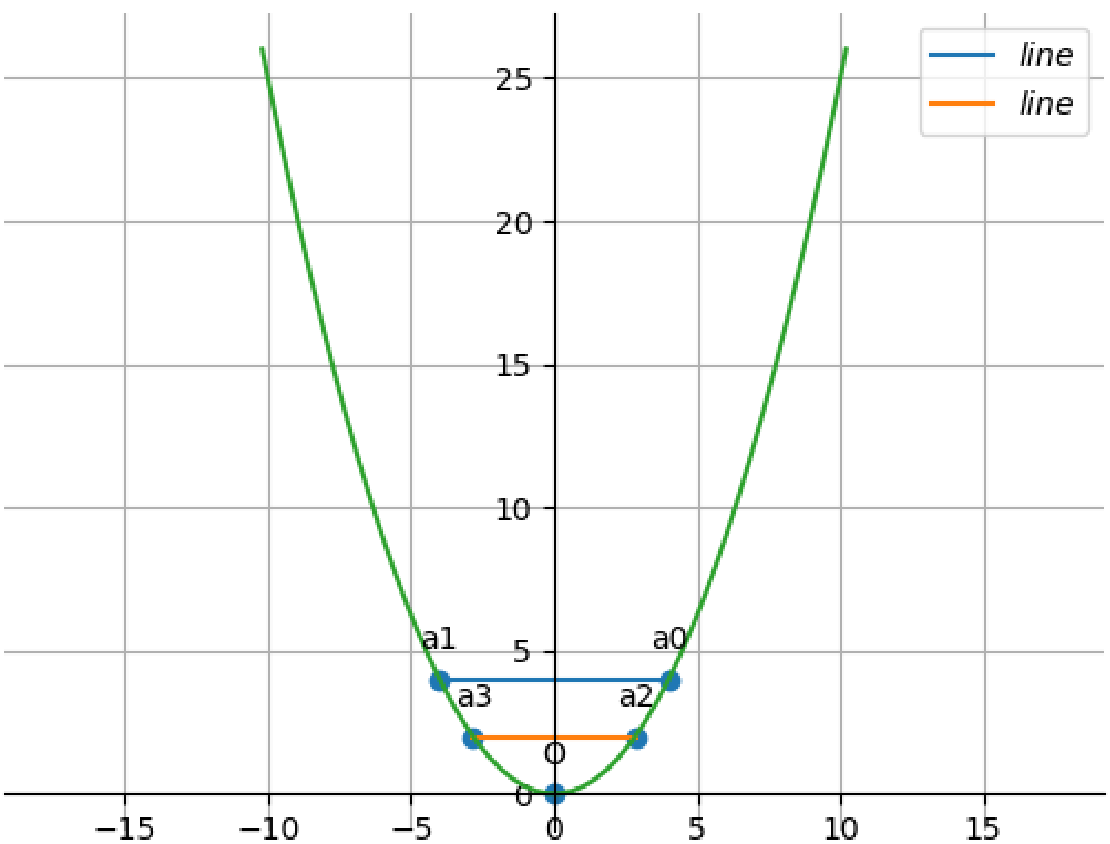


Figure 8.3.3.1:

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0 \tag{8.3.3.1}$$

The vector parameters of $y - 4 = 0$ are

$$\mathbf{h}_1 = \begin{pmatrix} 0 \\ 4 \end{pmatrix}, \mathbf{m}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{8.3.3.2}$$

Substituting the above in (F.3.1.3),

$$\mu_i = 4, -4 \tag{8.3.3.3}$$

yielding the points of intersection with the parabola as

$$\mathbf{a}_0 = \begin{pmatrix} 4 \\ 4 \end{pmatrix}, \mathbf{a}_1 = \begin{pmatrix} -4 \\ 4 \end{pmatrix} \tag{8.3.3.4}$$

Similarly, for the line $y - 2 = 0$, the vector parameters are

$$\mathbf{h}_2 = \begin{pmatrix} 0 \\ 2 \end{pmatrix}, \mathbf{m}_2 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{8.3.3.5}$$

yielding

$$\mu_i = 2.8, -2.8 \tag{8.3.3.6}$$

and the points of intersection

$$\mathbf{a}_2 = \begin{pmatrix} 2.8 \\ 2 \end{pmatrix}, \mathbf{a}_3 = \begin{pmatrix} -2.8 \\ 2 \end{pmatrix} \tag{8.3.3.7}$$

From Fig. 8.3.3.1, the area of the parabola between the lines $y = 2$ and $y = 4$ is given by

$$\int_0^4 2\sqrt{y}\, dy - \int_0^2 2\sqrt{y}\, dy = 6.895 \tag{8.3.3.8}$$

8.3.4

8.3.5

8.3.6

8.3.7 Find the area enclosed by the parabola $4y = 3x^2$ and the line $2y = 3x + 12$.

Solution: The parameters of the given conic are

$$\mathbf{V} = \begin{pmatrix} 3 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0. \tag{8.3.7.1}$$

For the line, the parameters are

$$\mathbf{h} = \begin{pmatrix} -2 \\ 3 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} 2 \\ 3 \end{pmatrix} \tag{8.3.7.2}$$

yielding

$$\mu = -2.5, 2.7 \tag{8.3.7.3}$$

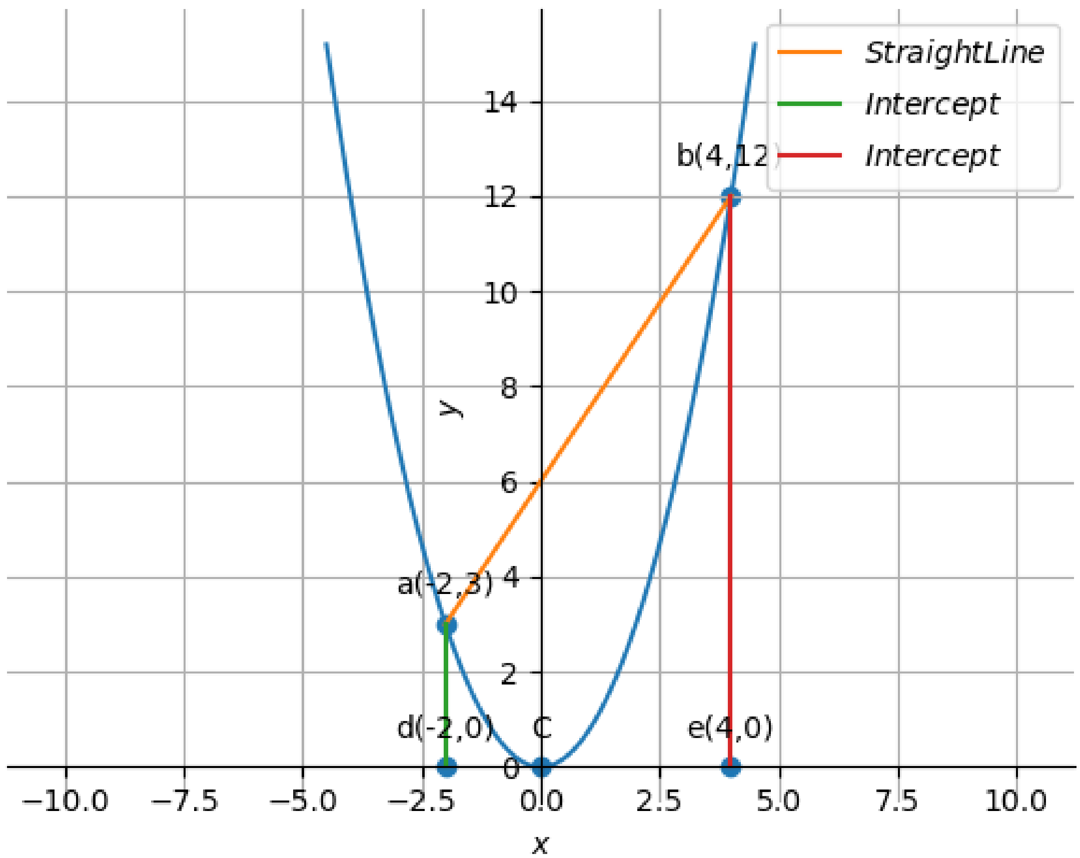


Figure 8.3.7.1:

upon substitution in (F.3.1.3) resulting in the points of intersection

$$\mathbf{A} = \begin{pmatrix} -2 \\ 3 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 4 \\ 12 \end{pmatrix}. \tag{8.3.7.4}$$

From Fig. 8.3.7.1, the desired area is

$$\int_{-2}^{4} \frac{3x+12}{2}\,dx - \int_{-2}^{4} \frac{3x^2}{4}\,dx = 27 \tag{8.3.7.5}$$

8.3.8 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: The given ellipse can be expressed as conics with parameters

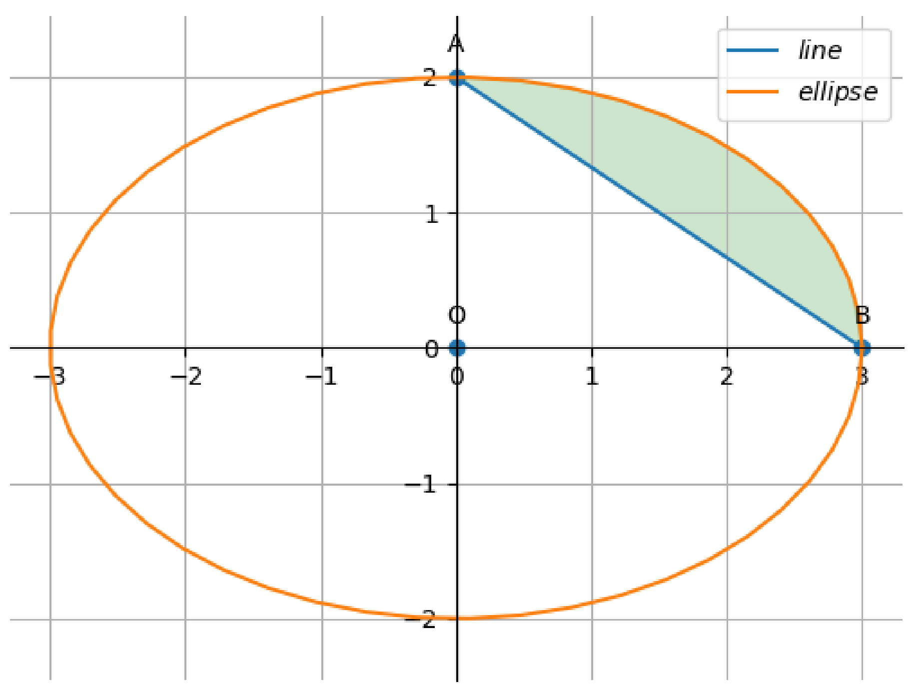


Figure 8.3.8.1:

$$\mathbf{V} = \begin{pmatrix} b^2 & 0 \\ 0 & a^2 \end{pmatrix}, \mathbf{u} = 0, f = -(a^2b^2). \tag{8.3.8.1}$$

The line parameters are

$$\mathbf{h} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} \frac{1}{b} \\ -\frac{1}{a} \end{pmatrix}. \tag{8.3.8.2}$$

Substituting the given parameters in (F.3.1.3),

$$\mu = 0, -6 \tag{8.3.8.3}$$

yielding the points of intersection

$$\mathbf{A} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 0 \\ b \end{pmatrix}. \tag{8.3.8.4}$$

From Fig. 8.3.8.1, the desired area is

$$\int_0^3 \frac{2}{3}\sqrt{9-x^2}\,dx - \int_0^3 \frac{2}{3}(3-x)\,dx = 3\left(\frac{\pi}{2} - 1\right) \tag{8.3.8.5}$$

8.3.9 Find the area of the smaller region bounded by the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$ and the line $\frac{x}{a} + \frac{y}{b} = 1$.

Solution: The given ellipse can be expressed as a conic with parameters

$$\mathbf{V} = \begin{pmatrix} b^2 & 0 \\ 0 & a^2 \end{pmatrix}, \mathbf{u} = 0, f = -(a^2b^2). \tag{8.3.9.1}$$

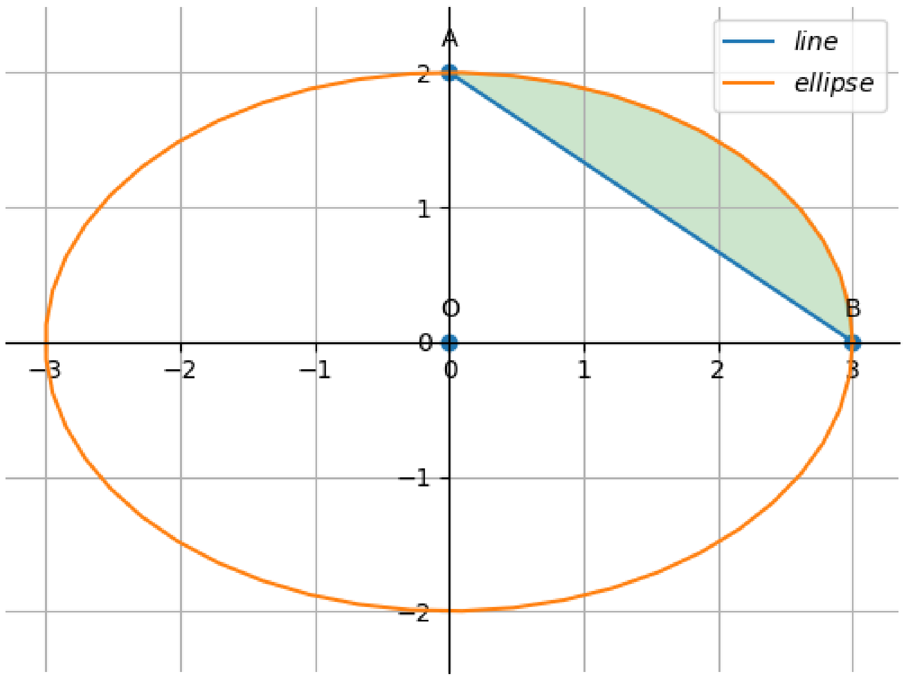


Figure 8.3.9.1:

The given line parameters are

$$\mathbf{h} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{m} = \begin{pmatrix} \frac{1}{b} \\ -\frac{1}{a} \end{pmatrix}. \tag{8.3.9.2}$$

Substituting the given parameters in (F.3.1.3)

$$\mu = 0, -6 \tag{8.3.9.3}$$

yielding the points of intersection

$$\mathbf{A} = \begin{pmatrix} a \\ 0 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} 0 \\ b \end{pmatrix} \tag{8.3.9.4}$$

From Fig. 8.3.9.1, the desired area is

$$\int_0^a \frac{b}{a}\sqrt{a^2 - x^2}\, dx - \int_0^a \frac{b}{a}(a - x)\, dx = \frac{ab}{2}\left(\frac{\pi}{2} - 1\right) \tag{8.3.9.5}$$

8.3.10 Find the area of the region bounded by the curve $x^2 = y$ and the lines $y = x + 2$ and the x axis.

Solution:

8.3.11 Find the area bounded by the curve $y = x|x|$, x-axis and the ordinates x=-1 and x=1.

Solution: The parameters of the given conics are

$$\mathbf{V}_1 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u_1} = \begin{pmatrix} 0 \\ -\frac{1}{2} \end{pmatrix}, f_1 = 0 \tag{8.3.11.1}$$

$$\mathbf{V}_2 = \begin{pmatrix} -1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u_2} = \begin{pmatrix} 0 \\ -\frac{1}{2} \end{pmatrix}, f_2 = 0 \tag{8.3.11.2}$$

The determinant equation for the intersection of two conics is

$$\begin{vmatrix} 1 - \mu & 0 & 0 \\ 0 & 0 & -\frac{1}{2} - \frac{\mu}{2} \\ 0 & -\frac{1}{2} - \frac{\mu}{2} & 0 \end{vmatrix} = 0 \tag{8.3.11.3}$$

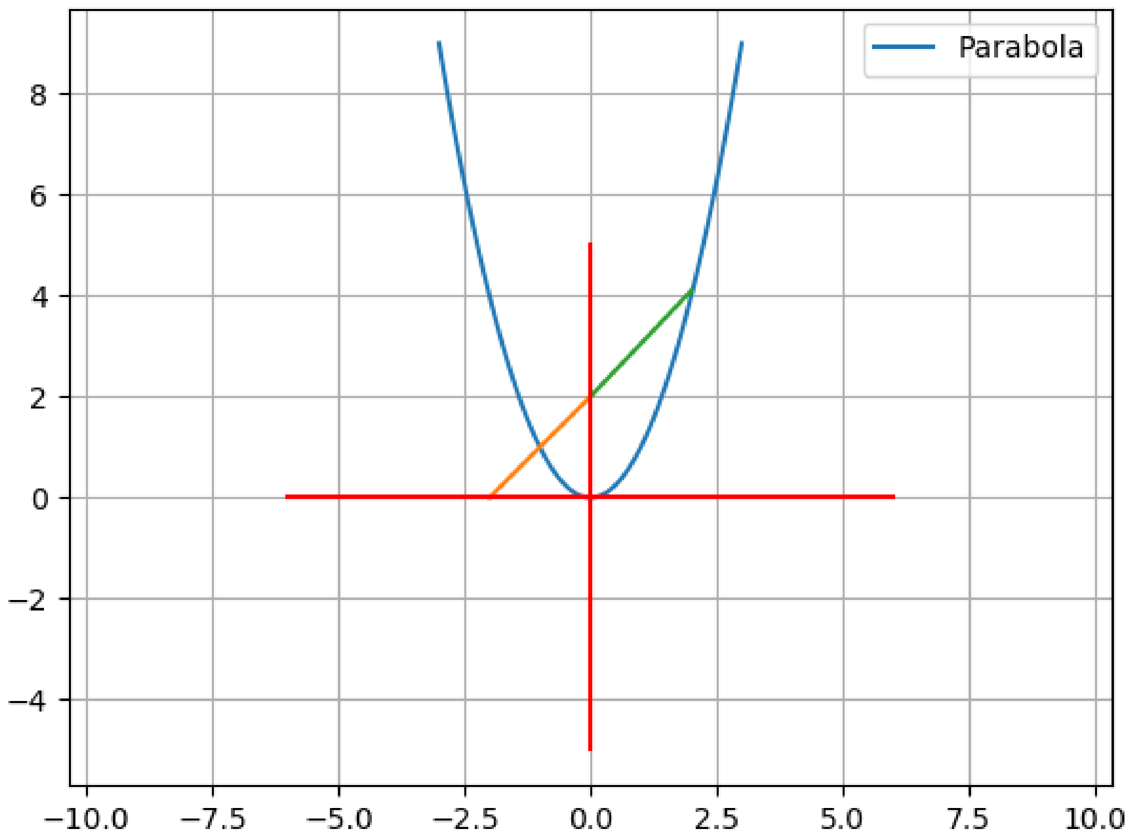


Figure 8.3.10.1:

yielding,

$$\mu^3 + \mu^2 - \mu - 1 = 0 \tag{8.3.11.4}$$

$$\implies \mu = -1, 1, 1 \tag{8.3.11.5}$$

8.3.12 Find the area of the circle $x^2 + y^2 = 16$ exterior to the parabola $y^2 = 6x$.

Solution: The given circle and parabola can be expressed as conics with respectivepa-

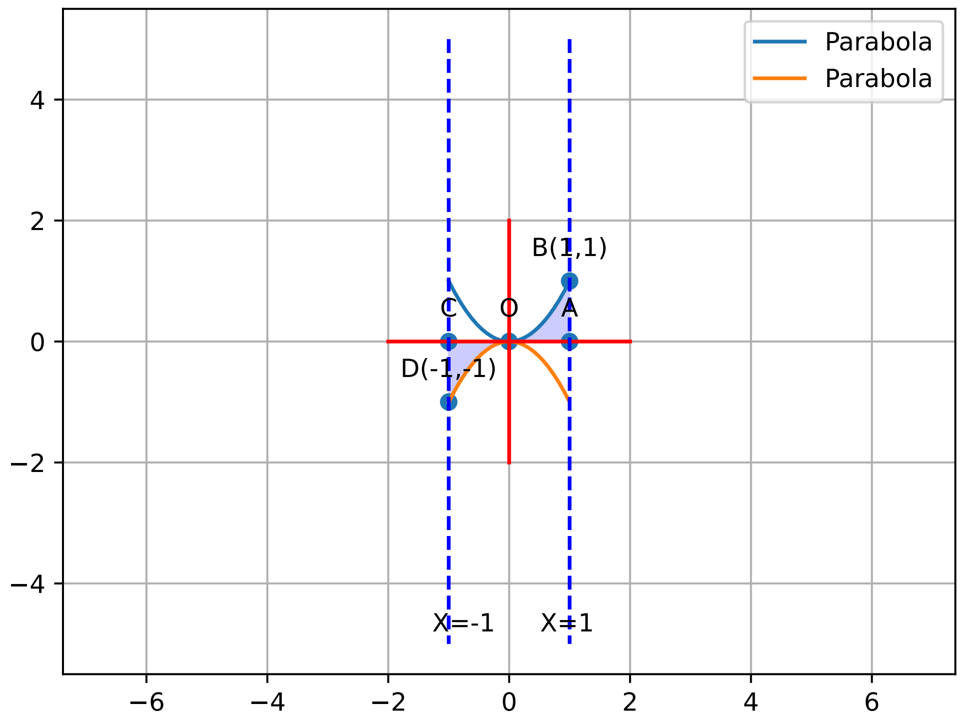


Figure 8.3.11.1:

rameters

$$\mathbf{V}_1 = \mathbf{I}, \mathbf{u_1} = 0, f_1 = -16, \tag{8.3.12.1}$$

$$\mathbf{V}_2 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u_2} = -\begin{pmatrix} 3 \\ 0 \end{pmatrix}, f_2 = 0 \tag{8.3.12.2}$$

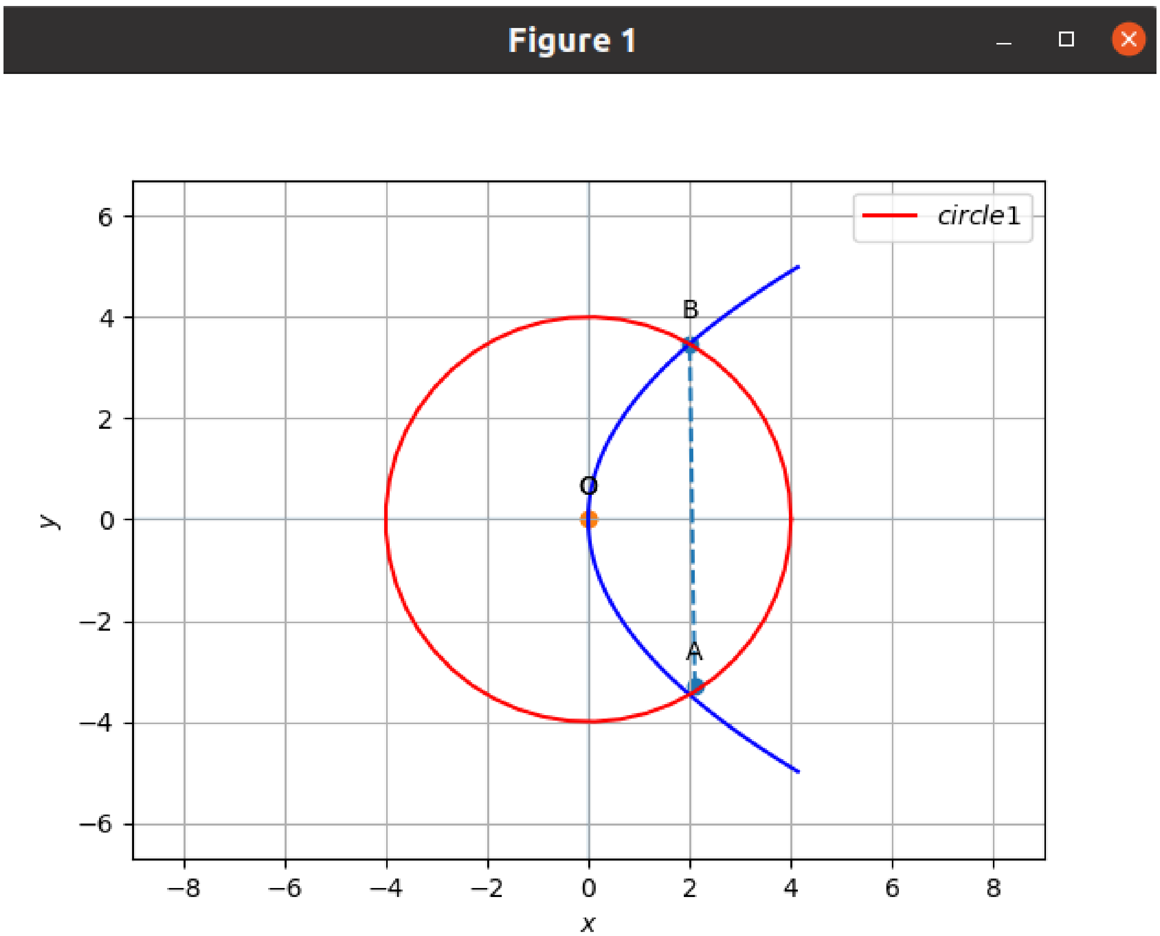


Figure 8.3.12.1:

The determinant of the intersection of the given conics is

$$\implies \begin{vmatrix} 1 & 0 & -3\mu \\ 0 & 1+\mu & 0 \\ -3\mu & 0 & -16 \end{vmatrix} = 0 \tag{8.3.12.3}$$

yielding

$$9\mu^3 + 9\mu^2 + 16\mu + 16 = 0 \tag{8.3.12.4}$$

$$\text{or, } \mu = -1 \tag{8.3.12.5}$$

Chapter 9

Tangent And Normal

9.1. Properties

9.1.1 Find the slope of the tangent to the curve

$$y = \frac{x-1}{x-2}, x \neq 2 \text{ at } x = 10. \tag{9.1.1.1}$$

9.1.2 Find a point on the curve

$$y = (x-2)^2 \tag{9.1.2.1}$$

at which a tangent is parallel to the chord joining the points (2,0) and (4,4).

Solution: The equation of the conic can be represented as

$$\mathbf{x}^\top \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{x} + 2 \begin{pmatrix} -2 & \frac{-1}{2} \end{pmatrix} \mathbf{x} + 4 = 0 \tag{9.1.2.2}$$

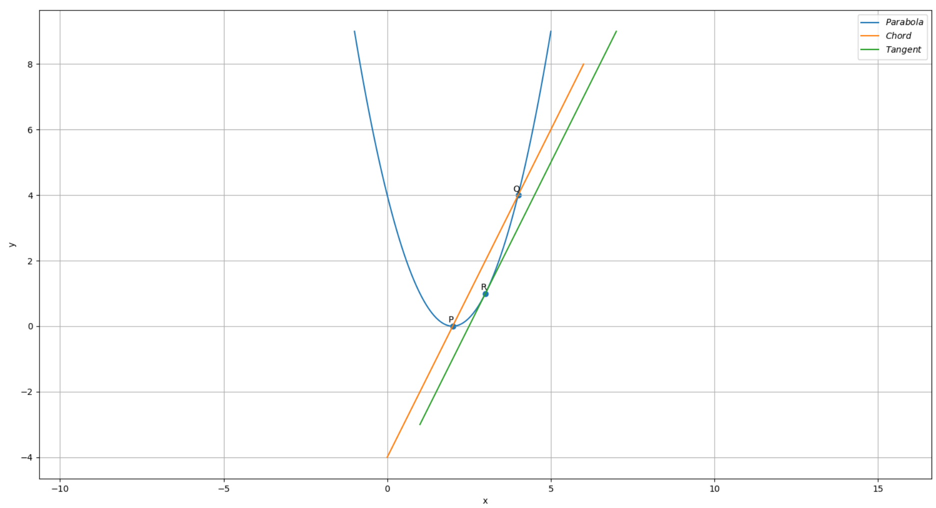


Figure 9.1.2.1:

So,

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u}^\top = \begin{pmatrix} -2 & \frac{-1}{2} \end{pmatrix}, f = 4 \tag{9.1.2.3}$$

The direction vector of the line passing through (2,0) and (4,4) is

$$\mathbf{m} = \begin{pmatrix} 1 \\ 2 \end{pmatrix} \implies \mathbf{n} = \begin{pmatrix} 2 \\ -1 \end{pmatrix}. \tag{9.1.2.4}$$

From (F.4.7.1), the point of contact to parabola is given by

$$\begin{pmatrix} (\mathbf{u} + \kappa\mathbf{n})^{\top} \\ \mathbf{V} \end{pmatrix} \mathbf{q} = \begin{pmatrix} -f \\ \kappa\mathbf{n} - \mathbf{u} \end{pmatrix} \tag{9.1.2.5}$$

$$\text{where } \kappa = \frac{\mathbf{p}_1^{\top}\mathbf{u}}{\mathbf{p}_1^{\top}\mathbf{n}}, \quad \mathbf{V}\mathbf{p}_1 = 0 \tag{9.1.2.6}$$

The eigenvector corresponding to the zero eigenvalue is

$$\mathbf{p}_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \tag{9.1.2.7}$$

from which,

$$\kappa = \frac{\begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} -2 \\ \frac{-1}{2} \end{pmatrix}}{\begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} 2 \\ -1 \end{pmatrix}} \tag{9.1.2.8}$$

$$= \frac{1}{2} \tag{9.1.2.9}$$

Substituting κ in (9.1.2.5),

$$\begin{pmatrix} \left[\begin{pmatrix} -2 \\ \frac{-1}{2} \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 2 \\ -1 \end{pmatrix}\right]^\top \\ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \mathbf{q} = \begin{pmatrix} -4 \\ \frac{1}{2}\begin{pmatrix} 2 \\ -1 \end{pmatrix} - \begin{pmatrix} -2 \\ \frac{-1}{2} \end{pmatrix} \end{pmatrix} \tag{9.1.2.10}$$

$$\implies \begin{pmatrix} -1 & -1 \\ 1 & 0 \\ 0 & 0 \end{pmatrix} \mathbf{q} = \begin{pmatrix} -4 \\ 3 \\ 0 \end{pmatrix} \tag{9.1.2.11}$$

As the last row elements are all zero, we can eliminate that row

$$\begin{pmatrix} -1 & -1 \\ 1 & 0 \end{pmatrix} \mathbf{q} = \begin{pmatrix} -4 \\ 3 \end{pmatrix} \tag{9.1.2.12}$$

For applying row reduction method the augmented matrix is written as

$$\left(\begin{array}{cc|c} -1 & -1 & -4 \\ 1 & 0 & 3 \end{array}\right) \tag{9.1.2.13}$$

$$\xleftrightarrow{R_1 \leftarrow R_1 + 2R_2} \left(\begin{array}{cc|c} 1 & -1 & 2 \\ 1 & 0 & 3 \end{array}\right) \tag{9.1.2.14}$$

$$\xleftrightarrow{R_2 \leftarrow R_2 - R_1} \left(\begin{array}{cc|c} 1 & -1 & 2 \\ 0 & 1 & 1 \end{array}\right) \tag{9.1.2.15}$$

$$\xleftrightarrow{R_1 \leftarrow R_1 + R_2} \left(\begin{array}{cc|c} 1 & 0 & 3 \\ 0 & 1 & 1 \end{array}\right) \tag{9.1.2.16}$$

$$\implies \mathbf{q} = \begin{pmatrix} 3 \\ 1 \end{pmatrix} \tag{9.1.2.17}$$

which is the desired point of contact. See Fig. 9.1.2.1.

9.1.3 Find the equation of all lines having slope -1 that are tangents to the curve

$$y = \frac{1}{x-1}, x \neq 1 \tag{9.1.3.1}$$

Solution: From the given information,

$$\mathbf{V} = \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -\frac{1}{2} \end{pmatrix}, f = -1, m = -1 \tag{9.1.3.2}$$

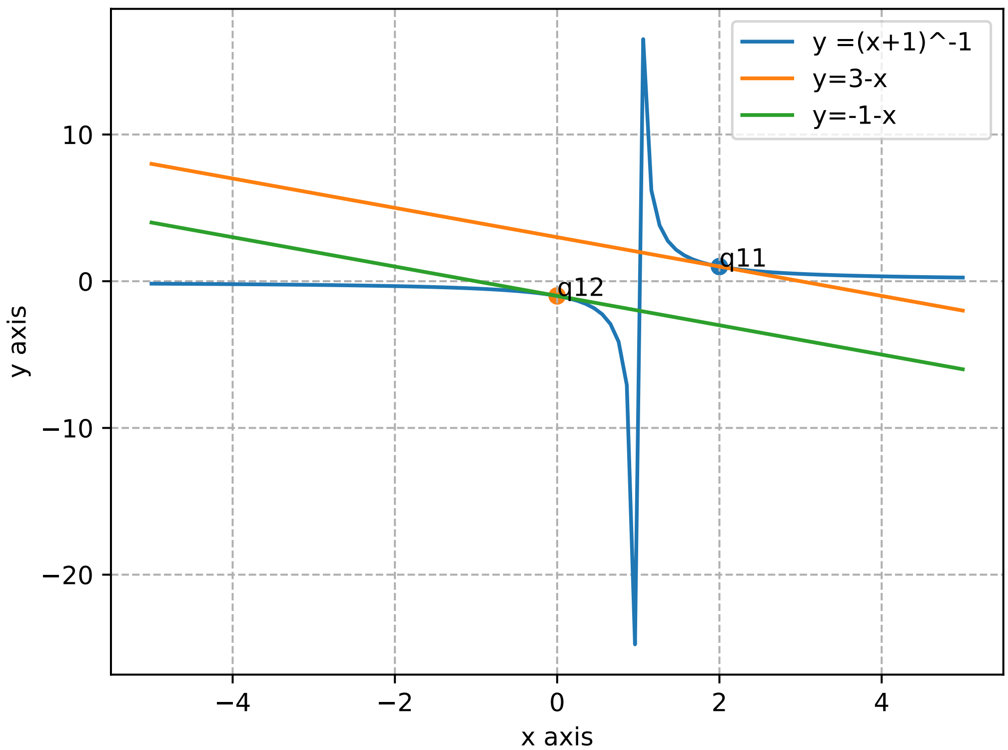


Figure 9.1.3.1:

From the above, the normal vector is

$$\mathbf{n} = \begin{pmatrix} -m \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 1 \end{pmatrix} \tag{9.1.3.3}$$

From (F.4.4.1), the point(s) of contact are given by

$$\mathbf{q} = \mathbf{V}^{-1}(k_i\mathbf{n} - \mathbf{u}) \text{ where,} \tag{9.1.3.4}$$

$$k_i = \pm\sqrt{\frac{f_0}{\mathbf{n}^\top\mathbf{V}^{-1}\mathbf{n}}} \tag{9.1.3.5}$$

$$f_0 = f + \mathbf{u}^\top\mathbf{V}^{-1}\mathbf{u} \tag{9.1.3.6}$$

Substituting from (9.1.3.3) and (9.1.3.2) in the above,

$$\mathbf{q} = \begin{pmatrix} 0 \\ -1 \end{pmatrix}, \begin{pmatrix} 2 \\ 1 \end{pmatrix}. \tag{9.1.3.7}$$

From (F.4.1.1), the equations of tangents are given by

$$(\mathbf{Vq} + \mathbf{u})^\top\mathbf{x} + \mathbf{u}^\top\mathbf{q} + f = 0 \tag{9.1.3.8}$$

yielding

$$\begin{pmatrix} 1 & 1 \end{pmatrix}\mathbf{x} + 1 = 0 \tag{9.1.3.9}$$

$$\begin{pmatrix} 1 & 1 \end{pmatrix}\mathbf{x} - 3 = 0 \tag{9.1.3.10}$$

$$\tag{9.1.3.11}$$

See Fig. 9.1.3.1.

9.1.4 Find the equation of all lines having slope 2 which are tangents to the curve

$$y = \frac{1}{x-3}, x \neq 3 \tag{9.1.4.1}$$

Solution: From the given information

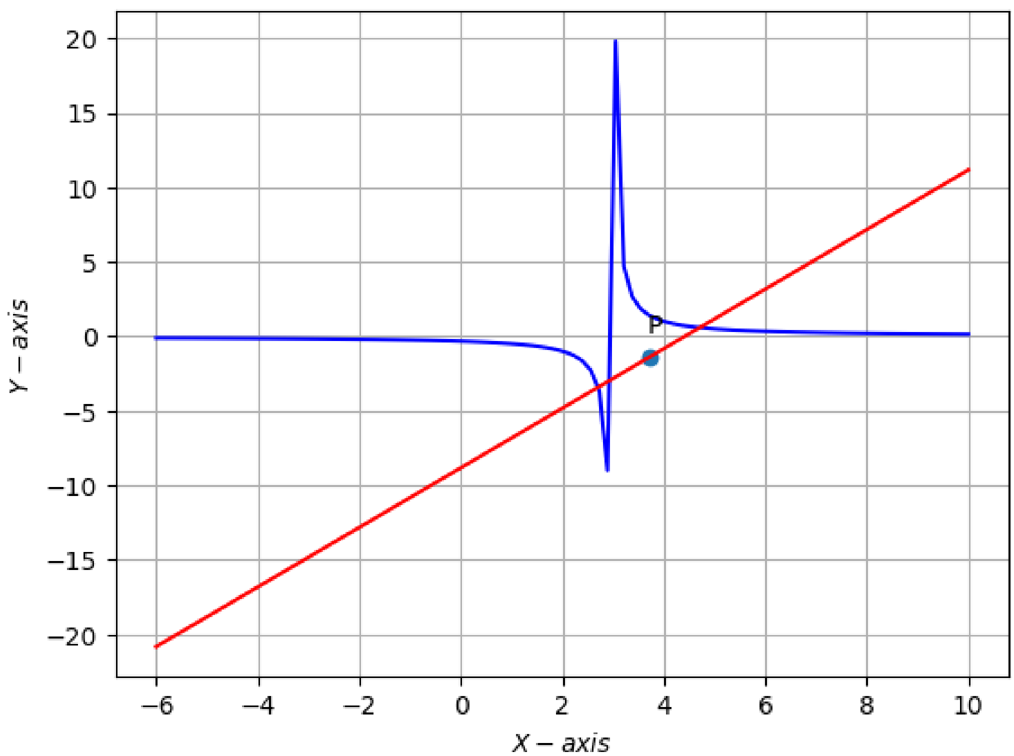


Figure 9.1.4.1:

$$\mathbf{V} = \begin{pmatrix} 0 & \frac{1}{2} \\ \frac{1}{2} & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -\frac{3}{2} \end{pmatrix}, f = -1, m = 2 \tag{9.1.4.2}$$

$$\implies \mathbf{n} = \begin{pmatrix} -m \\ 1 \end{pmatrix} = \begin{pmatrix} -2 \\ 1 \end{pmatrix} \tag{9.1.4.3}$$

$$\tag{9.1.4.4}$$

Hence, the given curve is a hyperbola. Substituting numerical values, we obtain the condition in (F.4.5), which implies that the line with slope 2 is not a tangent. This can be verified from Fig. 9.1.4.1.

9.1.5 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: The parameters of the given conic are

$$\lambda_1 = 16, \lambda_2 = 9 \tag{9.1.5.1}$$

$$\mathbf{V} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}, f = -144 \tag{9.1.5.2}$$

(a) The normal vector in this case is

$$\mathbf{n_1} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} \tag{9.1.5.3}$$

which can be used along with the parameters in (9.1.5.2) to obtain

$$\mathbf{q_1} = \begin{pmatrix} 0 \\ 4 \end{pmatrix}, \mathbf{q_2} = \begin{pmatrix} 0 \\ -4 \end{pmatrix} \tag{9.1.5.4}$$

using (F.4.4.1).

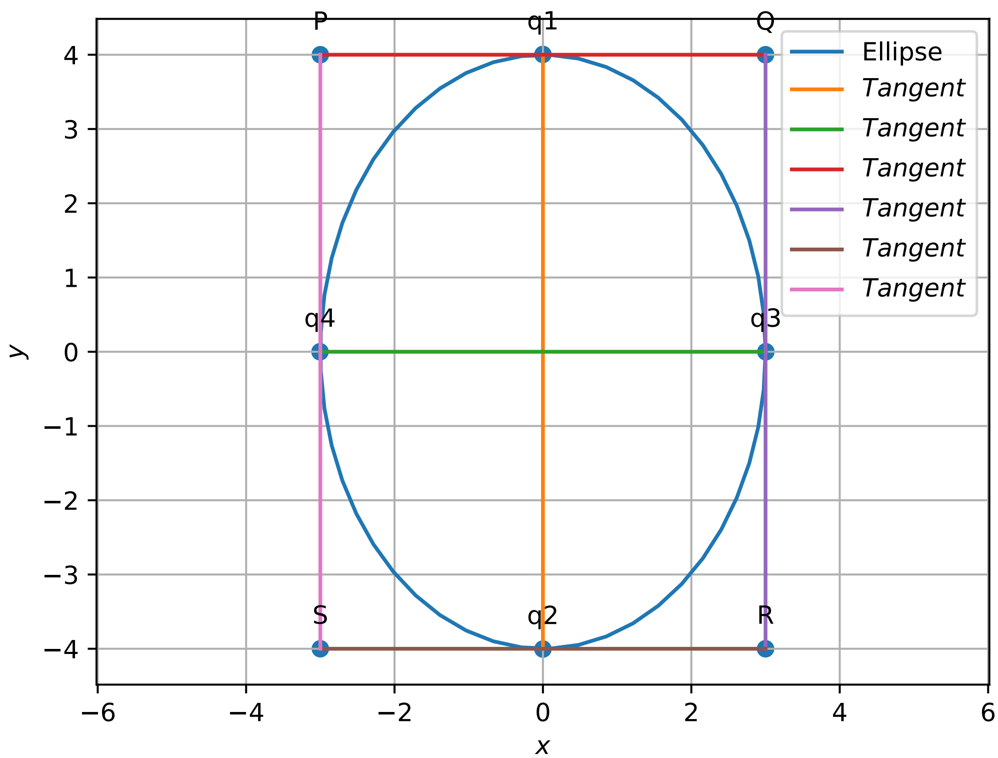


Figure 9.1.5.1:

(b) Simlarly, choosing

$$\mathbf{n_2} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \tag{9.1.5.5}$$

$$\mathbf{q_3} = \begin{pmatrix} 3 \\ 0 \end{pmatrix}, \mathbf{q_4} = \begin{pmatrix} -3 \\ 0 \end{pmatrix} \tag{9.1.5.6}$$

9.1.6 Find the equation of the tangent line to the curve

$$y = x^2 - 2x + 7 \tag{9.1.6.1}$$

(a) parallel to the line $2x - y + 9 = 0$.

(b) perpendicular to the line $5y - 15x = 13$.

Solution: The parameters of the given conic are

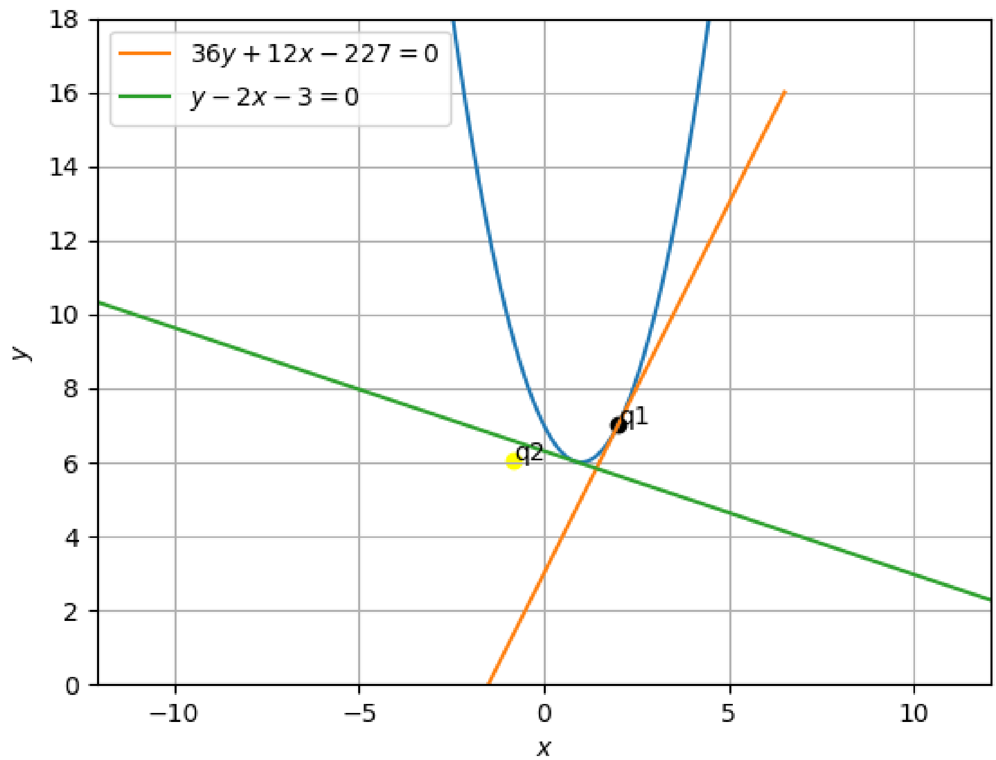


Figure 9.1.6.1:

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = -\begin{pmatrix} 1 \\ \frac{1}{2} \end{pmatrix}, f = 7 \tag{9.1.6.2}$$

(a) In this case, the normal vector

$$\mathbf{n}_1 = \begin{pmatrix} 2 \\ -1 \end{pmatrix} \tag{9.1.6.3}$$

Since $\mathbf{V}$ is not invertible, the point of contact is given by (F.4.7.1) resulting in

$$\begin{pmatrix} \left(\begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} + \frac{1}{2}\begin{pmatrix} 2 \\ -1 \end{pmatrix}\right)^\top \\ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \mathbf{q}_1 = \begin{pmatrix} -7 \\ \frac{1}{2}\begin{pmatrix} 2 \\ -1 \end{pmatrix} - \begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} \end{pmatrix} \tag{9.1.6.4}$$

By solving the above equation, we can get the point of contact as

$$\mathbf{q}_1 = \begin{pmatrix} 2 \\ 7 \end{pmatrix} \tag{9.1.6.5}$$

The tangent equation is then obtained as

$$\mathbf{n}_1^\top (\mathbf{x} - \mathbf{q}_1) = 0 \tag{9.1.6.6}$$

$$\implies \begin{pmatrix} 2 & -1 \end{pmatrix} \mathbf{x} + 3 = 0 \tag{9.1.6.7}$$

(b) In this case,

$$\mathbf{n}_2 = \begin{pmatrix} 1 \\ 3 \end{pmatrix} \tag{9.1.6.8}$$

resulting in

$$\begin{pmatrix} \left(\begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} + -\frac{1}{6}\begin{pmatrix} 1 \\ 3 \end{pmatrix}\right)^\top \\ \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \end{pmatrix} \mathbf{q}_2 = \begin{pmatrix} -7 \\ -\frac{1}{6}\begin{pmatrix} 1 \\ 3 \end{pmatrix} - \begin{pmatrix} -1 \\ -\frac{1}{2} \end{pmatrix} \end{pmatrix} \tag{9.1.6.9}$$

$$\text{or, } \mathbf{q}_2 = \begin{pmatrix} \frac{5}{6} \\ \frac{217}{36} \end{pmatrix} \tag{9.1.6.10}$$

The tangent equation is

$$\mathbf{n}_2^\top (\mathbf{x} - \mathbf{q}_2) = 0 \tag{9.1.6.11}$$

$$\text{or, } \begin{pmatrix} 1 & 3 \end{pmatrix} \mathbf{x} = \frac{227}{12} \tag{9.1.6.12}$$

9.1.7

9.1.8 Find the equation of the tangent to the curve

$$y = \sqrt{3x - 2} \tag{9.1.8.1}$$

which is parallel to the line

$$4x - 2y + 5 = 0 \tag{9.1.8.2}$$

Solution: The parameters for the given conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \tag{9.1.8.3}$$

$$\mathbf{u} = \begin{pmatrix} -3/2 \\ 0 \end{pmatrix}, \tag{9.1.8.4}$$

$$f = 2 \tag{9.1.8.5}$$

which represent a parabola. Following the approach in problem 9.1.6,

$$\mathbf{p_1} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \tag{9.1.8.6}$$

$$\mathbf{n} = \begin{pmatrix} -2 \\ 1 \end{pmatrix}, \tag{9.1.8.7}$$

yielding the matrix equation

$$\begin{pmatrix} -3 & 0 \\ 0 & 0 \\ 0 & 1 \end{pmatrix} \mathbf{q} = \begin{pmatrix} -41/16 \\ 0 \\ 3/4 \end{pmatrix} \tag{9.1.8.8}$$

(9.1.8.9)

The augmented matrix for (9.1.8.8) can be expressed as

$$\xleftrightarrow{R_2 \leftrightarrow R_3} \left(\begin{array}{cc|c} -3 & 0 & -41/16 \\ 0 & 1 & 0 \\ 0 & 0 & 3/4 \end{array}\right) \tag{9.1.8.10}$$

$$\xleftrightarrow{-\frac{R_1}{-3} \leftarrow R_2} \left(\begin{array}{cc|c} 1 & 0 & 41/48 \\ 0 & 1 & 0 \\ 0 & 0 & 3/4 \end{array}\right) \tag{9.1.8.11}$$

$$\implies \mathbf{q} = \begin{pmatrix} \frac{41}{48} \\ \frac{3}{4} \end{pmatrix} \tag{9.1.8.12}$$

The equation of tangent is then obtained as

$$\begin{pmatrix} -2 & 1 \end{pmatrix} \mathbf{x} + \frac{23}{24} = 0 \tag{9.1.8.13}$$

See Fig. 9.1.8.1.

9.1.9 Find the point at which the line $y = x + 1$ is a tangent to the curve $y^2 = 4x$.

Solution: The parameters of the conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} -2 & 0 \end{pmatrix}, f = 0 \tag{9.1.9.1}$$

Following the approach in Problem 9.1.6, since

$$\mathbf{n} = \begin{pmatrix} 1 \\ -1 \end{pmatrix} \tag{9.1.9.2}$$

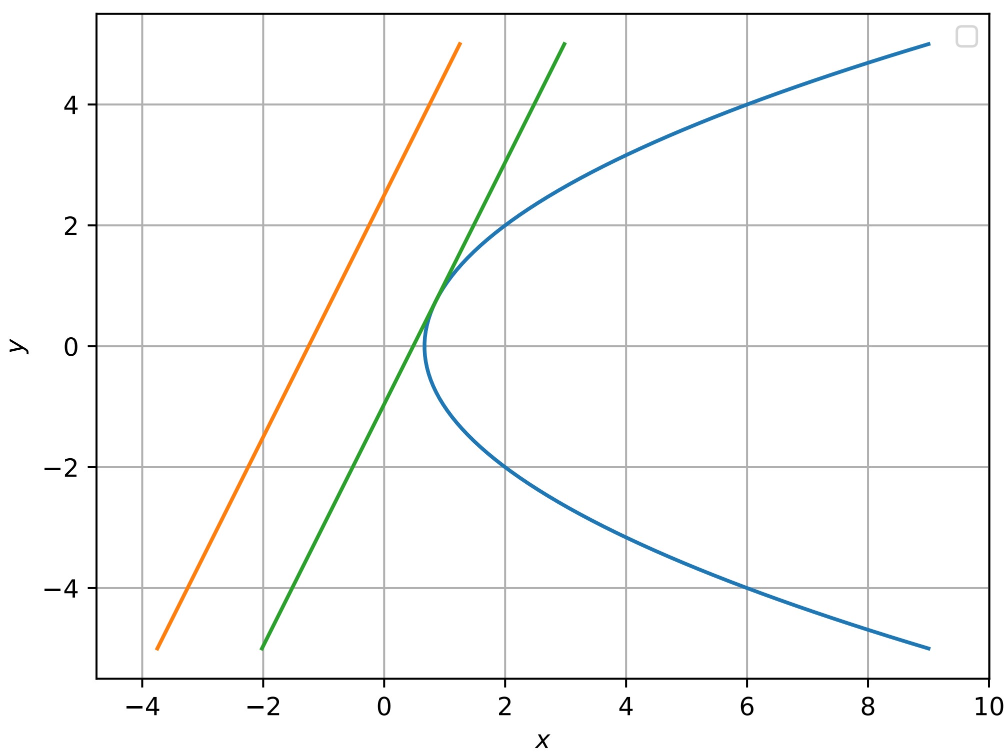


Figure 9.1.8.1:

we obtain

$$\mathbf{q} = \begin{pmatrix} 1 \\ 2 \end{pmatrix} \tag{9.1.9.3}$$

See Fig. 9.1.9.1,

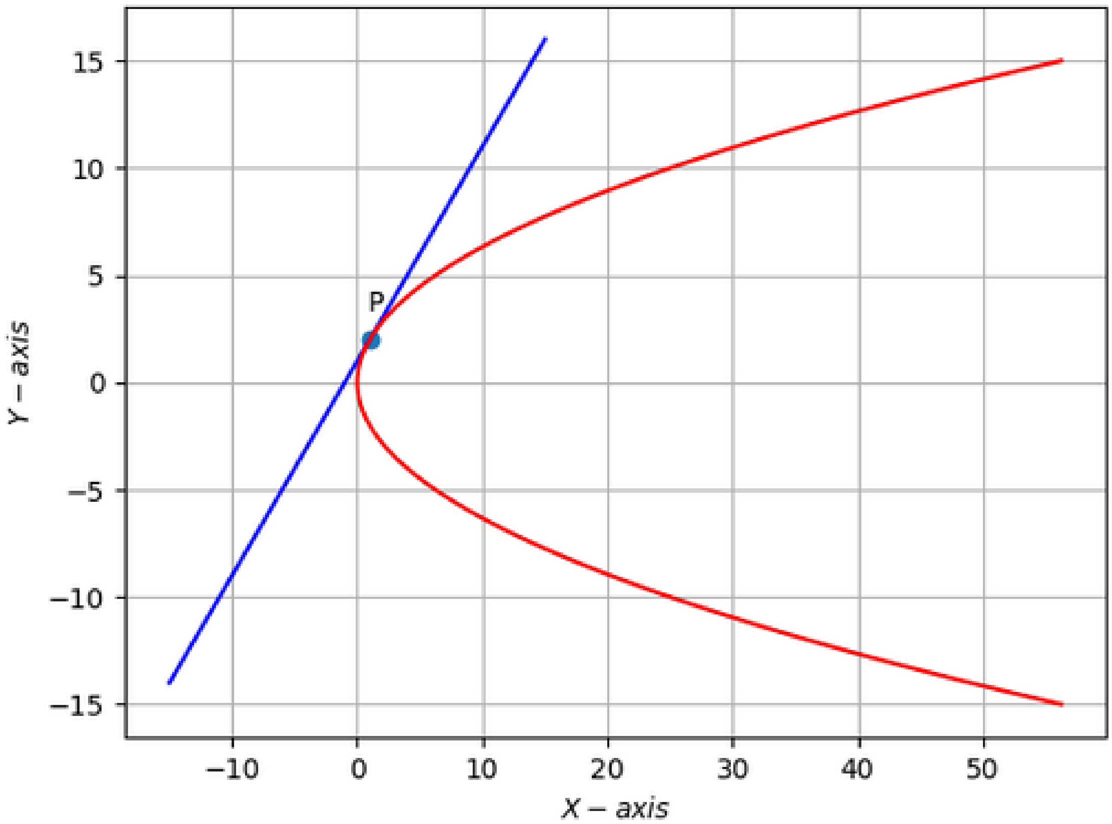


Figure 9.1.9.1:

9.2. Miscellaneous

9.2.1 Find the equation of the normal to curve $x^2 = 4y$ which passes through the point (1, 2).

Solution: The conic parameters are

$$\mathbf{V} = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} 0 \\ -2 \end{pmatrix}, f = 0 \tag{9.2.1.1}$$

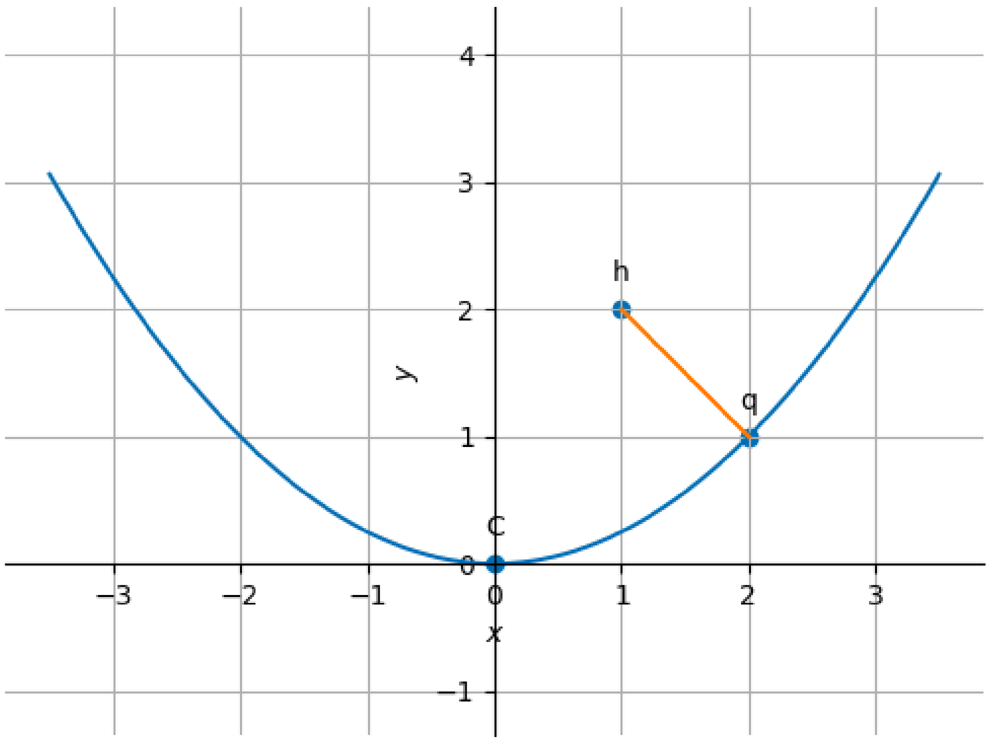


Figure 9.2.1.1:

Substituting these values in (F.4.10.1), we obtain

$$m = 1 \tag{9.2.1.2}$$

as the only real solution. Thus,

$$\mathbf{m} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \tag{9.2.1.3}$$

and the equation of the normal is then obtained as

$$\mathbf{m}^{\top}(\mathbf{x}-\mathbf{h}) = 0 \tag{9.2.1.4}$$

$$\implies \begin{pmatrix} 1 & 1 \end{pmatrix}\mathbf{x} = \begin{pmatrix} 1 & 1 \end{pmatrix}\begin{pmatrix} 1 \\ 2 \end{pmatrix} \tag{9.2.1.5}$$

$$= 3 \tag{9.2.1.6}$$

9.2.2 The line $y = mx + 1$ is a tangent to the curve $y^2 = 4x$, find the value of m.

Solution: The parameters for the given conic are

$$\mathbf{V} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}, \mathbf{u} = \begin{pmatrix} -2 \\ 0 \end{pmatrix}, f = 0 \tag{9.2.2.1}$$

The given tangent can be expressed in parametric form as

$$\mathbf{x} = \mathbf{e}_2 + \mu\mathbf{m} \tag{9.2.2.2}$$

Substituting from (9.2.2.2) and (9.2.2.1) in (F.4.8.1) and solving, we obtain

$$m = 1. \tag{9.2.2.3}$$

9.2.3 Find the normal at the point (1,1) on the curve

$$2y + x^2 = 3 \tag{9.2.3.1}$$

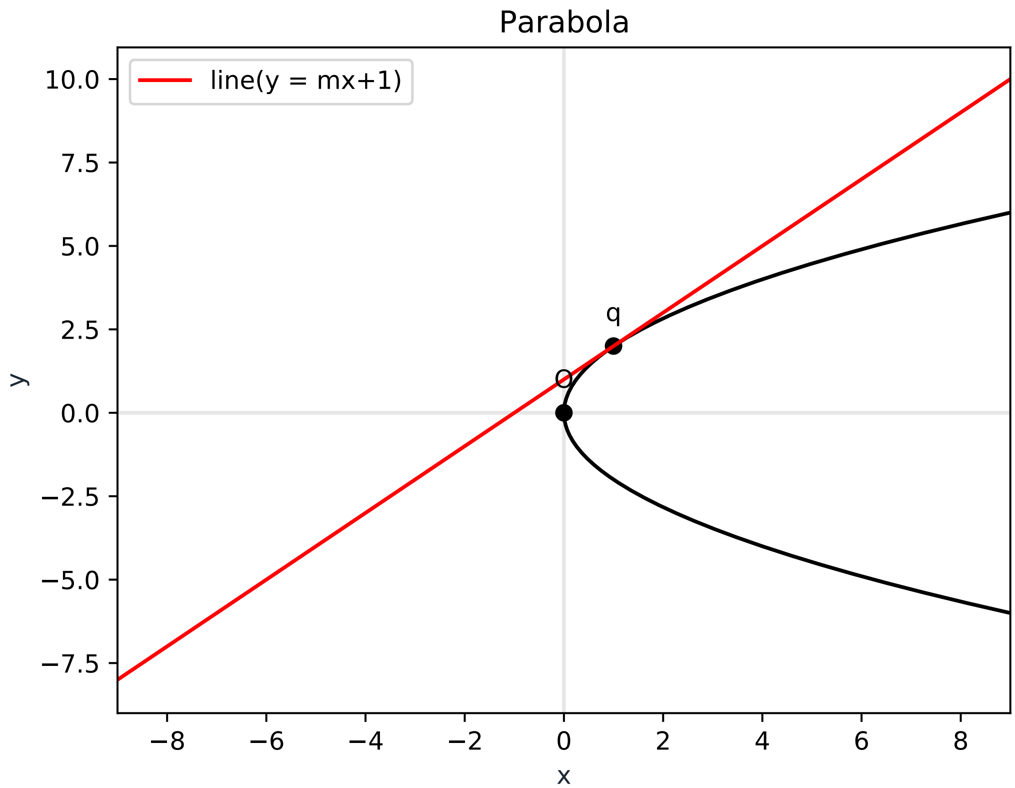


Figure 9.2.2.1:

Solution: Use (F.3.2.1) with

$$\mathbf{m} = \begin{pmatrix} 1 \\ m \end{pmatrix} \tag{9.2.3.2}$$

Appendix A

Vectors

A.1. 2×1 vectors

A.1.1. Let

$$\mathbf{A} \equiv \overrightarrow{A} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} \tag{A.1.1.1}$$

$$\equiv a_1 \overrightarrow{i} + a_2 \overrightarrow{j}, \tag{A.1.1.2}$$

$$\mathbf{B} = \begin{pmatrix} b_1 \\ b_2 \end{pmatrix}, \tag{A.1.1.3}$$

be 2×1 vectors. Then, the determinant of the 2×2 matrix

$$\mathbf{M} = \begin{pmatrix} \mathbf{A} & \mathbf{B} \end{pmatrix} \tag{A.1.1.4}$$

is defined as

$$\left|\mathbf{M}\right| = \left|\mathbf{A} \quad \mathbf{B}\right| \tag{A.1.1.5}$$

$$= \begin{vmatrix} a_1 & b_1 \\ a_2 & b_2 \end{vmatrix} = a_1 b_2 - a_2 b_1 \tag{A.1.1.6}$$

A.1.2. The value of the cross product of two vectors is given by (A.1.1.5).

A.1.3. The area of the triangle with vertices $\mathbf{A}, \mathbf{B}, \mathbf{C}$ is given by

$$\frac{1}{2} \left\|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{C})\right\| = \frac{1}{2} \left\|\mathbf{A} \times \mathbf{B} + \mathbf{B} \times \mathbf{C} + \mathbf{C} \times \mathbf{A}\right\| \tag{A.1.3.1}$$

A.1.4. If

$$\left\|\mathbf{A} \times \mathbf{B}\right\| = \left\|\mathbf{C} \times \mathbf{D}\right\|, \quad \text{then} \tag{A.1.4.1}$$

$$\mathbf{A} \times \mathbf{B} = \pm \left(\mathbf{C} \times \mathbf{D}\right) \tag{A.1.4.2}$$

where the sign depends on the orientation of the vectors.

A.1.5. The median divides the triangle into two triangles of equal area.

A.1.6. The transpose of $\mathbf{A}$ is defined as

$$\mathbf{A}^\top = \begin{pmatrix} a_1 & a_2 \end{pmatrix} \tag{A.1.6.1}$$

A.1.7. The inner product or dot product is defined as

$$\mathbf{A}^\top \mathbf{B} \equiv \mathbf{A} \cdot \mathbf{B} \tag{A.1.7.1}$$

$$= \begin{pmatrix} a_1 & a_2 \end{pmatrix} \begin{pmatrix} b_1 \\ b_2 \end{pmatrix} = a_1 b_1 + a_2 b_2 \tag{A.1.7.2}$$

A.1.8. norm of **A** is defined as

$$\|A\| \equiv \left|\overrightarrow{A}\right| \tag{A.1.8.1}$$

$$= \sqrt{\mathbf{A}^\top \mathbf{A}} = \sqrt{a_1^2 + a_2^2} \tag{A.1.8.2}$$

Thus,

$$\|\lambda \mathbf{A}\| \equiv \left|\lambda \overrightarrow{A}\right| \tag{A.1.8.3}$$

$$= |\lambda| \, \|\mathbf{A}\| \tag{A.1.8.4}$$

A.1.9. The distance betwen the points **A** and **B** is given by

$$\|\mathbf{A} - \mathbf{B}\| \tag{A.1.9.1}$$

A.1.10. Let **x** be equidistant from the points **A** and **B**. Then

$$(\mathbf{A} - \mathbf{B})^\top \mathbf{x} = \frac{\|\mathbf{A}\|^2 - \|\mathbf{B}\|^2}{2} \tag{A.1.10.1}$$

Solution:

$$\|\mathbf{x} - \mathbf{A}\| = \|\mathbf{A} - \mathbf{B}\| \tag{A.1.10.2}$$

$$\implies \|\mathbf{x} - \mathbf{A}\|^2 = \|\mathbf{x} - \mathbf{B}\|^2 \tag{A.1.10.3}$$

which can be expressed as

$$(\mathbf{x} - \mathbf{A})^\top (\mathbf{x} - \mathbf{A}) = (\mathbf{x} - \mathbf{B})^\top (\mathbf{x} - \mathbf{B})$$

$$\implies \|\mathbf{x}\|^2 - 2\mathbf{x}^\top \mathbf{A} + \|\mathbf{A}\|^2$$

$$= \|\mathbf{x}\|^2 - 2\mathbf{x}^\top \mathbf{B} + \|\mathbf{B}\|^2 \tag{A.1.10.4}$$

which can be simplified to obtain (A.1.10.1).

A.1.11. If $\mathbf{x}$ lies on the x-axis and is equidistant from the points $\mathbf{A}$ and $\mathbf{B}$,

$$\mathbf{x} = x\mathbf{e}_1 \tag{A.1.11.1}$$

where

$$x = \frac{\|\mathbf{A}\|^2 - \|\mathbf{B}\|^2}{2(\mathbf{A} - \mathbf{B})^\top \mathbf{e}_1} \tag{A.1.11.2}$$

Solution: From (A.1.10.1).

$$x(\mathbf{A} - \mathbf{B})^\top \mathbf{e}_1 = \frac{\|\mathbf{A}\|^2 - \|\mathbf{B}\|^2}{2} \tag{A.1.11.3}$$

yielding (A.1.11.2).

A.1.12. The angle between two vectors is given by

$$\theta = \cos^{-1} \frac{\mathbf{A}^\top \mathbf{B}}{\|A\| \, \|B\|} \tag{A.1.12.1}$$

A.1.13. If two vectors are orthogonal (perpendicular),

$$\mathbf{A}^\top \mathbf{B} = 0 \tag{A.1.13.1}$$

A.1.14. For an isoceles triangle ABC ith $AB = AC$, the median $AD \perp BC$.

A.1.15. The <u>direction vector</u> of the line joining two points $\mathbf{A}, \mathbf{B}$ is given by

$$\mathbf{m} = \mathbf{A} - \mathbf{B} \tag{A.1.15.1}$$

A.1.16. The points $\mathbf{AAA}$

A.1.17. The unit vector in the direction of $\mathbf{m}$ is defined as

$$\frac{\mathbf{m}}{\|\mathbf{m}\|} \tag{A.1.17.1}$$

A.1.18. If the direction vector of a line is expressed as

$$\mathbf{m} = \begin{pmatrix} 1 \\ m \end{pmatrix}, \tag{A.1.18.1}$$

the m is defined to be the slope of the line.

A.1.19. $AB \parallel CD$ if

$$\mathbf{A} - \mathbf{B} = k\left(\mathbf{C} - \mathbf{D}\right) \tag{A.1.19.1}$$

A.1.20. The <u>normal vector</u> to $\mathbf{m}$ is defined by

$$\mathbf{m}^{\top}\mathbf{n} = 0 \tag{A.1.20.1}$$

A.1.21. If

$$\mathbf{m}^{\top}\mathbf{n}_1 = 0 \tag{A.1.21.1}$$

$$\mathbf{m}^{\top}\mathbf{n}_2 = 0, \tag{A.1.21.2}$$

$$\mathbf{n}_1 \parallel \mathbf{n}_2 \tag{A.1.21.3}$$

A.1.22. The point $\mathbf{P}$ that divides the line segment AB in the ratio $k : 1$ is given by

$$\mathbf{P} = \frac{k\mathbf{B} + \mathbf{A}}{k+1} \tag{A.1.22.1}$$

A.1.23. The standard basis vectors are defined as

$$\mathbf{e}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \tag{A.1.23.1}$$

$$\mathbf{e}_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \tag{A.1.23.2}$$

A.1.24. If $ABCD$ be a parallelogram,

$$\mathbf{B} - \mathbf{A} = \mathbf{C} - \mathbf{D} \tag{A.1.24.1}$$

A.1.25. Diagonals of a parallelogram bisect each other.

A.1.26. The area of the parallelogram with vertices $\mathbf{A}, \mathbf{B}, \mathbf{C}$ and $\mathbf{D}$ is given by

$$\left\|(\mathbf{A} - \mathbf{B}) \times (\mathbf{A} - \mathbf{D})\right\| = \left\|\mathbf{A} \times \mathbf{B} + \mathbf{B} \times \mathbf{C} + \mathbf{C} \times \mathbf{A}\right\| \tag{A.1.26.1}$$

A.1.27. Points $\mathbf{A}, \mathbf{B}$ and $\mathbf{C}$ form a triangle if

$$p\left(\mathbf{A} - \mathbf{B}\right) + q\left(\mathbf{A} - \mathbf{C}\right) = 0 \tag{A.1.27.1}$$

$$\text{or, } \left(p + q\right)\mathbf{A} - p\mathbf{B} - q\mathbf{C} = 0 \tag{A.1.27.2}$$

$$\implies p = 0, q = 0 \tag{A.1.27.3}$$

are linearly independent.

A.1.28. In $\triangle ABC$, if $\mathbf{D}, \mathbf{E}$ divide the lines AB, AC in the ratio $k : 1$ respectively, then $DE \parallel BC$.

Proof. From (A.1.22.1),

$$\mathbf{D} = \frac{k\mathbf{B} + \mathbf{A}}{k+1} \tag{A.1.28.1}$$

$$\mathbf{E} = \frac{k\mathbf{C} + \mathbf{A}}{k+1} \tag{A.1.28.2}$$

$$\implies \mathbf{D} - \mathbf{E} = \frac{k}{k+1}\left(\mathbf{B} - \mathbf{C}\right) \tag{A.1.28.3}$$

Thus, from Appendix A.1.18, $DE \parallel BC$.

□

A.1.29. In $\triangle ABC$, if $DE \parallel BC$, $\mathbf{D}$ and $\mathbf{E}$ divide the lines AB, AC in the same ratio.

Proof. If $DE \parallel BC$, from (A.1.19.1)

$$\left(\mathbf{B} - \mathbf{C}\right) = k\left(\mathbf{D} - \mathbf{E}\right) \tag{A.1.29.1}$$

Using (A.1.22.1), let

$$\mathbf{D} = \frac{k_1\mathbf{B} + \mathbf{A}}{k_1+1} \tag{A.1.29.2}$$

$$\mathbf{E} = \frac{k_2\mathbf{C} + \mathbf{A}}{k_2+1} \tag{A.1.29.3}$$

Subtituting the above in (A.1.29.1), after some algebra, we obtain

$$\left(p+q\right)\mathbf{A} - p\mathbf{B} - q\mathbf{C} = 0 \tag{A.1.29.4}$$

where

$$p = \frac{1}{k} - \frac{k_1}{k_1+1}, q = \frac{1}{k} - \frac{k_1}{k_1+1} \quad \text{(A.1.29.5)}$$

From (A.1.27.2),

$$p = q = 0 \quad \text{(A.1.29.6)}$$

$$\implies k_1 = k_2 = \frac{1}{k-1} \quad \text{(A.1.29.7)}$$

□

A.2. 3×1 vectors

A.2.1. Let

$$\mathbf{A} = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix} \equiv a_1 \overrightarrow{i} + a_2 \overrightarrow{j} + a_3 \overrightarrow{j}, \quad \text{(A.2.1.1)}$$

$$\mathbf{B} = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix}, \quad \text{(A.2.1.2)}$$

and

$$\mathbf{A}_{ij} = \begin{pmatrix} a_i \\ a_j \end{pmatrix}, \tag{A.2.1.3}$$

$$\mathbf{B}_{ij} = \begin{pmatrix} b_i \\ b_j \end{pmatrix}. \tag{A.2.1.4}$$

A.2.2. The <u>cross product</u> or <u>vector product</u> of $\mathbf{A}, \mathbf{B}$ is defined as

$$\mathbf{A} \times \mathbf{B} = \begin{pmatrix} \begin{vmatrix} \mathbf{A}_{23} & \mathbf{B}_{23} \end{vmatrix} \\ \begin{vmatrix} \mathbf{A}_{31} & \mathbf{B}_{31} \end{vmatrix} \\ \begin{vmatrix} \mathbf{A}_{12} & \mathbf{B}_{12} \end{vmatrix} \end{pmatrix} \tag{A.2.2.1}$$

A.2.3. Verify that

$$\mathbf{A} \times \mathbf{B} = -\mathbf{B} \times \mathbf{A} \tag{A.2.3.1}$$

A.2.4. The area of a triangle is given by

$$\frac{1}{2} \|\mathbf{A} \times \mathbf{B}\| \tag{A.2.4.1}$$

Appendix B

Matrices

B.1. Eigenvalues and Eigenvectors

B.1.1. The eigenvalue λ and the eigenvector $\mathbf{x}$ for a matrix $\mathbf{A}$ are defined as,

$$\mathbf{A}\mathbf{x} = \lambda\mathbf{x} \tag{B.1.1.1}$$

B.1.2. The eigenvalues are calculated by solving the equation

$$f(\lambda) = \left|\lambda\mathbf{I} - \mathbf{A}\right| = 0 \tag{B.1.2.1}$$

The above equation is known as the characteristic equation.

B.1.3. According to the Cayley-Hamilton theorem,

$$f(\lambda) = 0 \implies f(\mathbf{A}) = 0 \tag{B.1.3.1}$$

B.1.4. The trace of a square matrix is defined to be the sum of the diagonal elements.

$$\operatorname{tr}(\mathbf{A}) = \sum_{i=1}^{N} a_{ii}. \tag{B.1.4.1}$$

where a_{ii} is the ith diagonal element of the matrix $\mathbf{A}$.

B.1.5. The trace of a matrix is equal to the sum of the eigenvalues

$$\operatorname{tr}(\mathbf{A}) = \sum_{i=1}^{N} \lambda_i \tag{B.1.5.1}$$

B.2. Determinants

B.2.1. Let

$$\mathbf{A} = \begin{pmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{pmatrix}. \tag{B.2.1.1}$$

be a 3×3 matrix. Then,

$$\left|\mathbf{A}\right| = a_1 \begin{pmatrix} b_2 & c_2 \\ b_3 & c_3 \end{pmatrix} - a_2 \begin{pmatrix} b_1 & c_1 \\ b_3 & c_3 \end{pmatrix} + a_3 \begin{pmatrix} a_1 & b_1 \\ a_2 & b_2 \end{pmatrix}. \tag{B.2.1.2}$$

B.2.2. Let $\lambda_1, \lambda_2, \ldots, \lambda_n$ be the eigenvalues of a matrix $\mathbf{A}$. Then, the product of the eigenvalues is equal to the determinant of $\mathbf{A}$.

$$\left|\mathbf{A}\right| = \prod_{i=1}^{n} \lambda_i \tag{B.2.2.1}$$

B.2.3.

$$\left|\mathbf{AB}\right| = \left|\mathbf{A}\right| \left|\mathbf{B}\right| \tag{B.2.3.1}$$

B.2.4. If $\mathbf{A}$ be an $n \times n$ matrix,

$$\left|k\mathbf{A}\right| = k^n \left|\mathbf{A}\right| \tag{B.2.4.1}$$

B.3. Rank of a Matrix

B.3.1. The rank of a matrix is defined as the number of linearly independent rows. This is also known as the row rank.

B.3.2. Row rank = Column rank.

B.3.3. The rank of a matrix is obtained as the number of nonzero rows obtained after row reduction.

B.3.4. An $n \times n$ matrix is invertible if and only if its rank is n.

B.3.5. Points $\mathbf{A}, \mathbf{B}, \mathbf{C}$ are on a line if

$$\text{rank} \begin{pmatrix} \mathbf{A} \\ \mathbf{B} \\ \mathbf{C} \end{pmatrix} = 1 \tag{B.3.5.1}$$

B.3.6. Points $\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$ form a paralelogram if

$$\text{rank}\begin{pmatrix}\mathbf{A}\\ \mathbf{B}\\ \mathbf{C}\\ \mathbf{D}\end{pmatrix} = 1, \text{rank}\begin{pmatrix}\mathbf{A}\\ \mathbf{B}\\ \mathbf{C}\end{pmatrix} = 2 \tag{B.3.6.1}$$

B.4. Inverse of a Matrix

B.4.1. For a 2×2 matrix

$$\mathbf{A} = \begin{pmatrix} a_1 & b_1 \\ a_2 & b_2 \end{pmatrix}, \tag{B.4.1.1}$$

the inverse is given by

$$\mathbf{A}^{-1} = \frac{1}{\left|\mathbf{A}\right|}\begin{pmatrix} b_2 & -b_1 \\ -a_2 & a_1 \end{pmatrix}, \tag{B.4.1.2}$$

B.4.2. For higher order matrices, the inverse should be calculated using row operations.

B.5. Orthogonality

B.5.1. The rotation matrix is defined as

$$\mathbf{R}_\theta = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}, \quad \theta \in [0, 2\pi] \tag{B.5.1.1}$$

B.5.2. The rotation matrix is orthogonal

$$\mathbf{R}_\theta^\top \mathbf{R}_\theta = \mathbf{R}_\theta \mathbf{R}_\theta^\top = \mathbf{I} \tag{B.5.2.1}$$

B.5.3. If the angle of rotation is $\frac{\pi}{2}$,

$$\mathbf{m}^\top \mathbf{n} = 0 \implies \mathbf{n} = \mathbf{R}_{\frac{\pi}{2}} \mathbf{m} \tag{B.5.3.1}$$

B.5.4.

$$\mathbf{n}^\top \mathbf{h} = 1 \implies \mathbf{n} = \frac{\mathbf{e}_1}{\mathbf{e}_1^\top \mathbf{h}} + \mu \mathbf{R}_{\frac{\pi}{2}} \mathbf{h}, \quad \mu \in \mathbb{R}. \tag{B.5.4.1}$$

B.5.5. The affine transformation is given by

$$\mathbf{x} = \mathbf{P}\mathbf{y} + \mathbf{c} \quad \text{(Affine Transformation)} \tag{B.5.5.1}$$

where $\mathbf{P}$ is invertible.

B.5.6. The eigenvalue decomposition of a symmetric matrix $\mathbf{V}$ is given by

$$\mathbf{P}^\top \mathbf{V} \mathbf{P} = \mathbf{D}. \quad \text{(Eigenvalue Decomposition)} \tag{B.5.6.1}$$

$$\mathbf{D} = \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}, \tag{B.5.6.2}$$

$$\mathbf{P} = \begin{pmatrix} \mathbf{p}_1 & \mathbf{p}_2 \end{pmatrix}, \quad \mathbf{P}^\top = \mathbf{P}^{-1}, \tag{B.5.6.3}$$

Appendix C

Linear Forms

C.1. Two Dimensions

C.1.1. The equation of a line is given by

$$\mathbf{n}^\top \mathbf{x} = c \tag{C.1.1.1}$$

where $\mathbf{n}$ is the normal vector of the line.

C.1.2. The equation of a line with normal vector $\mathbf{n}$ and passing through a point $\mathbf{A}$ is given by

$$\mathbf{n}^\top \left(\mathbf{x} - \mathbf{A}\right) = 0 \tag{C.1.2.1}$$

C.1.3. The equation of a line L is also given by

$$\mathbf{n}^\top \mathbf{x} = \begin{cases} 0 & \mathbf{0} \in L \\ 1 & \text{otherwise} \end{cases} \tag{C.1.3.1}$$

C.1.4. Points $\mathbf{A}, \mathbf{B}, \mathbf{C}$ are collinear if

$$\operatorname{rank}\begin{pmatrix}\mathbf{B}-\mathbf{A} & \mathbf{C}-\mathbf{A}\end{pmatrix} < 2 \tag{C.1.4.1}$$

Proof. From (C.1.1.1),

$$\mathbf{n}^{\top}\mathbf{A} = c \tag{C.1.4.2}$$

$$\mathbf{n}^{\top}\mathbf{B} = c \tag{C.1.4.3}$$

$$\mathbf{n}^{\top}\mathbf{C} = c \tag{C.1.4.4}$$

which can be expressed as

$$\begin{pmatrix}\mathbf{A} & \mathbf{B} & \mathbf{C}\end{pmatrix}^{\top}\mathbf{n} = c\begin{pmatrix}1\\1\\1\end{pmatrix} \tag{C.1.4.5}$$

The above set of equations are consistent if

$$\operatorname{rank}\begin{pmatrix}1 & 1 & 1\\ \mathbf{A} & \mathbf{B} & \mathbf{C}\end{pmatrix} < 3 \tag{C.1.4.6}$$

$$\implies \operatorname{rank}\begin{pmatrix}1 & 0 & 0\\ \mathbf{A} & \mathbf{B}-\mathbf{A} & \mathbf{C}-\mathbf{A}\end{pmatrix} < 3 \tag{C.1.4.7}$$

using the fact that row rank = column rank. The above condition can then be expressed as (C.1.4.1).

$\square$

C.1.5. The parametric equation of a line is given by

$$\mathbf{x} = \mathbf{A} + \lambda \mathbf{m} \tag{C.1.5.1}$$

where $\mathbf{m}$ is the direction vector of the line and $\mathbf{A}$ is any point on the line.

C.1.6. Let $\mathbf{A}$ and $\mathbf{B}$ be two points on a straight line and let $\mathbf{P} = \begin{pmatrix} p_1 \\ p_2 \end{pmatrix}$ be any point on it. If p_2 is known, then

$$\mathbf{P} = \mathbf{A} + \frac{p_2 - \mathbf{e}_2^\top \mathbf{A}}{\mathbf{e}_2^\top (\mathbf{B} - \mathbf{A})} (\mathbf{B} - \mathbf{A}) \tag{C.1.6.1}$$

Solution: The equation of the line can be expressed in parametric from as

$$\mathbf{x} = \mathbf{A} + \lambda (\mathbf{B} - \mathbf{A}) \tag{C.1.6.2}$$

$$\implies \mathbf{P} = \mathbf{A} + \lambda (\mathbf{B} - \mathbf{A}) \tag{C.1.6.3}$$

$$\implies \mathbf{e}_2^\top \mathbf{P} = \mathbf{e}_2^\top \mathbf{A} + \lambda \mathbf{e}_2^\top (\mathbf{B} - \mathbf{A}) \tag{C.1.6.4}$$

$$\implies p_2 = \mathbf{e}_2^\top \mathbf{A} + \lambda \mathbf{e}_2^\top (\mathbf{B} - \mathbf{A}) \tag{C.1.6.5}$$

$$\text{or, } \lambda = \frac{p_2 - \mathbf{e}_2^\top \mathbf{A}}{\mathbf{e}_2^\top (\mathbf{B} - \mathbf{A})} \tag{C.1.6.6}$$

yielding (C.1.6.1).

C.1.7. The distance from a point $\mathbf{P}$ to the line in (C.1.1.1) is given by

$$d = \frac{\left|\mathbf{n}^\top \mathbf{P} - c\right|}{\|\mathbf{n}\|} \tag{C.1.7.1}$$

Solution: Without loss of generality, let $\mathbf{A}$ be the foot of the perpendicular from $\mathbf{P}$ to the line in (C.1.5.1). The equation of the normal to (C.1.1.1) can then be expressed as

$$\mathbf{x} = \mathbf{A} + \lambda \mathbf{n} \tag{C.1.7.2}$$

$$\implies \mathbf{P} - \mathbf{A} = \lambda \mathbf{n} \tag{C.1.7.3}$$

$\because$ $\mathbf{P}$ lies on (C.1.7.2). From the above, the desired distance can be expressed as

$$d = \left\|\mathbf{P} - \mathbf{A}\right\| = \left|\lambda\right| \left\|\mathbf{n}\right\| \tag{C.1.7.4}$$

From (C.1.7.3),

$$\mathbf{n}^\top \left(\mathbf{P} - \mathbf{A}\right) = \lambda \mathbf{n}^\top \mathbf{n} = \lambda \left\|\mathbf{n}\right\|^2 \tag{C.1.7.5}$$

$$\implies \left|\lambda\right| = \frac{\left|\mathbf{n}^\top \left(\mathbf{P} - \mathbf{A}\right)\right|}{\left\|\mathbf{n}\right\|^2} \tag{C.1.7.6}$$

Substituting the above in (C.1.7.4) and using the fact that

$$\mathbf{n}^\top \mathbf{A} = c \tag{C.1.7.7}$$

from (C.1.1.1), yields (C.1.7.1)

C.1.8. The distance from the origin to the line in (C.1.1.1) is given by

$$d = \frac{\left|c\right|}{\left\|\mathbf{n}\right\|} \tag{C.1.8.1}$$

C.1.9. The distance between the parallel lines

$$\begin{aligned} \mathbf{n}^\top \mathbf{x} &= c_1 \\ \mathbf{n}^\top \mathbf{x} &= c_2 \end{aligned} \tag{C.1.9.1}$$

is given by

$$d = \frac{|c_1 - c_2|}{\|\mathbf{n}\|} \tag{C.1.9.2}$$

C.1.10. The equation of the line perpendicular to (C.1.1.1) and passing through the point $\mathbf{P}$ is given by

$$\mathbf{m}^\top (\mathbf{x} - \mathbf{P}) = 0 \tag{C.1.10.1}$$

C.1.11. The foot of the perpendicular from $\mathbf{P}$ to the line in (C.1.1.1) is given by

$$\begin{pmatrix} \mathbf{m} & \mathbf{n} \end{pmatrix}^\top \mathbf{x} = \begin{pmatrix} \mathbf{m}^\top \mathbf{P} \\ c \end{pmatrix} \tag{C.1.11.1}$$

Solution: From (C.1.1.1) and (C.1.2.1) the foot of the perpendicular satisfies the equations

$$\mathbf{n}^\top \mathbf{x} = c \tag{C.1.11.2}$$

$$\mathbf{m}^\top (\mathbf{x} - \mathbf{P}) = 0 \tag{C.1.11.3}$$

where $\mathbf{m}$ is the direction vector of the given line. Combining the above into a matrix equation results in (C.1.11.1).

C.1.12. The equations of the angle bisectors of the lines

$$\mathbf{n}_1^\top \mathbf{x} = c_1 \tag{C.1.12.1}$$

$$\mathbf{n}_2^\top \mathbf{x} = c_2 \tag{C.1.12.2}$$

are given by

$$\frac{\mathbf{n}_1^\top \mathbf{x} - c_1}{\|\mathbf{n}_1\|} = \pm \frac{\mathbf{n}_2^\top \mathbf{x} - c_2}{\|\mathbf{n}_2\|} \tag{C.1.12.3}$$

Proof. Any point on the angle bisector is equidistant from the lines. □

C.2. Three Dimensions

C.2.1. Points $\mathbf{A}, \mathbf{B}, \mathbf{C}$ are on a line if

$$\operatorname{rank}\begin{pmatrix}\mathbf{A}\\ \mathbf{B}\\ \mathbf{C}\end{pmatrix} = 1 \tag{C.2.1.1}$$

C.2.2. Points $\mathbf{A}, \mathbf{B}, \mathbf{C}, \mathbf{D}$ form a paralelogram if

$$\operatorname{rank}\begin{pmatrix}\mathbf{A}\\ \mathbf{B}\\ \mathbf{C}\\ \mathbf{D}\end{pmatrix} = 1, \operatorname{rank}\begin{pmatrix}\mathbf{A}\\ \mathbf{B}\\ \mathbf{C}\end{pmatrix} = 2 \tag{C.2.2.1}$$

C.2.3. The equation of a line is given by (C.1.5.1)

C.2.4. The equation of a plane is given by (C.1.1.1)

C.2.5. The distance from the origin to the line in (C.1.1.1) is given by (C.1.8.1)

C.2.6. The distance from a point $\mathbf{P}$ to the line in (C.1.5.1) is given by

$$d = \left\|\mathbf{A} - \mathbf{P}\right\|^2 - \frac{\left\{\mathbf{m}^\top \left(\mathbf{A} - \mathbf{P}\right)\right\}^2}{\left\|\mathbf{m}\right\|^2} \tag{C.2.6.1}$$

Solution:

$$d\left(\lambda\right) = \left\|\mathbf{A} + \lambda\mathbf{m} - \mathbf{P}\right\| \tag{C.2.6.2}$$

$$\implies d^2\left(\lambda\right) = \left\|\mathbf{A} + \lambda\mathbf{m} - \mathbf{P}\right\|^2 \tag{C.2.6.3}$$

which can be simplified to obtain

$$d^2\left(\lambda\right) = \lambda^2\left\|\mathbf{m}\right\|^2 + 2\lambda\mathbf{m}^\top\left(\mathbf{A} - \mathbf{P}\right) + \left\|\mathbf{A} - \mathbf{P}\right\|^2 \tag{C.2.6.4}$$

which is of the form

$$d^2\left(\lambda\right) = a\lambda^2 + 2b\lambda + c \tag{C.2.6.5}$$

$$= a\left\{\left(\lambda + \frac{b}{a}\right)^2 + \left[\frac{c}{a} - \left(\frac{b}{a}\right)^2\right]\right\} \tag{C.2.6.6}$$

with

$$a = \left\|\mathbf{m}\right\|^2, b = \mathbf{m}^\top\left(\mathbf{A} - \mathbf{P}\right), c = \left\|\mathbf{A} - \mathbf{P}\right\|^2 \tag{C.2.6.7}$$

which can be expressed as From the above, $d^2\left(\lambda\right)$ is smallest when upon substituting from (C.2.6.7)

$$\lambda + \frac{b}{2a} = 0 \implies \lambda = -\frac{b}{2a} \tag{C.2.6.8}$$

$$= -\frac{\mathbf{m}^\top (\mathbf{A} - \mathbf{P})}{\|\mathbf{m}\|^2} \tag{C.2.6.9}$$

and consequently,

$$d_{\min}(\lambda) = a\left(\frac{c}{a} - \left(\frac{b}{a}\right)^2\right) \tag{C.2.6.10}$$

$$= c - \frac{b^2}{a} \tag{C.2.6.11}$$

yielding (C.2.6.1) after substituting from (C.2.6.7).

C.2.7. The distance between the parallel planes (C.1.9.1) is given by (C.1.9.2).

C.2.8. The plane

$$\mathbf{n}^\top \mathbf{x} = c \tag{C.2.8.1}$$

contains the line

$$\mathbf{x} = \mathbf{A} + \lambda \mathbf{m} \tag{C.2.8.2}$$

if

$$\mathbf{m}^\top \mathbf{n} = 0 \tag{C.2.8.3}$$

Solution: Any point on the line (C.2.8.2) should also satisfy (C.2.8.1). Hence,

$$\mathbf{n}^\top (\mathbf{A} + \lambda\mathbf{m}) = \mathbf{n}^\top \mathbf{A} = c \tag{C.2.8.4}$$

which can be simplified to obtain (C.2.8.3)

C.2.9. The foot of the perpendicular from a point $\mathbf{P}$ to the plane

$$\mathbf{n}^\top \mathbf{x} = c \tag{C.2.9.1}$$

is given by

$$\mathbf{x} = \mathbf{P} + \frac{c - \mathbf{n}^\top \mathbf{P}}{\|\mathbf{n}\|^2}\mathbf{n} \tag{C.2.9.2}$$

Solution: The equation of the line perpendicular to the given plane and passing through $\mathbf{P}$ is

$$\mathbf{x} = \mathbf{P} + \lambda\mathbf{n} \tag{C.2.9.3}$$

From (C.2.12.1), the intersection of the above line with the given plane is (C.2.9.2).

C.2.10. The image of a point $\mathbf{P}$ with respect to the plane

$$\mathbf{n}^\top \mathbf{x} = c \tag{C.2.10.1}$$

is given by

$$\mathbf{R} = \mathbf{P} + 2\frac{c - \mathbf{n}^\top \mathbf{P}}{\|\mathbf{n}\|^2} \tag{C.2.10.2}$$

Solution: Let $\mathbf{R}$ be the desired image. Then, subtituting the expression for the foot of the perpendicular from $\mathbf{P}$ to the given plane using (C.2.9.2),

$$\frac{\mathbf{P} + \mathbf{R}}{2} = \mathbf{P} + \frac{c - \mathbf{n}^\top \mathbf{P}}{\|\mathbf{n}\|^2} \tag{C.2.10.3}$$

C.2.11. Let a plane pass through the points $\mathbf{A}, \mathbf{B}$ and be perpendicular to the plane

$$\mathbf{n}^\top \mathbf{x} = c \tag{C.2.11.1}$$

Then the equation of this plane is given by

$$\mathbf{p}^\top \mathbf{x} = 1 \tag{C.2.11.2}$$

where

$$\mathbf{p} = \begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{n} \end{pmatrix}^{-\top} \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \tag{C.2.11.3}$$

Solution: From the given information,

$$\mathbf{p}^\top \mathbf{A} = d \tag{C.2.11.4}$$

$$\mathbf{p}^\top \mathbf{B} = d \tag{C.2.11.5}$$

$$\mathbf{p}^\top \mathbf{n} = 0 \tag{C.2.11.6}$$

$\because$ the normal vectors to the two planes will also be perpendicular. The system of equations in (C.2.11.6) can be expressed as the matrix equation

$$\begin{pmatrix} \mathbf{A} & \mathbf{B} & \mathbf{n} \end{pmatrix}^\top \mathbf{p} = d \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix} \tag{C.2.11.7}$$

which yields (C.2.11.3) upon normalising with d.

C.2.12. The intersection of the line represented by (C.1.5.1) with the plane represented by (C.1.1.1) is given by

$$\mathbf{x} = \mathbf{A} + \frac{c - \mathbf{n}^\top \mathbf{A}}{\mathbf{n}^\top \mathbf{m}} \mathbf{m} \tag{C.2.12.1}$$

Solution: From (C.1.5.1) and (C.1.1.1),

$$\mathbf{x} = \mathbf{A} + \lambda \mathbf{m} \tag{C.2.12.2}$$

$$\mathbf{n}^\top \mathbf{x} = c \tag{C.2.12.3}$$

$$\implies \mathbf{n}^\top \left(\mathbf{A} + \lambda \mathbf{m} \right) = c \tag{C.2.12.4}$$

which can be simplified to obtain

$$\mathbf{n}^\top \mathbf{A} + \lambda \mathbf{n}^\top \mathbf{m} = c \tag{C.2.12.5}$$

$$\implies \lambda = \frac{c - \mathbf{n}^\top \mathbf{A}}{\mathbf{n}^\top \mathbf{m}} \tag{C.2.12.6}$$

Substituting the above in (C.2.12.4) yields (C.2.12.1).

C.2.13. The foot of the perpendicular from the point $\mathbf{P}$ to the line represented by (C.1.5.1) is given by

$$\mathbf{x} = \mathbf{A} + \frac{\mathbf{m}^\top (\mathbf{P} - \mathbf{A})}{\|\mathbf{m}\|^2}\mathbf{m} \tag{C.2.13.1}$$

Solution: Let the equation of the line be

$$\mathbf{x} = \mathbf{A} + \lambda \mathbf{m} \tag{C.2.13.2}$$

The equation of the plane perpendicular to the given line passing through $\mathbf{P}$ is given by

$$\mathbf{m}^\top (\mathbf{x} - \mathbf{P}) = 0 \tag{C.2.13.3}$$

$$\implies \mathbf{m}^\top \mathbf{x} = \mathbf{m}^\top \mathbf{P} \tag{C.2.13.4}$$

The desired foot of the perpendicular is the intersection of (C.2.13.2) with (C.2.13.3) which can be obtained from (C.2.12.1) as (C.2.13.1)

C.2.14. The foot of the perpendicular from a point $\mathbf{P}$ to a plane is $\mathbf{Q}$. The equation of the plane is given by

$$\left(\mathbf{P}-\mathbf{Q}\right)^\top\left(\mathbf{x}-\mathbf{Q}\right)=0 \tag{C.2.14.1}$$

Solution: The normal vector to the plane is given by

$$\mathbf{n}=\mathbf{P}-\mathbf{Q} \tag{C.2.14.2}$$

Hence, the equation of the plane is (C.2.14.1).

C.2.15. Let $\mathbf{A}, \mathbf{B}, \mathbf{C}$ be points on a plane. The equation of the plane is then given by

$$\begin{pmatrix}\mathbf{A} & \mathbf{B} & \mathbf{C}\end{pmatrix}^\top\mathbf{n}=\begin{pmatrix}1\\1\\1\end{pmatrix} \tag{C.2.15.1}$$

Solution: Let the equation of the plane be

$$\mathbf{n}^\top\mathbf{x}=1 \tag{C.2.15.2}$$

Then

$$\mathbf{n}^\top\mathbf{A}=1 \tag{C.2.15.3}$$

$$\mathbf{n}^\top\mathbf{B}=1 \tag{C.2.15.4}$$

$$\mathbf{n}^\top\mathbf{C}=1 \tag{C.2.15.5}$$

which can be combined to obtain (C.2.15.1).

C.2.16. (Parallelogram Law) Let $\mathbf{A}, \mathbf{B}, \mathbf{D}$ be three vertices of a parallelogram. Then the vertex

$\mathbf{C}$ is given by

$$\mathbf{C} = \mathbf{B} + \mathbf{C} - \mathbf{A} \tag{C.2.16.1}$$

Solution: Shifting $\mathbf{A}$ to the origin, we obtain a parallelogram with corresponding vertices

$$\mathbf{0}, \mathbf{B} - \mathbf{A}, \mathbf{D} - \mathbf{A} \tag{C.2.16.2}$$

The fourth vertex of this parallelogram is then obtained as

$$(\mathbf{B} - \mathbf{A}) + (\mathbf{D} - \mathbf{A}) = \mathbf{D} + \mathbf{B} - 2\mathbf{A} \tag{C.2.16.3}$$

Shifting the origin to $\mathbf{A}$, the fourth vertex is obtained as

$$\mathbf{C} = \mathbf{D} + \mathbf{B} - 2\mathbf{A} + \mathbf{A} \tag{C.2.16.4}$$

$$= \mathbf{D} + \mathbf{B} - \mathbf{A} \tag{C.2.16.5}$$

C.2.17. (Affine Transformation) Let $\mathbf{A}, \mathbf{C}$, be opposite vertices of a square. The other two points can be obtained as

$$\mathbf{B} = \frac{\|\mathbf{A} - \mathbf{C}\|}{\sqrt{2}} \mathbf{P}\mathbf{e}_1 + \mathbf{A} \tag{C.2.17.1}$$

$$\mathbf{D} = \frac{\|\mathbf{A} - \mathbf{C}\|}{\sqrt{2}} \mathbf{P}\mathbf{e}_2 + \mathbf{A} \tag{C.2.17.2}$$

where

$$\mathbf{P} = \begin{pmatrix} \cos\left(\theta - \frac{\pi}{4}\right) & \sin\left(\theta - \frac{\pi}{4}\right) \\ \sin\left(\theta - \frac{\pi}{4}\right) & \cos\left(\theta - \frac{\pi}{4}\right) \end{pmatrix} \tag{C.2.17.3}$$

and

$$\cos\theta = \frac{(\mathbf{C} - \mathbf{A})^{\top} \mathbf{e}_1}{\|\mathbf{A} - \mathbf{C}\| \, \|\mathbf{e}_1\|} \tag{C.2.17.4}$$

Appendix D

Quadratic Forms

D.1. Conic equation

D.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

$$L : \mathbf{n}^\top \mathbf{x} = c \tag{D.1.1.1}$$

is constant, given by

$$\frac{\|\mathbf{q} - \mathbf{F}\|}{d} = e \tag{D.1.1.2}$$

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

D.1.2. The equation of a conic with directrix $\mathbf{n}^\top\mathbf{x} = c$, eccentricity e and focus $\mathbf{F}$ is given by

$$\mathrm{g}\left(\mathbf{x}\right) = \mathbf{x}^\top\mathbf{V}\mathbf{x} + 2\mathbf{u}^\top\mathbf{x} + f = 0 \tag{D.1.2.1}$$

where

$$\mathbf{V} = \left\|\mathbf{n}\right\|^2\mathbf{I} - e^2\mathbf{n}\mathbf{n}^\top, \tag{D.1.2.2}$$

$$\mathbf{u} = ce^2\mathbf{n} - \left\|\mathbf{n}\right\|^2\mathbf{F}, \tag{D.1.2.3}$$

$$f = \left\|\mathbf{n}\right\|^2\left\|\mathbf{F}\right\|^2 - c^2e^2 \tag{D.1.2.4}$$

Proof. Using Definition D.1.1 and Lemma C.1.7.1, for any point $\mathbf{x}$ on the conic,

$$\left\|\mathbf{x} - \mathbf{F}\right\|^2 = e^2\frac{\left(\mathbf{n}^\top\mathbf{x} - c\right)^2}{\left\|\mathbf{n}\right\|^2} \tag{D.1.2.5}$$

$$\implies \left\|\mathbf{n}\right\|^2\left(\mathbf{x} - \mathbf{F}\right)^\top\left(\mathbf{x} - \mathbf{F}\right) = e^2\left(\mathbf{n}^\top\mathbf{x} - c\right)^2 \tag{D.1.2.6}$$

$$\implies \left\|\mathbf{n}\right\|^2\left(\mathbf{x}^\top\mathbf{x} - 2\mathbf{F}^\top\mathbf{x} + \left\|\mathbf{F}\right\|^2\right) = e^2\left(c^2 + \left(\mathbf{n}^\top\mathbf{x}\right)^2 - 2c\mathbf{n}^\top\mathbf{x}\right) \tag{D.1.2.7}$$

$$= e^2\left(c^2 + \left(\mathbf{x}^\top\mathbf{n}\mathbf{n}^\top\mathbf{x}\right) - 2c\mathbf{n}^\top\mathbf{x}\right) \tag{D.1.2.8}$$

which can be expressed as (D.1.2.1) after simplification.

∎

D.1.3. The eccentricity, directrices and foci of (D.1.2.1) are given by

$$e = \sqrt{1 - \frac{\lambda_1}{\lambda_2}} \tag{D.1.3.1}$$

$$\mathbf{n} = \sqrt{\lambda_2}\mathbf{p}_1,$$

$$c = \begin{cases} \frac{e\mathbf{u}^\top\mathbf{n} \pm \sqrt{e^2\left(\mathbf{u}^\top\mathbf{n}\right)^2 - \lambda_2(e^2-1)\left(\|\mathbf{u}\|^2 - \lambda_2 f\right)}}{\lambda_2 e(e^2-1)} & e \neq 1 \\ \frac{\|\mathbf{u}\|^2 - \lambda_2 f}{2\mathbf{u}^\top\mathbf{n}} & e = 1 \end{cases} \tag{D.1.3.2}$$

$$\mathbf{F} = \frac{ce^2\mathbf{n} - \mathbf{u}}{\lambda_2} \tag{D.1.3.3}$$

Proof. From (D.1.2.2), using the fact that $\mathbf{V}$ is symmetric with $\mathbf{V} = \mathbf{V}^\top$,

$$\mathbf{V}^\top\mathbf{V} = \left(\|\mathbf{n}\|^2\mathbf{I} - e^2\mathbf{n}\mathbf{n}^\top\right)^\top\left(\|\mathbf{n}\|^2\mathbf{I} - e^2\mathbf{n}\mathbf{n}^\top\right) \tag{D.1.3.4}$$

$$\implies \mathbf{V}^2 = \|\mathbf{n}\|^4\mathbf{I} + e^4\mathbf{n}\mathbf{n}^\top\mathbf{n}\mathbf{n}^\top - 2e^2\|\mathbf{n}\|^2\mathbf{n}\mathbf{n}^\top \tag{D.1.3.5}$$

$$= \|\mathbf{n}\|^4\mathbf{I} + e^4\|\mathbf{n}\|^2\mathbf{n}\mathbf{n}^\top - 2e^2\|\mathbf{n}\|^2\mathbf{n}\mathbf{n}^\top \tag{D.1.3.6}$$

$$= \|\mathbf{n}\|^4\mathbf{I} + e^2\left(e^2 - 2\right)\|\mathbf{n}\|^2\mathbf{n}\mathbf{n}^\top \tag{D.1.3.7}$$

$$= \|\mathbf{n}\|^4\mathbf{I} + \left(e^2 - 2\right)\|\mathbf{n}\|^2\left(\|\mathbf{n}\|^2\mathbf{I} - \mathbf{V}\right) \tag{D.1.3.8}$$

which can be expressed as

$$\mathbf{V}^2 + \left(e^2 - 2\right)\|\mathbf{n}\|^2\mathbf{V} - \left(e^2 - 1\right)\|\mathbf{n}\|^4\mathbf{I} = 0 \tag{D.1.3.9}$$

Using the Cayley-Hamilton theorem, (D.1.3.9) results in the characteristic equation,

$$\lambda^2 - \left(2 - e^2\right)\|\mathbf{n}\|^2\lambda + \left(1 - e^2\right)\|\mathbf{n}\|^4 = 0 \tag{D.1.3.10}$$

which can be expressed as

$$\left(\frac{\lambda}{\|\mathbf{n}\|^2}\right)^2 - \left(2 - e^2\right)\left(\frac{\lambda}{\|\mathbf{n}\|^2}\right) + \left(1 - e^2\right) = 0 \tag{D.1.3.11}$$

$$\implies \frac{\lambda}{\|\mathbf{n}\|^2} = 1 - e^2, 1 \tag{D.1.3.12}$$

$$\text{or, } \lambda_2 = \|\mathbf{n}\|^2, \lambda_1 = \left(1 - e^2\right)\lambda_2 \tag{D.1.3.13}$$

From (D.1.3.13), the eccentricity of (D.1.2.1) is given by (D.1.3.1). Multiplying both sides of (D.1.2.2) by $\mathbf{n}$,

$$\mathbf{V}\mathbf{n} = \|\mathbf{n}\|^2 \mathbf{n} - e^2\mathbf{n}\mathbf{n}^\top\mathbf{n} \tag{D.1.3.14}$$

$$= \|\mathbf{n}\|^2 \left(1 - e^2\right)\mathbf{n} \tag{D.1.3.15}$$

$$= \lambda_1\mathbf{n} \tag{D.1.3.16}$$

$$\tag{D.1.3.17}$$

from (D.1.3.13). Thus, λ_1 is the corresponding eigenvalue for $\mathbf{n}$. From (B.5.6.3) and (D.1.3.17), this implies that

$$\mathbf{p}_1 = \frac{\mathbf{n}}{\|\mathbf{n}\|} \tag{D.1.3.18}$$

$$\text{or, } \mathbf{n} = \|\mathbf{n}\|\,\mathbf{p}_1 = \sqrt{\lambda_2}\mathbf{p}_1 \tag{D.1.3.19}$$

from (D.1.3.13) . From (D.1.2.3) and (D.1.3.13),

$$\mathbf{F} = \frac{ce^2\mathbf{n} - \mathbf{u}}{\lambda_2} \tag{D.1.3.20}$$

$$\implies \|\mathbf{F}\|^2 = \frac{\left(ce^2\mathbf{n} - \mathbf{u}\right)^\top \left(ce^2\mathbf{n} - \mathbf{u}\right)}{\lambda_2^2} \tag{D.1.3.21}$$

$$\implies \lambda_2^2 \|\mathbf{F}\|^2 = c^2e^4\lambda_2 - 2ce^2\mathbf{u}^\top\mathbf{n} + \|\mathbf{u}\|^2 \tag{D.1.3.22}$$

Also, (D.1.2.4) can be expressed as

$$\lambda_2 \|\mathbf{F}\|^2 = f + c^2e^2 \tag{D.1.3.23}$$

From (D.1.3.22) and (D.1.3.23),

$$c^2e^4\lambda_2 - 2ce^2\mathbf{u}^\top\mathbf{n} + \|\mathbf{u}\|^2 = \lambda_2\left(f + c^2e^2\right) \tag{D.1.3.24}$$

$$\implies \lambda_2 e^2\left(e^2 - 1\right)c^2 - 2ce^2\mathbf{u}^\top\mathbf{n} + \|\mathbf{u}\|^2 - \lambda_2 f = 0 \tag{D.1.3.25}$$

yielding (D.1.3.3). □

D.1.4. (D.1.2.1) represents

(a) a parabola for $\left|\mathbf{V}\right| = 0$,

(b) ellipse for $\left|\mathbf{V}\right| > 0$ and

(c) hyperbola for $\left|\mathbf{V}\right| < 0$.

Proof. From (D.1.3.1),

$$\frac{\lambda_1}{\lambda_2} = 1 - e^2 \tag{D.1.4.1}$$

Also,

$$\left|\mathbf{V}\right| = \lambda_1\lambda_2 \tag{D.1.4.2}$$

yielding Table D.1.4.2 □

Eccentricity	**Conic**	**Eigenvalue**	**Determinant**
$e = 1$	Parabola	$\lambda_1 = 0$	$\left|\mathbf{V}\right| = 0$
$e < 1$	Ellipse	$\lambda_1 > 0, \lambda_2 > 0$	$\left|\mathbf{V}\right| > 0$
$e > 1$	Hyperbola	$\lambda_1 < 0, \lambda_2 > 0$	$\left|\mathbf{V}\right| < 0$

Table D.1.4.2:

D.2. Circles

D.2.1. The equation of a circle is given by

$$\|\mathbf{x}\|^2 + 2\mathbf{u}^\top\mathbf{x} + f = 0 \tag{D.2.1.1}$$

D.2.2. For a circle with centre $\mathbf{c}$ and radius r,

$$\mathbf{u} = -\mathbf{c}, f = \|\mathbf{u}\|^2 - r^2 \tag{D.2.2.1}$$

D.2.3. Any point $\mathbf{x}$ on a circle can be expressed as

$$\mathbf{x} = \mathbf{c} + r \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}. \tag{D.2.3.1}$$

D.2.4. The equation of the common chord of intersection of two circles is given by

$$\mathbf{u}_1^\top \mathbf{x} - \mathbf{u}_2^\top \mathbf{x} + f_1 - f_2 = 0 \tag{D.2.4.1}$$

D.2.5. The line joining the centre of a circle to the mid point of any chord is perpendicular to the chord.

Proof. Let AB be any chord of a circle with centre $\mathbf{O} = \mathbf{0}$ and radius r. Then,

$$\left\|\mathbf{A}\right\|^2 = \left\|\mathbf{B}\right\|^2 = r^2 \tag{D.2.5.1}$$

$$\implies \left\|\mathbf{A}\right\|^2 - \left\|\mathbf{B}\right\|^2 = \mathbf{0} \tag{D.2.5.2}$$

$$\text{or, } \left(\mathbf{A} - \mathbf{B}\right)^\top \left(\mathbf{A} + \mathbf{B}\right) = \mathbf{0} \tag{D.2.5.3}$$

which can be expressed as

$$\left(\mathbf{A} - \mathbf{B}\right)^\top \left(\frac{\mathbf{A} + \mathbf{B}}{2} - \mathbf{O}\right) = \mathbf{0} \tag{D.2.5.4}$$

$\square$

D.2.6. Let

$$\mathbf{A} = \begin{pmatrix} \cos\theta_1 \\ \sin\theta_1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} \cos\theta_2 \\ \sin\theta_2 \end{pmatrix}, \tag{D.2.6.1}$$

be points on a unit circle with centre $\mathbf{O}$ at the origin. Then

$$\cos AOB = \mathbf{A}^\top \mathbf{B} \tag{D.2.6.2}$$

D.2.7. Let

$$\mathbf{A} = \begin{pmatrix} \cos\theta_1 \\ \sin\theta_1 \end{pmatrix}, \mathbf{B} = \begin{pmatrix} \cos\theta_2 \\ \sin\theta_2 \end{pmatrix}, \mathbf{C} = \begin{pmatrix} \cos\theta \\ \sin\theta \end{pmatrix}, \tag{D.2.7.1}$$

be points on a unit circle. Then

$$\begin{aligned} \cos ACB &= \frac{(\mathbf{C}-\mathbf{A})^\top (\mathbf{C}-\mathbf{B})}{\|\mathbf{C}-\mathbf{A}\| \|\mathbf{C}-\mathbf{B}\|} && \text{(D.2.7.2)} \\ &= \cos\left(\frac{\theta_1-\theta_2}{2}\right) && \text{(D.2.7.3)} \end{aligned}$$

Proof. Since

$$\begin{aligned} (\mathbf{C}-\mathbf{A})^\top (\mathbf{C}-\mathbf{B}) &= \|\mathbf{C}\|^2 - \mathbf{C}^\top (\mathbf{A}+\mathbf{B}) + \mathbf{A}^\top\mathbf{B} && \text{(D.2.7.4)} \\ &= 1 - \cos(\theta-\theta_1) - \cos(\theta-\theta_2) + \cos(\theta_1-\theta_2) && \text{(D.2.7.5)} \\ &= 2\cos^2\left(\frac{\theta_1-\theta_2}{2}\right) - 2\cos\left(\frac{\theta_1-\theta_2}{2}\right)\cos\left(\theta - \frac{\theta_1+\theta_2}{2}\right) \\ & && \text{(D.2.7.6)} \\ &= 4\cos\left(\frac{\theta_1-\theta_2}{2}\right)\sin\left(\frac{\theta-\theta_1}{2}\right)\sin\left(\frac{\theta-\theta_2}{2}\right), && \text{(D.2.7.7)} \end{aligned}$$

and

$$\|\mathbf{C}-\mathbf{A}\|^2 = \|\mathbf{C}\|^2 + \|\mathbf{A}\|^2 - 2\mathbf{C}^\top\mathbf{A}, \tag{D.2.7.8}$$

$$= 4\sin^2\left(\frac{\theta-\theta_1}{2}\right), \tag{D.2.7.9}$$

$$\|\mathbf{C}-\mathbf{B}\|^2 = \|\mathbf{C}\|^2 + \|\mathbf{B}\|^2 - 2\mathbf{C}^\top\mathbf{B}, \tag{D.2.7.10}$$

$$= 4\sin^2\left(\frac{\theta-\theta_2}{2}\right), \tag{D.2.7.11}$$

(D.2.7.2) can be expressed as

$$\frac{\cos\left(\frac{\theta_1-\theta_2}{2}\right)\sin\left(\frac{\theta-\theta_1}{2}\right)\sin\left(\frac{\theta-\theta_2}{2}\right)}{\sin\left(\frac{\theta-\theta_1}{2}\right)\sin\left(\frac{\theta-\theta_1}{2}\right)} \tag{D.2.7.12}$$

yielding (D.2.7.3) $\square$

D.2.8. From (D.2.6.2) and (D.2.7.3),

$$\angle AOB = 2\angle AOC \tag{D.2.8.1}$$

D.3. Standard Form

D.3.1. Using the affine transformation in (B.5.5.1), the conic in (D.1.2.1) can be expressed in standard form as

$$\mathbf{y}^\top\left(\frac{\mathbf{D}}{f_0}\right)\mathbf{y} = 1 \qquad |\mathbf{V}| \neq 0 \tag{D.3.1.1}$$

$$\mathbf{y}^\top\mathbf{D}\mathbf{y} = -\eta\mathbf{e}_1^\top\mathbf{y} \qquad |\mathbf{V}| = 0 \tag{D.3.1.2}$$

where

$$f_0 = \mathbf{u}^\top \mathbf{V}^{-1}\mathbf{u} - f \neq 0 \tag{D.3.1.3}$$

$$\eta = 2\mathbf{u}^\top \mathbf{p}_1 \tag{D.3.1.4}$$

$$\mathbf{e}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{D.3.1.5}$$

Proof. Using (B.5.5.1) (D.1.2.1) can be expressed as

$$(\mathbf{Py} + \mathbf{c})^\top \mathbf{V} (\mathbf{Py} + \mathbf{c}) + 2\mathbf{u}^\top (\mathbf{Py} + \mathbf{c}) + f = 0, \tag{D.3.1.6}$$

yielding

$$\mathbf{y}^\top \mathbf{P}^\top \mathbf{VPy} + 2(\mathbf{Vc} + \mathbf{u})^\top \mathbf{Py} + \mathbf{c}^\top \mathbf{Vc} + 2\mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.7}$$

From (D.3.1.7) and (B.5.6.1),

$$\mathbf{y}^\top \mathbf{Dy} + 2(\mathbf{Vc} + \mathbf{u})^\top \mathbf{Py} + \mathbf{c}^\top (\mathbf{Vc} + \mathbf{u}) + \mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.8}$$

When $\mathbf{V}^{-1}$ exists, choosing

$$\mathbf{Vc} + \mathbf{u} = \mathbf{0}, \quad \text{or}, \mathbf{c} = -\mathbf{V}^{-1}\mathbf{u}, \tag{D.3.1.9}$$

and substituting (D.3.1.9) in (D.3.1.8) yields (D.3.1.1). When $|\mathbf{V}| = 0, \lambda_1 = 0$ and

$$\mathbf{Vp}_1 = 0, \mathbf{Vp}_2 = \lambda_2 \mathbf{p}_2. \tag{D.3.1.10}$$

where $\mathbf{p}_1, \mathbf{p}_2$ are the eigenvectors of $\mathbf{V}$ such that (B.5.6.1)

$$\mathbf{P} = \begin{pmatrix} \mathbf{p}_1 & \mathbf{p}_2 \end{pmatrix}, \tag{D.3.1.11}$$

Substituting (D.3.1.11) in (D.3.1.8),

$$\mathbf{y}^\top \mathbf{D}\mathbf{y} + 2\left(\mathbf{c}^\top \mathbf{V} + \mathbf{u}^\top\right)\begin{pmatrix} \mathbf{p}_1 & \mathbf{p}_2 \end{pmatrix}\mathbf{y} + \mathbf{c}^\top\left(\mathbf{V}\mathbf{c} + \mathbf{u}\right) + \mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.12}$$

$$\implies \mathbf{y}^\top \mathbf{D}\mathbf{y} + 2\begin{pmatrix} \left(\mathbf{c}^\top \mathbf{V} + \mathbf{u}^\top\right)\mathbf{p}_1 \left(\mathbf{c}^\top \mathbf{V} + \mathbf{u}^\top\right)\mathbf{p}_2 \end{pmatrix}\mathbf{y} + \mathbf{c}^\top\left(\mathbf{V}\mathbf{c} + \mathbf{u}\right) + \mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.13}$$

$$\implies \mathbf{y}^\top \mathbf{D}\mathbf{y} + 2\begin{pmatrix} \mathbf{u}^\top \mathbf{p}_1 & \left(\lambda_2 \mathbf{c}^\top + \mathbf{u}^\top\right)\mathbf{p}_2 \end{pmatrix}\mathbf{y} + \mathbf{c}^\top\left(\mathbf{V}\mathbf{c} + \mathbf{u}\right) + \mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.14}$$

upon substituting from (D.3.1.10) yielding

$$\lambda_2 y_2^2 + 2\left(\mathbf{u}^\top \mathbf{p}_1\right) y_1 + 2y_2\left(\lambda_2 \mathbf{c} + \mathbf{u}\right)^\top \mathbf{p}_2 + \mathbf{c}^\top\left(\mathbf{V}\mathbf{c} + \mathbf{u}\right) + \mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.15}$$

Thus, (D.3.1.15) can be expressed as (D.3.1.2) by choosing

$$\eta = 2\mathbf{u}^\top \mathbf{p}_1 \tag{D.3.1.16}$$

and $\mathbf{c}$ in (D.3.1.8) such that

$$2\mathbf{P}^\top\left(\mathbf{V}\mathbf{c} + \mathbf{u}\right) = \eta \begin{pmatrix} 1 \\ 0 \end{pmatrix} \tag{D.3.1.17}$$

$$\mathbf{c}^\top\left(\mathbf{V}\mathbf{c} + \mathbf{u}\right) + \mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.18}$$

$\because \mathbf{P}^\top \mathbf{P} = \mathbf{I}$, multiplying (D.3.1.17) by $\mathbf{P}$ yields

$$(\mathbf{V}\mathbf{c} + \mathbf{u}) = \frac{\eta}{2}\mathbf{p}_1, \tag{D.3.1.19}$$

which, upon substituting in (D.3.1.18) results in

$$\frac{\eta}{2}\mathbf{c}^\top \mathbf{p}_1 + \mathbf{u}^\top \mathbf{c} + f = 0 \tag{D.3.1.20}$$

(D.3.1.19) and (D.3.1.20) can be clubbed together to obtain (E.2.1.2). $\square$

D.3.2. For the standard conic,

$$\mathbf{P} = \mathbf{I} \tag{D.3.2.1}$$

$$\mathbf{u} = \begin{cases} 0 & e \neq 1 \\ \frac{\eta}{2}\mathbf{e}_1 & e = 1 \end{cases} \tag{D.3.2.2}$$

$$\lambda_1 \begin{cases} = 0 & e = 1 \\ \neq 0 & e \neq 1 \end{cases} \tag{D.3.2.3}$$

where

$$\mathbf{I} = \begin{pmatrix} \mathbf{e}_1 & \mathbf{e}_2 \end{pmatrix} \tag{D.3.2.4}$$

is the identity matrix.

D.3.3.

(a) The directrices for the standard conic are given by

$$\mathbf{e}_1^\top \mathbf{y} = \pm\frac{1}{e}\sqrt{\frac{|f_0|}{\lambda_2\left(1-e^2\right)}} \qquad e \neq 1 \tag{D.3.3.1}$$

$$\mathbf{e}_1^\top \mathbf{y} = \frac{\eta}{2\lambda_2} \qquad e = 1 \tag{D.3.3.2}$$

(b) The foci of the standard ellipse and hyperbola are given by

$$\mathbf{F} = \begin{cases} \pm e\sqrt{\frac{|f_0|}{\lambda_2(1-e^2)}}\mathbf{e}_1 & e \neq 1 \\ -\frac{\eta}{4\lambda_2}\mathbf{e}_1 & e = 1 \end{cases} \tag{D.3.3.3}$$

Proof. (a) For the standard hyperbola/ellipse in (D.3.1.1), from (D.3.2.1), (D.1.3.2) and (D.3.2.2),

$$\mathbf{n} = \sqrt{\frac{\lambda_2}{f_0}}\mathbf{e}_1 \tag{D.3.3.4}$$

$$c = \pm\frac{\sqrt{-\frac{\lambda_2}{f_0}\left(e^2-1\right)\left(\frac{\lambda_2}{f_0}\right)}}{\frac{\lambda_2}{f_0}e\left(e^2-1\right)} \tag{D.3.3.5}$$

$$= \pm\frac{1}{e\sqrt{1-e^2}} \tag{D.3.3.6}$$

yielding (D.3.3.1) upon substituting from (D.1.3.1) and simplifying. For the standard parabola in (D.3.1.2), from (D.3.2.1), (D.1.3.2) and (D.3.2.2), noting that $f = 0$,

$$\mathbf{n} = \sqrt{\lambda_2}\mathbf{e}_1 \tag{D.3.3.7}$$

$$c = \frac{\left\|\frac{\eta}{2}\mathbf{e}_1\right\|^2}{2\left(\frac{\eta}{\mathbf{2}}\right)\left(\mathbf{e_1}\right)^\top \mathbf{n}} \tag{D.3.3.8}$$

$$\tag{D.3.3.9}$$

$$= \frac{\eta}{4\sqrt{\lambda_2}} \tag{D.3.3.10}$$

yielding (D.3.3.2).

(b) For the standard ellipse/hyperbola, substituting from (D.3.3.6), (D.3.3.4), (D.3.2.2) and (D.1.3.1) in (D.1.3.3),

$$\mathbf{F} = \pm\frac{\left(\frac{1}{e\sqrt{1-e^2}}\right)\left(e^2\right)\sqrt{\frac{\lambda_2}{f_0}}\mathbf{e}_1}{\frac{\lambda_2}{f_0}} \tag{D.3.3.11}$$

yielding (D.3.3.3) after simplification. For the standard parabola, substituting from (D.3.3.10), (D.3.3.7), (D.3.2.2) and (D.1.3.1) in (D.1.3.3),

$$\mathbf{F} = \frac{\left(\frac{\eta}{4\sqrt{\lambda_2}}\right)\sqrt{\lambda_2}\mathbf{e}_1 - \frac{\eta}{\mathbf{2}}\mathbf{e_1}}{\lambda_2} \tag{D.3.3.12}$$

$$\tag{D.3.3.13}$$

yielding (D.3.3.3) after simplification.

□

Appendix E

Conic Parameters

E.1. Standard Form

E.1.1. The center of the standard ellipse/hyperbola, defined to be the mid point of the line joining the foci, is the origin.

E.1.2. The principal (major) axis of the standard ellipse/hyperbola, defined to be the line joining the two foci is the x-axis.

Proof. From (D.3.3.3), 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. □

E.1.3. The minor axis of the standard ellipse/hyperbola, defined to be the line orthogonal to the x-axis is the y-axis.

E.1.4. 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 (D.3.3.7) and (D.3.3.3), the axis of the parabola can be expressed using

(C.1.2.1) as

$$\mathbf{e}_2^\top \left(\mathbf{y} + \frac{\eta}{4\lambda_2}\mathbf{e}_1\right) = 0 \tag{E.1.4.1}$$

$$\implies \mathbf{e}_2^\top \mathbf{y} = 0, \tag{E.1.4.2}$$

which is the equation of the x-axis. □

E.1.5. The point where the parabola intersects its axis of symmetry is called the vertex. For the standard parabola, the vertex is the origin.

Proof. (E.1.4.2) can be expressed as

$$\mathbf{y} = \alpha\mathbf{e}_1, \tag{E.1.5.1}$$

using (C.1.2.1). Substituting (E.1.5.1) in (D.3.1.2),

$$\alpha^2\mathbf{e}_1^\top \mathbf{D}\mathbf{e}_1 = -\eta\alpha\mathbf{e}_1^\top \mathbf{e}_1 \tag{E.1.5.2}$$

$$\implies \alpha = 0, \text{ or, } \mathbf{y} = \mathbf{0}. \tag{E.1.5.3}$$

□

E.1.6. 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 $\left|\frac{\eta}{4\lambda_2}\right|$

E.2. Quadratic Form

E.2.1. The center/vertex of a conic section are given by

$$\mathbf{c} = -\mathbf{V}^{-1}\mathbf{u} \qquad \left|\mathbf{V}\right| \neq 0 \tag{E.2.1.1}$$

$$\begin{pmatrix} \mathbf{u}^\top + \frac{\eta}{2}\mathbf{p}_1^\top \\ \mathbf{V} \end{pmatrix} \mathbf{c} = \begin{pmatrix} -f \\ \frac{\eta}{2}\mathbf{p}_1 - \mathbf{u} \end{pmatrix} \qquad \left|\mathbf{V}\right| = 0 \tag{E.2.1.2}$$

Proof. In (B.5.5.1), substituting $\mathbf{y} = \mathbf{0}$, the center/vertex for the quadratic form is obtained as

$$\mathbf{x} = \mathbf{c}, \tag{E.2.1.3}$$

where $\mathbf{c}$ is derived as (E.2.1.1) and (E.2.1.2) in Appendix D.3.1. □

E.2.2. The equation of the minor and major axes for the ellipse/hyperbola are respectively given by

$$\mathbf{p}_i^\top (\mathbf{x} - \mathbf{c}) = 0, i = 1, 2 \tag{E.2.2.1}$$

The axis of symmetry for the parabola is also given by (E.2.2.1).

Proof. From (E.1.2), the major/symmetry axis for the hyperbola/ellipse/parabola can be expressed using (B.5.5.1) as

$$\mathbf{e}_2^\top \mathbf{P}^\top (\mathbf{x} - \mathbf{c}) = 0 \tag{E.2.2.2}$$

$$\implies (\mathbf{P}\mathbf{e}_2)^\top (\mathbf{x} - \mathbf{c}) = 0 \tag{E.2.2.3}$$

yielding (E.2.2.1), and the proof for the minor axis is similar. $\square$

Appendix F

Conic Lines

F.1. Pair of Straight Lines

F.1.1. The asymptotes of the hyperbola in (D.3.1.1), defined to be the lines that do not intersect the hyperbola, are given by

$$\left(\sqrt{|\lambda_1|} \quad \pm\sqrt{|\lambda_2|}\right)\mathbf{y} = 0 \tag{F.1.1.1}$$

Proof. From (D.3.1.1), it is obvious that the pair of lines represented by

$$\mathbf{y}^\top \mathbf{D}\mathbf{y} = 0 \tag{F.1.1.2}$$

do not intersect the conic

$$\mathbf{y}^\top \mathbf{D}\mathbf{y} = f_0 \tag{F.1.1.3}$$

Thus, (F.1.1.2) represents the asysmptotes of the hyperbola in (D.3.1.1) and can be expressed as

$$\lambda_1 y_1^2 + \lambda_2 y_1^2 = 0, \tag{F.1.1.4}$$

which can then be simplified to obtain (F.1.1.1).

$\square$

F.1.2. (D.1.2.1) represents a pair of straight lines if

$$\mathbf{u}^\top \mathbf{V}^{-1}\mathbf{u} - f = 0 \tag{F.1.2.1}$$

F.1.3. (D.1.2.1) represents a pair of straight lines if the matrix

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u} & f \end{pmatrix} \tag{F.1.3.1}$$

is singular.

Proof. Let

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u} & f \end{pmatrix} \mathbf{x} = \mathbf{0} \tag{F.1.3.2}$$

Expressing

$$\mathbf{x} = \begin{pmatrix} \mathbf{y} \\ y_3 \end{pmatrix}, \tag{F.1.3.3}$$

$$\begin{pmatrix} \mathbf{V} & \mathbf{u} \\ \mathbf{u}^\top & f \end{pmatrix} \begin{pmatrix} \mathbf{y} \\ y_3 \end{pmatrix} = \mathbf{0} \tag{F.1.3.4}$$

$$\implies \mathbf{V}\mathbf{y} + y_3\mathbf{u} = \mathbf{0} \quad \text{and} \tag{F.1.3.5}$$

$$\mathbf{u}^\top\mathbf{y} + f y_3 = 0 \tag{F.1.3.6}$$

From (F.1.3.5) we obtain,

$$\mathbf{y}^\top\mathbf{V}\mathbf{y} + y_3\mathbf{y}^\top\mathbf{u} = \mathbf{0} \tag{F.1.3.7}$$

$$\implies \mathbf{y}^\top\mathbf{V}\mathbf{y} + y_3\mathbf{u}^\top\mathbf{y} = \mathbf{0} \tag{F.1.3.8}$$

yielding (F.1.2.1) upon substituting from (F.1.3.6). □

F.1.4. Using the affine transformation, (F.1.1.1) can be expressed as the lines

$$\begin{pmatrix} \sqrt{|\lambda_1|} & \pm\sqrt{|\lambda_2|} \end{pmatrix} \mathbf{P}^\top (\mathbf{x} - \mathbf{c}) = 0 \tag{F.1.4.1}$$

F.1.5. The angle between the asymptotes can be expressed as

$$\cos\theta = \frac{|\lambda_1| - |\lambda_2|}{|\lambda_1| + |\lambda_2|} \tag{F.1.5.1}$$

Proof. The normal vectors of the lines in (F.1.4.1) are

$$\begin{aligned} \mathbf{n}_1 &= \mathbf{P}\begin{pmatrix} \sqrt{|\lambda_1|} \\ \sqrt{|\lambda_2|} \end{pmatrix} \\ \mathbf{n}_2 &= \mathbf{P}\begin{pmatrix} \sqrt{|\lambda_1|} \\ -\sqrt{|\lambda_2|} \end{pmatrix} \end{aligned} \tag{F.1.5.2}$$

The angle between the asymptotes is given by

$$\cos\theta = \frac{\mathbf{n_1}^\top \mathbf{n_2}}{\|\mathbf{n_1}\| \, \|\mathbf{n_2}\|} \tag{F.1.5.3}$$

The orthogonal matrix $\mathbf{P}$ preserves the norm, i.e.

$$\|\mathbf{n_1}\| = \left\| \mathbf{P} \begin{pmatrix} \sqrt{|\lambda_1|} \\ \\ \sqrt{|\lambda_2|} \end{pmatrix} \right\| = \left\| \begin{pmatrix} \sqrt{|\lambda_1|} \\ \\ \sqrt{|\lambda_2|} \end{pmatrix} \right\| \tag{F.1.5.4}$$

$$= \sqrt{|\lambda_1| + |\lambda_2|} = \|\mathbf{n_2}\| \tag{F.1.5.5}$$

It is easy to verify that

$$\mathbf{n_1}^\top \mathbf{n_2} = |\lambda_1| - |\lambda_2| \tag{F.1.5.6}$$

Thus, the angle between the asymptotes is obtained from (F.1.5.3) as (F.1.5.1). □

F.2. Intersection of Conics

F.2.1. Let

$$\mathbf{x}^\top \mathbf{V}_i \mathbf{x} + 2\mathbf{u}_i^\top \mathbf{x} + f_i = 0, \quad i = 1, 2 \tag{F.2.1.1}$$

be the equation of two conics. The locus of their intersection is a pair of straight lines if

$$\begin{vmatrix} \mathbf{V}_1 + \mu \mathbf{V}_2 & \mathbf{u}_1 + \mu \mathbf{u}_2 \\ (\mathbf{u}_1 + \mu \mathbf{u}_2)^\top & f \end{vmatrix} = 0, \left| \mathbf{V}_1 + \mu \mathbf{V}_2 \right| < 0 \tag{F.2.1.2}$$

Proof. The intersection of the conics in (F.2.1.1) is given by the curve

$$\mathbf{x}^\top (\mathbf{V}_1 + \mu \mathbf{V}_2) \mathbf{x} + 2 (\mathbf{u}_1 + \mu \mathbf{u}_2)^\top \mathbf{x} + f_1 + \mu f_2 = 0, \tag{F.2.1.3}$$

which, from Theorem F.1.3 represents a pair of straight lines if (F.2.1.2) is satisfied. □

F.2.2. The points of intersection of the conics in (F.2.1.1) are the points of the intersection of the lines in (F.2.1.3).

F.3. Chords of a Conic

F.3.1. The points of intersection of the line

$$L: \quad \mathbf{x} = \mathbf{h} + \mu \mathbf{m} \quad \mu \in \mathbb{R} \tag{F.3.1.1}$$

with the conic section in (D.1.2.1) are given by

$$\mathbf{x}_i = \mathbf{h} + \mu_i \mathbf{m} \tag{F.3.1.2}$$

where

$$\mu_i = \frac{1}{\mathbf{m}^\top \mathbf{V}\mathbf{m}} \left(-\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) \right.$$
$$\left. \pm \sqrt{\left[\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u})\right]^2 - \mathrm{g}(\mathbf{h})(\mathbf{m}^\top \mathbf{V}\mathbf{m})}\right) \quad \text{(F.3.1.3)}$$

Proof. Substituting (F.3.1.1) in (D.1.2.1),

$$(\mathbf{h} + \mu\mathbf{m})^\top \mathbf{V}(\mathbf{h} + \mu\mathbf{m}) + 2\mathbf{u}^\top (\mathbf{h} + \mu\mathbf{m}) + f = 0 \quad \text{(F.3.1.4)}$$
$$\implies \mu^2 \mathbf{m}^\top \mathbf{V}\mathbf{m} + 2\mu\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) + \mathbf{h}^\top \mathbf{V}\mathbf{h} + 2\mathbf{u}^\top \mathbf{h} + f = 0 \quad \text{(F.3.1.5)}$$
$$\text{or, } \mu^2 \mathbf{m}^\top \mathbf{V}\mathbf{m} + 2\mu\mathbf{m}^\top (\mathbf{V}\mathbf{h} + \mathbf{u}) + \mathrm{g}(\mathbf{h}) = 0 \quad \text{(F.3.1.6)}$$

for g defined in (D.1.2.1). Solving the above quadratic in (F.3.1.6) yields (F.3.1.3). □

F.3.2. If L in (F.3.1.1) touches (D.1.2.1) at exactly one point $\mathbf{q}$,

$$\mathbf{m}^\top (\mathbf{V}\mathbf{q} + \mathbf{u}) = 0 \quad \text{(F.3.2.1)}$$

Proof. In this case, (F.3.1.6) has exactly one root. Hence, in (F.3.1.3)

$$\left[\mathbf{m}^\top (\mathbf{V}\mathbf{q} + \mathbf{u})\right]^2 - \left(\mathbf{m}^\top \mathbf{V}\mathbf{m}\right) \mathrm{g}(\mathbf{q}) = 0 \quad \text{(F.3.2.2)}$$

$\because$ $\mathbf{q}$ is the point of contact,

$$\mathrm{g}(\mathbf{q}) = 0 \quad \text{(F.3.2.3)}$$

Substituting (F.3.2.3) in (F.3.2.2) and simplifying, we obtain (F.3.2.1). □

F.3.3. The length of the chord in (F.3.1.1) is given by

$$\frac{2\sqrt{\left[\mathbf{m}^\top\left(\mathbf{V}\mathbf{h}+\mathbf{u}\right)\right]^2-\left(\mathbf{h}^\top\mathbf{V}\mathbf{h}+2\mathbf{u}^\top\mathbf{h}+f\right)\left(\mathbf{m}^\top\mathbf{V}\mathbf{m}\right)}}{\mathbf{m}^\top\mathbf{V}\mathbf{m}}\left\|\mathbf{m}\right\| \tag{F.3.3.1}$$

Proof. The distance between the points in (F.3.1.2) is given by

$$\left\|\mathbf{x}_1-\mathbf{x}_2\right\| = \left|\mu_1-\mu_2\right|\left\|\mathbf{m}\right\| \tag{F.3.3.2}$$

Substituing μ_i from (F.3.1.3) in (F.3.3.2) yields (F.3.3.1). □

F.3.4. 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

$$\mathbf{x}_i = \mathbf{P}\mathbf{y}_i + \mathbf{c} \tag{F.3.4.1}$$

be any two points on the conic. Then the distance between the points is given by

$$\left\|\mathbf{x}_1-\mathbf{x}_2\right\| = \left\|\mathbf{P}\left(\mathbf{y}_1-\mathbf{y}_2\right)\right\| \tag{F.3.4.2}$$

which can be expressed as

$$\left\|\mathbf{x}_1-\mathbf{x}_2\right\|^2 = \left(\mathbf{y}_1-\mathbf{y}_2\right)^\top\mathbf{P}^\top\mathbf{P}\left(\mathbf{y}_1-\mathbf{y}_2\right) \tag{F.3.4.3}$$

$$= \left\|\mathbf{y}_1-\mathbf{y}_2\right\|^2 \tag{F.3.4.4}$$

since

$$\mathbf{P}^\top \mathbf{P} = \mathbf{I} \tag{F.3.4.5}$$

$\square$

F.3.5. For the standard hyperbola/ellipse, the length of the major axis is

$$2\sqrt{\left|\frac{f_0}{\lambda_1}\right|} \tag{F.3.5.1}$$

and the minor axis is

$$2\sqrt{\left|\frac{f_0}{\lambda_2}\right|} \tag{F.3.5.2}$$

Proof. Since the major axis passes through the origin,

$$\mathbf{q} = \mathbf{0} \tag{F.3.5.3}$$

Further, from Corollary (E.1.2),

$$\mathbf{m} = \mathbf{e}_2, \tag{F.3.5.4}$$

and from (D.3.1.1),

$$\mathbf{V} = \frac{\mathbf{D}}{f_0}, \mathbf{u} = 0, f = -1 \tag{F.3.5.5}$$

Substituting the above in (F.3.3.1),

$$\frac{2\sqrt{\mathbf{e}_1^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_1}}{\mathbf{e}_1^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_1} \|\mathbf{e}_1\| \tag{F.3.5.6}$$

yielding (F.3.5.1). Similarly, for the minor axis, the only different parameter is

$$\mathbf{m} = \mathbf{e}_2, \tag{F.3.5.7}$$

Substituting the above in (F.3.3.1),

$$\frac{2\sqrt{\mathbf{e}_2^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_2}}{\mathbf{e}_2^\top \frac{\mathbf{D}}{f_0} \mathbf{e}_2} \|\mathbf{e}_2\| \tag{F.3.5.8}$$

yielding (F.3.5.2).

□

F.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

$$l = \begin{cases} 2\frac{\sqrt{|f_0\lambda_1|}}{\lambda_2} & e \neq 1 \\ \frac{\eta}{\lambda_2} & e = 1 \end{cases} \tag{F.3.6.1}$$

Proof. The latus rectum is perpendicular to the major axis for the standard conic. Hence, from Corollary (E.1.2),

$$\mathbf{m} = \mathbf{e}_2, \tag{F.3.6.2}$$

Since it passes through the focus, from (D.3.3.3)

$$\mathbf{q} = \mathbf{F} = \pm e\sqrt{\frac{f_0}{\lambda_2\left(1-e^2\right)}}\mathbf{e}_1 \tag{F.3.6.3}$$

for the standard hyperbola/ellipse. Also, from (D.3.1.1),

$$\mathbf{V} = \frac{\mathbf{D}}{f_0}, \mathbf{u} = 0, f = -1 \tag{F.3.6.4}$$

Substituting the above in (F.3.3.1),

$$\frac{2\sqrt{\left[\mathbf{e}_2^\top\left(\frac{\mathbf{D}}{f_0}e\sqrt{\frac{f_0}{\lambda_2(1-e^2)}}\mathbf{e}_1\right)\right]^2 - \left(e\sqrt{\frac{f_0}{\lambda_2(1-e^2)}}\mathbf{e}_1^\top\frac{\mathbf{D}}{f_0}e\sqrt{\frac{f_0}{\lambda_2(1-e^2)}}\mathbf{e}_1 - 1\right)\left(\mathbf{e}_2^\top\frac{\mathbf{D}}{f_0}\mathbf{e}_2\right)}}{\mathbf{e}_2^\top\frac{\mathbf{D}}{f_0}\mathbf{e}_2}\left\|\mathbf{e}_2\right\| \tag{F.3.6.5}$$

Since

$$\mathbf{e}_2^\top\mathbf{D}\mathbf{e}_1 = 0, \mathbf{e}_1^\top\mathbf{D}\mathbf{e}_1 = \lambda_1, \mathbf{e}_1^\top\mathbf{e}_1 = 1, \left\|\mathbf{e}_2\right\| = 1, \mathbf{e}_2^\top\mathbf{D}\mathbf{e}_2 = \lambda_2, \tag{F.3.6.6}$$

(F.3.6.5) can be expressed as

$$\begin{aligned}
&\frac{2\sqrt{\left(1-\frac{\lambda_1e^2}{\lambda_2(1-e^2)}\right)\left(\frac{\lambda_2}{f_0}\right)}}{\frac{\lambda_2}{f_0}} && \text{(F.3.6.7)}\\
&= 2\frac{\sqrt{f_0\lambda_1}}{\lambda_2} \qquad \left(\because e^2 = 1-\frac{\lambda_1}{\lambda_2}\right) && \text{(F.3.6.8)}
\end{aligned}$$

For the standard parabola, the parameters in (F.3.3.1) are

$$\mathbf{q} = \mathbf{F} = -\frac{\eta}{4\lambda_2}\mathbf{e}_1, \mathbf{m} = \mathbf{e}_1, \mathbf{V} = \mathbf{D}, \mathbf{u} = \frac{\eta}{2}\mathbf{e}_1^\top, f = 0 \tag{F.3.6.9}$$

Substituting the above in (F.3.3.1), the length of the latus rectum can be expressed as

$$2\frac{\sqrt{\left[\mathbf{e}_2^\top\left(\mathbf{D}\left(-\frac{\eta}{4\lambda_2}\mathbf{e}_1\right)+\frac{\eta}{2}\mathbf{e}_1\right)\right]^2-\left(\left(-\frac{\eta}{4\lambda_2}\mathbf{e}_1\right)^\top\mathbf{D}\left(-\frac{\eta}{4\lambda_2}\mathbf{e}_1\right)+2\frac{\eta}{2}\mathbf{e}_1^\top\left(-\frac{\eta}{4\lambda_2}\mathbf{e}_1\right)\right)\left(\mathbf{e}_2^\top\mathbf{D}\mathbf{e}_2\right)}}{\mathbf{e}_2^\top\mathbf{D}\mathbf{e}_2}\left\|\mathbf{e}_2\right\| \tag{F.3.6.10}$$

Since

$$\mathbf{e}_2^\top\mathbf{D}\mathbf{e}_1=0, \mathbf{e}_2^\top\mathbf{e}_2=0, \mathbf{e}_1^\top\mathbf{D}\mathbf{e}_1=0, \mathbf{e}_1^\top\mathbf{e}_1=1, \left\|\mathbf{e}_1\right\|=1, \mathbf{e}_2^\top\mathbf{D}\mathbf{e}_2=\lambda_2, \tag{F.3.6.11}$$

(F.3.6.10) can be expressed as

$$2\frac{\sqrt{\frac{\eta^2}{4\lambda_2}\lambda_2}}{\lambda_2}=\frac{\eta}{\lambda_2} \tag{F.3.6.12}$$

□

F.4. Tangent and Normal

F.4.1. Given the point of contact $\mathbf{q}$, the equation of a tangent to (D.1.2.1) is

$$\left(\mathbf{V}\mathbf{q}+\mathbf{u}\right)^\top\mathbf{x}+\mathbf{u}^\top\mathbf{q}+f=0 \tag{F.4.1.1}$$

Proof. The normal vector is obtained from (F.3.2.1) and (A.1.20.1) as

$$\kappa\mathbf{n}=\mathbf{V}\mathbf{q}+\mathbf{u}, \kappa\in\mathbb{R} \tag{F.4.1.2}$$

From (F.4.1.2) and (C.1.2.1), the equation of the tangent is

$$\left(\mathbf{V}\mathbf{q}+\mathbf{u}\right)^{\top}\left(\mathbf{x}-\mathbf{q}\right)=0 \tag{F.4.1.3}$$

$$\implies \left(\mathbf{V}\mathbf{q}+\mathbf{u}\right)^{\top}\mathbf{x}-\mathbf{q}^{\top}\mathbf{V}\mathbf{q}-\mathbf{u}^{\top}\mathbf{q}=0 \tag{F.4.1.4}$$

which, upon substituting from (F.3.2.3) and simplifying yields (F.4.1.1) □

F.4.2. Given the point of contact $\mathbf{q}$, the equation of the normal to (D.1.2.1) is

$$\left(\mathbf{V}\mathbf{q}+\mathbf{u}\right)^{\top}\mathbf{R}\left(\mathbf{x}-\mathbf{q}\right)=0 \tag{F.4.2.1}$$

Proof. The direction vector of the tangent is obtained from (F.4.1.2) as as

$$\mathbf{m}=\mathbf{R}\left(\mathbf{V}\mathbf{q}+\mathbf{u}\right), \tag{F.4.2.2}$$

where $\mathbf{R}$ is the rotation matrix. From (F.4.2.2) and (C.1.2.1), the equation of the normal is given by (F.4.2.1) □

F.4.3. Given the tangent

$$\mathbf{n}^{\top}\mathbf{x}=c, \tag{F.4.3.1}$$

the point of contact to the conic in (D.1.2.1) is given by

$$\begin{pmatrix}\mathbf{n}^{\top}\\ \mathbf{m}^{\top}\mathbf{V}\end{pmatrix}\mathbf{q}=\begin{pmatrix}c\\ -\mathbf{m}^{\top}\mathbf{u}\end{pmatrix} \tag{F.4.3.2}$$

Proof. From (F.3.2.1),

$$\mathbf{m}^\top(\mathbf{V}\mathbf{q}+\mathbf{u})=0 \tag{F.4.3.3}$$

$$\implies \mathbf{m}^\top\mathbf{V}\mathbf{q}=-\mathbf{m}^\top\mathbf{u} \tag{F.4.3.4}$$

Combining (F.4.3.1) and (F.4.3.4), (F.4.3.2) is obtained.

$\square$

F.4.4. If $\mathbf{V}^{-1}$ exists, given the normal vector $\mathbf{n}$, the tangent points of contact to (D.1.2.1) are given by

$$\begin{aligned}\mathbf{q}_i &= \mathbf{V}^{-1}\left(\kappa_i\mathbf{n}-\mathbf{u}\right), i=1,2\\ \text{where } \kappa_i &= \pm\sqrt{\frac{f_0}{\mathbf{n}^\top\mathbf{V}^{-1}\mathbf{n}}}\end{aligned} \tag{F.4.4.1}$$

Proof. From (F.4.1.2),

$$\mathbf{q}=\mathbf{V}^{-1}\left(\kappa\mathbf{n}-\mathbf{u}\right),\quad \kappa\in\mathbb{R} \tag{F.4.4.2}$$

Substituting (F.4.4.2) in (F.3.2.3),

$$\left(\kappa\mathbf{n}-\mathbf{u}\right)^\top\mathbf{V}^{-1}\left(\kappa\mathbf{n}-\mathbf{u}\right)+2\mathbf{u}^\top\mathbf{V}^{-1}\left(\kappa\mathbf{n}-\mathbf{u}\right)+f=0 \tag{F.4.4.3}$$

$$\implies \kappa^2\mathbf{n}^\top\mathbf{V}^{-1}\mathbf{n}-\mathbf{u}^\top\mathbf{V}^{-1}\mathbf{u}+f=0 \tag{F.4.4.4}$$

$$\text{or, } \kappa=\pm\sqrt{\frac{f_0}{\mathbf{n}^\top\mathbf{V}^{-1}\mathbf{n}}} \tag{F.4.4.5}$$

Substituting (F.4.4.5) in (F.4.4.2) yields (F.4.4.1). $\square$

F.4.5. For a conic/hyperbola, a line with normal vector $\mathbf{n}$ cannot be a tangent if

$$\frac{\mathbf{u}^\top \mathbf{V}^{-1}\mathbf{u} - f}{\mathbf{n}^\top \mathbf{V}^{-1}\mathbf{n}} < 0 \tag{F.4.5.1}$$

F.4.6. For a circle,

$$\mathbf{q}_{ij} = \left(\pm r \frac{\mathbf{n}_j}{\|\mathbf{n}_j\|} - \mathbf{u}\right), \quad i, j = 1, 2 \tag{F.4.6.1}$$

Proof. From (F.4.4.1), and (D.2.2.1),

$$\kappa_{ij} = \pm \frac{r}{\|\mathbf{n}_j\|} \tag{F.4.6.2}$$

□

F.4.7. If $\mathbf{V}$ is not invertible, given the normal vector $\mathbf{n}$, the point of contact to (D.1.2.1) is given by the matrix equation

$$\begin{pmatrix} (\mathbf{u} + \kappa \mathbf{n})^\top \\ \mathbf{V} \end{pmatrix} \mathbf{q} = \begin{pmatrix} -f \\ \kappa \mathbf{n} - \mathbf{u} \end{pmatrix} \tag{F.4.7.1}$$

$$\text{where } \kappa = \frac{\mathbf{p}_1^\top \mathbf{u}}{\mathbf{p}_1^\top \mathbf{n}}, \quad \mathbf{V}\mathbf{p}_1 = 0 \tag{F.4.7.2}$$

Proof. If $\mathbf{V}$ is non-invertible, it has a zero eigenvalue. If the corresponding eigenvector is $\mathbf{p}_1$, then,

$$\mathbf{V}\mathbf{p}_1 = 0 \tag{F.4.7.3}$$

From (F.4.1.2),

$$\kappa\mathbf{n} = \mathbf{V}\mathbf{q} + \mathbf{u}, \quad \kappa \in \mathbb{R} \tag{F.4.7.4}$$

$$\implies \kappa\mathbf{p}_1^\top\mathbf{n} = \mathbf{p}_1^\top\mathbf{V}\mathbf{q} + \mathbf{p}_1^\top\mathbf{u} \tag{F.4.7.5}$$

$$\text{or, } \kappa\mathbf{p}_1^\top\mathbf{n} = \mathbf{p}_1^\top\mathbf{u}, \quad \because \mathbf{p}_1^\top\mathbf{V} = 0, \quad (\text{ from (F.4.7.3)}) \tag{F.4.7.6}$$

yielding κ in (F.4.7.2). From (F.4.7.4),

$$\kappa\mathbf{q}^\top\mathbf{n} = \mathbf{q}^\top\mathbf{V}\mathbf{q} + \mathbf{q}^\top\mathbf{u} \tag{F.4.7.7}$$

$$\implies \kappa\mathbf{q}^\top\mathbf{n} = -f - \mathbf{q}^\top\mathbf{u} \quad \text{from (F.3.2.3),} \tag{F.4.7.8}$$

$$\text{or, } \left(\kappa\mathbf{n} + \mathbf{u}\right)^\top\mathbf{q} = -f \tag{F.4.7.9}$$

(F.4.7.4) can be expressed as

$$\mathbf{V}\mathbf{q} = \kappa\mathbf{n} - \mathbf{u}. \tag{F.4.7.10}$$

(F.4.7.9) and (F.4.7.10) clubbed together result in (F.4.7.1). □

F.4.8. A point $\mathbf{h}$ lies on a tangent to the conic in (D.1.2.1) if

$$\mathbf{m}^\top\left[\left(\mathbf{V}\mathbf{h} + \mathbf{u}\right)\left(\mathbf{V}\mathbf{h} + \mathbf{u}\right)^\top - \mathbf{V}\mathrm{g}\left(\mathbf{h}\right)\right]\mathbf{m} = 0 \tag{F.4.8.1}$$

Proof. From (F.3.1.3) and (F.3.2.2)

$$\left[\mathbf{m}^\top\left(\mathbf{V}\mathbf{h} + \mathbf{u}\right)\right]^2 - \left(\mathbf{m}^\top\mathbf{V}\mathbf{m}\right)\mathrm{g}\left(\mathbf{h}\right) = 0 \tag{F.4.8.2}$$

yielding (F.4.8.1). □

F.4.9. The normal vectors of the tangents to the conic in (D.1.2.1) from a point $\mathbf{h}$ are given by

$$\begin{aligned}\mathbf{n}_1 &= \mathbf{P}\begin{pmatrix}\sqrt{|\lambda_1|}\\ \sqrt{|\lambda_2|}\end{pmatrix}\\ \mathbf{n}_2 &= \mathbf{P}\begin{pmatrix}\sqrt{|\lambda_1|}\\ -\sqrt{|\lambda_2|}\end{pmatrix}\end{aligned} \tag{F.4.9.1}$$

where $\lambda_i, \mathbf{P}$ are the eigenparameters of

$$\mathbf{\Sigma} = \left(\mathbf{V}\mathbf{h} + \mathbf{u}\right)\left(\mathbf{V}\mathbf{h} + \mathbf{u}\right)^\top - \left(\mathrm{g}\left(\mathbf{h}\right)\right)\mathbf{V}. \tag{F.4.9.2}$$

Proof. From (F.4.8.1) we obtain (F.4.9.2). Consequently, from (F.1.5.2), (F.4.9.1) can be obtained. ☐

F.4.10. A point $\mathbf{h}$ lies on a normal to the conic in (D.1.2.1) if

$$\left(\mathbf{m}^\top(\mathbf{V}\mathbf{h} + \mathbf{u})\right)^2\left(\mathbf{n}^\top\mathbf{V}\mathbf{n}\right) - 2\left(\mathbf{m}^\top\mathbf{V}\mathbf{n}\right)\left(\mathbf{m}^\top(\mathbf{V}\mathbf{h} + \mathbf{u})\mathbf{n}^\top\left(\mathbf{V}\mathbf{h} + \mathbf{u}\right)\right) \\ + \mathrm{g}\left(\mathbf{h}\right)\left(\mathbf{m}^\top\mathbf{V}\mathbf{n}\right)^2 = 0 \tag{F.4.10.1}$$

Proof. The point of contact for the normal passing through a point $\mathbf{h}$ is given by

$$\mathbf{q} = \mathbf{h} + \mu\mathbf{n} \tag{F.4.10.2}$$

From (F.3.2.1), the tangent at $\mathbf{q}$ satisfies

$$\mathbf{m}^\top(\mathbf{V}\mathbf{q} + \mathbf{u}) = 0 \tag{F.4.10.3}$$

Substituting (F.4.10.2) in (F.4.10.3),

$$\mathbf{m}^\top(\mathbf{V}(\mathbf{h}+\mu\mathbf{n})+\mathbf{u})=0 \tag{F.4.10.4}$$

$$\implies \mu\mathbf{m}^\top\mathbf{V}\mathbf{n}=-\mathbf{m}^\top(\mathbf{V}\mathbf{h}+\mathbf{u}) \tag{F.4.10.5}$$

yielding

$$\mu=-\frac{\mathbf{m}^\top(\mathbf{V}\mathbf{h}+\mathbf{u})}{\mathbf{m}^\top\mathbf{V}\mathbf{n}}, \tag{F.4.10.6}$$

From (F.3.1.6),

$$\mu^2\mathbf{n}^\top\mathbf{V}\mathbf{n}+2\mu\mathbf{n}^\top\left(\mathbf{V}\mathbf{h}+\mathbf{u}\right)+\mathrm{g}\left(\mathbf{h}\right)=0 \tag{F.4.10.7}$$

From (F.4.10.6), (F.4.10.7) can be expressed as

$$\left(-\frac{\mathbf{m}^\top(\mathbf{V}\mathbf{h}+\mathbf{u})}{\mathbf{m}^\top\mathbf{V}\mathbf{n}}\right)^2\mathbf{n}^\top\mathbf{V}\mathbf{n}+2\left(-\frac{\mathbf{m}^\top(\mathbf{V}\mathbf{h}+\mathbf{u})}{\mathbf{m}^\top\mathbf{V}\mathbf{n}}\right)\mathbf{n}^\top\left(\mathbf{V}\mathbf{h}+\mathbf{u}\right)+\mathrm{g}\left(\mathbf{h}\right)=0 \tag{F.4.10.8}$$

yielding (F.4.10.1). □