

A third method for visualizing the twisted cubic is to realize that it also lies on the cylinder $z = x^3$. So it can be viewed as the curve of intersection of the cylinders $y = x^2$ and $z = x^3$. (See Figure 11.)

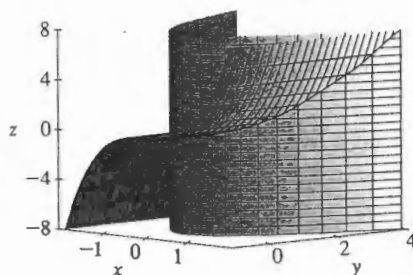
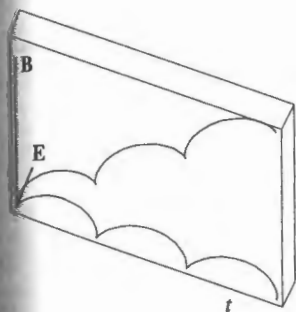


FIGURE 11

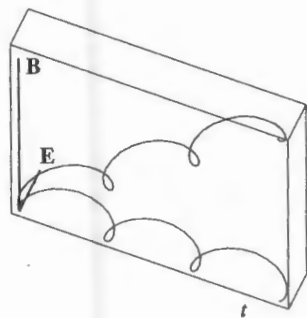
TEC Visual 13.1C shows how curves arise as intersections of surfaces.

Some computer algebra systems provide us with a clearer picture of a space curve by enclosing it in a tube. Such a plot enables us to see whether one part of a curve passes in front of or behind another part of the curve. For example, Figure 13 shows the curve of Figure 12(b) as rendered by the `tubeplot` command in Maple.

We have seen that an interesting space curve, the helix, occurs in the model of DNA. Another notable example of a space curve in science is the trajectory of a positively charged particle in orthogonally oriented electric and magnetic fields \mathbf{E} and \mathbf{B} . Depending on the initial velocity given the particle at the origin, the path of the particle is either a space curve whose projection on the horizontal plane is the cycloid we studied in Section 10.1 [Figure 12(a)] or a curve whose projection is the trochoid investigated in Exercise 40 in Section 10.1 [Figure 12(b)].



$$(a) \mathbf{r}(t) = \langle t - \sin t, 1 - \cos t, t \rangle$$



$$(b) \mathbf{r}(t) = \langle t - \frac{3}{2} \sin t, 1 - \frac{3}{2} \cos t, t \rangle$$

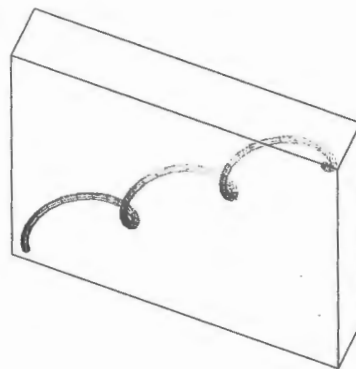


FIGURE 13

FIGURE 12

Motion of a charged particle in orthogonally oriented electric and magnetic fields

For further details concerning the physics involved and animations of the trajectories of the particles, see the following web sites:

- www.phy.ntnu.edu.tw/java/emField/emField.html
- www.physics.ucla.edu/plasma-exp/Beam/

Exercises

1–2 Find the domain of the vector function.

$$1. \mathbf{r}(t) = \langle \sqrt{4 - t^2}, e^{-3t}, \ln(t + 1) \rangle$$

$$2. \mathbf{r}(t) = \frac{t-2}{t+2} \mathbf{i} + \sin t \mathbf{j} + \ln(9 - t^2) \mathbf{k}$$

3–6 Find the limit.

$$3. \lim_{t \rightarrow 0} \left(e^{-3t} \mathbf{i} + \frac{t^2}{\sin^2 t} \mathbf{j} + \cos 2t \mathbf{k} \right)$$

$$4. \lim_{t \rightarrow 1} \left(\frac{t^2 - t}{t - 1} \mathbf{i} + \sqrt{t + 8} \mathbf{j} + \frac{\sin \pi t}{\ln t} \mathbf{k} \right)$$

graphing calculator or computer required

1. Homework Hints available at stewartcalculus.com

$$5. \lim_{t \rightarrow \infty} \left\langle \frac{1+t^2}{1-t^2}, \tan^{-1} t, \frac{1-e^{-2t}}{t} \right\rangle$$

$$6. \lim_{t \rightarrow \infty} \left\langle te^{-t}, \frac{t^3+t}{2t^3-1}, t \sin \frac{1}{t} \right\rangle$$

7–14 Sketch the curve with the given vector equation. Indicate with an arrow the direction in which t increases.

$$7. \mathbf{r}(t) = \langle \sin t, t \rangle$$

$$8. \mathbf{r}(t) = \langle t^3, t^2 \rangle$$

$$9. \mathbf{r}(t) = \langle t, 2-t, 2t \rangle$$

$$10. \mathbf{r}(t) = \langle \sin \pi t, t, \cos \pi t \rangle$$

$$11. \mathbf{r}(t) = \langle 1, \cos t, 2 \sin t \rangle$$

$$12. \mathbf{r}(t) = t^2 \mathbf{i} + t \mathbf{j} + 2 \mathbf{k}$$

$$13. \mathbf{r}(t) = t^2 \mathbf{i} + t^4 \mathbf{j} + t^6 \mathbf{k}$$

$$14. \mathbf{r}(t) = \cos t \mathbf{i} - \cos t \mathbf{j} + \sin t \mathbf{k}$$

15–16 Draw the projections of the curve on the three coordinate planes. Use these projections to help sketch the curve.

$$15. \mathbf{r}(t) = \langle t, \sin t, 2 \cos t \rangle$$

$$16. \mathbf{r}(t) = \langle t, t, t^2 \rangle$$

17–20 Find a vector equation and parametric equations for the line segment that joins P to Q .

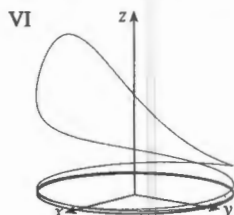
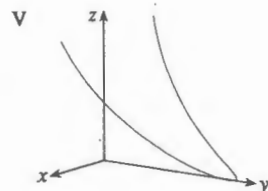
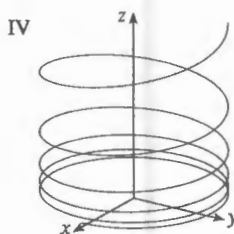
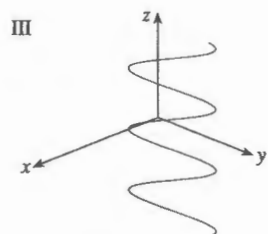
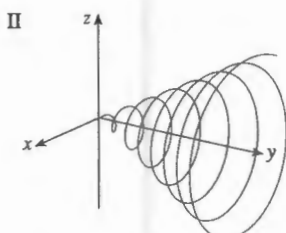
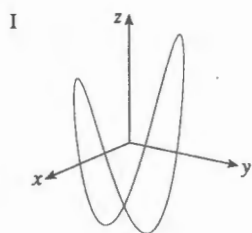
$$17. P(2, 0, 0), Q(6, 2, -2)$$

$$18. P(-1, 2, -2), Q(-3, 5, 1)$$

$$19. P(0, -1, 1), Q\left(\frac{1}{2}, \frac{1}{3}, \frac{1}{4}\right)$$

$$20. P(a, b, c), Q(u, v, w)$$

21–26 Match the parametric equations with the graphs (labeled I–VI). Give reasons for your choices.



$$21. x = t \cos t, y = t, z = t \sin t, t \geq 0$$

$$22. x = \cos t, y = \sin t, z = 1/(1+t^2)$$

$$23. x = t, y = 1/(1+t^2), z = t^2$$

$$24. x = \cos t, y = \sin t, z = \cos 2t$$

$$25. x = \cos 8t, y = \sin 8t, z = e^{0.8t}, t \geq 0$$

$$26. x = \cos^2 t, y = \sin^2 t, z = t$$

27. Show that the curve with parametric equations $x = t \cos t$, $y = t \sin t$, $z = t$ lies on the cone $z^2 = x^2 + y^2$, and use this fact to help sketch the curve.

28. Show that the curve with parametric equations $x = \sin t$, $y = \cos t$, $z = \sin^2 t$ is the curve of intersection of the surfaces $z = x^2$ and $x^2 + y^2 = 1$. Use this fact to help sketch the curve.

29. At what points does the curve $\mathbf{r}(t) = t \mathbf{i} + (2t - t^2) \mathbf{k}$ intersect the paraboloid $z = x^2 + y^2$?

30. At what points does the helix $\mathbf{r}(t) = \langle \sin t, \cos t, t \rangle$ intersect the sphere $x^2 + y^2 + z^2 = 5$?

31–35 Use a computer to graph the curve with the given vector equation. Make sure you choose a parameter domain and view points that reveal the true nature of the curve.

$$31. \mathbf{r}(t) = \langle \cos t \sin 2t, \sin t \sin 2t, \cos 2t \rangle$$

$$32. \mathbf{r}(t) = \langle t^2, \ln t, t \rangle$$

$$33. \mathbf{r}(t) = \langle t, t \sin t, t \cos t \rangle$$

$$34. \mathbf{r}(t) = \langle t, e^t, \cos t \rangle$$

$$35. \mathbf{r}(t) = \langle \cos 2t, \cos 3t, \cos 4t \rangle$$

36. Graph the curve with parametric equations $x = \sin t$, $y = \sin 2t$, $z = \cos 4t$. Explain its shape by graphing its projections onto the three coordinate planes.

37. Graph the curve with parametric equations

$$x = (1 + \cos 16t) \cos t$$

$$y = (1 + \cos 16t) \sin t$$

$$z = 1 + \cos 16t$$

Explain the appearance of the graph by showing that it lies on a cone.

38. Graph the curve with parametric equations

$$x = \sqrt{1 - 0.25 \cos^2 10t} \cos t$$

$$y = \sqrt{1 - 0.25 \cos^2 10t} \sin t$$

$$z = 0.5 \cos 10t$$

Explain the appearance of the graph by showing that it lies on a sphere.

39. Show that the curve with parametric equations $x = t^2$, $y = 1 - 3t$, $z = 1 + t^3$ passes through the points $(1, 4, 0)$ and $(9, -8, 28)$ but not through the point $(4, 7, -6)$.

40–44 Find a vector function that represents the curve of intersection of the two surfaces.

40. The cylinder $x^2 + y^2 = 4$ and the surface $z = xy$

41. The cone $z = \sqrt{x^2 + y^2}$ and the plane $z = 1 + y$

42. The paraboloid $z = 4x^2 + y^2$ and the parabolic cylinder $y = x^2$

43. The hyperboloid $z = x^2 - y^2$ and the cylinder $x^2 + y^2 = 1$

44. The semiellipsoid $x^2 + y^2 + 4z^2 = 4$, $y \geq 0$, and the cylinder $x^2 + z^2 = 1$

45. Try to sketch by hand the curve of intersection of the circular cylinder $x^2 + y^2 = 4$ and the parabolic cylinder $z = x^2$. Then find parametric equations for this curve and use these equations and a computer to graph the curve.

46. Try to sketch by hand the curve of intersection of the parabolic cylinder $y = x^2$ and the top half of the ellipsoid $x^2 + 4y^2 + 4z^2 = 16$. Then find parametric equations for this curve and use these equations and a computer to graph the curve.

47. If two objects travel through space along two different curves, it's often important to know whether they will collide. (Will a missile hit its moving target? Will two aircraft collide?) The curves might intersect, but we need to know whether the objects are in the same position *at the same time*. Suppose the trajectories of two particles are given by the vector functions

$$\mathbf{r}_1(t) = \langle t^2, 7t - 12, t^2 \rangle \quad \mathbf{r}_2(t) = \langle 4t - 3, t^2, 5t - 6 \rangle$$

for $t \geq 0$. Do the particles collide?

48. Two particles travel along the space curves

$$\mathbf{r}_1(t) = \langle t, t^2, t^3 \rangle \quad \mathbf{r}_2(t) = \langle 1 + 2t, 1 + 6t, 1 + 14t \rangle$$

Do the particles collide? Do their paths intersect?

49. Suppose \mathbf{u} and \mathbf{v} are vector functions that possess limits as $t \rightarrow a$ and let c be a constant. Prove the following properties of limits.

$$(a) \lim_{t \rightarrow a} [\mathbf{u}(t) + \mathbf{v}(t)] = \lim_{t \rightarrow a} \mathbf{u}(t) + \lim_{t \rightarrow a} \mathbf{v}(t)$$

$$(b) \lim_{t \rightarrow a} c\mathbf{u}(t) = c \lim_{t \rightarrow a} \mathbf{u}(t)$$

$$(c) \lim_{t \rightarrow a} [\mathbf{u}(t) \cdot \mathbf{v}(t)] = \lim_{t \rightarrow a} \mathbf{u}(t) \cdot \lim_{t \rightarrow a} \mathbf{v}(t)$$

$$(d) \lim_{t \rightarrow a} [\mathbf{u}(t) \times \mathbf{v}(t)] = \lim_{t \rightarrow a} \mathbf{u}(t) \times \lim_{t \rightarrow a} \mathbf{v}(t)$$

50. The view of the trefoil knot shown in Figure 8 is accurate, but it doesn't reveal the whole story. Use the parametric equations

$$x = (2 + \cos 1.5t) \cos t$$

$$y = (2 + \cos 1.5t) \sin t$$

$$z = \sin 1.5t$$

to sketch the curve by hand as viewed from above, with gaps indicating where the curve passes over itself. Start by showing that the projection of the curve onto the xy -plane has polar coordinates $r = 2 + \cos 1.5t$ and $\theta = t$, so r varies between 1 and 3. Then show that z has maximum and minimum values when the projection is halfway between $r = 1$ and $r = 3$.

- When you have finished your sketch, use a computer to draw the curve with viewpoint directly above and compare with your sketch. Then use the computer to draw the curve from several other viewpoints. You can get a better impression of the curve if you plot a tube with radius 0.2 around the curve. (Use the `tubeplot` command in Maple or the `tubecurve` or `Tube` command in Mathematica.)

51. Show that $\lim_{t \rightarrow a} \mathbf{r}(t) = \mathbf{b}$ if and only if for every $\varepsilon > 0$ there is a number $\delta > 0$ such that

$$\text{if } 0 < |t - a| < \delta \text{ then } |\mathbf{r}(t) - \mathbf{b}| < \varepsilon$$

2 Derivatives and Integrals of Vector Functions

Later in this chapter we are going to use vector functions to describe the motion of planets and other objects through space. Here we prepare the way by developing the calculus of vector functions.

Derivatives

The **derivative** \mathbf{r}' of a vector function \mathbf{r} is defined in much the same way as for real-valued functions:

1

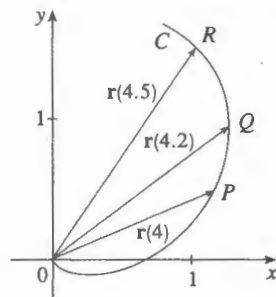
$$\frac{d\mathbf{r}}{dt} = \mathbf{r}'(t) = \lim_{h \rightarrow 0} \frac{\mathbf{r}(t+h) - \mathbf{r}(t)}{h}$$

13.2 Exercises

1. The figure shows a curve C given by a vector function $\mathbf{r}(t)$.
- (a) Draw the vectors $\mathbf{r}(4.5) - \mathbf{r}(4)$ and $\mathbf{r}(4.2) - \mathbf{r}(4)$.
- (b) Draw the vectors

$$\frac{\mathbf{r}(4.5) - \mathbf{r}(4)}{0.5} \quad \text{and} \quad \frac{\mathbf{r}(4.2) - \mathbf{r}(4)}{0.2}$$

- (c) Write expressions for $\mathbf{r}'(4)$ and the unit tangent vector $\mathbf{T}(4)$.
- (d) Draw the vector $\mathbf{T}(4)$.



2. (a) Make a large sketch of the curve described by the vector function $\mathbf{r}(t) = \langle t^2, t \rangle$, $0 \leq t \leq 2$, and draw the vectors $\mathbf{r}(1)$, $\mathbf{r}(1.1)$, and $\mathbf{r}(1.1) - \mathbf{r}(1)$.
- (b) Draw the vector $\mathbf{r}'(1)$ starting at $(1, 1)$, and compare it with the vector

$$\frac{\mathbf{r}(1.1) - \mathbf{r}(1)}{0.1}$$

Explain why these vectors are so close to each other in length and direction.

3-8

- (a) Sketch the plane curve with the given vector equation.
- (b) Find $\mathbf{r}'(t)$.
- (c) Sketch the position vector $\mathbf{r}(t)$ and the tangent vector $\mathbf{r}'(t)$ for the given value of t .

3. $\mathbf{r}(t) = \langle t - 2, t^2 + 1 \rangle$, $t = -1$
4. $\mathbf{r}(t) = \langle t^2, t^3 \rangle$, $t = 1$
5. $\mathbf{r}(t) = \sin t \mathbf{i} + 2 \cos t \mathbf{j}$, $t = \pi/4$
6. $\mathbf{r}(t) = e^t \mathbf{i} + e^{-t} \mathbf{j}$, $t = 0$
7. $\mathbf{r}(t) = e^{2t} \mathbf{i} + e^t \mathbf{j}$, $t = 0$
8. $\mathbf{r}(t) = (1 + \cos t) \mathbf{i} + (2 + \sin t) \mathbf{j}$, $t = \pi/6$

9-16 Find the derivative of the vector function.

9. $\mathbf{r}(t) = \langle t \sin t, t^2, t \cos 2t \rangle$
10. $\mathbf{r}(t) = \langle \tan t, \sec t, 1/t^2 \rangle$
11. $\mathbf{r}(t) = t \mathbf{i} + \mathbf{j} + 2\sqrt{t} \mathbf{k}$
12. $\mathbf{r}(t) = \frac{1}{1+t} \mathbf{i} + \frac{t}{1+t} \mathbf{j} + \frac{t^2}{1+t} \mathbf{k}$

13. $\mathbf{r}(t) = e^{t^2} \mathbf{i} - \mathbf{j} + \ln(1 + 3t) \mathbf{k}$
14. $\mathbf{r}(t) = at \cos 3t \mathbf{i} + b \sin^3 t \mathbf{j} + c \cos^3 t \mathbf{k}$
15. $\mathbf{r}(t) = \mathbf{a} + t \mathbf{b} + t^2 \mathbf{c}$
16. $\mathbf{r}(t) = t \mathbf{a} \times (\mathbf{b} + t \mathbf{c})$

17-20 Find the unit tangent vector $\mathbf{T}(t)$ at the point with the given value of the parameter t .

17. $\mathbf{r}(t) = \langle te^{-t}, 2 \arctan t, 2e^t \rangle$, $t = 0$
18. $\mathbf{r}(t) = \langle t^3 + 3t, t^2 + 1, 3t + 4 \rangle$, $t = 1$
19. $\mathbf{r}(t) = \cos t \mathbf{i} + 3t \mathbf{j} + 2 \sin 2t \mathbf{k}$, $t = 0$
20. $\mathbf{r}(t) = \sin^2 t \mathbf{i} + \cos^2 t \mathbf{j} + \tan^2 t \mathbf{k}$, $t = \pi/4$

21. If $\mathbf{r}(t) = \langle t, t^2, t^3 \rangle$, find $\mathbf{r}'(t)$, $\mathbf{T}(1)$, $\mathbf{r}''(t)$, and $\mathbf{r}'(t) \times \mathbf{r}''(t)$.
22. If $\mathbf{r}(t) = \langle e^{2t}, e^{-2t}, te^{2t} \rangle$, find $\mathbf{T}(0)$, $\mathbf{r}''(0)$, and $\mathbf{r}'(t) \cdot \mathbf{r}''(t)$.

23-26 Find parametric equations for the tangent line to the curve with the given parametric equations at the specified point.

23. $x = 1 + 2\sqrt{t}$, $y = t^3 - t$, $z = t^3 + t$; $(3, 0, 2)$
24. $x = e^t$, $y = te^t$, $z = te^{t^2}$; $(1, 0, 0)$
25. $x = e^{-t} \cos t$, $y = e^{-t} \sin t$, $z = e^{-t}$; $(1, 0, 1)$
26. $x = \sqrt{t^2 + 3}$, $y = \ln(t^2 + 3)$, $z = t$; $(2, \ln 4, 1)$

27. Find a vector equation for the tangent line to the curve of intersection of the cylinders $x^2 + y^2 = 25$ and $y^2 + z^2 = 20$ at the point $(3, 4, 2)$.

28. Find the point on the curve $\mathbf{r}(t) = \langle 2 \cos t, 2 \sin t, e^t \rangle$, $0 \leq t \leq \pi$, where the tangent line is parallel to the plane $\sqrt{3}x + y = 1$.

CAS 29-31 Find parametric equations for the tangent line to the curve with the given parametric equations at the specified point. Illustrate by graphing both the curve and the tangent line on a common screen.

29. $x = t$, $y = e^{-t}$, $z = 2t - t^2$; $(0, 1, 0)$
30. $x = 2 \cos t$, $y = 2 \sin t$, $z = 4 \cos 2t$; $(\sqrt{3}, 1, 2)$
31. $x = t \cos t$, $y = t$, $z = t \sin t$; $(-\pi, \pi, 0)$

32. (a) Find the point of intersection of the tangent lines to the curve $\mathbf{r}(t) = \langle \sin \pi t, 2 \sin \pi t, \cos \pi t \rangle$ at the points where $t = 0$ and $t = 0.5$.

Graphing (b) Illustrate by graphing the curve and both tangent lines.

33. The curves $\mathbf{r}_1(t) = \langle t, t^2, t^3 \rangle$ and $\mathbf{r}_2(t) = \langle \sin t, \sin 2t, t \rangle$ intersect at the origin. Find their angle of intersection correct to the nearest degree.

34. At what point do the curves $\mathbf{r}_1(t) = \langle t, 1 - t, 3 + t^2 \rangle$ and $\mathbf{r}_2(s) = \langle 3 - s, s - 2, s^2 \rangle$ intersect? Find their angle of intersection correct to the nearest degree.

35–40 Evaluate the integral.

35. $\int_0^2 (t\mathbf{i} - t^3\mathbf{j} + 3t^5\mathbf{k}) dt$

36. $\int_0^1 \left(\frac{4}{1+t^2} \mathbf{j} + \frac{2t}{1+t^2} \mathbf{k} \right) dt$

37. $\int_0^{\pi/2} (3 \sin^2 t \cos t \mathbf{i} + 3 \sin t \cos^2 t \mathbf{j} + 2 \sin t \cos t \mathbf{k}) dt$

38. $\int_1^2 (t^2 \mathbf{i} + t\sqrt{t-1} \mathbf{j} + t \sin \pi t \mathbf{k}) dt$

39. $\int (\sec^2 t \mathbf{i} + t(t^2 + 1)^3 \mathbf{j} + t^2 \ln t \mathbf{k}) dt$

40. $\int \left(te^{2t} \mathbf{i} + \frac{t}{1-t} \mathbf{j} + \frac{1}{\sqrt{1-t^2}} \mathbf{k} \right) dt$

41. Find $\mathbf{r}(t)$ if $\mathbf{r}'(t) = 2t\mathbf{i} + 3t^2\mathbf{j} + \sqrt{t}\mathbf{k}$ and $\mathbf{r}(1) = \mathbf{i} + \mathbf{j}$.
 42. Find $\mathbf{r}(t)$ if $\mathbf{r}'(t) = t\mathbf{i} + e^t\mathbf{j} + te^t\mathbf{k}$ and $\mathbf{r}(0) = \mathbf{i} + \mathbf{j} + \mathbf{k}$.
 43. Prove Formula 1 of Theorem 3.
 44. Prove Formula 3 of Theorem 3.
 45. Prove Formula 5 of Theorem 3.
 46. Prove Formula 6 of Theorem 3.
 47. If $\mathbf{u}(t) = \langle \sin t, \cos t, t \rangle$ and $\mathbf{v}(t) = \langle t, \cos t, \sin t \rangle$, use Formula 4 of Theorem 3 to find

$$\frac{d}{dt} [\mathbf{u}(t) \cdot \mathbf{v}(t)]$$

48. If \mathbf{u} and \mathbf{v} are the vector functions in Exercise 47, use Formula 5 of Theorem 3 to find

$$\frac{d}{dt} [\mathbf{u}(t) \times \mathbf{v}(t)]$$

49. Find $f'(2)$, where $f(t) = \mathbf{u}(t) \cdot \mathbf{v}(t)$, $\mathbf{u}(2) = \langle 1, 2, -1 \rangle$, $\mathbf{u}'(2) = \langle 3, 0, 4 \rangle$, and $\mathbf{v}(t) = \langle t, t^2, t^3 \rangle$.
 50. If $\mathbf{r}(t) = \mathbf{u}(t) \times \mathbf{v}(t)$, where \mathbf{u} and \mathbf{v} are the vector functions in Exercise 49, find $\mathbf{r}'(2)$.
 51. Show that if \mathbf{r} is a vector function such that \mathbf{r}'' exists, then

$$\frac{d}{dt} [\mathbf{r}(t) \times \mathbf{r}'(t)] = \mathbf{r}(t) \times \mathbf{r}''(t)$$

52. Find an expression for $\frac{d}{dt} [\mathbf{u}(t) \cdot (\mathbf{v}(t) \times \mathbf{w}(t))]$.

53. If $\mathbf{r}(t) \neq \mathbf{0}$, show that $\frac{d}{dt} |\mathbf{r}(t)| = \frac{1}{|\mathbf{r}(t)|} \mathbf{r}(t) \cdot \mathbf{r}'(t)$.

$$[\text{Hint: } |\mathbf{r}(t)|^2 = \mathbf{r}(t) \cdot \mathbf{r}(t)]$$

54. If a curve has the property that the position vector $\mathbf{r}(t)$ is always perpendicular to the tangent vector $\mathbf{r}'(t)$, show that the curve lies on a sphere with center the origin.
 55. If $\mathbf{u}(t) = \mathbf{r}(t) \cdot [\mathbf{r}'(t) \times \mathbf{r}''(t)]$, show that

$$\mathbf{u}'(t) = \mathbf{r}(t) \cdot [\mathbf{r}'(t) \times \mathbf{r}'''(t)]$$

56. Show that the tangent vector to a curve defined by a vector function $\mathbf{r}(t)$ points in the direction of increasing t . [Hint: Refer to Figure 1 and consider the cases $h > 0$ and $h < 0$ separately.]

Arc Length and Curvature

In Section 10.2 we defined the length of a plane curve with parametric equations $x = f(t)$, $y = g(t)$, $a \leq t \leq b$, as the limit of lengths of inscribed polygons and, for the case where f' and g' are continuous, we arrived at the formula

$$[1] \quad L = \int_a^b \sqrt{[f'(t)]^2 + [g'(t)]^2} dt = \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$$

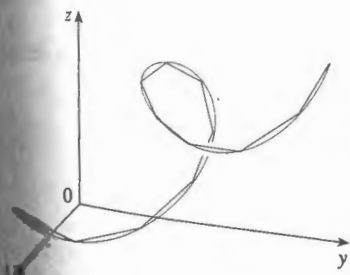


FIGURE 1

The length of a space curve is the limit of lengths of inscribed polygons.

The length of a space curve is defined in exactly the same way (see Figure 1). Suppose that the curve has the vector equation $\mathbf{r}(t) = \langle f(t), g(t), h(t) \rangle$, $a \leq t \leq b$, or, equivalently, the parametric equations $x = f(t)$, $y = g(t)$, $z = h(t)$, where f' , g' , and h' are continuous. If the curve is traversed exactly once as t increases from a to b , then it can be shown that its length is

[2]

$$\begin{aligned} L &= \int_a^b \sqrt{[f'(t)]^2 + [g'(t)]^2 + [h'(t)]^2} dt \\ &= \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2 + \left(\frac{dz}{dt}\right)^2} dt \end{aligned}$$


13.3 Exercises

1–6 Find the length of the curve.

1. $\mathbf{r}(t) = \langle t, 3 \cos t, 3 \sin t \rangle, -5 \leq t \leq 5$
2. $\mathbf{r}(t) = \langle 2t, t^2, \frac{1}{3}t^3 \rangle, 0 \leq t \leq 1$
3. $\mathbf{r}(t) = \sqrt{2}t\mathbf{i} + e^t\mathbf{j} + e^{-t}\mathbf{k}, 0 \leq t \leq 1$
4. $\mathbf{r}(t) = \cos t\mathbf{i} + \sin t\mathbf{j} + \ln \cos t\mathbf{k}, 0 \leq t \leq \pi/4$
5. $\mathbf{r}(t) = \mathbf{i} + t^2\mathbf{j} + t^3\mathbf{k}, 0 \leq t \leq 1$
6. $\mathbf{r}(t) = 12t\mathbf{i} + 8t^{3/2}\mathbf{j} + 3t^2\mathbf{k}, 0 \leq t \leq 1$

7–9 Find the length of the curve correct to four decimal places. (Use your calculator to approximate the integral.)

7. $\mathbf{r}(t) = \langle t^2, t^3, t^4 \rangle, 0 \leq t \leq 2$
8. $\mathbf{r}(t) = \langle t, e^{-t}, te^{-t} \rangle, 1 \leq t \leq 3$
9. $\mathbf{r}(t) = \langle \sin t, \cos t, \tan t \rangle, 0 \leq t \leq \pi/4$

-  10. Graph the curve with parametric equations $x = \sin t$, $y = \sin 2t$, $z = \sin 3t$. Find the total length of this curve correct to four decimal places.
11. Let C be the curve of intersection of the parabolic cylinder $x^2 = 2y$ and the surface $3z = xy$. Find the exact length of C from the origin to the point $(6, 18, 36)$.
12. Find, correct to four decimal places, the length of the curve of intersection of the cylinder $4x^2 + y^2 = 4$ and the plane $x + y + z = 2$.

13–14 Reparametrize the curve with respect to arc length measured from the point where $t = 0$ in the direction of increasing t .

13. $\mathbf{r}(t) = 2t\mathbf{i} + (1 - 3t)\mathbf{j} + (5 + 4t)\mathbf{k}$
14. $\mathbf{r}(t) = e^{2t} \cos 2t\mathbf{i} + 2\mathbf{j} + e^{2t} \sin 2t\mathbf{k}$

15. Suppose you start at the point $(0, 0, 3)$ and move 5 units along the curve $x = 3 \sin t$, $y = 4t$, $z = 3 \cos t$ in the positive direction. Where are you now?

16. Reparametrize the curve

$$\mathbf{r}(t) = \left(\frac{2}{t^2 + 1} - 1 \right) \mathbf{i} + \frac{2t}{t^2 + 1} \mathbf{j}$$

with respect to arc length measured from the point $(1, 0)$ in the direction of increasing t . Express the reparametrization in its simplest form. What can you conclude about the curve?


17–20

- (a) Find the unit tangent and unit normal vectors $\mathbf{T}(t)$ and $\mathbf{N}(t)$.
- (b) Use Formula 9 to find the curvature.

17. $\mathbf{r}(t) = \langle t, 3 \cos t, 3 \sin t \rangle$
18. $\mathbf{r}(t) = \langle t^2, \sin t - t \cos t, \cos t + t \sin t \rangle, t > 0$
19. $\mathbf{r}(t) = \langle \sqrt{2}t, e^t, e^{-t} \rangle$
20. $\mathbf{r}(t) = \langle t, \frac{1}{2}t^2, t^2 \rangle$

21–23 Use Theorem 10 to find the curvature.

21. $\mathbf{r}(t) = t^3\mathbf{j} + t^2\mathbf{k}$
22. $\mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j} + e^t\mathbf{k}$
23. $\mathbf{r}(t) = 3t\mathbf{i} + 4 \sin t\mathbf{j} + 4 \cos t\mathbf{k}$

24. Find the curvature of $\mathbf{r}(t) = \langle t^2, \ln t, t \ln t \rangle$ at the point $(1, 0, 0)$.
25. Find the curvature of $\mathbf{r}(t) = \langle t, t^2, t^3 \rangle$ at the point $(1, 1, 1)$.
-  26. Graph the curve with parametric equations $x = \cos t$, $y = \sin t$, $z = \sin 5t$ and find the curvature at the point $(1, 0, 0)$.

27–29 Use Formula 11 to find the curvature.

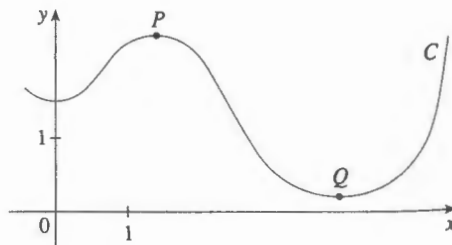
27. $y = x^4$
28. $y = \tan x$
29. $y = xe^x$

30–31 At what point does the curve have maximum curvature? What happens to the curvature as $x \rightarrow \infty$?

30. $y = \ln x$
31. $y = e^x$

32. Find an equation of a parabola that has curvature 4 at the origin.

33. (a) Is the curvature of the curve C shown in the figure greater at P or at Q ? Explain.
- (b) Estimate the curvature at P and at Q by sketching the osculating circles at those points.



- 34–35 Use a graphing calculator or computer to graph both the curve and its curvature function $\kappa(x)$ on the same screen. Is the graph of κ what you would expect?

34. $y = x^4 - 2x^2$

35. $y = x^{-2}$

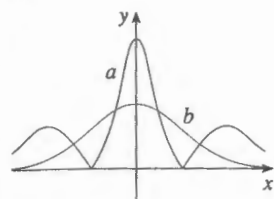
- 36–37 Plot the space curve and its curvature function $\kappa(t)$. Comment on how the curvature reflects the shape of the curve.

36. $\mathbf{r}(t) = \langle t - \sin t, 1 - \cos t, 4 \cos(t/2) \rangle, \quad 0 \leq t \leq 8\pi$

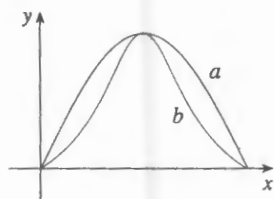
37. $\mathbf{r}(t) = \langle te^t, e^{-t}, \sqrt{2}t \rangle, \quad -5 \leq t \leq 5$

- 38–39 Two graphs, a and b , are shown. One is a curve $y = f(x)$ and the other is the graph of its curvature function $y = \kappa(x)$. Identify each curve and explain your choices.

38.



39.



40. (a) Graph the curve $\mathbf{r}(t) = \langle \sin 3t, \sin 2t, \sin t \rangle$. At how many points on the curve does it appear that the curvature has a local or absolute maximum?
 (b) Use a CAS to find and graph the curvature function. Does this graph confirm your conclusion from part (a)?
41. The graph of $\mathbf{r}(t) = \langle t - \frac{3}{2} \sin t, 1 - \frac{3}{2} \cos t, t \rangle$ is shown in Figure 12(b) in Section 13.1. Where do you think the curvature is largest? Use a CAS to find and graph the curvature function. For which values of t is the curvature largest?
42. Use Theorem 10 to show that the curvature of a plane parametric curve $x = f(t)$, $y = g(t)$ is

$$\kappa = \frac{|\dot{x}\ddot{y} - \ddot{x}\dot{y}|}{[\dot{x}^2 + \dot{y}^2]^{3/2}}$$

where the dots indicate derivatives with respect to t .

- 43–45 Use the formula in Exercise 42 to find the curvature.

43. $x = t^2, \quad y = t^3$

44. $x = a \cos \omega t, \quad y = b \sin \omega t$

45. $x = e^t \cos t, \quad y = e^t \sin t$

46. Consider the curvature at $x = 0$ for each member of the family of functions $f(x) = e^{\alpha x}$. For which members is $\kappa(0)$ largest?

- 47–48 Find the vectors \mathbf{T} , \mathbf{N} , and \mathbf{B} at the given point.

47. $\mathbf{r}(t) = \langle t^2, \frac{2}{3}t^3, t \rangle, \quad (1, \frac{2}{3}, 1)$

48. $\mathbf{r}(t) = \langle \cos t, \sin t, \ln \cos t \rangle, \quad (1, 0, 0)$

- 49–50 Find equations of the normal plane and osculating plane of the curve at the given point.

49. $x = 2 \sin 3t, \quad y = t, \quad z = 2 \cos 3t; \quad (0, \pi, -2)$

50. $x = t, \quad y = t^2, \quad z = t^3; \quad (1, 1, 1)$

51. Find equations of the osculating circles of the ellipse $9x^2 + 4y^2 = 36$ at the points $(2, 0)$ and $(0, 3)$. Use a graphing calculator or computer to graph the ellipse and both osculating circles on the same screen.

52. Find equations of the osculating circles of the parabola $y = \frac{1}{2}x^2$ at the points $(0, 0)$ and $(1, \frac{1}{2})$. Graph both osculating circles and the parabola on the same screen.

53. At what point on the curve $x = t^3, y = 3t, z = t^4$ is the normal plane parallel to the plane $6x + 6y - 8z = 1$?

54. Is there a point on the curve in Exercise 53 where the osculating plane is parallel to the plane $x + y + z = 1$? [Note: You will need a CAS for differentiating, for simplifying, and for computing a cross product.]

55. Find equations of the normal and osculating planes of the curve of intersection of the parabolic cylinders $x = y^2$ and $z = x^2$ at the point $(1, 1, 1)$.

56. Show that the osculating plane at every point on the curve $\mathbf{r}(t) = \langle t + 2, 1 - t, \frac{1}{2}t^2 \rangle$ is the same plane. What can you conclude about the curve?

57. Show that the curvature κ is related to the tangent and normal vectors by the equation

$$\frac{d\mathbf{T}}{ds} = \kappa \mathbf{N}$$

58. Show that the curvature of a plane curve is $\kappa = |d\phi/ds|$, where ϕ is the angle between \mathbf{T} and \mathbf{i} ; that is, ϕ is the angle of inclination of the tangent line. (This shows that the definition of curvature is consistent with the definition for plane curves given in Exercise 69 in Section 10.2.)

59. (a) Show that $d\mathbf{B}/ds$ is perpendicular to \mathbf{B} .
 (b) Show that $d\mathbf{B}/ds$ is perpendicular to \mathbf{T} .
 (c) Deduce from parts (a) and (b) that $d\mathbf{B}/ds = -\tau(s)\mathbf{N}$ for some number $\tau(s)$ called the **torsion** of the curve. (The torsion measures the degree of twisting of a curve.)
 (d) Show that for a plane curve the torsion is $\tau(s) = 0$.

60. The following formulas, called the **Frenet-Serret formulas**, are of fundamental importance in differential geometry:

1. $d\mathbf{T}/ds = \kappa\mathbf{N}$
2. $d\mathbf{N}/ds = -\kappa\mathbf{T} + \tau\mathbf{B}$
3. $d\mathbf{B}/ds = -\tau\mathbf{N}$

(Formula 1 comes from Exercise 57 and Formula 3 comes from Exercise 59.) Use the fact that $\mathbf{N} = \mathbf{B} \times \mathbf{T}$ to deduce Formula 2 from Formulas 1 and 3.

61. Use the Frenet-Serret formulas to prove each of the following. (Primes denote derivatives with respect to t . Start as in the proof of Theorem 10.)

- (a) $\mathbf{r}'' = s''\mathbf{T} + \kappa(s')^2\mathbf{N}$
- (b) $\mathbf{r}' \times \mathbf{r}'' = \kappa(s')^3\mathbf{B}$
- (c) $\mathbf{r}''' = [s''' - \kappa^2(s')^3]\mathbf{T} + [3\kappa s's'' + \kappa'(s')^2]\mathbf{N} + \kappa\tau(s')^3\mathbf{B}$
- (d) $\tau = \frac{(\mathbf{r}' \times \mathbf{r}'') \cdot \mathbf{r}'''}{|\mathbf{r}' \times \mathbf{r}''|^2}$

62. Show that the circular helix $\mathbf{r}(t) = \langle a \cos t, a \sin t, bt \rangle$, where a and b are positive constants, has constant curvature and constant torsion. [Use the result of Exercise 61(d).]

63. Use the formula in Exercise 61(d) to find the torsion of the curve $\mathbf{r}(t) = \langle t, \frac{1}{2}t^2, \frac{1}{3}t^3 \rangle$.

64. Find the curvature and torsion of the curve $x = \sinh t$, $y = \cosh t$, $z = t$ at the point $(0, 1, 0)$.

65. The DNA molecule has the shape of a double helix (see Figure 3 on page 842). The radius of each helix is about 10 angstroms ($1 \text{ \AA} = 10^{-8} \text{ cm}$). Each helix rises about 34 \AA during each complete turn, and there are about 2.9×10^8 complete turns. Estimate the length of each helix.

66. Let's consider the problem of designing a railroad track to make a smooth transition between sections of straight track. Existing track along the negative x -axis is to be joined smoothly to a track along the line $y = 1$ for $x \geq 1$.

(a) Find a polynomial $P = P(x)$ of degree 5 such that the function F defined by

$$F(x) = \begin{cases} 0 & \text{if } x \leq 0 \\ P(x) & \text{if } 0 < x < 1 \\ 1 & \text{if } x \geq 1 \end{cases}$$

is continuous and has continuous slope and continuous curvature.



(b) Use a graphing calculator or computer to draw the graph of F .

13.4 Motion in Space: Velocity and Acceleration

In this section we show how the ideas of tangent and normal vectors and curvature can be used in physics to study the motion of an object, including its velocity and acceleration along a space curve. In particular, we follow in the footsteps of Newton by using these methods to derive Kepler's First Law of planetary motion.

Suppose a particle moves through space so that its position vector at time t is $\mathbf{r}(t)$. Notice from Figure 1 that, for small values of h , the vector

$$\frac{\mathbf{r}(t+h) - \mathbf{r}(t)}{h}$$

approximates the direction of the particle moving along the curve $\mathbf{r}(t)$. Its magnitude measures the size of the displacement vector per unit time. The vector [1] gives the average velocity over a time interval of length h and its limit is the **velocity vector** $\mathbf{v}(t)$ at time t :

$$\mathbf{v}(t) = \lim_{h \rightarrow 0} \frac{\mathbf{r}(t+h) - \mathbf{r}(t)}{h} = \mathbf{r}'(t)$$

Thus the velocity vector is also the tangent vector and points in the direction of the tangent line.

The **speed** of the particle at time t is the magnitude of the velocity vector, that is, $|\mathbf{v}(t)|$. This is appropriate because, from [2] and from Equation 13.3.7, we have

$$|\mathbf{v}(t)| = |\mathbf{r}'(t)| = \frac{ds}{dt} = \text{rate of change of distance with respect to time}$$

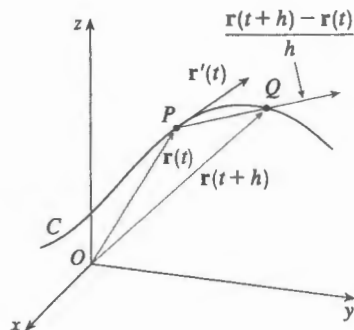


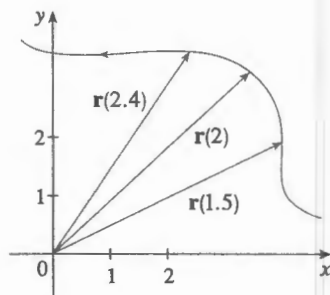
FIGURE 1

13.4 Exercises

1. The table gives coordinates of a particle moving through space along a smooth curve.
- (a) Find the average velocities over the time intervals $[0, 1]$, $[0.5, 1]$, $[1, 2]$, and $[1, 1.5]$.
- (b) Estimate the velocity and speed of the particle at $t = 1$.

t	x	y	z
0	2.7	9.8	3.7
0.5	3.5	7.2	3.3
1.0	4.5	6.0	3.0
1.5	5.9	6.4	2.8
2.0	7.3	7.8	2.7

2. The figure shows the path of a particle that moves with position vector $\mathbf{r}(t)$ at time t .
- (a) Draw a vector that represents the average velocity of the particle over the time interval $2 \leq t \leq 2.4$.
- (b) Draw a vector that represents the average velocity over the time interval $1.5 \leq t \leq 2$.
- (c) Write an expression for the velocity vector $\mathbf{v}(2)$.
- (d) Draw an approximation to the vector $\mathbf{v}(2)$ and estimate the speed of the particle at $t = 2$.



- 3–8 Find the velocity, acceleration, and speed of a particle with the given position function. Sketch the path of the particle and draw the velocity and acceleration vectors for the specified value of t .

3. $\mathbf{r}(t) = \langle -\frac{1}{2}t^2, t \rangle$, $t = 2$
4. $\mathbf{r}(t) = \langle 2 - t, 4\sqrt{t} \rangle$, $t = 1$
5. $\mathbf{r}(t) = 3 \cos t \mathbf{i} + 2 \sin t \mathbf{j}$, $t = \pi/3$
6. $\mathbf{r}(t) = e^t \mathbf{i} + e^{2t} \mathbf{j}$, $t = 0$
7. $\mathbf{r}(t) = t \mathbf{i} + t^2 \mathbf{j} + 2 \mathbf{k}$, $t = 1$
8. $\mathbf{r}(t) = t \mathbf{i} + 2 \cos t \mathbf{j} + \sin t \mathbf{k}$, $t = 0$

- 9–14 Find the velocity, acceleration, and speed of a particle with the given position function.

9. $\mathbf{r}(t) = \langle t^2 + t, t^2 - t, t^3 \rangle$ 10. $\mathbf{r}(t) = \langle 2 \cos t, 3t, 2 \sin t \rangle$
11. $\mathbf{r}(t) = \sqrt{2}t \mathbf{i} + e^t \mathbf{j} + e^{-t} \mathbf{k}$ 12. $\mathbf{r}(t) = t^2 \mathbf{i} + 2t \mathbf{j} + \ln t \mathbf{k}$
13. $\mathbf{r}(t) = e^t(\cos t \mathbf{i} + \sin t \mathbf{j} + t \mathbf{k})$
14. $\mathbf{r}(t) = \langle t^2, \sin t - t \cos t, \cos t + t \sin t \rangle$, $t \geq 0$

- 15–16 Find the velocity and position vectors of a particle that has the given acceleration and the given initial velocity and position.

15. $\mathbf{a}(t) = \mathbf{i} + 2\mathbf{j}$, $\mathbf{v}(0) = \mathbf{k}$, $\mathbf{r}(0) = \mathbf{i}$
16. $\mathbf{a}(t) = 2\mathbf{i} + 6t\mathbf{j} + 12t^2\mathbf{k}$, $\mathbf{v}(0) = \mathbf{i}$, $\mathbf{r}(0) = \mathbf{j} - \mathbf{k}$

17–18

- (a) Find the position vector of a particle that has the given acceleration and the specified initial velocity and position.

(b) Use a computer to graph the path of the particle.

17. $\mathbf{a}(t) = 2t \mathbf{i} + \sin t \mathbf{j} + \cos 2t \mathbf{k}$, $\mathbf{v}(0) = \mathbf{i}$, $\mathbf{r}(0) = \mathbf{j}$
18. $\mathbf{a}(t) = t \mathbf{i} + e^t \mathbf{j} + e^{-t} \mathbf{k}$, $\mathbf{v}(0) = \mathbf{k}$, $\mathbf{r}(0) = \mathbf{j} + \mathbf{k}$

19. The position function of a particle is given by $\mathbf{r}(t) = \langle t^2, 5t, t^2 - 16t \rangle$. When is the speed a minimum?
20. What force is required so that a particle of mass m has the position function $\mathbf{r}(t) = t^3 \mathbf{i} + t^2 \mathbf{j} + t^3 \mathbf{k}$?
21. A force with magnitude 20 N acts directly upward from the xy -plane on an object with mass 4 kg. The object starts at the origin with initial velocity $\mathbf{v}(0) = \mathbf{i} - \mathbf{j}$. Find its position function and its speed at time t .
22. Show that if a particle moves with constant speed, then the velocity and acceleration vectors are orthogonal.
23. A projectile is fired with an initial speed of 200 m/s and angle of elevation 60° . Find (a) the range of the projectile, (b) the maximum height reached, and (c) the speed at impact.
24. Rework Exercise 23 if the projectile is fired from a position 100 m above the ground.
25. A ball is thrown at an angle of 45° to the ground. If the ball lands 90 m away, what was the initial speed of the ball?
26. A gun is fired with angle of elevation 30° . What is the muzzle speed if the maximum height of the shell is 500 m?
27. A gun has muzzle speed 150 m/s. Find two angles of elevation that can be used to hit a target 800 m away.

28. A batter hits a baseball 3 ft above the ground toward the center field fence, which is 10 ft high and 400 ft from home plate. The ball leaves the bat with speed 115 ft/s at an angle 50° above the horizontal. Is it a home run? (In other words, does the ball clear the fence?)
29. A medieval city has the shape of a square and is protected by walls with length 500 m and height 15 m. You are the commander of an attacking army and the closest you can get to the wall is 100 m. Your plan is to set fire to the city by catapulting heated rocks over the wall (with an initial speed of 80 m/s). At what range of angles should you tell your men to set the catapult? (Assume the path of the rocks is perpendicular to the wall.)
30. Show that a projectile reaches three-quarters of its maximum height in half the time needed to reach its maximum height.
31. A ball is thrown eastward into the air from the origin (in the direction of the positive x -axis). The initial velocity is $50\mathbf{i} + 80\mathbf{k}$, with speed measured in feet per second. The spin of the ball results in a southward acceleration of 4 ft/s^2 , so the acceleration vector is $\mathbf{a} = -4\mathbf{j} - 32\mathbf{k}$. Where does the ball land and with what speed?
32. A ball with mass 0.8 kg is thrown southward into the air with a speed of 30 m/s at an angle of 30° to the ground. A west wind applies a steady force of 4 N to the ball in an easterly direction. Where does the ball land and with what speed?
33. Water traveling along a straight portion of a river normally flows fastest in the middle, and the speed slows to almost zero at the banks. Consider a long straight stretch of river flowing north, with parallel banks 40 m apart. If the maximum water speed is 3 m/s, we can use a quadratic function as a basic model for the rate of water flow x units from the west bank: $f(x) = \frac{3}{400}x(40 - x)$.
- (a) A boat proceeds at a constant speed of 5 m/s from a point A on the west bank while maintaining a heading perpendicular to the bank. How far down the river on the opposite bank will the boat touch shore? Graph the path of the boat.
- (b) Suppose we would like to pilot the boat to land at the point B on the east bank directly opposite A. If we maintain a constant speed of 5 m/s and a constant heading, find the angle at which the boat should head. Then graph the actual path the boat follows. Does the path seem realistic?
34. Another reasonable model for the water speed of the river in Exercise 33 is a sine function: $f(x) = 3 \sin(\pi x/40)$. If a boater would like to cross the river from A to B with constant heading and a constant speed of 5 m/s, determine the angle at which the boat should head.
35. A particle has position function $\mathbf{r}(t)$. If $\mathbf{r}'(t) = \mathbf{c} \times \mathbf{r}(t)$, where \mathbf{c} is a constant vector, describe the path of the particle.
36. (a) If a particle moves along a straight line, what can you say about its acceleration vector?

- (b) If a particle moves with constant speed along a curve, what can you say about its acceleration vector?

37–42 Find the tangential and normal components of the acceleration vector.

37. $\mathbf{r}(t) = (3t - t^3)\mathbf{i} + 3t^2\mathbf{j}$

38. $\mathbf{r}(t) = (1 + t)\mathbf{i} + (t^2 - 2t)\mathbf{j}$

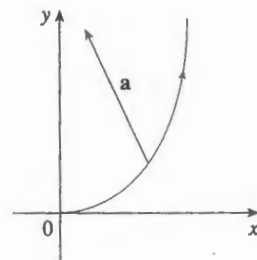
39. $\mathbf{r}(t) = \cos t\mathbf{i} + \sin t\mathbf{j} + t\mathbf{k}$

40. $\mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j} + 3t\mathbf{k}$

41. $\mathbf{r}(t) = e^t\mathbf{i} + \sqrt{2}t\mathbf{j} + e^{-t}\mathbf{k}$

42. $\mathbf{r}(t) = t\mathbf{i} + \cos^2 t\mathbf{j} + \sin^2 t\mathbf{k}$

43. The magnitude of the acceleration vector \mathbf{a} is 10 cm/s^2 . Use the figure to estimate the tangential and normal components of \mathbf{a} .



44. If a particle with mass m moves with position vector $\mathbf{r}(t)$, then its **angular momentum** is defined as $\mathbf{L}(t) = m\mathbf{r}(t) \times \mathbf{v}(t)$ and its **torque** as $\boldsymbol{\tau}(t) = m\mathbf{r}(t) \times \mathbf{a}(t)$. Show that $\mathbf{L}'(t) = \boldsymbol{\tau}(t)$. Deduce that if $\boldsymbol{\tau}(t) = \mathbf{0}$ for all t , then $\mathbf{L}(t)$ is constant. (This is the *law of conservation of angular momentum*.)

45. The position function of a spaceship is

$$\mathbf{r}(t) = (3 + t)\mathbf{i} + (2 + \ln t)\mathbf{j} + \left(7 - \frac{4}{t^2 + 1}\right)\mathbf{k}$$

and the coordinates of a space station are (6, 4, 9). The captain wants the spaceship to coast into the space station. When should the engines be turned off?

46. A rocket burning its onboard fuel while moving through space has velocity $\mathbf{v}(t)$ and mass $m(t)$ at time t . If the exhaust gases escape with velocity \mathbf{v}_e relative to the rocket, it can be deduced from Newton's Second Law of Motion that

$$m \frac{d\mathbf{v}}{dt} = \frac{dm}{dt} \mathbf{v}_e$$

- (a) Show that $\mathbf{v}(t) = \mathbf{v}(0) - \ln \frac{m(0)}{m(t)} \mathbf{v}_e$.
- (b) For the rocket to accelerate in a straight line from rest to twice the speed of its own exhaust gases, what fraction of its initial mass would the rocket have to burn as fuel?