

## Exercises 10.1

### Finding Terms of a Sequence

Each of Exercises 1–6 gives a formula for the  $n$ th term  $a_n$  of a sequence  $\{a_n\}$ . Find the values of  $a_1$ ,  $a_2$ ,  $a_3$ , and  $a_4$ .

1.  $a_n = \frac{1-n}{n^2}$
2.  $a_n = \frac{1}{n!}$
3.  $a_n = \frac{(-1)^{n+1}}{2n-1}$
4.  $a_n = 2 + (-1)^n$
5.  $a_n = \frac{2^n}{2^{n+1}}$
6.  $a_n = \frac{2^n - 1}{2^n}$

Each of Exercises 7–12 gives the first term or two of a sequence along with a recursion formula for the remaining terms. Write out the first ten terms of the sequence.

7.  $a_1 = 1$ ,  $a_{n+1} = a_n + (1/2^n)$
8.  $a_1 = 1$ ,  $a_{n+1} = a_n/(n+1)$
9.  $a_1 = 2$ ,  $a_{n+1} = (-1)^{n+1}a_n/2$
10.  $a_1 = -2$ ,  $a_{n+1} = na_n/(n+1)$
11.  $a_1 = a_2 = 1$ ,  $a_{n+2} = a_{n+1} + a_n$
12.  $a_1 = 2$ ,  $a_2 = -1$ ,  $a_{n+2} = a_{n+1}/a_n$

### Finding a Sequence's Formula

In Exercises 13–26, find a formula for the  $n$ th term of the sequence.

13. The sequence 1, -1, 1, -1, 1, ... 1's with alternating signs
14. The sequence -1, 1, -1, 1, -1, ... 1's with alternating signs
15. The sequence 1, -4, 9, -16, 25, ... Squares of the positive integers, with alternating signs
16. The sequence 1,  $-\frac{1}{4}$ ,  $\frac{1}{9}$ ,  $-\frac{1}{16}$ ,  $\frac{1}{25}$ , ... Reciprocals of squares of the positive integers, with alternating signs
17.  $\frac{1}{9}$ ,  $\frac{2}{12}$ ,  $\frac{2^2}{15}$ ,  $\frac{2^3}{18}$ ,  $\frac{2^4}{21}$ , ... Powers of 2 divided by multiples of 3

$$18. -\frac{3}{2}, -\frac{1}{6}, \frac{1}{12}, \frac{3}{20}, \frac{5}{30}, \dots$$

Integers differing by 2 divided by products of consecutive integers

$$19. \text{The sequence } 0, 3, 8, 15, 24, \dots$$

Squares of the positive integers diminished by 1

$$20. \text{The sequence } -3, -2, -1, 0, 1, \dots$$

Integers, beginning with -3

$$21. \text{The sequence } 1, 5, 9, 13, 17, \dots$$

Every other odd positive integer

$$22. \text{The sequence } 2, 6, 10, 14, 18, \dots$$

Every other even positive integer

$$23. \frac{5}{1}, \frac{8}{2}, \frac{11}{6}, \frac{14}{24}, \frac{17}{120}, \dots$$

Integers differing by 3 divided by factorials

$$24. \frac{1}{25}, \frac{8}{125}, \frac{27}{625}, \frac{64}{3125}, \frac{125}{15625}, \dots$$

Cubes of positive integers divided by powers of 5

$$25. \text{The sequence } 1, 0, 1, 0, 1, \dots$$

Alternating 1's and 0's

$$26. \text{The sequence } 0, 1, 1, 2, 2, 3, 3, 4, \dots$$

Each positive integer repeated

### Convergence and Divergence

Which of the sequences  $\{a_n\}$  in Exercises 27–90 converge, and which diverge? Find the limit of each convergent sequence.

$$27. a_n = 2 + (0.1)^n \qquad 28. a_n = \frac{n + (-1)^n}{n}$$

$$29. a_n = \frac{1 - 2n}{1 + 2n} \qquad 30. a_n = \frac{2n + 1}{1 - 3\sqrt{n}}$$

$$31. a_n = \frac{1 - 5n^4}{n^4 + 8n^3} \qquad 32. a_n = \frac{n + 3}{n^2 + 5n + 6}$$

$$33. a_n = \frac{n^2 - 2n + 1}{n - 1} \qquad 34. a_n = \frac{1 - n^3}{70 - 4n^2}$$

35.  $a_n = 1 + (-1)^n$ 
 36.  $a_n = (-1)^n \left(1 - \frac{1}{n}\right)$ 
 37.  $a_n = \left(\frac{n+1}{2n}\right) \left(1 - \frac{1}{n}\right)$ 
 38.  $a_n = \left(2 - \frac{1}{2^n}\right) \left(3 + \frac{1}{2^n}\right)$ 
 39.  $a_n = \frac{(-1)^{n+1}}{2n-1}$ 
 40.  $a_n = \left(-\frac{1}{2}\right)^n$ 
 41.  $a_n = \sqrt{\frac{2n}{n+1}}$ 
 42.  $a_n = \frac{1}{(0.9)^n}$ 
 43.  $a_n = \sin\left(\frac{\pi}{2} + \frac{1}{n}\right)$ 
 44.  $a_n = n\pi \cos(n\pi)$ 
 45.  $a_n = \frac{\sin n}{n}$ 
 46.  $a_n = \frac{\sin^2 n}{2^n}$ 
 47.  $a_n = \frac{n}{2^n}$ 
 48.  $a_n = \frac{3^n}{n^3}$ 
 49.  $a_n = \frac{\ln(n+1)}{\sqrt{n}}$ 
 50.  $a_n = \frac{\ln n}{\ln 2n}$ 
 51.  $a_n = 8^{1/n}$ 
 52.  $a_n = (0.03)^{1/n}$ 
 53.  $a_n = \left(1 + \frac{7}{n}\right)^n$ 
 54.  $a_n = \left(1 - \frac{1}{n}\right)^n$ 
 55.  $a_n = \sqrt[n]{10n}$ 
 56.  $a_n = \sqrt[n]{n^2}$ 
 57.  $a_n = \left(\frac{3}{n}\right)^{1/n}$ 
 58.  $a_n = (n+4)^{1/(n+4)}$ 
 59.  $a_n = \frac{\ln n}{n^{1/n}}$ 
 60.  $a_n = \ln n - \ln(n+1)$ 
 61.  $a_n = \sqrt[n]{4^n n}$ 
 62.  $a_n = \sqrt[n]{3^{2n+1}}$ 
 63.  $a_n = \frac{n!}{n^n}$  (Hint: Compare with  $1/n$ .)
 64.  $a_n = \frac{(-4)^n}{n!}$ 
 65.  $a_n = \frac{n!}{10^{6n}}$ 
 66.  $a_n = \frac{n!}{2^n \cdot 3^n}$ 
 67.  $a_n = \left(\frac{1}{n}\right)^{1/(\ln n)}$ 
 68.  $a_n = \ln\left(1 + \frac{1}{n}\right)^n$ 
 69.  $a_n = \left(\frac{3n+1}{3n-1}\right)^n$ 
 70.  $a_n = \left(\frac{n}{n+1}\right)^n$ 
 71.  $a_n = \left(\frac{x^n}{2n+1}\right)^{1/n}, \quad x > 0$ 
 72.  $a_n = \left(1 - \frac{1}{n^2}\right)^n$ 
 73.  $a_n = \frac{3^n \cdot 6^n}{2^n \cdot n!}$ 
 74.  $a_n = \frac{(10/11)^n}{(9/10)^n + (11/12)^n}$ 
 75.  $a_n = \tanh n$ 
 76.  $a_n = \sinh(\ln n)$ 
 77.  $a_n = \frac{n^2}{2n-1} \sin \frac{1}{n}$ 
 78.  $a_n = n \left(1 - \cos \frac{1}{n}\right)$ 
 79.  $a_n = \sqrt{n} \sin \frac{1}{\sqrt{n}}$ 
 80.  $a_n = (3^n + 5^n)^{1/n}$ 
 81.  $a_n = \tan^{-1} n$ 
 82.  $a_n = \frac{1}{\sqrt{n}} \tan^{-1} n$ 
 83.  $a_n = \left(\frac{1}{3}\right)^n + \frac{1}{\sqrt{2^n}}$

84.  $a_n = \sqrt[n]{n^2 + n}$ 
 85.  $a_n = \frac{(\ln n)^{200}}{n}$ 
 86.  $a_n = \frac{(\ln n)^5}{\sqrt{n}}$ 
 87.  $a_n = n - \sqrt{n^2 - n}$ 
 88.  $a_n = \frac{1}{\sqrt{n^2 - 1} - \sqrt{n^2 + n}}$ 
 89.  $a_n = \frac{1}{n} \int_1^n \frac{1}{x} dx$ 
 90.  $a_n = \int_1^n \frac{1}{x^p} dx, \quad p > 1$

### Recursively Defined Sequences

In Exercises 91–98, assume that each sequence converges and find its limit.

91.  $a_1 = 2, \quad a_{n+1} = \frac{72}{1 + a_n}$   
 92.  $a_1 = -1, \quad a_{n+1} = \frac{a_n + 6}{a_n + 2}$   
 93.  $a_1 = -4, \quad a_{n+1} = \sqrt{8 + 2a_n}$   
 94.  $a_1 = 0, \quad a_{n+1} = \sqrt{8 + 2a_n}$   
 95.  $a_1 = 5, \quad a_{n+1} = \sqrt{5a_n}$   
 96.  $a_1 = 3, \quad a_{n+1} = 12 - \sqrt{a_n}$   
 97.  $2, 2 + \frac{1}{2}, 2 + \frac{1}{2 + \frac{1}{2}}, 2 + \frac{1}{2 + \frac{1}{2 + \frac{1}{2}}}, \dots$   
 98.  $\sqrt{1}, \sqrt{1 + \sqrt{1}}, \sqrt{1 + \sqrt{1 + \sqrt{1}}}, \dots$   
 $\sqrt{1 + \sqrt{1 + \sqrt{1 + \sqrt{1}}}}, \dots$

### Theory and Examples

99. The first term of a sequence is  $x_1 = 1$ . Each succeeding term is the sum of all those that come before it:

$$x_{n+1} = x_1 + x_2 + \dots + x_n.$$

Write out enough early terms of the sequence to deduce a general formula for  $x_n$  that holds for  $n \geq 2$ .

100. A sequence of rational numbers is described as follows:

$$\frac{1}{1}, \frac{3}{2}, \frac{7}{5}, \frac{17}{12}, \dots, \frac{a}{b}, \frac{a+2b}{a+b}, \dots$$

Here the numerators form one sequence, the denominators form a second sequence, and their ratios form a third sequence. Let  $x_n$  and  $y_n$  be, respectively, the numerator and the denominator of the  $n$ th fraction  $r_n = x_n/y_n$ .

- a. Verify that  $x_1^2 - 2y_1^2 = -1, x_2^2 - 2y_2^2 = +1$  and, more generally, that if  $a^2 - 2b^2 = -1$  or  $+1$ , then

$$(a + 2b)^2 - 2(a + b)^2 = +1 \quad \text{or} \quad -1,$$

respectively.

- b. The fractions  $r_n = x_n/y_n$  approach a limit as  $n$  increases. What is that limit? (Hint: Use part (a) to show that  $r_n^2 - 2 = \pm(1/y_n)^2$  and that  $y_n$  is not less than  $n$ .)

101. **Newton's method** The following sequences come from the recursion formula for Newton's method,

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}.$$

Do the sequences converge? If so, to what value? In each case, begin by identifying the function  $f$  that generates the sequence.

a.  $x_0 = 1, \quad x_{n+1} = x_n - \frac{x_n^2 - 2}{2x_n} = \frac{x_n}{2} + \frac{1}{x_n}$

b.  $x_0 = 1, \quad x_{n+1} = x_n - \frac{\tan x_n - 1}{\sec^2 x_n}$

c.  $x_0 = 1, \quad x_{n+1} = x_n - 1$

102. a. Suppose that  $f(x)$  is differentiable for all  $x$  in  $[0, 1]$  and that  $f(0) = 0$ . Define sequence  $\{a_n\}$  by the rule  $a_n = nf(1/n)$ . Show that  $\lim_{n \rightarrow \infty} a_n = f'(0)$ . Use the result in part (a) to find the limits of the following sequences  $\{a_n\}$ .

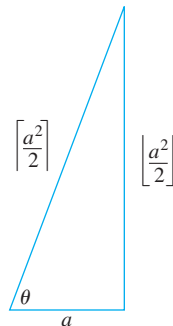
b.  $a_n = n \tan^{-1} \frac{1}{n}$                       c.  $a_n = n(e^{1/n} - 1)$

d.  $a_n = n \ln \left( 1 + \frac{2}{n} \right)$

103. **Pythagorean triples** A triple of positive integers  $a, b$ , and  $c$  is called a **Pythagorean triple** if  $a^2 + b^2 = c^2$ . Let  $a$  be an odd positive integer and let

$$b = \left\lfloor \frac{a^2}{2} \right\rfloor \quad \text{and} \quad c = \left\lceil \frac{a^2}{2} \right\rceil$$

be, respectively, the integer floor and ceiling for  $a^2/2$ .



- a. Show that  $a^2 + b^2 = c^2$ . (Hint: Let  $a = 2n + 1$  and express  $b$  and  $c$  in terms of  $n$ .)  
b. By direct calculation, or by appealing to the accompanying figure, find

$$\lim_{a \rightarrow \infty} \frac{\left\lfloor \frac{a^2}{2} \right\rfloor}{\left\lceil \frac{a^2}{2} \right\rceil}.$$

#### 104. The $n$ th root of $n$ !

- a. Show that  $\lim_{n \rightarrow \infty} (2n\pi)^{1/(2n)} = 1$  and hence, using Stirling's approximation (Chapter 8, Additional Exercise 52a), that

$$\sqrt[n]{n!} \approx \frac{n}{e} \quad \text{for large values of } n.$$

- T** b. Test the approximation in part (a) for  $n = 40, 50, 60, \dots$ , as far as your calculator will allow.

105. a. Assuming that  $\lim_{n \rightarrow \infty} (1/n^c) = 0$  if  $c$  is any positive constant, show that

$$\lim_{n \rightarrow \infty} \frac{\ln n}{n^c} = 0$$

if  $c$  is any positive constant.

- b. Prove that  $\lim_{n \rightarrow \infty} (1/n^c) = 0$  if  $c$  is any positive constant. (Hint: If  $\epsilon = 0.001$  and  $c = 0.04$ , how large should  $N$  be to ensure that  $|1/n^c - 0| < \epsilon$  if  $n > N$ ?)

106. **The zipper theorem** Prove the “zipper theorem” for sequences: If  $\{a_n\}$  and  $\{b_n\}$  both converge to  $L$ , then the sequence

$$a_1, b_1, a_2, b_2, \dots, a_n, b_n, \dots$$

converges to  $L$ .

107. Prove that  $\lim_{n \rightarrow \infty} \sqrt[n]{n} = 1$ .

108. Prove that  $\lim_{n \rightarrow \infty} x^{1/n} = 1, (x > 0)$ .

109. Prove Theorem 2.                      110. Prove Theorem 3.

In Exercises 111–114, determine if the sequence is monotonic and if it is bounded.

111.  $a_n = \frac{3n+1}{n+1}$

112.  $a_n = \frac{(2n+3)!}{(n+1)!}$

113.  $a_n = \frac{2^n 3^n}{n!}$

114.  $a_n = 2 - \frac{2}{n} - \frac{1}{2^n}$

Which of the sequences in Exercises 115–124 converge, and which diverge? Give reasons for your answers.

115.  $a_n = 1 - \frac{1}{n}$

116.  $a_n = n - \frac{1}{n}$

117.  $a_n = \frac{2^n - 1}{2^n}$

118.  $a_n = \frac{2^n - 1}{3^n}$

119.  $a_n = ((-1)^n + 1) \left( \frac{n+1}{n} \right)$

120. The first term of a sequence is  $x_1 = \cos(1)$ . The next terms are  $x_2 = x_1$  or  $\cos(2)$ , whichever is larger; and  $x_3 = x_2$  or  $\cos(3)$ , whichever is larger (farther to the right). In general,

$$x_{n+1} = \max \{x_n, \cos(n+1)\}.$$

121.  $a_n = \frac{1 + \sqrt{2n}}{\sqrt{n}}$

122.  $a_n = \frac{n+1}{n}$

123.  $a_n = \frac{4^{n+1} + 3^n}{4^n}$

124.  $a_1 = 1, \quad a_{n+1} = 2a_n - 3$

In Exercises 125–126, use the definition of convergence to prove the given limit.

125.  $\lim_{n \rightarrow \infty} \frac{\sin n}{n} = 0$

126.  $\lim_{n \rightarrow \infty} \left( 1 - \frac{1}{n^2} \right) = 1$

127. **The sequence  $\{n/(n+1)\}$  has a least upper bound of 1** Show that if  $M$  is a number less than 1, then the terms of  $\{n/(n+1)\}$  eventually exceed  $M$ . That is, if  $M < 1$  there is an integer  $N$  such that  $n/(n+1) > M$  whenever  $n > N$ . Since  $n/(n+1) < 1$  for every  $n$ , this proves that 1 is a least upper bound for  $\{n/(n+1)\}$ .

128. **Uniqueness of least upper bounds** Show that if  $M_1$  and  $M_2$  are least upper bounds for the sequence  $\{a_n\}$ , then  $M_1 = M_2$ . That is, a sequence cannot have two different least upper bounds.

129. Is it true that a sequence  $\{a_n\}$  of positive numbers must converge if it is bounded from above? Give reasons for your answer.

- 130.** Prove that if  $\{a_n\}$  is a convergent sequence, then to every positive number  $\epsilon$  there corresponds an integer  $N$  such that for all  $m$  and  $n$ ,

$$m > N \text{ and } n > N \Rightarrow |a_m - a_n| < \epsilon.$$

- 131. Uniqueness of limits** Prove that limits of sequences are unique. That is, show that if  $L_1$  and  $L_2$  are numbers such that  $a_n \rightarrow L_1$  and  $a_n \rightarrow L_2$ , then  $L_1 = L_2$ .

- 132. Limits and subsequences** If the terms of one sequence appear in another sequence in their given order, we call the first sequence a **subsequence** of the second. Prove that if two subsequences of a sequence  $\{a_n\}$  have different limits  $L_1 \neq L_2$ , then  $\{a_n\}$  diverges.

- 133.** For a sequence  $\{a_n\}$  the terms of even index are denoted by  $a_{2k}$  and the terms of odd index by  $a_{2k+1}$ . Prove that if  $a_{2k} \rightarrow L$  and  $a_{2k+1} \rightarrow L$ , then  $a_n \rightarrow L$ .

- 134.** Prove that a sequence  $\{a_n\}$  converges to 0 if and only if the sequence of absolute values  $\{|a_n|\}$  converges to 0.

- 135. Sequences generated by Newton's method** Newton's method, applied to a differentiable function  $f(x)$ , begins with a starting value  $x_0$  and constructs from it a sequence of numbers  $\{x_n\}$  that under favorable circumstances converges to a zero of  $f$ . The recursion formula for the sequence is

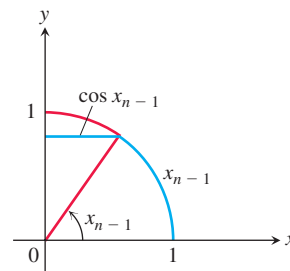
$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}.$$

- a.** Show that the recursion formula for  $f(x) = x^2 - a$ ,  $a > 0$ , can be written as  $x_{n+1} = (x_n + a/x_n)/2$ .

- T b.** Starting with  $x_0 = 1$  and  $a = 3$ , calculate successive terms of the sequence until the display begins to repeat. What number is being approximated? Explain.

- T 136. A recursive definition of  $\pi/2$**  If you start with  $x_1 = 1$  and define the subsequent terms of  $\{x_n\}$  by the rule  $x_n = x_{n-1} + \cos x_{n-1}$ , you generate a sequence that converges

rapidly to  $\pi/2$ . **(a)** Try it. **(b)** Use the accompanying figure to explain why the convergence is so rapid.



### COMPUTER EXPLORATIONS

Use a CAS to perform the following steps for the sequences in Exercises 137–148.

- a.** Calculate and then plot the first 25 terms of the sequence. Does the sequence appear to be bounded from above or below? Does it appear to converge or diverge? If it does converge, what is the limit  $L$ ?

- b.** If the sequence converges, find an integer  $N$  such that  $|a_n - L| \leq 0.01$  for  $n \geq N$ . How far in the sequence do you have to get for the terms to lie within 0.0001 of  $L$ ?

$$137. a_n = \sqrt[n]{n} \qquad 138. a_n = \left(1 + \frac{0.5}{n}\right)^n$$

$$139. a_1 = 1, \quad a_{n+1} = a_n + \frac{1}{5^n}$$

$$140. a_1 = 1, \quad a_{n+1} = a_n + (-2)^n$$

$$141. a_n = \sin n \qquad 142. a_n = n \sin \frac{1}{n}$$

$$143. a_n = \frac{\sin n}{n} \qquad 144. a_n = \frac{\ln n}{n}$$

$$145. a_n = (0.9999)^n \qquad 146. a_n = (123456)^{1/n}$$

$$147. a_n = \frac{8^n}{n!} \qquad 148. a_n = \frac{n^{41}}{19^n}$$

## Exercises 10.2

### Finding $n$ th Partial Sums

In Exercises 1–6, find a formula for the  $n$ th partial sum of each series and use it to find the series' sum if the series converges.

- $2 + \frac{2}{3} + \frac{2}{9} + \frac{2}{27} + \cdots + \frac{2}{3^{n-1}} + \cdots$
- $\frac{9}{100} + \frac{9}{100^2} + \frac{9}{100^3} + \cdots + \frac{9}{100^n} + \cdots$
- $1 - \frac{1}{2} + \frac{1}{4} - \frac{1}{8} + \cdots + (-1)^{n-1} \frac{1}{2^{n-1}} + \cdots$
- $1 - 2 + 4 - 8 + \cdots + (-1)^{n-1} 2^{n-1} + \cdots$
- $\frac{1}{2 \cdot 3} + \frac{1}{3 \cdot 4} + \frac{1}{4 \cdot 5} + \cdots + \frac{1}{(n+1)(n+2)} + \cdots$
- $\frac{5}{1 \cdot 2} + \frac{5}{2 \cdot 3} + \frac{5}{3 \cdot 4} + \cdots + \frac{5}{n(n+1)} + \cdots$

### Series with Geometric Terms

In Exercises 7–14, write out the first eight terms of each series to show how the series starts. Then find the sum of the series or show that it diverges.

- $\sum_{n=0}^{\infty} \frac{(-1)^n}{4^n}$
- $\sum_{n=2}^{\infty} \frac{1}{4^n}$
- $\sum_{n=1}^{\infty} \left(1 - \frac{7}{4^n}\right)$
- $\sum_{n=0}^{\infty} (-1)^n \frac{5}{4^n}$
- $\sum_{n=0}^{\infty} \left(\frac{5}{2^n} + \frac{1}{3^n}\right)$
- $\sum_{n=0}^{\infty} \left(\frac{5}{2^n} - \frac{1}{3^n}\right)$
- $\sum_{n=0}^{\infty} \left(\frac{1}{2^n} + \frac{(-1)^n}{5^n}\right)$
- $\sum_{n=0}^{\infty} \left(\frac{2^{n+1}}{5^n}\right)$

In Exercises 15–18, determine if the geometric series converges or diverges. If a series converges, find its sum.

- $1 + \left(\frac{2}{5}\right) + \left(\frac{2}{5}\right)^2 + \left(\frac{2}{5}\right)^3 + \left(\frac{2}{5}\right)^4 + \cdots$
- $1 + (-3) + (-3)^2 + (-3)^3 + (-3)^4 + \cdots$
- $\left(\frac{1}{8}\right) + \left(\frac{1}{8}\right)^2 + \left(\frac{1}{8}\right)^3 + \left(\frac{1}{8}\right)^4 + \left(\frac{1}{8}\right)^5 + \cdots$

$$18. \left(\frac{-2}{3}\right)^2 + \left(\frac{-2}{3}\right)^3 + \left(\frac{-2}{3}\right)^4 + \left(\frac{-2}{3}\right)^5 + \left(\frac{-2}{3}\right)^6 + \cdots$$

### Repeating Decimals

Express each of the numbers in Exercises 19–26 as the ratio of two integers.

- $0.\overline{23} = 0.23\ 23\ 23 \dots$
- $0.\overline{234} = 0.234\ 234\ 234 \dots$
- $0.\overline{7} = 0.7777 \dots$
- $0.\overline{d} = 0.dddd \dots$ , where  $d$  is a digit
- $0.0\overline{6} = 0.06666 \dots$
- $1.\overline{414} = 1.414\ 414\ 414 \dots$
- $1.24\overline{123} = 1.24\ 123\ 123\ 123 \dots$
- $3.\overline{142857} = 3.142857\ 142857 \dots$

### Using the $n$ th-Term Test

In Exercises 27–34, use the  $n$ th-Term Test for divergence to show that the series is divergent, or state that the test is inconclusive.

- $\sum_{n=1}^{\infty} \frac{n}{n+10}$
- $\sum_{n=1}^{\infty} \frac{n(n+1)}{(n+2)(n+3)}$
- $\sum_{n=0}^{\infty} \frac{1}{n+4}$
- $\sum_{n=1}^{\infty} \frac{n}{n^2+3}$
- $\sum_{n=1}^{\infty} \cos \frac{1}{n}$
- $\sum_{n=0}^{\infty} \frac{e^n}{e^n + n}$
- $\sum_{n=1}^{\infty} \ln \frac{1}{n}$
- $\sum_{n=0}^{\infty} \cos n\pi$

### Telescoping Series

In Exercises 35–40, find a formula for the  $n$ th partial sum of the series and use it to determine if the series converges or diverges. If a series converges, find its sum.

- $\sum_{n=1}^{\infty} \left(\frac{1}{n} - \frac{1}{n+1}\right)$
- $\sum_{n=1}^{\infty} \left(\frac{3}{n^2} - \frac{3}{(n+1)^2}\right)$
- $\sum_{n=1}^{\infty} (\ln \sqrt{n+1} - \ln \sqrt{n})$

$$38. \sum_{n=1}^{\infty} (\tan(n) - \tan(n-1))$$

$$39. \sum_{n=1}^{\infty} \left( \cos^{-1}\left(\frac{1}{n+1}\right) - \cos^{-1}\left(\frac{1}{n+2}\right) \right)$$

$$40. \sum_{n=1}^{\infty} (\sqrt{n+4} - \sqrt{n+3})$$

Find the sum of each series in Exercises 41–48.

$$41. \sum_{n=1}^{\infty} \frac{4}{(4n-3)(4n+1)} \quad 42. \sum_{n=1}^{\infty} \frac{6}{(2n-1)(2n+1)}$$

$$43. \sum_{n=1}^{\infty} \frac{40n}{(2n-1)^2(2n+1)^2} \quad 44. \sum_{n=1}^{\infty} \frac{2n+1}{n^2(n+1)^2}$$

$$45. \sum_{n=1}^{\infty} \left( \frac{1}{\sqrt{n}} - \frac{1}{\sqrt{n+1}} \right) \quad 46. \sum_{n=1}^{\infty} \left( \frac{1}{2^{1/n}} - \frac{1}{2^{1/(n+1)}} \right)$$

$$47. \sum_{n=1}^{\infty} \left( \frac{1}{\ln(n+2)} - \frac{1}{\ln(n+1)} \right)$$

$$48. \sum_{n=1}^{\infty} (\tan^{-1}(n) - \tan^{-1}(n+1))$$

### Convergence or Divergence

Which series in Exercises 49–68 converge, and which diverge? Give reasons for your answers. If a series converges, find its sum.

$$49. \sum_{n=0}^{\infty} \left( \frac{1}{\sqrt{2}} \right)^n \quad 50. \sum_{n=0}^{\infty} (\sqrt{2})^n$$

$$51. \sum_{n=1}^{\infty} (-1)^{n+1} \frac{3}{2^n} \quad 52. \sum_{n=1}^{\infty} (-1)^{n+1} n$$

$$53. \sum_{n=0}^{\infty} \cos\left(\frac{n\pi}{2}\right) \quad 54. \sum_{n=0}^{\infty} \frac{\cos n\pi}{5^n}$$

$$55. \sum_{n=0}^{\infty} e^{-2n} \quad 56. \sum_{n=1}^{\infty} \ln \frac{1}{3^n}$$

$$57. \sum_{n=1}^{\infty} \frac{2}{10^n} \quad 58. \sum_{n=0}^{\infty} \frac{1}{x^n}, \quad |x| > 1$$

$$59. \sum_{n=0}^{\infty} \frac{2^n - 1}{3^n} \quad 60. \sum_{n=1}^{\infty} \left( 1 - \frac{1}{n} \right)^n$$

$$61. \sum_{n=0}^{\infty} \frac{n!}{1000^n} \quad 62. \sum_{n=1}^{\infty} \frac{n^n}{n!}$$

$$63. \sum_{n=1}^{\infty} \frac{2^n + 3^n}{4^n} \quad 64. \sum_{n=1}^{\infty} \frac{2^n + 4^n}{3^n + 4^n}$$

$$65. \sum_{n=1}^{\infty} \ln\left(\frac{n}{n+1}\right) \quad 66. \sum_{n=1}^{\infty} \ln\left(\frac{n}{2n+1}\right)$$

$$67. \sum_{n=0}^{\infty} \left( \frac{e}{\pi} \right)^n \quad 68. \sum_{n=0}^{\infty} \frac{e^{n\pi}}{\pi^{ne}}$$

### Geometric Series with a Variable $x$

In each of the geometric series in Exercises 69–72, write out the first few terms of the series to find  $a$  and  $r$ , and find the sum of the series. Then express the inequality  $|r| < 1$  in terms of  $x$  and find the values of  $x$  for which the inequality holds and the series converges.

$$69. \sum_{n=0}^{\infty} (-1)^n x^n \quad 70. \sum_{n=0}^{\infty} (-1)^n x^{2n}$$

$$71. \sum_{n=0}^{\infty} 3 \left( \frac{x-1}{2} \right)^n \quad 72. \sum_{n=0}^{\infty} \frac{(-1)^n}{2} \left( \frac{1}{3 + \sin x} \right)^n$$

In Exercises 73–78, find the values of  $x$  for which the given geometric series converges. Also, find the sum of the series (as a function of  $x$ ) for those values of  $x$ .

$$73. \sum_{n=0}^{\infty} 2^n x^n \quad 74. \sum_{n=0}^{\infty} (-1)^n x^{-2n}$$

$$75. \sum_{n=0}^{\infty} (-1)^n (x+1)^n \quad 76. \sum_{n=0}^{\infty} \left( -\frac{1}{2} \right)^n (x-3)^n$$

$$77. \sum_{n=0}^{\infty} \sin^n x \quad 78. \sum_{n=0}^{\infty} (\ln x)^n$$

### Theory and Examples

79. The series in Exercise 5 can also be written as

$$\sum_{n=1}^{\infty} \frac{1}{(n+1)(n+2)} \quad \text{and} \quad \sum_{n=1}^{\infty} \frac{1}{(n+3)(n+4)}.$$

Write it as a sum beginning with (a)  $n = -2$ , (b)  $n = 0$ , (c)  $n = 5$ .

80. The series in Exercise 6 can also be written as

$$\sum_{n=1}^{\infty} \frac{5}{n(n+1)} \quad \text{and} \quad \sum_{n=0}^{\infty} \frac{5}{(n+1)(n+2)}.$$

Write it as a sum beginning with (a)  $n = -1$ , (b)  $n = 3$ , (c)  $n = 20$ .

81. Make up an infinite series of nonzero terms whose sum is

a. 1    b.  $-3$     c. 0.

82. (Continuation of Exercise 81.) Can you make an infinite series of nonzero terms that converges to any number you want? Explain.

83. Show by example that  $\sum(a_n/b_n)$  may diverge even though  $\sum a_n$  and  $\sum b_n$  converge and no  $b_n$  equals 0.

84. Find convergent geometric series  $A = \sum a_n$  and  $B = \sum b_n$  that illustrate the fact that  $\sum a_n b_n$  may converge without being equal to  $AB$ .

85. Show by example that  $\sum(a_n/b_n)$  may converge to something other than  $A/B$  even when  $A = \sum a_n$ ,  $B = \sum b_n \neq 0$ , and no  $b_n$  equals 0.

86. If  $\sum a_n$  converges and  $a_n > 0$  for all  $n$ , can anything be said about  $\sum(1/a_n)$ ? Give reasons for your answer.

87. What happens if you add a finite number of terms to a divergent series or delete a finite number of terms from a divergent series? Give reasons for your answer.

88. If  $\sum a_n$  converges and  $\sum b_n$  diverges, can anything be said about their term-by-term sum  $\sum(a_n + b_n)$ ? Give reasons for your answer.

89. Make up a geometric series  $\sum ar^{n-1}$  that converges to the number 5 if

a.  $a = 2$     b.  $a = 13/2$ .

90. Find the value of  $b$  for which

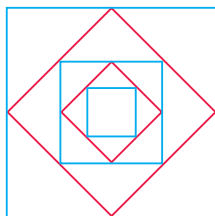
$$1 + e^b + e^{2b} + e^{3b} + \cdots = 9.$$

91. For what values of  $r$  does the infinite series

$$1 + 2r + r^2 + 2r^3 + r^4 + 2r^5 + r^6 + \cdots$$

converge? Find the sum of the series when it converges.

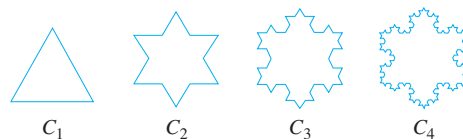
92. The accompanying figure shows the first five of a sequence of squares. The outermost square has an area of  $4 \text{ m}^2$ . Each of the other squares is obtained by joining the midpoints of the sides of the squares before it. Find the sum of the areas of all the squares.



93. **Drug dosage** A patient takes a 300 mg tablet for the control of high blood pressure every morning at the same time. The concentration of the drug in the patient's system decays exponentially at a constant hourly rate of  $k = 0.12$ .
- How many milligrams of the drug are in the patient's system just before the second tablet is taken? Just before the third tablet is taken?
  - In the long run, after taking the medication for at least six months, what quantity of drug is in the patient's body just before taking the next regularly scheduled morning tablet?
94. Show that the error  $(L - s_n)$  obtained by replacing a convergent geometric series with one of its partial sums  $s_n$  is  $ar^n/(1 - r)$ .
95. **The Cantor set** To construct this set, we begin with the closed interval  $[0, 1]$ . From that interval, remove the middle open interval  $(1/3, 2/3)$ , leaving the two closed intervals  $[0, 1/3]$  and  $[2/3, 1]$ . At the second step we remove the open middle third interval from each of those remaining. From  $[0, 1/3]$  we remove the open interval  $(1/9, 2/9)$ , and from  $[2/3, 1]$  we remove  $(7/9, 8/9)$ , leaving behind the four closed intervals  $[0, 1/9]$ ,

$[2/9, 1/3]$ ,  $[2/3, 7/9]$ , and  $[8/9, 1]$ . At the next step, we remove the middle open third interval from each closed interval left behind, so  $(1/27, 2/27)$  is removed from  $[0, 1/9]$ , leaving the closed intervals  $[0, 1/27]$  and  $[2/27, 1/9]$ ;  $(7/27, 8/27)$  is removed from  $[2/9, 1/3]$ , leaving behind  $[2/9, 7/27]$  and  $[8/27, 1/3]$ , and so forth. We continue this process repeatedly without stopping, at each step removing the open third interval from every closed interval remaining behind from the preceding step. The numbers remaining in the interval  $[0, 1]$ , after all open middle third intervals have been removed, are the points in the Cantor set (named after Georg Cantor, 1845–1918). The set has some interesting properties.

- The Cantor set contains infinitely many numbers in  $[0, 1]$ . List 12 numbers that belong to the Cantor set.
  - Show, by summing an appropriate geometric series, that the total length of all the open middle third intervals that have been removed from  $[0, 1]$  is equal to 1.
96. **Helga von Koch's snowflake curve** Helga von Koch's snowflake is a curve of infinite length that encloses a region of finite area. To see why this is so, suppose the curve is generated by starting with an equilateral triangle whose sides have length 1.
- Find the length  $L_n$  of the  $n$ th curve  $C_n$  and show that  $\lim_{n \rightarrow \infty} L_n = \infty$ .
  - Find the area  $A_n$  of the region enclosed by  $C_n$  and show that  $\lim_{n \rightarrow \infty} A_n = (8/5)A_1$ .



## Exercises 10.3

## Applying the Integral Test

Use the Integral Test to determine if the series in Exercises 1–10 converge or diverge. Be sure to check that the conditions of the Integral Test are satisfied.

1.  $\sum_{n=1}^{\infty} \frac{1}{n^2}$
2.  $\sum_{n=1}^{\infty} \frac{1}{n^{0.2}}$
3.  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 4}$
4.  $\sum_{n=1}^{\infty} \frac{1}{n + 4}$
5.  $\sum_{n=1}^{\infty} e^{-2n}$
6.  $\sum_{n=2}^{\infty} \frac{1}{n(\ln n)^2}$
7.  $\sum_{n=1}^{\infty} \frac{n}{n^2 + 4}$
8.  $\sum_{n=2}^{\infty} \frac{\ln(n^2)}{n}$
9.  $\sum_{n=1}^{\infty} \frac{n^2}{e^{n/3}}$
10.  $\sum_{n=2}^{\infty} \frac{n - 4}{n^2 - 2n + 1}$

## Determining Convergence or Divergence

Which of the series in Exercises 11–40 converge, and which diverge? Give reasons for your answers. (When you check an answer, remember that there may be more than one way to determine the series' convergence or divergence.)

11.  $\sum_{n=1}^{\infty} \frac{1}{10^n}$
12.  $\sum_{n=1}^{\infty} e^{-n}$
13.  $\sum_{n=1}^{\infty} \frac{n}{n + 1}$
14.  $\sum_{n=1}^{\infty} \frac{5}{n + 1}$
15.  $\sum_{n=1}^{\infty} \frac{3}{\sqrt{n}}$
16.  $\sum_{n=1}^{\infty} \frac{-2}{n\sqrt{n}}$
17.  $\sum_{n=1}^{\infty} -\frac{1}{8^n}$
18.  $\sum_{n=1}^{\infty} \frac{-8}{n}$
19.  $\sum_{n=2}^{\infty} \frac{\ln n}{n}$
20.  $\sum_{n=2}^{\infty} \frac{\ln n}{\sqrt{n}}$
21.  $\sum_{n=1}^{\infty} \frac{2^n}{3^n}$
22.  $\sum_{n=1}^{\infty} \frac{5^n}{4^n + 3}$
23.  $\sum_{n=0}^{\infty} \frac{-2}{n + 1}$
24.  $\sum_{n=1}^{\infty} \frac{1}{2n - 1}$
25.  $\sum_{n=1}^{\infty} \frac{2^n}{n + 1}$
26.  $\sum_{n=1}^{\infty} \left(1 + \frac{1}{n}\right)^n$
27.  $\sum_{n=2}^{\infty} \frac{\sqrt{n}}{\ln n}$
28.  $\sum_{n=1}^{\infty} \frac{1}{\sqrt{n}(\sqrt{n} + 1)}$
29.  $\sum_{n=1}^{\infty} \frac{1}{(\ln 2)^n}$
30.  $\sum_{n=1}^{\infty} \frac{1}{(\ln 3)^n}$
31.  $\sum_{n=3}^{\infty} \frac{(1/n)}{(\ln n)\sqrt{\ln^2 n - 1}}$
32.  $\sum_{n=1}^{\infty} \frac{1}{n(1 + \ln^2 n)}$
33.  $\sum_{n=1}^{\infty} n \sin \frac{1}{n}$
34.  $\sum_{n=1}^{\infty} n \tan \frac{1}{n}$
35.  $\sum_{n=1}^{\infty} \frac{e^n}{1 + e^{2n}}$
36.  $\sum_{n=1}^{\infty} \frac{2}{1 + e^n}$
37.  $\sum_{n=1}^{\infty} \frac{8 \tan^{-1} n}{1 + n^2}$
38.  $\sum_{n=1}^{\infty} \frac{n}{n^2 + 1}$

$$39. \sum_{n=1}^{\infty} \operatorname{sech} n$$

$$40. \sum_{n=1}^{\infty} \operatorname{sech}^2 n$$

## Theory and Examples

For what values of  $a$ , if any, do the series in Exercises 41 and 42 converge?

$$41. \sum_{n=1}^{\infty} \left( \frac{a}{n+2} - \frac{1}{n+4} \right) \quad 42. \sum_{n=3}^{\infty} \left( \frac{1}{n-1} - \frac{2a}{n+1} \right)$$

43. a. Draw illustrations like those in Figures 10.11a and 10.11b to show that the partial sums of the harmonic series satisfy the inequalities

$$\begin{aligned} \ln(n+1) &= \int_1^{n+1} \frac{1}{x} dx \leq 1 + \frac{1}{2} + \cdots + \frac{1}{n} \\ &\leq 1 + \int_1^n \frac{1}{x} dx = 1 + \ln n. \end{aligned}$$

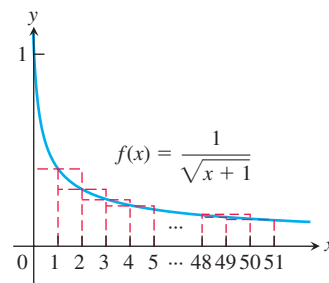
- T** b. There is absolutely no empirical evidence for the divergence of the harmonic series even though we know it diverges. The partial sums just grow too slowly. To see what we mean, suppose you had started with  $s_1 = 1$  the day the universe was formed, 13 billion years ago, and added a new term every second. About how large would the partial sum  $s_n$  be today, assuming a 365-day year?
44. Are there any values of  $x$  for which  $\sum_{n=1}^{\infty} (1/nx)$  converges? Give reasons for your answer.
45. Is it true that if  $\sum_{n=1}^{\infty} a_n$  is a divergent series of positive numbers, then there is also a divergent series  $\sum_{n=1}^{\infty} b_n$  of positive numbers with  $b_n < a_n$  for every  $n$ ? Is there a “smallest” divergent series of positive numbers? Give reasons for your answers.
46. (Continuation of Exercise 45.) Is there a “largest” convergent series of positive numbers? Explain.
47.  $\sum_{n=1}^{\infty} (1/\sqrt{n+1})$  diverges

- a. Use the accompanying graph to show that the partial sum

$$s_{50} = \sum_{n=1}^{50} (1/\sqrt{n+1}) \text{ satisfies}$$

$$\int_1^{51} \frac{1}{\sqrt{x+1}} dx < s_{50} < \int_0^{50} \frac{1}{\sqrt{x+1}} dx.$$

Conclude that  $11.5 < s_{50} < 12.3$ .



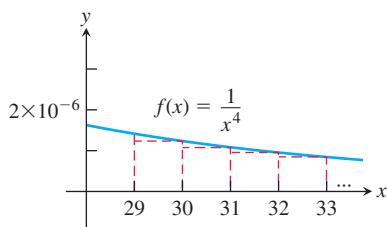


- b. What should  $n$  be in order that the partial sum

$$s_n = \sum_{i=1}^n \left(1/\sqrt{i+1}\right) \text{ satisfy } s_n > 1000?$$

**48.  $\sum_{n=1}^{\infty} (1/n^4)$  converges**

- a. Use the accompanying graph to find an upper bound for the error if  $s_{30} = \sum_{n=1}^{30} (1/n^4)$  is used to estimate the value of  $\sum_{n=1}^{\infty} (1/n^4)$ .



- b. Find  $n$  so that the partial sum  $s_n = \sum_{i=1}^n (1/i^4)$  estimates the value of  $\sum_{n=1}^{\infty} (1/n^4)$  with an error of at most 0.000001.

- 49.** Estimate the value of  $\sum_{n=1}^{\infty} (1/n^3)$  to within 0.01 of its exact value.

- 50.** Estimate the value of  $\sum_{n=2}^{\infty} (1/(n^2 + 4))$  to within 0.1 of its exact value.

- 51.** How many terms of the convergent series  $\sum_{n=1}^{\infty} (1/n^{1.1})$  should be used to estimate its value with error at most 0.00001?

- 52.** How many terms of the convergent series  $\sum_{n=4}^{\infty} (1/(n(\ln n)^3))$  should be used to estimate its value with error at most 0.01?

- 53. The Cauchy condensation test** The Cauchy condensation test says: Let  $\{a_n\}$  be a nonincreasing sequence ( $a_n \geq a_{n+1}$  for all  $n$ ) of positive terms that converges to 0. Then  $\sum a_n$  converges if and only if  $\sum 2^n a_{2^n}$  converges. For example,  $\sum (1/n)$  diverges because  $\sum 2^n \cdot (1/2^n) = \sum 1$  diverges. Show why the test works.

- 54.** Use the Cauchy condensation test from Exercise 53 to show that

a.  $\sum_{n=2}^{\infty} \frac{1}{n \ln n}$  diverges;

b.  $\sum_{n=1}^{\infty} \frac{1}{n^p}$  converges if  $p > 1$  and diverges if  $p \leq 1$ .

**55. Logarithmic  $p$ -series**

- a. Show that the improper integral

$$\int_2^{\infty} \frac{dx}{x(\ln x)^p} \quad (p \text{ a positive constant})$$

converges if and only if  $p > 1$ .

- b. What implications does the fact in part (a) have for the convergence of the series

$$\sum_{n=2}^{\infty} \frac{1}{n(\ln n)^p}?$$

Give reasons for your answer.

- 56. (Continuation of Exercise 55.)** Use the result in Exercise 55 to determine which of the following series converge and which diverge. Support your answer in each case.

a.  $\sum_{n=2}^{\infty} \frac{1}{n(\ln n)}$

b.  $\sum_{n=2}^{\infty} \frac{1}{n(\ln n)^{1.01}}$

c.  $\sum_{n=2}^{\infty} \frac{1}{n \ln(n^3)}$

d.  $\sum_{n=2}^{\infty} \frac{1}{n(\ln n)^3}$

- 57. Euler's constant** Graphs like those in Figure 10.11 suggest that as  $n$  increases there is little change in the difference between the sum

$$1 + \frac{1}{2} + \cdots + \frac{1}{n}$$

and the integral

$$\ln n = \int_1^n \frac{1}{x} dx.$$

To explore this idea, carry out the following steps.

- a. By taking  $f(x) = 1/x$  in the proof of Theorem 9, show that

$$\ln(n+1) \leq 1 + \frac{1}{2} + \cdots + \frac{1}{n} \leq 1 + \ln n$$

or

$$0 < \ln(n+1) - \ln n \leq 1 + \frac{1}{2} + \cdots + \frac{1}{n} - \ln n \leq 1.$$

Thus, the sequence

$$a_n = 1 + \frac{1}{2} + \cdots + \frac{1}{n} - \ln n$$

is bounded from below and from above.

- b. Show that

$$\frac{1}{n+1} < \int_n^{n+1} \frac{1}{x} dx = \ln(n+1) - \ln n,$$

and use this result to show that the sequence  $\{a_n\}$  in part (a) is decreasing.

Since a decreasing sequence that is bounded from below converges, the numbers  $a_n$  defined in part (a) converge:

$$1 + \frac{1}{2} + \cdots + \frac{1}{n} - \ln n \rightarrow \gamma.$$

The number  $\gamma$ , whose value is 0.5772..., is called *Euler's constant*.

- 58.** Use the Integral Test to show that the series

$$\sum_{n=0}^{\infty} e^{-n^2}$$

converges.

- 59. a.** For the series  $\sum (1/n^3)$ , use the inequalities in Equation (2) with  $n = 10$  to find an interval containing the sum  $S$ .

- b.** As in Example 5, use the midpoint of the interval found in part (a) to approximate the sum of the series. What is the maximum error for your approximation?

- 60.** Repeat Exercise 59 using the series  $\sum (1/n^4)$ .

- 61. Area** Consider the sequence  $\{1/n\}_{n=1}^{\infty}$ . On each subinterval  $(1/(n+1), 1/n)$  within the interval  $[0, 1]$ , erect the rectangle with area  $a_n$  having height  $1/n$  and width equal to the length of the subinterval. Find the total area  $\sum a_n$  of all the rectangles. (Hint: Use the result of Example 5 in Section 10.2.)

- 62. Area** Repeat Exercise 61, using trapezoids instead of rectangles. That is, on the subinterval  $(1/(n+1), 1/n)$ , let  $a_n$  denote the area of the trapezoid having heights  $y = 1/(n+1)$  at  $x = 1/(n+1)$  and  $y = 1/n$  at  $x = 1/n$ .

## Exercises 10.4

### Comparison Test

In Exercises 1–8, use the Comparison Test to determine if each series converges or diverges.

1.  $\sum_{n=1}^{\infty} \frac{1}{n^2 + 30}$
2.  $\sum_{n=1}^{\infty} \frac{n-1}{n^4 + 2}$
3.  $\sum_{n=2}^{\infty} \frac{1}{\sqrt{n} - 1}$
4.  $\sum_{n=2}^{\infty} \frac{n+2}{n^2 - n}$
5.  $\sum_{n=1}^{\infty} \frac{\cos^2 n}{n^{3/2}}$
6.  $\sum_{n=1}^{\infty} \frac{1}{n3^n}$
7.  $\sum_{n=1}^{\infty} \sqrt{\frac{n+4}{n^4 + 4}}$
8.  $\sum_{n=1}^{\infty} \frac{\sqrt{n} + 1}{\sqrt{n^2 + 3}}$

### Limit Comparison Test

In Exercises 9–16, use the Limit Comparison Test to determine if each series converges or diverges.

9.  $\sum_{n=1}^{\infty} \frac{n-2}{n^3 - n^2 + 3}$   
(Hint: Limit Comparison with  $\sum_{n=1}^{\infty} (1/n^2)$ )
10.  $\sum_{n=1}^{\infty} \sqrt{\frac{n+1}{n^2 + 2}}$   
(Hint: Limit Comparison with  $\sum_{n=1}^{\infty} (1/\sqrt{n})$ )
11.  $\sum_{n=2}^{\infty} \frac{n(n+1)}{(n^2+1)(n-1)}$
12.  $\sum_{n=1}^{\infty} \frac{2^n}{3+4^n}$
13.  $\sum_{n=1}^{\infty} \frac{5^n}{\sqrt{n} 4^n}$
14.  $\sum_{n=1}^{\infty} \left( \frac{2n+3}{5n+4} \right)^n$
15.  $\sum_{n=2}^{\infty} \frac{1}{\ln n}$   
(Hint: Limit Comparison with  $\sum_{n=2}^{\infty} (1/n)$ )
16.  $\sum_{n=1}^{\infty} \ln \left( 1 + \frac{1}{n^2} \right)$   
(Hint: Limit Comparison with  $\sum_{n=1}^{\infty} (1/n^2)$ )

### Determining Convergence or Divergence

Which of the series in Exercises 17–54 converge, and which diverge? Use any method, and give reasons for your answers.

17.  $\sum_{n=1}^{\infty} \frac{1}{2\sqrt{n} + \sqrt[3]{n}}$
18.  $\sum_{n=1}^{\infty} \frac{3}{n + \sqrt{n}}$
19.  $\sum_{n=1}^{\infty} \frac{\sin^2 n}{2^n}$
20.  $\sum_{n=1}^{\infty} \frac{1 + \cos n}{n^2}$
21.  $\sum_{n=1}^{\infty} \frac{2n}{3n-1}$
22.  $\sum_{n=1}^{\infty} \frac{n+1}{n^2\sqrt{n}}$

23.  $\sum_{n=1}^{\infty} \frac{10n+1}{n(n+1)(n+2)}$
24.  $\sum_{n=3}^{\infty} \frac{5n^3 - 3n}{n^2(n-2)(n^2+5)}$
25.  $\sum_{n=1}^{\infty} \left( \frac{n}{3n+1} \right)^n$
26.  $\sum_{n=1}^{\infty} \frac{1}{\sqrt{n^3 + 2}}$
27.  $\sum_{n=3}^{\infty} \frac{1}{\ln(\ln n)}$
28.  $\sum_{n=1}^{\infty} \frac{(\ln n)^2}{n^3}$
29.  $\sum_{n=2}^{\infty} \frac{1}{\sqrt{n} \ln n}$
30.  $\sum_{n=1}^{\infty} \frac{(\ln n)^2}{n^{3/2}}$
31.  $\sum_{n=1}^{\infty} \frac{1}{1 + \ln n}$
32.  $\sum_{n=2}^{\infty} \frac{\ln(n+1)}{n+1}$
33.  $\sum_{n=2}^{\infty} \frac{1}{n\sqrt{n^2 - 1}}$
34.  $\sum_{n=1}^{\infty} \frac{\sqrt{n}}{n^2 + 1}$
35.  $\sum_{n=1}^{\infty} \frac{1-n}{n2^n}$
36.  $\sum_{n=1}^{\infty} \frac{n+2^n}{n^2 2^n}$
37.  $\sum_{n=1}^{\infty} \frac{1}{3^{n-1} + 1}$
38.  $\sum_{n=1}^{\infty} \frac{3^{n-1} + 1}{3^n}$
39.  $\sum_{n=1}^{\infty} \frac{n+1}{n^2 + 3n} \cdot \frac{1}{5n}$
40.  $\sum_{n=1}^{\infty} \frac{2^n + 3^n}{3^n + 4^n}$
41.  $\sum_{n=1}^{\infty} \frac{2^n - n}{n2^n}$
42.  $\sum_{n=1}^{\infty} \frac{\ln n}{\sqrt{n} e^n}$
43.  $\sum_{n=2}^{\infty} \frac{1}{n!}$   
(Hint: First show that  $(1/n!) \leq (1/(n(n-1)))$  for  $n \geq 2$ .)
44.  $\sum_{n=1}^{\infty} \frac{(n-1)!}{(n+2)!}$
45.  $\sum_{n=1}^{\infty} \sin \frac{1}{n}$
46.  $\sum_{n=1}^{\infty} \tan \frac{1}{n}$
47.  $\sum_{n=1}^{\infty} \frac{\tan^{-1} n}{n^{1.1}}$
48.  $\sum_{n=1}^{\infty} \frac{\sec^{-1} n}{n^{1.3}}$
49.  $\sum_{n=1}^{\infty} \frac{\coth n}{n^2}$
50.  $\sum_{n=1}^{\infty} \frac{\tanh n}{n^2}$
51.  $\sum_{n=1}^{\infty} \frac{1}{n\sqrt[n]{n}}$
52.  $\sum_{n=1}^{\infty} \frac{\sqrt[n]{n}}{n^2}$
53.  $\sum_{n=1}^{\infty} \frac{1}{1+2+3+\cdots+n}$
54.  $\sum_{n=1}^{\infty} \frac{1}{1+2^2+3^2+\cdots+n^2}$

### Theory and Examples

55. Prove (a) Part 2 and (b) Part 3 of the Limit Comparison Test.
56. If  $\sum_{n=1}^{\infty} a_n$  is a convergent series of nonnegative numbers, can anything be said about  $\sum_{n=1}^{\infty} (a_n/n)$ ? Explain.
57. Suppose that  $a_n > 0$  and  $b_n > 0$  for  $n \geq N$  ( $N$  an integer). If  $\lim_{n \rightarrow \infty} (a_n/b_n) = \infty$  and  $\sum a_n$  converges, can anything be said about  $\sum b_n$ ? Give reasons for your answer.
58. Prove that if  $\sum a_n$  is a convergent series of nonnegative terms, then  $\sum a_n^2$  converges.

59. Suppose that  $a_n > 0$  and  $\lim_{n \rightarrow \infty} a_n = \infty$ . Prove that  $\sum a_n$  diverges.
60. Suppose that  $a_n > 0$  and  $\lim_{n \rightarrow \infty} n^2 a_n = 0$ . Prove that  $\sum a_n$  converges.
61. Show that  $\sum_{n=2}^{\infty} ((\ln n)^q / n^p)$  converges for  $-\infty < q < \infty$  and  $p > 1$ .  
(Hint: Limit Comparison with  $\sum_{n=2}^{\infty} 1/n^r$  for  $1 < r < p$ .)
62. (Continuation of Exercise 61.) Show that  $\sum_{n=2}^{\infty} ((\ln n)^q / n^p)$  diverges for  $-\infty < q < \infty$  and  $0 < p < 1$ .  
(Hint: Limit Comparison with an appropriate  $p$ -series.)
63. **Decimal numbers** Any real number in the interval  $[0, 1]$  can be represented by a decimal (not necessarily unique) as

$$0.d_1 d_2 d_3 d_4 \dots = \frac{d_1}{10} + \frac{d_2}{10^2} + \frac{d_3}{10^3} + \frac{d_4}{10^4} + \dots,$$

where  $d_i$  is one of the integers  $0, 1, 2, 3, \dots, 9$ . Prove that the series on the right-hand side always converges.

64. If  $\sum a_n$  is a convergent series of positive terms, prove that  $\sum \sin(a_n)$  converges.

In Exercises 65–70, use the results of Exercises 61 and 62 to determine if each series converges or diverges.

65.  $\sum_{n=2}^{\infty} \frac{(\ln n)^3}{n^4}$       66.  $\sum_{n=2}^{\infty} \sqrt{\frac{\ln n}{n}}$
67.  $\sum_{n=2}^{\infty} \frac{(\ln n)^{1000}}{n^{1.001}}$       68.  $\sum_{n=2}^{\infty} \frac{(\ln n)^{1/5}}{n^{0.99}}$
69.  $\sum_{n=2}^{\infty} \frac{1}{n^{1.1}(\ln n)^3}$       70.  $\sum_{n=2}^{\infty} \frac{1}{\sqrt{n \cdot \ln n}}$

### COMPUTER EXPLORATIONS

71. It is not yet known whether the series

$$\sum_{n=1}^{\infty} \frac{1}{n^3 \sin^2 n}$$

converges or diverges. Use a CAS to explore the behavior of the series by performing the following steps.

- a. Define the sequence of partial sums

$$s_k = \sum_{n=1}^k \frac{1}{n^3 \sin^2 n}.$$

What happens when you try to find the limit of  $s_k$  as  $k \rightarrow \infty$ ? Does your CAS find a closed form answer for this limit?

- b. Plot the first 100 points  $(k, s_k)$  for the sequence of partial sums. Do they appear to converge? What would you estimate the limit to be?
- c. Next plot the first 200 points  $(k, s_k)$ . Discuss the behavior in your own words.
- d. Plot the first 400 points  $(k, s_k)$ . What happens when  $k = 355$ ? Calculate the number  $355/113$ . Explain from your calculation what happened at  $k = 355$ . For what values of  $k$  would you guess this behavior might occur again?

72. a. Use Theorem 8 to show that

$$S = \sum_{n=1}^{\infty} \frac{1}{n(n+1)} + \sum_{n=1}^{\infty} \left( \frac{1}{n^2} - \frac{1}{n(n+1)} \right)$$

where  $S = \sum_{n=1}^{\infty} (1/n^2)$ , the sum of a convergent  $p$ -series.

- b. From Example 5, Section 10.2, show that

$$S = 1 + \sum_{n=1}^{\infty} \frac{1}{n^2(n+1)}.$$

- c. Explain why taking the first  $M$  terms in the series in part (b) gives a better approximation to  $S$  than taking the first  $M$  terms in the original series  $\sum_{n=1}^{\infty} (1/n^2)$ .
- d. We know the exact value of  $S$  is  $\pi^2/6$ . Which of the sums

$$\sum_{n=1}^{1000000} \frac{1}{n^2} \quad \text{or} \quad 1 + \sum_{n=1}^{1000} \frac{1}{n^2(n+1)}$$

gives a better approximation to  $S$ ?

## Exercises 10.5

### Using the Ratio Test

In Exercises 1–8, use the Ratio Test to determine if each series converges absolutely or diverges.

1.  $\sum_{n=1}^{\infty} \frac{2^n}{n!}$
2.  $\sum_{n=1}^{\infty} (-1)^n \frac{n+2}{3^n}$
3.  $\sum_{n=1}^{\infty} \frac{(n-1)!}{(n+1)^2}$
4.  $\sum_{n=1}^{\infty} \frac{2^{n+1}}{n3^{n-1}}$
5.  $\sum_{n=1}^{\infty} \frac{n^4}{(-4)^n}$
6.  $\sum_{n=2}^{\infty} \frac{3^{n+2}}{\ln n}$
7.  $\sum_{n=1}^{\infty} (-1)^n \frac{n^2(n+2)!}{n! 3^{2n}}$
8.  $\sum_{n=1}^{\infty} \frac{n5^n}{(2n+3) \ln(n+1)}$

### Using the Root Test

In Exercises 9–16, use the Root Test to determine if each series converges absolutely or diverges.

9.  $\sum_{n=1}^{\infty} \frac{7}{(2n+5)^n}$
10.  $\sum_{n=1}^{\infty} \frac{4^n}{(3n)^n}$
11.  $\sum_{n=1}^{\infty} \left( \frac{4n+3}{3n-5} \right)^n$
12.  $\sum_{n=1}^{\infty} \left( -\ln \left( e^2 + \frac{1}{n} \right) \right)^{n+1}$

$$13. \sum_{n=1}^{\infty} \frac{-8}{(3 + (1/n))^{2n}} \quad 14. \sum_{n=1}^{\infty} \sin^n \left( \frac{1}{\sqrt{n}} \right)$$

$$15. \sum_{n=1}^{\infty} (-1)^n \left( 1 - \frac{1}{n} \right)^{n^2}$$

(Hint:  $\lim_{n \rightarrow \infty} (1 + x/n)^n = e^x$ )

$$16. \sum_{n=2}^{\infty} \frac{(-1)^n}{n^{1+n}}$$

### Determining Convergence or Divergence

In Exercises 17–44, use any method to determine if the series converges or diverges. Give reasons for your answer.

17.  $\sum_{n=1}^{\infty} \frac{n^{\sqrt{2}}}{2^n}$
18.  $\sum_{n=1}^{\infty} (-1)^n n^2 e^{-n}$
19.  $\sum_{n=1}^{\infty} n! (-e)^{-n}$
20.  $\sum_{n=1}^{\infty} \frac{n!}{10^n}$
21.  $\sum_{n=1}^{\infty} \frac{n^{10}}{10^n}$
22.  $\sum_{n=1}^{\infty} \left( \frac{n-2}{n} \right)^n$

23.  $\sum_{n=1}^{\infty} \frac{2 + (-1)^n}{1.25^n}$       24.  $\sum_{n=1}^{\infty} \frac{(-2)^n}{3^n}$
25.  $\sum_{n=1}^{\infty} (-1)^n \left(1 - \frac{3}{n}\right)^n$       26.  $\sum_{n=1}^{\infty} \left(1 - \frac{1}{3n}\right)^n$
27.  $\sum_{n=1}^{\infty} \frac{\ln n}{n^3}$       28.  $\sum_{n=1}^{\infty} \frac{(-\ln n)^n}{n^n}$
29.  $\sum_{n=1}^{\infty} \left(\frac{1}{n} - \frac{1}{n^2}\right)$       30.  $\sum_{n=1}^{\infty} \left(\frac{1}{n} - \frac{1}{n^2}\right)^n$
31.  $\sum_{n=1}^{\infty} \frac{e^n}{n^e}$       32.  $\sum_{n=1}^{\infty} \frac{n \ln n}{(-2)^n}$
33.  $\sum_{n=1}^{\infty} \frac{(n+1)(n+2)}{n!}$       34.  $\sum_{n=1}^{\infty} e^{-n}(n^3)$
35.  $\sum_{n=1}^{\infty} \frac{(n+3)!}{3!n!3^n}$       36.  $\sum_{n=1}^{\infty} \frac{n2^n(n+1)!}{3^n n!}$
37.  $\sum_{n=1}^{\infty} \frac{n!}{(2n+1)!}$       38.  $\sum_{n=1}^{\infty} \frac{n!}{(-n)^n}$
39.  $\sum_{n=2}^{\infty} \frac{-n}{(\ln n)^n}$       40.  $\sum_{n=2}^{\infty} \frac{n}{(\ln n)^{(n/2)}}$
41.  $\sum_{n=1}^{\infty} \frac{n! \ln n}{n(n+2)!}$       42.  $\sum_{n=1}^{\infty} \frac{(-3)^n}{n^3 2^n}$
43.  $\sum_{n=1}^{\infty} \frac{(n!)^2}{(2n)!}$       44.  $\sum_{n=1}^{\infty} \frac{(2n+3)(2^n+3)}{3^n+2}$

**Recursively Defined Terms** Which of the series  $\sum_{n=1}^{\infty} a_n$  defined by the formulas in Exercises 45–54 converge, and which diverge? Give reasons for your answers.

45.  $a_1 = 2, \quad a_{n+1} = \frac{1 + \sin n}{n} a_n$
46.  $a_1 = 1, \quad a_{n+1} = \frac{1 + \tan^{-1} n}{n} a_n$
47.  $a_1 = \frac{1}{3}, \quad a_{n+1} = \frac{3n-1}{2n+5} a_n$
48.  $a_1 = 3, \quad a_{n+1} = \frac{n}{n+1} a_n$
49.  $a_1 = 2, \quad a_{n+1} = \frac{2}{n} a_n$
50.  $a_1 = 5, \quad a_{n+1} = \frac{\sqrt[n]{n}}{2} a_n$
51.  $a_1 = 1, \quad a_{n+1} = \frac{1 + \ln n}{n} a_n$

52.  $a_1 = \frac{1}{2}, \quad a_{n+1} = \frac{n + \ln n}{n + 10} a_n$

53.  $a_1 = \frac{1}{3}, \quad a_{n+1} = \sqrt[n]{a_n}$

54.  $a_1 = \frac{1}{2}, \quad a_{n+1} = (a_n)^{n+1}$

### Convergence or Divergence

Which of the series in Exercises 55–62 converge, and which diverge? Give reasons for your answers.

55.  $\sum_{n=1}^{\infty} \frac{2^n n! n!}{(2n)!}$       56.  $\sum_{n=1}^{\infty} \frac{(-1)^n (3n)!}{n!(n+1)!(n+2)!}$
57.  $\sum_{n=1}^{\infty} \frac{(n!)^n}{(n^n)^2}$       58.  $\sum_{n=1}^{\infty} (-1)^n \frac{(n!)^n}{n^{(n^2)}}$
59.  $\sum_{n=1}^{\infty} \frac{n^n}{2^{(n^2)}}$       60.  $\sum_{n=1}^{\infty} \frac{n^n}{(2^n)^2}$
61.  $\sum_{n=1}^{\infty} \frac{1 \cdot 3 \cdot \cdots \cdot (2n-1)}{4^n 2^n n!}$
62.  $\sum_{n=1}^{\infty} \frac{1 \cdot 3 \cdot \cdots \cdot (2n-1)}{[2 \cdot 4 \cdot \cdots \cdot (2n)](3^n + 1)}$

### Theory and Examples

63. Neither the Ratio Test nor the Root Test helps with  $p$ -series. Try them on

$$\sum_{n=1}^{\infty} \frac{1}{n^p}$$

and show that both tests fail to provide information about convergence.

64. Show that neither the Ratio Test nor the Root Test provides information about the convergence of

$$\sum_{n=2}^{\infty} \frac{1}{(\ln n)^p} \quad (p \text{ constant}).$$

65. Let  $a_n = \begin{cases} n/2^n, & \text{if } n \text{ is a prime number} \\ 1/2^n, & \text{otherwise.} \end{cases}$

Does  $\sum a_n$  converge? Give reasons for your answer.

66. Show that  $\sum_{n=1}^{\infty} 2^{(n^2)}/n!$  diverges. Recall from the Laws of Exponents that  $2^{(n^2)} = (2^n)^n$ .

## Exercises 10.6

### Determining Convergence or Divergence

In Exercises 1–14, determine if the alternating series converges or diverges. Some of the series do not satisfy the conditions of the Alternating Series Test.

1.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{\sqrt{n}}$
2.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{n^{3/2}}$
3.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{n^{3^n}}$
4.  $\sum_{n=2}^{\infty} (-1)^n \frac{4}{(\ln n)^2}$
5.  $\sum_{n=1}^{\infty} (-1)^n \frac{n}{n^2 + 1}$
6.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{n^2 + 5}{n^2 + 4}$
7.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{2^n}{n^2}$
8.  $\sum_{n=1}^{\infty} (-1)^n \frac{10^n}{(n+1)!}$
9.  $\sum_{n=1}^{\infty} (-1)^{n+1} \left(\frac{n}{10}\right)^n$
10.  $\sum_{n=2}^{\infty} (-1)^{n+1} \frac{1}{\ln n}$
11.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{\ln n}{n}$
12.  $\sum_{n=1}^{\infty} (-1)^n \ln \left(1 + \frac{1}{n}\right)$
13.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{\sqrt{n} + 1}{n + 1}$
14.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{3\sqrt{n} + 1}{\sqrt{n} + 1}$

### Absolute and Conditional Convergence

Which of the series in Exercises 15–48 converge absolutely, which converge, and which diverge? Give reasons for your answers.

15.  $\sum_{n=1}^{\infty} (-1)^{n+1} (0.1)^n$
16.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{(0.1)^n}{n}$
17.  $\sum_{n=1}^{\infty} (-1)^n \frac{1}{\sqrt{n}}$
18.  $\sum_{n=1}^{\infty} \frac{(-1)^n}{1 + \sqrt{n}}$
19.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{n}{n^3 + 1}$
20.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{n!}{2^n}$
21.  $\sum_{n=1}^{\infty} (-1)^n \frac{1}{n + 3}$
22.  $\sum_{n=1}^{\infty} (-1)^n \frac{\sin n}{n^2}$
23.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{3 + n}{5 + n}$
24.  $\sum_{n=1}^{\infty} \frac{(-2)^{n+1}}{n + 5^n}$
25.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1 + n}{n^2}$
26.  $\sum_{n=1}^{\infty} (-1)^{n+1} (\sqrt[n]{10})$
27.  $\sum_{n=1}^{\infty} (-1)^n n^2 (2/3)^n$
28.  $\sum_{n=2}^{\infty} (-1)^{n+1} \frac{1}{n \ln n}$
29.  $\sum_{n=1}^{\infty} (-1)^n \frac{\tan^{-1} n}{n^2 + 1}$
30.  $\sum_{n=1}^{\infty} (-1)^n \frac{\ln n}{n - \ln n}$
31.  $\sum_{n=1}^{\infty} (-1)^n \frac{n}{n + 1}$
32.  $\sum_{n=1}^{\infty} (-5)^{-n}$
33.  $\sum_{n=1}^{\infty} \frac{(-100)^n}{n!}$
34.  $\sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n^2 + 2n + 1}$
35.  $\sum_{n=1}^{\infty} \frac{\cos n\pi}{n\sqrt{n}}$
36.  $\sum_{n=1}^{\infty} \frac{\cos n\pi}{n}$
37.  $\sum_{n=1}^{\infty} \frac{(-1)^n (n+1)^n}{(2n)^n}$
38.  $\sum_{n=1}^{\infty} \frac{(-1)^{n+1} (n!)^2}{(2n)!}$

39.  $\sum_{n=1}^{\infty} (-1)^n \frac{(2n)!}{2^n n! n}$
40.  $\sum_{n=1}^{\infty} (-1)^n \frac{(n!)^2 3^n}{(2n+1)!}$
41.  $\sum_{n=1}^{\infty} (-1)^n (\sqrt{n+1} - \sqrt{n})$
42.  $\sum_{n=1}^{\infty} (-1)^n (\sqrt{n^2 + n} - n)$
43.  $\sum_{n=1}^{\infty} (-1)^n (\sqrt{n + \sqrt{n}} - \sqrt{n})$
44.  $\sum_{n=1}^{\infty} \frac{(-1)^n}{\sqrt{n} + \sqrt{n+1}}$
45.  $\sum_{n=1}^{\infty} (-1)^n \operatorname{sech} n$
46.  $\sum_{n=1}^{\infty} (-1)^n \operatorname{csch} n$
47.  $\frac{1}{4} - \frac{1}{6} + \frac{1}{8} - \frac{1}{10} + \frac{1}{12} - \frac{1}{14} + \cdots$
48.  $1 + \frac{1}{4} - \frac{1}{9} - \frac{1}{16} + \frac{1}{25} + \frac{1}{36} - \frac{1}{49} - \frac{1}{64} + \cdots$

### Error Estimation

In Exercises 49–52, estimate the magnitude of the error involved in using the sum of the first four terms to approximate the sum of the entire series.

49.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{n}$
50.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{10^n}$
51.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{(0.01)^n}{n}$  As you will see in Section 10.7, the sum is  $\ln(1.01)$ .
52.  $\frac{1}{1+t} = \sum_{n=0}^{\infty} (-1)^n t^n, \quad 0 < t < 1$

In Exercises 53–56, determine how many terms should be used to estimate the sum of the entire series with an error of less than 0.001.

53.  $\sum_{n=1}^{\infty} (-1)^n \frac{1}{n^2 + 3}$
54.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{n}{n^2 + 1}$
55.  $\sum_{n=1}^{\infty} (-1)^{n+1} \frac{1}{(n + 3\sqrt{n})^3}$
56.  $\sum_{n=1}^{\infty} (-1)^n \frac{1}{\ln(\ln(n+2))}$

**T** Approximate the sums in Exercises 57 and 58 with an error of magnitude less than  $5 \times 10^{-6}$ .

57.  $\sum_{n=0}^{\infty} (-1)^n \frac{1}{(2n)!}$  As you will see in Section 10.9, the sum is  $\cos 1$ , the cosine of 1 radian.
58.  $\sum_{n=0}^{\infty} (-1)^n \frac{1}{n!}$  As you will see in Section 10.9, the sum is  $e^{-1}$ .

### Theory and Examples

59. a. The series

$$\frac{1}{3} - \frac{1}{2} + \frac{1}{9} - \frac{1}{4} + \frac{1}{27} - \frac{1}{8} + \cdots + \frac{1}{3^n} - \frac{1}{2^n} + \cdots$$

does not meet one of the conditions of Theorem 14. Which one?

b. Use Theorem 17 to find the sum of the series in part (a).

- T 60.** The limit  $L$  of an alternating series that satisfies the conditions of Theorem 15 lies between the values of any two consecutive partial sums. This suggests using the average

$$\frac{s_n + s_{n+1}}{2} = s_n + \frac{1}{2}(-1)^{n+2}a_{n+1}$$

to estimate  $L$ . Compute

$$s_{20} + \frac{1}{2} \cdot \frac{1}{21}$$

as an approximation to the sum of the alternating harmonic series. The exact sum is  $\ln 2 = 0.69314718 \dots$

- 61. The sign of the remainder of an alternating series that satisfies the conditions of Theorem 15** Prove the assertion in Theorem 16 that whenever an alternating series satisfying the conditions of Theorem 15 is approximated with one of its partial sums, then the remainder (sum of the unused terms) has the same sign as the first unused term. (*Hint:* Group the remainder's terms in consecutive pairs.)
- 62.** Show that the sum of the first  $2n$  terms of the series

$$1 - \frac{1}{2} + \frac{1}{2} - \frac{1}{3} + \frac{1}{3} - \frac{1}{4} + \frac{1}{4} - \frac{1}{5} + \frac{1}{5} - \frac{1}{6} + \dots$$

is the same as the sum of the first  $n$  terms of the series

$$\frac{1}{1 \cdot 2} + \frac{1}{2 \cdot 3} + \frac{1}{3 \cdot 4} + \frac{1}{4 \cdot 5} + \frac{1}{5 \cdot 6} + \dots$$

Do these series converge? What is the sum of the first  $2n + 1$  terms of the first series? If the series converge, what is their sum?

- 63.** Show that if  $\sum_{n=1}^{\infty} a_n$  diverges, then  $\sum_{n=1}^{\infty} |a_n|$  diverges.
- 64.** Show that if  $\sum_{n=1}^{\infty} a_n$  converges absolutely, then

$$\left| \sum_{n=1}^{\infty} a_n \right| \leq \sum_{n=1}^{\infty} |a_n|.$$

- 65.** Show that if  $\sum_{n=1}^{\infty} a_n$  and  $\sum_{n=1}^{\infty} b_n$  both converge absolutely, then so do the following.

- a.  $\sum_{n=1}^{\infty} (a_n + b_n)$       b.  $\sum_{n=1}^{\infty} (a_n - b_n)$
- c.  $\sum_{n=1}^{\infty} k a_n$  ( $k$  any number)

- 66.** Show by example that  $\sum_{n=1}^{\infty} a_n b_n$  may diverge even if  $\sum_{n=1}^{\infty} a_n$  and  $\sum_{n=1}^{\infty} b_n$  both converge.

- 67.** If  $\sum a_n$  converges absolutely, prove that  $\sum a_n^2$  converges.

- 68.** Does the series

$$\sum_{n=1}^{\infty} \left( \frac{1}{n} - \frac{1}{n^2} \right)$$

converge or diverge? Justify your answer.

- T 69.** In the alternating harmonic series, suppose the goal is to arrange the terms to get a new series that converges to  $-1/2$ . Start the new arrangement with the first negative term, which is  $-1/2$ . Whenever you have a sum that is less than or equal to  $-1/2$ , start introducing positive terms, taken in order, until the new total is greater than  $-1/2$ . Then add negative terms until the total is less than or equal to  $-1/2$  again. Continue this process until your partial sums have been above the target at least three times and finish at or below it. If  $s_n$  is the sum of the first  $n$  terms of your new series, plot the points  $(n, s_n)$  to illustrate how the sums are behaving.

- 70. Outline of the proof of the Rearrangement Theorem (Theorem 17)**

- a. Let  $\epsilon$  be a positive real number, let  $L = \sum_{n=1}^{\infty} a_n$ , and let  $s_k = \sum_{n=1}^k a_n$ . Show that for some index  $N_1$  and for some index  $N_2 \geq N_1$ ,

$$\sum_{n=N_1}^{\infty} |a_n| < \frac{\epsilon}{2} \quad \text{and} \quad |s_{N_2} - L| < \frac{\epsilon}{2}.$$

Since all the terms  $a_1, a_2, \dots, a_{N_2}$  appear somewhere in the sequence  $\{b_n\}$ , there is an index  $N_3 \geq N_2$  such that if  $n \geq N_3$ , then  $(\sum_{k=1}^n b_k) - s_{N_2}$  is at most a sum of terms  $a_m$  with  $m \geq N_1$ . Therefore, if  $n \geq N_3$ ,

$$\begin{aligned} \left| \sum_{k=1}^n b_k - L \right| &\leq \left| \sum_{k=1}^n b_k - s_{N_2} \right| + |s_{N_2} - L| \\ &\leq \sum_{k=N_1}^{\infty} |a_k| + |s_{N_2} - L| < \epsilon. \end{aligned}$$

- b. The argument in part (a) shows that if  $\sum_{n=1}^{\infty} a_n$  converges absolutely then  $\sum_{n=1}^{\infty} b_n$  converges and  $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} a_n$ . Now show that because  $\sum_{n=1}^{\infty} |a_n|$  converges,  $\sum_{n=1}^{\infty} |b_n|$  converges to  $\sum_{n=1}^{\infty} |a_n|$ .

## Exercises 10.7

## Intervals of Convergence

In Exercises 1–36, (a) find the series' radius and interval of convergence. For what values of  $x$  does the series converge (b) absolutely, (c) conditionally?

1.  $\sum_{n=0}^{\infty} x^n$
2.  $\sum_{n=0}^{\infty} (x + 5)^n$
3.  $\sum_{n=0}^{\infty} (-1)^n (4x + 1)^n$
4.  $\sum_{n=1}^{\infty} \frac{(3x - 2)^n}{n}$
5.  $\sum_{n=0}^{\infty} \frac{(x - 2)^n}{10^n}$
6.  $\sum_{n=0}^{\infty} (2x)^n$
7.  $\sum_{n=0}^{\infty} \frac{nx^n}{n + 2}$
8.  $\sum_{n=1}^{\infty} \frac{(-1)^n (x + 2)^n}{n}$
9.  $\sum_{n=1}^{\infty} \frac{x^n}{n \sqrt{n} 3^n}$
10.  $\sum_{n=1}^{\infty} \frac{(x - 1)^n}{\sqrt{n}}$
11.  $\sum_{n=0}^{\infty} \frac{(-1)^n x^n}{n!}$
12.  $\sum_{n=0}^{\infty} \frac{3^n x^n}{n!}$
13.  $\sum_{n=1}^{\infty} \frac{4^n x^{2n}}{n}$
14.  $\sum_{n=1}^{\infty} \frac{(x - 1)^n}{n^3 3^n}$
15.  $\sum_{n=0}^{\infty} \frac{x^n}{\sqrt{n^2 + 3}}$
16.  $\sum_{n=0}^{\infty} \frac{(-1)^n x^{n+1}}{\sqrt{n + 3}}$
17.  $\sum_{n=0}^{\infty} \frac{n(x + 3)^n}{5^n}$
18.  $\sum_{n=0}^{\infty} \frac{nx^n}{4^n(n^2 + 1)}$
19.  $\sum_{n=0}^{\infty} \frac{\sqrt{n} x^n}{3^n}$
20.  $\sum_{n=1}^{\infty} \sqrt[n]{n} (2x + 5)^n$
21.  $\sum_{n=1}^{\infty} (2 + (-1)^n) \cdot (x + 1)^{n-1}$
22.  $\sum_{n=1}^{\infty} \frac{(-1)^n 3^{2n} (x - 2)^n}{3n}$
23.  $\sum_{n=1}^{\infty} \left(1 + \frac{1}{n}\right)^n x^n$
24.  $\sum_{n=1}^{\infty} (\ln n) x^n$
25.  $\sum_{n=1}^{\infty} n^n x^n$
26.  $\sum_{n=0}^{\infty} n! (x - 4)^n$
27.  $\sum_{n=1}^{\infty} \frac{(-1)^{n+1} (x + 2)^n}{n 2^n}$
28.  $\sum_{n=0}^{\infty} (-2)^n (n + 1) (x - 1)^n$
29.  $\sum_{n=2}^{\infty} \frac{x^n}{n (\ln n)^2}$
30.  $\sum_{n=2}^{\infty} \frac{x^n}{n \ln n}$
31.  $\sum_{n=0}^{\infty} \frac{(4x - 5)^{2n+1}}{n^{3/2}}$
32.  $\sum_{n=1}^{\infty} \frac{(3x + 1)^{n+1}}{2n + 2}$

Get the information you need about  $\sum 1/(n(\ln n)^2)$  from Section 10.3, Exercise 55.

Get the information you need about  $\sum 1/(n \ln n)$  from Section 10.3, Exercise 54.



33.  $\sum_{n=1}^{\infty} \frac{1}{2 \cdot 4 \cdot 6 \cdots (2n)} x^n$
34.  $\sum_{n=1}^{\infty} \frac{3 \cdot 5 \cdot 7 \cdots (2n+1)}{n^2 \cdot 2^n} x^{n+1}$
35.  $\sum_{n=1}^{\infty} \frac{1+2+3+\cdots+n}{1^2+2^2+3^2+\cdots+n^2} x^n$
36.  $\sum_{n=1}^{\infty} (\sqrt{n+1} - \sqrt{n})(x-3)^n$

In Exercises 37–40, find the series' radius of convergence.

37.  $\sum_{n=1}^{\infty} \frac{n!}{3 \cdot 6 \cdot 9 \cdots 3n} x^n$
38.  $\sum_{n=1}^{\infty} \left( \frac{2 \cdot 4 \cdot 6 \cdots (2n)}{2 \cdot 5 \cdot 8 \cdots (3n-1)} \right)^2 x^n$
39.  $\sum_{n=1}^{\infty} \frac{(n!)^2}{2^n (2n)!} x^n$
40.  $\sum_{n=1}^{\infty} \left( \frac{n}{n+1} \right)^{n^2} x^n$

(Hint: Apply the Root Test.)

In Exercises 41–48, use Theorem 20 to find the series' interval of convergence and, within this interval, the sum of the series as a function of  $x$ .

41.  $\sum_{n=0}^{\infty} 3^n x^n$
42.  $\sum_{n=0}^{\infty} (e^x - 4)^n$
43.  $\sum_{n=0}^{\infty} \frac{(x-1)^{2n}}{4^n}$
44.  $\sum_{n=0}^{\infty} \frac{(x+1)^{2n}}{9^n}$
45.  $\sum_{n=0}^{\infty} \left( \frac{\sqrt{x}}{2} - 1 \right)^n$
46.  $\sum_{n=0}^{\infty} (\ln x)^n$
47.  $\sum_{n=0}^{\infty} \left( \frac{x^2+1}{3} \right)^n$
48.  $\sum_{n=0}^{\infty} \left( \frac{x^2-1}{2} \right)^n$

### Using the Geometric Series

49. In Example 2 we represented the function  $f(x) = 2/x$  as a power series about  $x = 2$ . Use a geometric series to represent  $f(x)$  as a power series about  $x = 1$ , and find its interval of convergence.
50. Use a geometric series to represent each of the given functions as a power series about  $x = 0$ , and find their intervals of convergence.
- a.  $f(x) = \frac{5}{3-x}$       b.  $g(x) = \frac{3}{x-2}$
51. Represent the function  $g(x)$  in Exercise 50 as a power series about  $x = 5$ , and find the interval of convergence.
52. a. Find the interval of convergence of the power series

$$\sum_{n=0}^{\infty} \frac{8}{4^{n+2}} x^n.$$

- b. Represent the power series in part (a) as a power series about  $x = 3$  and identify the interval of convergence of the new series. (Later in the chapter you will understand why the new interval of convergence does not necessarily include all of the numbers in the original interval of convergence.)

### Theory and Examples

53. For what values of  $x$  does the series

$$1 - \frac{1}{2}(x-3) + \frac{1}{4}(x-3)^2 + \cdots + \left(-\frac{1}{2}\right)^n (x-3)^n + \cdots$$

converge? What is its sum? What series do you get if you differentiate the given series term by term? For what values of  $x$  does the new series converge? What is its sum?

54. If you integrate the series in Exercise 53 term by term, what new series do you get? For what values of  $x$  does the new series converge, and what is another name for its sum?

55. The series

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} + \frac{x^9}{9!} - \frac{x^{11}}{11!} + \cdots$$

converges to  $\sin x$  for all  $x$ .

- a. Find the first six terms of a series for  $\cos x$ . For what values of  $x$  should the series converge?
- b. By replacing  $x$  by  $2x$  in the series for  $\sin x$ , find a series that converges to  $\sin 2x$  for all  $x$ .
- c. Using the result in part (a) and series multiplication, calculate the first six terms of a series for  $2 \sin x \cos x$ . Compare your answer with the answer in part (b).

56. The series

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \frac{x^5}{5!} + \cdots$$

converges to  $e^x$  for all  $x$ .

- a. Find a series for  $(d/dx)e^x$ . Do you get the series for  $e^x$ ? Explain your answer.
- b. Find a series for  $\int e^x dx$ . Do you get the series for  $e^x$ ? Explain your answer.
- c. Replace  $x$  by  $-x$  in the series for  $e^x$  to find a series that converges to  $e^{-x}$  for all  $x$ . Then multiply the series for  $e^x$  and  $e^{-x}$  to find the first six terms of a series for  $e^{-x} \cdot e^x$ .

57. The series

$$\tan x = x + \frac{x^3}{3} + \frac{2x^5}{15} + \frac{17x^7}{315} + \frac{62x^9}{2835} + \cdots$$

converges to  $\tan x$  for  $-\pi/2 < x < \pi/2$ .

- a. Find the first five terms of the series for  $\ln|\sec x|$ . For what values of  $x$  should the series converge?
- b. Find the first five terms of the series for  $\sec^2 x$ . For what values of  $x$  should this series converge?
- c. Check your result in part (b) by squaring the series given for  $\sec x$  in Exercise 58.

58. The series

$$\sec x = 1 + \frac{x^2}{2} + \frac{5}{24}x^4 + \frac{61}{720}x^6 + \frac{277}{8064}x^8 + \cdots$$

converges to  $\sec x$  for  $-\pi/2 < x < \pi/2$ .

- a. Find the first five terms of a power series for the function  $\ln|\sec x + \tan x|$ . For what values of  $x$  should the series converge?

- b. Find the first four terms of a series for  $\sec x \tan x$ . For what values of  $x$  should the series converge?
- c. Check your result in part (b) by multiplying the series for  $\sec x$  by the series given for  $\tan x$  in Exercise 57.

### 59. Uniqueness of convergent power series

- a. Show that if two power series  $\sum_{n=0}^{\infty} a_n x^n$  and  $\sum_{n=0}^{\infty} b_n x^n$  are convergent and equal for all values of  $x$  in an open interval  $(-c, c)$ , then  $a_n = b_n$  for every  $n$ . (*Hint:* Let  $f(x) = \sum_{n=0}^{\infty} a_n x^n = \sum_{n=0}^{\infty} b_n x^n$ . Differentiate term by term to show that  $a_n$  and  $b_n$  both equal  $f^{(n)}(0)/(n!)$ .)

- b. Show that if  $\sum_{n=0}^{\infty} a_n x^n = 0$  for all  $x$  in an open interval  $(-c, c)$ , then  $a_n = 0$  for every  $n$ .

- 60. The sum of the series  $\sum_{n=0}^{\infty} (n^2/2^n)$**  To find the sum of this series, express  $1/(1-x)$  as a geometric series, differentiate both sides of the resulting equation with respect to  $x$ , multiply both sides of the result by  $x$ , differentiate again, multiply by  $x$  again, and set  $x$  equal to  $1/2$ . What do you get?

## Exercises 10.8

## Finding Taylor Polynomials

In Exercises 1–10, find the Taylor polynomials of orders 0, 1, 2, and 3 generated by  $f$  at  $a$ .

1.  $f(x) = e^{2x}$ ,  $a = 0$
2.  $f(x) = \sin x$ ,  $a = 0$
3.  $f(x) = \ln x$ ,  $a = 1$
4.  $f(x) = \ln(1 + x)$ ,  $a = 0$
5.  $f(x) = 1/x$ ,  $a = 2$
6.  $f(x) = 1/(x + 2)$ ,  $a = 0$
7.  $f(x) = \sin x$ ,  $a = \pi/4$
8.  $f(x) = \tan x$ ,  $a = \pi/4$
9.  $f(x) = \sqrt{x}$ ,  $a = 4$
10.  $f(x) = \sqrt{1 - x}$ ,  $a = 0$

Finding Taylor Series at  $x = 0$  (Maclaurin Series)

Find the Maclaurin series for the functions in Exercises 11–22.

11.  $e^{-x}$
12.  $xe^x$
13.  $\frac{1}{1+x}$
14.  $\frac{2+x}{1-x}$
15.  $\sin 3x$
16.  $\sin \frac{x}{2}$
17.  $7 \cos(-x)$
18.  $5 \cos \pi x$
19.  $\cosh x = \frac{e^x + e^{-x}}{2}$
20.  $\sinh x = \frac{e^x - e^{-x}}{2}$
21.  $x^4 - 2x^3 - 5x + 4$
22.  $\frac{x^2}{x+1}$

## Finding Taylor and Maclaurin Series

In Exercises 23–32, find the Taylor series generated by  $f$  at  $x = a$ .

23.  $f(x) = x^3 - 2x + 4$ ,  $a = 2$
24.  $f(x) = 2x^3 + x^2 + 3x - 8$ ,  $a = 1$

25.  $f(x) = x^4 + x^2 + 1$ ,  $a = -2$
26.  $f(x) = 3x^5 - x^4 + 2x^3 + x^2 - 2$ ,  $a = -1$
27.  $f(x) = 1/x^2$ ,  $a = 1$
28.  $f(x) = 1/(1 - x)^3$ ,  $a = 0$
29.  $f(x) = e^x$ ,  $a = 2$
30.  $f(x) = 2^x$ ,  $a = 1$
31.  $f(x) = \cos(2x + (\pi/2))$ ,  $a = \pi/4$
32.  $f(x) = \sqrt{x+1}$ ,  $a = 0$

In Exercises 33–36, find the first three nonzero terms of the Maclaurin series for each function and the values of  $x$  for which the series converges absolutely.

33.  $f(x) = \cos x - (2/(1 - x))$
34.  $f(x) = (1 - x + x^2)e^x$
35.  $f(x) = (\sin x) \ln(1 + x)$
36.  $f(x) = x \sin^2 x$

## Theory and Examples

37. Use the Taylor series generated by  $e^x$  at  $x = a$  to show that

$$e^x = e^a \left[ 1 + (x - a) + \frac{(x - a)^2}{2!} + \cdots \right].$$

38. (Continuation of Exercise 37.) Find the Taylor series generated by  $e^x$  at  $x = 1$ . Compare your answer with the formula in Exercise 37.
39. Let  $f(x)$  have derivatives through order  $n$  at  $x = a$ . Show that the Taylor polynomial of order  $n$  and its first  $n$  derivatives have the same values that  $f$  and its first  $n$  derivatives have at  $x = a$ .

**40. Approximation properties of Taylor polynomials** Suppose that  $f(x)$  is differentiable on an interval centered at  $x = a$  and that  $g(x) = b_0 + b_1(x - a) + \cdots + b_n(x - a)^n$  is a polynomial of degree  $n$  with constant coefficients  $b_0, \dots, b_n$ . Let  $E(x) = f(x) - g(x)$ . Show that if we impose on  $g$  the conditions

i)  $E(a) = 0$       The approximation error is zero at  $x = a$ .

ii)  $\lim_{x \rightarrow a} \frac{E(x)}{(x - a)^n} = 0$ ,      The error is negligible when compared to  $(x - a)^n$ .

then

$$g(x) = f(a) + f'(a)(x - a) + \frac{f''(a)}{2!}(x - a)^2 + \cdots + \frac{f^{(n)}(a)}{n!}(x - a)^n.$$

Thus, the Taylor polynomial  $P_n(x)$  is the only polynomial of degree less than or equal to  $n$  whose error is both zero at  $x = a$  and negligible when compared with  $(x - a)^n$ .

**Quadratic Approximations** The Taylor polynomial of order 2 generated by a twice-differentiable function  $f(x)$  at  $x = a$  is called the *quadratic approximation* of  $f$  at  $x = a$ . In Exercises 41–46, find the (a) linearization (Taylor polynomial of order 1) and (b) quadratic approximation of  $f$  at  $x = 0$ .

41.  $f(x) = \ln(\cos x)$

42.  $f(x) = e^{\sin x}$

43.  $f(x) = 1/\sqrt{1 - x^2}$

44.  $f(x) = \cosh x$

45.  $f(x) = \sin x$

46.  $f(x) = \tan x$

## Exercises 10.9

### Finding Taylor Series

Use substitution (as in Example 4) to find the Taylor series at  $x = 0$  of the functions in Exercises 1–10.

1.  $e^{-5x}$
2.  $e^{-x/2}$
3.  $5 \sin(-x)$
4.  $\sin\left(\frac{\pi x}{2}\right)$
5.  $\cos 5x^2$
6.  $\cos(x^{2/3}/\sqrt{2})$
7.  $\ln(1 + x^2)$
8.  $\tan^{-1}(3x^4)$
9.  $\frac{1}{1 + \frac{3}{4}x^3}$
10.  $\frac{1}{2 - x}$

Use power series operations to find the Taylor series at  $x = 0$  for the functions in Exercises 11–28.

11.  $xe^x$
12.  $x^2 \sin x$
13.  $\frac{x^2}{2} - 1 + \cos x$
14.  $\sin x - x + \frac{x^3}{3!}$
15.  $x \cos \pi x$
16.  $x^2 \cos(x^2)$
17.  $\cos^2 x$  (Hint:  $\cos^2 x = (1 + \cos 2x)/2$ .)
18.  $\sin^2 x$
19.  $\frac{x^2}{1 - 2x}$
20.  $x \ln(1 + 2x)$
21.  $\frac{1}{(1 - x)^2}$
22.  $\frac{2}{(1 - x)^3}$
23.  $x \tan^{-1} x^2$
24.  $\sin x \cdot \cos x$
25.  $e^x + \frac{1}{1 + x}$
26.  $\cos x - \sin x$
27.  $\frac{x}{3} \ln(1 + x^2)$
28.  $\ln(1 + x) - \ln(1 - x)$

Find the first four nonzero terms in the Maclaurin series for the functions in Exercises 29–34.

29.  $e^x \sin x$
30.  $\frac{\ln(1 + x)}{1 - x}$
31.  $(\tan^{-1} x)^2$
32.  $\cos^2 x \cdot \sin x$
33.  $e^{\sin x}$
34.  $\sin(\tan^{-1} x)$

### Error Estimates

35. Estimate the error if  $P_3(x) = x - (x^3/6)$  is used to estimate the value of  $\sin x$  at  $x = 0.1$ .
36. Estimate the error if  $P_4(x) = 1 + x + (x^2/2) + (x^3/6) + (x^4/24)$  is used to estimate the value of  $e^x$  at  $x = 1/2$ .
37. For approximately what values of  $x$  can you replace  $\sin x$  by  $x - (x^3/6)$  with an error of magnitude no greater than  $5 \times 10^{-4}$ ? Give reasons for your answer.

38. If  $\cos x$  is replaced by  $1 - (x^2/2)$  and  $|x| < 0.5$ , what estimate can be made of the error? Does  $1 - (x^2/2)$  tend to be too large, or too small? Give reasons for your answer.
39. How close is the approximation  $\sin x = x$  when  $|x| < 10^{-3}$ ? For which of these values of  $x$  is  $x < \sin x$ ?
40. The estimate  $\sqrt{1 + x} = 1 + (x/2)$  is used when  $x$  is small. Estimate the error when  $|x| < 0.01$ .
41. The approximation  $e^x = 1 + x + (x^2/2)$  is used when  $x$  is small. Use the Remainder Estimation Theorem to estimate the error when  $|x| < 0.1$ .
42. (Continuation of Exercise 41.) When  $x < 0$ , the series for  $e^x$  is an alternating series. Use the Alternating Series Estimation Theorem to estimate the error that results from replacing  $e^x$  by  $1 + x + (x^2/2)$  when  $-0.1 < x < 0$ . Compare your estimate with the one you obtained in Exercise 41.

### Theory and Examples

43. Use the identity  $\sin^2 x = (1 - \cos 2x)/2$  to obtain the Maclaurin series for  $\sin^2 x$ . Then differentiate this series to obtain the Maclaurin series for  $2 \sin x \cos x$ . Check that this is the series for  $\sin 2x$ .
44. (Continuation of Exercise 43.) Use the identity  $\cos^2 x = \cos 2x + \sin^2 x$  to obtain a power series for  $\cos^2 x$ .
45. **Taylor's Theorem and the Mean Value Theorem** Explain how the Mean Value Theorem (Section 4.2, Theorem 4) is a special case of Taylor's Theorem.
46. **Linearizations at inflection points** Show that if the graph of a twice-differentiable function  $f(x)$  has an inflection point at  $x = a$ , then the linearization of  $f$  at  $x = a$  is also the quadratic approximation of  $f$  at  $x = a$ . This explains why tangent lines fit so well at inflection points.
47. **The (second) second derivative test** Use the equation

$$f(x) = f(a) + f'(a)(x - a) + \frac{f''(c_2)}{2}(x - a)^2$$

to establish the following test.

Let  $f$  have continuous first and second derivatives and suppose that  $f'(a) = 0$ . Then

- a.  $f$  has a local maximum at  $a$  if  $f'' \leq 0$  throughout an interval whose interior contains  $a$ ;
- b.  $f$  has a local minimum at  $a$  if  $f'' \geq 0$  throughout an interval whose interior contains  $a$ .

**48. A cubic approximation** Use Taylor's formula with  $a = 0$  and  $n = 3$  to find the standard cubic approximation of  $f(x) = 1/(1 - x)$  at  $x = 0$ . Give an upper bound for the magnitude of the error in the approximation when  $|x| \leq 0.1$ .

**49. a.** Use Taylor's formula with  $n = 2$  to find the quadratic approximation of  $f(x) = (1 + x)^k$  at  $x = 0$  ( $k$  a constant).

**b.** If  $k = 3$ , for approximately what values of  $x$  in the interval  $[0, 1]$  will the error in the quadratic approximation be less than  $1/100$ ?

**50. Improving approximations of  $\pi$**

**a.** Let  $P$  be an approximation of  $\pi$  accurate to  $n$  decimals. Show that  $P + \sin P$  gives an approximation correct to  $3n$  decimals. (*Hint:* Let  $P = \pi + x$ .)

**T b.** Try it with a calculator.

**51. The Taylor series generated by  $f(x) = \sum_{n=0}^{\infty} a_n x^n$  is  $\sum_{n=0}^{\infty} a_n x^n$**   
A function defined by a power series  $\sum_{n=0}^{\infty} a_n x^n$  with a radius of convergence  $R > 0$  has a Taylor series that converges to the function at every point of  $(-R, R)$ . Show this by showing that the Taylor series generated by  $f(x) = \sum_{n=0}^{\infty} a_n x^n$  is the series  $\sum_{n=0}^{\infty} a_n x^n$  itself.

An immediate consequence of this is that series like

$$x \sin x = x^2 - \frac{x^4}{3!} + \frac{x^6}{5!} - \frac{x^8}{7!} + \cdots$$

and

$$x^2 e^x = x^2 + x^3 + \frac{x^4}{2!} + \frac{x^5}{3!} + \cdots,$$

obtained by multiplying Taylor series by powers of  $x$ , as well as series obtained by integration and differentiation of convergent power series, are themselves the Taylor series generated by the functions they represent.

**52. Taylor series for even functions and odd functions** (*Continuation of Section 10.7, Exercise 59.*) Suppose that  $f(x) = \sum_{n=0}^{\infty} a_n x^n$  converges for all  $x$  in an open interval  $(-R, R)$ . Show that

**a.** If  $f$  is even, then  $a_1 = a_3 = a_5 = \cdots = 0$ , i.e., the Taylor series for  $f$  at  $x = 0$  contains only even powers of  $x$ .

**b.** If  $f$  is odd, then  $a_0 = a_2 = a_4 = \cdots = 0$ , i.e., the Taylor series for  $f$  at  $x = 0$  contains only odd powers of  $x$ .

### COMPUTER EXPLORATIONS

Taylor's formula with  $n = 1$  and  $a = 0$  gives the linearization of a function at  $x = 0$ . With  $n = 2$  and  $n = 3$  we obtain the standard

quadratic and cubic approximations. In these exercises we explore the errors associated with these approximations. We seek answers to two questions:

- For what values of  $x$  can the function be replaced by each approximation with an error less than  $10^{-2}$ ?
- What is the maximum error we could expect if we replace the function by each approximation over the specified interval?

Using a CAS, perform the following steps to aid in answering questions (a) and (b) for the functions and intervals in Exercises 53–58.

*Step 1:* Plot the function over the specified interval.

*Step 2:* Find the Taylor polynomials  $P_1(x)$ ,  $P_2(x)$ , and  $P_3(x)$  at  $x = 0$ .

*Step 3:* Calculate the  $(n + 1)$ st derivative  $f^{(n+1)}(c)$  associated with the remainder term for each Taylor polynomial. Plot the derivative as a function of  $c$  over the specified interval and estimate its maximum absolute value,  $M$ .

*Step 4:* Calculate the remainder  $R_n(x)$  for each polynomial. Using the estimate  $M$  from Step 3 in place of  $f^{(n+1)}(c)$ , plot  $R_n(x)$  over the specified interval. Then estimate the values of  $x$  that answer question (a).

*Step 5:* Compare your estimated error with the actual error  $E_n(x) = |f(x) - P_n(x)|$  by plotting  $E_n(x)$  over the specified interval. This will help answer question (b).

*Step 6:* Graph the function and its three Taylor approximations together. Discuss the graphs in relation to the information discovered in Steps 4 and 5.

**53.**  $f(x) = \frac{1}{\sqrt{1+x}}, \quad |x| \leq \frac{3}{4}$

**54.**  $f(x) = (1+x)^{3/2}, \quad -\frac{1}{2} \leq x \leq 2$

**55.**  $f(x) = \frac{x}{x^2+1}, \quad |x| \leq 2$

**56.**  $f(x) = (\cos x)(\sin 2x), \quad |x| \leq 2$

**57.**  $f(x) = e^{-x} \cos 2x, \quad |x| \leq 1$

**58.**  $f(x) = e^{x/3} \sin 2x, \quad |x| \leq 2$

# Exercises 10.10

## Binomial Series

Find the first four terms of the binomial series for the functions in Exercises 1–10.

1.  $(1 + x)^{1/2}$
2.  $(1 + x)^{1/3}$
3.  $(1 - x)^{-3}$
4.  $(1 - 2x)^{1/2}$
5.  $\left(1 + \frac{x}{2}\right)^{-2}$
6.  $\left(1 - \frac{x}{3}\right)^4$
7.  $(1 + x^3)^{-1/2}$
8.  $(1 + x^2)^{-1/3}$
9.  $\left(1 + \frac{1}{x}\right)^{1/2}$
10.  $\frac{x}{\sqrt[3]{1+x}}$

Find the binomial series for the functions in Exercises 11–14.

11.  $(1 + x)^4$
12.  $(1 + x^2)^3$
13.  $(1 - 2x)^3$
14.  $\left(1 - \frac{x}{2}\right)^4$

## Approximations and Nonelementary Integrals

**T** In Exercises 15–18, use series to estimate the integrals' values with an error of magnitude less than  $10^{-5}$ . (The answer section gives the integrals' values rounded to seven decimal places.)

15.  $\int_0^{0.6} \sin x^2 dx$
16.  $\int_0^{0.4} \frac{e^{-x} - 1}{x} dx$
17.  $\int_0^{0.5} \frac{1}{\sqrt{1+x^4}} dx$
18.  $\int_0^{0.35} \sqrt[3]{1+x^2} dx$

**T** Use series to approximate the values of the integrals in Exercises 19–22 with an error of magnitude less than  $10^{-8}$ .

19.  $\int_0^{0.1} \frac{\sin x}{x} dx$
20.  $\int_0^{0.1} e^{-x^2} dx$
21.  $\int_0^{0.1} \sqrt{1+x^4} dx$
22.  $\int_0^1 \frac{1 - \cos x}{x^2} dx$

23. Estimate the error if  $\cos t^2$  is approximated by  $1 - \frac{t^4}{2} + \frac{t^8}{4!}$  in the integral  $\int_0^1 \cos t^2 dt$ .

24. Estimate the error if  $\cos \sqrt{t}$  is approximated by  $1 - \frac{t}{2} + \frac{t^2}{4!} - \frac{t^3}{6!}$  in the integral  $\int_0^1 \cos \sqrt{t} dt$ .

In Exercises 25–28, find a polynomial that will approximate  $F(x)$  throughout the given interval with an error of magnitude less than  $10^{-3}$ .

25.  $F(x) = \int_0^x \sin t^2 dt, \quad [0, 1]$
26.  $F(x) = \int_0^x t^2 e^{-t^2} dt, \quad [0, 1]$
27.  $F(x) = \int_0^x \tan^{-1} t dt, \quad \text{(a) } [0, 0.5] \quad \text{(b) } [0, 1]$
28.  $F(x) = \int_0^x \frac{\ln(1+t)}{t} dt, \quad \text{(a) } [0, 0.5] \quad \text{(b) } [0, 1]$

## Indeterminate Forms

Use series to evaluate the limits in Exercises 29–40.

29.  $\lim_{x \rightarrow 0} \frac{e^x - (1 + x)}{x^2}$
30.  $\lim_{x \rightarrow 0} \frac{e^x - e^{-x}}{x}$
31.  $\lim_{t \rightarrow 0} \frac{1 - \cos t - (t^2/2)}{t^4}$
32.  $\lim_{\theta \rightarrow 0} \frac{\sin \theta - \theta + (\theta^3/6)}{\theta^5}$
33.  $\lim_{y \rightarrow 0} \frac{y - \tan^{-1} y}{y^3}$
34.  $\lim_{y \rightarrow 0} \frac{\tan^{-1} y - \sin y}{y^3 \cos y}$
35.  $\lim_{x \rightarrow \infty} x^2 (e^{-1/x^2} - 1)$
36.  $\lim_{x \rightarrow \infty} (x + 1) \sin \frac{1}{x + 1}$
37.  $\lim_{x \rightarrow 0} \frac{\ln(1 + x^2)}{1 - \cos x}$
38.  $\lim_{x \rightarrow 2} \frac{x^2 - 4}{\ln(x - 1)}$
39.  $\lim_{x \rightarrow 0} \frac{\sin 3x^2}{1 - \cos 2x}$
40.  $\lim_{x \rightarrow 0} \frac{\ln(1 + x^3)}{x \cdot \sin x^2}$

## Using Table 10.1

In Exercises 41–52, use Table 10.1 to find the sum of each series.

41.  $1 + 1 + \frac{1}{2!} + \frac{1}{3!} + \frac{1}{4!} + \dots$
42.  $\left(\frac{1}{4}\right)^3 + \left(\frac{1}{4}\right)^4 + \left(\frac{1}{4}\right)^5 + \left(\frac{1}{4}\right)^6 + \dots$
43.  $1 - \frac{3^2}{4^2 \cdot 2!} + \frac{3^4}{4^4 \cdot 4!} - \frac{3^6}{4^6 \cdot 6!} + \dots$
44.  $\frac{1}{2} - \frac{1}{2 \cdot 2^2} + \frac{1}{3 \cdot 2^3} - \frac{1}{4 \cdot 2^4} + \dots$
45.  $\frac{\pi}{3} - \frac{\pi^3}{3^3 \cdot 3!} + \frac{\pi^5}{3^5 \cdot 5!} - \frac{\pi^7}{3^7 \cdot 7!} + \dots$
46.  $\frac{2}{3} - \frac{2^3}{3^3 \cdot 3} + \frac{2^5}{3^5 \cdot 5} - \frac{2^7}{3^7 \cdot 7} + \dots$
47.  $x^3 + x^4 + x^5 + x^6 + \dots$
48.  $1 - \frac{3^2 x^2}{2!} + \frac{3^4 x^4}{4!} - \frac{3^6 x^6}{6!} + \dots$
49.  $x^3 - x^5 + x^7 - x^9 + x^{11} - \dots$
50.  $x^2 - 2x^3 + \frac{2^2 x^4}{2!} - \frac{2^3 x^5}{3!} + \frac{2^4 x^6}{4!} - \dots$
51.  $-1 + 2x - 3x^2 + 4x^3 - 5x^4 + \dots$
52.  $1 + \frac{x}{2} + \frac{x^2}{3} + \frac{x^3}{4} + \frac{x^4}{5} + \dots$

## Theory and Examples

53. Replace  $x$  by  $-x$  in the Taylor series for  $\ln(1 + x)$  to obtain a series for  $\ln(1 - x)$ . Then subtract this from the Taylor series for  $\ln(1 + x)$  to show that for  $|x| < 1$ ,

$$\ln \frac{1+x}{1-x} = 2 \left( x + \frac{x^3}{3} + \frac{x^5}{5} + \dots \right).$$

54. How many terms of the Taylor series for  $\ln(1 + x)$  should you add to be sure of calculating  $\ln(1.1)$  with an error of magnitude less than  $10^{-8}$ ? Give reasons for your answer.

55. According to the Alternating Series Estimation Theorem, how many terms of the Taylor series for  $\tan^{-1} 1$  would you have to add to be sure of finding  $\pi/4$  with an error of magnitude less than  $10^{-3}$ ? Give reasons for your answer.

56. Show that the Taylor series for  $f(x) = \tan^{-1} x$  diverges for  $|x| > 1$ .

**T** 57. **Estimating Pi** About how many terms of the Taylor series for  $\tan^{-1} x$  would you have to use to evaluate each term on the right-hand side of the equation

$$\pi = 48 \tan^{-1} \frac{1}{18} + 32 \tan^{-1} \frac{1}{57} - 20 \tan^{-1} \frac{1}{239}$$

with an error of magnitude less than  $10^{-6}$ ? In contrast, the convergence of  $\sum_{n=1}^{\infty} (1/n^2)$  to  $\pi^2/6$  is so slow that even 50 terms will not yield two-place accuracy.

58. Use the following steps to prove that the binomial series in Equation (1) converges to  $(1+x)^m$ .

a. Differentiate the series

$$f(x) = 1 + \sum_{k=1}^{\infty} \binom{m}{k} x^k$$

to show that

$$f'(x) = \frac{mf(x)}{1+x}, \quad -1 < x < 1.$$

b. Define  $g(x) = (1+x)^{-m} f(x)$  and show that  $g'(x) = 0$ .

c. From part (b), show that

$$f(x) = (1+x)^m.$$

59. a. Use the binomial series and the fact that

$$\frac{d}{dx} \sin^{-1} x = (1-x^2)^{-1/2}$$

to generate the first four nonzero terms of the Taylor series for  $\sin^{-1} x$ . What is the radius of convergence?

b. **Series for  $\cos^{-1} x$**  Use your result in part (a) to find the first five nonzero terms of the Taylor series for  $\cos^{-1} x$ .

60. a. **Series for  $\sinh^{-1} x$**  Find the first four nonzero terms of the Taylor series for

$$\sinh^{-1} x = \int_0^x \frac{dt}{\sqrt{1+t^2}}.$$

**T** b. Use the first *three* terms of the series in part (a) to estimate  $\sinh^{-1} 0.25$ . Give an upper bound for the magnitude of the estimation error.

61. Obtain the Taylor series for  $1/(1+x)^2$  from the series for  $-1/(1+x)$ .

62. Use the Taylor series for  $1/(1-x^2)$  to obtain a series for  $2x/(1-x^2)^2$ .

**T** 63. **Estimating Pi** The English mathematician Wallis discovered the formula

$$\frac{\pi}{4} = \frac{2 \cdot 4 \cdot 4 \cdot 6 \cdot 6 \cdot 8 \cdot \dots}{3 \cdot 3 \cdot 5 \cdot 5 \cdot 7 \cdot 7 \cdot \dots}.$$

Find  $\pi$  to two decimal places with this formula.

64. **The complete elliptic integral of the first kind** is the integral

$$K = \int_0^{\pi/2} \frac{d\theta}{\sqrt{1-k^2 \sin^2 \theta}},$$

where  $0 < k < 1$  is constant.

a. Show that the first four terms of the binomial series for  $1/\sqrt{1-x}$  are

$$(1-x)^{-1/2} = 1 + \frac{1}{2}x + \frac{1 \cdot 3}{2 \cdot 4}x^2 + \frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6}x^3 + \dots$$

b. From part (a) and the reduction integral Formula 67 at the back of the book, show that

$$K = \frac{\pi}{2} \left[ 1 + \left(\frac{1}{2}\right)^2 k^2 + \left(\frac{1 \cdot 3}{2 \cdot 4}\right)^2 k^4 + \left(\frac{1 \cdot 3 \cdot 5}{2 \cdot 4 \cdot 6}\right)^2 k^6 + \dots \right].$$

65. **Series for  $\sin^{-1} x$**  Integrate the binomial series for  $(1-x^2)^{-1/2}$  to show that for  $|x| < 1$ ,

$$\sin^{-1} x = x + \sum_{n=1}^{\infty} \frac{1 \cdot 3 \cdot 5 \cdot \dots \cdot (2n-1)}{2 \cdot 4 \cdot 6 \cdot \dots \cdot (2n)} \frac{x^{2n+1}}{2n+1}.$$

66. **Series for  $\tan^{-1} x$  for  $|x| > 1$**  Derive the series

$$\tan^{-1} x = \frac{\pi}{2} - \frac{1}{x} + \frac{1}{3x^3} - \frac{1}{5x^5} + \dots, \quad x > 1$$

$$\tan^{-1} x = -\frac{\pi}{2} - \frac{1}{x} + \frac{1}{3x^3} - \frac{1}{5x^5} + \dots, \quad x < -1,$$

by integrating the series

$$\frac{1}{1+t^2} = \frac{1}{t^2} \cdot \frac{1}{1+(1/t^2)} = \frac{1}{t^2} - \frac{1}{t^4} + \frac{1}{t^6} - \frac{1}{t^8} + \dots$$

in the first case from  $x$  to  $\infty$  and in the second case from  $-\infty$  to  $x$ .

### Euler's Identity

67. Use Equation (4) to write the following powers of  $e$  in the form  $a + bi$ .

a.  $e^{-i\pi}$                       b.  $e^{i\pi/4}$                       c.  $e^{-i\pi/2}$

68. Use Equation (4) to show that

$$\cos \theta = \frac{e^{i\theta} + e^{-i\theta}}{2} \quad \text{and} \quad \sin \theta = \frac{e^{i\theta} - e^{-i\theta}}{2i}.$$

69. Establish the equations in Exercise 68 by combining the formal Taylor series for  $e^{i\theta}$  and  $e^{-i\theta}$ .

70. Show that

a.  $\cosh i\theta = \cos \theta$ ,                      b.  $\sinh i\theta = i \sin \theta$ .

71. By multiplying the Taylor series for  $e^x$  and  $\sin x$ , find the terms through  $x^5$  of the Taylor series for  $e^x \sin x$ . This series is the imaginary part of the series for

$$e^x \cdot e^{ix} = e^{(1+i)x}.$$

Use this fact to check your answer. For what values of  $x$  should the series for  $e^x \sin x$  converge?

72. When  $a$  and  $b$  are real, we define  $e^{(a+ib)x}$  with the equation

$$e^{(a+ib)x} = e^{ax} \cdot e^{ibx} = e^{ax}(\cos bx + i \sin bx).$$



Differentiate the right-hand side of this equation to show that

$$\frac{d}{dx} e^{(a+ib)x} = (a+ib)e^{(a+ib)x}.$$

Thus the familiar rule  $(d/dx)e^{kx} = ke^{kx}$  holds for  $k$  complex as well as real.

73. Use the definition of  $e^{i\theta}$  to show that for any real numbers  $\theta$ ,  $\theta_1$ , and  $\theta_2$ ,

a.  $e^{i\theta_1}e^{i\theta_2} = e^{i(\theta_1+\theta_2)}$ ,                      b.  $e^{-i\theta} = 1/e^{i\theta}$ .

74. Two complex numbers  $a+ib$  and  $c+id$  are equal if and only if  $a=c$  and  $b=d$ . Use this fact to evaluate

$$\int e^{ax} \cos bx \, dx \quad \text{and} \quad \int e^{ax} \sin bx \, dx$$

from

$$\int e^{(a+ib)x} \, dx = \frac{a-ib}{a^2+b^2} e^{(a+ib)x} + C,$$

where  $C = C_1 + iC_2$  is a complex constant of integration.

## Exercises 11.1

### Finding Cartesian from Parametric Equations

Exercises 1–18 give parametric equations and parameter intervals for the motion of a particle in the  $xy$ -plane. Identify the particle's path by finding a Cartesian equation for it. Graph the Cartesian equation. (The graphs will vary with the equation used.) Indicate the portion of the graph traced by the particle and the direction of motion.

- $x = 3t, y = 9t^2, -\infty < t < \infty$
- $x = -\sqrt{t}, y = t, t \geq 0$
- $x = 2t - 5, y = 4t - 7, -\infty < t < \infty$
- $x = 3 - 3t, y = 2t, 0 \leq t \leq 1$
- $x = \cos 2t, y = \sin 2t, 0 \leq t \leq \pi$
- $x = \cos(\pi - t), y = \sin(\pi - t), 0 \leq t \leq \pi$
- $x = 4 \cos t, y = 2 \sin t, 0 \leq t \leq 2\pi$
- $x = 4 \sin t, y = 5 \cos t, 0 \leq t \leq 2\pi$
- $x = \sin t, y = \cos 2t, -\frac{\pi}{2} \leq t \leq \frac{\pi}{2}$
- $x = 1 + \sin t, y = \cos t - 2, 0 \leq t \leq \pi$
- $x = t^2, y = t^6 - 2t^4, -\infty < t < \infty$
- $x = \frac{t}{t-1}, y = \frac{t-2}{t+1}, -1 < t < 1$
- $x = t, y = \sqrt{1-t^2}, -1 \leq t \leq 0$
- $x = \sqrt{t+1}, y = \sqrt{t}, t \geq 0$
- $x = \sec^2 t - 1, y = \tan t, -\pi/2 < t < \pi/2$
- $x = -\sec t, y = \tan t, -\pi/2 < t < \pi/2$
- $x = -\cosh t, y = \sinh t, -\infty < t < \infty$
- $x = 2 \sinh t, y = 2 \cosh t, -\infty < t < \infty$

### Finding Parametric Equations

- Find parametric equations and a parameter interval for the motion of a particle that starts at  $(a, 0)$  and traces the circle  $x^2 + y^2 = a^2$ 
  - once clockwise.
  - once counterclockwise.
  - twice clockwise.
  - twice counterclockwise.

(There are many ways to do these, so your answers may not be the same as the ones in the back of the book.)
- Find parametric equations and a parameter interval for the motion of a particle that starts at  $(a, 0)$  and traces the ellipse  $(x^2/a^2) + (y^2/b^2) = 1$ 
  - once clockwise.
  - once counterclockwise.
  - twice clockwise.
  - twice counterclockwise.

(As in Exercise 19, there are many correct answers.)

In Exercises 21–26, find a parametrization for the curve.

- the line segment with endpoints  $(-1, -3)$  and  $(4, 1)$
- the line segment with endpoints  $(-1, 3)$  and  $(3, -2)$
- the lower half of the parabola  $x - 1 = y^2$
- the left half of the parabola  $y = x^2 + 2x$
- the ray (half line) with initial point  $(2, 3)$  that passes through the point  $(-1, -1)$

- the ray (half line) with initial point  $(-1, 2)$  that passes through the point  $(0, 0)$
- Find parametric equations and a parameter interval for the motion of a particle starting at the point  $(2, 0)$  and tracing the top half of the circle  $x^2 + y^2 = 4$  four times.
- Find parametric equations and a parameter interval for the motion of a particle that moves along the graph of  $y = x^2$  in the following way: Beginning at  $(0, 0)$  it moves to  $(3, 9)$ , and then travels back and forth from  $(3, 9)$  to  $(-3, 9)$  infinitely many times.
- Find parametric equations for the semicircle

$$x^2 + y^2 = a^2, y > 0,$$

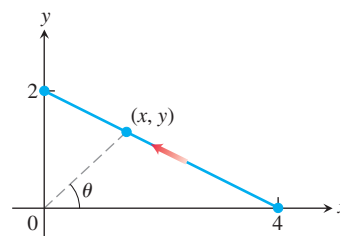
using as parameter the slope  $t = dy/dx$  of the tangent to the curve at  $(x, y)$ .

- Find parametric equations for the circle

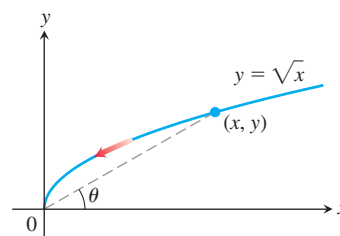
$$x^2 + y^2 = a^2,$$

using as parameter the arc length  $s$  measured counterclockwise from the point  $(a, 0)$  to the point  $(x, y)$ .

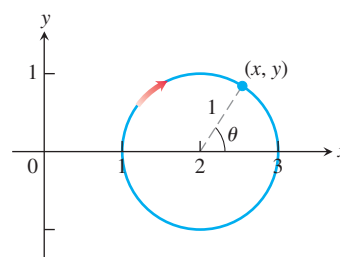
- Find a parametrization for the line segment joining points  $(0, 2)$  and  $(4, 0)$  using the angle  $\theta$  in the accompanying figure as the parameter.



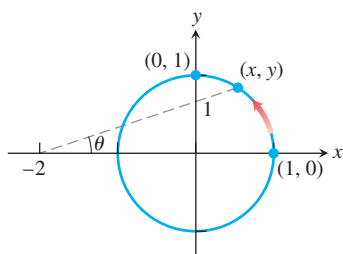
- Find a parametrization for the curve  $y = \sqrt{x}$  with terminal point  $(0, 0)$  using the angle  $\theta$  in the accompanying figure as the parameter.



- Find a parametrization for the circle  $(x - 2)^2 + y^2 = 1$  starting at  $(1, 0)$  and moving clockwise once around the circle, using the central angle  $\theta$  in the accompanying figure as the parameter.

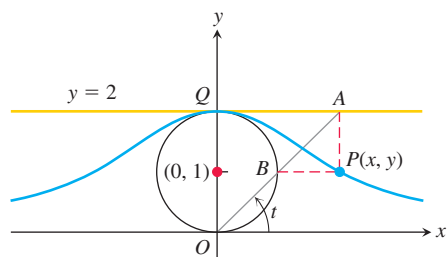


34. Find a parametrization for the circle  $x^2 + y^2 = 1$  starting at  $(1, 0)$  and moving counterclockwise to the terminal point  $(0, 1)$ , using the angle  $\theta$  in the accompanying figure as the parameter.



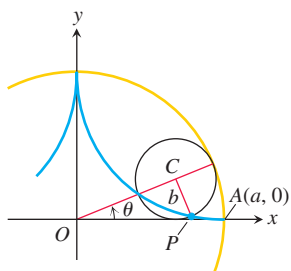
35. **The witch of Maria Agnesi** The bell-shaped witch of Maria Agnesi can be constructed in the following way. Start with a circle of radius 1, centered at the point  $(0, 1)$ , as shown in the accompanying figure. Choose a point  $A$  on the line  $y = 2$  and connect it to the origin with a line segment. Call the point where the segment crosses the circle  $B$ . Let  $P$  be the point where the vertical line through  $A$  crosses the horizontal line through  $B$ . The witch is the curve traced by  $P$  as  $A$  moves along the line  $y = 2$ . Find parametric equations and a parameter interval for the witch by expressing the coordinates of  $P$  in terms of  $t$ , the radian measure of the angle that segment  $OA$  makes with the positive  $x$ -axis. The following equalities (which you may assume) will help.

- a.  $x = AQ$                       b.  $y = 2 - AB \sin t$   
c.  $AB \cdot OA = (AQ)^2$

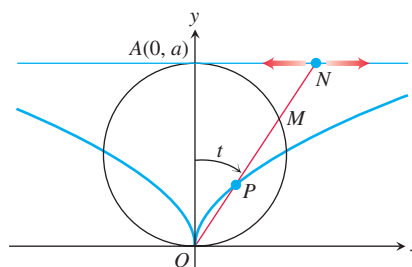


36. **Hypocycloid** When a circle rolls on the inside of a fixed circle, any point  $P$  on the circumference of the rolling circle describes a *hypocycloid*. Let the fixed circle be  $x^2 + y^2 = a^2$ , let the radius of the rolling circle be  $b$ , and let the initial position of the tracing point  $P$  be  $A(a, 0)$ . Find parametric equations for the hypocycloid, using as the parameter the angle  $\theta$  from the positive  $x$ -axis to the line joining the circles' centers. In particular, if  $b = a/4$ , as in the accompanying figure, show that the hypocycloid is the astroid

$$x = a \cos^3 \theta, \quad y = a \sin^3 \theta.$$



37. As the point  $N$  moves along the line  $y = a$  in the accompanying figure,  $P$  moves in such a way that  $OP = MN$ . Find parametric equations for the coordinates of  $P$  as functions of the angle  $t$  that the line  $ON$  makes with the positive  $y$ -axis.



38. **Trochoids** A wheel of radius  $a$  rolls along a horizontal straight line without slipping. Find parametric equations for the curve traced out by a point  $P$  on a spoke of the wheel  $b$  units from its center. As parameter, use the angle  $\theta$  through which the wheel turns. The curve is called a *trochoid*, which is a *trochoid* when  $b = a$ .

### Distance Using Parametric Equations

39. Find the point on the parabola  $x = t, y = t^2, -\infty < t < \infty$ , closest to the point  $(2, 1/2)$ . (Hint: Minimize the square of the distance as a function of  $t$ .)  
40. Find the point on the ellipse  $x = 2 \cos t, y = \sin t, 0 \leq t \leq 2\pi$  closest to the point  $(3/4, 0)$ . (Hint: Minimize the square of the distance as a function of  $t$ .)

### GRAPHER EXPLORATIONS

If you have a parametric equation grapher, graph the equations over the given intervals in Exercises 41–48.

41. **Ellipse**  $x = 4 \cos t, y = 2 \sin t$ , over  
a.  $0 \leq t \leq 2\pi$   
b.  $0 \leq t \leq \pi$   
c.  $-\pi/2 \leq t \leq \pi/2$ .  
42. **Hyperbola branch**  $x = \sec t$  (enter as  $1/\cos(t)$ ),  $y = \tan t$  (enter as  $\sin(t)/\cos(t)$ ), over  
a.  $-1.5 \leq t \leq 1.5$   
b.  $-0.5 \leq t \leq 0.5$   
c.  $-0.1 \leq t \leq 0.1$ .  
43. **Parabola**  $x = 2t + 3, y = t^2 - 1, -2 \leq t \leq 2$   
44. **Cycloid**  $x = t - \sin t, y = 1 - \cos t$ , over  
a.  $0 \leq t \leq 2\pi$   
b.  $0 \leq t \leq 4\pi$   
c.  $\pi \leq t \leq 3\pi$ .

### 45. Deltoid

$$x = 2 \cos t + \cos 2t, \quad y = 2 \sin t - \sin 2t; \quad 0 \leq t \leq 2\pi$$

What happens if you replace 2 with  $-2$  in the equations for  $x$  and  $y$ ? Graph the new equations and find out.

### 46. A nice curve

$$x = 3 \cos t + \cos 3t, \quad y = 3 \sin t - \sin 3t; \quad 0 \leq t \leq 2\pi$$

What happens if you replace 3 with  $-3$  in the equations for  $x$  and  $y$ ? Graph the new equations and find out.

**47. a. Epicycloid**

$$x = 9 \cos t - \cos 9t, \quad y = 9 \sin t - \sin 9t; \quad 0 \leq t \leq 2\pi$$

**b. Hypocycloid**

$$x = 8 \cos t + 2 \cos 4t, \quad y = 8 \sin t - 2 \sin 4t; \quad 0 \leq t \leq 2\pi$$

**c. Hypotrochoid**

$$x = \cos t + 5 \cos 3t, \quad y = 6 \cos t - 5 \sin 3t; \quad 0 \leq t \leq 2\pi$$

**48. a.**  $x = 6 \cos t + 5 \cos 3t, \quad y = 6 \sin t - 5 \sin 3t;$   
 $0 \leq t \leq 2\pi$

**b.**  $x = 6 \cos 2t + 5 \cos 6t, \quad y = 6 \sin 2t - 5 \sin 6t;$   
 $0 \leq t \leq \pi$

**c.**  $x = 6 \cos t + 5 \cos 3t, \quad y = 6 \sin 2t - 5 \sin 3t;$   
 $0 \leq t \leq 2\pi$

**d.**  $x = 6 \cos 2t + 5 \cos 6t, \quad y = 6 \sin 4t - 5 \sin 6t;$   
 $0 \leq t \leq \pi$

## Exercises 11.2

### Tangents to Parametrized Curves

In Exercises 1–14, find an equation for the line tangent to the curve at the point defined by the given value of  $t$ . Also, find the value of  $d^2y/dx^2$  at this point.

1.  $x = 2 \cos t$ ,  $y = 2 \sin t$ ,  $t = \pi/4$
2.  $x = \sin 2\pi t$ ,  $y = \cos 2\pi t$ ,  $t = -1/6$
3.  $x = 4 \sin t$ ,  $y = 2 \cos t$ ,  $t = \pi/4$
4.  $x = \cos t$ ,  $y = \sqrt{3} \cos t$ ,  $t = 2\pi/3$
5.  $x = t$ ,  $y = \sqrt{t}$ ,  $t = 1/4$
6.  $x = \sec^2 t - 1$ ,  $y = \tan t$ ,  $t = -\pi/4$
7.  $x = \sec t$ ,  $y = \tan t$ ,  $t = \pi/6$
8.  $x = -\sqrt{t+1}$ ,  $y = \sqrt{3t}$ ,  $t = 3$
9.  $x = 2t^2 + 3$ ,  $y = t^4$ ,  $t = -1$
10.  $x = 1/t$ ,  $y = -2 + \ln t$ ,  $t = 1$
11.  $x = t - \sin t$ ,  $y = 1 - \cos t$ ,  $t = \pi/3$
12.  $x = \cos t$ ,  $y = 1 + \sin t$ ,  $t = \pi/2$
13.  $x = \frac{1}{t+1}$ ,  $y = \frac{t}{t-1}$ ,  $t = 2$
14.  $x = t + e^t$ ,  $y = 1 - e^t$ ,  $t = 0$

### Implicitly Defined Parametrizations

Assuming that the equations in Exercises 15–20 define  $x$  and  $y$  implicitly as differentiable functions  $x = f(t)$ ,  $y = g(t)$ , find the slope of the curve  $x = f(t)$ ,  $y = g(t)$  at the given value of  $t$ .

15.  $x^3 + 2t^2 = 9$ ,  $2y^3 - 3t^2 = 4$ ,  $t = 2$
16.  $x = \sqrt{5 - \sqrt{t}}$ ,  $y(t - 1) = \sqrt{t}$ ,  $t = 4$
17.  $x + 2x^{3/2} = t^2 + t$ ,  $y\sqrt{t+1} + 2t\sqrt{y} = 4$ ,  $t = 0$
18.  $x \sin t + 2x = t$ ,  $t \sin t - 2t = y$ ,  $t = \pi$

19.  $x = t^3 + t$ ,  $y + 2t^3 = 2x + t^2$ ,  $t = 1$
20.  $t = \ln(x - t)$ ,  $y = te^t$ ,  $t = 0$

### Area

21. Find the area under one arch of the cycloid  
 $x = a(t - \sin t)$ ,  $y = a(1 - \cos t)$ .
22. Find the area enclosed by the  $y$ -axis and the curve  
 $x = t - t^2$ ,  $y = 1 + e^{-t}$ .
23. Find the area enclosed by the ellipse  
 $x = a \cos t$ ,  $y = b \sin t$ ,  $0 \leq t \leq 2\pi$ .
24. Find the area under  $y = x^3$  over  $[0, 1]$  using the following parametrizations.  
a.  $x = t^2$ ,  $y = t^6$       b.  $x = t^3$ ,  $y = t^9$

### Lengths of Curves

Find the lengths of the curves in Exercises 25–30.

25.  $x = \cos t$ ,  $y = t + \sin t$ ,  $0 \leq t \leq \pi$
26.  $x = t^3$ ,  $y = 3t^2/2$ ,  $0 \leq t \leq \sqrt{3}$
27.  $x = t^2/2$ ,  $y = (2t + 1)^{3/2}/3$ ,  $0 \leq t \leq 4$
28.  $x = (2t + 3)^{3/2}/3$ ,  $y = t + t^2/2$ ,  $0 \leq t \leq 3$
29.  $x = 8 \cos t + 8t \sin t$   
 $y = 8 \sin t - 8t \cos t$ ,  $0 \leq t \leq \pi/2$
30.  $x = \ln(\sec t + \tan t) - \sin t$   
 $y = \cos t$ ,  $0 \leq t \leq \pi/3$

### Surface Area

Find the areas of the surfaces generated by revolving the curves in Exercises 31–34 about the indicated axes.

31.  $x = \cos t$ ,  $y = 2 + \sin t$ ,  $0 \leq t \leq 2\pi$ ;  $x$ -axis

32.  $x = (2/3)t^{3/2}$ ,  $y = 2\sqrt{t}$ ,  $0 \leq t \leq \sqrt{3}$ ;  $y$ -axis
33.  $x = t + \sqrt{2}$ ,  $y = (t^2/2) + \sqrt{2}t$ ,  $-\sqrt{2} \leq t \leq \sqrt{2}$ ;  $y$ -axis
34.  $x = \ln(\sec t + \tan t) - \sin t$ ,  $y = \cos t$ ,  $0 \leq t \leq \pi/3$ ;  $x$ -axis
35. **A cone frustum** The line segment joining the points  $(0, 1)$  and  $(2, 2)$  is revolved about the  $x$ -axis to generate a frustum of a cone. Find the surface area of the frustum using the parametrization  $x = 2t$ ,  $y = t + 1$ ,  $0 \leq t \leq 1$ . Check your result with the geometry formula:  $\text{Area} = \pi(r_1 + r_2)(\text{slant height})$ .
36. **A cone** The line segment joining the origin to the point  $(h, r)$  is revolved about the  $x$ -axis to generate a cone of height  $h$  and base radius  $r$ . Find the cone's surface area with the parametric equations  $x = ht$ ,  $y = rt$ ,  $0 \leq t \leq 1$ . Check your result with the geometry formula:  $\text{Area} = \pi r(\text{slant height})$ .

### Centroids

37. Find the coordinates of the centroid of the curve  
 $x = \cos t + t \sin t$ ,  $y = \sin t - t \cos t$ ,  $0 \leq t \leq \pi/2$ .
38. Find the coordinates of the centroid of the curve  
 $x = e^t \cos t$ ,  $y = e^t \sin t$ ,  $0 \leq t \leq \pi$ .
39. Find the coordinates of the centroid of the curve  
 $x = \cos t$ ,  $y = t + \sin t$ ,  $0 \leq t \leq \pi$ .

**T** 40. Most centroid calculations for curves are done with a calculator or computer that has an integral evaluation program. As a case in point, find, to the nearest hundredth, the coordinates of the centroid of the curve

$$x = t^3, \quad y = 3t^2/2, \quad 0 \leq t \leq \sqrt{3}.$$

### Theory and Examples

41. **Length is independent of parametrization** To illustrate the fact that the numbers we get for length do not depend on the way we parametrize our curves (except for the mild restrictions preventing doubling back mentioned earlier), calculate the length of the semicircle  $y = \sqrt{1 - x^2}$  with these two different parametrizations:
- a.  $x = \cos 2t$ ,  $y = \sin 2t$ ,  $0 \leq t \leq \pi/2$ .
- b.  $x = \sin \pi t$ ,  $y = \cos \pi t$ ,  $-1/2 \leq t \leq 1/2$ .
42. a. Show that the Cartesian formula

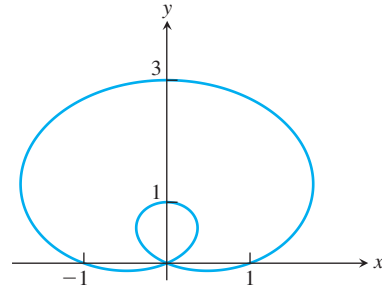
$$L = \int_c^d \sqrt{1 + \left(\frac{dx}{dy}\right)^2} dy$$

for the length of the curve  $x = g(y)$ ,  $c \leq y \leq d$  (Section 6.3, Equation 4), is a special case of the parametric length formula

$$L = \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt.$$

Use this result to find the length of each curve.

- b.  $x = y^{3/2}$ ,  $0 \leq y \leq 4/3$
- c.  $x = \frac{3}{2}y^{2/3}$ ,  $0 \leq y \leq 1$
43. The curve with parametric equations  
 $x = (1 + 2 \sin \theta) \cos \theta$ ,  $y = (1 + 2 \sin \theta) \sin \theta$
- is called a *limaçon* and is shown in the accompanying figure. Find the points  $(x, y)$  and the slopes of the tangent lines at these points for
- a.  $\theta = 0$ . b.  $\theta = \pi/2$ . c.  $\theta = 4\pi/3$ .

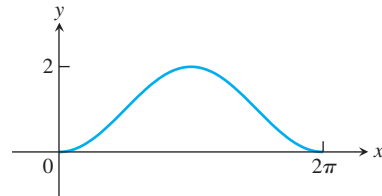


44. The curve with parametric equations

$$x = t, \quad y = 1 - \cos t, \quad 0 \leq t \leq 2\pi$$

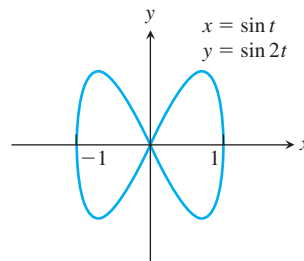
is called a *sinusoid* and is shown in the accompanying figure. Find the point  $(x, y)$  where the slope of the tangent line is

- a. largest. b. smallest.

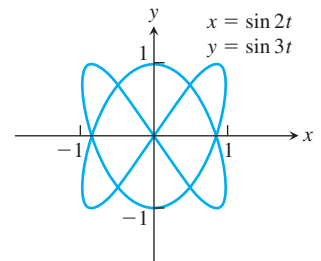


**T** The curves in Exercises 45 and 46 are called *Bowditch curves* or *Lissajous figures*. In each case, find the point in the interior of the first quadrant where the tangent to the curve is horizontal, and find the equations of the two tangents at the origin.

45.



46.



47. **Cycloid**

- a. Find the length of one arch of the cycloid

$$x = a(t - \sin t), \quad y = a(1 - \cos t).$$

- b. Find the area of the surface generated by revolving one arch of the cycloid in part (a) about the  $x$ -axis for  $a = 1$ .

48. **Volume** Find the volume swept out by revolving the region bounded by the  $x$ -axis and one arch of the cycloid

$$x = t - \sin t, \quad y = 1 - \cos t$$

about the  $x$ -axis.

### COMPUTER EXPLORATIONS

In Exercises 49–52, use a CAS to perform the following steps for the given curve over the closed interval.

- a. Plot the curve together with the polygonal path approximations for  $n = 2, 4, 8$  partition points over the interval. (See Figure 11.15.)

- b. Find the corresponding approximation to the length of the curve by summing the lengths of the line segments.
- c. Evaluate the length of the curve using an integral. Compare your approximations for  $n = 2, 4, 8$  with the actual length given by the integral. How does the actual length compare with the approximations as  $n$  increases? Explain your answer.
49.  $x = \frac{1}{3}t^3, \quad y = \frac{1}{2}t^2, \quad 0 \leq t \leq 1$
50.  $x = 2t^3 - 16t^2 + 25t + 5, \quad y = t^2 + t - 3, \quad 0 \leq t \leq 6$
51.  $x = t - \cos t, \quad y = 1 + \sin t, \quad -\pi \leq t \leq \pi$
52.  $x = e^t \cos t, \quad y = e^t \sin t, \quad 0 \leq t \leq \pi$

## Exercises 11.3

## Polar Coordinates

- Which polar coordinate pairs label the same point?
  - $(3, 0)$
  - $(-3, 0)$
  - $(2, 2\pi/3)$
  - $(2, 7\pi/3)$
  - $(-3, \pi)$
  - $(2, \pi/3)$
  - $(-3, 2\pi)$
  - $(-2, -\pi/3)$
- Which polar coordinate pairs label the same point?
  - $(-2, \pi/3)$
  - $(2, -\pi/3)$
  - $(r, \theta)$
  - $(r, \theta + \pi)$
  - $(-r, \theta)$
  - $(2, -2\pi/3)$
  - $(-r, \theta + \pi)$
  - $(-2, 2\pi/3)$
- Plot the following points (given in polar coordinates). Then find all the polar coordinates of each point.
  - $(2, \pi/2)$
  - $(2, 0)$
  - $(-2, \pi/2)$
  - $(-2, 0)$
- Plot the following points (given in polar coordinates). Then find all the polar coordinates of each point.
  - $(3, \pi/4)$
  - $(-3, \pi/4)$
  - $(3, -\pi/4)$
  - $(-3, -\pi/4)$

## Polar to Cartesian Coordinates

- Find the Cartesian coordinates of the points in Exercise 1.
- Find the Cartesian coordinates of the following points (given in polar coordinates).
  - $(\sqrt{2}, \pi/4)$
  - $(1, 0)$
  - $(0, \pi/2)$
  - $(-\sqrt{2}, \pi/4)$

- $(-3, 5\pi/6)$
- $(5, \tan^{-1}(4/3))$
- $(-1, 7\pi)$
- $(2\sqrt{3}, 2\pi/3)$

## Cartesian to Polar Coordinates

- Find the polar coordinates,  $0 \leq \theta < 2\pi$  and  $r \geq 0$ , of the following points given in Cartesian coordinates.
  - $(1, 1)$
  - $(-3, 0)$
  - $(\sqrt{3}, -1)$
  - $(-3, 4)$
- Find the polar coordinates,  $-\pi \leq \theta < \pi$  and  $r \geq 0$ , of the following points given in Cartesian coordinates.
  - $(-2, -2)$
  - $(0, 3)$
  - $(-\sqrt{3}, 1)$
  - $(5, -12)$
- Find the polar coordinates,  $0 \leq \theta < 2\pi$  and  $r \leq 0$ , of the following points given in Cartesian coordinates.
  - $(3, 3)$
  - $(-1, 0)$
  - $(-1, \sqrt{3})$
  - $(4, -3)$
- Find the polar coordinates,  $-\pi \leq \theta < 2\pi$  and  $r \leq 0$ , of the following points given in Cartesian coordinates.
  - $(-2, 0)$
  - $(1, 0)$
  - $(0, -3)$
  - $(\frac{\sqrt{3}}{2}, \frac{1}{2})$

## Graphing Sets of Polar Coordinate Points

Graph the sets of points whose polar coordinates satisfy the equations and inequalities in Exercises 11–26.

- $r = 2$
- $0 \leq r \leq 2$
- $r \geq 1$
- $1 \leq r \leq 2$



15.  $0 \leq \theta \leq \pi/6, \quad r \geq 0$       16.  $\theta = 2\pi/3, \quad r \leq -2$   
 17.  $\theta = \pi/3, \quad -1 \leq r \leq 3$       18.  $\theta = 11\pi/4, \quad r \geq -1$   
 19.  $\theta = \pi/2, \quad r \geq 0$       20.  $\theta = \pi/2, \quad r \leq 0$   
 21.  $0 \leq \theta \leq \pi, \quad r = 1$       22.  $0 \leq \theta \leq \pi, \quad r = -1$   
 23.  $\pi/4 \leq \theta \leq 3\pi/4, \quad 0 \leq r \leq 1$   
 24.  $-\pi/4 \leq \theta \leq \pi/4, \quad -1 \leq r \leq 1$   
 25.  $-\pi/2 \leq \theta \leq \pi/2, \quad 1 \leq r \leq 2$   
 26.  $0 \leq \theta \leq \pi/2, \quad 1 \leq |r| \leq 2$

**Polar to Cartesian Equations**

Replace the polar equations in Exercises 27–52 with equivalent Cartesian equations. Then describe or identify the graph.

27.  $r \cos \theta = 2$       28.  $r \sin \theta = -1$   
 29.  $r \sin \theta = 0$       30.  $r \cos \theta = 0$   
 31.  $r = 4 \csc \theta$       32.  $r = -3 \sec \theta$   
 33.  $r \cos \theta + r \sin \theta = 1$       34.  $r \sin \theta = r \cos \theta$   
 35.  $r^2 = 1$       36.  $r^2 = 4r \sin \theta$   
 37.  $r = \frac{5}{\sin \theta - 2 \cos \theta}$       38.  $r^2 \sin 2\theta = 2$   
 39.  $r = \cot \theta \csc \theta$       40.  $r = 4 \tan \theta \sec \theta$   
 41.  $r = \csc \theta e^{r \cos \theta}$       42.  $r \sin \theta = \ln r + \ln \cos \theta$

43.  $r^2 + 2r^2 \cos \theta \sin \theta = 1$       44.  $\cos^2 \theta = \sin^2 \theta$   
 45.  $r^2 = -4r \cos \theta$       46.  $r^2 = -6r \sin \theta$   
 47.  $r = 8 \sin \theta$       48.  $r = 3 \cos \theta$   
 49.  $r = 2 \cos \theta + 2 \sin \theta$       50.  $r = 2 \cos \theta - \sin \theta$   
 51.  $r \sin \left( \theta + \frac{\pi}{6} \right) = 2$       52.  $r \sin \left( \frac{2\pi}{3} - \theta \right) = 5$

**Cartesian to Polar Equations**

Replace the Cartesian equations in Exercises 53–66 with equivalent polar equations.

53.  $x = 7$       54.  $y = 1$       55.  $x = y$   
 56.  $x - y = 3$       57.  $x^2 + y^2 = 4$       58.  $x^2 - y^2 = 1$   
 59.  $\frac{x^2}{9} + \frac{y^2}{4} = 1$       60.  $xy = 2$   
 61.  $y^2 = 4x$       62.  $x^2 + xy + y^2 = 1$   
 63.  $x^2 + (y - 2)^2 = 4$       64.  $(x - 5)^2 + y^2 = 25$   
 65.  $(x - 3)^2 + (y + 1)^2 = 4$       66.  $(x + 2)^2 + (y - 5)^2 = 16$   
 67. Find all polar coordinates of the origin.  
 68. **Vertical and horizontal lines**  
 a. Show that every vertical line in the  $xy$ -plane has a polar equation of the form  $r = a \sec \theta$ .  
 b. Find the analogous polar equation for horizontal lines in the  $xy$ -plane.

## Exercises 11.4

### Symmetries and Polar Graphs

Identify the symmetries of the curves in Exercises 1–12. Then sketch the curves in the  $xy$ -plane.

1.  $r = 1 + \cos \theta$
2.  $r = 2 - 2 \cos \theta$
3.  $r = 1 - \sin \theta$
4.  $r = 1 + \sin \theta$
5.  $r = 2 + \sin \theta$
6.  $r = 1 + 2 \sin \theta$
7.  $r = \sin(\theta/2)$
8.  $r = \cos(\theta/2)$
9.  $r^2 = \cos \theta$
10.  $r^2 = \sin \theta$
11.  $r^2 = -\sin \theta$
12.  $r^2 = -\cos \theta$

Graph the lemniscates in Exercises 13–16. What symmetries do these curves have?

13.  $r^2 = 4 \cos 2\theta$
14.  $r^2 = 4 \sin 2\theta$
15.  $r^2 = -\sin 2\theta$
16.  $r^2 = -\cos 2\theta$

### Slopes of Polar Curves in the $xy$ -Plane

Find the slopes of the curves in Exercises 17–20 at the given points. Sketch the curves along with their tangents at these points.

17. **Cardioid**  $r = -1 + \cos \theta$ ;  $\theta = \pm \pi/2$
18. **Cardioid**  $r = -1 + \sin \theta$ ;  $\theta = 0, \pi$
19. **Four-leaved rose**  $r = \sin 2\theta$ ;  $\theta = \pm \pi/4, \pm 3\pi/4$
20. **Four-leaved rose**  $r = \cos 2\theta$ ;  $\theta = 0, \pm \pi/2, \pi$

**Graphing Limaçons**

Graph the limaçons in Exercises 21–24. Limaçon (“lee-ma-sahn”) is Old French for “snail.” You will understand the name when you graph the limaçons in Exercise 21. Equations for limaçons have the form  $r = a \pm b \cos \theta$  or  $r = a \pm b \sin \theta$ . There are four basic shapes.

**21. Limaçons with an inner loop**

a.  $r = \frac{1}{2} + \cos \theta$       b.  $r = \frac{1}{2} + \sin \theta$

**22. Cardioids**

a.  $r = 1 - \cos \theta$       b.  $r = -1 + \sin \theta$

**23. Dimpled limaçons**

a.  $r = \frac{3}{2} + \cos \theta$       b.  $r = \frac{3}{2} - \sin \theta$

**24. Oval limaçons**

a.  $r = 2 + \cos \theta$       b.  $r = -2 + \sin \theta$

**Graphing Polar Regions and Curves in the  $xy$ -Plane**

**25.** Sketch the region defined by the inequalities  $-1 \leq r \leq 2$  and  $-\pi/2 \leq \theta \leq \pi/2$ .

**26.** Sketch the region defined by the inequalities  $0 \leq r \leq 2 \sec \theta$  and  $-\pi/4 \leq \theta \leq \pi/4$ .

In Exercises 27 and 28, sketch the region defined by the inequality.

**27.**  $0 \leq r \leq 2 - 2 \cos \theta$       **28.**  $0 \leq r^2 \leq \cos \theta$

**T 29.** Which of the following has the same graph as  $r = 1 - \cos \theta$ ?

a.  $r = -1 - \cos \theta$       b.  $r = 1 + \cos \theta$

Confirm your answer with algebra.

**T 30.** Which of the following has the same graph as  $r = \cos 2\theta$ ?

a.  $r = -\sin(2\theta + \pi/2)$       b.  $r = -\cos(\theta/2)$

Confirm your answer with algebra.

**T 31. A rose within a rose** Graph the equation  $r = 1 - 2 \sin 3\theta$ .

**T 32. The nephroid of Freeth** Graph the nephroid of Freeth:

$$r = 1 + 2 \sin \frac{\theta}{2}.$$

**T 33. Roses** Graph the roses  $r = \cos m\theta$  for  $m = 1/3, 2, 3$ , and  $7$ .

**T 34. Spirals** Polar coordinates are just the thing for defining spirals. Graph the following spirals.

a.  $r = \theta$

b.  $r = -\theta$

c. A logarithmic spiral:  $r = e^{\theta/10}$

d. A hyperbolic spiral:  $r = 8/\theta$

e. An equilateral hyperbola:  $r = \pm 10/\sqrt{\theta}$

(Use different colors for the two branches.)

**T 35.** Graph the equation  $r = \sin\left(\frac{8}{7}\theta\right)$  for  $0 \leq \theta \leq 14\pi$ .

**T 36.** Graph the equation

$$r = \sin^2(2.3\theta) + \cos^4(2.3\theta)$$

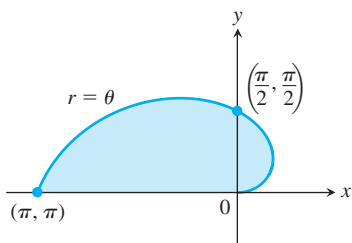
for  $0 \leq \theta \leq 10\pi$ .

## Exercises 11.5

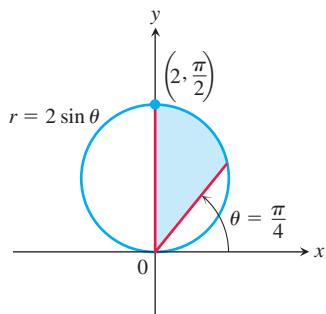
## Finding Polar Areas

Find the areas of the regions in Exercises 1–8.

1. Bounded by the spiral  $r = \theta$  for  $0 \leq \theta \leq \pi$

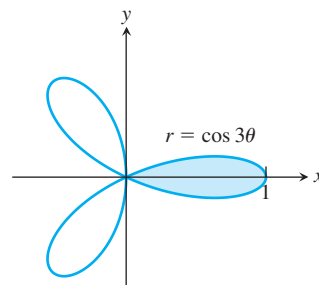


2. Bounded by the circle  $r = 2 \sin \theta$  for  $\pi/4 \leq \theta \leq \pi/2$



3. Inside the oval limaçon  $r = 4 + 2 \cos \theta$

4. Inside the cardioid  $r = a(1 + \cos \theta)$ ,  $a > 0$   
 5. Inside one leaf of the four-leaved rose  $r = \cos 2\theta$   
 6. Inside one leaf of the three-leaved rose  $r = \cos 3\theta$

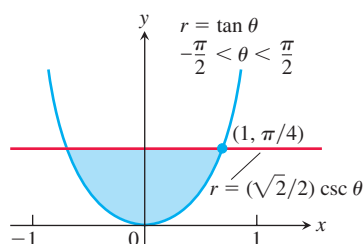


7. Inside one loop of the lemniscate  $r^2 = 4 \sin 2\theta$   
 8. Inside the six-leaved rose  $r^2 = 2 \sin 3\theta$

Find the areas of the regions in Exercises 9–18.

9. Shared by the circles  $r = 2 \cos \theta$  and  $r = 2 \sin \theta$   
 10. Shared by the circles  $r = 1$  and  $r = 2 \sin \theta$   
 11. Shared by the circle  $r = 2$  and the cardioid  $r = 2(1 - \cos \theta)$   
 12. Shared by the cardioids  $r = 2(1 + \cos \theta)$  and  $r = 2(1 - \cos \theta)$   
 13. Inside the lemniscate  $r^2 = 6 \cos 2\theta$  and outside the circle  $r = \sqrt{3}$

14. Inside the circle  $r = 3a \cos \theta$  and outside the cardioid  $r = a(1 + \cos \theta)$ ,  $a > 0$
15. Inside the circle  $r = -2 \cos \theta$  and outside the circle  $r = 1$
16. Inside the circle  $r = 6$  above the line  $r = 3 \csc \theta$
17. Inside the circle  $r = 4 \cos \theta$  and to the right of the vertical line  $r = \sec \theta$
18. Inside the circle  $r = 4 \sin \theta$  and below the horizontal line  $r = 3 \csc \theta$
19. a. Find the area of the shaded region in the accompanying figure.



- b. It looks as if the graph of  $r = \tan \theta$ ,  $-\pi/2 < \theta < \pi/2$ , could be asymptotic to the lines  $x = 1$  and  $x = -1$ . Is it? Give reasons for your answer.
20. The area of the region that lies inside the cardioid curve  $r = \cos \theta + 1$  and outside the circle  $r = \cos \theta$  is not

$$\frac{1}{2} \int_0^{2\pi} [(\cos \theta + 1)^2 - \cos^2 \theta] d\theta = \pi.$$

Why not? What is the area? Give reasons for your answers.

### Finding Lengths of Polar Curves

Find the lengths of the curves in Exercises 21–28.

21. The spiral  $r = \theta^2$ ,  $0 \leq \theta \leq \sqrt{5}$
22. The spiral  $r = e^\theta / \sqrt{2}$ ,  $0 \leq \theta \leq \pi$
23. The cardioid  $r = 1 + \cos \theta$
24. The curve  $r = a \sin^2(\theta/2)$ ,  $0 \leq \theta \leq \pi$ ,  $a > 0$
25. The parabolic segment  $r = 6/(1 + \cos \theta)$ ,  $0 \leq \theta \leq \pi/2$
26. The parabolic segment  $r = 2/(1 - \cos \theta)$ ,  $\pi/2 \leq \theta \leq \pi$
27. The curve  $r = \cos^3(\theta/3)$ ,  $0 \leq \theta \leq \pi/4$
28. The curve  $r = \sqrt{1 + \sin 2\theta}$ ,  $0 \leq \theta \leq \pi\sqrt{2}$
29. **The length of the curve  $r = f(\theta)$ ,  $\alpha \leq \theta \leq \beta$**  Assuming that the necessary derivatives are continuous, show how the substitutions
- $$x = f(\theta) \cos \theta, \quad y = f(\theta) \sin \theta$$
- (Equations 2 in the text) transform
- $$L = \int_{\alpha}^{\beta} \sqrt{\left(\frac{dx}{d\theta}\right)^2 + \left(\frac{dy}{d\theta}\right)^2} d\theta$$
- into
- $$L = \int_{\alpha}^{\beta} \sqrt{r^2 + \left(\frac{dr}{d\theta}\right)^2} d\theta.$$
30. **Circumferences of circles** As usual, when faced with a new formula, it is a good idea to try it on familiar objects to be sure it gives results consistent with past experience. Use the length formula in Equation (3) to calculate the circumferences of the following circles ( $a > 0$ ).
- a.  $r = a$       b.  $r = a \cos \theta$       c.  $r = a \sin \theta$

### Theory and Examples

31. **Average value** If  $f$  is continuous, the average value of the polar coordinate  $r$  over the curve  $r = f(\theta)$ ,  $\alpha \leq \theta \leq \beta$ , with respect to  $\theta$  is given by the formula

$$r_{\text{av}} = \frac{1}{\beta - \alpha} \int_{\alpha}^{\beta} f(\theta) d\theta.$$

Use this formula to find the average value of  $r$  with respect to  $\theta$  over the following curves ( $a > 0$ ).

- a. The cardioid  $r = a(1 - \cos \theta)$
- b. The circle  $r = a$
- c. The circle  $r = a \cos \theta$ ,  $-\pi/2 \leq \theta \leq \pi/2$
32.  **$r = f(\theta)$  vs.  $r = 2f(\theta)$**  Can anything be said about the relative lengths of the curves  $r = f(\theta)$ ,  $\alpha \leq \theta \leq \beta$ , and  $r = 2f(\theta)$ ,  $\alpha \leq \theta \leq \beta$ ? Give reasons for your answer.

## Exercises 12.1

### Geometric Interpretations of Equations

In Exercises 1–16, give a geometric description of the set of points in space whose coordinates satisfy the given pairs of equations.

1.  $x = 2, y = 3$
2.  $x = -1, z = 0$
3.  $y = 0, z = 0$
4.  $x = 1, y = 0$
5.  $x^2 + y^2 = 4, z = 0$
6.  $x^2 + y^2 = 4, z = -2$
7.  $x^2 + z^2 = 4, y = 0$
8.  $y^2 + z^2 = 1, x = 0$
9.  $x^2 + y^2 + z^2 = 1, x = 0$
10.  $x^2 + y^2 + z^2 = 25, y = -4$
11.  $x^2 + y^2 + (z + 3)^2 = 25, z = 0$
12.  $x^2 + (y - 1)^2 + z^2 = 4, y = 0$
13.  $x^2 + y^2 = 4, z = y$
14.  $x^2 + y^2 + z^2 = 4, y = x$
15.  $y = x^2, z = 0$
16.  $z = y^2, x = 1$

### Geometric Interpretations of Inequalities and Equations

In Exercises 17–24, describe the sets of points in space whose coordinates satisfy the given inequalities or combinations of equations and inequalities.

17. a.  $x \geq 0, y \geq 0, z = 0$     b.  $x \geq 0, y \leq 0, z = 0$
18. a.  $0 \leq x \leq 1$     b.  $0 \leq x \leq 1, 0 \leq y \leq 1$   
c.  $0 \leq x \leq 1, 0 \leq y \leq 1, 0 \leq z \leq 1$
19. a.  $x^2 + y^2 + z^2 \leq 1$     b.  $x^2 + y^2 + z^2 > 1$
20. a.  $x^2 + y^2 \leq 1, z = 0$     b.  $x^2 + y^2 \leq 1, z = 3$   
c.  $x^2 + y^2 \leq 1$ , no restriction on  $z$
21. a.  $1 \leq x^2 + y^2 + z^2 \leq 4$   
b.  $x^2 + y^2 + z^2 \leq 1, z \geq 0$
22. a.  $x = y, z = 0$     b.  $x = y$ , no restriction on  $z$
23. a.  $y \geq x^2, z \geq 0$     b.  $x \leq y^2, 0 \leq z \leq 2$
24. a.  $z = 1 - y$ , no restriction on  $x$   
b.  $z = y^3, x = 2$

In Exercises 25–34, describe the given set with a single equation or with a pair of equations.

25. The plane perpendicular to the
  - a.  $x$ -axis at  $(3, 0, 0)$
  - b.  $y$ -axis at  $(0, -1, 0)$
  - c.  $z$ -axis at  $(0, 0, -2)$
26. The plane through the point  $(3, -1, 2)$  perpendicular to the
  - a.  $x$ -axis
  - b.  $y$ -axis
  - c.  $z$ -axis
27. The plane through the point  $(3, -1, 1)$  parallel to the
  - a.  $xy$ -plane
  - b.  $yz$ -plane
  - c.  $xz$ -plane
28. The circle of radius 2 centered at  $(0, 0, 0)$  and lying in the
  - a.  $xy$ -plane
  - b.  $yz$ -plane
  - c.  $xz$ -plane
29. The circle of radius 2 centered at  $(0, 2, 0)$  and lying in the
  - a.  $xy$ -plane
  - b.  $yz$ -plane
  - c. plane  $y = 2$
30. The circle of radius 1 centered at  $(-3, 4, 1)$  and lying in a plane parallel to the
  - a.  $xy$ -plane
  - b.  $yz$ -plane
  - c.  $xz$ -plane
31. The line through the point  $(1, 3, -1)$  parallel to the
  - a.  $x$ -axis
  - b.  $y$ -axis
  - c.  $z$ -axis
32. The set of points in space equidistant from the origin and the point  $(0, 2, 0)$
33. The circle in which the plane through the point  $(1, 1, 3)$  perpendicular to the  $z$ -axis meets the sphere of radius 5 centered at the origin
34. The set of points in space that lie 2 units from the point  $(0, 0, 1)$  and, at the same time, 2 units from the point  $(0, 0, -1)$

### Inequalities to Describe Sets of Points

Write inequalities to describe the sets in Exercises 35–40.

35. The slab bounded by the planes  $z = 0$  and  $z = 1$  (planes included)
36. The solid cube in the first octant bounded by the coordinate planes and the planes  $x = 2$ ,  $y = 2$ , and  $z = 2$
37. The half-space consisting of the points on and below the  $xy$ -plane
38. The upper hemisphere of the sphere of radius 1 centered at the origin
39. The (a) interior and (b) exterior of the sphere of radius 1 centered at the point  $(1, 1, 1)$
40. The closed region bounded by the spheres of radius 1 and radius 2 centered at the origin. (*Closed* means the spheres are to be included. Had we wanted the spheres left out, we would have asked for the *open* region bounded by the spheres. This is analogous to the way we use *closed* and *open* to describe intervals: *closed* means endpoints included, *open* means endpoints left out. Closed sets include boundaries; open sets leave them out.)

### Distance

In Exercises 41–46, find the distance between points  $P_1$  and  $P_2$ .

41.  $P_1(1, 1, 1)$ ,  $P_2(3, 3, 0)$
42.  $P_1(-1, 1, 5)$ ,  $P_2(2, 5, 0)$
43.  $P_1(1, 4, 5)$ ,  $P_2(4, -2, 7)$

44.  $P_1(3, 4, 5)$ ,  $P_2(2, 3, 4)$
45.  $P_1(0, 0, 0)$ ,  $P_2(2, -2, -2)$
46.  $P_1(5, 3, -2)$ ,  $P_2(0, 0, 0)$

### Spheres

Find the centers and radii of the spheres in Exercises 47–50.

47.  $(x + 2)^2 + y^2 + (z - 2)^2 = 8$
48.  $(x - 1)^2 + \left(y + \frac{1}{2}\right)^2 + (z + 3)^2 = 25$
49.  $(x - \sqrt{2})^2 + (y - \sqrt{2})^2 + (z + \sqrt{2})^2 = 2$
50.  $x^2 + \left(y + \frac{1}{3}\right)^2 + \left(z - \frac{1}{3}\right)^2 = \frac{16}{9}$

Find equations for the spheres whose centers and radii are given in Exercises 51–54.

	Center	Radius
51.	$(1, 2, 3)$	$\sqrt{14}$
52.	$(0, -1, 5)$	2
53.	$\left(-1, \frac{1}{2}, -\frac{2}{3}\right)$	$\frac{4}{9}$
54.	$(0, -7, 0)$	7

Find the centers and radii of the spheres in Exercises 55–58.

55.  $x^2 + y^2 + z^2 + 4x - 4z = 0$
56.  $x^2 + y^2 + z^2 - 6y + 8z = 0$
57.  $2x^2 + 2y^2 + 2z^2 + x + y + z = 9$
58.  $3x^2 + 3y^2 + 3z^2 + 2y - 2z = 9$

### Theory and Examples

59. Find a formula for the distance from the point  $P(x, y, z)$  to the
  - a.  $x$ -axis.
  - b.  $y$ -axis.
  - c.  $z$ -axis.
60. Find a formula for the distance from the point  $P(x, y, z)$  to the
  - a.  $xy$ -plane.
  - b.  $yz$ -plane.
  - c.  $xz$ -plane.
61. Find the perimeter of the triangle with vertices  $A(-1, 2, 1)$ ,  $B(1, -1, 3)$ , and  $C(3, 4, 5)$ .
62. Show that the point  $P(3, 1, 2)$  is equidistant from the points  $A(2, -1, 3)$  and  $B(4, 3, 1)$ .
63. Find an equation for the set of all points equidistant from the planes  $y = 3$  and  $y = -1$ .
64. Find an equation for the set of all points equidistant from the point  $(0, 0, 2)$  and the  $xy$ -plane.
65. Find the point on the sphere  $x^2 + (y - 3)^2 + (z + 5)^2 = 4$  nearest
  - a. the  $xy$ -plane.
  - b. the point  $(0, 7, -5)$ .
66. Find the point equidistant from the points  $(0, 0, 0)$ ,  $(0, 4, 0)$ ,  $(3, 0, 0)$ , and  $(2, 2, -3)$ .

## Exercises 12.2

## Vectors in the Plane

In Exercises 1–8, let  $\mathbf{u} = \langle 3, -2 \rangle$  and  $\mathbf{v} = \langle -2, 5 \rangle$ . Find the (a) component form and (b) magnitude (length) of the vector.

1.  $3\mathbf{u}$
2.  $-2\mathbf{v}$
3.  $\mathbf{u} + \mathbf{v}$
4.  $\mathbf{u} - \mathbf{v}$
5.  $2\mathbf{u} - 3\mathbf{v}$
6.  $-2\mathbf{u} + 5\mathbf{v}$
7.  $\frac{3}{5}\mathbf{u} + \frac{4}{5}\mathbf{v}$
8.  $-\frac{5}{13}\mathbf{u} + \frac{12}{13}\mathbf{v}$

In Exercises 9–16, find the component form of the vector.

9. The vector  $\overrightarrow{PQ}$ , where  $P = (1, 3)$  and  $Q = (2, -1)$
10. The vector  $\overrightarrow{OP}$  where  $O$  is the origin and  $P$  is the midpoint of segment  $RS$ , where  $R = (2, -1)$  and  $S = (-4, 3)$
11. The vector from the point  $A = (2, 3)$  to the origin
12. The sum of  $\overrightarrow{AB}$  and  $\overrightarrow{CD}$ , where  $A = (1, -1)$ ,  $B = (2, 0)$ ,  $C = (-1, 3)$ , and  $D = (-2, 2)$
13. The unit vector that makes an angle  $\theta = 2\pi/3$  with the positive  $x$ -axis
14. The unit vector that makes an angle  $\theta = -3\pi/4$  with the positive  $x$ -axis
15. The unit vector obtained by rotating the vector  $\langle 0, 1 \rangle$   $120^\circ$  counterclockwise about the origin
16. The unit vector obtained by rotating the vector  $\langle 1, 0 \rangle$   $135^\circ$  counterclockwise about the origin

## Vectors in Space

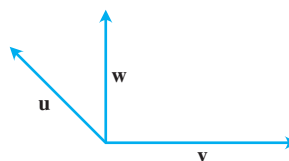
In Exercises 17–22, express each vector in the form  $\mathbf{v} = v_1\mathbf{i} + v_2\mathbf{j} + v_3\mathbf{k}$ .

17.  $\overrightarrow{P_1P_2}$  if  $P_1$  is the point  $(5, 7, -1)$  and  $P_2$  is the point  $(2, 9, -2)$
18.  $\overrightarrow{P_1P_2}$  if  $P_1$  is the point  $(1, 2, 0)$  and  $P_2$  is the point  $(-3, 0, 5)$
19.  $\overrightarrow{AB}$  if  $A$  is the point  $(-7, -8, 1)$  and  $B$  is the point  $(-10, 8, 1)$
20.  $\overrightarrow{AB}$  if  $A$  is the point  $(1, 0, 3)$  and  $B$  is the point  $(-1, 4, 5)$
21.  $5\mathbf{u} - \mathbf{v}$  if  $\mathbf{u} = \langle 1, 1, -1 \rangle$  and  $\mathbf{v} = \langle 2, 0, 3 \rangle$
22.  $-2\mathbf{u} + 3\mathbf{v}$  if  $\mathbf{u} = \langle -1, 0, 2 \rangle$  and  $\mathbf{v} = \langle 1, 1, 1 \rangle$

## Geometric Representations

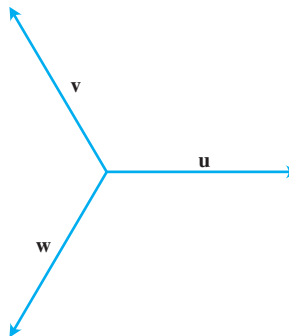
In Exercises 23 and 24, copy vectors  $\mathbf{u}$ ,  $\mathbf{v}$ , and  $\mathbf{w}$  head to tail as needed to sketch the indicated vector.

23.



- a.  $\mathbf{u} + \mathbf{v}$
- b.  $\mathbf{u} + \mathbf{v} + \mathbf{w}$
- c.  $\mathbf{u} - \mathbf{v}$
- d.  $\mathbf{u} - \mathbf{w}$

24.



- a.  $\mathbf{u} - \mathbf{v}$
- b.  $\mathbf{u} - \mathbf{v} + \mathbf{w}$
- c.  $2\mathbf{u} - \mathbf{v}$
- d.  $\mathbf{u} + \mathbf{v} + \mathbf{w}$

## Length and Direction

In Exercises 25–30, express each vector as a product of its length and direction.

25.  $2\mathbf{i} + \mathbf{j} - 2\mathbf{k}$

26.  $9\mathbf{i} - 2\mathbf{j} + 6\mathbf{k}$

27.  $5\mathbf{k}$

28.  $\frac{3}{5}\mathbf{i} + \frac{4}{5}\mathbf{k}$

29.  $\frac{1}{\sqrt{6}}\mathbf{i} - \frac{1}{\sqrt{6}}\mathbf{j} - \frac{1}{\sqrt{6}}\mathbf{k}$

30.  $\frac{\mathbf{i}}{\sqrt{3}} + \frac{\mathbf{j}}{\sqrt{3}} + \frac{\mathbf{k}}{\sqrt{3}}$



31. Find the vectors whose lengths and directions are given. Try to do the calculations without writing.

Length	Direction
a. 2	$\mathbf{i}$
b. $\sqrt{3}$	$-\mathbf{k}$
c. $\frac{1}{2}$	$\frac{3}{5}\mathbf{j} + \frac{4}{5}\mathbf{k}$
d. 7	$\frac{6}{7}\mathbf{i} - \frac{2}{7}\mathbf{j} + \frac{3}{7}\mathbf{k}$

32. Find the vectors whose lengths and directions are given. Try to do the calculations without writing.

Length	Direction
a. 7	$-\mathbf{j}$
b. $\sqrt{2}$	$-\frac{3}{5}\mathbf{i} - \frac{4}{5}\mathbf{k}$
c. $\frac{13}{12}$	$\frac{3}{13}\mathbf{i} - \frac{4}{13}\mathbf{j} - \frac{12}{13}\mathbf{k}$
d. $a > 0$	$\frac{1}{\sqrt{2}}\mathbf{i} + \frac{1}{\sqrt{3}}\mathbf{j} - \frac{1}{\sqrt{6}}\mathbf{k}$

33. Find a vector of magnitude 7 in the direction of  $\mathbf{v} = 12\mathbf{i} - 5\mathbf{k}$ .  
 34. Find a vector of magnitude 3 in the direction opposite to the direction of  $\mathbf{v} = (1/2)\mathbf{i} - (1/2)\mathbf{j} - (1/2)\mathbf{k}$ .

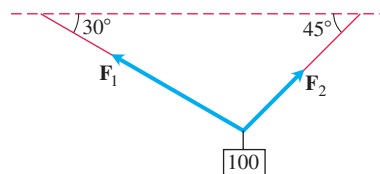
### Direction and Midpoints

In Exercises 35–38, find

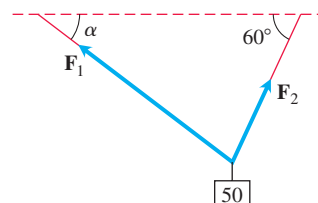
- the direction of  $\vec{P_1P_2}$  and
  - the midpoint of line segment  $P_1P_2$ .
35.  $P_1(-1, 1, 5)$   $P_2(2, 5, 0)$   
 36.  $P_1(1, 4, 5)$   $P_2(4, -2, 7)$   
 37.  $P_1(3, 4, 5)$   $P_2(2, 3, 4)$   
 38.  $P_1(0, 0, 0)$   $P_2(2, -2, -2)$   
 39. If  $\vec{AB} = \mathbf{i} + 4\mathbf{j} - 2\mathbf{k}$  and  $B$  is the point  $(5, 1, 3)$ , find  $A$ .  
 40. If  $\vec{AB} = -7\mathbf{i} + 3\mathbf{j} + 8\mathbf{k}$  and  $A$  is the point  $(-2, -3, 6)$ , find  $B$ .

### Theory and Applications

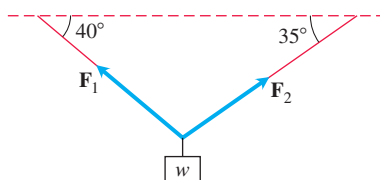
41. **Linear combination** Let  $\mathbf{u} = 2\mathbf{i} + \mathbf{j}$ ,  $\mathbf{v} = \mathbf{i} + \mathbf{j}$ , and  $\mathbf{w} = \mathbf{i} - \mathbf{j}$ . Find scalars  $a$  and  $b$  such that  $\mathbf{u} = a\mathbf{v} + b\mathbf{w}$ .  
 42. **Linear combination** Let  $\mathbf{u} = \mathbf{i} - 2\mathbf{j}$ ,  $\mathbf{v} = 2\mathbf{i} + 3\mathbf{j}$ , and  $\mathbf{w} = \mathbf{i} + \mathbf{j}$ . Write  $\mathbf{u} = \mathbf{u}_1 + \mathbf{u}_2$ , where  $\mathbf{u}_1$  is parallel to  $\mathbf{v}$  and  $\mathbf{u}_2$  is parallel to  $\mathbf{w}$ . (See Exercise 41.)  
 43. **Velocity** An airplane is flying in the direction  $25^\circ$  west of north at 800 km/h. Find the component form of the velocity of the airplane, assuming that the positive  $x$ -axis represents due east and the positive  $y$ -axis represents due north.  
 44. (Continuation of Example 8.) What speed and direction should the jetliner in Example 8 have in order for the resultant vector to be 800 km/h due east?  
 45. Consider a 100-N weight suspended by two wires as shown in the accompanying figure. Find the magnitudes and components of the force vectors  $\mathbf{F}_1$  and  $\mathbf{F}_2$ .



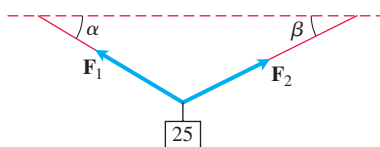
46. Consider a 50-N weight suspended by two wires as shown in the accompanying figure. If the magnitude of vector  $\mathbf{F}_1$  is 35 N, find angle  $\alpha$  and the magnitude of vector  $\mathbf{F}_2$ .



47. Consider a  $w$ -N weight suspended by two wires as shown in the accompanying figure. If the magnitude of vector  $\mathbf{F}_2$  is 100 N, find  $w$  and the magnitude of vector  $\mathbf{F}_1$ .



48. Consider a 25-N weight suspended by two wires as shown in the accompanying figure. If the magnitudes of vectors  $\mathbf{F}_1$  and  $\mathbf{F}_2$  are both 75 N, then angles  $\alpha$  and  $\beta$  are equal. Find  $\alpha$ .



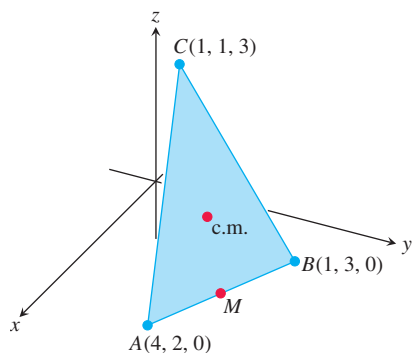
49. **Location** A bird flies from its nest 5 km in the direction  $60^\circ$  north of east, where it stops to rest on a tree. It then flies 10 km in the direction due southeast and lands atop a telephone pole. Place an  $xy$ -coordinate system so that the origin is the bird's nest, the  $x$ -axis points east, and the  $y$ -axis points north.

- At what point is the tree located?
- At what point is the telephone pole?

50. Use similar triangles to find the coordinates of the point  $Q$  that divides the segment from  $P_1(x_1, y_1, z_1)$  to  $P_2(x_2, y_2, z_2)$  into two lengths whose ratio is  $p/q = r$ .

51. **Medians of a triangle** Suppose that  $A$ ,  $B$ , and  $C$  are the corner points of the thin triangular plate of constant density shown here.

- Find the vector from  $C$  to the midpoint  $M$  of side  $AB$ .
- Find the vector from  $C$  to the point that lies two-thirds of the way from  $C$  to  $M$  on the median  $CM$ .
- Find the coordinates of the point in which the medians of  $\triangle ABC$  intersect. According to Exercise 19, Section 6.6, this point is the plate's center of mass. (See the accompanying figure.)



52. Find the vector from the origin to the point of intersection of the medians of the triangle whose vertices are

$$A(1, -1, 2), \quad B(2, 1, 3), \quad \text{and} \quad C(-1, 2, -1).$$

53. Let  $ABCD$  be a general, not necessarily planar, quadrilateral in space. Show that the two segments joining the midpoints of opposite sides of  $ABCD$  bisect each other. (*Hint*: Show that the segments have the same midpoint.)
54. Vectors are drawn from the center of a regular  $n$ -sided polygon in the plane to the vertices of the polygon. Show that the sum of the vectors is zero. (*Hint*: What happens to the sum if you rotate the polygon about its center?)
55. Suppose that  $A$ ,  $B$ , and  $C$  are vertices of a triangle and that  $a$ ,  $b$ , and  $c$  are, respectively, the midpoints of the opposite sides. Show that  $\vec{Aa} + \vec{Bb} + \vec{Cc} = 0$ .
56. **Unit vectors in the plane** Show that a unit vector in the plane can be expressed as  $\mathbf{u} = (\cos \theta)\mathbf{i} + (\sin \theta)\mathbf{j}$ , obtained by rotating  $\mathbf{i}$  through an angle  $\theta$  in the counterclockwise direction. Explain why this form gives *every* unit vector in the plane.

## Exercises 12.3

## Dot Product and Projections

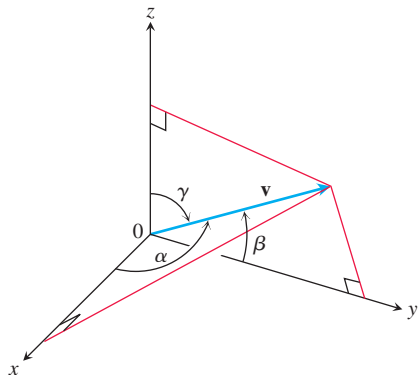
In Exercises 1–8, find

- $\mathbf{v} \cdot \mathbf{u}$ ,  $|\mathbf{v}|$ ,  $|\mathbf{u}|$
  - the cosine of the angle between  $\mathbf{v}$  and  $\mathbf{u}$
  - the scalar component of  $\mathbf{u}$  in the direction of  $\mathbf{v}$
  - the vector  $\text{proj}_{\mathbf{v}} \mathbf{u}$ .
- $\mathbf{v} = 2\mathbf{i} - 4\mathbf{j} + \sqrt{5}\mathbf{k}$ ,  $\mathbf{u} = -2\mathbf{i} + 4\mathbf{j} - \sqrt{5}\mathbf{k}$
  - $\mathbf{v} = (3/5)\mathbf{i} + (4/5)\mathbf{k}$ ,  $\mathbf{u} = 5\mathbf{i} + 12\mathbf{j}$
  - $\mathbf{v} = 10\mathbf{i} + 11\mathbf{j} - 2\mathbf{k}$ ,  $\mathbf{u} = 3\mathbf{j} + 4\mathbf{k}$
  - $\mathbf{v} = 2\mathbf{i} + 10\mathbf{j} - 11\mathbf{k}$ ,  $\mathbf{u} = 2\mathbf{i} + 2\mathbf{j} + \mathbf{k}$
  - $\mathbf{v} = 5\mathbf{j} - 3\mathbf{k}$ ,  $\mathbf{u} = \mathbf{i} + \mathbf{j} + \mathbf{k}$
  - $\mathbf{v} = -\mathbf{i} + \mathbf{j}$ ,  $\mathbf{u} = \sqrt{2}\mathbf{i} + \sqrt{3}\mathbf{j} + 2\mathbf{k}$
  - $\mathbf{v} = 5\mathbf{i} + \mathbf{j}$ ,  $\mathbf{u} = 2\mathbf{i} + \sqrt{17}\mathbf{j}$
  - $\mathbf{v} = \left\langle \frac{1}{\sqrt{2}}, \frac{1}{\sqrt{3}} \right\rangle$ ,  $\mathbf{u} = \left\langle \frac{1}{\sqrt{2}}, -\frac{1}{\sqrt{3}} \right\rangle$

## Angle Between Vectors

**T** Find the angles between the vectors in Exercises 9–12 to the nearest hundredth of a radian.

- $\mathbf{u} = 2\mathbf{i} + \mathbf{j}$ ,  $\mathbf{v} = \mathbf{i} + 2\mathbf{j} - \mathbf{k}$
  - $\mathbf{u} = 2\mathbf{i} - 2\mathbf{j} + \mathbf{k}$ ,  $\mathbf{v} = 3\mathbf{i} + 4\mathbf{k}$
  - $\mathbf{u} = \sqrt{3}\mathbf{i} - 7\mathbf{j}$ ,  $\mathbf{v} = \sqrt{3}\mathbf{i} + \mathbf{j} - 2\mathbf{k}$
  - $\mathbf{u} = \mathbf{i} + \sqrt{2}\mathbf{j} - \sqrt{2}\mathbf{k}$ ,  $\mathbf{v} = -\mathbf{i} + \mathbf{j} + \mathbf{k}$
- 13. Triangle** Find the measures of the angles of the triangle whose vertices are  $A = (-1, 0)$ ,  $B = (2, 1)$ , and  $C = (1, -2)$ .
- 14. Rectangle** Find the measures of the angles between the diagonals of the rectangle whose vertices are  $A = (1, 0)$ ,  $B = (0, 3)$ ,  $C = (3, 4)$ , and  $D = (4, 1)$ .
- 15. Direction angles and direction cosines** The *direction angles*  $\alpha$ ,  $\beta$ , and  $\gamma$  of a vector  $\mathbf{v} = a\mathbf{i} + b\mathbf{j} + c\mathbf{k}$  are defined as follows:  
 $\alpha$  is the angle between  $\mathbf{v}$  and the positive  $x$ -axis ( $0 \leq \alpha \leq \pi$ )  
 $\beta$  is the angle between  $\mathbf{v}$  and the positive  $y$ -axis ( $0 \leq \beta \leq \pi$ )  
 $\gamma$  is the angle between  $\mathbf{v}$  and the positive  $z$ -axis ( $0 \leq \gamma \leq \pi$ ).



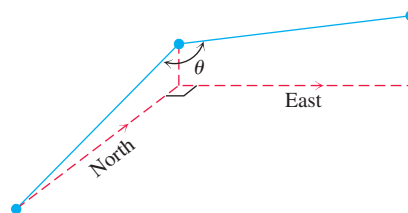
a. Show that

$$\cos \alpha = \frac{a}{|\mathbf{v}|}, \quad \cos \beta = \frac{b}{|\mathbf{v}|}, \quad \cos \gamma = \frac{c}{|\mathbf{v}|},$$

and  $\cos^2 \alpha + \cos^2 \beta + \cos^2 \gamma = 1$ . These cosines are called the *direction cosines* of  $\mathbf{v}$ .

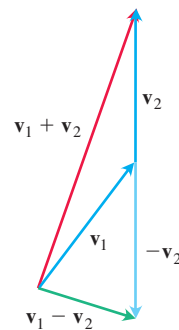
**b. Unit vectors are built from direction cosines** Show that if  $\mathbf{v} = a\mathbf{i} + b\mathbf{j} + c\mathbf{k}$  is a unit vector, then  $a$ ,  $b$ , and  $c$  are the direction cosines of  $\mathbf{v}$ .

- 16. Water main construction** A water main is to be constructed with a 20% grade in the north direction and a 10% grade in the east direction. Determine the angle  $\theta$  required in the water main for the turn from north to east.

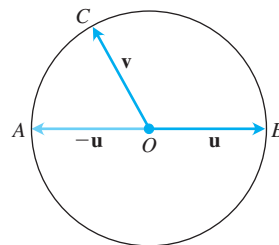


## Theory and Examples

- 17. Sums and differences** In the accompanying figure, it looks as if  $\mathbf{v}_1 + \mathbf{v}_2$  and  $\mathbf{v}_1 - \mathbf{v}_2$  are orthogonal. Is this mere coincidence, or are there circumstances under which we may expect the sum of two vectors to be orthogonal to their difference? Give reasons for your answer.

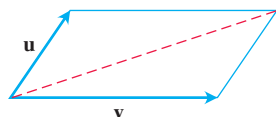


- 18. Orthogonality on a circle** Suppose that  $AB$  is the diameter of a circle with center  $O$  and that  $C$  is a point on one of the two arcs joining  $A$  and  $B$ . Show that  $\vec{CA}$  and  $\vec{CB}$  are orthogonal.

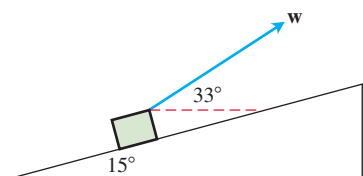


- 19. Diagonals of a rhombus** Show that the diagonals of a rhombus (parallelogram with sides of equal length) are perpendicular.

- 20. Perpendicular diagonals** Show that squares are the only rectangles with perpendicular diagonals.
- 21. When parallelograms are rectangles** Prove that a parallelogram is a rectangle if and only if its diagonals are equal in length. (This fact is often exploited by carpenters.)
- 22. Diagonal of parallelogram** Show that the indicated diagonal of the parallelogram determined by vectors  $\mathbf{u}$  and  $\mathbf{v}$  bisects the angle between  $\mathbf{u}$  and  $\mathbf{v}$  if  $|\mathbf{u}| = |\mathbf{v}|$ .



- 23. Projectile motion** A gun with muzzle velocity of 400 m/s is fired at an angle of  $8^\circ$  above the horizontal. Find the horizontal and vertical components of the velocity.
- 24. Inclined plane** Suppose that a box is being towed up an inclined plane as shown in the figure. Find the force  $\mathbf{w}$  needed to make the component of the force parallel to the inclined plane equal to 2.5 N.



- 25. a. Cauchy-Schwarz inequality** Since  $\mathbf{u} \cdot \mathbf{v} = |\mathbf{u}||\mathbf{v}| \cos \theta$ , show that the inequality  $|\mathbf{u} \cdot \mathbf{v}| \leq |\mathbf{u}||\mathbf{v}|$  holds for any vectors  $\mathbf{u}$  and  $\mathbf{v}$ .
- b.** Under what circumstances, if any, does  $|\mathbf{u} \cdot \mathbf{v}|$  equal  $|\mathbf{u}||\mathbf{v}|$ ? Give reasons for your answer.
- 26. Dot multiplication is positive definite** Show that dot multiplication of vectors is *positive definite*; that is, show that  $\mathbf{u} \cdot \mathbf{u} \geq 0$  for every vector  $\mathbf{u}$  and that  $\mathbf{u} \cdot \mathbf{u} = 0$  if and only if  $\mathbf{u} = \mathbf{0}$ .
- 27. Orthogonal unit vectors** If  $\mathbf{u}_1$  and  $\mathbf{u}_2$  are orthogonal unit vectors and  $\mathbf{v} = a\mathbf{u}_1 + b\mathbf{u}_2$ , find  $\mathbf{v} \cdot \mathbf{u}_1$ .
- 28. Cancellation in dot products** In real-number multiplication, if  $uv_1 = uv_2$  and  $u \neq 0$ , we can cancel the  $u$  and conclude that  $v_1 = v_2$ . Does the same rule hold for the dot product? That is, if  $\mathbf{u} \cdot \mathbf{v}_1 = \mathbf{u} \cdot \mathbf{v}_2$  and  $\mathbf{u} \neq \mathbf{0}$ , can you conclude that  $\mathbf{v}_1 = \mathbf{v}_2$ ? Give reasons for your answer.
- 29.** Using the definition of the projection of  $\mathbf{u}$  onto  $\mathbf{v}$ , show by direct calculation that  $(\mathbf{u} - \text{proj}_{\mathbf{v}} \mathbf{u}) \cdot \text{proj}_{\mathbf{v}} \mathbf{u} = 0$ .
- 30.** A force  $\mathbf{F} = 2\mathbf{i} + \mathbf{j} - 3\mathbf{k}$  is applied to a spacecraft with velocity vector  $\mathbf{v} = 3\mathbf{i} - \mathbf{j}$ . Express  $\mathbf{F}$  as a sum of a vector parallel to  $\mathbf{v}$  and a vector orthogonal to  $\mathbf{v}$ .

### Equations for Lines in the Plane

- 31. Line perpendicular to a vector** Show that  $\mathbf{v} = a\mathbf{i} + b\mathbf{j}$  is perpendicular to the line  $ax + by = c$  by establishing that the slope of the vector  $\mathbf{v}$  is the negative reciprocal of the slope of the given line.

- 32. Line parallel to a vector** Show that the vector  $\mathbf{v} = a\mathbf{i} + b\mathbf{j}$  is parallel to the line  $bx - ay = c$  by establishing that the slope of the line segment representing  $\mathbf{v}$  is the same as the slope of the given line.

In Exercises 33–36, use the result of Exercise 31 to find an equation for the line through  $P$  perpendicular to  $\mathbf{v}$ . Then sketch the line. Include  $\mathbf{v}$  in your sketch as a vector starting at the origin.

**33.**  $P(2, 1)$ ,  $\mathbf{v} = \mathbf{i} + 2\mathbf{j}$       **34.**  $P(-1, 2)$ ,  $\mathbf{v} = -2\mathbf{i} - \mathbf{j}$

**35.**  $P(-2, -7)$ ,  $\mathbf{v} = -2\mathbf{i} + \mathbf{j}$       **36.**  $P(11, 10)$ ,  $\mathbf{v} = 2\mathbf{i} - 3\mathbf{j}$

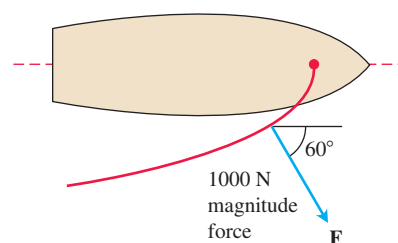
In Exercises 37–40, use the result of Exercise 32 to find an equation for the line through  $P$  parallel to  $\mathbf{v}$ . Then sketch the line. Include  $\mathbf{v}$  in your sketch as a vector starting at the origin.

**37.**  $P(-2, 1)$ ,  $\mathbf{v} = \mathbf{i} - \mathbf{j}$       **38.**  $P(0, -2)$ ,  $\mathbf{v} = 2\mathbf{i} + 3\mathbf{j}$

**39.**  $P(1, 2)$ ,  $\mathbf{v} = -\mathbf{i} - 2\mathbf{j}$       **40.**  $P(1, 3)$ ,  $\mathbf{v} = 3\mathbf{i} - 2\mathbf{j}$

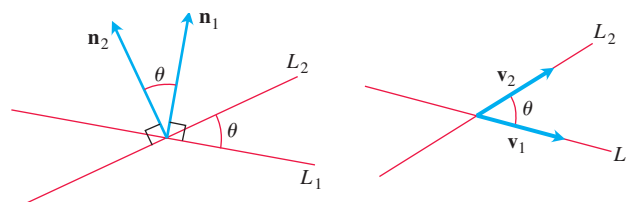
### Work

- 41. Work along a line** Find the work done by a force  $\mathbf{F} = 5\mathbf{i}$  (magnitude 5 N) in moving an object along the line from the origin to the point  $(1, 1)$  (distance in meters).
- 42. Locomotive** The Union Pacific's *Big Boy* locomotive could pull 6000-tonne trains with a tractive effort (pull) of 602,148 N. At this level of effort, about how much work did *Big Boy* do on the (approximately straight) 605-km journey from San Francisco to Los Angeles?
- 43. Inclined plane** How much work does it take to slide a crate 20 m along a loading dock by pulling on it with a 200-N force at an angle of  $30^\circ$  from the horizontal?
- 44. Sailboat** The wind passing over a boat's sail exerted a 1000 N magnitude force  $\mathbf{F}$  as shown here. How much work did the wind perform in moving the boat forward 1 km? Answer in joules.



### Angles Between Lines in the Plane

The **acute angle between intersecting lines** that do not cross at right angles is the same as the angle determined by vectors normal to the lines or by the vectors parallel to the lines.



Use this fact and the results of Exercise 31 or 32 to find the acute angles between the lines in Exercises 45–50.

45.  $3x + y = 5$ ,  $2x - y = 4$

46.  $y = \sqrt{3}x - 1$ ,  $y = -\sqrt{3}x + 2$

47.  $\sqrt{3}x - y = -2$ ,  $x - \sqrt{3}y = 1$

48.  $x + \sqrt{3}y = 1$ ,  $(1 - \sqrt{3})x + (1 + \sqrt{3})y = 8$

49.  $3x - 4y = 3$ ,  $x - y = 7$

50.  $12x + 5y = 1$ ,  $2x - 2y = 3$

## Exercises 12.4

## Cross Product Calculations

In Exercises 1–8, find the length and direction (when defined) of  $\mathbf{u} \times \mathbf{v}$  and  $\mathbf{v} \times \mathbf{u}$ .

1.  $\mathbf{u} = 2\mathbf{i} - 2\mathbf{j} - \mathbf{k}$ ,  $\mathbf{v} = \mathbf{i} - \mathbf{k}$
2.  $\mathbf{u} = 2\mathbf{i} + 3\mathbf{j}$ ,  $\mathbf{v} = -\mathbf{i} + \mathbf{j}$
3.  $\mathbf{u} = 2\mathbf{i} - 2\mathbf{j} + 4\mathbf{k}$ ,  $\mathbf{v} = -\mathbf{i} + \mathbf{j} - 2\mathbf{k}$
4.  $\mathbf{u} = \mathbf{i} + \mathbf{j} - \mathbf{k}$ ,  $\mathbf{v} = \mathbf{0}$
5.  $\mathbf{u} = 2\mathbf{i}$ ,  $\mathbf{v} = -3\mathbf{j}$
6.  $\mathbf{u} = \mathbf{i} \times \mathbf{j}$ ,  $\mathbf{v} = \mathbf{j} \times \mathbf{k}$

7.  $\mathbf{u} = -8\mathbf{i} - 2\mathbf{j} - 4\mathbf{k}$ ,  $\mathbf{v} = 2\mathbf{i} + 2\mathbf{j} + \mathbf{k}$

8.  $\mathbf{u} = \frac{3}{2}\mathbf{i} - \frac{1}{2}\mathbf{j} + \mathbf{k}$ ,  $\mathbf{v} = \mathbf{i} + \mathbf{j} + 2\mathbf{k}$

In Exercises 9–14, sketch the coordinate axes and then include the vectors  $\mathbf{u}$ ,  $\mathbf{v}$ , and  $\mathbf{u} \times \mathbf{v}$  as vectors starting at the origin.

- |   |   |
|---|---|
| 9. $\mathbf{u} = \mathbf{i}$ , $\mathbf{v} = \mathbf{j}$                            | 10. $\mathbf{u} = \mathbf{i} - \mathbf{k}$ , $\mathbf{v} = \mathbf{j}$                |
| 11. $\mathbf{u} = \mathbf{i} - \mathbf{k}$ , $\mathbf{v} = \mathbf{j} + \mathbf{k}$ | 12. $\mathbf{u} = 2\mathbf{i} - \mathbf{j}$ , $\mathbf{v} = \mathbf{i} + 2\mathbf{j}$ |
| 13. $\mathbf{u} = \mathbf{i} + \mathbf{j}$ , $\mathbf{v} = \mathbf{i} - \mathbf{j}$ | 14. $\mathbf{u} = \mathbf{j} + 2\mathbf{k}$ , $\mathbf{v} = \mathbf{i}$               |

## Triangles in Space

In Exercises 15–18,

- Find the area of the triangle determined by the points  $P$ ,  $Q$ , and  $R$ .
  - Find a unit vector perpendicular to plane  $PQR$ .
- $P(1, -1, 2)$ ,  $Q(2, 0, -1)$ ,  $R(0, 2, 1)$
  - $P(1, 1, 1)$ ,  $Q(2, 1, 3)$ ,  $R(3, -1, 1)$
  - $P(2, -2, 1)$ ,  $Q(3, -1, 2)$ ,  $R(3, -1, 1)$
  - $P(-2, 2, 0)$ ,  $Q(0, 1, -1)$ ,  $R(-1, 2, -2)$

## Triple Scalar Products

In Exercises 19–22, verify that  $(\mathbf{u} \times \mathbf{v}) \cdot \mathbf{w} = (\mathbf{v} \times \mathbf{w}) \cdot \mathbf{u} = (\mathbf{w} \times \mathbf{u}) \cdot \mathbf{v}$  and find the volume of the parallelepiped (box) determined by  $\mathbf{u}$ ,  $\mathbf{v}$ , and  $\mathbf{w}$ .

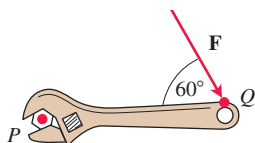
$\mathbf{u}$	$\mathbf{v}$	$\mathbf{w}$
19. $2\mathbf{i}$	$2\mathbf{j}$	$2\mathbf{k}$
20. $\mathbf{i} - \mathbf{j} + \mathbf{k}$	$2\mathbf{i} + \mathbf{j} - 2\mathbf{k}$	$-\mathbf{i} + 2\mathbf{j} - \mathbf{k}$
21. $2\mathbf{i} + \mathbf{j}$	$2\mathbf{i} - \mathbf{j} + \mathbf{k}$	$\mathbf{i} + 2\mathbf{k}$
22. $\mathbf{i} + \mathbf{j} - 2\mathbf{k}$	$-\mathbf{i} - \mathbf{k}$	$2\mathbf{i} + 4\mathbf{j} - 2\mathbf{k}$

## Theory and Examples

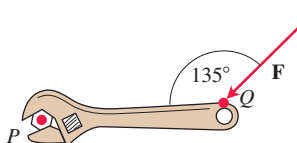
- Parallel and perpendicular vectors** Let  $\mathbf{u} = 5\mathbf{i} - \mathbf{j} + \mathbf{k}$ ,  $\mathbf{v} = \mathbf{j} - 5\mathbf{k}$ ,  $\mathbf{w} = -15\mathbf{i} + 3\mathbf{j} - 3\mathbf{k}$ . Which vectors, if any, are (a) perpendicular? (b) Parallel? Give reasons for your answers.
- Parallel and perpendicular vectors** Let  $\mathbf{u} = \mathbf{i} + 2\mathbf{j} - \mathbf{k}$ ,  $\mathbf{v} = -\mathbf{i} + \mathbf{j} + \mathbf{k}$ ,  $\mathbf{w} = \mathbf{i} + \mathbf{k}$ ,  $\mathbf{r} = -(\pi/2)\mathbf{i} - \pi\mathbf{j} + (\pi/2)\mathbf{k}$ . Which vectors, if any, are (a) perpendicular? (b) Parallel? Give reasons for your answers.

In Exercises 25 and 26, find the magnitude of the torque exerted by  $\mathbf{F}$  on the bolt at  $P$  if  $|PQ| = 20$  cm and  $|\mathbf{F}| = 15$  N. Answer in newton-meters.

25.



26.



- Which of the following are *always true*, and which are *not always true*? Give reasons for your answers.
  - $|\mathbf{u}| = \sqrt{\mathbf{u} \cdot \mathbf{u}}$
  - $\mathbf{u} \cdot \mathbf{u} = |\mathbf{u}|$
  - $\mathbf{u} \times \mathbf{0} = \mathbf{0} \times \mathbf{u} = \mathbf{0}$
  - $\mathbf{u} \times (-\mathbf{u}) = \mathbf{0}$
  - $\mathbf{u} \times \mathbf{v} = \mathbf{v} \times \mathbf{u}$
  - $\mathbf{u} \times (\mathbf{v} + \mathbf{w}) = \mathbf{u} \times \mathbf{v} + \mathbf{u} \times \mathbf{w}$
  - $(\mathbf{u} \times \mathbf{v}) \cdot \mathbf{v} = 0$
  - $(\mathbf{u} \times \mathbf{v}) \cdot \mathbf{w} = \mathbf{u} \cdot (\mathbf{v} \times \mathbf{w})$
- Which of the following are *always true*, and which are *not always true*? Give reasons for your answers.
  - $\mathbf{u} \cdot \mathbf{v} = \mathbf{v} \cdot \mathbf{u}$
  - $\mathbf{u} \times \mathbf{v} = -(\mathbf{v} \times \mathbf{u})$
  - $(-\mathbf{u}) \times \mathbf{v} = -(\mathbf{u} \times \mathbf{v})$

- $(c\mathbf{u}) \cdot \mathbf{v} = \mathbf{u} \cdot (c\mathbf{v}) = c(\mathbf{u} \cdot \mathbf{v})$  (any number  $c$ )
- $c(\mathbf{u} \times \mathbf{v}) = (c\mathbf{u}) \times \mathbf{v} = \mathbf{u} \times (c\mathbf{v})$  (any number  $c$ )
- $\mathbf{u} \cdot \mathbf{u} = |\mathbf{u}|^2$
- $(\mathbf{u} \times \mathbf{u}) \cdot \mathbf{u} = 0$
- $(\mathbf{u} \times \mathbf{v}) \cdot \mathbf{u} = \mathbf{v} \cdot (\mathbf{u} \times \mathbf{v})$

- Given nonzero vectors  $\mathbf{u}$ ,  $\mathbf{v}$ , and  $\mathbf{w}$ , use dot product and cross product notation, as appropriate, to describe the following.
  - The vector projection of  $\mathbf{u}$  onto  $\mathbf{v}$
  - A vector orthogonal to  $\mathbf{u}$  and  $\mathbf{v}$
  - A vector orthogonal to  $\mathbf{u} \times \mathbf{v}$  and  $\mathbf{w}$
  - The volume of the parallelepiped determined by  $\mathbf{u}$ ,  $\mathbf{v}$ , and  $\mathbf{w}$
  - A vector orthogonal to  $\mathbf{u} \times \mathbf{v}$  and  $\mathbf{u} \times \mathbf{w}$
  - A vector of length  $|\mathbf{u}|$  in the direction of  $\mathbf{v}$
- Compute  $(\mathbf{i} \times \mathbf{j}) \times \mathbf{j}$  and  $\mathbf{i} \times (\mathbf{j} \times \mathbf{j})$ . What can you conclude about the associativity of the cross product?
- Let  $\mathbf{u}$ ,  $\mathbf{v}$ , and  $\mathbf{w}$  be vectors. Which of the following make sense, and which do not? Give reasons for your answers.
  - $(\mathbf{u} \times \mathbf{v}) \cdot \mathbf{w}$
  - $\mathbf{u} \times (\mathbf{v} \cdot \mathbf{w})$
  - $\mathbf{u} \times (\mathbf{v} \times \mathbf{w})$
  - $\mathbf{u} \cdot (\mathbf{v} \cdot \mathbf{w})$
- Cross products of three vectors** Show that except in degenerate cases,  $(\mathbf{u} \times \mathbf{v}) \times \mathbf{w}$  lies in the plane of  $\mathbf{u}$  and  $\mathbf{v}$ , whereas  $\mathbf{u} \times (\mathbf{v} \times \mathbf{w})$  lies in the plane of  $\mathbf{v}$  and  $\mathbf{w}$ . What are the degenerate cases?
- Cancellation in cross products** If  $\mathbf{u} \times \mathbf{v} = \mathbf{u} \times \mathbf{w}$  and  $\mathbf{u} \neq \mathbf{0}$ , then does  $\mathbf{v} = \mathbf{w}$ ? Give reasons for your answer.
- Double cancellation** If  $\mathbf{u} \neq \mathbf{0}$  and if  $\mathbf{u} \times \mathbf{v} = \mathbf{u} \times \mathbf{w}$  and  $\mathbf{u} \cdot \mathbf{v} = \mathbf{u} \cdot \mathbf{w}$ , then does  $\mathbf{v} = \mathbf{w}$ ? Give reasons for your answer.

## Area of a Parallelogram

Find the areas of the parallelograms whose vertices are given in Exercises 35–40.

- $A(1, 0)$ ,  $B(0, 1)$ ,  $C(-1, 0)$ ,  $D(0, -1)$
- $A(0, 0)$ ,  $B(7, 3)$ ,  $C(9, 8)$ ,  $D(2, 5)$
- $A(-1, 2)$ ,  $B(2, 0)$ ,  $C(7, 1)$ ,  $D(4, 3)$
- $A(-6, 0)$ ,  $B(1, -4)$ ,  $C(3, 1)$ ,  $D(-4, 5)$
- $A(0, 0, 0)$ ,  $B(3, 2, 4)$ ,  $C(5, 1, 4)$ ,  $D(2, -1, 0)$
- $A(1, 0, -1)$ ,  $B(1, 7, 2)$ ,  $C(2, 4, -1)$ ,  $D(0, 3, 2)$

## Area of a Triangle

Find the areas of the triangles whose vertices are given in Exercises 41–47.

- $A(0, 0)$ ,  $B(-2, 3)$ ,  $C(3, 1)$
- $A(-1, -1)$ ,  $B(3, 3)$ ,  $C(2, 1)$
- $A(-5, 3)$ ,  $B(1, -2)$ ,  $C(6, -2)$
- $A(-6, 0)$ ,  $B(10, -5)$ ,  $C(-2, 4)$
- $A(1, 0, 0)$ ,  $B(0, 2, 0)$ ,  $C(0, 0, -1)$
- $A(0, 0, 0)$ ,  $B(-1, 1, -1)$ ,  $C(3, 0, 3)$
- $A(1, -1, 1)$ ,  $B(0, 1, 1)$ ,  $C(1, 0, -1)$

48. Find the volume of a parallelepiped if four of its eight vertices are  $A(0, 0, 0)$ ,  $B(1, 2, 0)$ ,  $C(0, -3, 2)$ , and  $D(3, -4, 5)$ .
49. **Triangle area** Find a  $2 \times 2$  determinant formula for the area of the triangle in the  $xy$ -plane with vertices at  $(0, 0)$ ,  $(a_1, a_2)$ , and  $(b_1, b_2)$ . Explain your work.
50. **Triangle area** Find a concise  $3 \times 3$  determinant formula that gives the area of a triangle in the  $xy$ -plane having vertices  $(a_1, a_2)$ ,  $(b_1, b_2)$ , and  $(c_1, c_2)$ .



## Exercises 12.5

## Lines and Line Segments

Find parametric equations for the lines in Exercises 1–12.

1. The line through the point  $P(3, -4, -1)$  parallel to the vector  $\mathbf{i} + \mathbf{j} + \mathbf{k}$
2. The line through  $P(1, 2, -1)$  and  $Q(-1, 0, 1)$
3. The line through  $P(-2, 0, 3)$  and  $Q(3, 5, -2)$
4. The line through  $P(1, 2, 0)$  and  $Q(1, 1, -1)$
5. The line through the origin parallel to the vector  $2\mathbf{j} + \mathbf{k}$
6. The line through the point  $(3, -2, 1)$  parallel to the line  $x = 1 + 2t, y = 2 - t, z = 3t$
7. The line through  $(1, 1, 1)$  parallel to the  $z$ -axis
8. The line through  $(2, 4, 5)$  perpendicular to the plane  $3x + 7y - 5z = 21$

9. The line through  $(0, -7, 0)$  perpendicular to the plane  $x + 2y + 2z = 13$
10. The line through  $(2, 3, 0)$  perpendicular to the vectors  $\mathbf{u} = \mathbf{i} + 2\mathbf{j} + 3\mathbf{k}$  and  $\mathbf{v} = 3\mathbf{i} + 4\mathbf{j} + 5\mathbf{k}$
11. The  $x$ -axis
12. The  $z$ -axis

Find parametrizations for the line segments joining the points in Exercises 13–20. Draw coordinate axes and sketch each segment, indicating the direction of increasing  $t$  for your parametrization.

13.  $(0, 0, 0), (1, 1, 3/2)$
14.  $(0, 0, 0), (1, 0, 0)$
15.  $(1, 0, 0), (1, 1, 0)$
16.  $(1, 1, 0), (1, 1, 1)$
17.  $(0, 1, 1), (0, -1, 1)$
18.  $(0, 2, 0), (3, 0, 0)$
19.  $(2, 0, 2), (0, 2, 0)$
20.  $(1, 0, -1), (0, 3, 0)$

## Planes

Find equations for the planes in Exercises 21–26.

21. The plane through  $P_0(0, 2, -1)$  normal to  $\mathbf{n} = 3\mathbf{i} - 2\mathbf{j} - \mathbf{k}$

22. The plane through  $(1, -1, 3)$  parallel to the plane

$$3x + y + z = 7$$

23. The plane through  $(1, 1, -1)$ ,  $(2, 0, 2)$ , and  $(0, -2, 1)$

24. The plane through  $(2, 4, 5)$ ,  $(1, 5, 7)$ , and  $(-1, 6, 8)$

25. The plane through  $P_0(2, 4, 5)$  perpendicular to the line

$$x = 5 + t, \quad y = 1 + 3t, \quad z = 4t$$

26. The plane through  $A(1, -2, 1)$  perpendicular to the vector from the origin to  $A$

27. Find the point of intersection of the lines  $x = 2t + 1$ ,  $y = 3t + 2$ ,  $z = 4t + 3$ , and  $x = s + 2$ ,  $y = 2s + 4$ ,  $z = -4s - 1$ , and then find the plane determined by these lines.

28. Find the point of intersection of the lines  $x = t$ ,  $y = -t + 2$ ,  $z = t + 1$ , and  $x = 2s + 2$ ,  $y = s + 3$ ,  $z = 5s + 6$ , and then find the plane determined by these lines.

In Exercises 29 and 30, find the plane containing the intersecting lines.

29.  $L1: x = -1 + t, \quad y = 2 + t, \quad z = 1 - t; \quad -\infty < t < \infty$

$L2: x = 1 - 4s, \quad y = 1 + 2s, \quad z = 2 - 2s; \quad -\infty < s < \infty$

30.  $L1: x = t, \quad y = 3 - 3t, \quad z = -2 - t; \quad -\infty < t < \infty$

$L2: x = 1 + s, \quad y = 4 + s, \quad z = -1 + s; \quad -\infty < s < \infty$

31. Find a plane through  $P_0(2, 1, -1)$  and perpendicular to the line of intersection of the planes  $2x + y - z = 3$ ,  $x + 2y + z = 2$ .

32. Find a plane through the points  $P_1(1, 2, 3)$ ,  $P_2(3, 2, 1)$  and perpendicular to the plane  $4x - y + 2z = 7$ .

## Distances

In Exercises 33–38, find the distance from the point to the line.

33.  $(0, 0, 12); \quad x = 4t, \quad y = -2t, \quad z = 2t$

34.  $(0, 0, 0); \quad x = 5 + 3t, \quad y = 5 + 4t, \quad z = -3 - 5t$

35.  $(2, 1, 3); \quad x = 2 + 2t, \quad y = 1 + 6t, \quad z = 3$

36.  $(2, 1, -1); \quad x = 2t, \quad y = 1 + 2t, \quad z = 2t$

37.  $(3, -1, 4); \quad x = 4 - t, \quad y = 3 + 2t, \quad z = -5 + 3t$

38.  $(-1, 4, 3); \quad x = 10 + 4t, \quad y = -3, \quad z = 4t$

In Exercises 39–44, find the distance from the point to the plane.

39.  $(2, -3, 4), \quad x + 2y + 2z = 13$

40.  $(0, 0, 0), \quad 3x + 2y + 6z = 6$

41.  $(0, 1, 1), \quad 4y + 3z = -12$

42.  $(2, 2, 3), \quad 2x + y + 2z = 4$

43.  $(0, -1, 0), \quad 2x + y + 2z = 4$

44.  $(1, 0, -1), \quad -4x + y + z = 4$

45. Find the distance from the plane  $x + 2y + 6z = 1$  to the plane  $x + 2y + 6z = 10$ .

46. Find the distance from the line  $x = 2 + t, y = 1 + t, z = -(1/2) - (1/2)t$  to the plane  $x + 2y + 6z = 10$ .

## Angles

Find the angles between the planes in Exercises 47 and 48.

47.  $x + y = 1, \quad 2x + y - 2z = 2$

48.  $5x + y - z = 10, \quad x - 2y + 3z = -1$

**T** Use a calculator to find the acute angles between the planes in Exercises 49–52 to the nearest hundredth of a radian.

49.  $2x + 2y + 2z = 3, \quad 2x - 2y - z = 5$

50.  $x + y + z = 1, \quad z = 0$  (the  $xy$ -plane)

51.  $2x + 2y - z = 3, \quad x + 2y + z = 2$

52.  $4y + 3z = -12, \quad 3x + 2y + 6z = 6$

## Intersecting Lines and Planes

In Exercises 53–56, find the point in which the line meets the plane.

53.  $x = 1 - t, \quad y = 3t, \quad z = 1 + t; \quad 2x - y + 3z = 6$

54.  $x = 2, \quad y = 3 + 2t, \quad z = -2 - 2t; \quad 6x + 3y - 4z = -12$

55.  $x = 1 + 2t, \quad y = 1 + 5t, \quad z = 3t; \quad x + y + z = 2$

56.  $x = -1 + 3t, \quad y = -2, \quad z = 5t; \quad 2x - 3z = 7$

Find parametrizations for the lines in which the planes in Exercises 57–60 intersect.

57.  $x + y + z = 1, \quad x + y = 2$

58.  $3x - 6y - 2z = 3, \quad 2x + y - 2z = 2$

59.  $x - 2y + 4z = 2, \quad x + y - 2z = 5$

60.  $5x - 2y = 11, \quad 4y - 5z = -17$

Given two lines in space, either they are parallel, they intersect, or they are skew (lie in parallel planes). In Exercises 61 and 62, determine whether the lines, taken two at a time, are parallel, intersect, or are skew. If they intersect, find the point of intersection. Otherwise, find the distance between the two lines.

61.  $L1: x = 3 + 2t, \quad y = -1 + 4t, \quad z = 2 - t; \quad -\infty < t < \infty$

$L2: x = 1 + 4s, \quad y = 1 + 2s, \quad z = -3 + 4s; \quad -\infty < s < \infty$

$L3: x = 3 + 2r, \quad y = 2 + r, \quad z = -2 + 2r; \quad -\infty < r < \infty$

62.  $L1: x = 1 + 2t, \quad y = -1 - t, \quad z = 3t; \quad -\infty < t < \infty$

$L2: x = 2 - s, \quad y = 3s, \quad z = 1 + s; \quad -\infty < s < \infty$

$L3: x = 5 + 2r, \quad y = 1 - r, \quad z = 8 + 3r; \quad -\infty < r < \infty$

## Theory and Examples

63. Use Equations (3) to generate a parametrization of the line through  $P(2, -4, 7)$  parallel to  $\mathbf{v}_1 = 2\mathbf{i} - \mathbf{j} + 3\mathbf{k}$ . Then generate another parametrization of the line using the point  $P_2(-2, -2, 1)$  and the vector  $\mathbf{v}_2 = -\mathbf{i} + (1/2)\mathbf{j} - (3/2)\mathbf{k}$ .

64. Use the component form to generate an equation for the plane through  $P_1(4, 1, 5)$  normal to  $\mathbf{n}_1 = \mathbf{i} - 2\mathbf{j} + \mathbf{k}$ . Then generate another equation for the same plane using the point  $P_2(3, -2, 0)$  and the normal vector  $\mathbf{n}_2 = -\sqrt{2}\mathbf{i} + 2\sqrt{2}\mathbf{j} - \sqrt{2}\mathbf{k}$ .

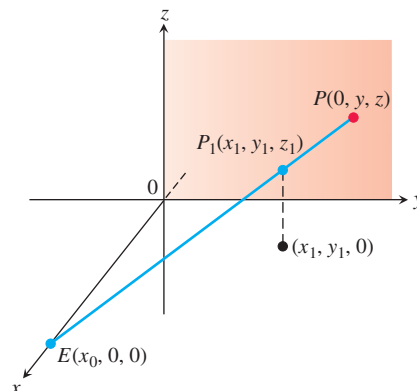
65. Find the points in which the line  $x = 1 + 2t, y = -1 - t, z = 3t$  meets the coordinate planes. Describe the reasoning behind your answer.

66. Find equations for the line in the plane  $z = 3$  that makes an angle of  $\pi/6$  rad with  $\mathbf{i}$  and an angle of  $\pi/3$  rad with  $\mathbf{j}$ . Describe the reasoning behind your answer.

67. Is the line  $x = 1 - 2t, y = 2 + 5t, z = -3t$  parallel to the plane  $2x + y - z = 8$ ? Give reasons for your answer.

68. How can you tell when two planes  $A_1x + B_1y + C_1z = D_1$  and  $A_2x + B_2y + C_2z = D_2$  are parallel? Perpendicular? Give reasons for your answer.
69. Find two different planes whose intersection is the line  $x = 1 + t, y = 2 - t, z = 3 + 2t$ . Write equations for each plane in the form  $Ax + By + Cz = D$ .
70. Find a plane through the origin that is perpendicular to the plane  $M: 2x + 3y + z = 12$  in a right angle. How do you know that your plane is perpendicular to  $M$ ?
71. The graph of  $(x/a) + (y/b) + (z/c) = 1$  is a plane for any nonzero numbers  $a, b$ , and  $c$ . Which planes have an equation of this form?
72. Suppose  $L_1$  and  $L_2$  are disjoint (nonintersecting) nonparallel lines. Is it possible for a nonzero vector to be perpendicular to both  $L_1$  and  $L_2$ ? Give reasons for your answer.
73. **Perspective in computer graphics** In computer graphics and perspective drawing, we need to represent objects seen by the eye in space as images on a two-dimensional plane. Suppose that the eye is at  $E(x_0, 0, 0)$  as shown here and that we want to represent a point  $P_1(x_1, y_1, z_1)$  as a point on the  $yz$ -plane. We do this by projecting  $P_1$  onto the plane with a ray from  $E$ . The point  $P_1$  will be portrayed as the point  $P(0, y, z)$ . The problem for us as graphics designers is to find  $y$  and  $z$  given  $E$  and  $P_1$ .
- a. Write a vector equation that holds between  $\vec{EP}$  and  $\vec{EP}_1$ . Use the equation to express  $y$  and  $z$  in terms of  $x_0, x_1, y_1$ , and  $z_1$ .

- b. Test the formulas obtained for  $y$  and  $z$  in part (a) by investigating their behavior at  $x_1 = 0$  and  $x_1 = x_0$  and by seeing what happens as  $x_0 \rightarrow \infty$ . What do you find?



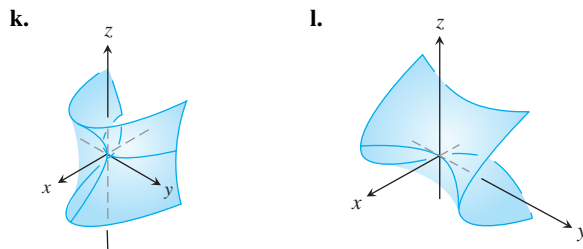
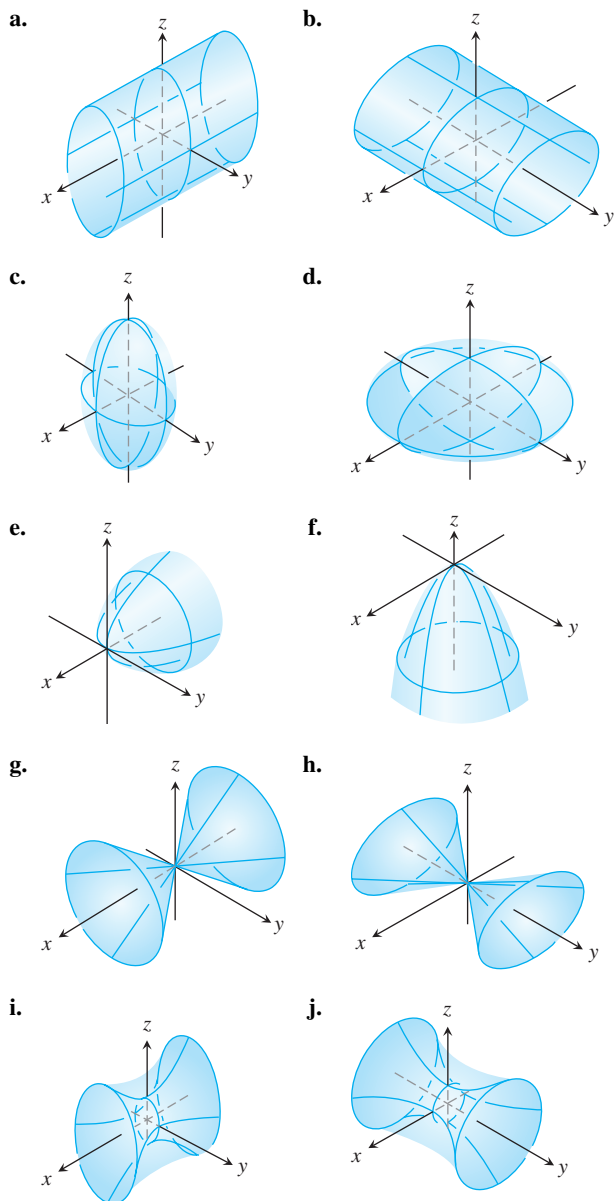
74. **Hidden lines in computer graphics** Here is another typical problem in computer graphics. Your eye is at  $(4, 0, 0)$ . You are looking at a triangular plate whose vertices are at  $(1, 0, 1)$ ,  $(1, 1, 0)$ , and  $(-2, 2, 2)$ . The line segment from  $(1, 0, 0)$  to  $(0, 2, 2)$  passes through the plate. What portion of the line segment is hidden from your view by the plate? (This is an exercise in finding intersections of lines and planes.)

## Exercises 12.6

## Matching Equations with Surfaces

In Exercises 1–12, match the equation with the surface it defines. Also, identify each surface by type (paraboloid, ellipsoid, etc.). The surfaces are labeled (a)–(l).

1.  $x^2 + y^2 + 4z^2 = 10$
2.  $z^2 + 4y^2 - 4x^2 = 4$
3.  $9y^2 + z^2 = 16$
4.  $y^2 + z^2 = x^2$
5.  $x = y^2 - z^2$
6.  $x = -y^2 - z^2$
7.  $x^2 + 2z^2 = 8$
8.  $z^2 + x^2 - y^2 = 1$
9.  $x = z^2 - y^2$
10.  $z = -4x^2 - y^2$
11.  $x^2 + 4z^2 = y^2$
12.  $9x^2 + 4y^2 + 2z^2 = 36$



## Drawing

Sketch the surfaces in Exercises 13–44.

## CYLINDERS

13.  $x^2 + y^2 = 4$
14.  $z = y^2 - 1$
15.  $x^2 + 4z^2 = 16$
16.  $4x^2 + y^2 = 36$

## ELLIPSOIDS

17.  $9x^2 + y^2 + z^2 = 9$
18.  $4x^2 + 4y^2 + z^2 = 16$
19.  $4x^2 + 9y^2 + 4z^2 = 36$
20.  $9x^2 + 4y^2 + 36z^2 = 36$

## PARABOLOIDS AND CONES

21.  $z = x^2 + 4y^2$
22.  $z = 8 - x^2 - y^2$
23.  $x = 4 - 4y^2 - z^2$
24.  $y = 1 - x^2 - z^2$
25.  $x^2 + y^2 = z^2$
26.  $4x^2 + 9z^2 = 9y^2$

## HYPERBOLOIDS

27.  $x^2 + y^2 - z^2 = 1$
28.  $y^2 + z^2 - x^2 = 1$
29.  $z^2 - x^2 - y^2 = 1$
30.  $(y^2/4) - (x^2/4) - z^2 = 1$

## HYPERBOLIC PARABOLOIDS

31.  $y^2 - x^2 = z$
32.  $x^2 - y^2 = z$

## ASSORTED

33.  $z = 1 + y^2 - x^2$
34.  $4x^2 + 4y^2 = z^2$
35.  $y = -(x^2 + z^2)$
36.  $16x^2 + 4y^2 = 1$
37.  $x^2 + y^2 - z^2 = 4$
38.  $x^2 + z^2 = y$
39.  $x^2 + z^2 = 1$
40.  $16y^2 + 9z^2 = 4x^2$
41.  $z = -(x^2 + y^2)$
42.  $y^2 - x^2 - z^2 = 1$
43.  $4y^2 + z^2 - 4x^2 = 4$
44.  $x^2 + y^2 = z$

## Theory and Examples

45. a. Express the area  $A$  of the cross-section cut from the ellipsoid

$$x^2 + \frac{y^2}{4} + \frac{z^2}{9} = 1$$

by the plane  $z = c$  as a function of  $c$ . (The area of an ellipse with semi-axes  $a$  and  $b$  is  $\pi ab$ .)

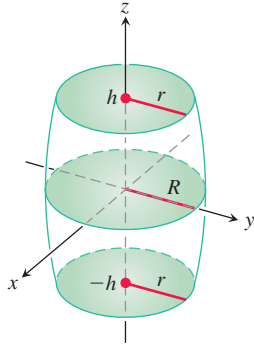
- b. Use slices perpendicular to the  $z$ -axis to find the volume of the ellipsoid in part (a).

- c. Now find the volume of the ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1.$$

Does your formula give the volume of a sphere of radius  $a$  if  $a = b = c$ ?

46. The barrel shown here is shaped like an ellipsoid with equal pieces cut from the ends by planes perpendicular to the  $z$ -axis. The cross-sections perpendicular to the  $z$ -axis are circular. The barrel is  $2h$  units high, its midsection radius is  $R$ , and its end radii are both  $r$ . Find a formula for the barrel's volume. Then check two things. First, suppose the sides of the barrel are straightened to turn the barrel into a cylinder of radius  $R$  and height  $2h$ . Does your formula give the cylinder's volume? Second, suppose  $r = 0$  and  $h = R$  so the barrel is a sphere. Does your formula give the sphere's volume?



47. Show that the volume of the segment cut from the paraboloid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = \frac{z}{c}$$

by the plane  $z = h$  equals half the segment's base times its altitude.

48. a. Find the volume of the solid bounded by the hyperboloid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} - \frac{z^2}{c^2} = 1$$

and the planes  $z = 0$  and  $z = h$ ,  $h > 0$ .

- b. Express your answer in part (a) in terms of  $h$  and the areas  $A_0$  and  $A_h$  of the regions cut by the hyperboloid from the planes  $z = 0$  and  $z = h$ .
- c. Show that the volume in part (a) is also given by the formula

$$V = \frac{h}{6}(A_0 + 4A_m + A_h),$$

where  $A_m$  is the area of the region cut by the hyperboloid from the plane  $z = h/2$ .

### Viewing Surfaces

**T** Plot the surfaces in Exercises 49–52 over the indicated domains. If you can, rotate the surface into different viewing positions.

49.  $z = y^2$ ,  $-2 \leq x \leq 2$ ,  $-0.5 \leq y \leq 2$
50.  $z = 1 - y^2$ ,  $-2 \leq x \leq 2$ ,  $-2 \leq y \leq 2$
51.  $z = x^2 + y^2$ ,  $-3 \leq x \leq 3$ ,  $-3 \leq y \leq 3$
52.  $z = x^2 + 2y^2$  over
- $-3 \leq x \leq 3$ ,  $-3 \leq y \leq 3$
  - $-1 \leq x \leq 1$ ,  $-2 \leq y \leq 3$
  - $-2 \leq x \leq 2$ ,  $-2 \leq y \leq 2$
  - $-2 \leq x \leq 2$ ,  $-1 \leq y \leq 1$

### COMPUTER EXPLORATIONS

Use a CAS to plot the surfaces in Exercises 53–58. Identify the type of quadric surface from your graph.

53.  $\frac{x^2}{9} + \frac{y^2}{36} = 1 - \frac{z^2}{25}$
54.  $\frac{x^2}{9} - \frac{z^2}{9} = 1 - \frac{y^2}{16}$
55.  $5x^2 = z^2 - 3y^2$
56.  $\frac{y^2}{16} = 1 - \frac{x^2}{9} + z$
57.  $\frac{x^2}{9} - 1 = \frac{y^2}{16} + \frac{z^2}{2}$
58.  $y - \sqrt{4 - z^2} = 0$

## Exercises 13.1

### Motion in the Plane

In Exercises 1–4,  $\mathbf{r}(t)$  is the position of a particle in the  $xy$ -plane at time  $t$ . Find an equation in  $x$  and  $y$  whose graph is the path of the particle. Then find the particle's velocity and acceleration vectors at the given value of  $t$ .

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

2.  $\mathbf{r}(t) = \frac{t}{t+1}\mathbf{i} + \frac{1}{t}\mathbf{j}, \quad t = -\frac{1}{2}$

3.  $\mathbf{r}(t) = e^t\mathbf{i} + \frac{2}{9}e^{2t}\mathbf{j}, \quad t = \ln 3$

4.  $\mathbf{r}(t) = (\cos 2t)\mathbf{i} + (3 \sin 2t)\mathbf{j}, \quad t = 0$

Exercises 5–8 give the position vectors of particles moving along various curves in the  $xy$ -plane. In each case, find the particle's velocity and acceleration vectors at the stated times and sketch them as vectors on the curve.

**5. Motion on the circle  $x^2 + y^2 = 1$**

$$\mathbf{r}(t) = (\sin t)\mathbf{i} + (\cos t)\mathbf{j}; \quad t = \pi/4 \text{ and } \pi/2$$

**6. Motion on the circle  $x^2 + y^2 = 16$**

$$\mathbf{r}(t) = \left(4 \cos \frac{t}{2}\right)\mathbf{i} + \left(4 \sin \frac{t}{2}\right)\mathbf{j}; \quad t = \pi \text{ and } 3\pi/2$$

**7. Motion on the cycloid  $x = t - \sin t$ ,  $y = 1 - \cos t$**

$$\mathbf{r}(t) = (t - \sin t)\mathbf{i} + (1 - \cos t)\mathbf{j}; \quad t = \pi \text{ and } 3\pi/2$$

**8. Motion on the parabola  $y = x^2 + 1$**

$$\mathbf{r}(t) = t\mathbf{i} + (t^2 + 1)\mathbf{j}; \quad t = -1, 0, \text{ and } 1$$

### Motion in Space

In Exercises 9–14,  $\mathbf{r}(t)$  is the position of a particle in space at time  $t$ . Find the particle's velocity and acceleration vectors. Then find the particle's speed and direction of motion at the given value of  $t$ . Write the particle's velocity at that time as the product of its speed and direction.

**9.**  $\mathbf{r}(t) = (t + 1)\mathbf{i} + (t^2 - 1)\mathbf{j} + 2t\mathbf{k}, \quad t = 1$

**10.**  $\mathbf{r}(t) = (1 + t)\mathbf{i} + \frac{t^2}{\sqrt{2}}\mathbf{j} + \frac{t^3}{3}\mathbf{k}, \quad t = 1$

**11.**  $\mathbf{r}(t) = (2 \cos t)\mathbf{i} + (3 \sin t)\mathbf{j} + 4t\mathbf{k}, \quad t = \pi/2$

**12.**  $\mathbf{r}(t) = (\sec t)\mathbf{i} + (\tan t)\mathbf{j} + \frac{4}{3}t\mathbf{k}, \quad t = \pi/6$

**13.**  $\mathbf{r}(t) = (2 \ln(t + 1))\mathbf{i} + t^2\mathbf{j} + \frac{t^2}{2}\mathbf{k}, \quad t = 1$

**14.**  $\mathbf{r}(t) = (e^{-t})\mathbf{i} + (2 \cos 3t)\mathbf{j} + (2 \sin 3t)\mathbf{k}, \quad t = 0$

In Exercises 15–18,  $\mathbf{r}(t)$  is the position of a particle in space at time  $t$ . Find the angle between the velocity and acceleration vectors at time  $t = 0$ .

**15.**  $\mathbf{r}(t) = (3t + 1)\mathbf{i} + \sqrt{3}t\mathbf{j} + t^2\mathbf{k}$

**16.**  $\mathbf{r}(t) = \left(\frac{\sqrt{2}}{2}t\right)\mathbf{i} + \left(\frac{\sqrt{2}}{2}t - 16t^2\right)\mathbf{j}$

**17.**  $\mathbf{r}(t) = (\ln(t^2 + 1))\mathbf{i} + (\tan^{-1}t)\mathbf{j} + \sqrt{t^2 + 1}\mathbf{k}$

**18.**  $\mathbf{r}(t) = \frac{4}{9}(1 + t)^{3/2}\mathbf{i} + \frac{4}{9}(1 - t)^{3/2}\mathbf{j} + \frac{1}{3}t\mathbf{k}$

### Tangents to Curves

As mentioned in the text, the **tangent line** to a smooth curve  $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k}$  at  $t = t_0$  is the line that passes through the point  $(f(t_0), g(t_0), h(t_0))$  parallel to  $\mathbf{v}(t_0)$ , the curve's velocity vector at  $t_0$ . In Exercises 19–22, find parametric equations for the line that is tangent to the given curve at the given parameter value  $t = t_0$ .

**19.**  $\mathbf{r}(t) = (\sin t)\mathbf{i} + (t^2 - \cos t)\mathbf{j} + e^t\mathbf{k}, \quad t_0 = 0$

**20.**  $\mathbf{r}(t) = t^2\mathbf{i} + (2t - 1)\mathbf{j} + t^3\mathbf{k}, \quad t_0 = 2$

**21.**  $\mathbf{r}(t) = \ln t\mathbf{i} + \frac{t-1}{t+2}\mathbf{j} + t \ln t\mathbf{k}, \quad t_0 = 1$

**22.**  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} + (\sin 2t)\mathbf{k}, \quad t_0 = \frac{\pi}{2}$

### Theory and Examples

**23. Motion along a circle** Each of the following equations in parts (a)–(e) describes the motion of a particle having the same path, namely the unit circle  $x^2 + y^2 = 1$ . Although the path of each particle in parts (a)–(e) is the same, the behavior, or “dynamics,” of each particle is different. For each particle, answer the following questions.

i) Does the particle have constant speed? If so, what is its constant speed?

ii) Is the particle's acceleration vector always orthogonal to its velocity vector?

iii) Does the particle move clockwise or counterclockwise around the circle?

iv) Does the particle begin at the point  $(1, 0)$ ?

a.  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j}, \quad t \geq 0$

b.  $\mathbf{r}(t) = \cos(2t)\mathbf{i} + \sin(2t)\mathbf{j}, \quad t \geq 0$

c.  $\mathbf{r}(t) = \cos(t - \pi/2)\mathbf{i} + \sin(t - \pi/2)\mathbf{j}, \quad t \geq 0$

d.  $\mathbf{r}(t) = (\cos t)\mathbf{i} - (\sin t)\mathbf{j}, \quad t \geq 0$

e.  $\mathbf{r}(t) = \cos(t^2)\mathbf{i} + \sin(t^2)\mathbf{j}, \quad t \geq 0$

**24. Motion along a circle** Show that the vector-valued function

$$\mathbf{r}(t) = (2\mathbf{i} + 2\mathbf{j} + \mathbf{k}) + \cos t \left( \frac{1}{\sqrt{2}}\mathbf{i} - \frac{1}{\sqrt{2}}\mathbf{j} \right) + \sin t \left( \frac{1}{\sqrt{3}}\mathbf{i} + \frac{1}{\sqrt{3}}\mathbf{j} + \frac{1}{\sqrt{3}}\mathbf{k} \right)$$

describes the motion of a particle moving in the circle of radius 1 centered at the point  $(2, 2, 1)$  and lying in the plane  $x + y - 2z = 2$ .

**25. Motion along a parabola** A particle moves along the top of the parabola  $y^2 = 2x$  from left to right at a constant speed of 5 units per second. Find the velocity of the particle as it moves through the point  $(2, 2)$ .

**26. Motion along a cycloid** A particle moves in the  $xy$ -plane in such a way that its position at time  $t$  is

$$\mathbf{r}(t) = (t - \sin t)\mathbf{i} + (1 - \cos t)\mathbf{j}.$$

**T a.** Graph  $\mathbf{r}(t)$ . The resulting curve is a cycloid.

b. Find the maximum and minimum values of  $|\mathbf{v}|$  and  $|\mathbf{a}|$ . (Hint: Find the extreme values of  $|\mathbf{v}|^2$  and  $|\mathbf{a}|^2$  first and take square roots later.)

**27.** Let  $\mathbf{r}$  be a differentiable vector function of  $t$ . Show that if  $\mathbf{r} \cdot (d\mathbf{r}/dt) = 0$  for all  $t$ , then  $|\mathbf{r}|$  is constant.

**28. Derivatives of triple scalar products**

a. Show that if  $\mathbf{u}$ ,  $\mathbf{v}$ , and  $\mathbf{w}$  are differentiable vector functions of  $t$ , then

$$\frac{d}{dt}(\mathbf{u} \cdot \mathbf{v} \times \mathbf{w}) = \frac{d\mathbf{u}}{dt} \cdot \mathbf{v} \times \mathbf{w} + \mathbf{u} \cdot \frac{d\mathbf{v}}{dt} \times \mathbf{w} + \mathbf{u} \cdot \mathbf{v} \times \frac{d\mathbf{w}}{dt}.$$

b. Show that

$$\frac{d}{dt} \left( \mathbf{r} \cdot \frac{d\mathbf{r}}{dt} \times \frac{d^2\mathbf{r}}{dt^2} \right) = \mathbf{r} \cdot \left( \frac{d\mathbf{r}}{dt} \times \frac{d^3\mathbf{r}}{dt^3} \right).$$

(Hint: Differentiate on the left and look for vectors whose products are zero.)

29. Prove the two Scalar Multiple Rules for vector functions.
30. Prove the Sum and Difference Rules for vector functions.
31. **Component test for continuity at a point** Show that the vector function  $\mathbf{r}$  defined by  $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k}$  is continuous at  $t = t_0$  if and only if  $f$ ,  $g$ , and  $h$  are continuous at  $t_0$ .
32. **Limits of cross products of vector functions** Suppose that  $\mathbf{r}_1(t) = f_1(t)\mathbf{i} + f_2(t)\mathbf{j} + f_3(t)\mathbf{k}$ ,  $\mathbf{r}_2(t) = g_1(t)\mathbf{i} + g_2(t)\mathbf{j} + g_3(t)\mathbf{k}$ ,  $\lim_{t \rightarrow t_0} \mathbf{r}_1(t) = \mathbf{A}$ , and  $\lim_{t \rightarrow t_0} \mathbf{r}_2(t) = \mathbf{B}$ . Use the determinant formula for cross products and the Limit Product Rule for scalar functions to show that

$$\lim_{t \rightarrow t_0} (\mathbf{r}_1(t) \times \mathbf{r}_2(t)) = \mathbf{A} \times \mathbf{B}.$$

33. **Differentiable vector functions are continuous** Show that if  $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j} + h(t)\mathbf{k}$  is differentiable at  $t = t_0$ , then it is continuous at  $t_0$  as well.
34. **Constant Function Rule** Prove that if  $\mathbf{u}$  is the vector function with the constant value  $\mathbf{C}$ , then  $d\mathbf{u}/dt = \mathbf{0}$ .

### COMPUTER EXPLORATIONS

Use a CAS to perform the following steps in Exercises 35–38.

- Plot the space curve traced out by the position vector  $\mathbf{r}$ .
- Find the components of the velocity vector  $d\mathbf{r}/dt$ .
- Evaluate  $d\mathbf{r}/dt$  at the given point  $t_0$  and determine the equation of the tangent line to the curve at  $\mathbf{r}(t_0)$ .
- Plot the tangent line together with the curve over the given interval.

35.  $\mathbf{r}(t) = (\sin t - t \cos t)\mathbf{i} + (\cos t + t \sin t)\mathbf{j} + t^2\mathbf{k}$ ,  
 $0 \leq t \leq 6\pi$ ,  $t_0 = 3\pi/2$

36.  $\mathbf{r}(t) = \sqrt{2}t\mathbf{i} + e^t\mathbf{j} + e^{-t}\mathbf{k}$ ,  $-2 \leq t \leq 3$ ,  $t_0 = 1$

37.  $\mathbf{r}(t) = (\sin 2t)\mathbf{i} + (\ln(1+t))\mathbf{j} + t\mathbf{k}$ ,  $0 \leq t \leq 4\pi$ ,  
 $t_0 = \pi/4$

38.  $\mathbf{r}(t) = (\ln(t^2 + 2))\mathbf{i} + (\tan^{-1} 3t)\mathbf{j} + \sqrt{t^2 + 1}\mathbf{k}$ ,  
 $-3 \leq t \leq 5$ ,  $t_0 = 3$

In Exercises 39 and 40, you will explore graphically the behavior of the helix

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

as you change the values of the constants  $a$  and  $b$ . Use a CAS to perform the steps in each exercise.

39. Set  $b = 1$ . Plot the helix  $\mathbf{r}(t)$  together with the tangent line to the curve at  $t = 3\pi/2$  for  $a = 1, 2, 4$ , and  $6$  over the interval  $0 \leq t \leq 4\pi$ . Describe in your own words what happens to the graph of the helix and the position of the tangent line as  $a$  increases through these positive values.
40. Set  $a = 1$ . Plot the helix  $\mathbf{r}(t)$  together with the tangent line to the curve at  $t = 3\pi/2$  for  $b = 1/4, 1/2, 2$ , and  $4$  over the interval  $0 \leq t \leq 4\pi$ . Describe in your own words what happens to the graph of the helix and the position of the tangent line as  $b$  increases through these positive values.



## Exercises 13.2

### Integrating Vector-Valued Functions

Evaluate the integrals in Exercises 1–10.

- $\int_0^1 [t^3 \mathbf{i} + 7\mathbf{j} + (t+1)\mathbf{k}] dt$
- $\int_1^2 \left[ (6-6t)\mathbf{i} + 3\sqrt{t}\mathbf{j} + \left(\frac{4}{t^2}\right)\mathbf{k} \right] dt$
- $\int_{-\pi/4}^{\pi/4} [(\sin t)\mathbf{i} + (1+\cos t)\mathbf{j} + (\sec^2 t)\mathbf{k}] dt$
- $\int_0^{\pi/3} [(\sec t \tan t)\mathbf{i} + (\tan t)\mathbf{j} + (2 \sin t \cos t)\mathbf{k}] dt$
- $\int_1^4 \left[ \frac{1}{t}\mathbf{i} + \frac{1}{5-t}\mathbf{j} + \frac{1}{2t}\mathbf{k} \right] dt$
- $\int_0^1 \left[ \frac{2}{\sqrt{1-t^2}}\mathbf{i} + \frac{\sqrt{3}}{1+t^2}\mathbf{k} \right] dt$
- $\int_0^1 [te^{t^2}\mathbf{i} + e^{-t}\mathbf{j} + \mathbf{k}] dt$
- $\int_1^{\ln 3} [te^t\mathbf{i} + e^t\mathbf{j} + \ln t\mathbf{k}] dt$
- $\int_0^{\pi/2} [\cos t\mathbf{i} - \sin 2t\mathbf{j} + \sin^2 t\mathbf{k}] dt$
- $\int_0^{\pi/4} [\sec t\mathbf{i} + \tan^2 t\mathbf{j} - t \sin t\mathbf{k}] dt$

### Initial Value Problems

Solve the initial value problems in Exercises 11–16 for  $\mathbf{r}$  as a vector function of  $t$ .

- Differential equation:  $\frac{d\mathbf{r}}{dt} = -t\mathbf{i} - t\mathbf{j} - t\mathbf{k}$   
Initial condition:  $\mathbf{r}(0) = \mathbf{i} + 2\mathbf{j} + 3\mathbf{k}$
- Differential equation:  $\frac{d\mathbf{r}}{dt} = (180t)\mathbf{i} + (180t - 16t^2)\mathbf{j}$   
Initial condition:  $\mathbf{r}(0) = 100\mathbf{j}$
- Differential equation:  $\frac{d\mathbf{r}}{dt} = \frac{3}{2}(t+1)^{1/2}\mathbf{i} + e^{-t}\mathbf{j} + \frac{1}{t+1}\mathbf{k}$   
Initial condition:  $\mathbf{r}(0) = \mathbf{k}$
- Differential equation:  $\frac{d\mathbf{r}}{dt} = (t^3 + 4t)\mathbf{i} + t\mathbf{j} + 2t^2\mathbf{k}$   
Initial condition:  $\mathbf{r}(0) = \mathbf{i} + \mathbf{j}$
- Differential equation:  $\frac{d^2\mathbf{r}}{dt^2} = -32\mathbf{k}$   
Initial conditions:  $\mathbf{r}(0) = 100\mathbf{k}$  and  $\left. \frac{d\mathbf{r}}{dt} \right|_{t=0} = 8\mathbf{i} + 8\mathbf{j}$

- Differential equation:  $\frac{d^2\mathbf{r}}{dt^2} = -(\mathbf{i} + \mathbf{j} + \mathbf{k})$   
Initial conditions:  $\mathbf{r}(0) = 10\mathbf{i} + 10\mathbf{j} + 10\mathbf{k}$  and  $\left. \frac{d\mathbf{r}}{dt} \right|_{t=0} = \mathbf{0}$

### Motion Along a Straight Line

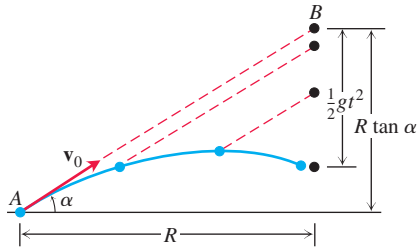
- At time  $t = 0$ , a particle is located at the point  $(1, 2, 3)$ . It travels in a straight line to the point  $(4, 1, 4)$ , has speed 2 at  $(1, 2, 3)$  and constant acceleration  $3\mathbf{i} - \mathbf{j} + \mathbf{k}$ . Find an equation for the position vector  $\mathbf{r}(t)$  of the particle at time  $t$ .
- A particle traveling in a straight line is located at the point  $(1, -1, 2)$  and has speed 2 at time  $t = 0$ . The particle moves toward the point  $(3, 0, 3)$  with constant acceleration  $2\mathbf{i} + \mathbf{j} + \mathbf{k}$ . Find its position vector  $\mathbf{r}(t)$  at time  $t$ .

### Projectile Motion

Projectile flights in the following exercises are to be treated as ideal unless stated otherwise. All launch angles are assumed to be measured from the horizontal. All projectiles are assumed to be launched from the origin over a horizontal surface unless stated otherwise.

- Travel time** A projectile is fired at a speed of 840 m/s at an angle of  $60^\circ$ . How long will it take to get 21 km downrange?
- Range and height versus speed**
  - Show that doubling a projectile's initial speed at a given launch angle multiplies its range by 4.
  - By about what percentage should you increase the initial speed to double the height and range?
- Flight time and height** A projectile is fired with an initial speed of 500 m/s at an angle of elevation of  $45^\circ$ .
  - When and how far away will the projectile strike?
  - How high overhead will the projectile be when it is 5 km downrange?
  - What is the greatest height reached by the projectile?
- Throwing a baseball** A baseball is thrown from the stands 9.8 m above the field at an angle of  $30^\circ$  up from the horizontal. When and how far away will the ball strike the ground if its initial speed is 9.8 m/s?
- Firing golf balls** A spring gun at ground level fires a golf ball at an angle of  $45^\circ$ . The ball lands 10 m away.
  - What was the ball's initial speed?
  - For the same initial speed, find the two firing angles that make the range 6 m.
- Beaming electrons** An electron in a TV tube is beamed horizontally at a speed of  $5 \times 10^6$  m/s toward the face of the tube 40 cm away. About how far will the electron drop before it hits?
- Equal-range firing angles** What two angles of elevation will enable a projectile to reach a target 16 km downrange on the same level as the gun if the projectile's initial speed is 400 m/s?
- Finding muzzle speed** Find the muzzle speed of a gun whose maximum range is 24.5 km.

27. Verify the results given in the text (following Example 4) for the maximum height, flight time, and range for ideal projectile motion.
28. **Colliding marbles** The accompanying figure shows an experiment with two marbles. Marble A was launched toward marble B with launch angle  $\alpha$  and initial speed  $v_0$ . At the same instant, marble B was released to fall from rest at  $R \tan \alpha$  units directly above a spot  $R$  units downrange from A. The marbles were found to collide regardless of the value of  $v_0$ . Was this mere coincidence, or must this happen? Give reasons for your answer.



29. **Firing from  $(x_0, y_0)$**  Derive the equations

$$x = x_0 + (v_0 \cos \alpha)t,$$

$$y = y_0 + (v_0 \sin \alpha)t - \frac{1}{2}gt^2$$

(see Equation (7) in the text) by solving the following initial value problem for a vector  $\mathbf{r}$  in the plane.

Differential equation:  $\frac{d^2 \mathbf{r}}{dt^2} = -g\mathbf{j}$

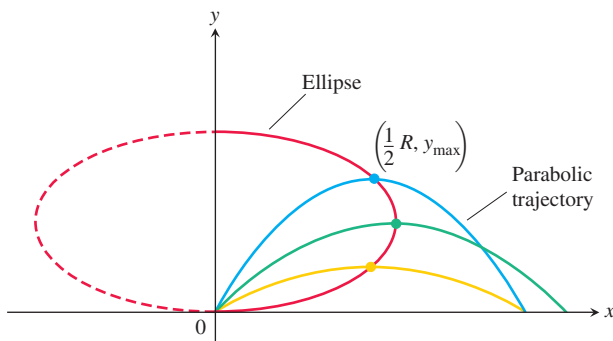
Initial conditions:  $\mathbf{r}(0) = x_0\mathbf{i} + y_0\mathbf{j}$

$$\frac{d\mathbf{r}}{dt}(0) = (v_0 \cos \alpha)\mathbf{i} + (v_0 \sin \alpha)\mathbf{j}$$

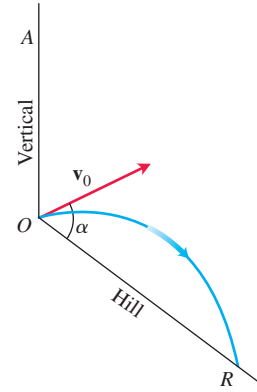
30. **Where trajectories crest** For a projectile fired from the ground at launch angle  $\alpha$  with initial speed  $v_0$ , consider  $\alpha$  as a variable and  $v_0$  as a fixed constant. For each  $\alpha$ ,  $0 < \alpha < \pi/2$ , we obtain a parabolic trajectory as shown in the accompanying figure. Show that the points in the plane that give the maximum heights of these parabolic trajectories all lie on the ellipse

$$x^2 + 4\left(y - \frac{v_0^2}{4g}\right)^2 = \frac{v_0^4}{4g^2},$$

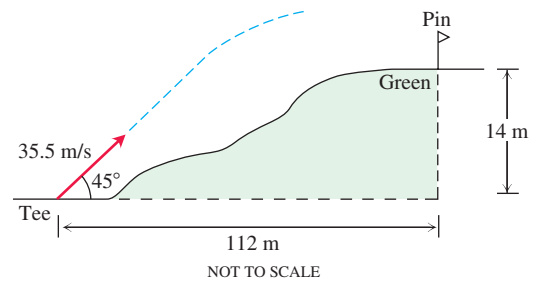
where  $x \geq 0$ .



31. **Launching downhill** An ideal projectile is launched straight down an inclined plane as shown in the accompanying figure.
- Show that the greatest downhill range is achieved when the initial velocity vector bisects angle  $AOR$ .
  - If the projectile were fired uphill instead of down, what launch angle would maximize its range? Give reasons for your answer.

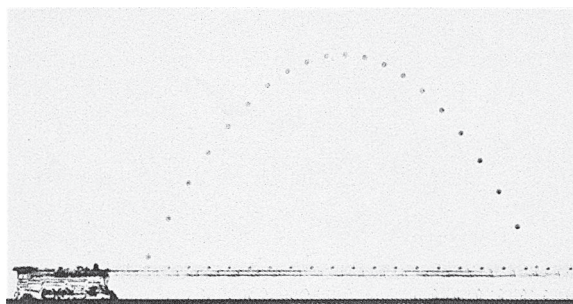


32. **Elevated green** A golf ball is hit with an initial speed of 35.5 m/s at an angle of elevation of  $45^\circ$  from the tee to a green that is elevated 14 m above the tee as shown in the diagram. Assuming that the pin, 112 m downrange, does not get in the way, where will the ball land in relation to the pin?



33. **Volleyball** A volleyball is hit when it is 1.3 m above the ground and 4 m from a 2-m-high net. It leaves the point of impact with an initial velocity of 12 m/s at an angle of  $27^\circ$  and slips by the opposing team untouched.
- Find a vector equation for the path of the volleyball.
  - How high does the volleyball go, and when does it reach maximum height?
  - Find its range and flight time.
  - When is the volleyball 2.3 m above the ground? How far (ground distance) is the volleyball from where it will land?
  - Suppose that the net is raised to 2.5 m. Does this change things? Explain.
34. **Shot put** In Moscow in 1987, Natalya Lisouskaya set a women's world record by putting an 4 kg shot 22.63 m. Assuming that she launched the shot at a  $40^\circ$  angle to the horizontal from 2 m above the ground, what was the shot's initial speed?
35. **Model train** The accompanying multiflash photograph shows a model train engine moving at a constant speed on a straight horizontal track. As the engine moved along, a marble was fired into the air by a spring in the engine's smokestack. The marble, which

continued to move with the same forward speed as the engine, rejoined the engine 1 s after it was fired. Measure the angle the marble's path made with the horizontal and use the information to find how high the marble went and how fast the engine was moving.

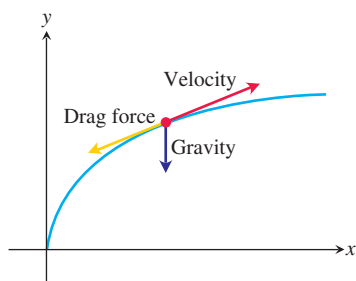


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- 36. Hitting a baseball under a wind gust** A baseball is hit when it is 0.8 m above the ground. It leaves the bat with an initial velocity of 40 m/s at a launch angle of  $23^\circ$ . At the instant the ball is hit, an instantaneous gust of wind blows against the ball, adding a component of  $-4\mathbf{i}$  (m/s) to the ball's initial velocity. A 5-m-high fence lies 90 m from home plate in the direction of the flight.
- Find a vector equation for the path of the baseball.
  - How high does the baseball go, and when does it reach maximum height?
  - Find the range and flight time of the baseball, assuming that the ball is not caught.
  - When is the baseball 6 m high? How far (ground distance) is the baseball from home plate at that height?
  - Has the batter hit a home run? Explain.

### Projectile Motion with Linear Drag

The main force affecting the motion of a projectile, other than gravity, is air resistance. This slowing down force is **drag force**, and it acts in a direction *opposite* to the velocity of the projectile (see accompanying figure). For projectiles moving through the air at relatively low speeds, however, the drag force is (very nearly) proportional to the speed (to the first power) and so is called **linear**.



- 37. Linear drag** Derive the equations

$$x = \frac{v_0}{k} (1 - e^{-kt}) \cos \alpha$$

$$y = \frac{v_0}{k} (1 - e^{-kt}) (\sin \alpha) + \frac{g}{k^2} (1 - kt - e^{-kt})$$

by solving the following initial value problem for a vector  $\mathbf{r}$  in the plane.

$$\text{Differential equation: } \frac{d^2 \mathbf{r}}{dt^2} = -g\mathbf{j} - k\mathbf{v} = -g\mathbf{j} - k \frac{d\mathbf{r}}{dt}$$

$$\text{Initial conditions: } \mathbf{r}(0) = \mathbf{0}$$

$$\left. \frac{d\mathbf{r}}{dt} \right|_{t=0} = \mathbf{v}_0 = (v_0 \cos \alpha)\mathbf{i} + (v_0 \sin \alpha)\mathbf{j}$$

The **drag coefficient**  $k$  is a positive constant representing resistance due to air density,  $v_0$  and  $\alpha$  are the projectile's initial speed and launch angle, and  $g$  is the acceleration of gravity.

- 38. Hitting a baseball with linear drag** Consider the baseball problem in Example 5 when there is linear drag (see Exercise 37). Assume a drag coefficient  $k = 0.12$ , but no gust of wind.
- From Exercise 37, find a vector form for the path of the baseball.
  - How high does the baseball go, and when does it reach maximum height?
  - Find the range and flight time of the baseball.
  - When is the baseball 9 m high? How far (ground distance) is the baseball from home plate at that height?
  - A 3-m-high outfield fence is 115 m from home plate in the direction of the flight of the baseball. The outfielder can jump and catch any ball up to 3.3 m off the ground to stop it from going over the fence. Has the batter hit a home run?

### Theory and Examples

- 39.** Establish the following properties of integrable vector functions.

- a. The *Constant Scalar Multiple Rule*:

$$\int_a^b k\mathbf{r}(t) dt = k \int_a^b \mathbf{r}(t) dt \quad (\text{any scalar } k)$$

The *Rule for Negatives*,

$$\int_a^b (-\mathbf{r}(t)) dt = - \int_a^b \mathbf{r}(t) dt,$$

is obtained by taking  $k = -1$ .

- b. The *Sum and Difference Rules*:

$$\int_a^b (\mathbf{r}_1(t) \pm \mathbf{r}_2(t)) dt = \int_a^b \mathbf{r}_1(t) dt \pm \int_a^b \mathbf{r}_2(t) dt$$

- c. The *Constant Vector Multiple Rules*:

$$\int_a^b \mathbf{C} \cdot \mathbf{r}(t) dt = \mathbf{C} \cdot \int_a^b \mathbf{r}(t) dt \quad (\text{any constant vector } \mathbf{C})$$

and

$$\int_a^b \mathbf{C} \times \mathbf{r}(t) dt = \mathbf{C} \times \int_a^b \mathbf{r}(t) dt \quad (\text{any constant vector } \mathbf{C})$$

**40. Products of scalar and vector functions** Suppose that the scalar function  $u(t)$  and the vector function  $\mathbf{r}(t)$  are both defined for  $a \leq t \leq b$ .

- Show that  $u\mathbf{r}$  is continuous on  $[a, b]$  if  $u$  and  $\mathbf{r}$  are continuous on  $[a, b]$ .
- If  $u$  and  $\mathbf{r}$  are both differentiable on  $[a, b]$ , show that  $u\mathbf{r}$  is differentiable on  $[a, b]$  and that

$$\frac{d}{dt}(u\mathbf{r}) = u \frac{d\mathbf{r}}{dt} + \mathbf{r} \frac{du}{dt}.$$

**41. Antiderivatives of vector functions**

- Use Corollary 2 of the Mean Value Theorem for scalar functions to show that if two vector functions  $\mathbf{R}_1(t)$  and  $\mathbf{R}_2(t)$  have identical derivatives on an interval  $I$ , then the functions differ by a constant vector value throughout  $I$ .
- Use the result in part (a) to show that if  $\mathbf{R}(t)$  is any antiderivative of  $\mathbf{r}(t)$  on  $I$ , then any other antiderivative of  $\mathbf{r}$  on  $I$  equals  $\mathbf{R}(t) + \mathbf{C}$  for some constant vector  $\mathbf{C}$ .

**42. The Fundamental Theorem of Calculus** The Fundamental Theorem of Calculus for scalar functions of a real variable holds for vector functions of a real variable as well. Prove this by using the theorem for scalar functions to show first that if a vector function  $\mathbf{r}(t)$  is continuous for  $a \leq t \leq b$ , then

$$\frac{d}{dt} \int_a^t \mathbf{r}(\tau) d\tau = \mathbf{r}(t)$$

at every point  $t$  of  $(a, b)$ . Then use the conclusion in part (b) of Exercise 41 to show that if  $\mathbf{R}$  is any antiderivative of  $\mathbf{r}$  on  $[a, b]$  then

$$\int_a^b \mathbf{r}(t) dt = \mathbf{R}(b) - \mathbf{R}(a).$$

**43. Hitting a baseball with linear drag under a wind gust** Consider again the baseball problem in Example 5. This time assume a drag coefficient of 0.08 and an instantaneous gust of wind that adds a component of  $-5\mathbf{i}$  (m/s) to the initial velocity at the instant the baseball is hit.

- Find a vector equation for the path of the baseball.
- How high does the baseball go, and when does it reach maximum height?
- Find the range and flight time of the baseball.
- When is the baseball 10 m high? How far (ground distance) is the baseball from home plate at that height?
- A 6-m-high outfield fence is 120 m from home plate in the direction of the flight of the baseball. Has the batter hit a home run? If “yes,” what change in the horizontal component of the ball’s initial velocity would have kept the ball in the park? If “no,” what change would have allowed it to be a home run?

**44. Height versus time** Show that a projectile attains three-quarters of its maximum height in half the time it takes to reach the maximum height.

## Exercises 13.3

### Finding Tangent Vectors and Lengths

In Exercises 1–8, find the curve's unit tangent vector. Also, find the length of the indicated portion of the curve.

- $\mathbf{r}(t) = (2 \cos t)\mathbf{i} + (2 \sin t)\mathbf{j} + \sqrt{5}t\mathbf{k}, \quad 0 \leq t \leq \pi$
- $\mathbf{r}(t) = (6 \sin 2t)\mathbf{i} + (6 \cos 2t)\mathbf{j} + 5t\mathbf{k}, \quad 0 \leq t \leq \pi$
- $\mathbf{r}(t) = t\mathbf{i} + (2/3)t^{3/2}\mathbf{k}, \quad 0 \leq t \leq 8$
- $\mathbf{r}(t) = (2 + t)\mathbf{i} - (t + 1)\mathbf{j} + t\mathbf{k}, \quad 0 \leq t \leq 3$
- $\mathbf{r}(t) = (\cos^3 t)\mathbf{j} + (\sin^3 t)\mathbf{k}, \quad 0 \leq t \leq \pi/2$
- $\mathbf{r}(t) = 6t^3\mathbf{i} - 2t^3\mathbf{j} - 3t^3\mathbf{k}, \quad 1 \leq t \leq 2$
- $\mathbf{r}(t) = (t \cos t)\mathbf{i} + (t \sin t)\mathbf{j} + (2\sqrt{2}/3)t^{3/2}\mathbf{k}, \quad 0 \leq t \leq \pi$
- $\mathbf{r}(t) = (t \sin t + \cos t)\mathbf{i} + (t \cos t - \sin t)\mathbf{j}, \quad \sqrt{2} \leq t \leq 2$
- Find the point on the curve

$$\mathbf{r}(t) = (5 \sin t)\mathbf{i} + (5 \cos t)\mathbf{j} + 12t\mathbf{k}$$

at a distance  $26\pi$  units along the curve from the point  $(0, 5, 0)$  in the direction of increasing arc length.

- Find the point on the curve

$$\mathbf{r}(t) = (12 \sin t)\mathbf{i} - (12 \cos t)\mathbf{j} + 5t\mathbf{k}$$

at a distance  $13\pi$  units along the curve from the point  $(0, -12, 0)$  in the direction opposite to the direction of increasing arc length.

### Arc Length Parameter

In Exercises 11–14, find the arc length parameter along the curve from the point where  $t = 0$  by evaluating the integral

$$s = \int_0^t |\mathbf{v}(\tau)| d\tau$$

from Equation (3). Then find the length of the indicated portion of the curve.

- $\mathbf{r}(t) = (4 \cos t)\mathbf{i} + (4 \sin t)\mathbf{j} + 3t\mathbf{k}, \quad 0 \leq t \leq \pi/2$
- $\mathbf{r}(t) = (\cos t + t \sin t)\mathbf{i} + (\sin t - t \cos t)\mathbf{j}, \quad \pi/2 \leq t \leq \pi$
- $\mathbf{r}(t) = (e^t \cos t)\mathbf{i} + (e^t \sin t)\mathbf{j} + e^t\mathbf{k}, \quad -\ln 4 \leq t \leq 0$
- $\mathbf{r}(t) = (1 + 2t)\mathbf{i} + (1 + 3t)\mathbf{j} + (6 - 6t)\mathbf{k}, \quad -1 \leq t \leq 0$

## Theory and Examples

- 15.
- Arc length**
- Find the length of the curve

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

from  $(0, 0, 1)$  to  $(\sqrt{2}, \sqrt{2}, 0)$ .

- 16.
- Length of helix**
- The length
- $2\pi\sqrt{2}$
- of the turn of the helix in Example 1 is also the length of the diagonal of a square
- $2\pi$
- units on a side. Show how to obtain this square by cutting away and flattening a portion of the cylinder around which the helix winds.

17. **Ellipse**

- Show that the curve  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} + (1 - \cos t)\mathbf{k}$ ,  $0 \leq t \leq 2\pi$ , is an ellipse by showing that it is the intersection of a right circular cylinder and a plane. Find equations for the cylinder and plane.
- Sketch the ellipse on the cylinder. Add to your sketch the unit tangent vectors at  $t = 0, \pi/2, \pi$ , and  $3\pi/2$ .
- Show that the acceleration vector always lies parallel to the plane (orthogonal to a vector normal to the plane). Thus, if you draw the acceleration as a vector attached to the ellipse, it will lie in the plane of the ellipse. Add the acceleration vectors for  $t = 0, \pi/2, \pi$ , and  $3\pi/2$  to your sketch.
- Write an integral for the length of the ellipse. Do not try to evaluate the integral; it is nonelementary.

- T** e. **Numerical integrator** Estimate the length of the ellipse to two decimal places.

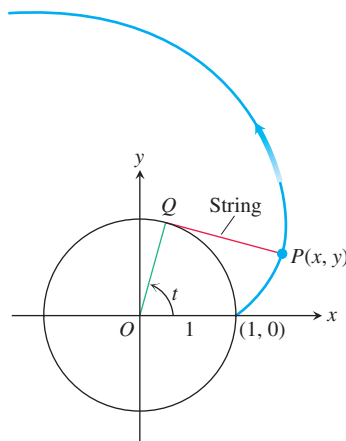
- 18.
- Length is independent of parametrization**
- To illustrate that the length of a smooth space curve does not depend on the parametrization you use to compute it, calculate the length of one turn of the helix in Example 1 with the following parametrizations.

- $\mathbf{r}(t) = (\cos 4t)\mathbf{i} + (\sin 4t)\mathbf{j} + 4t\mathbf{k}$ ,  $0 \leq t \leq \pi/2$
- $\mathbf{r}(t) = [\cos(t/2)]\mathbf{i} + [\sin(t/2)]\mathbf{j} + (t/2)\mathbf{k}$ ,  $0 \leq t \leq 4\pi$
- $\mathbf{r}(t) = (\cos t)\mathbf{i} - (\sin t)\mathbf{j} - t\mathbf{k}$ ,  $-2\pi \leq t \leq 0$

- 19.
- The involute of a circle**
- If a string wound around a fixed circle is unwound while held taut in the plane of the circle, its end
- $P$
- traces an
- involute*
- of the circle. In the accompanying figure, the circle in question is the circle
- $x^2 + y^2 = 1$
- and the tracing point starts at
- $(1, 0)$
- . The unwound portion of the string is tangent to the circle at
- $Q$
- , and
- $t$
- is the radian measure of the angle from the positive
- $x$
- axis to segment
- $OQ$
- . Derive the parametric equations

$$x = \cos t + t \sin t, \quad y = \sin t - t \cos t, \quad t > 0$$

of the point  $P(x, y)$  for the involute.



- (Continuation of Exercise 19.) Find the unit tangent vector to the involute of the circle at the point  $P(x, y)$ .
- Distance along a line** Show that if  $\mathbf{u}$  is a unit vector, then the arc length parameter along the line  $\mathbf{r}(t) = P_0 + t\mathbf{u}$  from the point  $P_0(x_0, y_0, z_0)$  where  $t = 0$ , is  $t$  itself.
- Use Simpson's Rule with  $n = 10$  to approximate the length of arc of  $\mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j} + t^3\mathbf{k}$  from the origin to the point  $(2, 4, 8)$ .

## Exercises 13.4

### Plane Curves

Find  $\mathbf{T}$ ,  $\mathbf{N}$ , and  $\kappa$  for the plane curves in Exercises 1–4.

- $\mathbf{r}(t) = t\mathbf{i} + (\ln \cos t)\mathbf{j}$ ,  $-\pi/2 < t < \pi/2$
- $\mathbf{r}(t) = (\ln \sec t)\mathbf{i} + t\mathbf{j}$ ,  $-\pi/2 < t < \pi/2$
- $\mathbf{r}(t) = (2t + 3)\mathbf{i} + (5 - t^2)\mathbf{j}$
- $\mathbf{r}(t) = (\cos t + t \sin t)\mathbf{i} + (\sin t - t \cos t)\mathbf{j}$ ,  $t > 0$
- A formula for the curvature of the graph of a function in the  $xy$ -plane**

- The graph  $y = f(x)$  in the  $xy$ -plane automatically has the parametrization  $x = x$ ,  $y = f(x)$ , and the vector formula  $\mathbf{r}(x) = x\mathbf{i} + f(x)\mathbf{j}$ . Use this formula to show that if  $f$  is a twice-differentiable function of  $x$ , then

$$\kappa(x) = \frac{|f''(x)|}{[1 + (f'(x))^2]^{3/2}}.$$

- Use the formula for  $\kappa$  in part (a) to find the curvature of  $y = \ln(\cos x)$ ,  $-\pi/2 < x < \pi/2$ . Compare your answer with the answer in Exercise 1.
  - Show that the curvature is zero at a point of inflection.
- A formula for the curvature of a parametrized plane curve**
  - Show that the curvature of a smooth curve  $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j}$  defined by twice-differentiable functions  $x = f(t)$  and  $y = g(t)$  is given by the formula

$$\kappa = \frac{|\dot{x}\ddot{y} - \dot{y}\ddot{x}|}{(\dot{x}^2 + \dot{y}^2)^{3/2}}.$$

The dots in the formula denote differentiation with respect to  $t$ , one derivative for each dot. Apply the formula to find the curvatures of the following curves.

- $\mathbf{r}(t) = t\mathbf{i} + (\ln \sin t)\mathbf{j}$ ,  $0 < t < \pi$
- $\mathbf{r}(t) = [\tan^{-1}(\sinh t)]\mathbf{i} + (\ln \cosh t)\mathbf{j}$

### 7. Normals to plane curves

- Show that  $\mathbf{n}(t) = -g'(t)\mathbf{i} + f'(t)\mathbf{j}$  and  $-\mathbf{n}(t) = g'(t)\mathbf{i} - f'(t)\mathbf{j}$  are both normal to the curve  $\mathbf{r}(t) = f(t)\mathbf{i} + g(t)\mathbf{j}$  at the point  $(f(t), g(t))$ .

To obtain  $\mathbf{N}$  for a particular plane curve, we can choose the one of  $\mathbf{n}$  or  $-\mathbf{n}$  from part (a) that points toward the concave side of the curve, and make it into a unit vector. (See Figure 13.19.) Apply this method to find  $\mathbf{N}$  for the following curves.

- $\mathbf{r}(t) = t\mathbf{i} + e^{2t}\mathbf{j}$
- $\mathbf{r}(t) = \sqrt{4 - t^2}\mathbf{i} + t\mathbf{j}$ ,  $-2 \leq t \leq 2$

### 8. (Continuation of Exercise 7.)

- Use the method of Exercise 7 to find  $\mathbf{N}$  for the curve  $\mathbf{r}(t) = t\mathbf{i} + (1/3)t^3\mathbf{j}$  when  $t < 0$ ; when  $t > 0$ .
- Calculate  $\mathbf{N}$  for  $t \neq 0$  directly from  $\mathbf{T}$  using Equation (4) for the curve in part (a). Does  $\mathbf{N}$  exist at  $t = 0$ ? Graph the curve and explain what is happening to  $\mathbf{N}$  as  $t$  passes from negative to positive values.

### Space Curves

Find  $\mathbf{T}$ ,  $\mathbf{N}$ , and  $\kappa$  for the space curves in Exercises 9–16.

- $\mathbf{r}(t) = (3 \sin t)\mathbf{i} + (3 \cos t)\mathbf{j} + 4t\mathbf{k}$
- $\mathbf{r}(t) = (\cos t + t \sin t)\mathbf{i} + (\sin t - t \cos t)\mathbf{j} + 3t\mathbf{k}$
- $\mathbf{r}(t) = (e^t \cos t)\mathbf{i} + (e^t \sin t)\mathbf{j} + 2t\mathbf{k}$
- $\mathbf{r}(t) = (6 \sin 2t)\mathbf{i} + (6 \cos 2t)\mathbf{j} + 5t\mathbf{k}$
- $\mathbf{r}(t) = (t^3/3)\mathbf{i} + (t^2/2)\mathbf{j}$ ,  $t > 0$
- $\mathbf{r}(t) = (\cos^3 t)\mathbf{i} + (\sin^3 t)\mathbf{j}$ ,  $0 < t < \pi/2$
- $\mathbf{r}(t) = t\mathbf{i} + (a \cosh(t/a))\mathbf{j}$ ,  $a > 0$
- $\mathbf{r}(t) = (\cosh t)\mathbf{i} - (\sinh t)\mathbf{j} + t\mathbf{k}$

### More on Curvature

- Show that the parabola  $y = ax^2$ ,  $a \neq 0$ , has its largest curvature at its vertex and has no minimum curvature. (Note: Since the curvature of a curve remains the same if the curve is translated or rotated, this result is true for any parabola.)

18. Show that the ellipse  $x = a \cos t$ ,  $y = b \sin t$ ,  $a > b > 0$ , has its largest curvature on its major axis and its smallest curvature on its minor axis. (As in Exercise 17, the same is true for any ellipse.)
19. **Maximizing the curvature of a helix** In Example 5, we found the curvature of the helix  $\mathbf{r}(t) = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j} + b t\mathbf{k}$  ( $a, b \geq 0$ ) to be  $\kappa = a/(a^2 + b^2)$ . What is the largest value  $\kappa$  can have for a given value of  $b$ ? Give reasons for your answer.
20. **Total curvature** We find the **total curvature** of the portion of a smooth curve that runs from  $s = s_0$  to  $s = s_1 > s_0$  by integrating  $\kappa$  from  $s_0$  to  $s_1$ . If the curve has some other parameter, say  $t$ , then the total curvature is

$$K = \int_{s_0}^{s_1} \kappa \, ds = \int_{t_0}^{t_1} \kappa \frac{ds}{dt} dt = \int_{t_0}^{t_1} \kappa |\mathbf{v}| \, dt,$$

where  $t_0$  and  $t_1$  correspond to  $s_0$  and  $s_1$ . Find the total curvatures of

- a. The portion of the helix  $\mathbf{r}(t) = (3 \cos t)\mathbf{i} + (3 \sin t)\mathbf{j} + t\mathbf{k}$ ,  $0 \leq t \leq 4\pi$ .
- b. The parabola  $y = x^2$ ,  $-\infty < x < \infty$ .
21. Find an equation for the circle of curvature of the curve  $\mathbf{r}(t) = t\mathbf{i} + (\sin t)\mathbf{j}$  at the point  $(\pi/2, 1)$ . (The curve parametrizes the graph of  $y = \sin x$  in the  $xy$ -plane.)
22. Find an equation for the circle of curvature of the curve  $\mathbf{r}(t) = (2 \ln t)\mathbf{i} - [t + (1/t)]\mathbf{j}$ ,  $e^{-2} \leq t \leq e^2$ , at the point  $(0, -2)$ , where  $t = 1$ .

**T** The formula

$$\kappa(x) = \frac{|f''(x)|}{[1 + (f'(x))^2]^{3/2}},$$

derived in Exercise 5, expresses the curvature  $\kappa(x)$  of a twice-differentiable plane curve  $y = f(x)$  as a function of  $x$ . Find the curvature function of each of the curves in Exercises 23–26. Then graph  $f(x)$  together with  $\kappa(x)$  over the given interval. You will find some surprises.

23.  $y = x^2$ ,  $-2 \leq x \leq 2$       24.  $y = x^4/4$ ,  $-2 \leq x \leq 2$
25.  $y = \sin x$ ,  $0 \leq x \leq 2\pi$       26.  $y = e^x$ ,  $-1 \leq x \leq 2$
27. **Osculating circle** Show that the center of the osculating circle for the parabola  $y = x^2$  at the point  $(a, a^2)$  is located at  $\left(-4a^3, 3a^2 + \frac{1}{2}\right)$ .

28. **Osculating circle** Find a parametrization of the osculating circle for the parabola  $y = x^2$  when  $x = 1$ .

### COMPUTER EXPLORATIONS

In Exercises 29–36 you will use a CAS to explore the osculating circle at a point  $P$  on a plane curve where  $\kappa \neq 0$ . Use a CAS to perform the following steps:

- a. Plot the plane curve given in parametric or function form over the specified interval to see what it looks like.
- b. Calculate the curvature  $\kappa$  of the curve at the given value  $t_0$  using the appropriate formula from Exercise 5 or 6. Use the parametrization  $x = t$  and  $y = f(t)$  if the curve is given as a function  $y = f(x)$ .
- c. Find the unit normal vector  $\mathbf{N}$  at  $t_0$ . Notice that the signs of the components of  $\mathbf{N}$  depend on whether the unit tangent vector  $\mathbf{T}$  is turning clockwise or counterclockwise at  $t = t_0$ . (See Exercise 7.)
- d. If  $\mathbf{C} = a\mathbf{i} + b\mathbf{j}$  is the vector from the origin to the center  $(a, b)$  of the osculating circle, find the center  $\mathbf{C}$  from the vector equation

$$\mathbf{C} = \mathbf{r}(t_0) + \frac{1}{\kappa(t_0)}\mathbf{N}(t_0).$$

The point  $P(x_0, y_0)$  on the curve is given by the position vector  $\mathbf{r}(t_0)$ .

- e. Plot implicitly the equation  $(x - a)^2 + (y - b)^2 = 1/\kappa^2$  of the osculating circle. Then plot the curve and osculating circle together. You may need to experiment with the size of the viewing window, but be sure the axes are equally scaled.
29.  $\mathbf{r}(t) = (3 \cos t)\mathbf{i} + (5 \sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$ ,  $t_0 = \pi/4$
30.  $\mathbf{r}(t) = (\cos^3 t)\mathbf{i} + (\sin^3 t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$ ,  $t_0 = \pi/4$
31.  $\mathbf{r}(t) = t^2\mathbf{i} + (t^3 - 3t)\mathbf{j}$ ,  $-4 \leq t \leq 4$ ,  $t_0 = 3/5$
32.  $\mathbf{r}(t) = (t^3 - 2t^2 - t)\mathbf{i} + \frac{3t}{\sqrt{1+t^2}}\mathbf{j}$ ,  $-2 \leq t \leq 5$ ,  $t_0 = 1$
33.  $\mathbf{r}(t) = (2t - \sin t)\mathbf{i} + (2 - 2 \cos t)\mathbf{j}$ ,  $0 \leq t \leq 3\pi$ ,  $t_0 = 3\pi/2$
34.  $\mathbf{r}(t) = (e^{-t} \cos t)\mathbf{i} + (e^{-t} \sin t)\mathbf{j}$ ,  $0 \leq t \leq 6\pi$ ,  $t_0 = \pi/4$
35.  $y = x^2 - x$ ,  $-2 \leq x \leq 5$ ,  $x_0 = 1$
36.  $y = x(1 - x)^{2/5}$ ,  $-1 \leq x \leq 2$ ,  $x_0 = 1/2$



# Exercises 14.1

## Domain, Range, and Level Curves

In Exercises 1–4, find the specific function values.

1.  $f(x, y) = x^2 + xy^3$ 
  - a.  $f(0, 0)$
  - b.  $f(-1, 1)$
  - c.  $f(2, 3)$
  - d.  $f(-3, -2)$
2.  $f(x, y) = \sin(xy)$ 
  - a.  $f\left(2, \frac{\pi}{6}\right)$
  - b.  $f\left(-3, \frac{\pi}{12}\right)$
  - c.  $f\left(\pi, \frac{1}{4}\right)$
  - d.  $f\left(-\frac{\pi}{2}, -7\right)$
3.  $f(x, y, z) = \frac{x - y}{y^2 + z^2}$ 
  - a.  $f(3, -1, 2)$
  - b.  $f\left(1, \frac{1}{2}, -\frac{1}{4}\right)$
  - c.  $f\left(0, -\frac{1}{3}, 0\right)$
  - d.  $f(2, 2, 100)$
4.  $f(x, y, z) = \sqrt{49 - x^2 - y^2 - z^2}$ 
  - a.  $f(0, 0, 0)$
  - b.  $f(2, -3, 6)$
  - c.  $f(-1, 2, 3)$
  - d.  $f\left(\frac{4}{\sqrt{2}}, \frac{5}{\sqrt{2}}, \frac{6}{\sqrt{2}}\right)$

In Exercises 5–12, find and sketch the domain for each function.

5.  $f(x, y) = \sqrt{y - x - 2}$
6.  $f(x, y) = \ln(x^2 + y^2 - 4)$
7.  $f(x, y) = \frac{(x - 1)(y + 2)}{(y - x)(y - x^3)}$
8.  $f(x, y) = \frac{\sin(xy)}{x^2 + y^2 - 25}$
9.  $f(x, y) = \cos^{-1}(y - x^2)$
10.  $f(x, y) = \ln(xy + x - y - 1)$
11.  $f(x, y) = \sqrt{(x^2 - 4)(y^2 - 9)}$
12.  $f(x, y) = \frac{1}{\ln(4 - x^2 - y^2)}$

In Exercises 13–16, find and sketch the level curves  $f(x, y) = c$  on the same set of coordinate axes for the given values of  $c$ . We refer to these level curves as a contour map.

13.  $f(x, y) = x + y - 1$ ,  $c = -3, -2, -1, 0, 1, 2, 3$
14.  $f(x, y) = x^2 + y^2$ ,  $c = 0, 1, 4, 9, 16, 25$
15.  $f(x, y) = xy$ ,  $c = -9, -4, -1, 0, 1, 4, 9$
16.  $f(x, y) = \sqrt{25 - x^2 - y^2}$ ,  $c = 0, 1, 2, 3, 4$

In Exercises 17–30, (a) find the function's domain, (b) find the function's range, (c) describe the function's level curves, (d) find the boundary of the function's domain, (e) determine if the domain is an open region, a closed region, or neither, and (f) decide if the domain is bounded or unbounded.

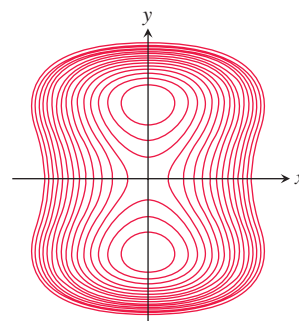
17.  $f(x, y) = y - x$
18.  $f(x, y) = \sqrt{y - x}$
19.  $f(x, y) = 4x^2 + 9y^2$
20.  $f(x, y) = x^2 - y^2$

21.  $f(x, y) = xy$
22.  $f(x, y) = y/x^2$
23.  $f(x, y) = \frac{1}{\sqrt{16 - x^2 - y^2}}$
24.  $f(x, y) = \sqrt{9 - x^2 - y^2}$
25.  $f(x, y) = \ln(x^2 + y^2)$
26.  $f(x, y) = e^{-(x^2 + y^2)}$
27.  $f(x, y) = \sin^{-1}(y - x)$
28.  $f(x, y) = \tan^{-1}\left(\frac{y}{x}\right)$
29.  $f(x, y) = \ln(x^2 + y^2 - 1)$
30.  $f(x, y) = \ln(9 - x^2 - y^2)$

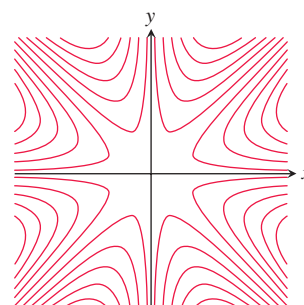
## Matching Surfaces with Level Curves

Exercises 31–36 show level curves for the functions graphed in (a)–(f) on the following page. Match each set of curves with the appropriate function.

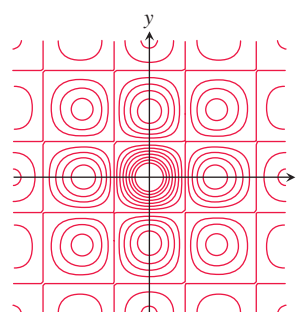
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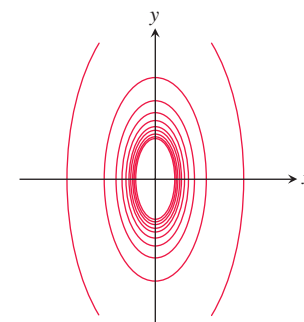
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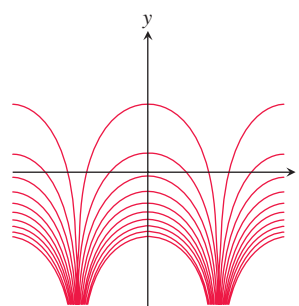
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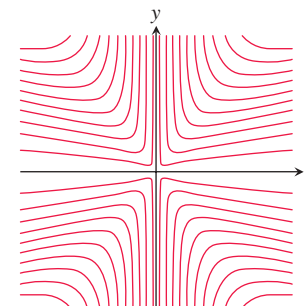
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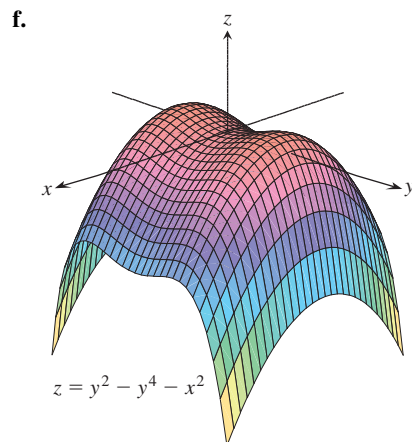
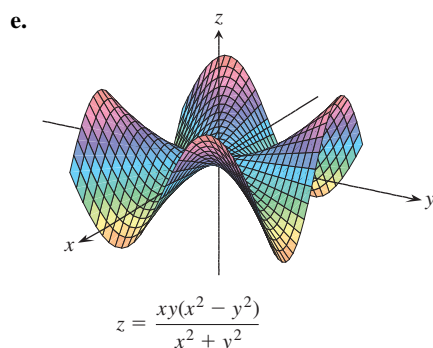
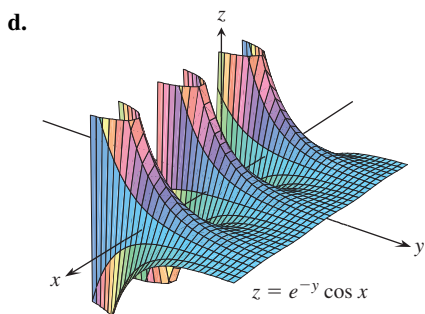
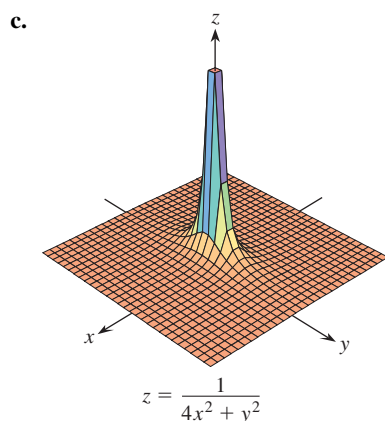
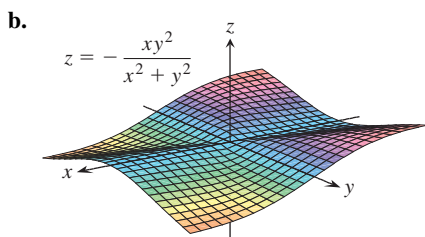
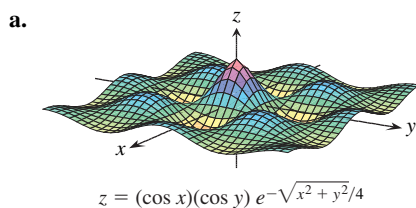


35.



36.





### Functions of Two Variables

Display the values of the functions in Exercises 37–48 in two ways: (a) by sketching the surface  $z = f(x, y)$  and (b) by drawing an assortment of level curves in the function's domain. Label each level curve with its function value.

- |                                      |                                      |
|--------------------------------------|--------------------------------------|
| 37. $f(x, y) = y^2$                  | 38. $f(x, y) = \sqrt{x}$             |
| 39. $f(x, y) = x^2 + y^2$            | 40. $f(x, y) = \sqrt{x^2 + y^2}$     |
| 41. $f(x, y) = x^2 - y$              | 42. $f(x, y) = 4 - x^2 - y^2$        |
| 43. $f(x, y) = 4x^2 + y^2$           | 44. $f(x, y) = 6 - 2x - 3y$          |
| 45. $f(x, y) = 1 -  y $              | 46. $f(x, y) = 1 -  x  -  y $        |
| 47. $f(x, y) = \sqrt{x^2 + y^2} + 4$ | 48. $f(x, y) = \sqrt{x^2 + y^2} - 4$ |

### Finding Level Curves

In Exercises 49–52, find an equation for and sketch the graph of the level curve of the function  $f(x, y)$  that passes through the given point.

49.  $f(x, y) = 16 - x^2 - y^2$ ,  $(2\sqrt{2}, \sqrt{2})$   
 50.  $f(x, y) = \sqrt{x^2 - 1}$ ,  $(1, 0)$   
 51.  $f(x, y) = \sqrt{x + y^2 - 3}$ ,  $(3, -1)$   
 52.  $f(x, y) = \frac{2y - x}{x + y + 1}$ ,  $(-1, 1)$

### Sketching Level Surfaces

In Exercises 53–60, sketch a typical level surface for the function.

53.  $f(x, y, z) = x^2 + y^2 + z^2$     54.  $f(x, y, z) = \ln(x^2 + y^2 + z^2)$   
 55.  $f(x, y, z) = x + z$     56.  $f(x, y, z) = z$   
 57.  $f(x, y, z) = x^2 + y^2$     58.  $f(x, y, z) = y^2 + z^2$   
 59.  $f(x, y, z) = z - x^2 - y^2$   
 60.  $f(x, y, z) = (x^2/25) + (y^2/16) + (z^2/9)$

### Finding Level Surfaces

In Exercises 61–64, find an equation for the level surface of the function through the given point.

61.  $f(x, y, z) = \sqrt{x - y} - \ln z$ ,  $(3, -1, 1)$   
 62.  $f(x, y, z) = \ln(x^2 + y + z^2)$ ,  $(-1, 2, 1)$

$$63. g(x, y, z) = \sqrt{x^2 + y^2 + z^2}, \quad (1, -1, \sqrt{2})$$

$$64. g(x, y, z) = \frac{x - y + z}{2x + y - z}, \quad (1, 0, -2)$$

In Exercises 65–68, find and sketch the domain of  $f$ . Then find an equation for the level curve or surface of the function passing through the given point.

$$65. f(x, y) = \sum_{n=0}^{\infty} \left(\frac{x}{y}\right)^n, \quad (1, 2)$$

$$66. g(x, y, z) = \sum_{n=0}^{\infty} \frac{(x + y)^n}{n!z^n}, \quad (\ln 4, \ln 9, 2)$$

$$67. f(x, y) = \int_x^y \frac{d\theta}{\sqrt{1 - \theta^2}}, \quad (0, 1)$$

$$68. g(x, y, z) = \int_x^y \frac{dt}{1 + t^2} + \int_0^z \frac{d\theta}{\sqrt{4 - \theta^2}}, \quad (0, 1, \sqrt{3})$$

### COMPUTER EXPLORATIONS

Use a CAS to perform the following steps for each of the functions in Exercises 69–72.

a. Plot the surface over the given rectangle.

b. Plot several level curves in the rectangle.

c. Plot the level curve of  $f$  through the given point.

$$69. f(x, y) = x \sin \frac{y}{2} + y \sin 2x, \quad 0 \leq x \leq 5\pi, \quad 0 \leq y \leq 5\pi, \quad P(3\pi, 3\pi)$$

$$70. f(x, y) = (\sin x)(\cos y)e^{\sqrt{x^2 + y^2}/8}, \quad 0 \leq x \leq 5\pi, \quad 0 \leq y \leq 5\pi, \quad P(4\pi, 4\pi)$$

$$71. f(x, y) = \sin(x + 2 \cos y), \quad -2\pi \leq x \leq 2\pi, \quad -2\pi \leq y \leq 2\pi, \quad P(\pi, \pi)$$

$$72. f(x, y) = e^{(x^{0.1} - y)} \sin(x^2 + y^2), \quad 0 \leq x \leq 2\pi, \quad -2\pi \leq y \leq \pi, \quad P(\pi, -\pi)$$

Use a CAS to plot the implicitly defined level surfaces in Exercises 73–76.

$$73. 4 \ln(x^2 + y^2 + z^2) = 1 \quad 74. x^2 + z^2 = 1$$

$$75. x + y^2 - 3z^2 = 1$$

$$76. \sin\left(\frac{x}{2}\right) - (\cos y)\sqrt{x^2 + z^2} = 2$$

**Parametrized Surfaces** Just as you describe curves in the plane parametrically with a pair of equations  $x = f(t)$ ,  $y = g(t)$  defined on some parameter interval  $I$ , you can sometimes describe surfaces in space with a triple of equations  $x = f(u, v)$ ,  $y = g(u, v)$ ,  $z = h(u, v)$  defined on some parameter rectangle  $a \leq u \leq b$ ,  $c \leq v \leq d$ . Many computer algebra systems permit you to plot such surfaces in *parametric mode*. (Parametrized surfaces are discussed in detail in Section 16.5.) Use a CAS to plot the surfaces in Exercises 77–80. Also plot several level curves in the  $xy$ -plane.

$$77. x = u \cos v, \quad y = u \sin v, \quad z = u, \quad 0 \leq u \leq 2, \quad 0 \leq v \leq 2\pi$$

$$78. x = u \cos v, \quad y = u \sin v, \quad z = v, \quad 0 \leq u \leq 2, \quad 0 \leq v \leq 2\pi$$

$$79. x = (2 + \cos u) \cos v, \quad y = (2 + \cos u) \sin v, \quad z = \sin u, \quad 0 \leq u \leq 2\pi, \quad 0 \leq v \leq 2\pi$$

$$80. x = 2 \cos u \cos v, \quad y = 2 \cos u \sin v, \quad z = 2 \sin u, \quad 0 \leq u \leq 2\pi, \quad 0 \leq v \leq \pi$$

**Exercises 14.2****Limits with Two Variables**

Find the limits in Exercises 1–12.

1.  $\lim_{(x,y) \rightarrow (0,0)} \frac{3x^2 - y^2 + 5}{x^2 + y^2 + 2}$

2.  $\lim_{(x,y) \rightarrow (0,4)} \frac{x}{\sqrt{y}}$

3.  $\lim_{(x,y) \rightarrow (3,4)} \sqrt{x^2 + y^2 - 1}$

4.  $\lim_{(x,y) \rightarrow (2,-3)} \left( \frac{1}{x} + \frac{1}{y} \right)^2$

5.  $\lim_{(x,y) \rightarrow (0,\pi/4)} \sec x \tan y$

6.  $\lim_{(x,y) \rightarrow (0,0)} \cos \frac{x^2 + y^3}{x + y + 1}$

7.  $\lim_{(x,y) \rightarrow (0, \ln 2)} e^{x-y}$       8.  $\lim_{(x,y) \rightarrow (1,1)} \ln |1 + x^2 y^2|$
9.  $\lim_{(x,y) \rightarrow (0,0)} \frac{e^y \sin x}{x}$       10.  $\lim_{(x,y) \rightarrow (1/27, \pi^3)} \cos \sqrt[3]{xy}$
11.  $\lim_{(x,y) \rightarrow (1, \pi/6)} \frac{x \sin y}{x^2 + 1}$       12.  $\lim_{(x,y) \rightarrow (\pi/2, 0)} \frac{\cos y + 1}{y - \sin x}$

**Limits of Quotients**

Find the limits in Exercises 13–24 by rewriting the fractions first.

13.  $\lim_{\substack{(x,y) \rightarrow (1,1) \\ x \neq y}} \frac{x^2 - 2xy + y^2}{x - y}$       14.  $\lim_{\substack{(x,y) \rightarrow (1,1) \\ x \neq y}} \frac{x^2 - y^2}{x - y}$
15.  $\lim_{\substack{(x,y) \rightarrow (1,1) \\ x \neq 1}} \frac{xy - y - 2x + 2}{x - 1}$
16.  $\lim_{\substack{(x,y) \rightarrow (2,-4) \\ x \neq -4, x \neq x^2}} \frac{y + 4}{x^2 y - xy + 4x^2 - 4x}$
17.  $\lim_{\substack{(x,y) \rightarrow (0,0) \\ x \neq y}} \frac{x - y + 2\sqrt{x} - 2\sqrt{y}}{\sqrt{x} - \sqrt{y}}$
18.  $\lim_{\substack{(x,y) \rightarrow (2,2) \\ x+y \neq 4}} \frac{x + y - 4}{\sqrt{x} + y - 2}$       19.  $\lim_{\substack{(x,y) \rightarrow (2,0) \\ 2x-y \neq 4}} \frac{\sqrt{2x} - y - 2}{2x - y - 4}$
20.  $\lim_{\substack{(x,y) \rightarrow (4,3) \\ x \neq y+1}} \frac{\sqrt{x} - \sqrt{y+1}}{x - y - 1}$
21.  $\lim_{(x,y) \rightarrow (0,0)} \frac{\sin(x^2 + y^2)}{x^2 + y^2}$       22.  $\lim_{(x,y) \rightarrow (0,0)} \frac{1 - \cos(xy)}{xy}$
23.  $\lim_{(x,y) \rightarrow (1,-1)} \frac{x^3 + y^3}{x + y}$       24.  $\lim_{(x,y) \rightarrow (2,2)} \frac{x - y}{x^4 - y^4}$

**Limits with Three Variables**

Find the limits in Exercises 25–30.

25.  $\lim_{P \rightarrow (1,3,4)} \left( \frac{1}{x} + \frac{1}{y} + \frac{1}{z} \right)$       26.  $\lim_{P \rightarrow (1,-1,-1)} \frac{2xy + yz}{x^2 + z^2}$
27.  $\lim_{P \rightarrow (\pi, \pi, 0)} (\sin^2 x + \cos^2 y + \sec^2 z)$
28.  $\lim_{P \rightarrow (-1/4, \pi/2, 2)} \tan^{-1} xyz$       29.  $\lim_{P \rightarrow (\pi, 0, 3)} ze^{-2y} \cos 2x$
30.  $\lim_{P \rightarrow (2, -3, 6)} \ln \sqrt{x^2 + y^2 + z^2}$

**Continuity for Two Variables**At what points  $(x, y)$  in the plane are the functions in Exercises 31–34 continuous?

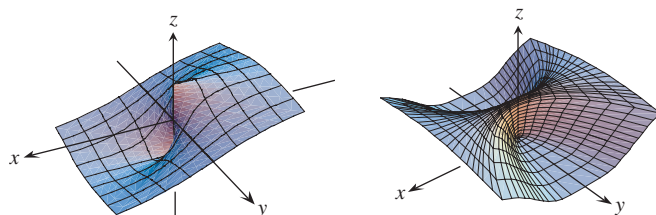
31. a.  $f(x, y) = \sin(x + y)$       b.  $f(x, y) = \ln(x^2 + y^2)$
32. a.  $f(x, y) = \frac{x + y}{x - y}$       b.  $f(x, y) = \frac{y}{x^2 + 1}$
33. a.  $g(x, y) = \sin \frac{1}{xy}$       b.  $g(x, y) = \frac{x + y}{2 + \cos x}$
34. a.  $g(x, y) = \frac{x^2 + y^2}{x^2 - 3x + 2}$       b.  $g(x, y) = \frac{1}{x^2 - y}$

**Continuity for Three Variables**At what points  $(x, y, z)$  in space are the functions in Exercises 35–40 continuous?

35. a.  $f(x, y, z) = x^2 + y^2 - 2z^2$   
b.  $f(x, y, z) = \sqrt{x^2 + y^2 - 1}$
36. a.  $f(x, y, z) = \ln xyz$       b.  $f(x, y, z) = e^{x+y} \cos z$
37. a.  $h(x, y, z) = xy \sin \frac{1}{z}$       b.  $h(x, y, z) = \frac{1}{x^2 + z^2 - 1}$
38. a.  $h(x, y, z) = \frac{1}{|y| + |z|}$       b.  $h(x, y, z) = \frac{1}{|xy| + |z|}$
39. a.  $h(x, y, z) = \ln(z - x^2 - y^2 - 1)$   
b.  $h(x, y, z) = \frac{1}{z - \sqrt{x^2 + y^2}}$
40. a.  $h(x, y, z) = \sqrt{4 - x^2 - y^2 - z^2}$   
b.  $h(x, y, z) = \frac{1}{4 - \sqrt{x^2 + y^2 + z^2} - 9}$

**No Limit Exists at the Origin**By considering different paths of approach, show that the functions in Exercises 41–48 have no limit as  $(x, y) \rightarrow (0, 0)$ .

41.  $f(x, y) = -\frac{x}{\sqrt{x^2 + y^2}}$       42.  $f(x, y) = \frac{x^4}{x^4 + y^2}$



43.  $f(x, y) = \frac{x^4 - y^2}{x^4 + y^2}$       44.  $f(x, y) = \frac{xy}{|xy|}$
45.  $g(x, y) = \frac{x - y}{x + y}$       46.  $g(x, y) = \frac{x^2 - y}{x - y}$
47.  $h(x, y) = \frac{x^2 + y}{y}$       48.  $h(x, y) = \frac{x^2 y}{x^4 + y^2}$

**Theory and Examples**

In Exercises 49 and 50, show that the limits do not exist.

49.  $\lim_{(x,y) \rightarrow (1,1)} \frac{xy^2 - 1}{y - 1}$       50.  $\lim_{(x,y) \rightarrow (1,-1)} \frac{xy + 1}{x^2 - y^2}$
51. Let  $f(x, y) = \begin{cases} 1, & y \geq x^4 \\ 1, & y \leq 0 \\ 0, & \text{otherwise.} \end{cases}$

Find each of the following limits, or explain that the limit does not exist.

- a.  $\lim_{(x,y) \rightarrow (0,1)} f(x, y)$
- b.  $\lim_{(x,y) \rightarrow (2,3)} f(x, y)$
- c.  $\lim_{(x,y) \rightarrow (0,0)} f(x, y)$

52. Let  $f(x, y) = \begin{cases} x^2, & x \geq 0 \\ x^3, & x < 0 \end{cases}$ .

Find the following limits.

a.  $\lim_{(x, y) \rightarrow (3, -2)} f(x, y)$

b.  $\lim_{(x, y) \rightarrow (-2, 1)} f(x, y)$

c.  $\lim_{(x, y) \rightarrow (0, 0)} f(x, y)$

53. Show that the function in Example 6 has limit 0 along every straight line approaching (0, 0).

54. If  $f(x_0, y_0) = 3$ , what can you say about

$$\lim_{(x, y) \rightarrow (x_0, y_0)} f(x, y)$$

if  $f$  is continuous at  $(x_0, y_0)$ ? If  $f$  is not continuous at  $(x_0, y_0)$ ? Give reasons for your answers.

**The Sandwich Theorem** for functions of two variables states that if  $g(x, y) \leq f(x, y) \leq h(x, y)$  for all  $(x, y) \neq (x_0, y_0)$  in a disk centered at  $(x_0, y_0)$  and if  $g$  and  $h$  have the same finite limit  $L$  as  $(x, y) \rightarrow (x_0, y_0)$ , then

$$\lim_{(x, y) \rightarrow (x_0, y_0)} f(x, y) = L.$$

Use this result to support your answers to the questions in Exercises 55–58.

55. Does knowing that

$$1 - \frac{x^2 y^2}{3} < \frac{\tan^{-1} xy}{xy} < 1$$

tell you anything about

$$\lim_{(x, y) \rightarrow (0, 0)} \frac{\tan^{-1} xy}{xy}?$$

Give reasons for your answer.

56. Does knowing that

$$2|xy| - \frac{x^2 y^2}{6} < 4 - 4 \cos \sqrt{|xy|} < 2|xy|$$

tell you anything about

$$\lim_{(x, y) \rightarrow (0, 0)} \frac{4 - 4 \cos \sqrt{|xy|}}{|xy|}?$$

Give reasons for your answer.

57. Does knowing that  $|\sin(1/x)| \leq 1$  tell you anything about

$$\lim_{(x, y) \rightarrow (0, 0)} y \sin \frac{1}{x}?$$

Give reasons for your answer.

58. Does knowing that  $|\cos(1/y)| \leq 1$  tell you anything about

$$\lim_{(x, y) \rightarrow (0, 0)} x \cos \frac{1}{y}?$$

Give reasons for your answer.

59. (Continuation of Example 5.)

a. Reread Example 5. Then substitute  $m = \tan \theta$  into the formula

$$f(x, y) \Big|_{y=mx} = \frac{2m}{1+m^2}$$

and simplify the result to show how the value of  $f$  varies with the line's angle of inclination.

b. Use the formula you obtained in part (a) to show that the limit of  $f$  as  $(x, y) \rightarrow (0, 0)$  along the line  $y = mx$  varies from  $-1$  to  $1$  depending on the angle of approach.

60. **Continuous extension** Define  $f(0, 0)$  in a way that extends

$$f(x, y) = xy \frac{x^2 - y^2}{x^2 + y^2}$$

to be continuous at the origin.

### Changing Variables to Polar Coordinates

If you cannot make any headway with  $\lim_{(x, y) \rightarrow (0, 0)} f(x, y)$  in rectangular coordinates, try changing to polar coordinates. Substitute  $x = r \cos \theta$ ,  $y = r \sin \theta$ , and investigate the limit of the resulting expression as  $r \rightarrow 0$ . In other words, try to decide whether there exists a number  $L$  satisfying the following criterion:

Given  $\epsilon > 0$ , there exists a  $\delta > 0$  such that for all  $r$  and  $\theta$ ,

$$|r| < \delta \implies |f(r \cos \theta, r \sin \theta) - L| < \epsilon. \quad (1)$$

If such an  $L$  exists, then

$$\lim_{(x, y) \rightarrow (0, 0)} f(x, y) = \lim_{r \rightarrow 0} f(r \cos \theta, r \sin \theta) = L.$$

For instance,

$$\lim_{(x, y) \rightarrow (0, 0)} \frac{x^3}{x^2 + y^2} = \lim_{r \rightarrow 0} \frac{r^3 \cos^3 \theta}{r^2} = \lim_{r \rightarrow 0} r \cos^3 \theta = 0.$$

To verify the last of these equalities, we need to show that Equation (1) is satisfied with  $f(r, \theta) = r \cos^3 \theta$  and  $L = 0$ . That is, we need to show that given any  $\epsilon > 0$ , there exists a  $\delta > 0$  such that for all  $r$  and  $\theta$ ,

$$|r| < \delta \implies |r \cos^3 \theta - 0| < \epsilon.$$

Since

$$|r \cos^3 \theta| = |r| |\cos^3 \theta| \leq |r| \cdot 1 = |r|,$$

the implication holds for all  $r$  and  $\theta$  if we take  $\delta = \epsilon$ .

In contrast,

$$\frac{x^2}{x^2 + y^2} = \frac{r^2 \cos^2 \theta}{r^2} = \cos^2 \theta$$

takes on all values from 0 to 1 regardless of how small  $|r|$  is, so that  $\lim_{(x, y) \rightarrow (0, 0)} x^2/(x^2 + y^2)$  does not exist.

In each of these instances, the existence or nonexistence of the limit as  $r \rightarrow 0$  is fairly clear. Shifting to polar coordinates does not always help, however, and may even tempt us to false conclusions. For example, the limit may exist along every straight line (or ray)  $\theta = \text{constant}$  and yet fail to exist in the broader sense. Example 5 illustrates this point. In polar coordinates,  $f(x, y) = (2x^2 y)/(x^4 + y^2)$  becomes

$$f(r \cos \theta, r \sin \theta) = \frac{r \cos \theta \sin 2\theta}{r^2 \cos^4 \theta + \sin^2 \theta}$$

for  $r \neq 0$ . If we hold  $\theta$  constant and let  $r \rightarrow 0$ , the limit is 0. On the path  $y = x^2$ , however, we have  $r \sin \theta = r^2 \cos^2 \theta$  and

$$\begin{aligned} f(r \cos \theta, r \sin \theta) &= \frac{r \cos \theta \sin 2\theta}{r^2 \cos^4 \theta + (r \cos^2 \theta)^2} \\ &= \frac{2r \cos^2 \theta \sin \theta}{2r^2 \cos^4 \theta} = \frac{r \sin \theta}{r^2 \cos^2 \theta} = 1. \end{aligned}$$

In Exercises 61–66, find the limit of  $f$  as  $(x, y) \rightarrow (0, 0)$  or show that the limit does not exist.

$$61. f(x, y) = \frac{x^3 - xy^2}{x^2 + y^2}$$

$$62. f(x, y) = \cos\left(\frac{x^3 - y^3}{x^2 + y^2}\right)$$

$$63. f(x, y) = \frac{y^2}{x^2 + y^2}$$

$$64. f(x, y) = \frac{2x}{x^2 + x + y^2}$$

$$65. f(x, y) = \tan^{-1}\left(\frac{|x| + |y|}{x^2 + y^2}\right)$$

$$66. f(x, y) = \frac{x^2 - y^2}{x^2 + y^2}$$

In Exercises 67 and 68, define  $f(0, 0)$  in a way that extends  $f$  to be continuous at the origin.

$$67. f(x, y) = \ln\left(\frac{3x^2 - x^2y^2 + 3y^2}{x^2 + y^2}\right)$$

$$68. f(x, y) = \frac{3x^2y}{x^2 + y^2}$$

### Using the Limit Definition

Each of Exercises 69–74 gives a function  $f(x, y)$  and a positive number  $\epsilon$ . In each exercise, show that there exists a  $\delta > 0$  such that for all  $(x, y)$ ,

$$\sqrt{x^2 + y^2} < \delta \implies |f(x, y) - f(0, 0)| < \epsilon.$$

$$69. f(x, y) = x^2 + y^2, \quad \epsilon = 0.01$$

$$70. f(x, y) = y/(x^2 + 1), \quad \epsilon = 0.05$$

$$71. f(x, y) = (x + y)/(x^2 + 1), \quad \epsilon = 0.01$$

$$72. f(x, y) = (x + y)/(2 + \cos x), \quad \epsilon = 0.02$$

$$73. f(x, y) = \frac{xy^2}{x^2 + y^2} \text{ and } f(0, 0) = 0, \quad \epsilon = 0.04$$

$$74. f(x, y) = \frac{x^3 + y^4}{x^2 + y^2} \text{ and } f(0, 0) = 0, \quad \epsilon = 0.02$$

Each of Exercises 75–78 gives a function  $f(x, y, z)$  and a positive number  $\epsilon$ . In each exercise, show that there exists a  $\delta > 0$  such that for all  $(x, y, z)$ ,

$$\sqrt{x^2 + y^2 + z^2} < \delta \implies |f(x, y, z) - f(0, 0, 0)| < \epsilon.$$

$$75. f(x, y, z) = x^2 + y^2 + z^2, \quad \epsilon = 0.015$$

$$76. f(x, y, z) = xyz, \quad \epsilon = 0.008$$

$$77. f(x, y, z) = \frac{x + y + z}{x^2 + y^2 + z^2 + 1}, \quad \epsilon = 0.015$$

$$78. f(x, y, z) = \tan^2 x + \tan^2 y + \tan^2 z, \quad \epsilon = 0.03$$

$$79. \text{ Show that } f(x, y, z) = x + y - z \text{ is continuous at every point } (x_0, y_0, z_0).$$

$$80. \text{ Show that } f(x, y, z) = x^2 + y^2 + z^2 \text{ is continuous at the origin.}$$

## Exercises 14.3

### Calculating First-Order Partial Derivatives

In Exercises 1–22, find  $\partial f/\partial x$  and  $\partial f/\partial y$ .

1.  $f(x, y) = 2x^2 - 3y - 4$
2.  $f(x, y) = x^2 - xy + y^2$
3.  $f(x, y) = (x^2 - 1)(y + 2)$
4.  $f(x, y) = 5xy - 7x^2 - y^2 + 3x - 6y + 2$
5.  $f(x, y) = (xy - 1)^2$
6.  $f(x, y) = (2x - 3y)^3$
7.  $f(x, y) = \sqrt{x^2 + y^2}$
8.  $f(x, y) = (x^3 + (y/2))^{2/3}$
9.  $f(x, y) = 1/(x + y)$
10.  $f(x, y) = x/(x^2 + y^2)$
11.  $f(x, y) = (x + y)/(xy - 1)$
12.  $f(x, y) = \tan^{-1}(y/x)$
13.  $f(x, y) = e^{(x+y+1)}$
14.  $f(x, y) = e^{-x} \sin(x + y)$
15.  $f(x, y) = \ln(x + y)$
16.  $f(x, y) = e^{xy} \ln y$
17.  $f(x, y) = \sin^2(x - 3y)$
18.  $f(x, y) = \cos^2(3x - y^2)$
19.  $f(x, y) = x^y$
20.  $f(x, y) = \log_y x$
21.  $f(x, y) = \int_x^y g(t) dt$  ( $g$  continuous for all  $t$ )
22.  $f(x, y) = \sum_{n=0}^{\infty} (xy)^n$  ( $|xy| < 1$ )

In Exercises 23–34, find  $f_x$ ,  $f_y$ , and  $f_z$ .

23.  $f(x, y, z) = 1 + xy^2 - 2z^2$
24.  $f(x, y, z) = xy + yz + xz$
25.  $f(x, y, z) = x - \sqrt{y^2 + z^2}$
26.  $f(x, y, z) = (x^2 + y^2 + z^2)^{-1/2}$
27.  $f(x, y, z) = \sin^{-1}(xyz)$
28.  $f(x, y, z) = \sec^{-1}(x + yz)$
29.  $f(x, y, z) = \ln(x + 2y + 3z)$
30.  $f(x, y, z) = yz \ln(xy)$
31.  $f(x, y, z) = e^{-(x^2 + y^2 + z^2)}$
32.  $f(x, y, z) = e^{-xyz}$
33.  $f(x, y, z) = \tanh(x + 2y + 3z)$
34.  $f(x, y, z) = \sinh(xy - z^2)$

In Exercises 35–40, find the partial derivative of the function with respect to each variable.

35.  $f(t, \alpha) = \cos(2\pi t - \alpha)$
36.  $g(u, v) = v^2 e^{(2u/v)}$
37.  $h(\rho, \phi, \theta) = \rho \sin \phi \cos \theta$
38.  $g(r, \theta, z) = r(1 - \cos \theta) - z$

39. **Work done by the heart** (Section 3.9, Exercise 61)

$$W(P, V, \delta, v, g) = PV + \frac{V\delta v^2}{2g}$$

40. **Wilson lot size formula** (Section 4.5, Exercise 53)

$$A(c, h, k, m, q) = \frac{km}{q} + cm + \frac{hq}{2}$$

### Calculating Second-Order Partial Derivatives

Find all the second-order partial derivatives of the functions in Exercises 41–50.

41.  $f(x, y) = x + y + xy$
42.  $f(x, y) = \sin xy$
43.  $g(x, y) = x^2y + \cos y + y \sin x$
44.  $h(x, y) = xe^y + y + 1$
45.  $r(x, y) = \ln(x + y)$
46.  $s(x, y) = \tan^{-1}(y/x)$
47.  $w = x^2 \tan(xy)$
48.  $w = ye^{x^2 - y}$
49.  $w = x \sin(x^2y)$
50.  $w = \frac{x - y}{x^2 + y}$

### Mixed Partial Derivatives

In Exercises 51–54, verify that  $w_{xy} = w_{yx}$ .

51.  $w = \ln(2x + 3y)$
52.  $w = e^x + x \ln y + y \ln x$
53.  $w = xy^2 + x^2y^3 + x^3y^4$
54.  $w = x \sin y + y \sin x + xy$
55. Which order of differentiation will calculate  $f_{xy}$  faster:  $x$  first or  $y$  first? Try to answer without writing anything down.
  - a.  $f(x, y) = x \sin y + e^y$
  - b.  $f(x, y) = 1/x$
  - c.  $f(x, y) = y + (x/y)$
  - d.  $f(x, y) = y + x^2y + 4y^3 - \ln(y^2 + 1)$
  - e.  $f(x, y) = x^2 + 5xy + \sin x + 7e^x$
  - f.  $f(x, y) = x \ln xy$
56. The fifth-order partial derivative  $\partial^5 f / \partial x^2 \partial y^3$  is zero for each of the following functions. To show this as quickly as possible, which variable would you differentiate with respect to first:  $x$  or  $y$ ? Try to answer without writing anything down.
  - a.  $f(x, y) = y^2 x^4 e^x + 2$
  - b.  $f(x, y) = y^2 + y(\sin x - x^4)$
  - c.  $f(x, y) = x^2 + 5xy + \sin x + 7e^x$
  - d.  $f(x, y) = xe^{y^2/2}$



## Using the Partial Derivative Definition

In Exercises 57–60, use the limit definition of partial derivative to compute the partial derivatives of the functions at the specified points.

57.  $f(x, y) = 1 - x + y - 3x^2y$ ,  $\frac{\partial f}{\partial x}$  and  $\frac{\partial f}{\partial y}$  at  $(1, 2)$

58.  $f(x, y) = 4 + 2x - 3y - xy^2$ ,  $\frac{\partial f}{\partial x}$  and  $\frac{\partial f}{\partial y}$  at  $(-2, 1)$

59.  $f(x, y) = \sqrt{2x + 3y - 1}$ ,  $\frac{\partial f}{\partial x}$  and  $\frac{\partial f}{\partial y}$  at  $(-2, 3)$

60.  $f(x, y) = \begin{cases} \frac{\sin(x^3 + y^4)}{x^2 + y^2}, & (x, y) \neq (0, 0) \\ 0, & (x, y) = (0, 0), \end{cases}$   
 $\frac{\partial f}{\partial x}$  and  $\frac{\partial f}{\partial y}$  at  $(0, 0)$

61. Let  $f(x, y) = 2x + 3y - 4$ . Find the slope of the line tangent to this surface at the point  $(2, -1)$  and lying in the **a.** plane  $x = 2$   
**b.** plane  $y = -1$ .

62. Let  $f(x, y) = x^2 + y^3$ . Find the slope of the line tangent to this surface at the point  $(-1, 1)$  and lying in the **a.** plane  $x = -1$   
**b.** plane  $y = 1$ .

63. **Three variables** Let  $w = f(x, y, z)$  be a function of three independent variables and write the formal definition of the partial derivative  $\partial f / \partial z$  at  $(x_0, y_0, z_0)$ . Use this definition to find  $\partial f / \partial z$  at  $(1, 2, 3)$  for  $f(x, y, z) = x^2yz^2$ .

64. **Three variables** Let  $w = f(x, y, z)$  be a function of three independent variables and write the formal definition of the partial derivative  $\partial f / \partial y$  at  $(x_0, y_0, z_0)$ . Use this definition to find  $\partial f / \partial y$  at  $(-1, 0, 3)$  for  $f(x, y, z) = -2xy^2 + yz^2$ .

## Differentiating Implicitly

65. Find the value of  $\partial z / \partial x$  at the point  $(1, 1, 1)$  if the equation

$$xy + z^3x - 2yz = 0$$

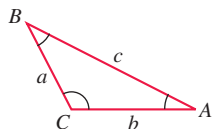
defines  $z$  as a function of the two independent variables  $x$  and  $y$  and the partial derivative exists.

66. Find the value of  $\partial x / \partial z$  at the point  $(1, -1, -3)$  if the equation

$$xz + y \ln x - x^2 + 4 = 0$$

defines  $x$  as a function of the two independent variables  $y$  and  $z$  and the partial derivative exists.

Exercises 67 and 68 are about the triangle shown here.



67. Express  $A$  implicitly as a function of  $a$ ,  $b$ , and  $c$  and calculate  $\partial A / \partial a$  and  $\partial A / \partial b$ .

68. Express  $a$  implicitly as a function of  $A$ ,  $b$ , and  $B$  and calculate  $\partial a / \partial A$  and  $\partial a / \partial B$ .

69. **Two dependent variables** Express  $v_x$  in terms of  $u$  and  $y$  if the equations  $x = v \ln u$  and  $y = u \ln v$  define  $u$  and  $v$  as functions of the independent variables  $x$  and  $y$ , and if  $v_x$  exists. (Hint: Differentiate both equations with respect to  $x$  and solve for  $v_x$  by eliminating  $u_x$ .)

70. **Two dependent variables** Find  $\partial x / \partial u$  and  $\partial y / \partial u$  if the equations  $u = x^2 - y^2$  and  $v = x^2 - y$  define  $x$  and  $y$  as functions of the independent variables  $u$  and  $v$ , and the partial derivatives exist. (See the hint in Exercise 69.) Then let  $s = x^2 + y^2$  and find  $\partial s / \partial u$ .

## Theory and Examples

71. Let  $f(x, y) = \begin{cases} y^3, & y \geq 0 \\ -y^2, & y < 0. \end{cases}$

Find  $f_x$ ,  $f_y$ ,  $f_{xy}$ , and  $f_{yx}$ , and state the domain for each partial derivative.

72. Let  $f(x, y) = \begin{cases} xy \frac{x^2 - y^2}{x^2 + y^2}, & \text{if } (x, y) \neq 0, \\ 0, & \text{if } (x, y) = 0. \end{cases}$

**a.** Show that  $\frac{\partial f}{\partial y}(x, 0) = x$  for all  $x$ , and  $\frac{\partial f}{\partial x}(0, y) = -y$  for all  $y$ .

**b.** Show that  $\frac{\partial^2 f}{\partial y \partial x}(0, 0) \neq \frac{\partial^2 f}{\partial x \partial y}(0, 0)$ .

The graph of  $f$  is shown on page 788.

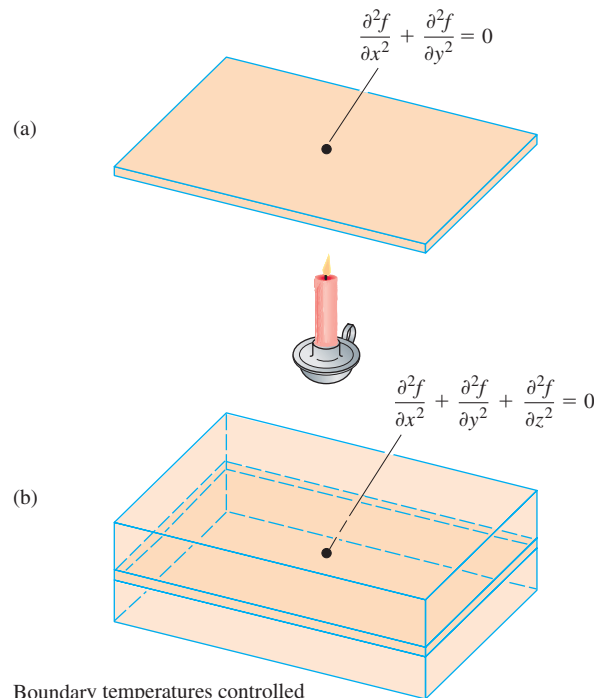
## The three-dimensional Laplace equation

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0$$

is satisfied by steady-state temperature distributions  $T = f(x, y, z)$  in space, by gravitational potentials, and by electrostatic potentials. The **two-dimensional Laplace equation**

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0,$$

obtained by dropping the  $\partial^2 f / \partial z^2$  term from the previous equation, describes potentials and steady-state temperature distributions in a plane (see the accompanying figure). The plane (a) may be treated as a thin slice of the solid (b) perpendicular to the  $z$ -axis.



Boundary temperatures controlled

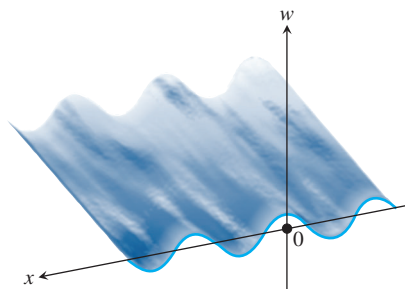
Show that each function in Exercises 73–80 satisfies a Laplace equation.

73.  $f(x, y, z) = x^2 + y^2 - 2z^2$   
 74.  $f(x, y, z) = 2z^3 - 3(x^2 + y^2)z$   
 75.  $f(x, y) = e^{-2y} \cos 2x$   
 76.  $f(x, y) = \ln \sqrt{x^2 + y^2}$   
 77.  $f(x, y) = 3x + 2y - 4$   
 78.  $f(x, y) = \tan^{-1} \frac{x}{y}$   
 79.  $f(x, y, z) = (x^2 + y^2 + z^2)^{-1/2}$   
 80.  $f(x, y, z) = e^{3x+4y} \cos 5z$

**The Wave Equation** If we stand on an ocean shore and take a snapshot of the waves, the picture shows a regular pattern of peaks and valleys in an instant of time. We see periodic vertical motion in space, with respect to distance. If we stand in the water, we can feel the rise and fall of the water as the waves go by. We see periodic vertical motion in time. In physics, this beautiful symmetry is expressed by the **one-dimensional wave equation**

$$\frac{\partial^2 w}{\partial t^2} = c^2 \frac{\partial^2 w}{\partial x^2},$$

where  $w$  is the wave height,  $x$  is the distance variable,  $t$  is the time variable, and  $c$  is the velocity with which the waves are propagated.



In our example,  $x$  is the distance across the ocean's surface, but in other applications,  $x$  might be the distance along a vibrating string, distance through air (sound waves), or distance through space (light waves). The number  $c$  varies with the medium and type of wave.

Show that the functions in Exercises 81–87 are all solutions of the wave equation.

81.  $w = \sin(x + ct)$   
 82.  $w = \cos(2x + 2ct)$   
 83.  $w = \sin(x + ct) + \cos(2x + 2ct)$   
 84.  $w = \ln(2x + 2ct)$   
 85.  $w = \tan(2x - 2ct)$   
 86.  $w = 5 \cos(3x + 3ct) + e^{x+ct}$   
 87.  $w = f(u)$ , where  $f$  is a differentiable function of  $u$ , and  $u = a(x + ct)$ , where  $a$  is a constant  
 88. Does a function  $f(x, y)$  with continuous first partial derivatives throughout an open region  $R$  have to be continuous on  $R$ ? Give reasons for your answer.  
 89. If a function  $f(x, y)$  has continuous second partial derivatives throughout an open region  $R$ , must the first-order partial derivatives of  $f$  be continuous on  $R$ ? Give reasons for your answer.  
 90. **The heat equation** An important partial differential equation that describes the distribution of heat in a region at time  $t$  can be represented by the **one-dimensional heat equation**

$$\frac{\partial f}{\partial t} = \frac{\partial^2 f}{\partial x^2}.$$

Show that  $u(x, t) = \sin(\alpha x) \cdot e^{-\beta t}$  satisfies the heat equation for constants  $\alpha$  and  $\beta$ . What is the relationship between  $\alpha$  and  $\beta$  for this function to be a solution?

91. Let  $f(x, y) = \begin{cases} \frac{xy^2}{x^2 + y^4}, & (x, y) \neq (0, 0) \\ 0, & (x, y) = (0, 0). \end{cases}$

Show that  $f_x(0, 0)$  and  $f_y(0, 0)$  exist, but  $f$  is not differentiable at  $(0, 0)$ . (Hint: Use Theorem 4 and show that  $f$  is not continuous at  $(0, 0)$ .)

92. Let  $f(x, y) = \begin{cases} 0, & x^2 < y < 2x^2 \\ 1, & \text{otherwise.} \end{cases}$

Show that  $f_x(0, 0)$  and  $f_y(0, 0)$  exist, but  $f$  is not differentiable at  $(0, 0)$ .

## Exercises 14.4

### Chain Rule: One Independent Variable

In Exercises 1–6, **(a)** express  $dw/dt$  as a function of  $t$ , both by using the Chain Rule and by expressing  $w$  in terms of  $t$  and differentiating directly with respect to  $t$ . Then **(b)** evaluate  $dw/dt$  at the given value of  $t$ .

1.  $w = x^2 + y^2$ ,  $x = \cos t$ ,  $y = \sin t$ ;  $t = \pi$
2.  $w = x^2 + y^2$ ,  $x = \cos t + \sin t$ ,  $y = \cos t - \sin t$ ;  $t = 0$
3.  $w = \frac{x}{z} + \frac{y}{z}$ ,  $x = \cos^2 t$ ,  $y = \sin^2 t$ ,  $z = 1/t$ ;  $t = 3$
4.  $w = \ln(x^2 + y^2 + z^2)$ ,  $x = \cos t$ ,  $y = \sin t$ ,  $z = 4\sqrt{t}$ ;  $t = 3$

5.  $w = 2ye^x - \ln z$ ,  $x = \ln(t^2 + 1)$ ,  $y = \tan^{-1} t$ ,  $z = e^t$ ;  $t = 1$
6.  $w = z - \sin xy$ ,  $x = t$ ,  $y = \ln t$ ,  $z = e^{t-1}$ ;  $t = 1$

### Chain Rule: Two and Three Independent Variables

In Exercises 7 and 8, **(a)** express  $\partial z/\partial u$  and  $\partial z/\partial v$  as functions of  $u$  and  $v$  both by using the Chain Rule and by expressing  $z$  directly in terms of  $u$  and  $v$  before differentiating. Then **(b)** evaluate  $\partial z/\partial u$  and  $\partial z/\partial v$  at the given point  $(u, v)$ .

7.  $z = 4e^x \ln y$ ,  $x = \ln(u \cos v)$ ,  $y = u \sin v$ ;  
 $(u, v) = (2, \pi/4)$

8.  $z = \tan^{-1}(x/y)$ ,  $x = u \cos v$ ,  $y = u \sin v$ ;  
 $(u, v) = (1.3, \pi/6)$

In Exercises 9 and 10, (a) express  $\partial w/\partial u$  and  $\partial w/\partial v$  as functions of  $u$  and  $v$  both by using the Chain Rule and by expressing  $w$  directly in terms of  $u$  and  $v$  before differentiating. Then (b) evaluate  $\partial w/\partial u$  and  $\partial w/\partial v$  at the given point  $(u, v)$ .

9.  $w = xy + yz + xz$ ,  $x = u + v$ ,  $y = u - v$ ,  $z = uv$ ;  
 $(u, v) = (1/2, 1)$
10.  $w = \ln(x^2 + y^2 + z^2)$ ,  $x = ue^v \sin u$ ,  $y = ue^v \cos u$ ,  
 $z = ue^v$ ;  $(u, v) = (-2, 0)$

In Exercises 11 and 12, (a) express  $\partial u/\partial x$ ,  $\partial u/\partial y$ , and  $\partial u/\partial z$  as functions of  $x$ ,  $y$ , and  $z$  both by using the Chain Rule and by expressing  $u$  directly in terms of  $x$ ,  $y$ , and  $z$  before differentiating. Then (b) evaluate  $\partial u/\partial x$ ,  $\partial u/\partial y$ , and  $\partial u/\partial z$  at the given point  $(x, y, z)$ .

11.  $u = \frac{p-q}{q-r}$ ,  $p = x + y + z$ ,  $q = x - y + z$ ,  
 $r = x + y - z$ ;  $(x, y, z) = (\sqrt{3}, 2, 1)$
12.  $u = e^{qr} \sin^{-1} p$ ,  $p = \sin x$ ,  $q = z^2 \ln y$ ,  $r = 1/z$ ;  
 $(x, y, z) = (\pi/4, 1/2, -1/2)$

### Using a Branch Diagram

In Exercises 13–24, draw a branch diagram and write a Chain Rule formula for each derivative.

13.  $\frac{dz}{dt}$  for  $z = f(x, y)$ ,  $x = g(t)$ ,  $y = h(t)$
14.  $\frac{dz}{dt}$  for  $z = f(u, v, w)$ ,  $u = g(t)$ ,  $v = h(t)$ ,  $w = k(t)$
15.  $\frac{\partial w}{\partial u}$  and  $\frac{\partial w}{\partial v}$  for  $w = h(x, y, z)$ ,  $x = f(u, v)$ ,  $y = g(u, v)$ ,  
 $z = k(u, v)$
16.  $\frac{\partial w}{\partial x}$  and  $\frac{\partial w}{\partial y}$  for  $w = f(r, s, t)$ ,  $r = g(x, y)$ ,  $s = h(x, y)$ ,  
 $t = k(x, y)$
17.  $\frac{\partial w}{\partial u}$  and  $\frac{\partial w}{\partial v}$  for  $w = g(x, y)$ ,  $x = h(u, v)$ ,  $y = k(u, v)$
18.  $\frac{\partial w}{\partial x}$  and  $\frac{\partial w}{\partial y}$  for  $w = g(u, v)$ ,  $u = h(x, y)$ ,  $v = k(x, y)$
19.  $\frac{\partial z}{\partial t}$  and  $\frac{\partial z}{\partial s}$  for  $z = f(x, y)$ ,  $x = g(t, s)$ ,  $y = h(t, s)$
20.  $\frac{\partial y}{\partial r}$  for  $y = f(u)$ ,  $u = g(r, s)$
21.  $\frac{\partial w}{\partial s}$  and  $\frac{\partial w}{\partial t}$  for  $w = g(u)$ ,  $u = h(s, t)$
22.  $\frac{\partial w}{\partial p}$  for  $w = f(x, y, z, v)$ ,  $x = g(p, q)$ ,  $y = h(p, q)$ ,  
 $z = j(p, q)$ ,  $v = k(p, q)$
23.  $\frac{\partial w}{\partial r}$  and  $\frac{\partial w}{\partial s}$  for  $w = f(x, y)$ ,  $x = g(r)$ ,  $y = h(s)$
24.  $\frac{\partial w}{\partial s}$  for  $w = g(x, y)$ ,  $x = h(r, s, t)$ ,  $y = k(r, s, t)$

### Implicit Differentiation

Assuming that the equations in Exercises 25–28 define  $y$  as a differentiable function of  $x$ , use Theorem 8 to find the value of  $dy/dx$  at the given point.

25.  $x^3 - 2y^2 + xy = 0$ ,  $(1, 1)$
26.  $xy + y^2 - 3x - 3 = 0$ ,  $(-1, 1)$
27.  $x^2 + xy + y^2 - 7 = 0$ ,  $(1, 2)$
28.  $xe^y + \sin xy + y - \ln 2 = 0$ ,  $(0, \ln 2)$

Find the values of  $\partial z/\partial x$  and  $\partial z/\partial y$  at the points in Exercises 29–32.

29.  $z^3 - xy + yz + y^3 - 2 = 0$ ,  $(1, 1, 1)$
30.  $\frac{1}{x} + \frac{1}{y} + \frac{1}{z} - 1 = 0$ ,  $(2, 3, 6)$
31.  $\sin(x + y) + \sin(y + z) + \sin(x + z) = 0$ ,  $(\pi, \pi, \pi)$
32.  $xe^y + ye^z + 2 \ln x - 2 - 3 \ln 2 = 0$ ,  $(1, \ln 2, \ln 3)$

### Finding Partial Derivatives at Specified Points

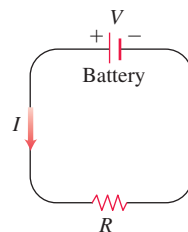
33. Find  $\partial w/\partial r$  when  $r = 1, s = -1$  if  $w = (x + y + z)^2$ ,  
 $x = r - s$ ,  $y = \cos(r + s)$ ,  $z = \sin(r + s)$ .
34. Find  $\partial w/\partial v$  when  $u = -1, v = 2$  if  $w = xy + \ln z$ ,  
 $x = v^2/u$ ,  $y = u + v$ ,  $z = \cos u$ .
35. Find  $\partial w/\partial v$  when  $u = 0, v = 0$  if  $w = x^2 + (y/x)$ ,  
 $x = u - 2v + 1$ ,  $y = 2u + v - 2$ .
36. Find  $\partial z/\partial u$  when  $u = 0, v = 1$  if  $z = \sin xy + x \sin y$ ,  
 $x = u^2 + v^2$ ,  $y = uv$ .
37. Find  $\partial z/\partial u$  and  $\partial z/\partial v$  when  $u = \ln 2, v = 1$  if  $z = 5 \tan^{-1} x$  and  
 $x = e^u + \ln v$ .
38. Find  $\partial z/\partial u$  and  $\partial z/\partial v$  when  $u = 1, v = -2$  if  $z = \ln q$  and  
 $q = \sqrt{v + 3} \tan^{-1} u$ .

### Theory and Examples

39. Assume that  $w = f(s^3 + t^2)$  and  $f'(x) = e^x$ . Find  $\frac{\partial w}{\partial t}$  and  $\frac{\partial w}{\partial s}$ .
40. Assume that  $w = f\left(\frac{ts^2}{t}, \frac{s}{t}\right)$ ,  $\frac{\partial f}{\partial x}(x, y) = xy$ , and  $\frac{\partial f}{\partial y}(x, y) = \frac{x^2}{2}$ .  
 Find  $\frac{\partial w}{\partial t}$  and  $\frac{\partial w}{\partial s}$ .
41. **Changing voltage in a circuit** The voltage  $V$  in a circuit that satisfies the law  $V = IR$  is slowly dropping as the battery wears out. At the same time, the resistance  $R$  is increasing as the resistor heats up. Use the equation

$$\frac{dV}{dt} = \frac{\partial V}{\partial I} \frac{dI}{dt} + \frac{\partial V}{\partial R} \frac{dR}{dt}$$

to find how the current is changing at the instant when  $R = 600$  ohms,  $I = 0.04$  amp,  $dR/dt = 0.5$  ohm/sec, and  $dV/dt = -0.01$  volt/sec.



42. **Changing dimensions in a box** The lengths  $a$ ,  $b$ , and  $c$  of the edges of a rectangular box are changing with time. At the instant in question,  $a = 1$  m,  $b = 2$  m,  $c = 3$  m,  $da/dt = db/dt = 1$  m/sec, and  $dc/dt = -3$  m/sec. At what rates are the box's volume  $V$  and surface area  $S$  changing at that instant? Are the box's interior diagonals increasing in length or decreasing?
43. If  $f(u, v, w)$  is differentiable and  $u = x - y$ ,  $v = y - z$ , and  $w = z - x$ , show that

$$\frac{\partial f}{\partial x} + \frac{\partial f}{\partial y} + \frac{\partial f}{\partial z} = 0.$$

- 44. Polar coordinates** Suppose that we substitute polar coordinates  $x = r \cos \theta$  and  $y = r \sin \theta$  in a differentiable function  $w = f(x, y)$ .

a. Show that

$$\frac{\partial w}{\partial r} = f_x \cos \theta + f_y \sin \theta$$

and

$$\frac{1}{r} \frac{\partial w}{\partial \theta} = -f_x \sin \theta + f_y \cos \theta.$$

b. Solve the equations in part (a) to express  $f_x$  and  $f_y$  in terms of  $\partial w / \partial r$  and  $\partial w / \partial \theta$ .

c. Show that

$$(f_x)^2 + (f_y)^2 = \left( \frac{\partial w}{\partial r} \right)^2 + \frac{1}{r^2} \left( \frac{\partial w}{\partial \theta} \right)^2.$$

- 45. Laplace equations** Show that if  $w = f(u, v)$  satisfies the Laplace equation  $f_{uu} + f_{vv} = 0$  and if  $u = (x^2 - y^2)/2$  and  $v = xy$ , then  $w$  satisfies the Laplace equation  $w_{xx} + w_{yy} = 0$ .

- 46. Laplace equations** Let  $w = f(u) + g(v)$ , where  $u = x + iy$ ,  $v = x - iy$ , and  $i = \sqrt{-1}$ . Show that  $w$  satisfies the Laplace equation  $w_{xx} + w_{yy} = 0$  if all the necessary functions are differentiable.

- 47. Extreme values on a helix** Suppose that the partial derivatives of a function  $f(x, y, z)$  at points on the helix  $x = \cos t$ ,  $y = \sin t$ ,  $z = t$  are

$$f_x = \cos t, \quad f_y = \sin t, \quad f_z = t^2 + t - 2.$$

At what points on the curve, if any, can  $f$  take on extreme values?

- 48. A space curve** Let  $w = x^2 e^{2y} \cos 3z$ . Find the value of  $dw/dt$  at the point  $(1, \ln 2, 0)$  on the curve  $x = \cos t$ ,  $y = \ln(t + 2)$ ,  $z = t$ .

- 49. Temperature on a circle** Let  $T = f(x, y)$  be the temperature at the point  $(x, y)$  on the circle  $x = \cos t$ ,  $y = \sin t$ ,  $0 \leq t \leq 2\pi$  and suppose that

$$\frac{\partial T}{\partial x} = 8x - 4y, \quad \frac{\partial T}{\partial y} = 8y - 4x.$$

- a. Find where the maximum and minimum temperatures on the circle occur by examining the derivatives  $dT/dt$  and  $d^2T/dt^2$ .  
b. Suppose that  $T = 4x^2 - 4xy + 4y^2$ . Find the maximum and minimum values of  $T$  on the circle.

- 50. Temperature on an ellipse** Let  $T = g(x, y)$  be the temperature at the point  $(x, y)$  on the ellipse

$$x = 2\sqrt{2} \cos t, \quad y = \sqrt{2} \sin t, \quad 0 \leq t \leq 2\pi,$$

and suppose that

$$\frac{\partial T}{\partial x} = y, \quad \frac{\partial T}{\partial y} = x.$$

- a. Locate the maximum and minimum temperatures on the ellipse by examining  $dT/dt$  and  $d^2T/dt^2$ .  
b. Suppose that  $T = xy - 2$ . Find the maximum and minimum values of  $T$  on the ellipse.

**Differentiating Integrals** Under mild continuity restrictions, it is true that if

$$F(x) = \int_a^b g(t, x) dt,$$

then  $F'(x) = \int_a^b g_x(t, x) dt$ . Using this fact and the Chain Rule, we can find the derivative of

$$F(x) = \int_a^{f(x)} g(t, x) dt$$

by letting

$$G(u, x) = \int_a^u g(t, x) dt,$$

where  $u = f(x)$ . Find the derivatives of the functions in Exercises 51 and 52.

$$51. F(x) = \int_0^{x^2} \sqrt{t^4 + x^3} dt \quad 52. F(x) = \int_{x^2}^1 \sqrt{t^3 + x^2} dt$$

## Exercises 14.5

## Calculating Gradients

In Exercises 1–6, find the gradient of the function at the given point. Then sketch the gradient together with the level curve that passes through the point.

1.  $f(x, y) = y - x$ ,  $(2, 1)$
2.  $f(x, y) = \ln(x^2 + y^2)$ ,  $(1, 1)$
3.  $g(x, y) = xy^2$ ,  $(2, -1)$
4.  $g(x, y) = \frac{x^2}{2} - \frac{y^2}{2}$ ,  $(\sqrt{2}, 1)$
5.  $f(x, y) = \sqrt{2x + 3y}$ ,  $(-1, 2)$
6.  $f(x, y) = \tan^{-1} \frac{\sqrt{x}}{y}$ ,  $(4, -2)$

In Exercises 7–10, find  $\nabla f$  at the given point.

7.  $f(x, y, z) = x^2 + y^2 - 2z^2 + z \ln x$ ,  $(1, 1, 1)$
8.  $f(x, y, z) = 2z^3 - 3(x^2 + y^2)z + \tan^{-1} xz$ ,  $(1, 1, 1)$
9.  $f(x, y, z) = (x^2 + y^2 + z^2)^{-1/2} + \ln(xyz)$ ,  $(-1, 2, -2)$
10.  $f(x, y, z) = e^{x+y} \cos z + (y + 1) \sin^{-1} x$ ,  $(0, 0, \pi/6)$

## Finding Directional Derivatives

In Exercises 11–18, find the derivative of the function at  $P_0$  in the direction of  $\mathbf{u}$ .

11.  $f(x, y) = 2xy - 3y^2$ ,  $P_0(5, 5)$ ,  $\mathbf{u} = 4\mathbf{i} + 3\mathbf{j}$
12.  $f(x, y) = 2x^2 + y^2$ ,  $P_0(-1, 1)$ ,  $\mathbf{u} = 3\mathbf{i} - 4\mathbf{j}$
13.  $g(x, y) = \frac{x - y}{xy + 2}$ ,  $P_0(1, -1)$ ,  $\mathbf{u} = 12\mathbf{i} + 5\mathbf{j}$
14.  $h(x, y) = \tan^{-1}(y/x) + \sqrt{3} \sin^{-1}(xy/2)$ ,  $P_0(1, 1)$ ,  $\mathbf{u} = 3\mathbf{i} - 2\mathbf{j}$
15.  $f(x, y, z) = xy + yz + zx$ ,  $P_0(1, -1, 2)$ ,  $\mathbf{u} = 3\mathbf{i} + 6\mathbf{j} - 2\mathbf{k}$
16.  $f(x, y, z) = x^2 + 2y^2 - 3z^2$ ,  $P_0(1, 1, 1)$ ,  $\mathbf{u} = \mathbf{i} + \mathbf{j} + \mathbf{k}$
17.  $g(x, y, z) = 3e^x \cos yz$ ,  $P_0(0, 0, 0)$ ,  $\mathbf{u} = 2\mathbf{i} + \mathbf{j} - 2\mathbf{k}$
18.  $h(x, y, z) = \cos xy + e^{yz} + \ln zx$ ,  $P_0(1, 0, 1/2)$ ,  $\mathbf{u} = \mathbf{i} + 2\mathbf{j} + 2\mathbf{k}$

In Exercises 19–24, find the directions in which the functions increase and decrease most rapidly at  $P_0$ . Then find the derivatives of the functions in these directions.

19.  $f(x, y) = x^2 + xy + y^2$ ,  $P_0(-1, 1)$
20.  $f(x, y) = x^2y + e^{xy} \sin y$ ,  $P_0(1, 0)$
21.  $f(x, y, z) = (x/y) - yz$ ,  $P_0(4, 1, 1)$
22.  $g(x, y, z) = xe^y + z^2$ ,  $P_0(1, \ln 2, 1/2)$
23.  $f(x, y, z) = \ln xy + \ln yz + \ln xz$ ,  $P_0(1, 1, 1)$
24.  $h(x, y, z) = \ln(x^2 + y^2 - 1) + y + 6z$ ,  $P_0(1, 1, 0)$

## Tangent Lines to Level Curves

In Exercises 25–28, sketch the curve  $f(x, y) = c$  together with  $\nabla f$  and the tangent line at the given point. Then write an equation for the tangent line.

25.  $x^2 + y^2 = 4$ ,  $(\sqrt{2}, \sqrt{2})$
26.  $x^2 - y = 1$ ,  $(\sqrt{2}, 1)$
27.  $xy = -4$ ,  $(2, -2)$
28.  $x^2 - xy + y^2 = 7$ ,  $(-1, 2)$

## Theory and Examples

29. Let  $f(x, y) = x^2 - xy + y^2 - y$ . Find the directions  $\mathbf{u}$  and the values of  $D_{\mathbf{u}}f(1, -1)$  for which

- a.  $D_{\mathbf{u}}f(1, -1)$  is largest
- b.  $D_{\mathbf{u}}f(1, -1)$  is smallest
- c.  $D_{\mathbf{u}}f(1, -1) = 0$
- d.  $D_{\mathbf{u}}f(1, -1) = 4$
- e.  $D_{\mathbf{u}}f(1, -1) = -3$

30. Let  $f(x, y) = \frac{(x - y)}{(x + y)}$ . Find the directions  $\mathbf{u}$  and the values of

$D_{\mathbf{u}}f\left(-\frac{1}{2}, \frac{3}{2}\right)$  for which

- a.  $D_{\mathbf{u}}f\left(-\frac{1}{2}, \frac{3}{2}\right)$  is largest
- b.  $D_{\mathbf{u}}f\left(-\frac{1}{2}, \frac{3}{2}\right)$  is smallest
- c.  $D_{\mathbf{u}}f\left(-\frac{1}{2}, \frac{3}{2}\right) = 0$
- d.  $D_{\mathbf{u}}f\left(-\frac{1}{2}, \frac{3}{2}\right) = -2$
- e.  $D_{\mathbf{u}}f\left(-\frac{1}{2}, \frac{3}{2}\right) = 1$

31. **Zero directional derivative** In what direction is the derivative of  $f(x, y) = xy + y^2$  at  $P(3, 2)$  equal to zero?

32. **Zero directional derivative** In what directions is the derivative of  $f(x, y) = (x^2 - y^2)/(x^2 + y^2)$  at  $P(1, 1)$  equal to zero?

33. Is there a direction  $\mathbf{u}$  in which the rate of change of  $f(x, y) = x^2 - 3xy + 4y^2$  at  $P(1, 2)$  equals 14? Give reasons for your answer.

34. **Changing temperature along a circle** Is there a direction  $\mathbf{u}$  in which the rate of change of the temperature function  $T(x, y, z) = 2xy - yz$  (temperature in degrees Celsius, distance in meters) at  $P(1, -1, 1)$  is  $-3^\circ\text{C}/\text{m}$ ? Give reasons for your answer.

35. The derivative of  $f(x, y)$  at  $P_0(1, 2)$  in the direction of  $\mathbf{i} + \mathbf{j}$  is  $2\sqrt{2}$  and in the direction of  $-2\mathbf{j}$  is  $-3$ . What is the derivative of  $f$  in the direction of  $-\mathbf{i} - 2\mathbf{j}$ ? Give reasons for your answer.

36. The derivative of  $f(x, y, z)$  at a point  $P$  is greatest in the direction of  $\mathbf{v} = \mathbf{i} + \mathbf{j} - \mathbf{k}$ . In this direction, the value of the derivative is  $2\sqrt{3}$ .

a. What is  $\nabla f$  at  $P$ ? Give reasons for your answer.

b. What is the derivative of  $f$  at  $P$  in the direction of  $\mathbf{i} + \mathbf{j}$ ?

37. **Directional derivatives and scalar components** How is the derivative of a differentiable function  $f(x, y, z)$  at a point  $P_0$  in the direction of a unit vector  $\mathbf{u}$  related to the scalar component of  $(\nabla f)_{P_0}$  in the direction of  $\mathbf{u}$ ? Give reasons for your answer.

38. **Directional derivatives and partial derivatives** Assuming that the necessary derivatives of  $f(x, y, z)$  are defined, how are  $D_{\mathbf{i}}f$ ,  $D_{\mathbf{j}}f$ , and  $D_{\mathbf{k}}f$  related to  $f_x$ ,  $f_y$ , and  $f_z$ ? Give reasons for your answer.

39. **Lines in the  $xy$ -plane** Show that  $A(x - x_0) + B(y - y_0) = 0$  is an equation for the line in the  $xy$ -plane through the point  $(x_0, y_0)$  normal to the vector  $\mathbf{N} = A\mathbf{i} + B\mathbf{j}$ .

40. **The algebra rules for gradients** Given a constant  $k$  and the gradients

$$\nabla f = \frac{\partial f}{\partial x} \mathbf{i} + \frac{\partial f}{\partial y} \mathbf{j} + \frac{\partial f}{\partial z} \mathbf{k}, \quad \nabla g = \frac{\partial g}{\partial x} \mathbf{i} + \frac{\partial g}{\partial y} \mathbf{j} + \frac{\partial g}{\partial z} \mathbf{k},$$

establish the algebra rules for gradients.

## Exercises 14.6

### Tangent Planes and Normal Lines to Surfaces

In Exercises 1–8, find equations for the

(a) tangent plane and

(b) normal line at the point  $P_0$  on the given surface.

1.  $x^2 + y^2 + z^2 = 3$ ,  $P_0(1, 1, 1)$
2.  $x^2 + y^2 - z^2 = 18$ ,  $P_0(3, 5, -4)$
3.  $2z - x^2 = 0$ ,  $P_0(2, 0, 2)$
4.  $x^2 + 2xy - y^2 + z^2 = 7$ ,  $P_0(1, -1, 3)$

5.  $\cos \pi x - x^2y + e^{xz} + yz = 4$ ,  $P_0(0, 1, 2)$

6.  $x^2 - xy - y^2 - z = 0$ ,  $P_0(1, 1, -1)$

7.  $x + y + z = 1$ ,  $P_0(0, 1, 0)$

8.  $x^2 + y^2 - 2xy - x + 3y - z = -4$ ,  $P_0(2, -3, 18)$

In Exercises 9–12, find an equation for the plane that is tangent to the given surface at the given point.

9.  $z = \ln(x^2 + y^2)$ ,  $(1, 0, 0)$       10.  $z = e^{-(x^2+y^2)}$ ,  $(0, 0, 1)$

11.  $z = \sqrt{y - x}$ ,  $(1, 2, 1)$       12.  $z = 4x^2 + y^2$ ,  $(1, 1, 5)$

**Tangent Lines to Intersecting Surfaces**

In Exercises 13–18, find parametric equations for the line tangent to the curve of intersection of the surfaces at the given point.

13. Surfaces:  $x + y^2 + 2z = 4$ ,  $x = 1$   
Point:  $(1, 1, 1)$
14. Surfaces:  $xyz = 1$ ,  $x^2 + 2y^2 + 3z^2 = 6$   
Point:  $(1, 1, 1)$
15. Surfaces:  $x^2 + 2y + 2z = 4$ ,  $y = 1$   
Point:  $(1, 1, 1/2)$
16. Surfaces:  $x + y^2 + z = 2$ ,  $y = 1$   
Point:  $(1/2, 1, 1/2)$
17. Surfaces:  $x^3 + 3x^2y^2 + y^3 + 4xy - z^2 = 0$ ,  
 $x^2 + y^2 + z^2 = 11$   
Point:  $(1, 1, 3)$
18. Surfaces:  $x^2 + y^2 = 4$ ,  $x^2 + y^2 - z = 0$   
Point:  $(\sqrt{2}, \sqrt{2}, 4)$

**Estimating Change**

19. By about how much will

$$f(x, y, z) = \ln \sqrt{x^2 + y^2 + z^2}$$

change if the point  $P(x, y, z)$  moves from  $P_0(3, 4, 12)$  a distance of  $ds = 0.1$  unit in the direction of  $3\mathbf{i} + 6\mathbf{j} - 2\mathbf{k}$ ?

20. By about how much will

$$f(x, y, z) = e^x \cos yz$$

change as the point  $P(x, y, z)$  moves from the origin a distance of  $ds = 0.1$  unit in the direction of  $2\mathbf{i} + 2\mathbf{j} - 2\mathbf{k}$ ?

21. By about how much will

$$g(x, y, z) = x + x \cos z - y \sin z + y$$

change if the point  $P(x, y, z)$  moves from  $P_0(2, -1, 0)$  a distance of  $ds = 0.2$  unit toward the point  $P_1(0, 1, 2)$ ?

22. By about how much will

$$h(x, y, z) = \cos(\pi xy) + xz^2$$

change if the point  $P(x, y, z)$  moves from  $P_0(-1, -1, -1)$  a distance of  $ds = 0.1$  unit toward the origin?

23. **Temperature change along a circle** Suppose that the Celsius temperature at the point  $(x, y)$  in the  $xy$ -plane is  $T(x, y) = x \sin 2y$  and that distance in the  $xy$ -plane is measured in meters. A particle is moving *clockwise* around the circle of radius 1 m centered at the origin at the constant rate of 2 m/sec.

- a. How fast is the temperature experienced by the particle changing in degrees Celsius per meter at the point  $P(1/2, \sqrt{3}/2)$ ?
- b. How fast is the temperature experienced by the particle changing in degrees Celsius per second at  $P$ ?

24. **Changing temperature along a space curve** The Celsius temperature in a region in space is given by  $T(x, y, z) = 2x^2 - xyz$ . A particle is moving in this region and its position at time  $t$  is given by  $x = 2t^2$ ,  $y = 3t$ ,  $z = -t^2$ , where time is measured in seconds and distance in meters.

- a. How fast is the temperature experienced by the particle changing in degrees Celsius per meter when the particle is at the point  $P(8, 6, -4)$ ?
- b. How fast is the temperature experienced by the particle changing in degrees Celsius per second at  $P$ ?

**Finding Linearizations**

In Exercises 25–30, find the linearization  $L(x, y)$  of the function at each point.

25.  $f(x, y) = x^2 + y^2 + 1$  at a.  $(0, 0)$ , b.  $(1, 1)$
26.  $f(x, y) = (x + y + 2)^2$  at a.  $(0, 0)$ , b.  $(1, 2)$
27.  $f(x, y) = 3x - 4y + 5$  at a.  $(0, 0)$ , b.  $(1, 1)$
28.  $f(x, y) = x^3y^4$  at a.  $(1, 1)$ , b.  $(0, 0)$
29.  $f(x, y) = e^x \cos y$  at a.  $(0, 0)$ , b.  $(0, \pi/2)$
30.  $f(x, y) = e^{2y-x}$  at a.  $(0, 0)$ , b.  $(1, 2)$

31. **Wind chill factor** Wind chill, a measure of the apparent temperature felt on exposed skin, is a function of air temperature and wind speed. The precise formula, updated by the National Weather Service in 2001 and based on modern heat transfer theory, a human face model, and skin tissue resistance, is (after unit conversion)

$$W = W(v, T) = 13.13 + 0.6215T - 11.36v^{0.16} + 0.396T \cdot v^{0.16},$$

where  $T$  is air temperature in  $^{\circ}\text{C}$  and  $v$  is wind speed in km/h. A partial wind chill chart is given.

		$T(^{\circ}\text{C})$						
		5	0	-5	-10	-15	-20	-25
$v$ (km/h)	10	2.7	-3.3	-9.3	-15.2	-21.2	-27.2	-33.1
	20	1.1	-5.2	-11.5	-17.8	-24.1	-30.4	-36.7
	30	0.1	-6.4	-13.0	-19.5	-26.0	-32.5	-39.0
	40	-0.7	-7.4	-14.0	-20.7	-27.4	-34.1	-40.8
	50	-1.3	-8.1	-14.9	-21.7	-28.5	-35.4	-42.2
	60	-1.8	-8.7	-15.7	-22.6	-29.5	-36.4	-43.3

- a. Use the table to find  $W(30, -5)$ ,  $W(50, -25)$ , and  $W(30, -10)$ .
- b. Use the formula to find  $W(15, -40)$ ,  $W(80, -40)$ , and  $W(90, 0)$ .
- c. Find the linearization  $L(v, T)$  of the function  $W(v, T)$  at the point  $(40, -10)$ .
- d. Use  $L(v, T)$  in part (c) to estimate the following wind chill values.
- i)  $W(39, -9)$  ii)  $W(42, -12)$
- iii)  $W(10, -25)$  (Explain why this value is much different from the value found in the table.)
32. Find the linearization  $L(v, T)$  of the function  $W(v, T)$  in Exercise 31 at the point  $(50, -20)$ . Use it to estimate the following wind chill values.
- a.  $W(49, -22)$
- b.  $W(53, -19)$
- c.  $W(60, -30)$



### Bounding the Error in Linear Approximations

In Exercises 33–38, find the linearization  $L(x, y)$  of the function  $f(x, y)$  at  $P_0$ . Then find an upper bound for the magnitude  $|E|$  of the error in the approximation  $f(x, y) \approx L(x, y)$  over the rectangle  $R$ .

33.  $f(x, y) = x^2 - 3xy + 5$  at  $P_0(2, 1)$ ,  
 $R: |x - 2| \leq 0.1, |y - 1| \leq 0.1$
34.  $f(x, y) = (1/2)x^2 + xy + (1/4)y^2 + 3x - 3y + 4$  at  $P_0(2, 2)$ ,  
 $R: |x - 2| \leq 0.1, |y - 2| \leq 0.1$
35.  $f(x, y) = 1 + y + x \cos y$  at  $P_0(0, 0)$ ,  
 $R: |x| \leq 0.2, |y| \leq 0.2$   
 (Use  $|\cos y| \leq 1$  and  $|\sin y| \leq 1$  in estimating  $E$ .)
36.  $f(x, y) = xy^2 + y \cos(x - 1)$  at  $P_0(1, 2)$ ,  
 $R: |x - 1| \leq 0.1, |y - 2| \leq 0.1$
37.  $f(x, y) = e^x \cos y$  at  $P_0(0, 0)$ ,  
 $R: |x| \leq 0.1, |y| \leq 0.1$   
 (Use  $e^x \leq 1.11$  and  $|\cos y| \leq 1$  in estimating  $E$ .)
38.  $f(x, y) = \ln x + \ln y$  at  $P_0(1, 1)$ ,  
 $R: |x - 1| \leq 0.2, |y - 1| \leq 0.2$

### Linearizations for Three Variables

Find the linearizations  $L(x, y, z)$  of the functions in Exercises 39–44 at the given points.

39.  $f(x, y, z) = xy + yz + xz$  at  $(1, 1, 1)$   
 a.  $(1, 1, 1)$       b.  $(1, 0, 0)$       c.  $(0, 0, 0)$
40.  $f(x, y, z) = x^2 + y^2 + z^2$  at  $(1, 1, 1)$   
 a.  $(1, 1, 1)$       b.  $(0, 1, 0)$       c.  $(1, 0, 0)$
41.  $f(x, y, z) = \sqrt{x^2 + y^2 + z^2}$  at  $(1, 0, 0)$   
 a.  $(1, 0, 0)$       b.  $(1, 1, 0)$       c.  $(1, 2, 2)$
42.  $f(x, y, z) = (\sin xy)/z$  at  $(\pi/2, 1, 1)$   
 a.  $(\pi/2, 1, 1)$       b.  $(2, 0, 1)$
43.  $f(x, y, z) = e^x + \cos(y + z)$  at  $(0, \frac{\pi}{2}, 0)$   
 a.  $(0, 0, 0)$       b.  $(0, \frac{\pi}{2}, 0)$       c.  $(0, \frac{\pi}{4}, \frac{\pi}{4})$
44.  $f(x, y, z) = \tan^{-1}(xyz)$  at  $(1, 0, 0)$   
 a.  $(1, 0, 0)$       b.  $(1, 1, 0)$       c.  $(1, 1, 1)$

In Exercises 45–48, find the linearization  $L(x, y, z)$  of the function  $f(x, y, z)$  at  $P_0$ . Then find an upper bound for the magnitude of the error  $E$  in the approximation  $f(x, y, z) \approx L(x, y, z)$  over the region  $R$ .

45.  $f(x, y, z) = xz - 3yz + 2$  at  $P_0(1, 1, 2)$ ,  
 $R: |x - 1| \leq 0.01, |y - 1| \leq 0.01, |z - 2| \leq 0.02$
46.  $f(x, y, z) = x^2 + xy + yz + (1/4)z^2$  at  $P_0(1, 1, 2)$ ,  
 $R: |x - 1| \leq 0.01, |y - 1| \leq 0.01, |z - 2| \leq 0.08$
47.  $f(x, y, z) = xy + 2yz - 3xz$  at  $P_0(1, 1, 0)$ ,  
 $R: |x - 1| \leq 0.01, |y - 1| \leq 0.01, |z| \leq 0.01$
48.  $f(x, y, z) = \sqrt{2} \cos x \sin(y + z)$  at  $P_0(0, 0, \pi/4)$ ,  
 $R: |x| \leq 0.01, |y| \leq 0.01, |z - \pi/4| \leq 0.01$

### Estimating Error; Sensitivity to Change

49. **Estimating maximum error** Suppose that  $T$  is to be found from the formula  $T = x(e^y + e^{-y})$ , where  $x$  and  $y$  are found to be 2 and  $\ln 2$  with maximum possible errors of  $|dx| = 0.1$  and

$|dy| = 0.02$ . Estimate the maximum possible error in the computed value of  $T$ .

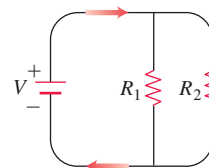
50. **Variation in electrical resistance** The resistance  $R$  produced by wiring resistors of  $R_1$  and  $R_2$  ohms in parallel (see accompanying figure) can be calculated from the formula

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}.$$

- a. Show that

$$dR = \left(\frac{R}{R_1}\right)^2 dR_1 + \left(\frac{R}{R_2}\right)^2 dR_2.$$

- b. You have designed a two-resistor circuit, like the one shown, to have resistances of  $R_1 = 100$  ohms and  $R_2 = 400$  ohms, but there is always some variation in manufacturing and the resistors received by your firm will probably not have these exact values. Will the value of  $R$  be more sensitive to variation in  $R_1$  or to variation in  $R_2$ ? Give reasons for your answer.



- c. In another circuit like the one shown, you plan to change  $R_1$  from 20 to 20.1 ohms and  $R_2$  from 25 to 24.9 ohms. By about what percentage will this change  $R$ ?
51. You plan to calculate the area of a long, thin rectangle from measurements of its length and width. Which dimension should you measure more carefully? Give reasons for your answer.
52. a. Around the point  $(1, 0)$ , is  $f(x, y) = x^2(y + 1)$  more sensitive to changes in  $x$  or to changes in  $y$ ? Give reasons for your answer.  
 b. What ratio of  $dx$  to  $dy$  will make  $df$  equal zero at  $(1, 0)$ ?
53. **Value of a  $2 \times 2$  determinant** If  $|a|$  is much greater than  $|b|$ ,  $|c|$ , and  $|d|$ , to which of  $a$ ,  $b$ ,  $c$ , and  $d$  is the value of the determinant

$$f(a, b, c, d) = \begin{vmatrix} a & b \\ c & d \end{vmatrix}$$

most sensitive? Give reasons for your answer.

54. **The Wilson lot size formula** The Wilson lot size formula in economics says that the most economical quantity  $Q$  of goods (radios, shoes, brooms, whatever) for a store to order is given by the formula  $Q = \sqrt{2KM/h}$ , where  $K$  is the cost of placing the order,  $M$  is the number of items sold per week, and  $h$  is the weekly holding cost for each item (cost of space, utilities, security, and so on). To which of the variables  $K$ ,  $M$ , and  $h$  is  $Q$  most sensitive near the point  $(K_0, M_0, h_0) = (2, 20, 0.05)$ ? Give reasons for your answer.

### Theory and Examples

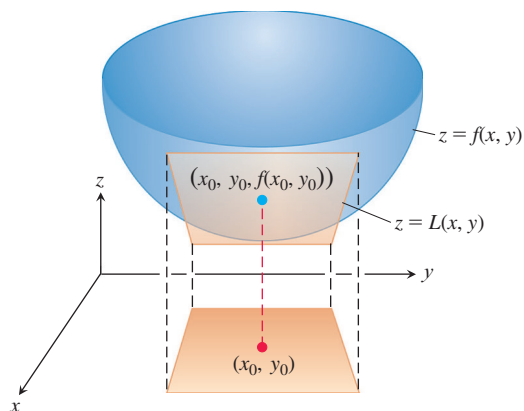
55. **The linearization of  $f(x, y)$  is a tangent-plane approximation** Show that the tangent plane at the point  $P_0(x_0, y_0, f(x_0, y_0))$  on the surface  $z = f(x, y)$  defined by a differentiable function  $f$  is the plane

$$f_x(x_0, y_0)(x - x_0) + f_y(x_0, y_0)(y - y_0) - (z - f(x_0, y_0)) = 0$$

or

$$z = f(x_0, y_0) + f_x(x_0, y_0)(x - x_0) + f_y(x_0, y_0)(y - y_0).$$

Thus, the tangent plane at  $P_0$  is the graph of the linearization of  $f$  at  $P_0$  (see accompanying figure).



**56. Change along the involute of a circle** Find the derivative of  $f(x, y) = x^2 + y^2$  in the direction of the unit tangent vector of the curve

$$\mathbf{r}(t) = (\cos t + t \sin t)\mathbf{i} + (\sin t - t \cos t)\mathbf{j}, \quad t > 0.$$

**57. Tangent curves** A smooth curve is *tangent* to the surface at a point of intersection if its velocity vector is orthogonal to  $\nabla f$  there.

Show that the curve

$$\mathbf{r}(t) = \sqrt{t}\mathbf{i} + \sqrt{t}\mathbf{j} + (2t - 1)\mathbf{k}$$

is tangent to the surface  $x^2 + y^2 - z = 1$  when  $t = 1$ .

**58. Normal curves** A smooth curve is *normal* to a surface  $f(x, y, z) = c$  at a point of intersection if the curve's velocity vector is a nonzero scalar multiple of  $\nabla f$  at the point.

Show that the curve

$$\mathbf{r}(t) = \sqrt{t}\mathbf{i} + \sqrt{t}\mathbf{j} - \frac{1}{4}(t + 3)\mathbf{k}$$

is normal to the surface  $x^2 + y^2 - z = 3$  when  $t = 1$ .

## Exercises 14.7

### Finding Local Extrema

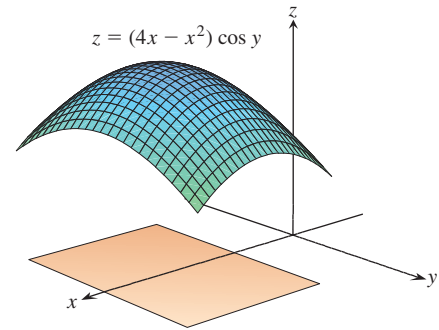
Find all the local maxima, local minima, and saddle points of the functions in Exercises 1–30.

1.  $f(x, y) = x^2 + xy + y^2 + 3x - 3y + 4$
2.  $f(x, y) = 2xy - 5x^2 - 2y^2 + 4x + 4y - 4$
3.  $f(x, y) = x^2 + xy + 3x + 2y + 5$
4.  $f(x, y) = 5xy - 7x^2 + 3x - 6y + 2$
5.  $f(x, y) = 2xy - x^2 - 2y^2 + 3x + 4$
6.  $f(x, y) = x^2 - 4xy + y^2 + 6y + 2$
7.  $f(x, y) = 2x^2 + 3xy + 4y^2 - 5x + 2y$
8.  $f(x, y) = x^2 - 2xy + 2y^2 - 2x + 2y + 1$
9.  $f(x, y) = x^2 - y^2 - 2x + 4y + 6$
10.  $f(x, y) = x^2 + 2xy$
11.  $f(x, y) = \sqrt{56x^2 - 8y^2 - 16x - 31} + 1 - 8x$
12.  $f(x, y) = 1 - \sqrt[3]{x^2 + y^2}$
13.  $f(x, y) = x^3 - y^3 - 2xy + 6$
14.  $f(x, y) = x^3 + 3xy + y^3$
15.  $f(x, y) = 6x^2 - 2x^3 + 3y^2 + 6xy$
16.  $f(x, y) = x^3 + y^3 + 3x^2 - 3y^2 - 8$
17.  $f(x, y) = x^3 + 3xy^2 - 15x + y^3 - 15y$
18.  $f(x, y) = 2x^3 + 2y^3 - 9x^2 + 3y^2 - 12y$
19.  $f(x, y) = 4xy - x^4 - y^4$
20.  $f(x, y) = x^4 + y^4 + 4xy$
21.  $f(x, y) = \frac{1}{x^2 + y^2 - 1}$
22.  $f(x, y) = \frac{1}{x} + xy + \frac{1}{y}$
23.  $f(x, y) = y \sin x$
24.  $f(x, y) = e^{2x} \cos y$
25.  $f(x, y) = e^{x^2 + y^2 - 4x}$
26.  $f(x, y) = e^y - ye^x$
27.  $f(x, y) = e^{-y}(x^2 + y^2)$
28.  $f(x, y) = e^x(x^2 - y^2)$
29.  $f(x, y) = 2 \ln x + \ln y - 4x - y$
30.  $f(x, y) = \ln(x + y) + x^2 - y$

### Finding Absolute Extrema

In Exercises 31–38, find the absolute maxima and minima of the functions on the given domains.

31.  $f(x, y) = 2x^2 - 4x + y^2 - 4y + 1$  on the closed triangular plate bounded by the lines  $x = 0$ ,  $y = 2$ ,  $y = 2x$  in the first quadrant
32.  $D(x, y) = x^2 - xy + y^2 + 1$  on the closed triangular plate in the first quadrant bounded by the lines  $x = 0$ ,  $y = 4$ ,  $y = x$
33.  $f(x, y) = x^2 + y^2$  on the closed triangular plate bounded by the lines  $x = 0$ ,  $y = 0$ ,  $y + 2x = 2$  in the first quadrant
34.  $T(x, y) = x^2 + xy + y^2 - 6x$  on the rectangular plate  $0 \leq x \leq 5$ ,  $-3 \leq y \leq 3$
35.  $T(x, y) = x^2 + xy + y^2 - 6x + 2$  on the rectangular plate  $0 \leq x \leq 5$ ,  $-3 \leq y \leq 0$
36.  $f(x, y) = 48xy - 32x^3 - 24y^2$  on the rectangular plate  $0 \leq x \leq 1$ ,  $0 \leq y \leq 1$
37.  $f(x, y) = (4x - x^2) \cos y$  on the rectangular plate  $1 \leq x \leq 3$ ,  $-\pi/4 \leq y \leq \pi/4$  (see accompanying figure)



38.  $f(x, y) = 4x - 8xy + 2y + 1$  on the triangular plate bounded by the lines  $x = 0$ ,  $y = 0$ ,  $x + y = 1$  in the first quadrant
39. Find two numbers  $a$  and  $b$  with  $a \leq b$  such that

$$\int_a^b (6 - x - x^2) dx$$

has its largest value.

40. Find two numbers  $a$  and  $b$  with  $a \leq b$  such that

$$\int_a^b (24 - 2x - x^2)^{1/3} dx$$

has its largest value.

41. **Temperatures** A flat circular plate has the shape of the region  $x^2 + y^2 \leq 1$ . The plate, including the boundary where  $x^2 + y^2 = 1$ , is heated so that the temperature at the point  $(x, y)$  is

$$T(x, y) = x^2 + 2y^2 - x.$$

Find the temperatures at the hottest and coldest points on the plate.

42. Find the critical point of

$$f(x, y) = xy + 2x - \ln x^2y$$

in the open first quadrant ( $x > 0$ ,  $y > 0$ ) and show that  $f$  takes on a minimum there.

### Theory and Examples

43. Find the maxima, minima, and saddle points of  $f(x, y)$ , if any, given that
  - a.  $f_x = 2x - 4y$  and  $f_y = 2y - 4x$
  - b.  $f_x = 2x - 2$  and  $f_y = 2y - 4$
  - c.  $f_x = 9x^2 - 9$  and  $f_y = 2y + 4$
 Describe your reasoning in each case.
44. The discriminant  $f_{xx}f_{yy} - f_{xy}^2$  is zero at the origin for each of the following functions, so the Second Derivative Test fails there. Determine whether the function has a maximum, a minimum, or neither at the origin by imagining what the surface  $z = f(x, y)$  looks like. Describe your reasoning in each case.
  - a.  $f(x, y) = x^2y^2$
  - b.  $f(x, y) = 1 - x^2y^2$
  - c.  $f(x, y) = xy^2$
  - d.  $f(x, y) = x^3y^2$
  - e.  $f(x, y) = x^3y^3$
  - f.  $f(x, y) = x^4y^4$

45. Show that  $(0, 0)$  is a critical point of  $f(x, y) = x^2 + kxy + y^2$  no matter what value the constant  $k$  has. (*Hint:* Consider two cases:  $k = 0$  and  $k \neq 0$ .)
46. For what values of the constant  $k$  does the Second Derivative Test guarantee that  $f(x, y) = x^2 + kxy + y^2$  will have a saddle point at  $(0, 0)$ ? A local minimum at  $(0, 0)$ ? For what values of  $k$  is the Second Derivative Test inconclusive? Give reasons for your answers.
47. If  $f_x(a, b) = f_y(a, b) = 0$ , must  $f$  have a local maximum or minimum value at  $(a, b)$ ? Give reasons for your answer.
48. Can you conclude anything about  $f(a, b)$  if  $f$  and its first and second partial derivatives are continuous throughout a disk centered at the critical point  $(a, b)$  and  $f_{xx}(a, b)$  and  $f_{yy}(a, b)$  differ in sign? Give reasons for your answer.
49. Among all the points on the graph of  $z = 10 - x^2 - y^2$  that lie above the plane  $x + 2y + 3z = 0$ , find the point farthest from the plane.
50. Find the point on the graph of  $z = x^2 + y^2 + 10$  nearest the plane  $x + 2y - z = 0$ .
51. Find the point on the plane  $3x + 2y + z = 6$  that is nearest the origin.
52. Find the minimum distance from the point  $(2, -1, 1)$  to the plane  $x + y - z = 2$ .
53. Find three numbers whose sum is 9 and whose sum of squares is a minimum.
54. Find three positive numbers whose sum is 3 and whose product is a maximum.
55. Find the maximum value of  $s = xy + yz + xz$  where  $x + y + z = 6$ .
56. Find the minimum distance from the cone  $z = \sqrt{x^2 + y^2}$  to the point  $(-6, 4, 0)$ .
57. Find the dimensions of the rectangular box of maximum volume that can be inscribed inside the sphere  $x^2 + y^2 + z^2 = 4$ .
58. Among all closed rectangular boxes of volume  $27 \text{ cm}^3$ , what is the smallest surface area?
59. You are to construct an open rectangular box from  $12 \text{ m}^2$  of material. What dimensions will result in a box of maximum volume?
60. Consider the function  $f(x, y) = x^2 + y^2 + 2xy - x - y + 1$  over the square  $0 \leq x \leq 1$  and  $0 \leq y \leq 1$ .
- Show that  $f$  has an absolute minimum along the line segment  $2x + 2y = 1$  in this square. What is the absolute minimum value?
  - Find the absolute maximum value of  $f$  over the square.

**Extreme Values on Parametrized Curves** To find the extreme values of a function  $f(x, y)$  on a curve  $x = x(t)$ ,  $y = y(t)$ , we treat  $f$  as a function of the single variable  $t$  and use the Chain Rule to find where  $df/dt$  is zero. As in any other single-variable case, the extreme values of  $f$  are then found among the values at the

- critical points (points where  $df/dt$  is zero or fails to exist), and
- endpoints of the parameter domain.

Find the absolute maximum and minimum values of the following functions on the given curves.

61. Functions:

a.  $f(x, y) = x + y$     b.  $g(x, y) = xy$     c.  $h(x, y) = 2x^2 + y^2$

Curves:

i) The semicircle  $x^2 + y^2 = 4$ ,  $y \geq 0$

ii) The quarter circle  $x^2 + y^2 = 4$ ,  $x \geq 0$ ,  $y \geq 0$

Use the parametric equations  $x = 2 \cos t$ ,  $y = 2 \sin t$ .

62. Functions:

a.  $f(x, y) = 2x + 3y$

b.  $g(x, y) = xy$

c.  $h(x, y) = x^2 + 3y^2$

Curves:

i) The semiellipse  $(x^2/9) + (y^2/4) = 1$ ,  $y \geq 0$

ii) The quarter ellipse  $(x^2/9) + (y^2/4) = 1$ ,  $x \geq 0$ ,  $y \geq 0$

Use the parametric equations  $x = 3 \cos t$ ,  $y = 2 \sin t$ .

63. Function:  $f(x, y) = xy$

Curves:

i) The line  $x = 2t$ ,  $y = t + 1$

ii) The line segment  $x = 2t$ ,  $y = t + 1$ ,  $-1 \leq t \leq 0$

iii) The line segment  $x = 2t$ ,  $y = t + 1$ ,  $0 \leq t \leq 1$

64. Functions:

a.  $f(x, y) = x^2 + y^2$

b.  $g(x, y) = 1/(x^2 + y^2)$

Curves:

i) The line  $x = t$ ,  $y = 2 - 2t$

ii) The line segment  $x = t$ ,  $y = 2 - 2t$ ,  $0 \leq t \leq 1$

**65. Least squares and regression lines** When we try to fit a line  $y = mx + b$  to a set of numerical data points  $(x_1, y_1)$ ,  $(x_2, y_2)$ ,  $\dots$ ,  $(x_n, y_n)$ , we usually choose the line that minimizes the sum of the squares of the vertical distances from the points to the line. In theory, this means finding the values of  $m$  and  $b$  that minimize the value of the function

$$w = (mx_1 + b - y_1)^2 + \cdots + (mx_n + b - y_n)^2. \quad (1)$$

(See the accompanying figure.) Show that the values of  $m$  and  $b$  that do this are

$$m = \frac{\left(\sum x_k\right)\left(\sum y_k\right) - n \sum x_k y_k}{\left(\sum x_k\right)^2 - n \sum x_k^2}, \quad (2)$$

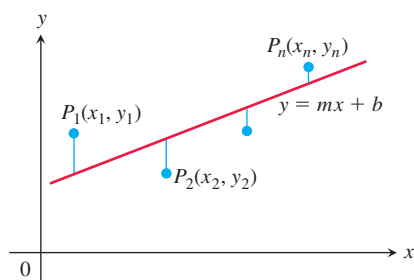
$$b = \frac{1}{n} \left( \sum y_k - m \sum x_k \right), \quad (3)$$

with all sums running from  $k = 1$  to  $k = n$ . Many scientific calculators have these formulas built in, enabling you to find  $m$  and  $b$  with only a few keystrokes after you have entered the data.

The line  $y = mx + b$  determined by these values of  $m$  and  $b$  is called the **least squares line**, **regression line**, or **trend line** for the data under study. Finding a least squares line lets you

- summarize data with a simple expression,
- predict values of  $y$  for other, experimentally untried values of  $x$ ,
- handle data analytically.

We demonstrated these ideas with a variety of applications in Section 1.4.



In Exercises 66–68, use Equations (2) and (3) to find the least squares line for each set of data points. Then use the linear equation you obtain to predict the value of  $y$  that would correspond to  $x = 4$ .

66.  $(-2, 0), (0, 2), (2, 3)$       67.  $(-1, 2), (0, 1), (3, -4)$

68.  $(0, 0), (1, 2), (2, 3)$

### COMPUTER EXPLORATIONS

In Exercises 69–74, you will explore functions to identify their local extrema. Use a CAS to perform the following steps:

- Plot the function over the given rectangle.
- Plot some level curves in the rectangle.

c. Calculate the function's first partial derivatives and use the CAS equation solver to find the critical points. How do the critical points relate to the level curves plotted in part (b)? Which critical points, if any, appear to give a saddle point? Give reasons for your answer.

d. Calculate the function's second partial derivatives and find the discriminant  $f_{xx}f_{yy} - f_{xy}^2$ .

e. Using the max-min tests, classify the critical points found in part (c). Are your findings consistent with your discussion in part (c)?

69.  $f(x, y) = x^2 + y^3 - 3xy, \quad -5 \leq x \leq 5, \quad -5 \leq y \leq 5$

70.  $f(x, y) = x^3 - 3xy^2 + y^2, \quad -2 \leq x \leq 2, \quad -2 \leq y \leq 2$

71.  $f(x, y) = x^4 + y^2 - 8x^2 - 6y + 16, \quad -3 \leq x \leq 3, \quad -6 \leq y \leq 6$

72.  $f(x, y) = 2x^4 + y^4 - 2x^2 - 2y^2 + 3, \quad -3/2 \leq x \leq 3/2, \quad -3/2 \leq y \leq 3/2$

73.  $f(x, y) = 5x^6 + 18x^5 - 30x^4 + 30xy^2 - 120x^3, \quad -4 \leq x \leq 3, \quad -2 \leq y \leq 2$

74.  $f(x, y) = \begin{cases} x^5 \ln(x^2 + y^2), & (x, y) \neq (0, 0) \\ 0, & (x, y) = (0, 0) \end{cases}, \quad -2 \leq x \leq 2, \quad -2 \leq y \leq 2$

## Exercises 14.8

## Two Independent Variables with One Constraint

1. **Extrema on an ellipse** Find the points on the ellipse  $x^2 + 2y^2 = 1$  where  $f(x, y) = xy$  has its extreme values.
2. **Extrema on a circle** Find the extreme values of  $f(x, y) = xy$  subject to the constraint  $g(x, y) = x^2 + y^2 - 10 = 0$ .
3. **Maximum on a line** Find the maximum value of  $f(x, y) = 49 - x^2 - y^2$  on the line  $x + 3y = 10$ .
4. **Extrema on a line** Find the local extreme values of  $f(x, y) = x^2y$  on the line  $x + y = 3$ .
5. **Constrained minimum** Find the points on the curve  $xy^2 = 54$  nearest the origin.
6. **Constrained minimum** Find the points on the curve  $x^2y = 2$  nearest the origin.
7. Use the method of Lagrange multipliers to find
  - a. **Minimum on a hyperbola** The minimum value of  $x + y$ , subject to the constraints  $xy = 16, x > 0, y > 0$
  - b. **Maximum on a line** The maximum value of  $xy$ , subject to the constraint  $x + y = 16$ .

Comment on the geometry of each solution.

8. **Extrema on a curve** Find the points on the curve  $x^2 + xy + y^2 = 1$  in the  $xy$ -plane that are nearest to and farthest from the origin.
9. **Minimum surface area with fixed volume** Find the dimensions of the closed right circular cylindrical can of smallest surface area whose volume is  $16\pi \text{ cm}^3$ .

10. **Cylinder in a sphere** Find the radius and height of the open right circular cylinder of largest surface area that can be inscribed in a sphere of radius  $a$ . What is the largest surface area?
11. **Rectangle of greatest area in an ellipse** Use the method of Lagrange multipliers to find the dimensions of the rectangle of greatest area that can be inscribed in the ellipse  $x^2/16 + y^2/9 = 1$  with sides parallel to the coordinate axes.
12. **Rectangle of longest perimeter in an ellipse** Find the dimensions of the rectangle of largest perimeter that can be inscribed in the ellipse  $x^2/a^2 + y^2/b^2 = 1$  with sides parallel to the coordinate axes. What is the largest perimeter?
13. **Extrema on a circle** Find the maximum and minimum values of  $x^2 + y^2$  subject to the constraint  $x^2 - 2x + y^2 - 4y = 0$ .
14. **Extrema on a circle** Find the maximum and minimum values of  $3x - y + 6$  subject to the constraint  $x^2 + y^2 = 4$ .
15. **Ant on a metal plate** The temperature at a point  $(x, y)$  on a metal plate is  $T(x, y) = 4x^2 - 4xy + y^2$ . An ant on the plate walks around the circle of radius 5 centered at the origin. What are the highest and lowest temperatures encountered by the ant?
16. **Cheapest storage tank** Your firm has been asked to design a storage tank for liquid petroleum gas. The customer's specifications call for a cylindrical tank with hemispherical ends, and the tank is to hold  $8000 \text{ m}^3$  of gas. The customer also wants to use the smallest amount of material possible in building the tank. What radius and height do you recommend for the cylindrical portion of the tank?

### Three Independent Variables with One Constraint

- 17. Minimum distance to a point** Find the point on the plane  $x + 2y + 3z = 13$  closest to the point  $(1, 1, 1)$ .
- 18. Maximum distance to a point** Find the point on the sphere  $x^2 + y^2 + z^2 = 4$  farthest from the point  $(1, -1, 1)$ .
- 19. Minimum distance to the origin** Find the minimum distance from the surface  $x^2 - y^2 - z^2 = 1$  to the origin.
- 20. Minimum distance to the origin** Find the point on the surface  $z = xy + 1$  nearest the origin.
- 21. Minimum distance to the origin** Find the points on the surface  $z^2 = xy + 4$  closest to the origin.
- 22. Minimum distance to the origin** Find the point(s) on the surface  $xyz = 1$  closest to the origin.
- 23. Extrema on a sphere** Find the maximum and minimum values of

$$f(x, y, z) = x - 2y + 5z$$

on the sphere  $x^2 + y^2 + z^2 = 30$ .

- 24. Extrema on a sphere** Find the points on the sphere  $x^2 + y^2 + z^2 = 25$  where  $f(x, y, z) = x + 2y + 3z$  has its maximum and minimum values.
- 25. Minimizing a sum of squares** Find three real numbers whose sum is 9 and the sum of whose squares is as small as possible.
- 26. Maximizing a product** Find the largest product the positive numbers  $x$ ,  $y$ , and  $z$  can have if  $x + y + z^2 = 16$ .
- 27. Rectangular box of largest volume in a sphere** Find the dimensions of the closed rectangular box with maximum volume that can be inscribed in the unit sphere.
- 28. Box with vertex on a plane** Find the volume of the largest closed rectangular box in the first octant having three faces in the coordinate planes and a vertex on the plane  $x/a + y/b + z/c = 1$ , where  $a > 0$ ,  $b > 0$ , and  $c > 0$ .
- 29. Hottest point on a space probe** A space probe in the shape of the ellipsoid

$$4x^2 + y^2 + 4z^2 = 16$$

enters Earth's atmosphere and its surface begins to heat. After 1 hour, the temperature at the point  $(x, y, z)$  on the probe's surface is

$$T(x, y, z) = 8x^2 + 4yz - 16z + 600.$$

Find the hottest point on the probe's surface.

- 30. Extreme temperatures on a sphere** Suppose that the Celsius temperature at the point  $(x, y, z)$  on the sphere  $x^2 + y^2 + z^2 = 1$  is  $T = 400xyz^2$ . Locate the highest and lowest temperatures on the sphere.
- 31. Cobb-Douglas production function** During the 1920s, Charles Cobb and Paul Douglas modeled total production output  $P$  (of a firm, industry, or entire economy) as a function of labor hours involved  $x$  and capital invested  $y$  (which includes the monetary worth of all buildings and equipment). The Cobb-Douglas production function is given by

$$P(x, y) = kx^\alpha y^{1-\alpha},$$

where  $k$  and  $\alpha$  are constants representative of a particular firm or economy.

- a. Show that a doubling of both labor and capital results in a doubling of production  $P$ .
- b. Suppose a particular firm has the production function for  $k = 120$  and  $\alpha = 3/4$ . Assume that each unit of labor costs \$250 and each unit of capital costs \$400, and that the total expenses for all costs cannot exceed \$100,000. Find the maximum production level for the firm.

- 32. (Continuation of Exercise 31.)** If the cost of a unit of labor is  $c_1$  and the cost of a unit of capital is  $c_2$ , and if the firm can spend only  $B$  dollars as its total budget, then production  $P$  is constrained by  $c_1x + c_2y = B$ . Show that the maximum production level subject to the constraint occurs at the point

$$x = \frac{\alpha B}{c_1} \quad \text{and} \quad y = \frac{(1 - \alpha)B}{c_2}.$$

- 33. Maximizing a utility function: an example from economics** In economics, the usefulness or *utility* of amounts  $x$  and  $y$  of two capital goods  $G_1$  and  $G_2$  is sometimes measured by a function  $U(x, y)$ . For example,  $G_1$  and  $G_2$  might be two chemicals a pharmaceutical company needs to have on hand and  $U(x, y)$  the gain from manufacturing a product whose synthesis requires different amounts of the chemicals depending on the process used. If  $G_1$  costs  $a$  dollars per kilogram,  $G_2$  costs  $b$  dollars per kilogram, and the total amount allocated for the purchase of  $G_1$  and  $G_2$  together is  $c$  dollars, then the company's managers want to maximize  $U(x, y)$  given that  $ax + by = c$ . Thus, they need to solve a typical Lagrange multiplier problem.

Suppose that

$$U(x, y) = xy + 2x$$

and that the equation  $ax + by = c$  simplifies to

$$2x + y = 30.$$

Find the maximum value of  $U$  and the corresponding values of  $x$  and  $y$  subject to this latter constraint.

- 34. Blood types** Human blood types are classified by three gene forms  $A$ ,  $B$ , and  $O$ . Blood types  $AA$ ,  $BB$ , and  $OO$  are *homozygous*, and blood types  $AB$ ,  $AO$ , and  $BO$  are *heterozygous*. If  $p$ ,  $q$ , and  $r$  represent the proportions of the three gene forms to the population, respectively, then the *Hardy-Weinberg Law* asserts that the proportion  $Q$  of heterozygous persons in any specific population is modeled by

$$Q(p, q, r) = 2(pq + pr + qr),$$

subject to  $p + q + r = 1$ . Find the maximum value of  $Q$ .

- 35. Length of a beam** In Section 4.5, Exercise 39, we posed a problem of finding the length  $L$  of the shortest beam that can reach over a wall of height  $h$  to a tall building located  $k$  units from the wall. Use Lagrange multipliers to show that

$$L = (h^{2/3} + k^{2/3})^{3/2}.$$

- 36. Locating a radio telescope** You are in charge of erecting a radio telescope on a newly discovered planet. To minimize interference, you want to place it where the magnetic field of the planet is weakest. The planet is spherical, with a radius of 6 units. Based on a coordinate system whose origin is at the center of the planet, the strength of the magnetic field is given by  $M(x, y, z) = 6x - y^2 + xz + 60$ . Where should you locate the radio telescope?



## Extreme Values Subject to Two Constraints

37. Maximize the function  $f(x, y, z) = x^2 + 2y - z^2$  subject to the constraints  $2x - y = 0$  and  $y + z = 0$ .
38. Minimize the function  $f(x, y, z) = x^2 + y^2 + z^2$  subject to the constraints  $x + 2y + 3z = 6$  and  $x + 3y + 9z = 9$ .
39. **Minimum distance to the origin** Find the point closest to the origin on the line of intersection of the planes  $y + 2z = 12$  and  $x + y = 6$ .
40. **Maximum value on line of intersection** Find the maximum value that  $f(x, y, z) = x^2 + 2y - z^2$  can have on the line of intersection of the planes  $2x - y = 0$  and  $y + z = 0$ .
41. **Extrema on a curve of intersection** Find the extreme values of  $f(x, y, z) = x^2yz + 1$  on the intersection of the plane  $z = 1$  with the sphere  $x^2 + y^2 + z^2 = 10$ .
42. a. **Maximum on line of intersection** Find the maximum value of  $w = xyz$  on the line of intersection of the two planes  $x + y + z = 40$  and  $x + y - z = 0$ .  
b. Give a geometric argument to support your claim that you have found a maximum, and not a minimum, value of  $w$ .
43. **Extrema on a circle of intersection** Find the extreme values of the function  $f(x, y, z) = xy + z^2$  on the circle in which the plane  $y - x = 0$  intersects the sphere  $x^2 + y^2 + z^2 = 4$ .
44. **Minimum distance to the origin** Find the point closest to the origin on the curve of intersection of the plane  $2y + 4z = 5$  and the cone  $z^2 = 4x^2 + 4y^2$ .

## Theory and Examples

45. **The condition  $\nabla f = \lambda \nabla g$  is not sufficient** Although  $\nabla f = \lambda \nabla g$  is a necessary condition for the occurrence of an extreme value of  $f(x, y)$  subject to the conditions  $g(x, y) = 0$  and  $\nabla g \neq \mathbf{0}$ , it does not in itself guarantee that one exists. As a case in point, try using the method of Lagrange multipliers to find a maximum value of  $f(x, y) = x + y$  subject to the constraint that  $xy = 16$ . The method will identify the two points  $(4, 4)$  and  $(-4, -4)$  as candidates for the location of extreme values. Yet the sum  $(x + y)$  has no maximum value on the hyperbola  $xy = 16$ . The farther you go from the origin on this hyperbola in the first quadrant, the larger the sum  $f(x, y) = x + y$  becomes.
46. **A least squares plane** The plane  $z = Ax + By + C$  is to be “fitted” to the following points  $(x_k, y_k, z_k)$ :

$$(0, 0, 0), \quad (0, 1, 1), \quad (1, 1, 1), \quad (1, 0, -1).$$

Find the values of  $A$ ,  $B$ , and  $C$  that minimize

$$\sum_{k=1}^4 (Ax_k + By_k + C - z_k)^2,$$

the sum of the squares of the deviations.

47. a. **Maximum on a sphere** Show that the maximum value of  $a^2b^2c^2$  on a sphere of radius  $r$  centered at the origin of a Cartesian  $abc$ -coordinate system is  $(r^2/3)^3$ .  
b. **Geometric and arithmetic means** Using part (a), show that for nonnegative numbers  $a$ ,  $b$ , and  $c$ ,

$$(abc)^{1/3} \leq \frac{a + b + c}{3};$$

that is, the *geometric mean* of three nonnegative numbers is less than or equal to their *arithmetic mean*.

48. **Sum of products** Let  $a_1, a_2, \dots, a_n$  be  $n$  positive numbers. Find the maximum of  $\sum_{i=1}^n a_i x_i$  subject to the constraint  $\sum_{i=1}^n x_i^2 = 1$ .

## COMPUTER EXPLORATIONS

In Exercises 49–54, use a CAS to perform the following steps implementing the method of Lagrange multipliers for finding constrained extrema:

- Form the function  $h = f - \lambda_1 g_1 - \lambda_2 g_2$ , where  $f$  is the function to optimize subject to the constraints  $g_1 = 0$  and  $g_2 = 0$ .
  - Determine all the first partial derivatives of  $h$ , including the partials with respect to  $\lambda_1$  and  $\lambda_2$ , and set them equal to 0.
  - Solve the system of equations found in part (b) for all the unknowns, including  $\lambda_1$  and  $\lambda_2$ .
  - Evaluate  $f$  at each of the solution points found in part (c) and select the extreme value subject to the constraints asked for in the exercise.
49. Minimize  $f(x, y, z) = xy + yz$  subject to the constraints  $x^2 + y^2 - 2 = 0$  and  $x^2 + z^2 - 2 = 0$ .
50. Minimize  $f(x, y, z) = xyz$  subject to the constraints  $x^2 + y^2 - 1 = 0$  and  $x - z = 0$ .
51. Maximize  $f(x, y, z) = x^2 + y^2 + z^2$  subject to the constraints  $2y + 4z - 5 = 0$  and  $4x^2 + 4y^2 - z^2 = 0$ .
52. Minimize  $f(x, y, z) = x^2 + y^2 + z^2$  subject to the constraints  $x^2 - xy + y^2 - z^2 - 1 = 0$  and  $x^2 + y^2 - 1 = 0$ .
53. Minimize  $f(x, y, z, w) = x^2 + y^2 + z^2 + w^2$  subject to the constraints  $2x - y + z - w - 1 = 0$  and  $x + y - z + w - 1 = 0$ .
54. Determine the distance from the line  $y = x + 1$  to the parabola  $y^2 = x$ . (Hint: Let  $(x, y)$  be a point on the line and  $(w, z)$  a point on the parabola. You want to minimize  $(x - w)^2 + (y - z)^2$ .)



## Exercises 14.9

## Finding Quadratic and Cubic Approximations

In Exercises 1–10, use Taylor's formula for  $f(x, y)$  at the origin to find quadratic and cubic approximations of  $f$  near the origin.

1.  $f(x, y) = xe^y$
2.  $f(x, y) = e^x \cos y$
3.  $f(x, y) = y \sin x$
4.  $f(x, y) = \sin x \cos y$
5.  $f(x, y) = e^x \ln(1 + y)$
6.  $f(x, y) = \ln(2x + y + 1)$
7.  $f(x, y) = \sin(x^2 + y^2)$
8.  $f(x, y) = \cos(x^2 + y^2)$

9.  $f(x, y) = \frac{1}{1 - x - y}$

10.  $f(x, y) = \frac{1}{1 - x - y + xy}$

11. Use Taylor's formula to find a quadratic approximation of  $f(x, y) = \cos x \cos y$  at the origin. Estimate the error in the approximation if  $|x| \leq 0.1$  and  $|y| \leq 0.1$ .
12. Use Taylor's formula to find a quadratic approximation of  $e^x \sin y$  at the origin. Estimate the error in the approximation if  $|x| \leq 0.1$  and  $|y| \leq 0.1$ .

## Exercises 15.1

## Evaluating Iterated Integrals

In Exercises 1–14, evaluate the iterated integral.

1.  $\int_1^2 \int_0^4 2xy \, dy \, dx$
2.  $\int_0^2 \int_{-1}^1 (x - y) \, dy \, dx$
3.  $\int_{-1}^0 \int_{-1}^1 (x + y + 1) \, dx \, dy$
4.  $\int_0^1 \int_0^1 \left(1 - \frac{x^2 + y^2}{2}\right) \, dx \, dy$
5.  $\int_0^3 \int_0^2 (4 - y^2) \, dy \, dx$
6.  $\int_0^3 \int_{-2}^0 (x^2y - 2xy) \, dy \, dx$
7.  $\int_0^1 \int_0^1 \frac{y}{1 + xy} \, dx \, dy$
8.  $\int_1^4 \int_0^4 \left(\frac{x}{2} + \sqrt{y}\right) \, dx \, dy$
9.  $\int_0^{\ln 2} \int_1^{\ln 5} e^{2x+y} \, dy \, dx$
10.  $\int_0^1 \int_1^2 xye^x \, dy \, dx$
11.  $\int_{-1}^2 \int_0^{\pi/2} y \sin x \, dx \, dy$
12.  $\int_{-\pi}^{2\pi} \int_0^{\pi} (\sin x + \cos y) \, dx \, dy$

$$13. \int_1^4 \int_1^e \frac{\ln x}{xy} \, dx \, dy \qquad 14. \int_{-1}^2 \int_1^2 x \ln y \, dy \, dx$$

## Evaluating Double Integrals over Rectangles

In Exercises 15–22, evaluate the double integral over the given region  $R$ .

15.  $\iint_R (6y^2 - 2x) \, dA$ ,  $R: 0 \leq x \leq 1, 0 \leq y \leq 2$
16.  $\iint_R \left(\frac{\sqrt{x}}{y^2}\right) \, dA$ ,  $R: 0 \leq x \leq 4, 1 \leq y \leq 2$
17.  $\iint_R xy \cos y \, dA$ ,  $R: -1 \leq x \leq 1, 0 \leq y \leq \pi$
18.  $\iint_R y \sin(x + y) \, dA$ ,  $R: -\pi \leq x \leq 0, 0 \leq y \leq \pi$

19.  $\iint_R e^{x-y} dA, \quad R: 0 \leq x \leq \ln 2, \quad 0 \leq y \leq \ln 2$

20.  $\iint_R xy e^{xy^2} dA, \quad R: 0 \leq x \leq 2, \quad 0 \leq y \leq 1$

21.  $\iint_R \frac{xy^3}{x^2 + 1} dA, \quad R: 0 \leq x \leq 1, \quad 0 \leq y \leq 2$

22.  $\iint_R \frac{y}{x^2 y^2 + 1} dA, \quad R: 0 \leq x \leq 1, \quad 0 \leq y \leq 1$

In Exercises 23 and 24, integrate  $f$  over the given region.

23. **Square**  $f(x, y) = 1/(xy)$  over the square  $1 \leq x \leq 2, 1 \leq y \leq 2$

24. **Rectangle**  $f(x, y) = y \cos xy$  over the rectangle  $0 \leq x \leq \pi, 0 \leq y \leq 1$

25. Find the volume of the region bounded above by the paraboloid  $z = x^2 + y^2$  and below by the square  $R: -1 \leq x \leq 1, -1 \leq y \leq 1$ .

26. Find the volume of the region bounded above by the elliptical paraboloid  $z = 16 - x^2 - y^2$  and below by the square  $R: 0 \leq x \leq 2, 0 \leq y \leq 2$ .

27. Find the volume of the region bounded above by the plane  $z = 2 - x - y$  and below by the square  $R: 0 \leq x \leq 1, 0 \leq y \leq 1$ .

28. Find the volume of the region bounded above by the plane  $z = y/2$  and below by the rectangle  $R: 0 \leq x \leq 4, 0 \leq y \leq 2$ .

29. Find the volume of the region bounded above by the surface  $z = 2 \sin x \cos y$  and below by the rectangle  $R: 0 \leq x \leq \pi/2, 0 \leq y \leq \pi/4$ .

30. Find the volume of the region bounded above by the surface  $z = 4 - y^2$  and below by the rectangle  $R: 0 \leq x \leq 1, 0 \leq y \leq 2$ .

31. Find a value of the constant  $k$  so that  $\int_1^2 \int_0^3 kx^2 y \, dx \, dy = 1$ .

32. Evaluate  $\int_{-1}^1 \int_0^{\pi/2} x \sin \sqrt{y} \, dy \, dx$ .

33. Use Fubini's Theorem to evaluate

$$\int_0^2 \int_0^1 \frac{x}{1 + xy} \, dx \, dy.$$

34. Use Fubini's Theorem to evaluate

$$\int_0^1 \int_0^3 x e^{xy} \, dx \, dy.$$

**T** 35. Use a software application to compute the integrals

a.  $\int_0^1 \int_0^2 \frac{y - x}{(x + y)^3} \, dx \, dy$

b.  $\int_0^2 \int_0^1 \frac{y - x}{(x + y)^3} \, dy \, dx$

Explain why your results do not contradict Fubini's Theorem.

36. If  $f(x, y)$  is continuous over  $R: a \leq x \leq b, c \leq y \leq d$  and

$$F(x, y) = \int_a^x \int_c^y f(u, v) \, dv \, du$$

on the interior of  $R$ , find the second partial derivatives  $F_{xy}$  and  $F_{yx}$ .

## Exercises 15.2

## Sketching Regions of Integration

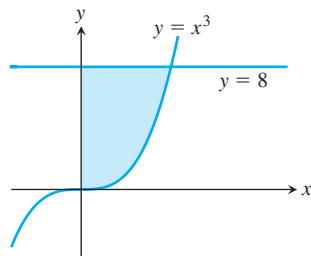
In Exercises 1–8, sketch the described regions of integration.

- $0 \leq x \leq 3, 0 \leq y \leq 2x$
- $-1 \leq x \leq 2, x - 1 \leq y \leq x^2$
- $-2 \leq y \leq 2, y^2 \leq x \leq 4$
- $0 \leq y \leq 1, y \leq x \leq 2y$
- $0 \leq x \leq 1, e^x \leq y \leq e$
- $1 \leq x \leq e^2, 0 \leq y \leq \ln x$
- $0 \leq y \leq 1, 0 \leq x \leq \sin^{-1} y$
- $0 \leq y \leq 8, \frac{1}{4}y \leq x \leq y^{1/3}$

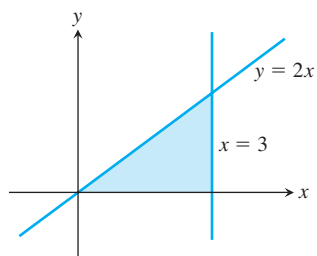
## Finding Limits of Integration

In Exercises 9–18, write an iterated integral for  $\iint_R dA$  over the described region  $R$  using (a) vertical cross-sections, (b) horizontal cross-sections.

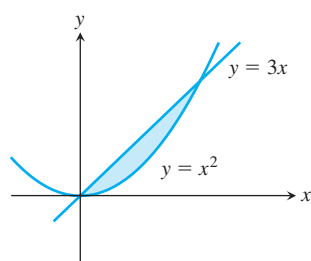
9.



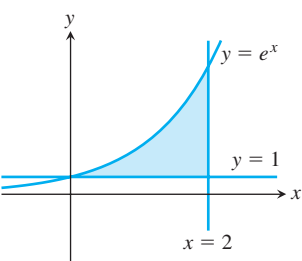
10.



11.



12.



- Bounded by  $y = \sqrt{x}$ ,  $y = 0$ , and  $x = 9$
- Bounded by  $y = \tan x$ ,  $x = 0$ , and  $y = 1$
- Bounded by  $y = e^{-x}$ ,  $y = 1$ , and  $x = \ln 3$
- Bounded by  $y = 0$ ,  $x = 0$ ,  $y = 1$ , and  $y = \ln x$
- Bounded by  $y = 3 - 2x$ ,  $y = x$ , and  $x = 0$
- Bounded by  $y = x^2$  and  $y = x + 2$

## Finding Regions of Integration and Double Integrals

In Exercises 19–24, sketch the region of integration and evaluate the integral.

$$19. \int_0^\pi \int_0^x x \sin y \, dy \, dx \qquad 20. \int_0^\pi \int_0^{\sin x} y \, dy \, dx$$

$$21. \int_1^{\ln 8} \int_0^{\ln y} e^{x+y} \, dx \, dy \qquad 22. \int_1^2 \int_y^{y^2} dx \, dy$$

$$23. \int_0^1 \int_0^{y^2} 3y^3 e^{xy} \, dx \, dy \qquad 24. \int_1^4 \int_0^{\sqrt{x}} \frac{3}{2} e^{y/\sqrt{x}} \, dy \, dx$$

In Exercises 25–28, integrate  $f$  over the given region.

- Quadrilateral**  $f(x, y) = x/y$  over the region in the first quadrant bounded by the lines  $y = x$ ,  $y = 2x$ ,  $x = 1$ , and  $x = 2$
- Triangle**  $f(x, y) = x^2 + y^2$  over the triangular region with vertices  $(0, 0)$ ,  $(1, 0)$ , and  $(0, 1)$
- Triangle**  $f(u, v) = v - \sqrt{u}$  over the triangular region cut from the first quadrant of the  $uv$ -plane by the line  $u + v = 1$
- Curved region**  $f(s, t) = e^s \ln t$  over the region in the first quadrant of the  $st$ -plane that lies above the curve  $s = \ln t$  from  $t = 1$  to  $t = 2$

Each of Exercises 29–32 gives an integral over a region in a Cartesian coordinate plane. Sketch the region and evaluate the integral.

$$29. \int_{-2}^0 \int_v^{-v} 2 \, dp \, dv \quad (\text{the } pv\text{-plane})$$

$$30. \int_0^1 \int_0^{\sqrt{1-s^2}} 8t \, dt \, ds \quad (\text{the } st\text{-plane})$$

$$31. \int_{-\pi/3}^{\pi/3} \int_0^{\sec t} 3 \cos t \, du \, dt \quad (\text{the } tu\text{-plane})$$

$$32. \int_0^{3/2} \int_1^{4-2u} \frac{4-2u}{v^2} \, dv \, du \quad (\text{the } uv\text{-plane})$$

## Reversing the Order of Integration

In Exercises 33–46, sketch the region of integration and write an equivalent double integral with the order of integration reversed.

$$33. \int_0^1 \int_2^{4-2x} dy \, dx \qquad 34. \int_0^2 \int_{y-2}^0 dx \, dy$$

$$35. \int_0^1 \int_y^{\sqrt{y}} dx \, dy \qquad 36. \int_0^1 \int_{1-x}^{1-x^2} dy \, dx$$

$$37. \int_0^1 \int_1^{e^x} dy \, dx \qquad 38. \int_0^{\ln 2} \int_{e^y}^2 dx \, dy$$

$$39. \int_0^{3/2} \int_0^{9-4x^2} 16x \, dy \, dx \qquad 40. \int_0^2 \int_0^{4-y^2} y \, dx \, dy$$

$$41. \int_0^1 \int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} 3y \, dx \, dy \qquad 42. \int_0^2 \int_{-\sqrt{4-x^2}}^{\sqrt{4-x^2}} 6x \, dy \, dx$$

$$43. \int_1^e \int_0^{\ln x} xy \, dy \, dx \qquad 44. \int_0^{\pi/6} \int_{\sin x}^{1/2} xy^2 \, dy \, dx$$

$$45. \int_0^3 \int_1^{e^y} (x + y) \, dx \, dy \qquad 46. \int_0^{\sqrt{3}} \int_0^{\tan^{-1} y} \sqrt{xy} \, dx \, dy$$

In Exercises 47–56, sketch the region of integration, reverse the order of integration, and evaluate the integral.

$$47. \int_0^{\pi} \int_x^{\pi} \frac{\sin y}{y} dy dx$$

$$48. \int_0^2 \int_x^2 2y^2 \sin xy dy dx$$

$$49. \int_0^1 \int_y^1 x^2 e^{xy} dx dy$$

$$50. \int_0^2 \int_0^{4-x^2} \frac{x e^{2y}}{4-y} dy dx$$

$$51. \int_0^{2\sqrt{\ln 3}} \int_{y/2}^{\sqrt{\ln 3}} e^{x^2} dx dy$$

$$52. \int_0^3 \int_{\sqrt{x/3}}^1 e^{y^3} dy dx$$

$$53. \int_0^{1/16} \int_{y^{1/4}}^{1/2} \cos(16\pi x^5) dx dy$$

$$54. \int_0^8 \int_{\sqrt[3]{x}}^2 \frac{dy dx}{y^4 + 1}$$

55. **Square region**  $\iint_R (y - 2x^2) dA$  where  $R$  is the region bounded by the square  $|x| + |y| = 1$

56. **Triangular region**  $\iint_R xy dA$  where  $R$  is the region bounded by the lines  $y = x$ ,  $y = 2x$ , and  $x + y = 2$

### Volume Beneath a Surface $z = f(x, y)$

57. Find the volume of the region bounded above by the paraboloid  $z = x^2 + y^2$  and below by the triangle enclosed by the lines  $y = x$ ,  $x = 0$ , and  $x + y = 2$  in the  $xy$ -plane.

58. Find the volume of the solid that is bounded above by the cylinder  $z = x^2$  and below by the region enclosed by the parabola  $y = 2 - x^2$  and the line  $y = x$  in the  $xy$ -plane.

59. Find the volume of the solid whose base is the region in the  $xy$ -plane that is bounded by the parabola  $y = 4 - x^2$  and the line  $y = 3x$ , while the top of the solid is bounded by the plane  $z = x + 4$ .

60. Find the volume of the solid in the first octant bounded by the coordinate planes, the cylinder  $x^2 + y^2 = 4$ , and the plane  $z + y = 3$ .

61. Find the volume of the solid in the first octant bounded by the coordinate planes, the plane  $x = 3$ , and the parabolic cylinder  $z = 4 - y^2$ .

62. Find the volume of the solid cut from the first octant by the surface  $z = 4 - x^2 - y$ .

63. Find the volume of the wedge cut from the first octant by the cylinder  $z = 12 - 3y^2$  and the plane  $x + y = 2$ .

64. Find the volume of the solid cut from the square column  $|x| + |y| \leq 1$  by the planes  $z = 0$  and  $3x + z = 3$ .

65. Find the volume of the solid that is bounded on the front and back by the planes  $x = 2$  and  $x = 1$ , on the sides by the cylinders  $y = \pm 1/x$ , and above and below by the planes  $z = x + 1$  and  $z = 0$ .

66. Find the volume of the solid bounded on the front and back by the planes  $x = \pm \pi/3$ , on the sides by the cylinders  $y = \pm \sec x$ , above by the cylinder  $z = 1 + y^2$ , and below by the  $xy$ -plane.

In Exercises 67 and 68, sketch the region of integration and the solid whose volume is given by the double integral.

$$67. \int_0^3 \int_0^{2-2x/3} \left(1 - \frac{1}{3}x - \frac{1}{2}y\right) dy dx$$

$$68. \int_0^4 \int_{-\sqrt{16-y^2}}^{\sqrt{16-y^2}} \sqrt{25 - x^2 - y^2} dx dy$$

### Integrals over Unbounded Regions

Improper double integrals can often be computed similarly to improper integrals of one variable. The first iteration of the following improper integrals is conducted just as if they were proper integrals. One then evaluates an improper integral of a single variable by taking appropriate limits, as in Section 8.8. Evaluate the improper integrals in Exercises 69–72 as iterated integrals.

$$69. \int_1^{\infty} \int_{e^{-x}}^1 \frac{1}{x^3 y} dy dx \quad 70. \int_{-1}^1 \int_{-1/\sqrt{1-x^2}}^{1/\sqrt{1-x^2}} (2y + 1) dy dx$$

$$71. \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{1}{(x^2 + 1)(y^2 + 1)} dx dy$$

$$72. \int_0^{\infty} \int_0^{\infty} x e^{-(x+2y)} dx dy$$

### Approximating Integrals with Finite Sums

In Exercises 73 and 74, approximate the double integral of  $f(x, y)$  over the region  $R$  partitioned by the given vertical lines  $x = a$  and horizontal lines  $y = c$ . In each subrectangle, use  $(x_k, y_k)$  as indicated for your approximation.

$$\iint_R f(x, y) dA \approx \sum_{k=1}^n f(x_k, y_k) \Delta A_k$$

73.  $f(x, y) = x + y$  over the region  $R$  bounded above by the semicircle  $y = \sqrt{1 - x^2}$  and below by the  $x$ -axis, using the partition  $x = -1, -1/2, 0, 1/4, 1/2, 1$  and  $y = 0, 1/2, 1$  with  $(x_k, y_k)$  the lower left corner in the  $k$ th subrectangle (provided the subrectangle lies within  $R$ )

74.  $f(x, y) = x + 2y$  over the region  $R$  inside the circle  $(x - 2)^2 + (y - 3)^2 = 1$  using the partition  $x = 1, 3/2, 2, 5/2, 3$  and  $y = 2, 5/2, 3, 7/2, 4$  with  $(x_k, y_k)$  the center (centroid) in the  $k$ th subrectangle (provided the subrectangle lies within  $R$ )

### Theory and Examples

75. **Circular sector** Integrate  $f(x, y) = \sqrt{4 - x^2}$  over the smaller sector cut from the disk  $x^2 + y^2 \leq 4$  by the rays  $\theta = \pi/6$  and  $\theta = \pi/2$ .

76. **Unbounded region** Integrate  $f(x, y) = 1/[(x^2 - x)(y - 1)^{2/3}]$  over the infinite rectangle  $2 \leq x < \infty, 0 \leq y \leq 2$ .

77. **Noncircular cylinder** A solid right (noncircular) cylinder has its base  $R$  in the  $xy$ -plane and is bounded above by the paraboloid  $z = x^2 + y^2$ . The cylinder's volume is

$$V = \int_0^1 \int_0^y (x^2 + y^2) dx dy + \int_1^2 \int_0^{2-y} (x^2 + y^2) dx dy.$$

Sketch the base region  $R$  and express the cylinder's volume as a single iterated integral with the order of integration reversed. Then evaluate the integral to find the volume.

**78. Converting to a double integral** Evaluate the integral

$$\int_0^2 (\tan^{-1} \pi x - \tan^{-1} x) dx.$$

(Hint: Write the integrand as an integral.)

**79. Maximizing a double integral** What region  $R$  in the  $xy$ -plane maximizes the value of

$$\iint_R (4 - x^2 - 2y^2) dA?$$

Give reasons for your answer.

**80. Minimizing a double integral** What region  $R$  in the  $xy$ -plane minimizes the value of

$$\iint_R (x^2 + y^2 - 9) dA?$$

Give reasons for your answer.

**81.** Is it possible to evaluate the integral of a continuous function  $f(x, y)$  over a rectangular region in the  $xy$ -plane and get different answers depending on the order of integration? Give reasons for your answer.

**82.** How would you evaluate the double integral of a continuous function  $f(x, y)$  over the region  $R$  in the  $xy$ -plane enclosed by the triangle with vertices  $(0, 1)$ ,  $(2, 0)$ , and  $(1, 2)$ ? Give reasons for your answer.

**83. Unbounded region** Prove that

$$\begin{aligned} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} e^{-x^2-y^2} dx dy &= \lim_{b \rightarrow \infty} \int_{-b}^b \int_{-b}^b e^{-x^2-y^2} dx dy \\ &= 4 \left( \int_0^{\infty} e^{-x^2} dx \right)^2. \end{aligned}$$

**84. Improper double integral** Evaluate the improper integral

$$\int_0^1 \int_0^3 \frac{x^2}{(y-1)^{2/3}} dy dx.$$

### COMPUTER EXPLORATIONS

Use a CAS double-integral evaluator to estimate the values of the integrals in Exercises 85–88.

$$85. \int_1^3 \int_1^x \frac{1}{xy} dy dx \qquad 86. \int_0^1 \int_0^1 e^{-(x^2+y^2)} dy dx$$

$$87. \int_0^1 \int_0^1 \tan^{-1} xy dy dx$$

$$88. \int_{-1}^1 \int_0^{\sqrt{1-x^2}} 3\sqrt{1-x^2-y^2} dy dx$$

Use a CAS double-integral evaluator to find the integrals in Exercises 89–94. Then reverse the order of integration and evaluate, again with a CAS.

$$89. \int_0^1 \int_{2y}^4 e^{x^2} dx dy$$

$$90. \int_0^3 \int_{x^2}^9 x \cos(y^2) dy dx$$

$$91. \int_0^2 \int_{y^3}^{4\sqrt{2y}} (x^2y - xy^2) dx dy$$

$$92. \int_0^2 \int_0^{4-y^2} e^{xy} dx dy$$

$$93. \int_1^2 \int_0^{x^2} \frac{1}{x+y} dy dx \qquad 94. \int_1^2 \int_{y^3}^8 \frac{1}{\sqrt{x^2+y^2}} dx dy$$

## Exercises 15.3

### Area by Double Integrals

In Exercises 1–12, sketch the region bounded by the given lines and curves. Then express the region's area as an iterated double integral and evaluate the integral.

- The coordinate axes and the line  $x + y = 2$
- The lines  $x = 0$ ,  $y = 2x$ , and  $y = 4$
- The parabola  $x = -y^2$  and the line  $y = x + 2$
- The parabola  $x = y - y^2$  and the line  $y = -x$
- The curve  $y = e^x$  and the lines  $y = 0$ ,  $x = 0$ , and  $x = \ln 2$
- The curves  $y = \ln x$  and  $y = 2 \ln x$  and the line  $x = e$ , in the first quadrant
- The parabolas  $x = y^2$  and  $x = 2y - y^2$
- The parabolas  $x = y^2 - 1$  and  $x = 2y^2 - 2$
- The lines  $y = x$ ,  $y = x/3$ , and  $y = 2$
- The lines  $y = 1 - x$  and  $y = 2$  and the curve  $y = e^x$
- The lines  $y = 2x$ ,  $y = x/2$ , and  $y = 3 - x$
- The lines  $y = x - 2$  and  $y = -x$  and the curve  $y = \sqrt{x}$

### Identifying the Region of Integration

The integrals and sums of integrals in Exercises 13–18 give the areas of regions in the  $xy$ -plane. Sketch each region, label each bounding curve with its equation, and give the coordinates of the points where the curves intersect. Then find the area of the region.

- $\int_0^6 \int_{y^2/3}^{2y} dx dy$
- $\int_0^3 \int_{-x}^{x(2-x)} dy dx$
- $\int_0^{\pi/4} \int_{\sin x}^{\cos x} dy dx$
- $\int_{-1}^2 \int_{y^2}^{y+2} dx dy$
- $\int_{-1}^0 \int_{-2x}^{1-x} dy dx + \int_0^2 \int_{-x/2}^{1-x} dy dx$
- $\int_0^2 \int_{x^2-4}^0 dy dx + \int_0^4 \int_0^{\sqrt{x}} dy dx$

### Finding Average Values

- Find the average value of  $f(x, y) = \sin(x + y)$  over
  - the rectangle  $0 \leq x \leq \pi$ ,  $0 \leq y \leq \pi$ .
  - the rectangle  $0 \leq x \leq \pi$ ,  $0 \leq y \leq \pi/2$ .
- Which do you think will be larger, the average value of  $f(x, y) = xy$  over the square  $0 \leq x \leq 1$ ,  $0 \leq y \leq 1$ , or the

average value of  $f$  over the quarter circle  $x^2 + y^2 \leq 1$  in the first quadrant? Calculate them to find out.

- Find the average height of the paraboloid  $z = x^2 + y^2$  over the square  $0 \leq x \leq 2$ ,  $0 \leq y \leq 2$ .
- Find the average value of  $f(x, y) = 1/(xy)$  over the square  $\ln 2 \leq x \leq 2 \ln 2$ ,  $\ln 2 \leq y \leq 2 \ln 2$ .

### Theory and Examples

- Geometric area** Find the area of the region

$$R: 0 \leq x \leq 2, 2 - x \leq y \leq \sqrt{4 - x^2},$$

using (a) Fubini's Theorem, (b) simple geometry.

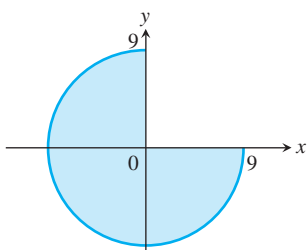
- Geometric area** Find the area of the circular washer with outer radius 2 and inner radius 1, using (a) Fubini's Theorem, (b) simple geometry.
- Bacterium population** If  $f(x, y) = (10,000e^y)/(1 + |x|/2)$  represents the "population density" of a certain bacterium on the  $xy$ -plane, where  $x$  and  $y$  are measured in centimeters, find the total population of bacteria within the rectangle  $-5 \leq x \leq 5$  and  $-2 \leq y \leq 0$ .
- Regional population** If  $f(x, y) = 100(y + 1)$  represents the population density of a planar region on Earth, where  $x$  and  $y$  are measured in kilometers, find the number of people in the region bounded by the curves  $x = y^2$  and  $x = 2y - y^2$ .
- Average temperature in Texas** According to the *Texas Almanac*, Texas has 254 counties and a National Weather Service station in each county. Assume that at time  $t_0$ , each of the 254 weather stations recorded the local temperature. Find a formula that would give a reasonable approximation of the average temperature in Texas at time  $t_0$ . Your answer should involve information that you would expect to be readily available in the *Texas Almanac*.
- If  $y = f(x)$  is a nonnegative continuous function over the closed interval  $a \leq x \leq b$ , show that the double integral definition of area for the closed plane region bounded by the graph of  $f$ , the vertical lines  $x = a$  and  $x = b$ , and the  $x$ -axis agrees with the definition for area beneath the curve in Section 5.3.
- Suppose  $f(x, y)$  is continuous over a region  $R$  in the plane and that the area  $A(R)$  of the region is defined. If there are constants  $m$  and  $M$  such that  $m \leq f(x, y) \leq M$  for all  $(x, y) \in R$ , prove that
 
$$mA(R) \leq \iint_R f(x, y) dA \leq MA(R).$$
- Suppose  $f(x, y)$  is continuous and nonnegative over a region  $R$  in the plane with a defined area  $A(R)$ . If  $\iint_R f(x, y) dA = 0$ , prove that  $f(x, y) = 0$  at every point  $(x, y) \in R$ .

## Exercises 15.4

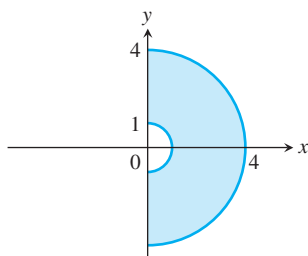
### Regions in Polar Coordinates

In Exercises 1–8, describe the given region in polar coordinates.

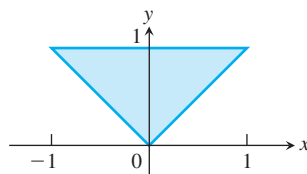
1.



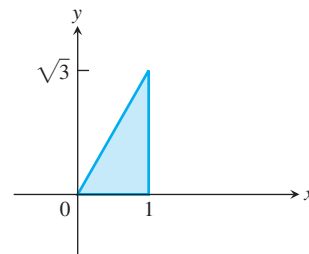
2.



3.

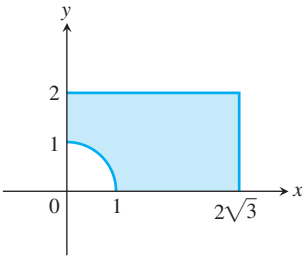


4.

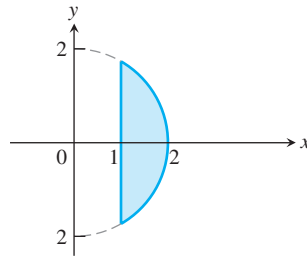




5.



6.



7. The region enclosed by the circle  $x^2 + y^2 = 2x$   
 8. The region enclosed by the semicircle  $x^2 + y^2 = 2y$ ,  $y \geq 0$

### Evaluating Polar Integrals

In Exercises 9–22, change the Cartesian integral into an equivalent polar integral. Then evaluate the polar integral.

9.  $\int_{-1}^1 \int_0^{\sqrt{1-x^2}} dy dx$       10.  $\int_0^1 \int_0^{\sqrt{1-y^2}} (x^2 + y^2) dx dy$   
 11.  $\int_0^2 \int_0^{\sqrt{4-y^2}} (x^2 + y^2) dx dy$   
 12.  $\int_{-a}^a \int_{-\sqrt{a^2-x^2}}^{\sqrt{a^2-x^2}} dy dx$       13.  $\int_0^6 \int_0^y x dx dy$   
 14.  $\int_0^2 \int_0^x y dy dx$       15.  $\int_1^{\sqrt{3}} \int_1^x dy dx$   
 16.  $\int_{\sqrt{2}}^2 \int_{\sqrt{4-y^2}}^y dx dy$       17.  $\int_{-1}^0 \int_{-\sqrt{1-x^2}}^0 \frac{2}{1 + \sqrt{x^2 + y^2}} dy dx$   
 18.  $\int_{-1}^1 \int_{-\sqrt{1-x^2}}^{\sqrt{1-x^2}} \frac{2}{(1 + x^2 + y^2)^2} dy dx$   
 19.  $\int_0^{\ln 2} \int_0^{\sqrt{(\ln 2)^2 - y^2}} e^{\sqrt{x^2 + y^2}} dx dy$   
 20.  $\int_{-1}^1 \int_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} \ln(x^2 + y^2 + 1) dx dy$   
 21.  $\int_0^1 \int_x^{\sqrt{2-x^2}} (x + 2y) dy dx$   
 22.  $\int_1^2 \int_0^{\sqrt{2x-x^2}} \frac{1}{(x^2 + y^2)^2} dy dx$

In Exercises 23–26, sketch the region of integration and convert each polar integral or sum of integrals to a Cartesian integral or sum of integrals. Do not evaluate the integrals.

23.  $\int_0^{\pi/2} \int_0^1 r^3 \sin \theta \cos \theta dr d\theta$   
 24.  $\int_{\pi/6}^{\pi/2} \int_1^{\csc \theta} r^2 \cos \theta dr d\theta$

25.  $\int_0^{\pi/4} \int_0^{2 \sec \theta} r^5 \sin^2 \theta dr d\theta$

26.  $\int_0^{\tan^{-1} \frac{4}{3}} \int_0^{3 \sec \theta} r^7 dr d\theta + \int_{\tan^{-1} \frac{4}{3}}^{\pi/2} \int_0^{4 \csc \theta} r^7 dr d\theta$

### Area in Polar Coordinates

27. Find the area of the region cut from the first quadrant by the curve  $r = 2(2 - \sin 2\theta)^{1/2}$ .  
 28. **Cardioid overlapping a circle** Find the area of the region that lies inside the cardioid  $r = 1 + \cos \theta$  and outside the circle  $r = 1$ .  
 29. **One leaf of a rose** Find the area enclosed by one leaf of the rose  $r = 12 \cos 3\theta$ .  
 30. **Snail shell** Find the area of the region enclosed by the positive  $x$ -axis and spiral  $r = 4\theta/3$ ,  $0 \leq \theta \leq 2\pi$ . The region looks like a snail shell.  
 31. **Cardioid in the first quadrant** Find the area of the region cut from the first quadrant by the cardioid  $r = 1 + \sin \theta$ .  
 32. **Overlapping cardioids** Find the area of the region common to the interiors of the cardioids  $r = 1 + \cos \theta$  and  $r = 1 - \cos \theta$ .

### Average Values

In polar coordinates, the **average value** of a function over a region  $R$  (Section 15.3) is given by

$$\frac{1}{\text{Area}(R)} \iint_R f(r, \theta) r dr d\theta.$$

33. **Average height of a hemisphere** Find the average height of the hemispherical surface  $z = \sqrt{a^2 - x^2 - y^2}$  above the disk  $x^2 + y^2 \leq a^2$  in the  $xy$ -plane.  
 34. **Average height of a cone** Find the average height of the (single) cone  $z = \sqrt{x^2 + y^2}$  above the disk  $x^2 + y^2 \leq a^2$  in the  $xy$ -plane.  
 35. **Average distance from interior of disk to center** Find the average distance from a point  $P(x, y)$  in the disk  $x^2 + y^2 \leq a^2$  to the origin.  
 36. **Average distance squared from a point in a disk to a point in its boundary** Find the average value of the *square* of the distance from the point  $P(x, y)$  in the disk  $x^2 + y^2 \leq 1$  to the boundary point  $A(1, 0)$ .

### Theory and Examples

37. **Converting to a polar integral** Integrate  $f(x, y) = [\ln(x^2 + y^2)] / \sqrt{x^2 + y^2}$  over the region  $1 \leq x^2 + y^2 \leq e$ .  
 38. **Converting to a polar integral** Integrate  $f(x, y) = [\ln(x^2 + y^2)] / (x^2 + y^2)$  over the region  $1 \leq x^2 + y^2 \leq e^2$ .  
 39. **Volume of noncircular right cylinder** The region that lies inside the cardioid  $r = 1 + \cos \theta$  and outside the circle  $r = 1$  is the base of a solid right cylinder. The top of the cylinder lies in the plane  $z = x$ . Find the cylinder's volume.  
 40. **Volume of noncircular right cylinder** The region enclosed by the lemniscate  $r^2 = 2 \cos 2\theta$  is the base of a solid right cylinder whose top is bounded by the sphere  $z = \sqrt{2 - r^2}$ . Find the cylinder's volume.

**41. Converting to polar integrals**

- a. The usual way to evaluate the improper integral

$I = \int_0^\infty e^{-x^2} dx$  is first to calculate its square:

$$I^2 = \left( \int_0^\infty e^{-x^2} dx \right) \left( \int_0^\infty e^{-y^2} dy \right) = \int_0^\infty \int_0^\infty e^{-(x^2+y^2)} dx dy.$$

Evaluate the last integral using polar coordinates and solve the resulting equation for  $I$ .

- b. Evaluate

$$\lim_{x \rightarrow \infty} \operatorname{erf}(x) = \lim_{x \rightarrow \infty} \int_0^x \frac{2e^{-t^2}}{\sqrt{\pi}} dt.$$

**42. Converting to a polar integral** Evaluate the integral

$$\int_0^\infty \int_0^\infty \frac{1}{(1+x^2+y^2)^2} dx dy.$$

- 43. Existence** Integrate the function  $f(x, y) = 1/(1 - x^2 - y^2)$  over the disk  $x^2 + y^2 \leq 3/4$ . Does the integral of  $f(x, y)$  over the disk  $x^2 + y^2 \leq 1$  exist? Give reasons for your answer.

- 44. Area formula in polar coordinates** Use the double integral in polar coordinates to derive the formula

$$A = \int_\alpha^\beta \frac{1}{2} r^2 d\theta$$

for the area of the fan-shaped region between the origin and polar curve  $r = f(\theta)$ ,  $\alpha \leq \theta \leq \beta$ .

- 45. Average distance to a given point inside a disk** Let  $P_0$  be a point inside a circle of radius  $a$  and let  $h$  denote the distance from  $P_0$  to the center of the circle. Let  $d$  denote the distance from an arbitrary point  $P$  to  $P_0$ . Find the average value of  $d^2$  over the region enclosed by the circle. (*Hint:* Simplify your work by placing the center of the circle at the origin and  $P_0$  on the  $x$ -axis.)

- 46. Area** Suppose that the area of a region in the polar coordinate plane is

$$A = \int_{\pi/4}^{3\pi/4} \int_{\csc \theta}^{2 \sin \theta} r dr d\theta.$$

Sketch the region and find its area.

- 47.** Evaluate the integral  $\iint_R \sqrt{x^2 + y^2} dA$ , where  $R$  is the region inside the upper semicircle of radius 2 centered at the origin, but outside the circle  $x^2 + (y - 1)^2 = 1$ .
- 48.** Evaluate the integral  $\iint_R (x^2 + y^2)^{-2} dA$ , where  $R$  is the region inside the circle  $x^2 + y^2 = 2$  for  $x \leq -1$ .

**COMPUTER EXPLORATIONS**

In Exercises 49–52, use a CAS to change the Cartesian integrals into an equivalent polar integral and evaluate the polar integral. Perform the following steps in each exercise.

- Plot the Cartesian region of integration in the  $xy$ -plane.
- Change each boundary curve of the Cartesian region in part (a) to its polar representation by solving its Cartesian equation for  $r$  and  $\theta$ .
- Using the results in part (b), plot the polar region of integration in the  $r\theta$ -plane.
- Change the integrand from Cartesian to polar coordinates. Determine the limits of integration from your plot in part (c) and evaluate the polar integral using the CAS integration utility.

**49.**  $\int_0^1 \int_x^1 \frac{y}{x^2 + y^2} dy dx$

**50.**  $\int_0^1 \int_0^{x/2} \frac{x}{x^2 + y^2} dy dx$

**51.**  $\int_0^1 \int_{-y/3}^{y/3} \frac{y}{\sqrt{x^2 + y^2}} dx dy$

**52.**  $\int_0^1 \int_y^{2-y} \sqrt{x + y} dx dy$

## Exercises 15.5

## Triple Integrals in Different Iteration Orders

1. Evaluate the integral in Example 2 taking  $F(x, y, z) = 1$  to find the volume of the tetrahedron in the order  $dz \, dx \, dy$ .
2. **Volume of rectangular solid** Write six different iterated triple integrals for the volume of the rectangular solid in the first octant bounded by the coordinate planes and the planes  $x = 1$ ,  $y = 2$ , and  $z = 3$ . Evaluate one of the integrals.
3. **Volume of tetrahedron** Write six different iterated triple integrals for the volume of the tetrahedron cut from the first octant by the plane  $6x + 3y + 2z = 6$ . Evaluate one of the integrals.
4. **Volume of solid** Write six different iterated triple integrals for the volume of the region in the first octant enclosed by the cylinder  $x^2 + z^2 = 4$  and the plane  $y = 3$ . Evaluate one of the integrals.
5. **Volume enclosed by paraboloids** Let  $D$  be the region bounded by the paraboloids  $z = 8 - x^2 - y^2$  and  $z = x^2 + y^2$ . Write six different triple iterated integrals for the volume of  $D$ . Evaluate one of the integrals.
6. **Volume inside paraboloid beneath a plane** Let  $D$  be the region bounded by the paraboloid  $z = x^2 + y^2$  and the plane  $z = 2y$ . Write triple iterated integrals in the order  $dz \, dx \, dy$  and  $dz \, dy \, dx$  that give the volume of  $D$ . Do not evaluate either integral.

## Evaluating Triple Iterated Integrals

Evaluate the integrals in Exercises 7–20.

7.  $\int_0^1 \int_0^1 \int_0^1 (x^2 + y^2 + z^2) \, dz \, dy \, dx$
8.  $\int_0^{\sqrt{2}} \int_0^{3y} \int_{x^2+3y^2}^{8-x^2-y^2} dz \, dx \, dy$
9.  $\int_1^e \int_1^{e^2} \int_1^{e^3} \frac{1}{xyz} \, dx \, dy \, dz$
10.  $\int_0^1 \int_0^{3-3x} \int_0^{3-3x-y} dz \, dy \, dx$
11.  $\int_0^{\pi/6} \int_0^1 \int_{-2}^3 y \sin z \, dx \, dy \, dz$
12.  $\int_{-1}^1 \int_0^1 \int_0^2 (x + y + z) \, dy \, dx \, dz$
13.  $\int_0^3 \int_0^{\sqrt{9-x^2}} \int_0^{\sqrt{9-x^2}} dz \, dy \, dx$
14.  $\int_0^2 \int_{-\sqrt{4-y^2}}^{\sqrt{4-y^2}} \int_0^{2x+y} dz \, dx \, dy$
15.  $\int_0^1 \int_0^{2-x} \int_0^{2-x-y} dz \, dy \, dx$
16.  $\int_0^1 \int_0^{1-x^2} \int_3^{4-x^2-y} x \, dz \, dy \, dx$
17.  $\int_0^\pi \int_0^\pi \int_0^\pi \cos(u + v + w) \, du \, dv \, dw \quad (uvw\text{-space})$
18.  $\int_0^1 \int_1^{\sqrt{e}} \int_1^e se^s \ln r \frac{(\ln t)^2}{t} \, dt \, dr \, ds \quad (rst\text{-space})$

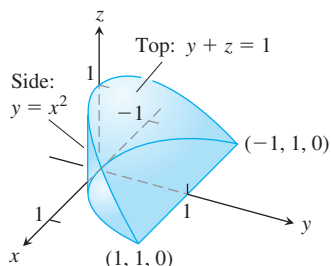
19.  $\int_0^{\pi/4} \int_0^{\ln \sec v} \int_{-\infty}^{2t} e^x dx dt dv$  ( $tvx$ -space)

20.  $\int_0^7 \int_0^2 \int_0^{\sqrt{4-q^2}} \frac{q}{r+1} dp dq dr$  ( $pqr$ -space)

### Finding Equivalent Iterated Integrals

21. Here is the region of integration of the integral

$$\int_{-1}^1 \int_{x^2}^1 \int_0^{1-y} dz dy dx.$$

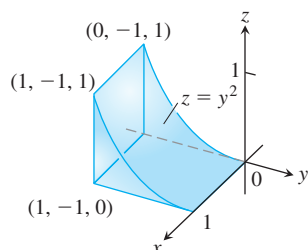


Rewrite the integral as an equivalent iterated integral in the order

- a.  $dy dz dx$
- b.  $dy dx dz$
- c.  $dx dy dz$
- d.  $dx dz dy$
- e.  $dz dx dy$ .

22. Here is the region of integration of the integral

$$\int_0^1 \int_{-1}^0 \int_0^{y^2} dz dy dx.$$



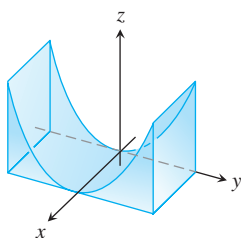
Rewrite the integral as an equivalent iterated integral in the order

- a.  $dy dz dx$
- b.  $dy dx dz$
- c.  $dx dy dz$
- d.  $dx dz dy$
- e.  $dz dx dy$ .

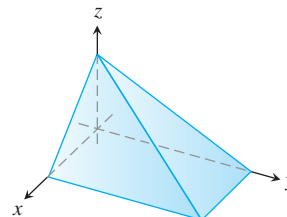
### Finding Volumes Using Triple Integrals

Find the volumes of the regions in Exercises 23–36.

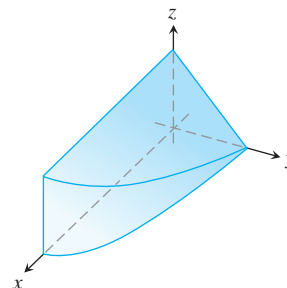
23. The region between the cylinder  $z = y^2$  and the  $xy$ -plane that is bounded by the planes  $x = 0$ ,  $x = 1$ ,  $y = -1$ ,  $y = 1$



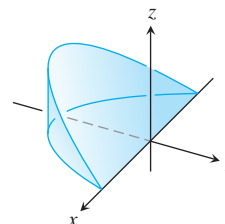
24. The region in the first octant bounded by the coordinate planes and the planes  $x + z = 1$ ,  $y + 2z = 2$



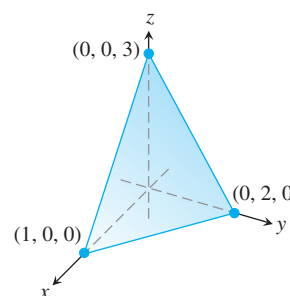
25. The region in the first octant bounded by the coordinate planes, the plane  $y + z = 2$ , and the cylinder  $x = 4 - y^2$



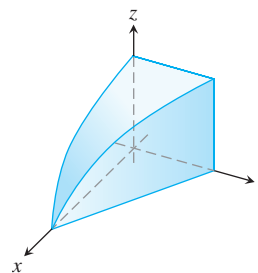
26. The wedge cut from the cylinder  $x^2 + y^2 = 1$  by the planes  $z = -y$  and  $z = 0$



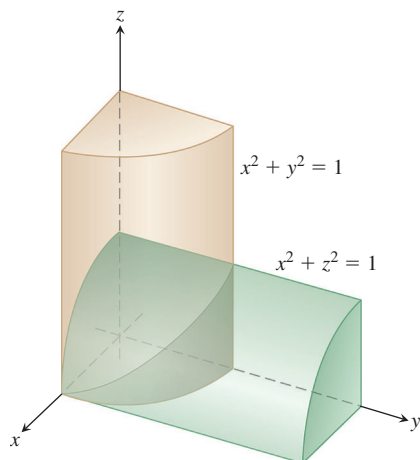
27. The tetrahedron in the first octant bounded by the coordinate planes and the plane passing through  $(1, 0, 0)$ ,  $(0, 2, 0)$ , and  $(0, 0, 3)$



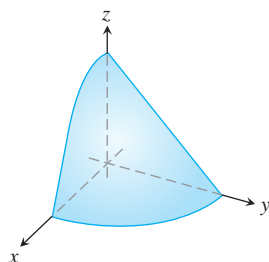
28. The region in the first octant bounded by the coordinate planes, the plane  $y = 1 - x$ , and the surface  $z = \cos(\pi x/2)$ ,  $0 \leq x \leq 1$



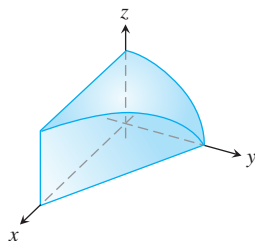
29. The region common to the interiors of the cylinders  $x^2 + y^2 = 1$  and  $x^2 + z^2 = 1$ , one-eighth of which is shown in the accompanying figure



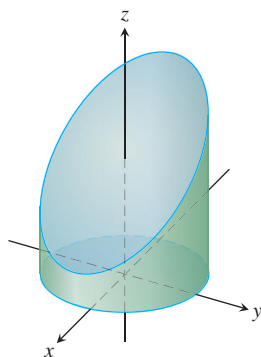
30. The region in the first octant bounded by the coordinate planes and the surface  $z = 4 - x^2 - y$



31. The region in the first octant bounded by the coordinate planes, the plane  $x + y = 4$ , and the cylinder  $y^2 + 4z^2 = 16$



32. The region cut from the cylinder  $x^2 + y^2 = 4$  by the plane  $z = 0$  and the plane  $x + z = 3$



33. The region between the planes  $x + y + 2z = 2$  and  $2x + 2y + z = 4$  in the first octant
34. The finite region bounded by the planes  $z = x$ ,  $x + z = 8$ ,  $z = y$ ,  $y = 8$ , and  $z = 0$
35. The region cut from the solid elliptical cylinder  $x^2 + 4y^2 \leq 4$  by the  $xy$ -plane and the plane  $z = x + 2$
36. The region bounded in back by the plane  $x = 0$ , on the front and sides by the parabolic cylinder  $x = 1 - y^2$ , on the top by the paraboloid  $z = x^2 + y^2$ , and on the bottom by the  $xy$ -plane

### Average Values

In Exercises 37–40, find the average value of  $F(x, y, z)$  over the given region.

37.  $F(x, y, z) = x^2 + 9$  over the cube in the first octant bounded by the coordinate planes and the planes  $x = 2$ ,  $y = 2$ , and  $z = 2$
38.  $F(x, y, z) = x + y - z$  over the rectangular solid in the first octant bounded by the coordinate planes and the planes  $x = 1$ ,  $y = 1$ , and  $z = 2$
39.  $F(x, y, z) = x^2 + y^2 + z^2$  over the cube in the first octant bounded by the coordinate planes and the planes  $x = 1$ ,  $y = 1$ , and  $z = 1$
40.  $F(x, y, z) = xyz$  over the cube in the first octant bounded by the coordinate planes and the planes  $x = 2$ ,  $y = 2$ , and  $z = 2$

### Changing the Order of Integration

Evaluate the integrals in Exercises 41–44 by changing the order of integration in an appropriate way.

41.  $\int_0^4 \int_0^1 \int_{2y}^2 \frac{4 \cos(x^2)}{2\sqrt{z}} dx dy dz$
42.  $\int_0^1 \int_0^1 \int_{x^2}^1 12xz e^{yz^2} dy dx dz$
43.  $\int_0^1 \int_{\sqrt[3]{z}}^1 \int_0^{\ln 3} \frac{\pi e^{2x} \sin \pi y^2}{y^2} dx dy dz$
44.  $\int_0^2 \int_0^{4-x^2} \int_0^x \frac{\sin 2z}{4-z} dy dz dx$

### Theory and Examples

45. **Finding an upper limit of an iterated integral** Solve for  $a$ :

$$\int_0^1 \int_0^{4-a-x^2} \int_a^{4-x^2-y} dz dy dx = \frac{4}{15}.$$

46. **Ellipsoid** For what value of  $c$  is the volume of the ellipsoid  $x^2 + (y/2)^2 + (z/c)^2 = 1$  equal to  $8\pi$ ?

47. **Minimizing a triple integral** What domain  $D$  in space minimizes the value of the integral

$$\iiint_D (4x^2 + 4y^2 + z^2 - 4) dV?$$

Give reasons for your answer.

48. **Maximizing a triple integral** What domain  $D$  in space maximizes the value of the integral

$$\iiint_D (1 - x^2 - y^2 - z^2) dV?$$

Give reasons for your answer.

## Exercises 15.7

## Evaluating Integrals in Cylindrical Coordinates

Evaluate the cylindrical coordinate integrals in Exercises 1–6.

1.  $\int_0^{2\pi} \int_0^1 \int_r^{\sqrt{2-r^2}} dz \, r \, dr \, d\theta$
2.  $\int_0^{2\pi} \int_0^3 \int_{r^2/3}^{\sqrt{18-r^2}} dz \, r \, dr \, d\theta$
3.  $\int_0^{2\pi} \int_0^{\theta/2\pi} \int_0^{3+24r^2} dz \, r \, dr \, d\theta$
4.  $\int_0^\pi \int_0^{\theta/\pi} \int_{-\sqrt{4-r^2}}^{3\sqrt{4-r^2}} z \, dz \, r \, dr \, d\theta$
5.  $\int_0^{2\pi} \int_0^1 \int_r^{1/\sqrt{2-r^2}} 3 \, dz \, r \, dr \, d\theta$
6.  $\int_0^{2\pi} \int_0^1 \int_{-1/2}^{1/2} (r^2 \sin^2 \theta + z^2) \, dz \, r \, dr \, d\theta$

## Changing the Order of Integration in Cylindrical Coordinates

The integrals we have seen so far suggest that there are preferred orders of integration for cylindrical coordinates, but other orders usually work well and are occasionally easier to evaluate. Evaluate the integrals in Exercises 7–10.

7.  $\int_0^{2\pi} \int_0^3 \int_0^{z/3} r^3 \, dr \, dz \, d\theta$
8.  $\int_{-1}^1 \int_0^{2\pi} \int_0^{1+\cos\theta} 4r \, dr \, d\theta \, dz$

$$9. \int_0^1 \int_0^{\sqrt{z}} \int_0^{2\pi} (r^2 \cos^2 \theta + z^2) r \, d\theta \, dr \, dz$$

$$10. \int_0^2 \int_{r-2}^{\sqrt{4-r^2}} \int_0^{2\pi} (r \sin \theta + 1) r \, d\theta \, dz \, dr$$

11. Let  $D$  be the region bounded below by the plane  $z = 0$ , above by the sphere  $x^2 + y^2 + z^2 = 4$ , and on the sides by the cylinder  $x^2 + y^2 = 1$ . Set up the triple integrals in cylindrical coordinates that give the volume of  $D$  using the following orders of integration.

a.  $dz \, dr \, d\theta$       b.  $dr \, dz \, d\theta$       c.  $d\theta \, dz \, dr$

12. Let  $D$  be the region bounded below by the cone  $z = \sqrt{x^2 + y^2}$  and above by the paraboloid  $z = 2 - x^2 - y^2$ . Set up the triple integrals in cylindrical coordinates that give the volume of  $D$  using the following orders of integration.

a.  $dz \, dr \, d\theta$       b.  $dr \, dz \, d\theta$       c.  $d\theta \, dz \, dr$

## Finding Iterated Integrals in Cylindrical Coordinates

13. Give the limits of integration for evaluating the integral

$$\iiint f(r, \theta, z) \, dz \, r \, dr \, d\theta$$

as an iterated integral over the region that is bounded below by the plane  $z = 0$ , on the side by the cylinder  $r = \cos \theta$ , and on top by the paraboloid  $z = 3r^2$ .

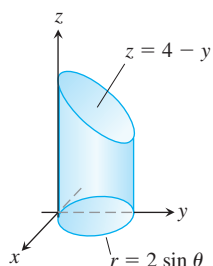
14. Convert the integral

$$\int_{-1}^1 \int_0^{\sqrt{1-y^2}} \int_0^x (x^2 + y^2) dz dx dy$$

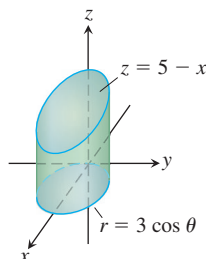
to an equivalent integral in cylindrical coordinates and evaluate the result.

In Exercises 15–20, set up the iterated integral for evaluating  $\iiint_D f(r, \theta, z) dz r dr d\theta$  over the given region  $D$ .

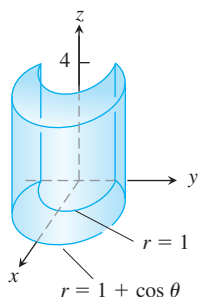
15.  $D$  is the right circular cylinder whose base is the circle  $r = 2 \sin \theta$  in the  $xy$ -plane and whose top lies in the plane  $z = 4 - y$ .



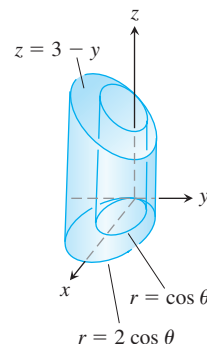
16.  $D$  is the right circular cylinder whose base is the circle  $r = 3 \cos \theta$  and whose top lies in the plane  $z = 5 - x$ .



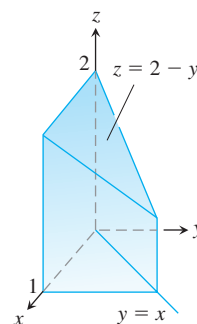
17.  $D$  is the solid right cylinder whose base is the region in the  $xy$ -plane that lies inside the cardioid  $r = 1 + \cos \theta$  and outside the circle  $r = 1$  and whose top lies in the plane  $z = 4$ .



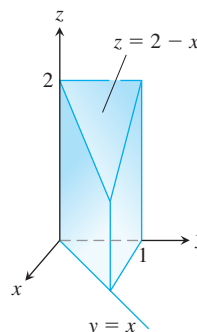
18.  $D$  is the solid right cylinder whose base is the region between the circles  $r = \cos \theta$  and  $r = 2 \cos \theta$  and whose top lies in the plane  $z = 3 - y$ .



19.  $D$  is the prism whose base is the triangle in the  $xy$ -plane bounded by the  $x$ -axis and the lines  $y = x$  and  $x = 1$  and whose top lies in the plane  $z = 2 - y$ .



20.  $D$  is the prism whose base is the triangle in the  $xy$ -plane bounded by the  $y$ -axis and the lines  $y = x$  and  $y = 1$  and whose top lies in the plane  $z = 2 - x$ .



### Evaluating Integrals in Spherical Coordinates

Evaluate the spherical coordinate integrals in Exercises 21–26.

21.  $\int_0^\pi \int_0^\pi \int_0^{2 \sin \phi} \rho^2 \sin \phi d\rho d\phi d\theta$

22.  $\int_0^{2\pi} \int_0^{\pi/4} \int_0^2 (\rho \cos \phi) \rho^2 \sin \phi d\rho d\phi d\theta$

23.  $\int_0^{2\pi} \int_0^\pi \int_0^{(1-\cos \phi)/2} \rho^2 \sin \phi d\rho d\phi d\theta$

24.  $\int_0^{3\pi/2} \int_0^\pi \int_0^1 5\rho^3 \sin^3 \phi d\rho d\phi d\theta$

25.  $\int_0^{2\pi} \int_0^{\pi/3} \int_{\sec \phi}^2 3\rho^2 \sin \phi d\rho d\phi d\theta$

$$26. \int_0^{2\pi} \int_0^{\pi/4} \int_0^{\sec \phi} (\rho \cos \phi) \rho^2 \sin \phi \, d\rho \, d\phi \, d\theta$$

### Changing the Order of Integration in Spherical Coordinates

The previous integrals suggest there are preferred orders of integration for spherical coordinates, but other orders give the same value and are occasionally easier to evaluate. Evaluate the integrals in Exercises 27–30.

$$27. \int_0^2 \int_{-\pi}^0 \int_{\pi/4}^{\pi/2} \rho^3 \sin 2\phi \, d\phi \, d\theta \, d\rho$$

$$28. \int_{\pi/6}^{\pi/3} \int_{\csc \phi}^{2 \csc \phi} \int_0^{2\pi} \rho^2 \sin \phi \, d\theta \, d\rho \, d\phi$$

$$29. \int_0^1 \int_0^{\pi} \int_0^{\pi/4} 12\rho \sin^3 \phi \, d\phi \, d\theta \, d\rho$$

$$30. \int_{\pi/6}^{\pi/2} \int_{-\pi/2}^{\pi/2} \int_{\csc \phi}^2 5\rho^4 \sin^3 \phi \, d\rho \, d\theta \, d\phi$$

31. Let  $D$  be the region in Exercise 11. Set up the triple integrals in spherical coordinates that give the volume of  $D$  using the following orders of integration.

a.  $d\rho \, d\phi \, d\theta$                       b.  $d\phi \, d\rho \, d\theta$

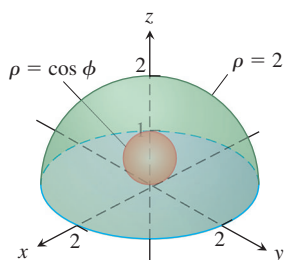
32. Let  $D$  be the region bounded below by the cone  $z = \sqrt{x^2 + y^2}$  and above by the plane  $z = 1$ . Set up the triple integrals in spherical coordinates that give the volume of  $D$  using the following orders of integration.

a.  $d\rho \, d\phi \, d\theta$                       b.  $d\phi \, d\rho \, d\theta$

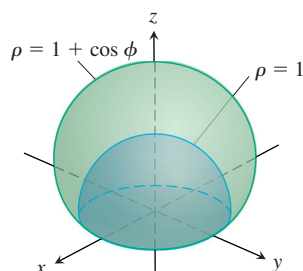
### Finding Iterated Integrals in Spherical Coordinates

In Exercises 33–38, (a) find the spherical coordinate limits for the integral that calculates the volume of the given solid and then (b) evaluate the integral.

33. The solid between the sphere  $\rho = \cos \phi$  and the hemisphere  $\rho = 2, z \geq 0$

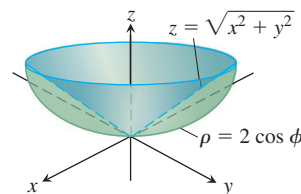


34. The solid bounded below by the hemisphere  $\rho = 1, z \geq 0$ , and above by the cardioid of revolution  $\rho = 1 + \cos \phi$

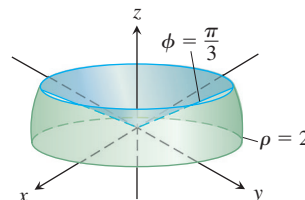


35. The solid enclosed by the cardioid of revolution  $\rho = 1 - \cos \phi$   
 36. The upper portion cut from the solid in Exercise 35 by the  $xy$ -plane

37. The solid bounded below by the sphere  $\rho = 2 \cos \phi$  and above by the cone  $z = \sqrt{x^2 + y^2}$



38. The solid bounded below by the  $xy$ -plane, on the sides by the sphere  $\rho = 2$ , and above by the cone  $\phi = \pi/3$



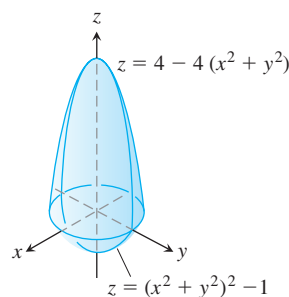
### Finding Triple Integrals

39. Set up triple integrals for the volume of the sphere  $\rho = 2$  in (a) spherical, (b) cylindrical, and (c) rectangular coordinates.  
 40. Let  $D$  be the region in the first octant that is bounded below by the cone  $\phi = \pi/4$  and above by the sphere  $\rho = 3$ . Express the volume of  $D$  as an iterated triple integral in (a) cylindrical and (b) spherical coordinates. Then (c) find  $V$ .  
 41. Let  $D$  be the smaller cap cut from a solid ball of radius 2 units by a plane 1 unit from the center of the sphere. Express the volume of  $D$  as an iterated triple integral in (a) spherical, (b) cylindrical, and (c) rectangular coordinates. Then (d) find the volume by evaluating one of the three triple integrals.  
 42. Express the moment of inertia  $I_z$  of the solid hemisphere  $x^2 + y^2 + z^2 \leq 1, z \geq 0$ , as an iterated integral in (a) cylindrical and (b) spherical coordinates. Then (c) find  $I_z$ .

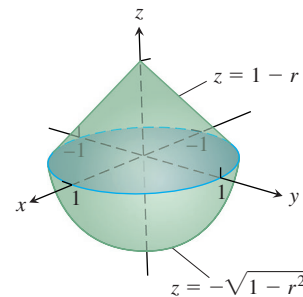
### Volumes

Find the volumes of the solids in Exercises 43–48.

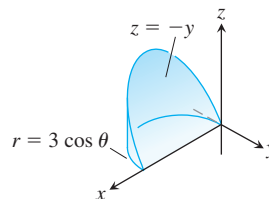
43.



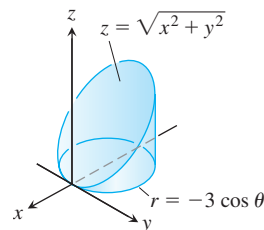
44.



45.

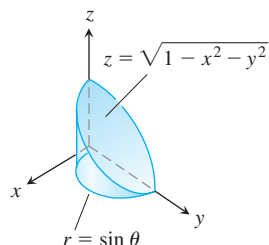


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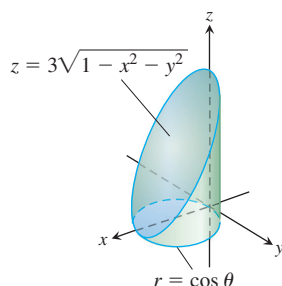




47.



48.



49. **Sphere and cones** Find the volume of the portion of the solid sphere  $\rho \leq a$  that lies between the cones  $\phi = \pi/3$  and  $\phi = 2\pi/3$ .

50. **Sphere and half-planes** Find the volume of the region cut from the solid sphere  $\rho \leq a$  by the half-planes  $\theta = 0$  and  $\theta = \pi/6$  in the first octant.

51. **Sphere and plane** Find the volume of the smaller region cut from the solid sphere  $\rho \leq 2$  by the plane  $z = 1$ .

52. **Cone and planes** Find the volume of the solid enclosed by the cone  $z = \sqrt{x^2 + y^2}$  between the planes  $z = 1$  and  $z = 2$ .

53. **Cylinder and paraboloid** Find the volume of the region bounded below by the plane  $z = 0$ , laterally by the cylinder  $x^2 + y^2 = 1$ , and above by the paraboloid  $z = x^2 + y^2$ .

54. **Cylinder and paraboloids** Find the volume of the region bounded below by the paraboloid  $z = x^2 + y^2$ , laterally by the cylinder  $x^2 + y^2 = 1$ , and above by the paraboloid  $z = x^2 + y^2 + 1$ .

55. **Cylinder and cones** Find the volume of the solid cut from the thick-walled cylinder  $1 \leq x^2 + y^2 \leq 2$  by the cones  $z = \pm \sqrt{x^2 + y^2}$ .

56. **Sphere and cylinder** Find the volume of the region that lies inside the sphere  $x^2 + y^2 + z^2 = 2$  and outside the cylinder  $x^2 + y^2 = 1$ .

57. **Cylinder and planes** Find the volume of the region enclosed by the cylinder  $x^2 + y^2 = 4$  and the planes  $z = 0$  and  $y + z = 4$ .

58. **Cylinder and planes** Find the volume of the region enclosed by the cylinder  $x^2 + y^2 = 4$  and the planes  $z = 0$  and  $x + y + z = 4$ .

59. **Region trapped by paraboloids** Find the volume of the region bounded above by the paraboloid  $z = 5 - x^2 - y^2$  and below by the paraboloid  $z = 4x^2 + 4y^2$ .

60. **Paraboloid and cylinder** Find the volume of the region bounded above by the paraboloid  $z = 9 - x^2 - y^2$ , below by the  $xy$ -plane, and lying outside the cylinder  $x^2 + y^2 = 1$ .

61. **Cylinder and sphere** Find the volume of the region cut from the solid cylinder  $x^2 + y^2 \leq 1$  by the sphere  $x^2 + y^2 + z^2 = 4$ .

62. **Sphere and paraboloid** Find the volume of the region bounded above by the sphere  $x^2 + y^2 + z^2 = 2$  and below by the paraboloid  $z = x^2 + y^2$ .

### Average Values

63. Find the average value of the function  $f(r, \theta, z) = r$  over the region bounded by the cylinder  $r = 1$  between the planes  $z = -1$  and  $z = 1$ .

64. Find the average value of the function  $f(r, \theta, z) = r$  over the solid ball bounded by the sphere  $r^2 + z^2 = 1$ . (This is the sphere  $x^2 + y^2 + z^2 = 1$ .)

65. Find the average value of the function  $f(\rho, \phi, \theta) = \rho$  over the solid ball  $\rho \leq 1$ .

66. Find the average value of the function  $f(\rho, \phi, \theta) = \rho \cos \phi$  over the solid upper ball  $\rho \leq 1, 0 \leq \phi \leq \pi/2$ .

### Masses, Moments, and Centroids

67. **Center of mass** A solid of constant density is bounded below by the plane  $z = 0$ , above by the cone  $z = r, r \geq 0$ , and on the sides by the cylinder  $r = 1$ . Find the center of mass.

68. **Centroid** Find the centroid of the region in the first octant that is bounded above by the cone  $z = \sqrt{x^2 + y^2}$ , below by the plane  $z = 0$ , and on the sides by the cylinder  $x^2 + y^2 = 4$  and the planes  $x = 0$  and  $y = 0$ .

69. **Centroid** Find the centroid of the solid in Exercise 38.

70. **Centroid** Find the centroid of the solid bounded above by the sphere  $\rho = a$  and below by the cone  $\phi = \pi/4$ .

71. **Centroid** Find the centroid of the region that is bounded above by the surface  $z = \sqrt{r}$ , on the sides by the cylinder  $r = 4$ , and below by the  $xy$ -plane.

72. **Centroid** Find the centroid of the region cut from the solid ball  $r^2 + z^2 \leq 1$  by the half-planes  $\theta = -\pi/3, r \geq 0$ , and  $\theta = \pi/3, r \geq 0$ .

73. **Moment of inertia of solid cone** Find the moment of inertia of a right circular cone of base radius 1 and height 1 about an axis through the vertex parallel to the base. (Take  $\delta = 1$ .)

74. **Moment of inertia of solid sphere** Find the moment of inertia of a solid sphere of radius  $a$  about a diameter. (Take  $\delta = 1$ .)

75. **Moment of inertia of solid cone** Find the moment of inertia of a right circular cone of base radius  $a$  and height  $h$  about its axis. (Hint: Place the cone with its vertex at the origin and its axis along the  $z$ -axis.)

76. **Variable density** A solid is bounded on the top by the paraboloid  $z = r^2$ , on the bottom by the plane  $z = 0$ , and on the sides by the cylinder  $r = 1$ . Find the center of mass and the moment of inertia about the  $z$ -axis if the density is

$$\text{a. } \delta(r, \theta, z) = z \qquad \text{b. } \delta(r, \theta, z) = r.$$

77. **Variable density** A solid is bounded below by the cone  $z = \sqrt{x^2 + y^2}$  and above by the plane  $z = 1$ . Find the center of mass and the moment of inertia about the  $z$ -axis if the density is

$$\text{a. } \delta(r, \theta, z) = z \qquad \text{b. } \delta(r, \theta, z) = z^2.$$

78. **Variable density** A solid ball is bounded by the sphere  $\rho = a$ . Find the moment of inertia about the  $z$ -axis if the density is

$$\text{a. } \delta(\rho, \phi, \theta) = \rho^2 \qquad \text{b. } \delta(\rho, \phi, \theta) = r = \rho \sin \phi.$$

79. **Centroid of solid semiellipsoid** Show that the centroid of the solid semiellipsoid of revolution  $(r^2/a^2) + (z^2/h^2) \leq 1, z \geq 0$ , lies on the  $z$ -axis three-eighths of the way from the base to the top. The special case  $h = a$  gives a solid hemisphere. Thus, the centroid of a solid hemisphere lies on the axis of symmetry three-eighths of the way from the base to the top.

80. **Centroid of solid cone** Show that the centroid of a solid right circular cone is one-fourth of the way from the base to the vertex. (In general, the centroid of a solid cone or pyramid is one-fourth of the way from the centroid of the base to the vertex.)

81. **Density of center of a planet** A planet is in the shape of a sphere of radius  $R$  and total mass  $M$  with spherically symmetric density distribution that increases linearly as one approaches its center.

What is the density at the center of this planet if the density at its edge (surface) is taken to be zero?

- 82. Mass of planet's atmosphere** A spherical planet of radius  $R$  has an atmosphere whose density is  $\mu = \mu_0 e^{-ch}$ , where  $h$  is the altitude above the surface of the planet,  $\mu_0$  is the density at sea level, and  $c$  is a positive constant. Find the mass of the planet's atmosphere.

### Theory and Examples

#### 83. Vertical planes in cylindrical coordinates

- a. Show that planes perpendicular to the  $x$ -axis have equations of the form  $r = a \sec \theta$  in cylindrical coordinates.
  - b. Show that planes perpendicular to the  $y$ -axis have equations of the form  $r = b \csc \theta$ .
- 84. (Continuation of Exercise 83.)** Find an equation of the form  $r = f(\theta)$  in cylindrical coordinates for the plane  $ax + by = c$ ,  $c \neq 0$ .
- 85. Symmetry** What symmetry will you find in a surface that has an equation of the form  $r = f(z)$  in cylindrical coordinates? Give reasons for your answer.
- 86. Symmetry** What symmetry will you find in a surface that has an equation of the form  $\rho = f(\phi)$  in spherical coordinates? Give reasons for your answer.

## Exercises 15.8

## Jacobians and Transformed Regions in the Plane

1. a. Solve the system

$$u = x - y, \quad v = 2x + y$$

for  $x$  and  $y$  in terms of  $u$  and  $v$ . Then find the value of the Jacobian  $\partial(x, y)/\partial(u, v)$ .

- b. Find the image under the transformation  $u = x - y$ ,  $v = 2x + y$  of the triangular region with vertices  $(0, 0)$ ,  $(1, 1)$ , and  $(1, -2)$  in the  $xy$ -plane. Sketch the transformed region in the  $uv$ -plane.

2. a. Solve the system

$$u = x + 2y, \quad v = x - y$$

for  $x$  and  $y$  in terms of  $u$  and  $v$ . Then find the value of the Jacobian  $\partial(x, y)/\partial(u, v)$ .

- b. Find the image under the transformation  $u = x + 2y$ ,  $v = x - y$  of the triangular region in the  $xy$ -plane bounded by the lines  $y = 0$ ,  $y = x$ , and  $x + 2y = 2$ . Sketch the transformed region in the  $uv$ -plane.

3. a. Solve the system

$$u = 3x + 2y, \quad v = x + 4y$$

for  $x$  and  $y$  in terms of  $u$  and  $v$ . Then find the value of the Jacobian  $\partial(x, y)/\partial(u, v)$ .

- b. Find the image under the transformation  $u = 3x + 2y$ ,  $v = x + 4y$  of the triangular region in the  $xy$ -plane bounded

by the  $x$ -axis, the  $y$ -axis, and the line  $x + y = 1$ . Sketch the transformed region in the  $uv$ -plane.

4. a. Solve the system

$$u = 2x - 3y, \quad v = -x + y$$

for  $x$  and  $y$  in terms of  $u$  and  $v$ . Then find the value of the Jacobian  $\partial(x, y)/\partial(u, v)$ .

- b. Find the image under the transformation  $u = 2x - 3y$ ,  $v = -x + y$  of the parallelogram  $R$  in the  $xy$ -plane with boundaries  $x = -3$ ,  $x = 0$ ,  $y = x$ , and  $y = x + 1$ . Sketch the transformed region in the  $uv$ -plane.

## Substitutions in Double Integrals

5. Evaluate the integral

$$\int_0^4 \int_{x=y/2}^{x=(y/2)+1} \frac{2x-y}{2} dx dy$$

from Example 1 directly by integration with respect to  $x$  and  $y$  to confirm that its value is 2.

6. Use the transformation in Exercise 1 to evaluate the integral

$$\iint_R (2x^2 - xy - y^2) dx dy$$

for the region  $R$  in the first quadrant bounded by the lines  $y = -2x + 4$ ,  $y = -2x + 7$ ,  $y = x - 2$ , and  $y = x + 1$ .

7. Use the transformation in Exercise 3 to evaluate the integral

$$\iint_R (3x^2 + 14xy + 8y^2) dx dy$$

for the region  $R$  in the first quadrant bounded by the lines  $y = -(3/2)x + 1$ ,  $y = -(3/2)x + 3$ ,  $y = -(1/4)x$ , and  $y = -(1/4)x + 1$ .

8. Use the transformation and parallelogram  $R$  in Exercise 4 to evaluate the integral

$$\iint_R 2(x - y) dx dy.$$

9. Let  $R$  be the region in the first quadrant of the  $xy$ -plane bounded by the hyperbolas  $xy = 1$ ,  $xy = 9$  and the lines  $y = x$ ,  $y = 4x$ . Use the transformation  $x = u/v$ ,  $y = uv$  with  $u > 0$  and  $v > 0$  to rewrite

$$\iint_R \left( \sqrt{\frac{y}{x}} + \sqrt{xy} \right) dx dy$$

as an integral over an appropriate region  $G$  in the  $uv$ -plane. Then evaluate the  $uv$ -integral over  $G$ .

10. a. Find the Jacobian of the transformation  $x = u$ ,  $y = uv$  and sketch the region  $G$ :  $1 \leq u \leq 2$ ,  $1 \leq uv \leq 2$ , in the  $uv$ -plane.  
b. Then use Equation (2) to transform the integral

$$\int_1^2 \int_1^{2/y} \frac{y}{x} dy dx$$

into an integral over  $G$ , and evaluate both integrals.

11. **Polar moment of inertia of an elliptical plate** A thin plate of constant density covers the region bounded by the ellipse  $x^2/a^2 + y^2/b^2 = 1$ ,  $a > 0$ ,  $b > 0$ , in the  $xy$ -plane. Find the first moment of the plate about the origin. (Hint: Use the transformation  $x = ar \cos \theta$ ,  $y = br \sin \theta$ .)  
12. **The area of an ellipse** The area  $\pi ab$  of the ellipse  $x^2/a^2 + y^2/b^2 = 1$  can be found by integrating the function  $f(x, y) = 1$  over the region bounded by the ellipse in the  $xy$ -plane. Evaluating the integral directly requires a trigonometric substitution. An easier way to evaluate the integral is to use the transformation  $x = au$ ,  $y = bv$  and evaluate the transformed integral over the disk  $G$ :  $u^2 + v^2 \leq 1$  in the  $uv$ -plane. Find the area this way.

13. Use the transformation in Exercise 2 to evaluate the integral

$$\int_0^{2/3} \int_y^{2-2y} (x + 2y)e^{(y-x)} dx dy$$

by first writing it as an integral over a region  $G$  in the  $uv$ -plane.

14. Use the transformation  $x = u + (1/2)v$ ,  $y = v$  to evaluate the integral

$$\int_0^2 \int_{y/2}^{(y+4)/2} y^3(2x - y)e^{(2x-y)^2} dx dy$$

by first writing it as an integral over a region  $G$  in the  $uv$ -plane.

15. Use the transformation  $x = u/v$ ,  $y = uv$  to evaluate the integral sum

$$\int_1^2 \int_{1/y}^y (x^2 + y^2) dx dy + \int_2^4 \int_{y/4}^{4/y} (x^2 + y^2) dx dy.$$

16. Use the transformation  $x = u^2 - v^2$ ,  $y = 2uv$  to evaluate the integral

$$\int_0^1 \int_0^{2\sqrt{1-x}} \sqrt{x^2 + y^2} dy dx.$$

(Hint: Show that the image of the triangular region  $G$  with vertices  $(0, 0)$ ,  $(1, 0)$ ,  $(1, 1)$  in the  $uv$ -plane is the region of integration  $R$  in the  $xy$ -plane defined by the limits of integration.)

### Substitutions in Triple Integrals

17. Evaluate the integral in Example 5 by integrating with respect to  $x$ ,  $y$ , and  $z$ .

18. **Volume of an ellipsoid** Find the volume of the ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1.$$

(Hint: Let  $x = au$ ,  $y = bv$ , and  $z = cw$ . Then find the volume of an appropriate region in  $uvw$ -space.)

19. Evaluate

$$\iiint |xyz| dx dy dz$$

over the solid ellipsoid

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} \leq 1.$$

(Hint: Let  $x = au$ ,  $y = bv$ , and  $z = cw$ . Then integrate over an appropriate region in  $uvw$ -space.)

20. Let  $D$  be the region in  $xyz$ -space defined by the inequalities

$$1 \leq x \leq 2, \quad 0 \leq xy \leq 2, \quad 0 \leq z \leq 1.$$

Evaluate

$$\iiint_D (x^2y + 3xyz) dx dy dz$$

by applying the transformation

$$u = x, \quad v = xy, \quad w = 3z$$

and integrating over an appropriate region  $G$  in  $uvw$ -space.

### Theory and Examples

21. Find the Jacobian  $\partial(x, y)/\partial(u, v)$  of the transformation

a.  $x = u \cos v$ ,  $y = u \sin v$

b.  $x = u \sin v$ ,  $y = u \cos v$

22. Find the Jacobian  $\partial(x, y, z)/\partial(u, v, w)$  of the transformation

a.  $x = u \cos v$ ,  $y = u \sin v$ ,  $z = w$

b.  $x = 2u - 1$ ,  $y = 3v - 4$ ,  $z = (1/2)(w - 4)$ .

- 23.** Evaluate the appropriate determinant to show that the Jacobian of the transformation from Cartesian  $\rho\phi\theta$ -space to Cartesian  $xyz$ -space is  $\rho^2 \sin \phi$ .
- 24. Substitutions in single integrals** How can substitutions in single definite integrals be viewed as transformations of regions? What is the Jacobian in such a case? Illustrate with an example.
- 25. Centroid of a solid semiellipsoid** Assuming the result that the centroid of a solid hemisphere lies on the axis of symmetry three-eighths of the way from the base toward the top, show, by transforming the appropriate integrals, that the center of mass of a solid semiellipsoid  $(x^2/a^2) + (y^2/b^2) + (z^2/c^2) \leq 1$ ,  $z \geq 0$ , lies on the  $z$ -axis three-eighths of the way from the base toward the top. (You can do this without evaluating any of the integrals.)
- 26. Cylindrical shells** In Section 6.2, we learned how to find the volume of a solid of revolution using the shell method; namely, if the region between the curve  $y = f(x)$  and the  $x$ -axis from  $a$  to  $b$  ( $0 < a < b$ ) is revolved about the  $y$ -axis, the volume of the resulting solid is  $\int_a^b 2\pi x f(x) dx$ . Prove that finding volumes by

using triple integrals gives the same result. (*Hint:* Use cylindrical coordinates with the roles of  $y$  and  $z$  changed.)

- 27. Inverse transform** The equations  $x = g(u, v)$ ,  $y = h(u, v)$  in Figure 15.54 transform the region  $G$  in the  $uv$ -plane into the region  $R$  in the  $xy$ -plane. Since the substitution transformation is one-to-one with continuous first partial derivatives, it has an inverse transformation and there are equations  $u = \alpha(x, y)$ ,  $v = \beta(x, y)$  with continuous first partial derivatives transforming  $R$  back into  $G$ . Moreover, the Jacobian determinants of the transformations are related reciprocally by

$$\frac{\partial(x, y)}{\partial(u, v)} = \left( \frac{\partial(u, v)}{\partial(x, y)} \right)^{-1}. \quad (10)$$

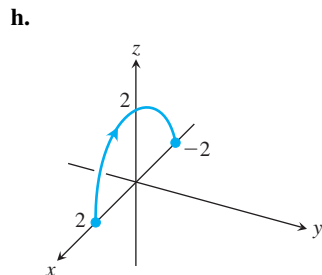
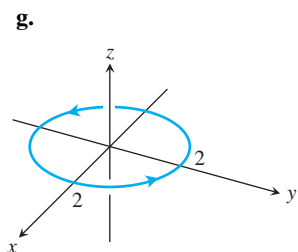
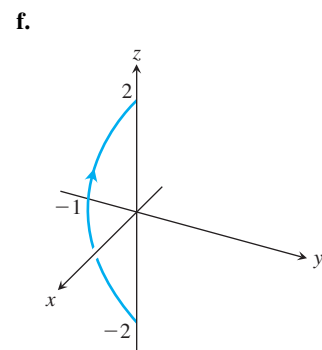
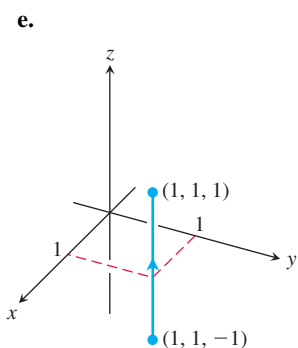
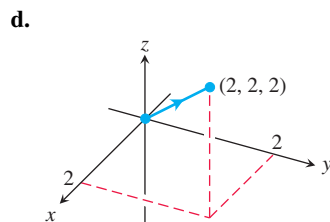
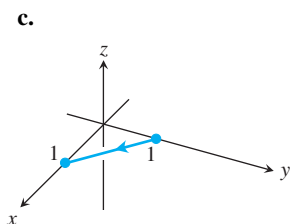
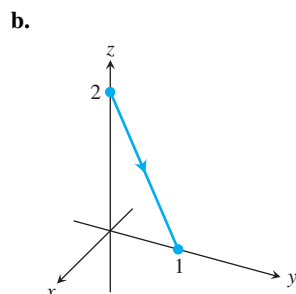
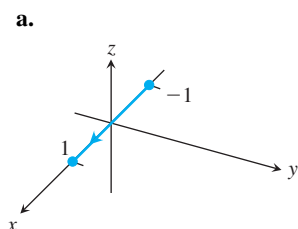
Equation (10) is proved in advanced calculus. Use it to find the area of the region  $R$  in the first quadrant of the  $xy$ -plane bounded by the lines  $y = 2x$ ,  $2y = x$ , and the curves  $xy = 2$ ,  $2xy = 1$  for  $u = xy$  and  $v = y/x$ .

- 28. (Continuation of Exercise 27.)** For the region  $R$  described in Exercise 27, evaluate the integral  $\iint_R y^2 dA$ .

## Exercises 16.1

### Graphs of Vector Equations

Match the vector equations in Exercises 1–8 with the graphs (a)–(h) given here.



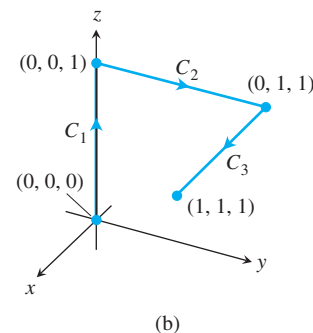
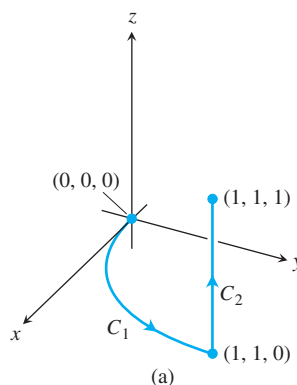
1.  $\mathbf{r}(t) = t\mathbf{i} + (1 - t)\mathbf{j}, \quad 0 \leq t \leq 1$
2.  $\mathbf{r}(t) = \mathbf{i} + \mathbf{j} + t\mathbf{k}, \quad -1 \leq t \leq 1$
3.  $\mathbf{r}(t) = (2 \cos t)\mathbf{i} + (2 \sin t)\mathbf{j}, \quad 0 \leq t \leq 2\pi$
4.  $\mathbf{r}(t) = t\mathbf{i}, \quad -1 \leq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

### Evaluating Line Integrals over Space Curves

9. Evaluate  $\int_C (x + y) ds$  where  $C$  is the straight-line segment  $x = t, y = (1 - t), z = 0$ , from  $(0, 1, 0)$  to  $(1, 0, 0)$ .
10. Evaluate  $\int_C (x - y + z - 2) ds$  where  $C$  is the straight-line segment  $x = t, y = (1 - t), z = 1$ , from  $(0, 1, 1)$  to  $(1, 0, 1)$ .
11. Evaluate  $\int_C (xy + y + z) ds$  along the curve  $\mathbf{r}(t) = 2t\mathbf{i} + t\mathbf{j} + (2 - 2t)\mathbf{k}, 0 \leq t \leq 1$ .
12. Evaluate  $\int_C \sqrt{x^2 + y^2} ds$  along the curve  $\mathbf{r}(t) = (4 \cos t)\mathbf{i} + (4 \sin t)\mathbf{j} + 3t\mathbf{k}, -2\pi \leq t \leq 2\pi$ .
13. Find the line integral of  $f(x, y, z) = x + y + z$  over the straight-line segment from  $(1, 2, 3)$  to  $(0, -1, 1)$ .
14. Find the line integral of  $f(x, y, z) = \sqrt{3}/(x^2 + y^2 + z^2)$  over the curve  $\mathbf{r}(t) = t\mathbf{i} + t\mathbf{j} + t\mathbf{k}, 1 \leq t \leq \infty$ .
15. Integrate  $f(x, y, z) = x + \sqrt{y} - z^2$  over the path from  $(0, 0, 0)$  to  $(1, 1, 1)$  (see accompanying figure) given by

$$C_1: \mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j}, \quad 0 \leq t \leq 1$$

$$C_2: \mathbf{r}(t) = \mathbf{i} + \mathbf{j} + t\mathbf{k}, \quad 0 \leq t \leq 1$$



The paths of integration for Exercises 15 and 16.

16. Integrate  $f(x, y, z) = x + \sqrt{y} - z^2$  over the path from  $(0, 0, 0)$  to  $(1, 1, 1)$  (see accompanying figure) given by

$$C_1: \mathbf{r}(t) = t\mathbf{k}, \quad 0 \leq t \leq 1$$

$$C_2: \mathbf{r}(t) = t\mathbf{j} + \mathbf{k}, \quad 0 \leq t \leq 1$$

$$C_3: \mathbf{r}(t) = t\mathbf{i} + \mathbf{j} + \mathbf{k}, \quad 0 \leq t \leq 1$$

17. Integrate  $f(x, y, z) = (x + y + z)/(x^2 + y^2 + z^2)$  over the path  $\mathbf{r}(t) = t\mathbf{i} + t\mathbf{j} + t\mathbf{k}$ ,  $0 < a \leq t \leq b$ .

18. Integrate  $f(x, y, z) = -\sqrt{x^2 + z^2}$  over the circle

$$\mathbf{r}(t) = (a \cos t)\mathbf{j} + (a \sin t)\mathbf{k}, \quad 0 \leq t \leq 2\pi.$$

### Line Integrals over Plane Curves

19. Evaluate  $\int_C x \, ds$ , where  $C$  is

- the straight-line segment  $x = t$ ,  $y = t/2$ , from  $(0, 0)$  to  $(4, 2)$ .
- the parabolic curve  $x = t$ ,  $y = t^2$ , from  $(0, 0)$  to  $(2, 4)$ .

20. Evaluate  $\int_C \sqrt{x + 2y} \, ds$ , where  $C$  is

- the straight-line segment  $x = t$ ,  $y = 4t$ , from  $(0, 0)$  to  $(1, 4)$ .
- $C_1 \cup C_2$ ;  $C_1$  is the line segment from  $(0, 0)$  to  $(1, 0)$  and  $C_2$  is the line segment from  $(1, 0)$  to  $(1, 2)$ .

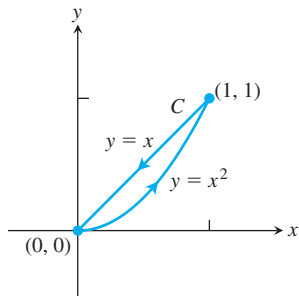
21. Find the line integral of  $f(x, y) = ye^{x^2}$  along the curve  $\mathbf{r}(t) = 4t\mathbf{i} - 3t\mathbf{j}$ ,  $-1 \leq t \leq 2$ .

22. Find the line integral of  $f(x, y) = x - y + 3$  along the curve  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$ .

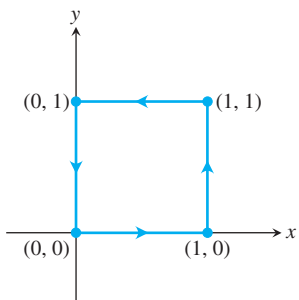
23. Evaluate  $\int_C \frac{x^2}{y^{4/3}} \, ds$ , where  $C$  is the curve  $x = t^2$ ,  $y = t^3$ , for  $1 \leq t \leq 2$ .

24. Find the line integral of  $f(x, y) = \sqrt{y}/x$  along the curve  $\mathbf{r}(t) = t^3\mathbf{i} + t^4\mathbf{j}$ ,  $1/2 \leq t \leq 1$ .

25. Evaluate  $\int_C (x + \sqrt{y}) \, ds$  where  $C$  is given in the accompanying figure.



26. Evaluate  $\int_C \frac{1}{x^2 + y^2 + 1} \, ds$  where  $C$  is given in the accompanying figure.



In Exercises 27–30, integrate  $f$  over the given curve.

27.  $f(x, y) = x^3/y$ ,  $C: y = x^2/2$ ,  $0 \leq x \leq 2$

28.  $f(x, y) = (x + y^2)/\sqrt{1 + x^2}$ ,  $C: y = x^2/2$  from  $(1, 1/2)$  to  $(0, 0)$

29.  $f(x, y) = x + y$ ,  $C: x^2 + y^2 = 4$  in the first quadrant from  $(2, 0)$  to  $(0, 2)$

30.  $f(x, y) = x^2 - y$ ,  $C: x^2 + y^2 = 4$  in the first quadrant from  $(0, 2)$  to  $(\sqrt{2}, \sqrt{2})$

31. Find the area of one side of the “winding wall” standing orthogonally on the curve  $y = x^2$ ,  $0 \leq x \leq 2$ , and beneath the curve on the surface  $f(x, y) = x + \sqrt{y}$ .

32. Find the area of one side of the “wall” standing orthogonally on the curve  $2x + 3y = 6$ ,  $0 \leq x \leq 6$ , and beneath the curve on the surface  $f(x, y) = 4 + 3x + 2y$ .

### Masses and Moments

33. **Mass of a wire** Find the mass of a wire that lies along the curve  $\mathbf{r}(t) = (t^2 - 1)\mathbf{j} + 2t\mathbf{k}$ ,  $0 \leq t \leq 1$ , if the density is  $\delta = (3/2)t$ .

34. **Center of mass of a curved wire** A wire of density  $\delta(x, y, z) = 15\sqrt{y + 2}$  lies along the curve  $\mathbf{r}(t) = (t^2 - 1)\mathbf{j} + 2t\mathbf{k}$ ,  $-1 \leq t \leq 1$ . Find its center of mass. Then sketch the curve and center of mass together.

35. **Mass of wire with variable density** Find the mass of a thin wire lying along the curve  $\mathbf{r}(t) = \sqrt{2}t\mathbf{i} + \sqrt{2}t\mathbf{j} + (4 - t^2)\mathbf{k}$ ,  $0 \leq t \leq 1$ , if the density is (a)  $\delta = 3t$  and (b)  $\delta = 1$ .

36. **Center of mass of wire with variable density** Find the center of mass of a thin wire lying along the curve  $\mathbf{r}(t) = t\mathbf{i} + 2t\mathbf{j} + (2/3)t^{3/2}\mathbf{k}$ ,  $0 \leq t \leq 2$ , if the density is  $\delta = 3\sqrt{5} + t$ .

37. **Moment of inertia of wire hoop** A circular wire hoop of constant density  $\delta$  lies along the circle  $x^2 + y^2 = a^2$  in the  $xy$ -plane. Find the hoop’s moment of inertia about the  $z$ -axis.

38. **Inertia of a slender rod** A slender rod of constant density lies along the line segment  $\mathbf{r}(t) = t\mathbf{j} + (2 - 2t)\mathbf{k}$ ,  $0 \leq t \leq 1$ , in the  $yz$ -plane. Find the moments of inertia of the rod about the three coordinate axes.

39. **Two springs of constant density** A spring of constant density  $\delta$  lies along the helix

$$\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} + t\mathbf{k}, \quad 0 \leq t \leq 2\pi.$$

- Find  $I_z$ .

- Suppose that you have another spring of constant density  $\delta$  that is twice as long as the spring in part (a) and lies along the helix for  $0 \leq t \leq 4\pi$ . Do you expect  $I_z$  for the longer spring to be the same as that for the shorter one, or should it be different? Check your prediction by calculating  $I_z$  for the longer spring.

40. **Wire of constant density** A wire of constant density  $\delta = 1$  lies along the curve

$$\mathbf{r}(t) = (t \cos t)\mathbf{i} + (t \sin t)\mathbf{j} + (2\sqrt{2}/3)t^{3/2}\mathbf{k}, \quad 0 \leq t \leq 1.$$

Find  $\bar{z}$  and  $I_z$ .

41. **The arch in Example 4** Find  $I_x$  for the arch in Example 4.

- 42. Center of mass and moments of inertia for wire with variable density** Find the center of mass and the moments of inertia about the coordinate axes of a thin wire lying along the curve

$$\mathbf{r}(t) = t\mathbf{i} + \frac{2\sqrt{2}}{3}t^{3/2}\mathbf{j} + \frac{t^2}{2}\mathbf{k}, \quad 0 \leq t \leq 2,$$

if the density is  $\delta = 1/(t + 1)$ .

### COMPUTER EXPLORATIONS

In Exercises 43–46, use a CAS to perform the following steps to evaluate the line integrals.

- Find  $ds = |\mathbf{v}(t)| dt$  for the path  $\mathbf{r}(t) = g(t)\mathbf{i} + h(t)\mathbf{j} + k(t)\mathbf{k}$ .
- Express the integrand  $f(g(t), h(t), k(t))|\mathbf{v}(t)|$  as a function of the parameter  $t$ .
- Evaluate  $\int_C f ds$  using Equation (2) in the text.

- $f(x, y, z) = \sqrt{1 + 30x^2 + 10y}$ ;  $\mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j} + 3t^2\mathbf{k}$ ,  $0 \leq t \leq 2$
- $f(x, y, z) = \sqrt{1 + x^3 + 5y^3}$ ;  $\mathbf{r}(t) = t\mathbf{i} + \frac{1}{3}t^2\mathbf{j} + \sqrt{t}\mathbf{k}$ ,  $0 \leq t \leq 2$
- $f(x, y, z) = x\sqrt{y} - 3z^2$ ;  $\mathbf{r}(t) = (\cos 2t)\mathbf{i} + (\sin 2t)\mathbf{j} + 5t\mathbf{k}$ ,  $0 \leq t \leq 2\pi$
- $f(x, y, z) = \left(1 + \frac{9}{4}z^{1/3}\right)^{1/4}$ ;  $\mathbf{r}(t) = (\cos 2t)\mathbf{i} + (\sin 2t)\mathbf{j} + t^{5/2}\mathbf{k}$ ,  $0 \leq t \leq 2\pi$



## Exercises 16.2

### Vector Fields

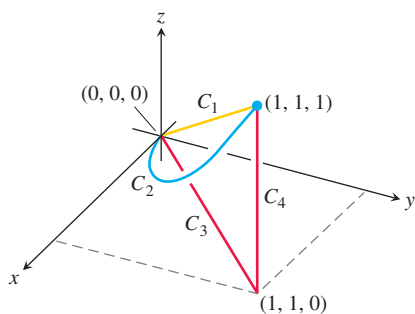
Find the gradient fields of the functions in Exercises 1–4.

1.  $f(x, y, z) = (x^2 + y^2 + z^2)^{-1/2}$
2.  $f(x, y, z) = \ln \sqrt{x^2 + y^2 + z^2}$
3.  $g(x, y, z) = e^z - \ln(x^2 + y^2)$
4.  $g(x, y, z) = xy + yz + xz$
5. Give a formula  $\mathbf{F} = M(x, y)\mathbf{i} + N(x, y)\mathbf{j}$  for the vector field in the plane that has the property that  $\mathbf{F}$  points toward the origin with magnitude inversely proportional to the square of the distance from  $(x, y)$  to the origin. (The field is not defined at  $(0, 0)$ .)
6. Give a formula  $\mathbf{F} = M(x, y)\mathbf{i} + N(x, y)\mathbf{j}$  for the vector field in the plane that has the properties that  $\mathbf{F} = \mathbf{0}$  at  $(0, 0)$  and that at any other point  $(a, b)$ ,  $\mathbf{F}$  is tangent to the circle  $x^2 + y^2 = a^2 + b^2$  and points in the clockwise direction with magnitude  $|\mathbf{F}| = \sqrt{a^2 + b^2}$ .

### Line Integrals of Vector Fields

In Exercises 7–12, find the line integrals of  $\mathbf{F}$  from  $(0, 0, 0)$  to  $(1, 1, 1)$  over each of the following paths in the accompanying figure.

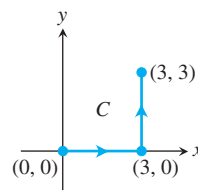
- a. The straight-line path  $C_1: \mathbf{r}(t) = t\mathbf{i} + t\mathbf{j} + t\mathbf{k}, \quad 0 \leq t \leq 1$
  - b. The curved path  $C_2: \mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j} + t^4\mathbf{k}, \quad 0 \leq t \leq 1$
  - c. The path  $C_3 \cup C_4$  consisting of the line segment from  $(0, 0, 0)$  to  $(1, 1, 0)$  followed by the segment from  $(1, 1, 0)$  to  $(1, 1, 1)$
7.  $\mathbf{F} = 3y\mathbf{i} + 2x\mathbf{j} + 4z\mathbf{k}$       8.  $\mathbf{F} = [1/(x^2 + 1)]\mathbf{j}$
  9.  $\mathbf{F} = \sqrt{z}\mathbf{i} - 2x\mathbf{j} + \sqrt{y}\mathbf{k}$       10.  $\mathbf{F} = xy\mathbf{i} + yz\mathbf{j} + xz\mathbf{k}$
  11.  $\mathbf{F} = (3x^2 - 3x)\mathbf{i} + 3z\mathbf{j} + \mathbf{k}$
  12.  $\mathbf{F} = (y + z)\mathbf{i} + (z + x)\mathbf{j} + (x + y)\mathbf{k}$



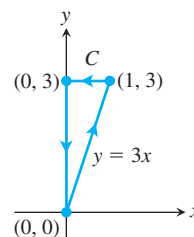
### Line Integrals with Respect to $x$ , $y$ , and $z$

In Exercises 13–16, find the line integrals along the given path  $C$ .

13.  $\int_C (x - y) dx$ , where  $C: x = t, y = 2t + 1$ , for  $0 \leq t \leq 3$
14.  $\int_C \frac{x}{y} dy$ , where  $C: x = t, y = t^2$ , for  $1 \leq t \leq 2$
15.  $\int_C (x^2 + y^2) dy$ , where  $C$  is given in the accompanying figure



16.  $\int_C \sqrt{x + y} dx$ , where  $C$  is given in the accompanying figure



17. Along the curve  $\mathbf{r}(t) = t\mathbf{i} - \mathbf{j} + t^2\mathbf{k}, 0 \leq t \leq 1$ , evaluate each of the following integrals.
  - a.  $\int_C (x + y - z) dx$
  - b.  $\int_C (x + y - z) dy$
  - c.  $\int_C (x + y - z) dz$
18. Along the curve  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} - (\cos t)\mathbf{k}, 0 \leq t \leq \pi$ , evaluate each of the following integrals.
  - a.  $\int_C xz dx$
  - b.  $\int_C xz dy$
  - c.  $\int_C xyz dz$

### Work

In Exercises 19–22, find the work done by  $\mathbf{F}$  over the curve in the direction of increasing  $t$ .

19.  $\mathbf{F} = xy\mathbf{i} + y\mathbf{j} - yz\mathbf{k}$   
 $\mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j} + t\mathbf{k}, \quad 0 \leq t \leq 1$
20.  $\mathbf{F} = 2y\mathbf{i} + 3x\mathbf{j} + (x + y)\mathbf{k}$   
 $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} + (t/6)\mathbf{k}, \quad 0 \leq t \leq 2\pi$
21.  $\mathbf{F} = z\mathbf{i} + x\mathbf{j} + y\mathbf{k}$   
 $\mathbf{r}(t) = (\sin t)\mathbf{i} + (\cos t)\mathbf{j} + t\mathbf{k}, \quad 0 \leq t \leq 2\pi$
22.  $\mathbf{F} = 6z\mathbf{i} + y^2\mathbf{j} + 12x\mathbf{k}$   
 $\mathbf{r}(t) = (\sin t)\mathbf{i} + (\cos t)\mathbf{j} + (t/6)\mathbf{k}, \quad 0 \leq t \leq 2\pi$

### Line Integrals in the Plane

23. Evaluate  $\int_C xy dx + (x + y) dy$  along the curve  $y = x^2$  from  $(-1, 1)$  to  $(2, 4)$ .
24. Evaluate  $\int_C (x - y) dx + (x + y) dy$  counterclockwise around the triangle with vertices  $(0, 0)$ ,  $(1, 0)$ , and  $(0, 1)$ .
25. Evaluate  $\int_C \mathbf{F} \cdot \mathbf{T} ds$  for the vector field  $\mathbf{F} = x^2\mathbf{i} - y\mathbf{j}$  along the curve  $x = y^2$  from  $(4, 2)$  to  $(1, -1)$ .
26. Evaluate  $\int_C \mathbf{F} \cdot d\mathbf{r}$  for the vector field  $\mathbf{F} = y\mathbf{i} - x\mathbf{j}$  counterclockwise along the unit circle  $x^2 + y^2 = 1$  from  $(1, 0)$  to  $(0, 1)$ .

## Work, Circulation, and Flux in the Plane

**27. Work** Find the work done by the force  $\mathbf{F} = xy\mathbf{i} + (y - x)\mathbf{j}$  over the straight line from  $(1, 1)$  to  $(2, 3)$ .

**28. Work** Find the work done by the gradient of  $f(x, y) = (x + y)^2$  counterclockwise around the circle  $x^2 + y^2 = 4$  from  $(2, 0)$  to itself.

**29. Circulation and flux** Find the circulation and flux of the fields

$$\mathbf{F}_1 = x\mathbf{i} + y\mathbf{j} \quad \text{and} \quad \mathbf{F}_2 = -y\mathbf{i} + x\mathbf{j}$$

around and across each of the following curves.

a. The circle  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$

b. The ellipse  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (4 \sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$

**30. Flux across a circle** Find the flux of the fields

$$\mathbf{F}_1 = 2x\mathbf{i} - 3y\mathbf{j} \quad \text{and} \quad \mathbf{F}_2 = 2x\mathbf{i} + (x - y)\mathbf{j}$$

across the circle

$$\mathbf{r}(t) = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j}, \quad 0 \leq t \leq 2\pi.$$

In Exercises 31–34, find the circulation and flux of the field  $\mathbf{F}$  around and across the closed semicircular path that consists of the semicircular arch  $\mathbf{r}_1(t) = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j}$ ,  $0 \leq t \leq \pi$ , followed by the line segment  $\mathbf{r}_2(t) = t\mathbf{i}$ ,  $-a \leq t \leq a$ .

**31.  $\mathbf{F} = x\mathbf{i} + y\mathbf{j}$**  **32.  $\mathbf{F} = x^2\mathbf{i} + y^2\mathbf{j}$**

**33.  $\mathbf{F} = -y\mathbf{i} + x\mathbf{j}$**  **34.  $\mathbf{F} = -y^2\mathbf{i} + x^2\mathbf{j}$**

**35. Flow integrals** Find the flow of the velocity field  $\mathbf{F} = (x + y)\mathbf{i} - (x^2 + y^2)\mathbf{j}$  along each of the following paths from  $(1, 0)$  to  $(-1, 0)$  in the  $xy$ -plane.

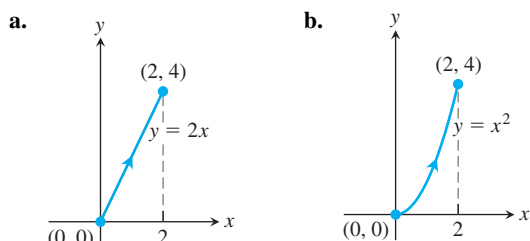
a. The upper half of the circle  $x^2 + y^2 = 1$

b. The line segment from  $(1, 0)$  to  $(-1, 0)$

c. The line segment from  $(1, 0)$  to  $(0, -1)$  followed by the line segment from  $(0, -1)$  to  $(-1, 0)$

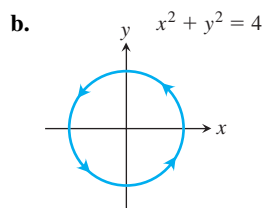
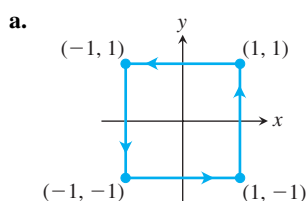
**36. Flux across a triangle** Find the flux of the field  $\mathbf{F}$  in Exercise 35 outward across the triangle with vertices  $(1, 0)$ ,  $(0, 1)$ ,  $(-1, 0)$ .

**37.** Find the flow of the velocity field  $\mathbf{F} = y^2\mathbf{i} + 2xy\mathbf{j}$  along each of the following paths from  $(0, 0)$  to  $(2, 4)$ .



c. Use any path from  $(0, 0)$  to  $(2, 4)$  different from parts (a) and (b).

**38.** Find the circulation of the field  $\mathbf{F} = y\mathbf{i} + (x + 2y)\mathbf{j}$  around each of the following closed paths.



c. Use any closed path different from parts (a) and (b).

## Vector Fields in the Plane

**39. Spin field** Draw the spin field

$$\mathbf{F} = -\frac{y}{\sqrt{x^2 + y^2}}\mathbf{i} + \frac{x}{\sqrt{x^2 + y^2}}\mathbf{j}$$

(see Figure 16.12) along with its horizontal and vertical components at a representative assortment of points on the circle  $x^2 + y^2 = 4$ .

**40. Radial field** Draw the radial field

$$\mathbf{F} = x\mathbf{i} + y\mathbf{j}$$

(see Figure 16.11) along with its horizontal and vertical components at a representative assortment of points on the circle  $x^2 + y^2 = 1$ .

**41. A field of tangent vectors**

a. Find a field  $\mathbf{G} = P(x, y)\mathbf{i} + Q(x, y)\mathbf{j}$  in the  $xy$ -plane with the property that at any point  $(a, b) \neq (0, 0)$ ,  $\mathbf{G}$  is a vector of magnitude  $\sqrt{a^2 + b^2}$  tangent to the circle  $x^2 + y^2 = a^2 + b^2$  and pointing in the counterclockwise direction. (The field is undefined at  $(0, 0)$ .)

b. How is  $\mathbf{G}$  related to the spin field  $\mathbf{F}$  in Figure 16.12?

**42. A field of tangent vectors**

a. Find a field  $\mathbf{G} = P(x, y)\mathbf{i} + Q(x, y)\mathbf{j}$  in the  $xy$ -plane with the property that at any point  $(a, b) \neq (0, 0)$ ,  $\mathbf{G}$  is a unit vector tangent to the circle  $x^2 + y^2 = a^2 + b^2$  and pointing in the clockwise direction.

b. How is  $\mathbf{G}$  related to the spin field  $\mathbf{F}$  in Figure 16.12?

**43. Unit vectors pointing toward the origin** Find a field  $\mathbf{F} = M(x, y)\mathbf{i} + N(x, y)\mathbf{j}$  in the  $xy$ -plane with the property that at each point  $(x, y) \neq (0, 0)$ ,  $\mathbf{F}$  is a unit vector pointing toward the origin. (The field is undefined at  $(0, 0)$ .)

**44. Two “central” fields** Find a field  $\mathbf{F} = M(x, y)\mathbf{i} + N(x, y)\mathbf{j}$  in the  $xy$ -plane with the property that at each point  $(x, y) \neq (0, 0)$ ,  $\mathbf{F}$  points toward the origin and  $|\mathbf{F}|$  is (a) the distance from  $(x, y)$  to the origin, (b) inversely proportional to the distance from  $(x, y)$  to the origin. (The field is undefined at  $(0, 0)$ .)

**45. Work and area** Suppose that  $f(t)$  is differentiable and positive for  $a \leq t \leq b$ . Let  $C$  be the path  $\mathbf{r}(t) = t\mathbf{i} + f(t)\mathbf{j}$ ,  $a \leq t \leq b$ , and  $\mathbf{F} = y\mathbf{i}$ . Is there any relation between the value of the work integral

$$\int_C \mathbf{F} \cdot d\mathbf{r}$$

and the area of the region bounded by the  $t$ -axis, the graph of  $f$ , and the lines  $t = a$  and  $t = b$ ? Give reasons for your answer.

**46. Work done by a radial force with constant magnitude** A particle moves along the smooth curve  $y = f(x)$  from  $(a, f(a))$  to

$(b, f(b))$ . The force moving the particle has constant magnitude  $k$  and always points away from the origin. Show that the work done by the force is

$$\int_C \mathbf{F} \cdot \mathbf{T} \, ds = k[(b^2 + (f(b))^2)^{1/2} - (a^2 + (f(a))^2)^{1/2}].$$

### Flow Integrals in Space

In Exercises 47–50,  $\mathbf{F}$  is the velocity field of a fluid flowing through a region in space. Find the flow along the given curve in the direction of increasing  $t$ .

47.  $\mathbf{F} = -4xy\mathbf{i} + 8y\mathbf{j} + 2\mathbf{k}$

$$\mathbf{r}(t) = t\mathbf{i} + t^2\mathbf{j} + \mathbf{k}, \quad 0 \leq t \leq 2$$

48.  $\mathbf{F} = x^2\mathbf{i} + yz\mathbf{j} + y^2\mathbf{k}$

$$\mathbf{r}(t) = 3t\mathbf{j} + 4t\mathbf{k}, \quad 0 \leq t \leq 1$$

49.  $\mathbf{F} = (x - z)\mathbf{i} + x\mathbf{k}$

$$\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{k}, \quad 0 \leq t \leq \pi$$

50.  $\mathbf{F} = -y\mathbf{i} + x\mathbf{j} + 2\mathbf{k}$

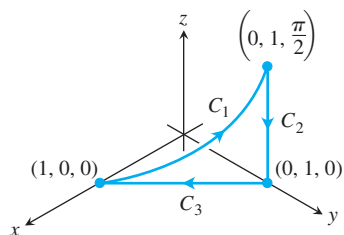
$$\mathbf{r}(t) = (-2\cos t)\mathbf{i} + (2\sin t)\mathbf{j} + 2t\mathbf{k}, \quad 0 \leq t \leq 2\pi$$

51. **Circulation** Find the circulation of  $\mathbf{F} = 2x\mathbf{i} + 2z\mathbf{j} + 2y\mathbf{k}$  around the closed path consisting of the following three curves traversed in the direction of increasing  $t$ .

$$C_1: \mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} + t\mathbf{k}, \quad 0 \leq t \leq \pi/2$$

$$C_2: \mathbf{r}(t) = \mathbf{j} + (\pi/2)(1 - t)\mathbf{k}, \quad 0 \leq t \leq 1$$

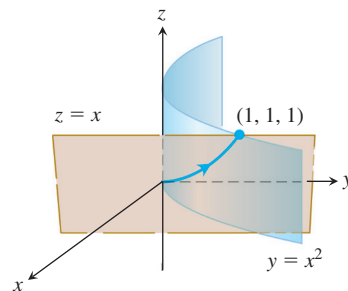
$$C_3: \mathbf{r}(t) = t\mathbf{i} + (1 - t)\mathbf{j}, \quad 0 \leq t \leq 1$$



52. **Zero circulation** Let  $C$  be the ellipse in which the plane  $2x + 3y - z = 0$  meets the cylinder  $x^2 + y^2 = 12$ . Show, without evaluating either line integral directly, that the circulation of the field  $\mathbf{F} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$  around  $C$  in either direction is zero.

53. **Flow along a curve** The field  $\mathbf{F} = xy\mathbf{i} + y\mathbf{j} - yz\mathbf{k}$  is the velocity field of a flow in space. Find the flow from  $(0, 0, 0)$  to

$(1, 1, 1)$  along the curve of intersection of the cylinder  $y = x^2$  and the plane  $z = x$ . (Hint: Use  $t = x$  as the parameter.)



54. **Flow of a gradient field** Find the flow of the field  $\mathbf{F} = \nabla(xy^2z^3)$ :

- Once around the curve  $C$  in Exercise 52, clockwise as viewed from above
- Along the line segment from  $(1, 1, 1)$  to  $(2, 1, -1)$ .

### COMPUTER EXPLORATIONS

In Exercises 55–60, use a CAS to perform the following steps for finding the work done by force  $\mathbf{F}$  over the given path:

- Find  $d\mathbf{r}$  for the path  $\mathbf{r}(t) = g(t)\mathbf{i} + h(t)\mathbf{j} + k(t)\mathbf{k}$ .
- Evaluate the force  $\mathbf{F}$  along the path.

- Evaluate  $\int_C \mathbf{F} \cdot d\mathbf{r}$ .

55.  $\mathbf{F} = xy^6\mathbf{i} + 3x(xy^5 + 2)\mathbf{j}$ ;  $\mathbf{r}(t) = (2\cos t)\mathbf{i} + (\sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$

56.  $\mathbf{F} = \frac{3}{1+x^2}\mathbf{i} + \frac{2}{1+y^2}\mathbf{j}$ ;  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j}$ ,  $0 \leq t \leq \pi$

57.  $\mathbf{F} = (y + yz \cos xyz)\mathbf{i} + (x^2 + xz \cos xyz)\mathbf{j} + (z + xy \cos xyz)\mathbf{k}$ ;  $\mathbf{r}(t) = (2\cos t)\mathbf{i} + (3\sin t)\mathbf{j} + \mathbf{k}$ ,  $0 \leq t \leq 2\pi$

58.  $\mathbf{F} = 2xy\mathbf{i} - y^2\mathbf{j} + ze^x\mathbf{k}$ ;  $\mathbf{r}(t) = -t\mathbf{i} + \sqrt{t}\mathbf{j} + 3t\mathbf{k}$ ,  $1 \leq t \leq 4$

59.  $\mathbf{F} = (2y + \sin x)\mathbf{i} + (z^2 + (1/3)\cos y)\mathbf{j} + x^4\mathbf{k}$ ;  $\mathbf{r}(t) = (\sin t)\mathbf{i} + (\cos t)\mathbf{j} + (\sin 2t)\mathbf{k}$ ,  $-\pi/2 \leq t \leq \pi/2$

60.  $\mathbf{F} = (x^2y)\mathbf{i} + \frac{1}{3}x^3\mathbf{j} + xy\mathbf{k}$ ;  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} + (2\sin^2 t - 1)\mathbf{k}$ ,  $0 \leq t \leq 2\pi$

## Exercises 16.3

### Testing for Conservative Fields

Which fields in Exercises 1–6 are conservative, and which are not?

1.  $\mathbf{F} = yz\mathbf{i} + xz\mathbf{j} + xy\mathbf{k}$
2.  $\mathbf{F} = (y \sin z)\mathbf{i} + (x \sin z)\mathbf{j} + (xy \cos z)\mathbf{k}$
3.  $\mathbf{F} = y\mathbf{i} + (x + z)\mathbf{j} - y\mathbf{k}$
4.  $\mathbf{F} = -y\mathbf{i} + x\mathbf{j}$
5.  $\mathbf{F} = (z + y)\mathbf{i} + z\mathbf{j} + (y + x)\mathbf{k}$
6.  $\mathbf{F} = (e^x \cos y)\mathbf{i} - (e^x \sin y)\mathbf{j} + z\mathbf{k}$

### Finding Potential Functions

In Exercises 7–12, find a potential function  $f$  for the field  $\mathbf{F}$ .

7.  $\mathbf{F} = 2x\mathbf{i} + 3y\mathbf{j} + 4z\mathbf{k}$

8.  $\mathbf{F} = (y + z)\mathbf{i} + (x + z)\mathbf{j} + (x + y)\mathbf{k}$

9.  $\mathbf{F} = e^{y+2z}(\mathbf{i} + x\mathbf{j} + 2x\mathbf{k})$

10.  $\mathbf{F} = (y \sin z)\mathbf{i} + (x \sin z)\mathbf{j} + (xy \cos z)\mathbf{k}$

11.  $\mathbf{F} = (\ln x + \sec^2(x + y))\mathbf{i} +$

$$\left( \sec^2(x + y) + \frac{y}{y^2 + z^2} \right) \mathbf{j} + \frac{z}{y^2 + z^2} \mathbf{k}$$

12.  $\mathbf{F} = \frac{y}{1 + x^2 y^2} \mathbf{i} + \left( \frac{x}{1 + x^2 y^2} + \frac{z}{\sqrt{1 - y^2 z^2}} \right) \mathbf{j} +$

$$\left( \frac{y}{\sqrt{1 - y^2 z^2}} + \frac{1}{z} \right) \mathbf{k}$$

**Exact Differential Forms**

In Exercises 13–17, show that the differential forms in the integrals are exact. Then evaluate the integrals.

13.  $\int_{(0,0,0)}^{(2,3,-6)} 2x \, dx + 2y \, dy + 2z \, dz$

14.  $\int_{(1,1,2)}^{(3,5,0)} yz \, dx + xz \, dy + xy \, dz$

15.  $\int_{(0,0,0)}^{(1,2,3)} 2xy \, dx + (x^2 - z^2) \, dy - 2yz \, dz$

16.  $\int_{(0,0,0)}^{(3,3,1)} 2x \, dx - y^2 \, dy - \frac{4}{1+z^2} \, dz$

17.  $\int_{(1,0,0)}^{(0,1,1)} \sin y \cos x \, dx + \cos y \sin x \, dy + dz$

**Finding Potential Functions to Evaluate Line Integrals**

Although they are not defined on all of space  $R^3$ , the fields associated with Exercises 18–22 are conservative. Find a potential function for each field and evaluate the integrals as in Example 6.

18.  $\int_{(0,2,1)}^{(1,\pi/2,2)} 2 \cos y \, dx + \left(\frac{1}{y} - 2x \sin y\right) \, dy + \frac{1}{z} \, dz$

19.  $\int_{(1,1,1)}^{(1,2,3)} 3x^2 \, dx + \frac{z^2}{y} \, dy + 2z \ln y \, dz$

20.  $\int_{(1,2,1)}^{(2,1,1)} (2x \ln y - yz) \, dx + \left(\frac{x^2}{y} - xz\right) \, dy - xy \, dz$

21.  $\int_{(1,1,1)}^{(2,2,2)} \frac{1}{y} \, dx + \left(\frac{1}{z} - \frac{x}{y^2}\right) \, dy - \frac{y}{z^2} \, dz$

22.  $\int_{(-1,-1,-1)}^{(2,2,2)} \frac{2x \, dx + 2y \, dy + 2z \, dz}{x^2 + y^2 + z^2}$

**Applications and Examples**

23. **Revisiting Example 6** Evaluate the integral

$$\int_{(1,1,1)}^{(2,3,-1)} y \, dx + x \, dy + 4 \, dz$$

from Example 6 by finding parametric equations for the line segment from  $(1, 1, 1)$  to  $(2, 3, -1)$  and evaluating the line integral of  $\mathbf{F} = y\mathbf{i} + x\mathbf{j} + 4\mathbf{k}$  along the segment. Since  $\mathbf{F}$  is conservative, the integral is independent of the path.

24. Evaluate

$$\int_C x^2 \, dx + yz \, dy + (y^2/2) \, dz$$

along the line segment  $C$  joining  $(0, 0, 0)$  to  $(0, 3, 4)$ .

**Independence of path** Show that the values of the integrals in Exercises 25 and 26 do not depend on the path taken from  $A$  to  $B$ .

25.  $\int_A^B z^2 \, dx + 2y \, dy + 2xz \, dz$       26.  $\int_A^B \frac{x \, dx + y \, dy + z \, dz}{\sqrt{x^2 + y^2 + z^2}}$

In Exercises 27 and 28, find a potential function for  $\mathbf{F}$ .

27.  $\mathbf{F} = \frac{2x}{y} \mathbf{i} + \left(\frac{1-x^2}{y^2}\right) \mathbf{j}, \quad \{(x, y): y > 0\}$

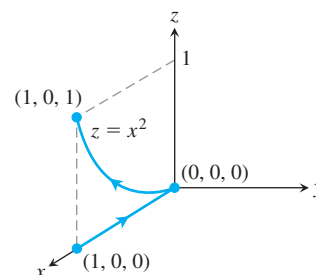
28.  $\mathbf{F} = (e^x \ln y) \mathbf{i} + \left(\frac{e^x}{y} + \sin z\right) \mathbf{j} + (y \cos z) \mathbf{k}$

29. **Work along different paths** Find the work done by  $\mathbf{F} = (x^2 + y)\mathbf{i} + (y^2 + x)\mathbf{j} + ze^z\mathbf{k}$  over the following paths from  $(1, 0, 0)$  to  $(1, 0, 1)$ .

a. The line segment  $x = 1, y = 0, 0 \leq z \leq 1$

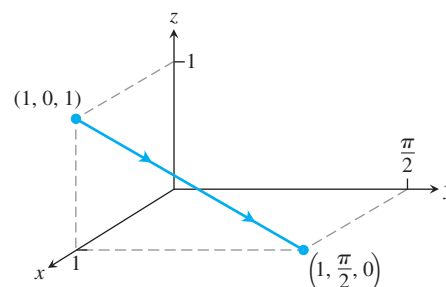
b. The helix  $\mathbf{r}(t) = (\cos t)\mathbf{i} + (\sin t)\mathbf{j} + (t/2\pi)\mathbf{k}, 0 \leq t \leq 2\pi$

c. The  $x$ -axis from  $(1, 0, 0)$  to  $(0, 0, 0)$  followed by the parabola  $z = x^2, y = 0$  from  $(0, 0, 0)$  to  $(1, 0, 1)$

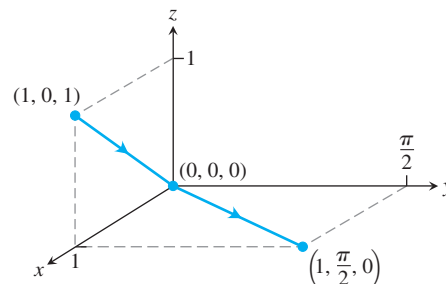


30. **Work along different paths** Find the work done by  $\mathbf{F} = e^{yz}\mathbf{i} + (xze^{yz} + z \cos y)\mathbf{j} + (xye^{yz} + \sin y)\mathbf{k}$  over the following paths from  $(1, 0, 1)$  to  $(1, \pi/2, 0)$ .

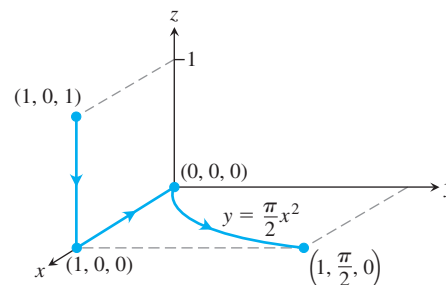
a. The line segment  $x = 1, y = \pi t/2, z = 1 - t, 0 \leq t \leq 1$



b. The line segment from  $(1, 0, 1)$  to the origin followed by the line segment from the origin to  $(1, \pi/2, 0)$



c. The line segment from  $(1, 0, 1)$  to  $(1, 0, 0)$ , followed by the  $x$ -axis from  $(1, 0, 0)$  to the origin, followed by the parabola  $y = \pi x^2/2, z = 0$  from there to  $(1, \pi/2, 0)$

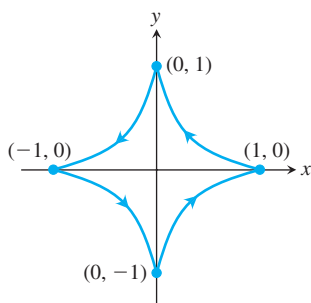


**31. Evaluating a work integral two ways** Let  $\mathbf{F} = \nabla(x^3y^2)$  and let  $C$  be the path in the  $xy$ -plane from  $(-1, 1)$  to  $(1, 1)$  that consists of the line segment from  $(-1, 1)$  to  $(0, 0)$  followed by the line segment from  $(0, 0)$  to  $(1, 1)$ . Evaluate  $\int_C \mathbf{F} \cdot d\mathbf{r}$  in two ways.

- Find parametrizations for the segments that make up  $C$  and evaluate the integral.
- Use  $f(x, y) = x^3y^2$  as a potential function for  $\mathbf{F}$ .

**32. Integral along different paths** Evaluate the line integral  $\int_C 2x \cos y \, dx - x^2 \sin y \, dy$  along the following paths  $C$  in the  $xy$ -plane.

- The parabola  $y = (x - 1)^2$  from  $(1, 0)$  to  $(0, 1)$
- The line segment from  $(-1, \pi)$  to  $(1, 0)$
- The  $x$ -axis from  $(-1, 0)$  to  $(1, 0)$
- The astroid  $\mathbf{r}(t) = (\cos^3 t)\mathbf{i} + (\sin^3 t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$ , counterclockwise from  $(1, 0)$  back to  $(1, 0)$



**33. a. Exact differential form** How are the constants  $a$ ,  $b$ , and  $c$  related if the following differential form is exact?

$$(ay^2 + 2czx) \, dx + y(bx + cz) \, dy + (ay^2 + cx^2) \, dz$$

**b. Gradient field** For what values of  $b$  and  $c$  will

$$\mathbf{F} = (y^2 + 2czx)\mathbf{i} + y(bx + cz)\mathbf{j} + (y^2 + cx^2)\mathbf{k}$$

be a gradient field?

**34. Gradient of a line integral** Suppose that  $\mathbf{F} = \nabla f$  is a conservative vector field and

$$g(x, y, z) = \int_{(0,0,0)}^{(x,y,z)} \mathbf{F} \cdot d\mathbf{r}.$$

Show that  $\nabla g = \mathbf{F}$ .

**35. Path of least work** You have been asked to find the path along which a force field  $\mathbf{F}$  will perform the least work in moving a particle between two locations. A quick calculation on your part shows  $\mathbf{F}$  to be conservative. How should you respond? Give reasons for your answer.

**36. A revealing experiment** By experiment, you find that a force field  $\mathbf{F}$  performs only half as much work in moving an object along path  $C_1$  from  $A$  to  $B$  as it does in moving the object along path  $C_2$  from  $A$  to  $B$ . What can you conclude about  $\mathbf{F}$ ? Give reasons for your answer.

**37. Work by a constant force** Show that the work done by a constant force field  $\mathbf{F} = a\mathbf{i} + b\mathbf{j} + c\mathbf{k}$  in moving a particle along any path from  $A$  to  $B$  is  $W = \mathbf{F} \cdot \overrightarrow{AB}$ .

**38. Gravitational field**

- Find a potential function for the gravitational field

$$\mathbf{F} = -GmM \frac{x\mathbf{i} + y\mathbf{j} + z\mathbf{k}}{(x^2 + y^2 + z^2)^{3/2}}$$

( $G$ ,  $m$ , and  $M$  are constants).

- Let  $P_1$  and  $P_2$  be points at distance  $s_1$  and  $s_2$  from the origin. Show that the work done by the gravitational field in part (a) in moving a particle from  $P_1$  to  $P_2$  is

$$GmM \left( \frac{1}{s_2} - \frac{1}{s_1} \right).$$

# Exercises 16.4

## Verifying Green's Theorem

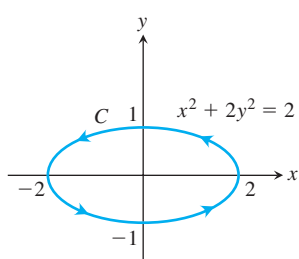
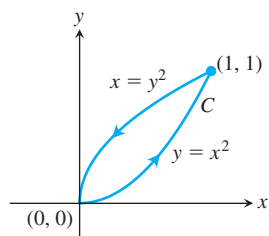
In Exercises 1–4, verify the conclusion of Green's Theorem by evaluating both sides of Equations (3) and (4) for the field  $\mathbf{F} = M\mathbf{i} + N\mathbf{j}$ . Take the domains of integration in each case to be the disk  $R: x^2 + y^2 \leq a^2$  and its bounding circle  $C: \mathbf{r} = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j}, 0 \leq t \leq 2\pi$ .

1.  $\mathbf{F} = -y\mathbf{i} + x\mathbf{j}$
2.  $\mathbf{F} = y\mathbf{i}$
3.  $\mathbf{F} = 2x\mathbf{i} - 3y\mathbf{j}$
4.  $\mathbf{F} = -x^2y\mathbf{i} + xy^2\mathbf{j}$

## Circulation and Flux

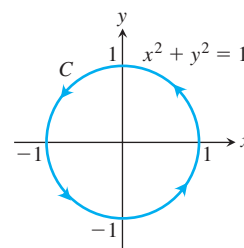
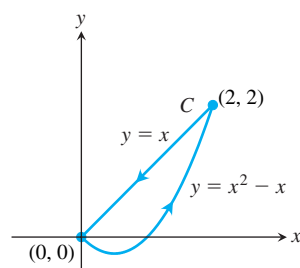
In Exercises 5–14, use Green's Theorem to find the counterclockwise circulation and outward flux for the field  $\mathbf{F}$  and curve  $C$ .

5.  $\mathbf{F} = (x - y)\mathbf{i} + (y - x)\mathbf{j}$   
 $C$ : The square bounded by  $x = 0, x = 1, y = 0, y = 1$
6.  $\mathbf{F} = (x^2 + 4y)\mathbf{i} + (x + y^2)\mathbf{j}$   
 $C$ : The square bounded by  $x = 0, x = 1, y = 0, y = 1$
7.  $\mathbf{F} = (y^2 - x^2)\mathbf{i} + (x^2 + y^2)\mathbf{j}$   
 $C$ : The triangle bounded by  $y = 0, x = 3$ , and  $y = x$
8.  $\mathbf{F} = (x + y)\mathbf{i} - (x^2 + y^2)\mathbf{j}$   
 $C$ : The triangle bounded by  $y = 0, x = 1$ , and  $y = x$
9.  $\mathbf{F} = (xy + y^2)\mathbf{i} + (x - y)\mathbf{j}$
10.  $\mathbf{F} = (x + 3y)\mathbf{i} + (2x - y)\mathbf{j}$



11.  $\mathbf{F} = x^3y^2\mathbf{i} + \frac{1}{2}x^4y\mathbf{j}$

12.  $\mathbf{F} = \frac{x}{1 + y^2}\mathbf{i} + (\tan^{-1} y)\mathbf{j}$



13.  $\mathbf{F} = (x + e^x \sin y)\mathbf{i} + (x + e^x \cos y)\mathbf{j}$

$C$ : The right-hand loop of the lemniscate  $r^2 = \cos 2\theta$

14.  $\mathbf{F} = \left(\tan^{-1} \frac{y}{x}\right)\mathbf{i} + \ln(x^2 + y^2)\mathbf{j}$

$C$ : The boundary of the region defined by the polar coordinate inequalities  $1 \leq r \leq 2, 0 \leq \theta \leq \pi$

15. Find the counterclockwise circulation and outward flux of the field  $\mathbf{F} = xy\mathbf{i} + y^2\mathbf{j}$  around and over the boundary of the region enclosed by the curves  $y = x^2$  and  $y = x$  in the first quadrant.

16. Find the counterclockwise circulation and the outward flux of the field  $\mathbf{F} = (-\sin y)\mathbf{i} + (x \cos y)\mathbf{j}$  around and over the square cut from the first quadrant by the lines  $x = \pi/2$  and  $y = \pi/2$ .

17. Find the outward flux of the field

$$\mathbf{F} = \left(3xy - \frac{x}{1 + y^2}\right)\mathbf{i} + (e^x + \tan^{-1} y)\mathbf{j}$$

across the cardioid  $r = a(1 + \cos \theta), a > 0$ .

18. Find the counterclockwise circulation of  $\mathbf{F} = (y + e^x \ln y)\mathbf{i} + (e^x/y)\mathbf{j}$  around the boundary of the region that is bounded above by the curve  $y = 3 - x^2$  and below by the curve  $y = x^4 + 1$ .

### Work

In Exercises 19 and 20, find the work done by  $\mathbf{F}$  in moving a particle once counterclockwise around the given curve.

19.  $\mathbf{F} = 2xy^3\mathbf{i} + 4x^2y^2\mathbf{j}$

C: The boundary of the “triangular” region in the first quadrant enclosed by the  $x$ -axis, the line  $x = 1$ , and the curve  $y = x^3$

20.  $\mathbf{F} = (4x - 2y)\mathbf{i} + (2x - 4y)\mathbf{j}$

C: The circle  $(x - 2)^2 + (y - 2)^2 = 4$

### Using Green's Theorem

Apply Green's Theorem to evaluate the integrals in Exercises 21–24.

21.  $\oint_C (y^2 dx + x^2 dy)$

C: The triangle bounded by  $x = 0$ ,  $x + y = 1$ ,  $y = 0$

22.  $\oint_C (3y dx + 2x dy)$

C: The boundary of  $0 \leq x \leq \pi$ ,  $0 \leq y \leq \sin x$

23.  $\oint_C (6y + x) dx + (y + 2x) dy$

C: The circle  $(x - 2)^2 + (y - 3)^2 = 4$

24.  $\oint_C (2x + y^2) dx + (2xy + 3y) dy$

C: Any simple closed curve in the plane for which Green's Theorem holds

**Calculating Area with Green's Theorem** If a simple closed curve  $C$  in the plane and the region  $R$  it encloses satisfy the hypotheses of Green's Theorem, the area of  $R$  is given by

### Green's Theorem Area Formula

$$\text{Area of } R = \frac{1}{2} \oint_C x dy - y dx$$

The reason is that by Equation (4), run backward,

$$\begin{aligned} \text{Area of } R &= \iint_R dy dx = \iint_R \left( \frac{1}{2} + \frac{1}{2} \right) dy dx \\ &= \oint_C \frac{1}{2} x dy - \frac{1}{2} y dx. \end{aligned}$$

Use the Green's Theorem area formula given above to find the areas of the regions enclosed by the curves in Exercises 25–28.

25. The circle  $\mathbf{r}(t) = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$

26. The ellipse  $\mathbf{r}(t) = (a \cos t)\mathbf{i} + (b \sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$

27. The astroid  $\mathbf{r}(t) = (\cos^3 t)\mathbf{i} + (\sin^3 t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$

28. One arch of the cycloid  $x = t - \sin t$ ,  $y = 1 - \cos t$

29. Let  $C$  be the boundary of a region on which Green's Theorem holds. Use Green's Theorem to calculate

a.  $\oint_C f(x) dx + g(y) dy$

b.  $\oint_C ky dx + hx dy$  ( $k$  and  $h$  constants).

30. **Integral dependent only on area** Show that the value of

$$\oint_C xy^2 dx + (x^2y + 2x) dy$$

around any square depends only on the area of the square and not on its location in the plane.

31. Evaluate the integral

$$\oint_C 4x^3y dx + x^4 dy$$

for any closed path  $C$ .

32. Evaluate the integral

$$\oint_C -y^3 dy + x^3 dx$$

for any closed path  $C$ .

33. **Area as a line integral** Show that if  $R$  is a region in the plane bounded by a piecewise smooth, simple closed curve  $C$ , then

$$\text{Area of } R = \oint_C x dy = - \oint_C y dx.$$

34. **Definite integral as a line integral** Suppose that a nonnegative function  $y = f(x)$  has a continuous first derivative on  $[a, b]$ . Let  $C$  be the boundary of the region in the  $xy$ -plane that is bounded below by the  $x$ -axis, above by the graph of  $f$ , and on the sides by the lines  $x = a$  and  $x = b$ . Show that

$$\int_a^b f(x) dx = - \oint_C y dx.$$

35. **Area and the centroid** Let  $A$  be the area and  $\bar{x}$  the  $x$ -coordinate of the centroid of a region  $R$  that is bounded by a piecewise smooth, simple closed curve  $C$  in the  $xy$ -plane. Show that

$$\frac{1}{2} \oint_C x^2 dy = - \oint_C xy dx = \frac{1}{3} \oint_C x^2 dy - xy dx = A\bar{x}.$$

36. **Moment of inertia** Let  $I_y$  be the moment of inertia about the  $y$ -axis of the region in Exercise 35. Show that

$$\frac{1}{3} \oint_C x^3 dy = - \oint_C x^2y dx = \frac{1}{4} \oint_C x^3 dy - x^2y dx = I_y.$$

37. **Green's Theorem and Laplace's equation** Assuming that all the necessary derivatives exist and are continuous, show that if  $f(x, y)$  satisfies the Laplace equation

$$\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} = 0,$$



then

$$\oint_C \frac{\partial f}{\partial y} dx - \frac{\partial f}{\partial x} dy = 0$$

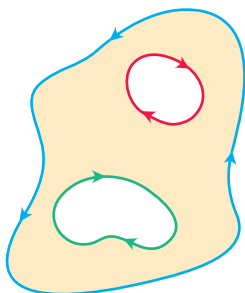
for all closed curves  $C$  to which Green's Theorem applies. (The converse is also true: If the line integral is always zero, then  $f$  satisfies the Laplace equation.)

- 38. Maximizing work** Among all smooth, simple closed curves in the plane, oriented counterclockwise, find the one along which the work done by

$$\mathbf{F} = \left( \frac{1}{4}x^2y + \frac{1}{3}y^3 \right) \mathbf{i} + x\mathbf{j}$$

is greatest. (*Hint*: Where is  $(\text{curl } \mathbf{F}) \cdot \mathbf{k}$  positive?)

- 39. Regions with many holes** Green's Theorem holds for a region  $R$  with any finite number of holes as long as the bounding curves are smooth, simple, and closed and we integrate over each component of the boundary in the direction that keeps  $R$  on our immediate left as we go along (see accompanying figure).



- a.** Let  $f(x, y) = \ln(x^2 + y^2)$  and let  $C$  be the circle  $x^2 + y^2 = a^2$ . Evaluate the flux integral

$$\oint_C \nabla f \cdot \mathbf{n} \, ds.$$

- b.** Let  $K$  be an arbitrary smooth, simple closed curve in the plane that does not pass through  $(0, 0)$ . Use Green's Theorem to show that

$$\oint_K \nabla f \cdot \mathbf{n} \, ds$$

has two possible values, depending on whether  $(0, 0)$  lies inside  $K$  or outside  $K$ .

- 40. Bendixson's criterion** The *streamlines* of a planar fluid flow are the smooth curves traced by the fluid's individual particles. The vectors  $\mathbf{F} = M(x, y)\mathbf{i} + N(x, y)\mathbf{j}$  of the flow's velocity field are the tangent vectors of the streamlines. Show that if the flow takes place over a simply connected region  $R$  (no holes or missing points) and that if  $M_x + N_y \neq 0$  throughout  $R$ , then none of the streamlines in  $R$  is closed. In other words, no particle of fluid ever has a closed trajectory in  $R$ . The criterion  $M_x + N_y \neq 0$  is called **Bendixson's criterion** for the nonexistence of closed trajectories.

- 41.** Establish Equation (7) to finish the proof of the special case of Green's Theorem.

- 42. Curl component of conservative fields** Can anything be said about the curl component of a conservative two-dimensional vector field? Give reasons for your answer.

### COMPUTER EXPLORATIONS

In Exercises 43–46, use a CAS and Green's Theorem to find the counterclockwise circulation of the field  $\mathbf{F}$  around the simple closed curve  $C$ . Perform the following CAS steps.

- Plot  $C$  in the  $xy$ -plane.
  - Determine the integrand  $(\partial N / \partial x) - (\partial M / \partial y)$  for the tangential form of Green's Theorem.
  - Determine the (double integral) limits of integration from your plot in part (a) and evaluate the curl integral for the circulation.
- 43.**  $\mathbf{F} = (2x - y)\mathbf{i} + (x + 3y)\mathbf{j}$ ,  $C$ : The ellipse  $x^2 + 4y^2 = 4$
- 44.**  $\mathbf{F} = (2x^3 - y^3)\mathbf{i} + (x^3 + y^3)\mathbf{j}$ ,  $C$ : The ellipse  $\frac{x^2}{4} + \frac{y^2}{9} = 1$
- 45.**  $\mathbf{F} = x^{-1}e^y\mathbf{i} + (e^y \ln x + 2x)\mathbf{j}$ ,  
 $C$ : The boundary of the region defined by  $y = 1 + x^4$  (below) and  $y = 2$  (above)
- 46.**  $\mathbf{F} = xe^y\mathbf{i} + (4x^2 \ln y)\mathbf{j}$ ,  
 $C$ : The triangle with vertices  $(0, 0)$ ,  $(2, 0)$ , and  $(0, 4)$

## Exercises 16.5

### Finding Parametrizations

In Exercises 1–16, find a parametrization of the surface. (There are many correct ways to do these, so your answers may not be the same as those in the back of the book.)

1. The paraboloid  $z = x^2 + y^2$ ,  $z \leq 4$
2. The paraboloid  $z = 9 - x^2 - y^2$ ,  $z \geq 0$
3. **Cone frustum** The first-octant portion of the cone  $z = \sqrt{x^2 + y^2}/2$  between the planes  $z = 0$  and  $z = 3$
4. **Cone frustum** The portion of the cone  $z = 2\sqrt{x^2 + y^2}$  between the planes  $z = 2$  and  $z = 4$
5. **Spherical cap** The cap cut from the sphere  $x^2 + y^2 + z^2 = 9$  by the cone  $z = \sqrt{x^2 + y^2}$
6. **Spherical cap** The portion of the sphere  $x^2 + y^2 + z^2 = 4$  in the first octant between the  $xy$ -plane and the cone  $z = \sqrt{x^2 + y^2}$
7. **Spherical band** The portion of the sphere  $x^2 + y^2 + z^2 = 3$  between the planes  $z = \sqrt{3}/2$  and  $z = -\sqrt{3}/2$
8. **Spherical cap** The upper portion cut from the sphere  $x^2 + y^2 + z^2 = 8$  by the plane  $z = -2$
9. **Parabolic cylinder between planes** The surface cut from the parabolic cylinder  $z = 4 - y^2$  by the planes  $x = 0$ ,  $x = 2$ , and  $z = 0$
10. **Parabolic cylinder between planes** The surface cut from the parabolic cylinder  $y = x^2$  by the planes  $z = 0$ ,  $z = 3$ , and  $y = 2$
11. **Circular cylinder band** The portion of the cylinder  $y^2 + z^2 = 9$  between the planes  $x = 0$  and  $x = 3$
12. **Circular cylinder band** The portion of the cylinder  $x^2 + z^2 = 4$  above the  $xy$ -plane between the planes  $y = -2$  and  $y = 2$
13. **Tilted plane inside cylinder** The portion of the plane  $x + y + z = 1$ 
  - a. Inside the cylinder  $x^2 + y^2 = 9$
  - b. Inside the cylinder  $y^2 + z^2 = 9$
14. **Tilted plane inside cylinder** The portion of the plane  $x - y + 2z = 2$ 
  - a. Inside the cylinder  $x^2 + z^2 = 3$
  - b. Inside the cylinder  $y^2 + z^2 = 2$
15. **Circular cylinder band** The portion of the cylinder  $(x - 2)^2 + z^2 = 4$  between the planes  $y = 0$  and  $y = 3$
16. **Circular cylinder band** The portion of the cylinder  $y^2 + (z - 5)^2 = 25$  between the planes  $x = 0$  and  $x = 10$
18. **Plane inside cylinder** The portion of the plane  $z = -x$  inside the cylinder  $x^2 + y^2 = 4$
19. **Cone frustum** The portion of the cone  $z = 2\sqrt{x^2 + y^2}$  between the planes  $z = 2$  and  $z = 6$
20. **Cone frustum** The portion of the cone  $z = \sqrt{x^2 + y^2}/3$  between the planes  $z = 1$  and  $z = 4/3$
21. **Circular cylinder band** The portion of the cylinder  $x^2 + y^2 = 1$  between the planes  $z = 1$  and  $z = 4$
22. **Circular cylinder band** The portion of the cylinder  $x^2 + z^2 = 10$  between the planes  $y = -1$  and  $y = 1$
23. **Parabolic cap** The cap cut from the paraboloid  $z = 2 - x^2 - y^2$  by the cone  $z = \sqrt{x^2 + y^2}$
24. **Parabolic band** The portion of the paraboloid  $z = x^2 + y^2$  between the planes  $z = 1$  and  $z = 4$
25. **Sawed-off sphere** The lower portion cut from the sphere  $x^2 + y^2 + z^2 = 2$  by the cone  $z = \sqrt{x^2 + y^2}$
26. **Spherical band** The portion of the sphere  $x^2 + y^2 + z^2 = 4$  between the planes  $z = -1$  and  $z = \sqrt{3}$

### Planes Tangent to Parametrized Surfaces

The tangent plane at a point  $P_0(f(u_0, v_0), g(u_0, v_0), h(u_0, v_0))$  on a parametrized surface  $\mathbf{r}(u, v) = f(u, v)\mathbf{i} + g(u, v)\mathbf{j} + h(u, v)\mathbf{k}$  is the plane through  $P_0$  normal to the vector  $\mathbf{r}_u(u_0, v_0) \times \mathbf{r}_v(u_0, v_0)$ , the cross product of the tangent vectors  $\mathbf{r}_u(u_0, v_0)$  and  $\mathbf{r}_v(u_0, v_0)$  at  $P_0$ . In Exercises 27–30, find an equation for the plane tangent to the surface at  $P_0$ . Then find a Cartesian equation for the surface and sketch the surface and tangent plane together.

27. **Cone** The cone  $\mathbf{r}(r, \theta) = (r \cos \theta)\mathbf{i} + (r \sin \theta)\mathbf{j} + r\mathbf{k}$ ,  $r \geq 0$ ,  $0 \leq \theta \leq 2\pi$  at the point  $P_0(\sqrt{2}, \sqrt{2}, 2)$  corresponding to  $(r, \theta) = (2, \pi/4)$
28. **Hemisphere** The hemisphere surface  $\mathbf{r}(\phi, \theta) = (4 \sin \phi \cos \theta)\mathbf{i} + (4 \sin \phi \sin \theta)\mathbf{j} + (4 \cos \phi)\mathbf{k}$ ,  $0 \leq \phi \leq \pi/2$ ,  $0 \leq \theta \leq 2\pi$ , at the point  $P_0(\sqrt{2}, \sqrt{2}, 2\sqrt{3})$  corresponding to  $(\phi, \theta) = (\pi/6, \pi/4)$
29. **Circular cylinder** The circular cylinder  $\mathbf{r}(\theta, z) = (3 \sin 2\theta)\mathbf{i} + (6 \sin^2 \theta)\mathbf{j} + z\mathbf{k}$ ,  $0 \leq \theta \leq \pi$ , at the point  $P_0(3\sqrt{3}/2, 9/2, 0)$  corresponding to  $(\theta, z) = (\pi/3, 0)$  (See Example 3.)
30. **Parabolic cylinder** The parabolic cylinder surface  $\mathbf{r}(x, y) = x\mathbf{i} + y\mathbf{j} - x^2\mathbf{k}$ ,  $-\infty < x < \infty$ ,  $-\infty < y < \infty$ , at the point  $P_0(1, 2, -1)$  corresponding to  $(x, y) = (1, 2)$

### More Parametrizations of Surfaces

31. a. A *torus of revolution* (doughnut) is obtained by rotating a circle  $C$  in the  $xz$ -plane about the  $z$ -axis in space. (See the accompanying figure.) If  $C$  has radius  $r > 0$  and center  $(R, 0, 0)$ , show that a parametrization of the torus is

$$\mathbf{r}(u, v) = ((R + r \cos u) \cos v)\mathbf{i} + ((R + r \cos u) \sin v)\mathbf{j} + (r \sin u)\mathbf{k},$$

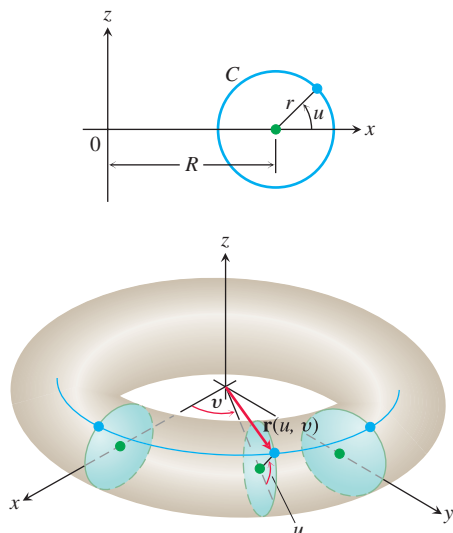
where  $0 \leq u \leq 2\pi$  and  $0 \leq v \leq 2\pi$  are the angles in the figure.

### Surface Area of Parametrized Surfaces

In Exercises 17–26, use a parametrization to express the area of the surface as a double integral. Then evaluate the integral. (There are many correct ways to set up the integrals, so your integrals may not be the same as those in the back of the book. They should have the same values, however.)

17. **Tilted plane inside cylinder** The portion of the plane  $y + 2z = 2$  inside the cylinder  $x^2 + y^2 = 1$

- b. Show that the surface area of the torus is  $A = 4\pi^2 Rr$ .

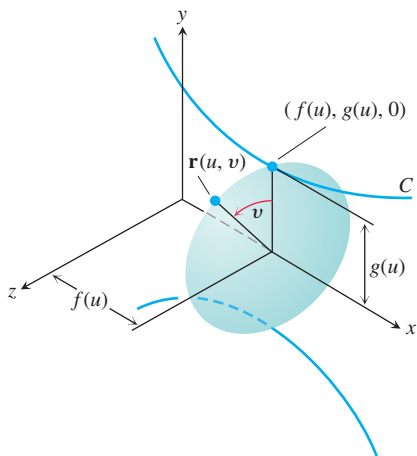


- 32. Parametrization of a surface of revolution** Suppose that the parametrized curve  $C: (f(u), g(u))$  is revolved about the  $x$ -axis, where  $g(u) > 0$  for  $a \leq u \leq b$ .

- a. Show that

$$\mathbf{r}(u, v) = f(u)\mathbf{i} + (g(u)\cos v)\mathbf{j} + (g(u)\sin v)\mathbf{k}$$

is a parametrization of the resulting surface of revolution, where  $0 \leq v \leq 2\pi$  is the angle from the  $xy$ -plane to the point  $\mathbf{r}(u, v)$  on the surface. (See the accompanying figure.) Notice that  $f(u)$  measures distance *along* the axis of revolution and  $g(u)$  measures distance *from* the axis of revolution.



- b. Find a parametrization for the surface obtained by revolving the curve  $x = y^2, y \geq 0$ , about the  $x$ -axis.
- 33. a. Parametrization of an ellipsoid** The parametrization  $x = a \cos \theta, y = b \sin \theta, 0 \leq \theta \leq 2\pi$  gives the ellipse  $(x^2/a^2) + (y^2/b^2) = 1$ . Using the angles  $\theta$  and  $\phi$  in spherical coordinates, show that
- $$\mathbf{r}(\theta, \phi) = (a \cos \theta \cos \phi)\mathbf{i} + (b \sin \theta \cos \phi)\mathbf{j} + (c \sin \phi)\mathbf{k}$$
- is a parametrization of the ellipsoid  $(x^2/a^2) + (y^2/b^2) + (z^2/c^2) = 1$ .
- b. Write an integral for the surface area of the ellipsoid, but do not evaluate the integral.

### 34. Hyperboloid of one sheet

- a. Find a parametrization for the hyperboloid of one sheet  $x^2 + y^2 - z^2 = 1$  in terms of the angle  $\theta$  associated with the circle  $x^2 + y^2 = r^2$  and the hyperbolic parameter  $u$  associated with the hyperbolic function  $r^2 - z^2 = 1$ . (Hint:  $\cosh^2 u - \sinh^2 u = 1$ .)
- b. Generalize the result in part (a) to the hyperboloid  $(x^2/a^2) + (y^2/b^2) - (z^2/c^2) = 1$ .
- 35. (Continuation of Exercise 34.)** Find a Cartesian equation for the plane tangent to the hyperboloid  $x^2 + y^2 - z^2 = 25$  at the point  $(x_0, y_0, 0)$ , where  $x_0^2 + y_0^2 = 25$ .
- 36. Hyperboloid of two sheets** Find a parametrization of the hyperboloid of two sheets  $(z^2/c^2) - (x^2/a^2) - (y^2/b^2) = 1$ .

### Surface Area for Implicit and Explicit Forms

- 37.** Find the area of the surface cut from the paraboloid  $x^2 + y^2 - z = 0$  by the plane  $z = 2$ .
- 38.** Find the area of the band cut from the paraboloid  $x^2 + y^2 - z = 0$  by the planes  $z = 2$  and  $z = 6$ .
- 39.** Find the area of the region cut from the plane  $x + 2y + 2z = 5$  by the cylinder whose walls are  $x = y^2$  and  $x = 2 - y^2$ .
- 40.** Find the area of the portion of the surface  $x^2 - 2z = 0$  that lies above the triangle bounded by the lines  $x = \sqrt{3}, y = 0$ , and  $y = x$  in the  $xy$ -plane.
- 41.** Find the area of the surface  $x^2 - 2y - 2z = 0$  that lies above the triangle bounded by the lines  $x = 2, y = 0$ , and  $y = 3x$  in the  $xy$ -plane.
- 42.** Find the area of the cap cut from the sphere  $x^2 + y^2 + z^2 = 2$  by the cone  $z = \sqrt{x^2 + y^2}$ .
- 43.** Find the area of the ellipse cut from the plane  $z = cx$  ( $c$  a constant) by the cylinder  $x^2 + y^2 = 1$ .
- 44.** Find the area of the upper portion of the cylinder  $x^2 + z^2 = 1$  that lies between the planes  $x = \pm 1/2$  and  $y = \pm 1/2$ .
- 45.** Find the area of the portion of the paraboloid  $x = 4 - y^2 - z^2$  that lies above the ring  $1 \leq y^2 + z^2 \leq 4$  in the  $yz$ -plane.
- 46.** Find the area of the surface cut from the paraboloid  $x^2 + y + z^2 = 2$  by the plane  $y = 0$ .
- 47.** Find the area of the surface  $x^2 - 2 \ln x + \sqrt{15}y - z = 0$  above the square  $R: 1 \leq x \leq 2, 0 \leq y \leq 1$ , in the  $xy$ -plane.
- 48.** Find the area of the surface  $2x^{3/2} + 2y^{3/2} - 3z = 0$  above the square  $R: 0 \leq x \leq 1, 0 \leq y \leq 1$ , in the  $xy$ -plane.

Find the area of the surfaces in Exercises 49–54.

- 49.** The surface cut from the bottom of the paraboloid  $z = x^2 + y^2$  by the plane  $z = 3$
- 50.** The surface cut from the “nose” of the paraboloid  $x = 1 - y^2 - z^2$  by the  $yz$ -plane
- 51.** The portion of the cone  $z = \sqrt{x^2 + y^2}$  that lies over the region between the circle  $x^2 + y^2 = 1$  and the ellipse  $9x^2 + 4y^2 = 36$  in the  $xy$ -plane. (Hint: Use formulas from geometry to find the area of the region.)
- 52.** The triangle cut from the plane  $2x + 6y + 3z = 6$  by the bounding planes of the first octant. Calculate the area three ways, using different explicit forms.
- 53.** The surface in the first octant cut from the cylinder  $y = (2/3)z^{3/2}$  by the planes  $x = 1$  and  $y = 16/3$

54. The portion of the plane  $y + z = 4$  that lies above the region cut from the first quadrant of the  $xz$ -plane by the parabola  $x = 4 - z^2$
55. Use the parametrization

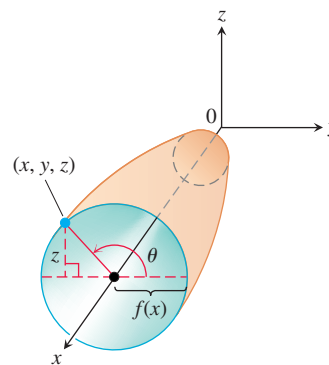
$$\mathbf{r}(x, z) = x\mathbf{i} + f(x, z)\mathbf{j} + z\mathbf{k}$$

and Equation (5) to derive a formula for  $d\sigma$  associated with the explicit form  $y = f(x, z)$ .

56. Let  $S$  be the surface obtained by rotating the smooth curve  $y = f(x)$ ,  $a \leq x \leq b$ , about the  $x$ -axis, where  $f(x) \geq 0$ .
- a. Show that the vector function

$$\mathbf{r}(x, \theta) = x\mathbf{i} + f(x)\cos\theta\mathbf{j} + f(x)\sin\theta\mathbf{k}$$

is a parametrization of  $S$ , where  $\theta$  is the angle of rotation around the  $x$ -axis (see the accompanying figure).



- b. Use Equation (4) to show that the surface area of this surface of revolution is given by

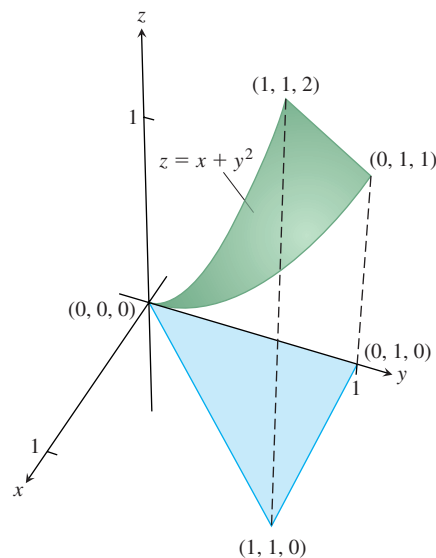
$$A = \int_a^b 2\pi f(x) \sqrt{1 + [f'(x)]^2} dx.$$

## Exercises 16.6

## Surface Integrals of Scalar Functions

In Exercises 1–8, integrate the given function over the given surface.

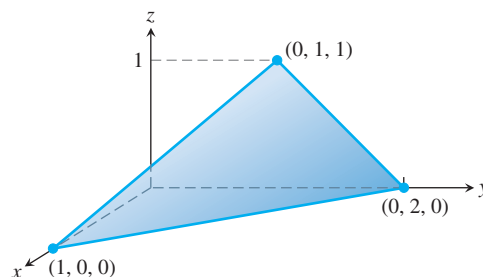
- Parabolic cylinder**  $G(x, y, z) = x$ , over the parabolic cylinder  $y = x^2$ ,  $0 \leq x \leq 2$ ,  $0 \leq z \leq 3$
- Circular cylinder**  $G(x, y, z) = z$ , over the cylindrical surface  $y^2 + z^2 = 4$ ,  $z \geq 0$ ,  $1 \leq x \leq 4$
- Sphere**  $G(x, y, z) = x^2$ , over the unit sphere  $x^2 + y^2 + z^2 = 1$
- Hemisphere**  $G(x, y, z) = z^2$ , over the hemisphere  $x^2 + y^2 + z^2 = a^2$ ,  $z \geq 0$
- Portion of plane**  $F(x, y, z) = z$ , over the portion of the plane  $x + y + z = 4$  that lies above the square  $0 \leq x \leq 1$ ,  $0 \leq y \leq 1$ , in the  $xy$ -plane
- Cone**  $F(x, y, z) = z - x$ , over the cone  $z = \sqrt{x^2 + y^2}$ ,  $0 \leq z \leq 1$
- Parabolic dome**  $H(x, y, z) = x^2\sqrt{5 - 4z}$ , over the parabolic dome  $z = 1 - x^2 - y^2$ ,  $z \geq 0$
- Spherical cap**  $H(x, y, z) = yz$ , over the part of the sphere  $x^2 + y^2 + z^2 = 4$  that lies above the cone  $z = \sqrt{x^2 + y^2}$
- Integrate  $G(x, y, z) = x + y + z$  over the surface of the cube cut from the first octant by the planes  $x = a$ ,  $y = a$ ,  $z = a$ .
- Integrate  $G(x, y, z) = y + z$  over the surface of the wedge in the first octant bounded by the coordinate planes and the planes  $x = 2$  and  $y + z = 1$ .
- Integrate  $G(x, y, z) = xyz$  over the surface of the rectangular solid cut from the first octant by the planes  $x = a$ ,  $y = b$ , and  $z = c$ .
- Integrate  $G(x, y, z) = xyz$  over the surface of the rectangular solid bounded by the planes  $x = \pm a$ ,  $y = \pm b$ , and  $z = \pm c$ .
- Integrate  $G(x, y, z) = x + y + z$  over the portion of the plane  $2x + 2y + z = 2$  that lies in the first octant.
- Integrate  $G(x, y, z) = x\sqrt{y^2 + 4}$  over the surface cut from the parabolic cylinder  $y^2 + 4z = 16$  by the planes  $x = 0$ ,  $x = 1$ , and  $z = 0$ .
- Integrate  $G(x, y, z) = z - x$  over the portion of the graph of  $z = x + y^2$  above the triangle in the  $xy$ -plane having vertices  $(0, 0)$ ,  $(1, 1, 0)$ , and  $(0, 1, 0)$ . (See accompanying figure.)



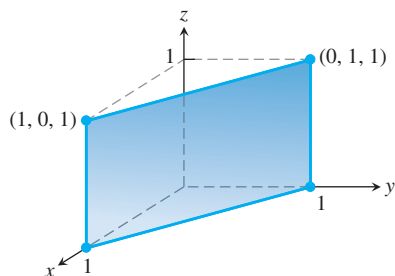
16. Integrate  $G(x, y, z) = x$  over the surface given by

$$z = x^2 + y \quad \text{for } 0 \leq x \leq 1, \quad -1 \leq y \leq 1.$$

17. Integrate  $G(x, y, z) = xyz$  over the triangular surface with vertices  $(1, 0, 0)$ ,  $(0, 2, 0)$ , and  $(0, 1, 1)$ .



18. Integrate  $G(x, y, z) = x - y - z$  over the portion of the plane  $x + y = 1$  in the first octant between  $z = 0$  and  $z = 1$  (see the accompanying figure on the next page).



### Finding Flux or Surface Integrals of Vector Fields

In Exercises 19–28, use a parametrization to find the flux  $\iint_S \mathbf{F} \cdot \mathbf{n} \, d\sigma$  across the surface in the specified direction.

19. **Parabolic cylinder**  $\mathbf{F} = z^2\mathbf{i} + x\mathbf{j} - 3z\mathbf{k}$  outward (normal away from the  $x$ -axis) through the surface cut from the parabolic cylinder  $z = 4 - y^2$  by the planes  $x = 0$ ,  $x = 1$ , and  $z = 0$
20. **Parabolic cylinder**  $\mathbf{F} = x^2\mathbf{j} - xz\mathbf{k}$  outward (normal away from the  $yz$ -plane) through the surface cut from the parabolic cylinder  $y = x^2$ ,  $-1 \leq x \leq 1$ , by the planes  $z = 0$  and  $z = 2$
21. **Sphere**  $\mathbf{F} = z\mathbf{k}$  across the portion of the sphere  $x^2 + y^2 + z^2 = a^2$  in the first octant in the direction away from the origin
22. **Sphere**  $\mathbf{F} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$  across the sphere  $x^2 + y^2 + z^2 = a^2$  in the direction away from the origin
23. **Plane**  $\mathbf{F} = 2xy\mathbf{i} + 2yz\mathbf{j} + 2xz\mathbf{k}$  upward across the portion of the plane  $x + y + z = 2a$  that lies above the square  $0 \leq x \leq a$ ,  $0 \leq y \leq a$ , in the  $xy$ -plane
24. **Cylinder**  $\mathbf{F} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$  outward through the portion of the cylinder  $x^2 + y^2 = 1$  cut by the planes  $z = 0$  and  $z = a$
25. **Cone**  $\mathbf{F} = xy\mathbf{i} - z\mathbf{k}$  outward (normal away from the  $z$ -axis) through the cone  $z = \sqrt{x^2 + y^2}$ ,  $0 \leq z \leq 1$
26. **Cone**  $\mathbf{F} = y^2\mathbf{i} + xz\mathbf{j} - \mathbf{k}$  outward (normal away from the  $z$ -axis) through the cone  $z = 2\sqrt{x^2 + y^2}$ ,  $0 \leq z \leq 2$
27. **Cone frustum**  $\mathbf{F} = -x\mathbf{i} - y\mathbf{j} + z^2\mathbf{k}$  outward (normal away from the  $z$ -axis) through the portion of the cone  $z = \sqrt{x^2 + y^2}$  between the planes  $z = 1$  and  $z = 2$
28. **Paraboloid**  $\mathbf{F} = 4x\mathbf{i} + 4y\mathbf{j} + 2\mathbf{k}$  outward (normal away from the  $z$ -axis) through the surface cut from the bottom of the paraboloid  $z = x^2 + y^2$  by the plane  $z = 1$

In Exercises 29 and 30, find the surface integral of the field  $\mathbf{F}$  over the portion of the given surface in the specified direction.

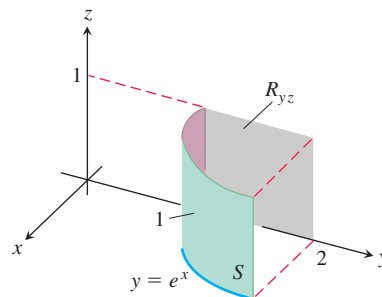
29.  $\mathbf{F}(x, y, z) = -\mathbf{i} + 2\mathbf{j} + 3\mathbf{k}$   
 $S$ : rectangular surface  $z = 0$ ,  $0 \leq x \leq 2$ ,  $0 \leq y \leq 3$ ,  
direction  $\mathbf{k}$
30.  $\mathbf{F}(x, y, z) = yx^2\mathbf{i} - 2\mathbf{j} + xz\mathbf{k}$   
 $S$ : rectangular surface  $y = 0$ ,  $-1 \leq x \leq 2$ ,  $2 \leq z \leq 7$ ,  
direction  $-\mathbf{j}$

In Exercises 31–36, use Equation (7) to find the surface integral of the field  $\mathbf{F}$  over the portion of the sphere  $x^2 + y^2 + z^2 = a^2$  in the first octant in the direction away from the origin.

31.  $\mathbf{F}(x, y, z) = z\mathbf{k}$
32.  $\mathbf{F}(x, y, z) = -y\mathbf{i} + x\mathbf{j}$

33.  $\mathbf{F}(x, y, z) = y\mathbf{i} - x\mathbf{j} + \mathbf{k}$
34.  $\mathbf{F}(x, y, z) = zx\mathbf{i} + zy\mathbf{j} + z^2\mathbf{k}$
35.  $\mathbf{F}(x, y, z) = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$
36.  $\mathbf{F}(x, y, z) = \frac{x\mathbf{i} + y\mathbf{j} + z\mathbf{k}}{\sqrt{x^2 + y^2 + z^2}}$

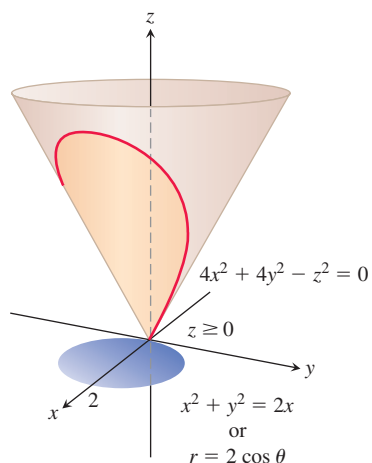
37. Find the flux of the field  $\mathbf{F}(x, y, z) = z^2\mathbf{i} + x\mathbf{j} - 3z\mathbf{k}$  outward through the surface cut from the parabolic cylinder  $z = 4 - y^2$  by the planes  $x = 0$ ,  $x = 1$ , and  $z = 0$ .
38. Find the flux of the field  $\mathbf{F}(x, y, z) = 4x\mathbf{i} + 4y\mathbf{j} + 2\mathbf{k}$  outward (away from the  $z$ -axis) through the surface cut from the bottom of the paraboloid  $z = x^2 + y^2$  by the plane  $z = 1$ .
39. Let  $S$  be the portion of the cylinder  $y = e^x$  in the first octant that projects parallel to the  $x$ -axis onto the rectangle  $R_{yz}$ :  $1 \leq y \leq 2$ ,  $0 \leq z \leq 1$  in the  $yz$ -plane (see the accompanying figure). Let  $\mathbf{n}$  be the unit vector normal to  $S$  that points away from the  $yz$ -plane. Find the flux of the field  $\mathbf{F}(x, y, z) = -2\mathbf{i} + 2y\mathbf{j} + z\mathbf{k}$  across  $S$  in the direction of  $\mathbf{n}$ .



40. Let  $S$  be the portion of the cylinder  $y = \ln x$  in the first octant whose projection parallel to the  $y$ -axis onto the  $xz$ -plane is the rectangle  $R_{xz}$ :  $1 \leq x \leq e$ ,  $0 \leq z \leq 1$ . Let  $\mathbf{n}$  be the unit vector normal to  $S$  that points away from the  $xz$ -plane. Find the flux of  $\mathbf{F} = 2y\mathbf{j} + z\mathbf{k}$  through  $S$  in the direction of  $\mathbf{n}$ .
41. Find the outward flux of the field  $\mathbf{F} = 2xy\mathbf{i} + 2yz\mathbf{j} + 2xz\mathbf{k}$  across the surface of the cube cut from the first octant by the planes  $x = a$ ,  $y = a$ ,  $z = a$ .
42. Find the outward flux of the field  $\mathbf{F} = xz\mathbf{i} + yz\mathbf{j} + \mathbf{k}$  across the surface of the upper cap cut from the solid sphere  $x^2 + y^2 + z^2 \leq 25$  by the plane  $z = 3$ .

### Moments and Masses

43. **Centroid** Find the centroid of the portion of the sphere  $x^2 + y^2 + z^2 = a^2$  that lies in the first octant.
44. **Centroid** Find the centroid of the surface cut from the cylinder  $y^2 + z^2 = 9$ ,  $z \geq 0$ , by the planes  $x = 0$  and  $x = 3$  (resembles the surface in Example 6).
45. **Thin shell of constant density** Find the center of mass and the moment of inertia about the  $z$ -axis of a thin shell of constant density  $\delta$  cut from the cone  $x^2 + y^2 - z^2 = 0$  by the planes  $z = 1$  and  $z = 2$ .
46. **Conical surface of constant density** Find the moment of inertia about the  $z$ -axis of a thin shell of constant density  $\delta$  cut from the cone  $4x^2 + 4y^2 - z^2 = 0$ ,  $z \geq 0$ , by the circular cylinder  $x^2 + y^2 = 2x$  (see the accompanying figure).

**47. Spherical shells**

- a. Find the moment of inertia about a diameter of a thin spherical shell of radius  $a$  and constant density  $\delta$ . (Work with a hemispherical shell and double the result.)
- b. Use the Parallel Axis Theorem (Exercises 15.6) and the result in part (a) to find the moment of inertia about a line tangent to the shell.

**48. Conical Surface** Find the centroid of the lateral surface of a solid cone of base radius  $a$  and height  $h$  (cone surface minus the base).

## Exercises 16.7

### Using Stokes' Theorem to Find Line Integrals

In Exercises 1–6, use the surface integral in Stokes' Theorem to calculate the circulation of the field  $\mathbf{F}$  around the curve  $C$  in the indicated direction.

1.  $\mathbf{F} = x^2\mathbf{i} + 2x\mathbf{j} + z^2\mathbf{k}$

$C$ : The ellipse  $4x^2 + y^2 = 4$  in the  $xy$ -plane, counterclockwise when viewed from above

2.  $\mathbf{F} = 2y\mathbf{i} + 3x\mathbf{j} - z^2\mathbf{k}$

$C$ : The circle  $x^2 + y^2 = 9$  in the  $xy$ -plane, counterclockwise when viewed from above

3.  $\mathbf{F} = y\mathbf{i} + xz\mathbf{j} + x^2\mathbf{k}$

$C$ : The boundary of the triangle cut from the plane  $x + y + z = 1$  by the first octant, counterclockwise when viewed from above

4.  $\mathbf{F} = (y^2 + z^2)\mathbf{i} + (x^2 + z^2)\mathbf{j} + (x^2 + y^2)\mathbf{k}$

$C$ : The boundary of the triangle cut from the plane  $x + y + z = 1$  by the first octant, counterclockwise when viewed from above

5.  $\mathbf{F} = (y^2 + z^2)\mathbf{i} + (x^2 + y^2)\mathbf{j} + (x^2 + y^2)\mathbf{k}$

$C$ : The square bounded by the lines  $x = \pm 1$  and  $y = \pm 1$  in the  $xy$ -plane, counterclockwise when viewed from above

6.  $\mathbf{F} = x^2y^3\mathbf{i} + \mathbf{j} + z\mathbf{k}$

$C$ : The intersection of the cylinder  $x^2 + y^2 = 4$  and the hemisphere  $x^2 + y^2 + z^2 = 16, z \geq 0$ , counterclockwise when viewed from above

### Integral of the Curl Vector Field

7. Let  $\mathbf{n}$  be the outer unit normal of the elliptical shell

$$S: 4x^2 + 9y^2 + 36z^2 = 36, \quad z \geq 0,$$

and let

$$\mathbf{F} = y\mathbf{i} + x^2\mathbf{j} + (x^2 + y^4)^{3/2} \sin e^{\sqrt{xyz}} \mathbf{k}.$$

Find the value of

$$\iint_S \nabla \times \mathbf{F} \cdot \mathbf{n} \, d\sigma.$$

(Hint: One parametrization of the ellipse at the base of the shell is  $x = 3 \cos t, y = 2 \sin t, 0 \leq t \leq 2\pi$ .)

8. Let  $\mathbf{n}$  be the outer unit normal (normal away from the origin) of the parabolic shell

$$S: 4x^2 + y + z^2 = 4, \quad y \geq 0,$$

and let

$$\mathbf{F} = \left(-z + \frac{1}{2+x}\right)\mathbf{i} + (\tan^{-1}y)\mathbf{j} + \left(x + \frac{1}{4+z}\right)\mathbf{k}.$$

Find the value of

$$\iint_S \nabla \times \mathbf{F} \cdot \mathbf{n} \, d\sigma.$$

9. Let  $S$  be the cylinder  $x^2 + y^2 = a^2, 0 \leq z \leq h$ , together with its top,  $x^2 + y^2 \leq a^2, z = h$ . Let  $\mathbf{F} = -y\mathbf{i} + x\mathbf{j} + x^2\mathbf{k}$ . Use Stokes' Theorem to find the flux of  $\nabla \times \mathbf{F}$  outward through  $S$ .

10. Evaluate

$$\iint_S \nabla \times (y\mathbf{i}) \cdot \mathbf{n} \, d\sigma,$$

where  $S$  is the hemisphere  $x^2 + y^2 + z^2 = 1, z \geq 0$ .



11. Suppose
- $\mathbf{F} = \nabla \times \mathbf{A}$
- , where

$$\mathbf{A} = (y + \sqrt{z})\mathbf{i} + e^{xyz}\mathbf{j} + \cos(xz)\mathbf{k}.$$

Determine the flux of  $\mathbf{F}$  outward through the hemisphere  $x^2 + y^2 + z^2 = 1, z \geq 0$ .

12. Repeat Exercise 11 for the flux of
- $\mathbf{F}$
- across the entire unit sphere.

### Stokes' Theorem for Parametrized Surfaces

In Exercises 13–18, use the surface integral in Stokes' Theorem to calculate the flux of the curl of the field  $\mathbf{F}$  across the surface  $S$  in the direction of the outward unit normal  $\mathbf{n}$ .

- 13.
- $\mathbf{F} = 2z\mathbf{i} + 3x\mathbf{j} + 5y\mathbf{k}$

$$S: \mathbf{r}(r, \theta) = (r \cos \theta)\mathbf{i} + (r \sin \theta)\mathbf{j} + (4 - r^2)\mathbf{k}, \\ 0 \leq r \leq 2, \quad 0 \leq \theta \leq 2\pi$$

- 14.
- $\mathbf{F} = (y - z)\mathbf{i} + (z - x)\mathbf{j} + (x + z)\mathbf{k}$

$$S: \mathbf{r}(r, \theta) = (r \cos \theta)\mathbf{i} + (r \sin \theta)\mathbf{j} + (9 - r^2)\mathbf{k}, \\ 0 \leq r \leq 3, \quad 0 \leq \theta \leq 2\pi$$

- 15.
- $\mathbf{F} = x^2y\mathbf{i} + 2y^3z\mathbf{j} + 3z\mathbf{k}$

$$S: \mathbf{r}(r, \theta) = (r \cos \theta)\mathbf{i} + (r \sin \theta)\mathbf{j} + r\mathbf{k}, \\ 0 \leq r \leq 1, \quad 0 \leq \theta \leq 2\pi$$

- 16.
- $\mathbf{F} = (x - y)\mathbf{i} + (y - z)\mathbf{j} + (z - x)\mathbf{k}$

$$S: \mathbf{r}(r, \theta) = (r \cos \theta)\mathbf{i} + (r \sin \theta)\mathbf{j} + (5 - r)\mathbf{k}, \\ 0 \leq r \leq 5, \quad 0 \leq \theta \leq 2\pi$$

- 17.
- $\mathbf{F} = 3y\mathbf{i} + (5 - 2x)\mathbf{j} + (z^2 - 2)\mathbf{k}$

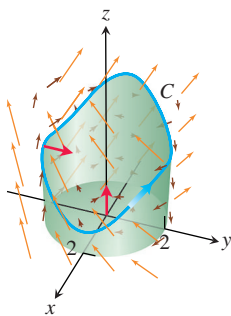
$$S: \mathbf{r}(\phi, \theta) = (\sqrt{3} \sin \phi \cos \theta)\mathbf{i} + (\sqrt{3} \sin \phi \sin \theta)\mathbf{j} + \\ (\sqrt{3} \cos \phi)\mathbf{k}, \quad 0 \leq \phi \leq \pi/2, \quad 0 \leq \theta \leq 2\pi$$

- 18.
- $\mathbf{F} = y^2\mathbf{i} + z^2\mathbf{j} + x\mathbf{k}$

$$S: \mathbf{r}(\phi, \theta) = (2 \sin \phi \cos \theta)\mathbf{i} + (2 \sin \phi \sin \theta)\mathbf{j} + (2 \cos \phi)\mathbf{k}, \\ 0 \leq \phi \leq \pi/2, \quad 0 \leq \theta \leq 2\pi$$

### Theory and Examples

19. Let  $C$  be the smooth curve  $\mathbf{r}(t) = (2 \cos t)\mathbf{i} + (2 \sin t)\mathbf{j} + (3 - 2 \cos^3 t)\mathbf{k}$ , oriented to be traversed counterclockwise around the  $z$ -axis when viewed from above. Let  $S$  be the piecewise smooth cylindrical surface  $x^2 + y^2 = 4$ , below the curve for  $z \geq 0$ , together with the base disk in the  $xy$ -plane. Note that  $C$  lies on the cylinder  $S$  and above the  $xy$ -plane (see the accompanying figure). Verify Equation (4) in Stokes' Theorem for the vector field  $\mathbf{F} = y\mathbf{i} - x\mathbf{j} + x^2\mathbf{k}$ .



20. Verify Stokes' Theorem for the vector field  $\mathbf{F} = 2xy\mathbf{i} + x\mathbf{j} + (y + z)\mathbf{k}$  and surface  $z = 4 - x^2 - y^2, z \geq 0$ , oriented with unit normal  $\mathbf{n}$  pointing upward.

21. **Zero circulation** Use Equation (8) and Stokes' Theorem to show that the circulations of the following fields around the boundary of any smooth orientable surface in space are zero.

a.  $\mathbf{F} = 2x\mathbf{i} + 2y\mathbf{j} + 2z\mathbf{k}$       b.  $\mathbf{F} = \nabla(xy^2z^3)$

c.  $\mathbf{F} = \nabla \times (x\mathbf{i} + y\mathbf{j} + z\mathbf{k})$       d.  $\mathbf{F} = \nabla f$

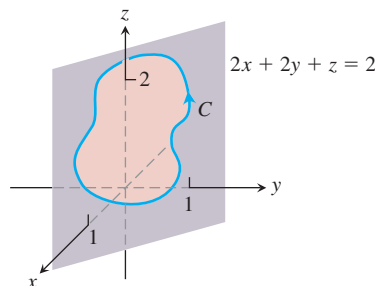
22. **Zero circulation** Let  $f(x, y, z) = (x^2 + y^2 + z^2)^{-1/2}$ . Show that the clockwise circulation of the field  $\mathbf{F} = \nabla f$  around the circle  $x^2 + y^2 = a^2$  in the  $xy$ -plane is zero

a. by taking  $\mathbf{r} = (a \cos t)\mathbf{i} + (a \sin t)\mathbf{j}$ ,  $0 \leq t \leq 2\pi$ , and integrating  $\mathbf{F} \cdot d\mathbf{r}$  over the circle.

b. by applying Stokes' Theorem.

23. Let  $C$  be a simple closed smooth curve in the plane  $2x + 2y + z = 2$ , oriented as shown here. Show that

$$\oint_C 2y \, dx + 3z \, dy - x \, dz$$



depends only on the area of the region enclosed by  $C$  and not on the position or shape of  $C$ .

24. Show that if  $\mathbf{F} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$ , then  $\nabla \times \mathbf{F} = \mathbf{0}$ .
25. Find a vector field with twice-differentiable components whose curl is  $x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$  or prove that no such field exists.
26. Does Stokes' Theorem say anything special about circulation in a field whose curl is zero? Give reasons for your answer.
27. Let  $R$  be a region in the  $xy$ -plane that is bounded by a piecewise smooth simple closed curve  $C$  and suppose that the moments of inertia of  $R$  about the  $x$ - and  $y$ -axes are known to be  $I_x$  and  $I_y$ . Evaluate the integral

$$\oint_C \nabla(r^4) \cdot \mathbf{n} \, ds,$$

where  $r = \sqrt{x^2 + y^2}$ , in terms of  $I_x$  and  $I_y$ .

28. **Zero curl, yet the field is not conservative** Show that the curl of

$$\mathbf{F} = \frac{-y}{x^2 + y^2}\mathbf{i} + \frac{x}{x^2 + y^2}\mathbf{j} + z\mathbf{k}$$

is zero but that

$$\oint_C \mathbf{F} \cdot d\mathbf{r}$$

is not zero if  $C$  is the circle  $x^2 + y^2 = 1$  in the  $xy$ -plane. (Theorem 7 does not apply here because the domain of  $\mathbf{F}$  is not simply connected. The field  $\mathbf{F}$  is not defined along the  $z$ -axis so there is no way to contract  $C$  to a point without leaving the domain of  $\mathbf{F}$ .)

## Exercises 16.8

### Calculating Divergence

In Exercises 1–4, find the divergence of the field.

1. The spin field in Figure 16.12
2. The radial field in Figure 16.11
3. The gravitational field in Figure 16.8 and Exercise 38a in Section 16.3
4. The velocity field in Figure 16.13

### Calculating Flux Using the Divergence Theorem

In Exercises 5–16, use the Divergence Theorem to find the outward flux of  $\mathbf{F}$  across the boundary of the region  $D$ .

5. **Cube**  $\mathbf{F} = (y - x)\mathbf{i} + (z - y)\mathbf{j} + (y - x)\mathbf{k}$

$D$ : The cube bounded by the planes  $x = \pm 1$ ,  $y = \pm 1$ , and  $z = \pm 1$

6.  $\mathbf{F} = x^2\mathbf{i} + y^2\mathbf{j} + z^2\mathbf{k}$

a. **Cube**  $D$ : The cube cut from the first octant by the planes  $x = 1$ ,  $y = 1$ , and  $z = 1$

b. **Cube**  $D$ : The cube bounded by the planes  $x = \pm 1$ ,  $y = \pm 1$ , and  $z = \pm 1$

c. **Cylindrical can**  $D$ : The region cut from the solid cylinder  $x^2 + y^2 \leq 4$  by the planes  $z = 0$  and  $z = 1$

7. **Cylinder and paraboloid**  $\mathbf{F} = y\mathbf{i} + xy\mathbf{j} - z\mathbf{k}$

$D$ : The region inside the solid cylinder  $x^2 + y^2 \leq 4$  between the plane  $z = 0$  and the paraboloid  $z = x^2 + y^2$

8. **Sphere**  $\mathbf{F} = x^2\mathbf{i} + xz\mathbf{j} + 3z\mathbf{k}$

$D$ : The solid sphere  $x^2 + y^2 + z^2 \leq 4$

9. **Portion of sphere**  $\mathbf{F} = x^2\mathbf{i} - 2xy\mathbf{j} + 3xz\mathbf{k}$

$D$ : The region cut from the first octant by the sphere  $x^2 + y^2 + z^2 = 4$

10. **Cylindrical can**  $\mathbf{F} = (6x^2 + 2xy)\mathbf{i} + (2y + x^2z)\mathbf{j} + 4x^2y^3\mathbf{k}$

$D$ : The region cut from the first octant by the cylinder  $x^2 + y^2 = 4$  and the plane  $z = 3$

**11. Wedge**  $\mathbf{F} = 2xz\mathbf{i} - xy\mathbf{j} - z^2\mathbf{k}$ 

$D$ : The wedge cut from the first octant by the plane  $y + z = 4$  and the elliptical cylinder  $4x^2 + y^2 = 16$

**12. Sphere**  $\mathbf{F} = x^3\mathbf{i} + y^3\mathbf{j} + z^3\mathbf{k}$ 

$D$ : The solid sphere  $x^2 + y^2 + z^2 \leq a^2$

**13. Thick sphere**  $\mathbf{F} = \sqrt{x^2 + y^2 + z^2}(x\mathbf{i} + y\mathbf{j} + z\mathbf{k})$ 

$D$ : The region  $1 \leq x^2 + y^2 + z^2 \leq 2$

**14. Thick sphere**  $\mathbf{F} = (x\mathbf{i} + y\mathbf{j} + z\mathbf{k})/\sqrt{x^2 + y^2 + z^2}$ 

$D$ : The region  $1 \leq x^2 + y^2 + z^2 \leq 4$

**15. Thick sphere**  $\mathbf{F} = (5x^3 + 12xy^2)\mathbf{i} + (y^3 + e^y \sin z)\mathbf{j} + (5z^3 + e^y \cos z)\mathbf{k}$ 

$D$ : The solid region between the spheres  $x^2 + y^2 + z^2 = 1$  and  $x^2 + y^2 + z^2 = 2$

**16. Thick cylinder**  $\mathbf{F} = \ln(x^2 + y^2)\mathbf{i} - \left(\frac{2z}{x} \tan^{-1} \frac{y}{x}\right)\mathbf{j} + z\sqrt{x^2 + y^2}\mathbf{k}$ 

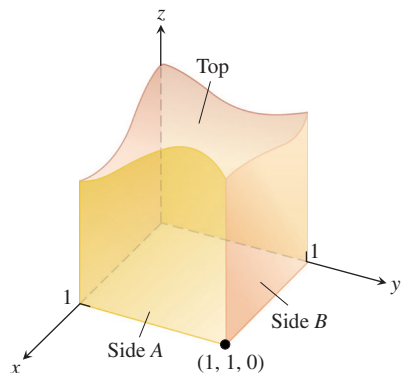
$D$ : The thick-walled cylinder  $1 \leq x^2 + y^2 \leq 2, -1 \leq z \leq 2$

**Theory and Examples**

**17. a.** Show that the outward flux of the position vector field  $\mathbf{F} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k}$  through a smooth closed surface  $S$  is three times the volume of the region enclosed by the surface.

**b.** Let  $\mathbf{n}$  be the outward unit normal vector field on  $S$ . Show that it is not possible for  $\mathbf{F}$  to be orthogonal to  $\mathbf{n}$  at every point of  $S$ .

**18.** The base of the closed cubelike surface shown here is the unit square in the  $xy$ -plane. The four sides lie in the planes  $x = 0$ ,  $x = 1$ ,  $y = 0$ , and  $y = 1$ . The top is an arbitrary smooth surface whose identity is unknown. Let  $\mathbf{F} = x\mathbf{i} - 2y\mathbf{j} + (z + 3)\mathbf{k}$  and suppose the outward flux of  $\mathbf{F}$  through Side A is 1 and through Side B is  $-3$ . Can you conclude anything about the outward flux through the top? Give reasons for your answer.



**19.** Let  $\mathbf{F} = (y \cos 2x)\mathbf{i} + (y^2 \sin 2x)\mathbf{j} + (x^2y + z)\mathbf{k}$ . Is there a vector field  $\mathbf{A}$  such that  $\mathbf{F} = \nabla \times \mathbf{A}$ ? Explain your answer.

**20. Outward flux of a gradient field** Let  $S$  be the surface of the portion of the solid sphere  $x^2 + y^2 + z^2 \leq a^2$  that lies in the first octant and let  $f(x, y, z) = \ln \sqrt{x^2 + y^2 + z^2}$ . Calculate

$$\iint_S \nabla f \cdot \mathbf{n} \, d\sigma.$$

( $\nabla f \cdot \mathbf{n}$  is the derivative of  $f$  in the direction of outward normal  $\mathbf{n}$ .)

**21.** Let  $\mathbf{F}$  be a field whose components have continuous first partial derivatives throughout a portion of space containing a region  $D$  bounded by a smooth closed surface  $S$ . If  $|\mathbf{F}| \leq 1$ , can any bound be placed on the size of

$$\iiint_D \nabla \cdot \mathbf{F} \, dV?$$

Give reasons for your answer.

**22. Maximum flux** Among all rectangular solids defined by the inequalities  $0 \leq x \leq a, 0 \leq y \leq b, 0 \leq z \leq 1$ , find the one for which the total flux of  $\mathbf{F} = (-x^2 - 4xy)\mathbf{i} - 6yz\mathbf{j} + 12z\mathbf{k}$  outward through the six sides is greatest. What is the greatest flux?

**23.** Calculate the net outward flux of the vector field

$$\mathbf{F} = xy\mathbf{i} + (\sin xz + y^2)\mathbf{j} + (e^{yz} + x)\mathbf{k}$$

over the surface  $S$  surrounding the region  $D$  bounded by the planes  $y = 0, z = 0, z = 2 - y$  and the parabolic cylinder  $z = 1 - x^2$ .

**24.** Compute the net outward flux of the vector field  $\mathbf{F} = (x\mathbf{i} + y\mathbf{j} + z\mathbf{k})/(x^2 + y^2 + z^2)^{3/2}$  across the ellipsoid  $9x^2 + 4y^2 + 6z^2 = 36$ .

**25.** Let  $\mathbf{F}$  be a differentiable vector field and let  $g(x, y, z)$  be a differentiable scalar function. Verify the following identities.

**a.**  $\nabla \cdot (g\mathbf{F}) = g\nabla \cdot \mathbf{F} + \nabla g \cdot \mathbf{F}$

**b.**  $\nabla \times (g\mathbf{F}) = g\nabla \times \mathbf{F} + \nabla g \times \mathbf{F}$

**26.** Let  $\mathbf{F}_1$  and  $\mathbf{F}_2$  be differentiable vector fields and let  $a$  and  $b$  be arbitrary real constants. Verify the following identities.

**a.**  $\nabla \cdot (a\mathbf{F}_1 + b\mathbf{F}_2) = a\nabla \cdot \mathbf{F}_1 + b\nabla \cdot \mathbf{F}_2$

**b.**  $\nabla \times (a\mathbf{F}_1 + b\mathbf{F}_2) = a\nabla \times \mathbf{F}_1 + b\nabla \times \mathbf{F}_2$

**c.**  $\nabla \cdot (\mathbf{F}_1 \times \mathbf{F}_2) = \mathbf{F}_2 \cdot \nabla \times \mathbf{F}_1 - \mathbf{F}_1 \cdot \nabla \times \mathbf{F}_2$

**27.** If  $\mathbf{F} = M\mathbf{i} + N\mathbf{j} + P\mathbf{k}$  is a differentiable vector field, we define the notation  $\mathbf{F} \cdot \nabla$  to mean

$$M \frac{\partial}{\partial x} + N \frac{\partial}{\partial y} + P \frac{\partial}{\partial z}.$$

For differentiable vector fields  $\mathbf{F}_1$  and  $\mathbf{F}_2$ , verify the following identities.

**a.**  $\nabla \times (\mathbf{F}_1 \times \mathbf{F}_2) = (\mathbf{F}_2 \cdot \nabla)\mathbf{F}_1 - (\mathbf{F}_1 \cdot \nabla)\mathbf{F}_2 + (\nabla \cdot \mathbf{F}_2)\mathbf{F}_1 - (\nabla \cdot \mathbf{F}_1)\mathbf{F}_2$

**b.**  $\nabla(\mathbf{F}_1 \cdot \mathbf{F}_2) = (\mathbf{F}_1 \cdot \nabla)\mathbf{F}_2 + (\mathbf{F}_2 \cdot \nabla)\mathbf{F}_1 + \mathbf{F}_1 \times (\nabla \times \mathbf{F}_2) + \mathbf{F}_2 \times (\nabla \times \mathbf{F}_1)$

**28. Harmonic functions** A function  $f(x, y, z)$  is said to be *harmonic* in a region  $D$  in space if it satisfies the Laplace equation

$$\nabla^2 f = \nabla \cdot \nabla f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} = 0$$

throughout  $D$ .

**a.** Suppose that  $f$  is harmonic throughout a bounded region  $D$  enclosed by a smooth surface  $S$  and that  $\mathbf{n}$  is the chosen unit normal vector on  $S$ . Show that the integral over  $S$  of  $\nabla f \cdot \mathbf{n}$ , the derivative of  $f$  in the direction of  $\mathbf{n}$ , is zero.

**b.** Show that if  $f$  is harmonic on  $D$ , then

$$\iint_S f \nabla f \cdot \mathbf{n} \, d\sigma = \iiint_D |\nabla f|^2 \, dV.$$

- 29. Green's first formula** Suppose that  $f$  and  $g$  are scalar functions with continuous first- and second-order partial derivatives throughout a region  $D$  that is bounded by a closed piecewise smooth surface  $S$ . Show that

$$\iint_S f \nabla g \cdot \mathbf{n} \, d\sigma = \iiint_D (f \nabla^2 g + \nabla f \cdot \nabla g) \, dV. \quad (10)$$

Equation (10) is **Green's first formula**. (*Hint: Apply the Divergence Theorem to the field  $\mathbf{F} = f \nabla g$ .*)

- 30. Green's second formula** (*Continuation of Exercise 29.*) Interchange  $f$  and  $g$  in Equation (10) to obtain a similar formula. Then subtract this formula from Equation (10) to show that

$$\iint_S (f \nabla g - g \nabla f) \cdot \mathbf{n} \, d\sigma = \iiint_D (f \nabla^2 g - g \nabla^2 f) \, dV. \quad (11)$$

This equation is **Green's second formula**.

- 31. Conservation of mass** Let  $\mathbf{v}(t, x, y, z)$  be a continuously differentiable vector field over the region  $D$  in space and let  $p(t, x, y, z)$  be a continuously differentiable scalar function. The variable  $t$  represents the time domain. The Law of Conservation of Mass asserts that

$$\frac{d}{dt} \iiint_D p(t, x, y, z) \, dV = - \iint_S p \mathbf{v} \cdot \mathbf{n} \, d\sigma,$$

where  $S$  is the surface enclosing  $D$ .

- a.** Give a physical interpretation of the conservation of mass law if  $\mathbf{v}$  is a velocity flow field and  $p$  represents the density of the fluid at point  $(x, y, z)$  at time  $t$ .

- b.** Use the Divergence Theorem and Leibniz's Rule,

$$\frac{d}{dt} \iiint_D p(t, x, y, z) \, dV = \iiint_D \frac{\partial p}{\partial t} \, dV,$$

to show that the Law of Conservation of Mass is equivalent to the continuity equation,

$$\nabla \cdot p \mathbf{v} + \frac{\partial p}{\partial t} = 0.$$

(In the first term  $\nabla \cdot p \mathbf{v}$ , the variable  $t$  is held fixed, and in the second term  $\partial p / \partial t$ , it is assumed that the point  $(x, y, z)$  in  $D$  is held fixed.)

- 32. The heat diffusion equation** Let  $T(t, x, y, z)$  be a function with continuous second derivatives giving the temperature at time  $t$  at the point  $(x, y, z)$  of a solid occupying a region  $D$  in space. If the solid's heat capacity and mass density are denoted by the constants  $c$  and  $\rho$ , respectively, the quantity  $c\rho T$  is called the solid's **heat energy per unit volume**.

- a.** Explain why  $-\nabla T$  points in the direction of heat flow.  
**b.** Let  $-k\nabla T$  denote the **energy flux vector**. (Here the constant  $k$  is called the **conductivity**.) Assuming the Law of Conservation of Mass with  $-k\nabla T = \mathbf{v}$  and  $c\rho T = p$  in Exercise 31, derive the diffusion (heat) equation

$$\frac{\partial T}{\partial t} = K \nabla^2 T,$$

where  $K = k/(c\rho) > 0$  is the *diffusivity* constant. (Notice that if  $T(t, x)$  represents the temperature at time  $t$  at position  $x$  in a uniform conducting rod with perfectly insulated sides, then  $\nabla^2 T = \partial^2 T / \partial x^2$  and the diffusion equation reduces to the one-dimensional heat equation in Chapter 14's Additional Exercises.)