

# 5 Applications of Integration

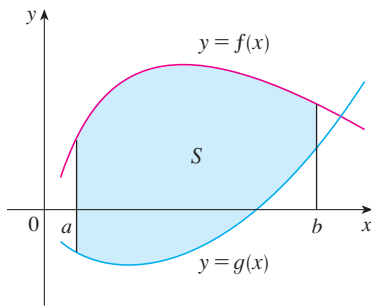
When a bat strikes a baseball, the collision lasts only about a thousandth of a second. In the project on page 392, you will use calculus to find the average force on the bat when this happens. Several other applications of calculus to the game of baseball are explored as well.



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**IN THIS CHAPTER WE EXPLORE** some of the applications of the definite integral by using it to compute areas between curves, volumes of solids, and the work done by a varying force. The common theme is the following general method, which is similar to the one we used to find areas under curves: we break up a quantity  $Q$  into a large number of small parts. We next approximate each small part by a quantity of the form  $f(x_i^*) \Delta x$  and thus approximate  $Q$  by a Riemann sum. Then we take the limit and express  $Q$  as an integral. Finally we evaluate the integral using the Fundamental Theorem of Calculus or the Midpoint Rule.

## 5.1 Areas Between Curves



**FIGURE 1**

$S = \{(x, y) \mid a \leq x \leq b, g(x) \leq y \leq f(x)\}$

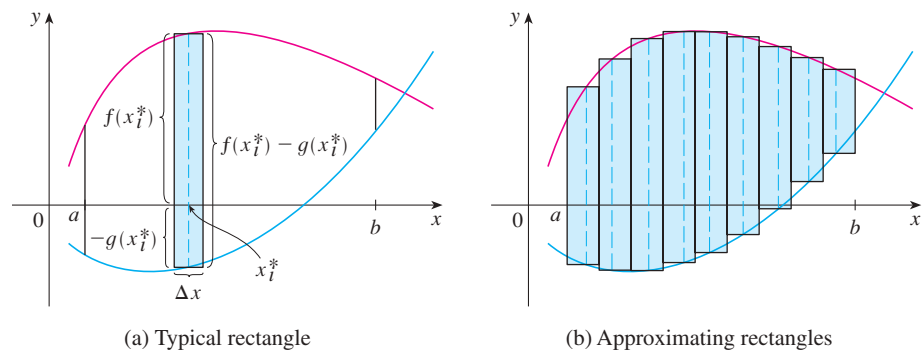
In Chapter 4 we defined and calculated areas of regions that lie under the graphs of functions. Here we use integrals to find areas of regions that lie between the graphs of two functions.

Consider the region  $S$  that lies between two curves  $y = f(x)$  and  $y = g(x)$  and between the vertical lines  $x = a$  and  $x = b$ , where  $f$  and  $g$  are continuous functions and  $f(x) \geq g(x)$  for all  $x$  in  $[a, b]$ . (See Figure 1.)

Just as we did for areas under curves in Section 4.1, we divide  $S$  into  $n$  strips of equal width and then we approximate the  $i$ th strip by a rectangle with base  $\Delta x$  and height  $f(x_i^*) - g(x_i^*)$ . (See Figure 2. If we like, we could take all of the sample points to be right endpoints, in which case  $x_i^* = x_i$ .) The Riemann sum

$$\sum_{i=1}^n [f(x_i^*) - g(x_i^*)] \Delta x$$

is therefore an approximation to what we intuitively think of as the area of  $S$ .



**FIGURE 2**

This approximation appears to become better and better as  $n \rightarrow \infty$ . Therefore we define the **area**  $A$  of the region  $S$  as the limiting value of the sum of the areas of these approximating rectangles.

**1**

$$A = \lim_{n \rightarrow \infty} \sum_{i=1}^n [f(x_i^*) - g(x_i^*)] \Delta x$$

We recognize the limit in (1) as the definite integral of  $f - g$ . Therefore we have the following formula for area.

**2**

The area  $A$  of the region bounded by the curves  $y = f(x)$ ,  $y = g(x)$ , and the lines  $x = a$ ,  $x = b$ , where  $f$  and  $g$  are continuous and  $f(x) \geq g(x)$  for all  $x$  in  $[a, b]$ , is

$$A = \int_a^b [f(x) - g(x)] dx$$

Notice that in the special case where  $g(x) = 0$ ,  $S$  is the region under the graph of  $f$  and our general definition of area (1) reduces to our previous definition (Definition 4.1.2).

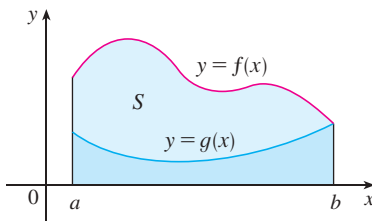


FIGURE 3

$$A = \int_a^b f(x) dx - \int_a^b g(x) dx$$

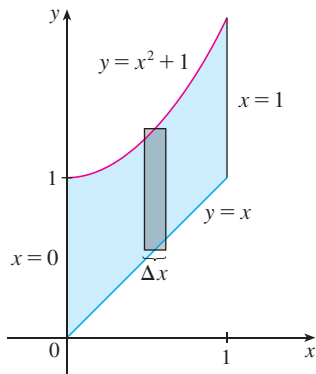


FIGURE 4

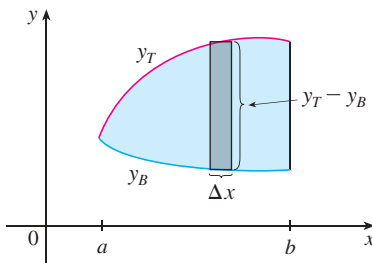


FIGURE 5

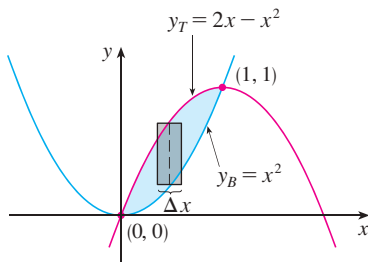


FIGURE 6

In the case where both  $f$  and  $g$  are positive, you can see from Figure 3 why (2) is true:

$$\begin{aligned} A &= [\text{area under } y = f(x)] - [\text{area under } y = g(x)] \\ &= \int_a^b f(x) dx - \int_a^b g(x) dx = \int_a^b [f(x) - g(x)] dx \end{aligned}$$

**EXAMPLE 1** Find the area of the region bounded above by  $y = x^2 + 1$ , bounded below by  $y = x$ , and bounded on the sides by  $x = 0$  and  $x = 1$ .

**SOLUTION** The region is shown in Figure 4. The upper boundary curve is  $y = x^2 + 1$  and the lower boundary curve is  $y = x$ . So we use the area formula (2) with  $f(x) = x^2 + 1$ ,  $g(x) = x$ ,  $a = 0$ , and  $b = 1$ :

$$\begin{aligned} A &= \int_0^1 [(x^2 + 1) - x] dx = \int_0^1 (x^2 - x + 1) dx \\ &= \left[ \frac{x^3}{3} - \frac{x^2}{2} + x \right]_0^1 = \frac{1}{3} - \frac{1}{2} + 1 = \frac{5}{6} \end{aligned}$$

In Figure 4 we drew a typical approximating rectangle with width  $\Delta x$  as a reminder of the procedure by which the area is defined in (1). In general, when we set up an integral for an area, it's helpful to sketch the region to identify the top curve  $y_T$ , the bottom curve  $y_B$ , and a typical approximating rectangle as in Figure 5. Then the area of a typical rectangle is  $(y_T - y_B) \Delta x$  and the equation

$$A = \lim_{n \rightarrow \infty} \sum_{i=1}^n (y_T - y_B) \Delta x = \int_a^b (y_T - y_B) dx$$

summarizes the procedure of adding (in a limiting sense) the areas of all the typical rectangles.

Notice that in Figure 5 the left-hand boundary reduces to a point, whereas in Figure 3 the right-hand boundary reduces to a point. In the next example both of the side boundaries reduce to a point, so the first step is to find  $a$  and  $b$ .

**EXAMPLE 2** Find the area of the region enclosed by the parabolas  $y = x^2$  and  $y = 2x - x^2$ .

**SOLUTION** We first find the points of intersection of the parabolas by solving their equations simultaneously. This gives  $x^2 = 2x - x^2$ , or  $2x^2 - 2x = 0$ . Thus  $2x(x - 1) = 0$ , so  $x = 0$  or  $1$ . The points of intersection are  $(0, 0)$  and  $(1, 1)$ .

We see from Figure 6 that the top and bottom boundaries are

$$y_T = 2x - x^2 \quad \text{and} \quad y_B = x^2$$

The area of a typical rectangle is

$$(y_T - y_B) \Delta x = (2x - x^2 - x^2) \Delta x$$

and the region lies between  $x = 0$  and  $x = 1$ . So the total area is

$$\begin{aligned} A &= \int_0^1 (2x - 2x^2) dx = 2 \int_0^1 (x - x^2) dx \\ &= 2 \left[ \frac{x^2}{2} - \frac{x^3}{3} \right]_0^1 = 2 \left( \frac{1}{2} - \frac{1}{3} \right) = \frac{1}{3} \end{aligned}$$

Sometimes it’s difficult, or even impossible, to find the points of intersection of two curves exactly. As shown in the following example, we can use a graphing calculator or computer to find approximate values for the intersection points and then proceed as before.

**EXAMPLE 3** Find the approximate area of the region bounded by the curves  $y = x/\sqrt{x^2 + 1}$  and  $y = x^4 - x$ .

**SOLUTION** If we were to try to find the exact intersection points, we would have to solve the equation

$$\frac{x}{\sqrt{x^2 + 1}} = x^4 - x$$

This looks like a very difficult equation to solve exactly (in fact, it’s impossible), so instead we use a graphing device to draw the graphs of the two curves in Figure 7. One intersection point is the origin. We zoom in toward the other point of intersection and find that  $x \approx 1.18$ . (If greater accuracy is required, we could use Newton’s method or solve numerically on our graphing device.) So an approximation to the area between the curves is

$$A \approx \int_0^{1.18} \left[ \frac{x}{\sqrt{x^2 + 1}} - (x^4 - x) \right] dx$$

To integrate the first term we use the substitution  $u = x^2 + 1$ . Then  $du = 2x \, dx$ , and when  $x = 1.18$ , we have  $u \approx 2.39$ ; when  $x = 0$ ,  $u = 1$ . So

$$\begin{aligned} A &\approx \frac{1}{2} \int_1^{2.39} \frac{du}{\sqrt{u}} - \int_0^{1.18} (x^4 - x) \, dx \\ &= \sqrt{u} \Big|_1^{2.39} - \left[ \frac{x^5}{5} - \frac{x^2}{2} \right]_0^{1.18} \\ &= \sqrt{2.39} - 1 - \frac{(1.18)^5}{5} + \frac{(1.18)^2}{2} \\ &\approx 0.785 \end{aligned}$$

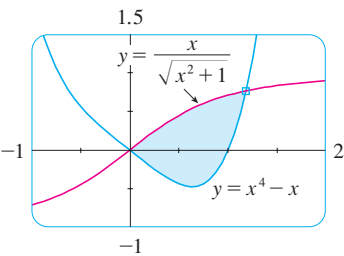


FIGURE 7

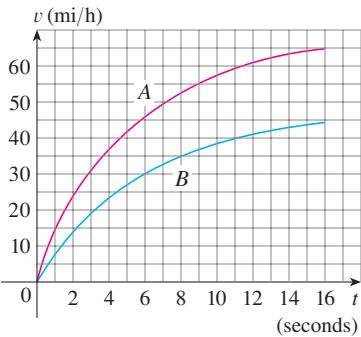


FIGURE 8

**EXAMPLE 4** Figure 8 shows velocity curves for two cars, A and B, that start side by side and move along the same road. What does the area between the curves represent? Use the Midpoint Rule to estimate it.

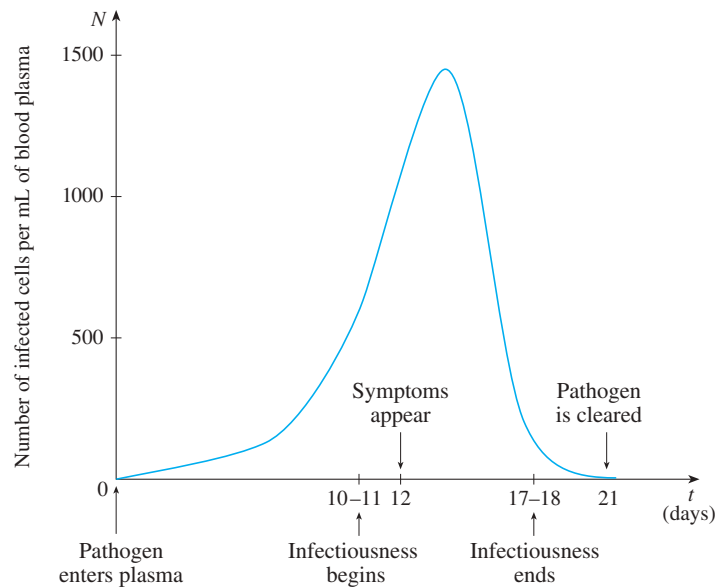
**SOLUTION** We know from Section 4.4 that the area under the velocity curve A represents the distance traveled by car A during the first 16 seconds. Similarly, the area under curve B is the distance traveled by car B during that time period. So the area between these curves, which is the difference of the areas under the curves, is the distance between the cars after 16 seconds. We read the velocities from the graph and convert them to feet per second ( $1 \text{ mi/h} = \frac{5280}{3600} \text{ ft/s}$ ).

| $t$         | 0 | 2  | 4  | 6  | 8  | 10 | 12 | 14 | 16 |
|-------------|---|----|----|----|----|----|----|----|----|
| $v_A$       | 0 | 34 | 54 | 67 | 76 | 84 | 89 | 92 | 95 |
| $v_B$       | 0 | 21 | 34 | 44 | 51 | 56 | 60 | 63 | 65 |
| $v_A - v_B$ | 0 | 13 | 20 | 23 | 25 | 28 | 29 | 29 | 30 |

We use the Midpoint Rule with  $n = 4$  intervals, so that  $\Delta t = 4$ . The midpoints of the intervals are  $\bar{t}_1 = 2$ ,  $\bar{t}_2 = 6$ ,  $\bar{t}_3 = 10$ , and  $\bar{t}_4 = 14$ . We estimate the distance between the cars after 16 seconds as follows:

$$\begin{aligned}\int_0^{16} (v_A - v_B) dt &\approx \Delta t [13 + 23 + 28 + 29] \\ &= 4(93) = 372 \text{ ft}\end{aligned}$$

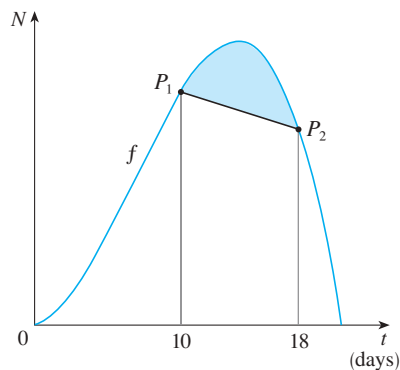
**EXAMPLE 5** Figure 9 is an example of a *pathogenesis curve* for a measles infection. It shows how the disease develops in an individual with no immunity after the measles virus spreads to the bloodstream from the respiratory tract.



**FIGURE 9**

Measles pathogenesis curve

Source: J. Heffernan et al., “An In-Host Model of Acute Infection: Measles as a Case Study,” *Theoretical Population Biology* 73 (2008): 134–47.



**FIGURE 10**

The patient becomes infectious to others once the concentration of infected cells becomes great enough, and he or she remains infectious until the immune system manages to prevent further transmission. However, symptoms don’t develop until the “amount of infection” reaches a particular threshold. The amount of infection needed to develop symptoms depends on both the concentration of infected cells and time, and corresponds to the area under the pathogenesis curve until symptoms appear. (See Exercise 4.1.19.)

(a) The pathogenesis curve in Figure 9 has been modeled by  $f(t) = -t(t - 21)(t + 1)$ . If infectiousness begins on day  $t_1 = 10$  and ends on day  $t_2 = 18$ , what are the corresponding concentration levels of infected cells?

(b) The *level of infectiousness* for an infected person is the area between  $N = f(t)$  and the line through the points  $P_1(t_1, f(t_1))$  and  $P_2(t_2, f(t_2))$ , measured in  $(\text{cells/mL}) \cdot \text{days}$ . (See Figure 10.) Compute the level of infectiousness for this particular patient.

**SOLUTION**

(a) Infectiousness begins when the concentration reaches  $f(10) = 1210$  cells/mL and ends when the concentration reduces to  $f(18) = 1026$  cells/mL.

(b) The line through  $P_1$  and  $P_2$  has slope  $\frac{1026 - 1210}{18 - 10} = -\frac{184}{8} = -23$  and equation  $N - 1210 = -23(t - 10)$ , or  $N = -23t + 1440$ . The area between  $f$  and this line is

$$\begin{aligned}\int_{10}^{18} [f(t) - (-23t + 1440)] dt &= \int_{10}^{18} (-t^3 + 20t^2 + 21t + 23t - 1440) dt \\&= \int_{10}^{18} (-t^3 + 20t^2 + 44t - 1440) dt \\&= \left[ -\frac{t^4}{4} + 20\frac{t^3}{3} + 44\frac{t^2}{2} - 1440t \right]_{10}^{18} \\&= -6156 - \left(-8033\frac{1}{3}\right) \approx 1877\end{aligned}$$

Thus the level of infectiousness for this patient is about 1877 (cells/mL) · days. ■

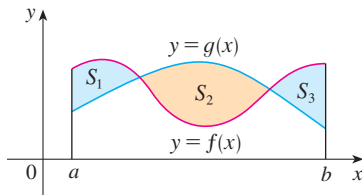


FIGURE 11

If we are asked to find the area between the curves  $y = f(x)$  and  $y = g(x)$  where  $f(x) \geq g(x)$  for some values of  $x$  but  $g(x) \geq f(x)$  for other values of  $x$ , then we split the given region  $S$  into several regions  $S_1, S_2, \dots$  with areas  $A_1, A_2, \dots$  as shown in Figure 11. We then define the area of the region  $S$  to be the sum of the areas of the smaller regions  $S_1, S_2, \dots$ , that is,  $A = A_1 + A_2 + \dots$ . Since

$$|f(x) - g(x)| = \begin{cases} f(x) - g(x) & \text{when } f(x) \geq g(x) \\ g(x) - f(x) & \text{when } g(x) \geq f(x) \end{cases}$$

we have the following expression for  $A$ .

**3** The area between the curves  $y = f(x)$  and  $y = g(x)$  and between  $x = a$  and  $x = b$  is

$$A = \int_a^b |f(x) - g(x)| dx$$

When evaluating the integral in (3), however, we must still split it into integrals corresponding to  $A_1, A_2, \dots$ .

**EXAMPLE 6** Find the area of the region bounded by the curves  $y = \sin x$ ,  $y = \cos x$ ,  $x = 0$ , and  $x = \pi/2$ .

**SOLUTION** The points of intersection occur when  $\sin x = \cos x$ , that is, when  $x = \pi/4$  (since  $0 \leq x \leq \pi/2$ ). The region is sketched in Figure 12.

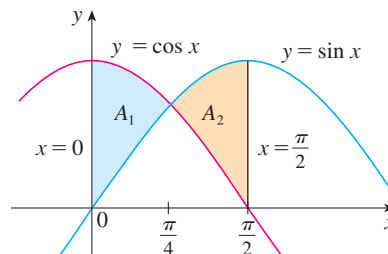


FIGURE 12



Observe that  $\cos x \geq \sin x$  when  $0 \leq x \leq \pi/4$  but  $\sin x \geq \cos x$  when  $\pi/4 \leq x \leq \pi/2$ . Therefore the required area is

$$\begin{aligned} A &= \int_0^{\pi/2} |\cos x - \sin x| dx = A_1 + A_2 \\ &= \int_0^{\pi/4} (\cos x - \sin x) dx + \int_{\pi/4}^{\pi/2} (\sin x - \cos x) dx \\ &= [\sin x + \cos x]_0^{\pi/4} + [-\cos x - \sin x]_{\pi/4}^{\pi/2} \\ &= \left( \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} - 0 - 1 \right) + \left( -0 - 1 + \frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} \right) \\ &= 2\sqrt{2} - 2 \end{aligned}$$

In this particular example we could have saved some work by noticing that the region is symmetric about  $x = \pi/4$  and so

$$A = 2A_1 = 2 \int_0^{\pi/4} (\cos x - \sin x) dx$$

Some regions are best treated by regarding  $x$  as a function of  $y$ . If a region is bounded by curves with equations  $x = f(y)$ ,  $x = g(y)$ ,  $y = c$ , and  $y = d$ , where  $f$  and  $g$  are continuous and  $f(y) \geq g(y)$  for  $c \leq y \leq d$  (see Figure 13), then its area is

$$A = \int_c^d [f(y) - g(y)] dy$$

If we write  $x_R$  for the right boundary and  $x_L$  for the left boundary, then, as Figure 14 illustrates, we have

$$A = \int_c^d (x_R - x_L) dy$$

Here a typical approximating rectangle has dimensions  $x_R - x_L$  and  $\Delta y$ .

**EXAMPLE 7** Find the area enclosed by the line  $y = x - 1$  and the parabola  $y^2 = 2x + 6$ .

**SOLUTION** By solving the two equations we find that the points of intersection are  $(-1, -2)$  and  $(5, 4)$ . We solve the equation of the parabola for  $x$  and notice from Figure 15 that the left and right boundary curves are

$$x_L = \frac{1}{2}y^2 - 3 \quad \text{and} \quad x_R = y + 1$$

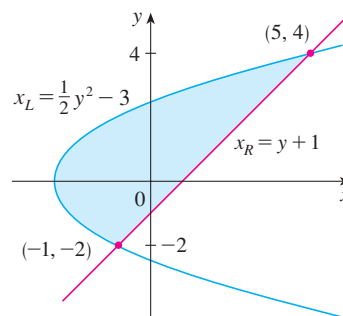


FIGURE 15

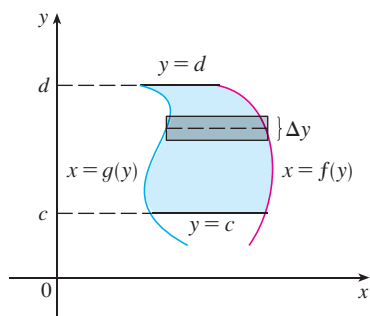


FIGURE 13

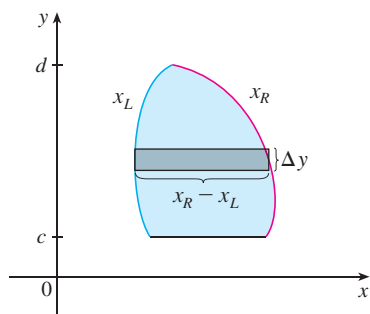


FIGURE 14

We must integrate between the appropriate  $y$ -values,  $y = -2$  and  $y = 4$ . Thus

$$\begin{aligned}
 A &= \int_{-2}^4 (x_R - x_L) dy = \int_{-2}^4 \left[ (y + 1) - \left( \frac{1}{2}y^2 - 3 \right) \right] dy \\
 &= \int_{-2}^4 \left( -\frac{1}{2}y^2 + y + 4 \right) dy \\
 &= -\frac{1}{2} \left( \frac{y^3}{3} \right) + \frac{y^2}{2} + 4y \Big|_{-2}^4 \\
 &= -\frac{1}{6}(64) + 8 + 16 - \left( \frac{4}{3} + 2 - 8 \right) = 18
 \end{aligned}$$

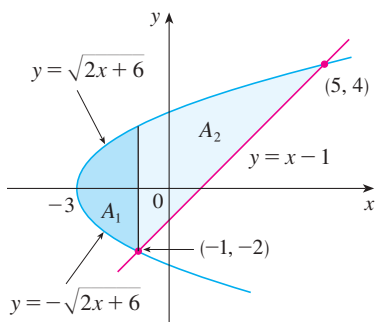
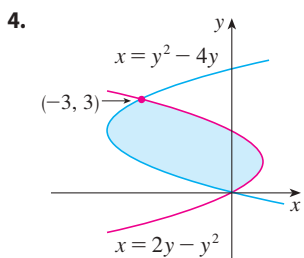
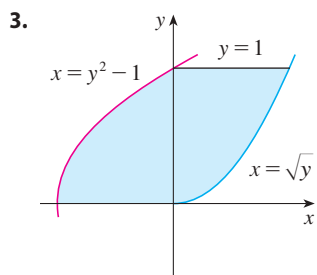
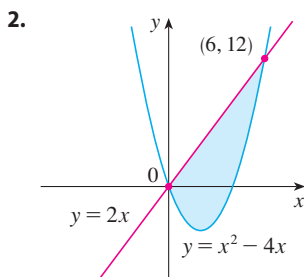
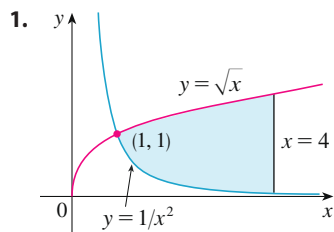


FIGURE 16

**NOTE** We could have found the area in Example 7 by integrating with respect to  $x$  instead of  $y$ , but the calculation is much more involved. Because the bottom boundary consists of two different curves, it would have meant splitting the region in two and computing the areas labeled  $A_1$  and  $A_2$  in Figure 16. The method we used in Example 7 is *much* easier.

## 5.1 EXERCISES

1–4 Find the area of the shaded region.



5–12 Sketch the region enclosed by the given curves. Decide whether to integrate with respect to  $x$  or  $y$ . Draw a typical approximating rectangle and label its height and width. Then find the area of the region.

5.  $y = x + 1$ ,  $y = 9 - x^2$ ,  $x = -1$ ,  $x = 2$

6.  $y = \sin x$ ,  $y = x$ ,  $x = \pi/2$ ,  $x = \pi$

7.  $y = (x - 2)^2$ ,  $y = x$

8.  $y = x^2 - 4x$ ,  $y = 2x$

9.  $y = \sqrt{x + 3}$ ,  $y = (x + 3)/2$

10.  $y = \sin x$ ,  $y = 2x/\pi$ ,  $x \geq 0$

11.  $x = 1 - y^2$ ,  $x = y^2 - 1$

12.  $4x + y^2 = 12$ ,  $x = y$

13–28 Sketch the region enclosed by the given curves and find its area.

13.  $y = 12 - x^2$ ,  $y = x^2 - 6$

14.  $y = x^2$ ,  $y = 4x - x^2$

15.  $y = \sec^2 x$ ,  $y = 8 \cos x$ ,  $-\pi/3 \leq x \leq \pi/3$

16.  $y = \cos x$ ,  $y = 2 - \cos x$ ,  $0 \leq x \leq 2\pi$

17.  $x = 2y^2$ ,  $x = 4 + y^2$

18.  $y = \sqrt{x - 1}$ ,  $x - y = 1$

19.  $y = \cos \pi x$ ,  $y = 4x^2 - 1$

20.  $x = y^4$ ,  $y = \sqrt{2 - x}$ ,  $y = 0$

21.  $y = \cos x$ ,  $y = 1 - 2x/\pi$

22.  $y = x^3$ ,  $y = x$

23.  $y = \sqrt[3]{2x}$ ,  $y = \frac{1}{8}x^2$ ,  $0 \leq x \leq 6$

24.  $y = \cos x$ ,  $y = 1 - \cos x$ ,  $0 \leq x \leq \pi$

25.  $y = x^4$ ,  $y = 2 - |x|$

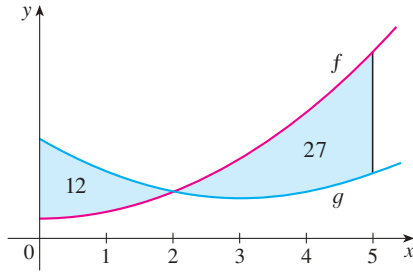
26.  $y = 3x - x^2$ ,  $y = x$ ,  $x = 3$

27.  $y = 1/x^2$ ,  $y = x$ ,  $y = \frac{1}{8}x$

28.  $y = \frac{1}{4}x^2$ ,  $y = 2x^2$ ,  $x + y = 3$ ,  $x \geq 0$



29. The graphs of two functions are shown with the areas of the regions between the curves indicated.
- (a) What is the total area between the curves for  $0 \leq x \leq 5$ ?
- (b) What is the value of  $\int_0^5 [f(x) - g(x)] dx$ ?



- 30–32 Sketch the region enclosed by the given curves and find its area.

30.  $y = \frac{x}{\sqrt{1+x^2}}, \quad y = \frac{x}{\sqrt{9-x^2}}, \quad x \geq 0$

31.  $y = \cos^2 x \sin x, \quad y = \sin x, \quad 0 \leq x \leq \pi$

32.  $y = x\sqrt{x^2+1}, \quad y = x^2\sqrt{x^3+1}$

- 33–34 Use calculus to find the area of the triangle with the given vertices.

33.  $(0, 0), (3, 1), (1, 2)$

34.  $(2, 0), (0, 2), (-1, 1)$

- 35–36 Evaluate the integral and interpret it as the area of a region. Sketch the region.

35.  $\int_0^{\pi/2} |\sin x - \cos 2x| dx$      36.  $\int_0^4 |\sqrt{x+2} - x| dx$

- 37–40 Use a graph to find approximate  $x$ -coordinates of the points of intersection of the given curves. Then find (approximately) the area of the region bounded by the curves.

37.  $y = x \sin(x^2), \quad y = x^4, \quad x \geq 0$

38.  $y = \frac{x}{(x^2+1)^2}, \quad y = x^5 - x, \quad x \geq 0$

39.  $y = 3x^2 - 2x, \quad y = x^3 - 3x + 4$

40.  $y = x - \cos x, \quad y = 2 - x^2$

- 41–44 Graph the region between the curves and use your calculator to compute the area correct to five decimal places.

41.  $y = \frac{2}{1+x^4}, \quad y = x^2$      42.  $y = x^6, \quad y = \sqrt{2-x^4}$

43.  $y = \tan^2 x, \quad y = \sqrt{x}$      44.  $y = \cos x, \quad y = x + 2 \sin^4 x$

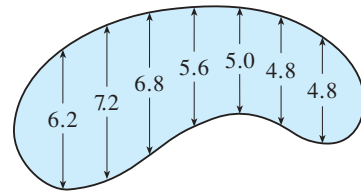
45. Use a computer algebra system to find the exact area enclosed by the curves  $y = x^5 - 6x^3 + 4x$  and  $y = x$ .

46. Sketch the region in the  $xy$ -plane defined by the inequalities  $x - 2y^2 \geq 0, 1 - x - |y| \geq 0$  and find its area.

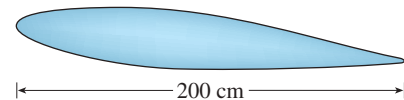
47. Racing cars driven by Chris and Kelly are side by side at the start of a race. The table shows the velocities of each car (in miles per hour) during the first ten seconds of the race. Use the Midpoint Rule to estimate how much farther Kelly travels than Chris does during the first ten seconds.

| $t$ | $v_C$ | $v_K$ | $t$ | $v_C$ | $v_K$ |
|-----|-------|-------|-----|-------|-------|
| 0   | 0     | 0     | 6   | 69    | 80    |
| 1   | 20    | 22    | 7   | 75    | 86    |
| 2   | 32    | 37    | 8   | 81    | 93    |
| 3   | 46    | 52    | 9   | 86    | 98    |
| 4   | 54    | 61    | 10  | 90    | 102   |
| 5   | 62    | 71    |     |       |       |

48. The widths (in meters) of a kidney-shaped swimming pool were measured at 2-meter intervals as indicated in the figure. Use the Midpoint Rule to estimate the area of the pool.



49. A cross-section of an airplane wing is shown. Measurements of the thickness of the wing, in centimeters, at 20-centimeter intervals are 5.8, 20.3, 26.7, 29.0, 27.6, 27.3, 23.8, 20.5, 15.1, 8.7, and 2.8. Use the Midpoint Rule to estimate the area of the wing's cross-section.



50. If the birth rate of a population is

$$b(t) = 2200 + 52.3t + 0.74t^2 \text{ people per year}$$

and the death rate is

$$d(t) = 1460 + 28.8t \text{ people per year}$$

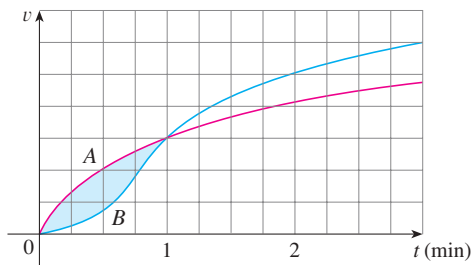
find the area between these curves for  $0 \leq t \leq 10$ . What does this area represent?

51. In Example 5, we modeled a measles pathogenesis curve by a function  $f$ . A patient infected with the measles virus

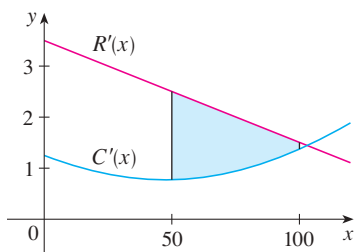
who has some immunity to the virus has a pathogenesis curve that can be modeled by, for instance,  $g(t) = 0.9f(t)$ .

- If the same threshold concentration of the virus is required for infectiousness to begin as in Example 5, on what day does this occur?
- Let  $P_3$  be the point on the graph of  $g$  where infectiousness begins. It has been shown that infectiousness ends at a point  $P_4$  on the graph of  $g$  where the line through  $P_3, P_4$  has the same slope as the line through  $P_1, P_2$  in Example 5(b). On what day does infectiousness end?
- Compute the level of infectiousness for this patient.

-  **52.** The rates at which rain fell, in inches per hour, in two different locations  $t$  hours after the start of a storm are given by  $f(t) = 0.73t^3 - 2t^2 + t + 0.6$  and  $g(t) = 0.17t^2 - 0.5t + 1.1$ . Compute the area between the graphs for  $0 \leq t \leq 2$  and interpret your result in this context.
- 53.** Two cars, A and B, start side by side and accelerate from rest. The figure shows the graphs of their velocity functions.
- Which car is ahead after one minute? Explain.
  - What is the meaning of the area of the shaded region?
  - Which car is ahead after two minutes? Explain.
  - Estimate the time at which the cars are again side by side.



- 54.** The figure shows graphs of the marginal revenue function  $R'$  and the marginal cost function  $C'$  for a manufacturer. [Recall



from Section 3.7 that  $R(x)$  and  $C(x)$  represent the revenue and cost when  $x$  units are manufactured. Assume that  $R$  and  $C$  are measured in thousands of dollars.] What is the meaning of the area of the shaded region? Use the Midpoint Rule to estimate the value of this quantity.

-  **55.** The curve with equation  $y^2 = x^2(x + 3)$  is called **Tschirnhausen's cubic**. If you graph this curve you will see that part of the curve forms a loop. Find the area enclosed by the loop.
- 56.** Find the area of the region bounded by the parabola  $y = x^2$ , the tangent line to this parabola at  $(1, 1)$ , and the  $x$ -axis.
- 57.** Find the number  $b$  such that the line  $y = b$  divides the region bounded by the curves  $y = x^2$  and  $y = 4$  into two regions with equal area.
- 58.** (a) Find the number  $a$  such that the line  $x = a$  bisects the area under the curve  $y = 1/x^2$ ,  $1 \leq x \leq 4$ .  
(b) Find the number  $b$  such that the line  $y = b$  bisects the area in part (a).
- 59.** Find the values of  $c$  such that the area of the region bounded by the parabolas  $y = x^2 - c^2$  and  $y = c^2 - x^2$  is 576.
- 60.** Suppose that  $0 < c < \pi/2$ . For what value of  $c$  is the area of the region enclosed by the curves  $y = \cos x$ ,  $y = \cos(x - c)$ , and  $x = 0$  equal to the area of the region enclosed by the curves  $y = \cos(x - c)$ ,  $x = \pi$ , and  $y = 0$ ?

The following exercises are intended only for those who have already covered Chapter 6.

- 61–63** Sketch the region bounded by the given curves and find the area of the region.

- 61.**  $y = 1/x$ ,  $y = 1/x^2$ ,  $x = 2$
- 62.**  $y = \sin x$ ,  $y = e^x$ ,  $x = 0$ ,  $x = \pi/2$
- 63.**  $y = \tan x$ ,  $y = 2 \sin x$ ,  $-\pi/3 \leq x \leq \pi/3$

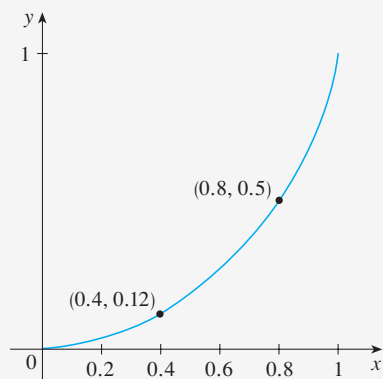
- 64.** For what values of  $m$  do the line  $y = mx$  and the curve  $y = x/(x^2 + 1)$  enclose a region? Find the area of the region.

## APPLIED PROJECT

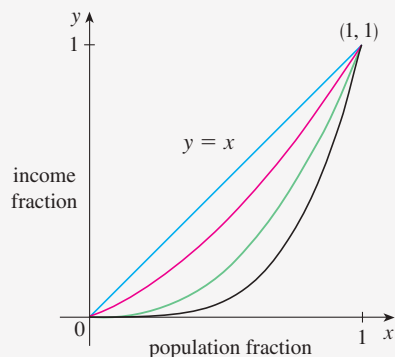
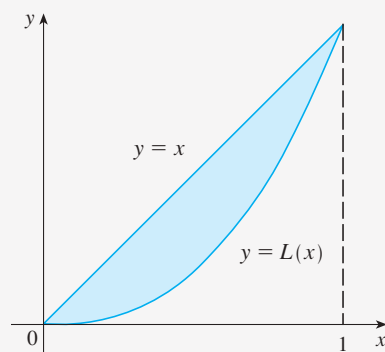
## THE GINI INDEX

How is it possible to measure the distribution of income among the inhabitants of a given country? One such measure is the *Gini index*, named after the Italian economist Corrado Gini, who first devised it in 1912.

We first rank all households in a country by income and then we compute the percentage of households whose income is at most a given percentage of the country's total income. We

**FIGURE 1**

Lorenz curve for the US in 2010

**FIGURE 2****FIGURE 3**

define a **Lorenz curve**  $y = L(x)$  on the interval  $[0, 1]$  by plotting the point  $(a/100, b/100)$  on the curve if the bottom  $a\%$  of households receive at most  $b\%$  of the total income. For instance, in Figure 1 the point  $(0.4, 0.12)$  is on the Lorenz curve for the United States in 2010 because the poorest 40% of the population received just 12% of the total income. Likewise, the bottom 80% of the population received 50% of the total income, so the point  $(0.8, 0.5)$  lies on the Lorenz curve. (The Lorenz curve is named after the American economist Max Lorenz.)

Figure 2 shows some typical Lorenz curves. They all pass through the points  $(0, 0)$  and  $(1, 1)$  and are concave upward. In the extreme case  $L(x) = x$ , society is perfectly egalitarian: the poorest  $a\%$  of the population receives  $a\%$  of the total income and so everybody receives the same income. The area between a Lorenz curve  $y = L(x)$  and the line  $y = x$  measures how much the income distribution differs from absolute equality. The **Gini index** (sometimes called the **Gini coefficient** or the **coefficient of inequality**) is the area between the Lorenz curve and the line  $y = x$  (shaded in Figure 3) divided by the area under  $y = x$ .

1. (a) Show that the Gini index  $G$  is twice the area between the Lorenz curve and the line  $y = x$ , that is,

$$G = 2 \int_0^1 [x - L(x)] dx$$

- (b) What is the value of  $G$  for a perfectly egalitarian society (everybody has the same income)? What is the value of  $G$  for a perfectly totalitarian society (a single person receives all the income)?
2. The following table (derived from data supplied by the US Census Bureau) shows values of the Lorenz function for income distribution in the United States for the year 2010.

| $x$    | 0.0   | 0.2   | 0.4   | 0.6   | 0.8   | 1.0   |
|--------|-------|-------|-------|-------|-------|-------|
| $L(x)$ | 0.000 | 0.034 | 0.120 | 0.266 | 0.498 | 1.000 |

- (a) What percentage of the total US income was received by the richest 20% of the population in 2010?
- (b) Use a calculator or computer to fit a quadratic function to the data in the table. Graph the data points and the quadratic function. Is the quadratic model a reasonable fit?
- (c) Use the quadratic model for the Lorenz function to estimate the Gini index for the United States in 2010.
3. The following table gives values for the Lorenz function in the years 1970, 1980, 1990, and 2000. Use the method of Problem 2 to estimate the Gini index for the United States for those years and compare with your answer to Problem 2(c). Do you notice a trend?

| $x$  | 0.0   | 0.2   | 0.4   | 0.6   | 0.8   | 1.0   |
|------|-------|-------|-------|-------|-------|-------|
| 1970 | 0.000 | 0.041 | 0.149 | 0.323 | 0.568 | 1.000 |
| 1980 | 0.000 | 0.042 | 0.144 | 0.312 | 0.559 | 1.000 |
| 1990 | 0.000 | 0.038 | 0.134 | 0.293 | 0.530 | 1.000 |
| 2000 | 0.000 | 0.036 | 0.125 | 0.273 | 0.503 | 1.000 |

- CAS** 4. A power model often provides a more accurate fit than a quadratic model for a Lorenz function. If you have a computer with Maple or Mathematica, fit a power function ( $y = ax^k$ ) to the data in Problem 2 and use it to estimate the Gini index for the United States in 2010. Compare with your answer to parts (b) and (c) of Problem 2.

## 5.2 Volumes

In trying to find the volume of a solid we face the same type of problem as in finding areas. We have an intuitive idea of what volume means, but we must make this idea precise by using calculus to give an exact definition of volume.

We start with a simple type of solid called a **cylinder** (or, more precisely, a *right cylinder*). As illustrated in Figure 1(a), a cylinder is bounded by a plane region  $B_1$ , called the **base**, and a congruent region  $B_2$  in a parallel plane. The cylinder consists of all points on line segments that are perpendicular to the base and join  $B_1$  to  $B_2$ . If the area of the base is  $A$  and the height of the cylinder (the distance from  $B_1$  to  $B_2$ ) is  $h$ , then the volume  $V$  of the cylinder is defined as

$$V = Ah$$

In particular, if the base is a circle with radius  $r$ , then the cylinder is a circular cylinder with volume  $V = \pi r^2 h$  [see Figure 1(b)], and if the base is a rectangle with length  $l$  and width  $w$ , then the cylinder is a rectangular box (also called a *rectangular parallelepiped*) with volume  $V = lwh$  [see Figure 1(c)].

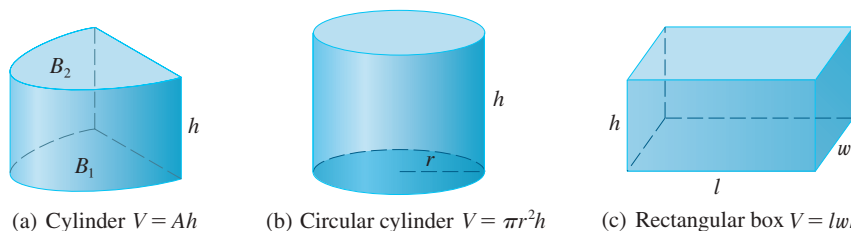


FIGURE 1

(a) Cylinder  $V = Ah$

(b) Circular cylinder  $V = \pi r^2 h$

(c) Rectangular box  $V = lwh$

For a solid  $S$  that isn't a cylinder we first "cut"  $S$  into pieces and approximate each piece by a cylinder. We estimate the volume of  $S$  by adding the volumes of the cylinders. We arrive at the exact volume of  $S$  through a limiting process in which the number of pieces becomes large.

We start by intersecting  $S$  with a plane and obtaining a plane region that is called a **cross-section** of  $S$ . Let  $A(x)$  be the area of the cross-section of  $S$  in a plane  $P_x$  perpendicular to the  $x$ -axis and passing through the point  $x$ , where  $a \leq x \leq b$ . (See Figure 2. Think of slicing  $S$  with a knife through  $x$  and computing the area of this slice.) The cross-sectional area  $A(x)$  will vary as  $x$  increases from  $a$  to  $b$ .

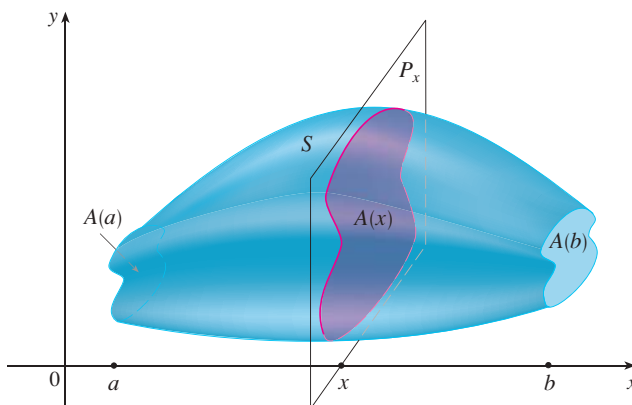


FIGURE 2

Let's divide  $S$  into  $n$  “slabs” of equal width  $\Delta x$  by using the planes  $P_{x_1}, P_{x_2}, \dots$  to slice the solid. (Think of slicing a loaf of bread.) If we choose sample points  $x_i^*$  in  $[x_{i-1}, x_i]$ , we can approximate the  $i$ th slab  $S_i$  (the part of  $S$  that lies between the planes  $P_{x_{i-1}}$  and  $P_{x_i}$ ) by a cylinder with base area  $A(x_i^*)$  and “height”  $\Delta x$ . (See Figure 3.)

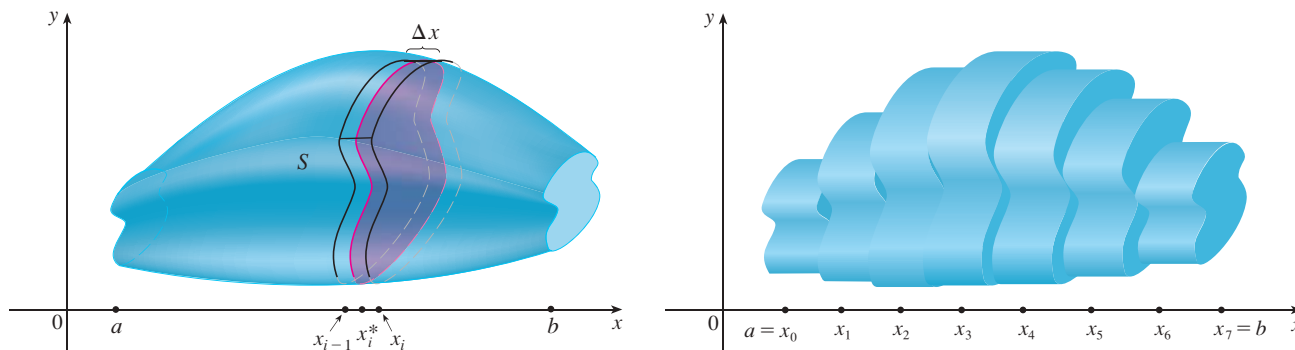


FIGURE 3

The volume of this cylinder is  $A(x_i^*) \Delta x$ , so an approximation to our intuitive conception of the volume of the  $i$ th slab  $S_i$  is

$$V(S_i) \approx A(x_i^*) \Delta x$$

Adding the volumes of these slabs, we get an approximation to the total volume (that is, what we think of intuitively as the volume):

$$V \approx \sum_{i=1}^n A(x_i^*) \Delta x$$

This approximation appears to become better and better as  $n \rightarrow \infty$ . (Think of the slices as becoming thinner and thinner.) Therefore we *define* the volume as the limit of these sums as  $n \rightarrow \infty$ . But we recognize the limit of Riemann sums as a definite integral and so we have the following definition.

It can be proved that this definition is independent of how  $S$  is situated with respect to the  $x$ -axis. In other words, no matter how we slice  $S$  with parallel planes, we always get the same answer for  $V$ .

**Definition of Volume** Let  $S$  be a solid that lies between  $x = a$  and  $x = b$ . If the cross-sectional area of  $S$  in the plane  $P_x$ , through  $x$  and perpendicular to the  $x$ -axis, is  $A(x)$ , where  $A$  is a continuous function, then the **volume** of  $S$  is

$$V = \lim_{n \rightarrow \infty} \sum_{i=1}^n A(x_i^*) \Delta x = \int_a^b A(x) dx$$

When we use the volume formula  $V = \int_a^b A(x) dx$ , it is important to remember that  $A(x)$  is the area of a moving cross-section obtained by slicing through  $x$  perpendicular to the  $x$ -axis.

Notice that, for a cylinder, the cross-sectional area is constant:  $A(x) = A$  for all  $x$ . So our definition of volume gives  $V = \int_a^b A dx = A(b - a)$ ; this agrees with the formula  $V = Ah$ .

**EXAMPLE 1** Show that the volume of a sphere of radius  $r$  is  $V = \frac{4}{3}\pi r^3$ .

**SOLUTION** If we place the sphere so that its center is at the origin, then the plane  $P_x$  intersects the sphere in a circle whose radius (from the Pythagorean Theorem) is

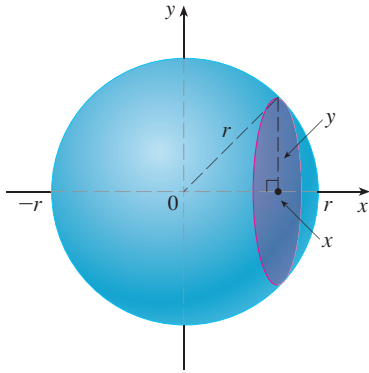


FIGURE 4

$y = \sqrt{r^2 - x^2}$ . (See Figure 4.) So the cross-sectional area is

$$A(x) = \pi y^2 = \pi(r^2 - x^2)$$

Using the definition of volume with  $a = -r$  and  $b = r$ , we have

$$\begin{aligned} V &= \int_{-r}^r A(x) dx = \int_{-r}^r \pi(r^2 - x^2) dx \\ &= 2\pi \int_0^r (r^2 - x^2) dx && \text{(The integrand is even.)} \\ &= 2\pi \left[ r^2x - \frac{x^3}{3} \right]_0^r = 2\pi \left( r^3 - \frac{r^3}{3} \right) \\ &= \frac{4}{3}\pi r^3 \end{aligned}$$

Figure 5 illustrates the definition of volume when the solid is a sphere with radius  $r = 1$ . From the result of Example 1, we know that the volume of the sphere is  $\frac{4}{3}\pi$ , which is approximately 4.18879. Here the slabs are circular cylinders, or *disks*, and the three parts of Figure 5 show the geometric interpretations of the Riemann sums

$$\sum_{i=1}^n A(\bar{x}_i) \Delta x = \sum_{i=1}^n \pi(1^2 - \bar{x}_i^2) \Delta x$$

**TEC** Visual 5.2A shows an animation of Figure 5.

when  $n = 5, 10$ , and  $20$  if we choose the sample points  $x_i^*$  to be the midpoints  $\bar{x}_i$ . Notice that as we increase the number of approximating cylinders, the corresponding Riemann sums become closer to the true volume.

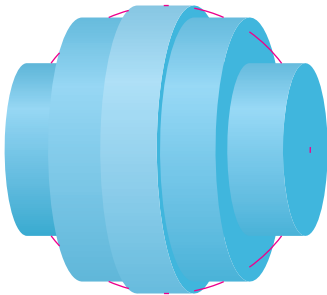
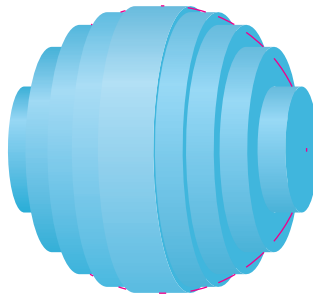
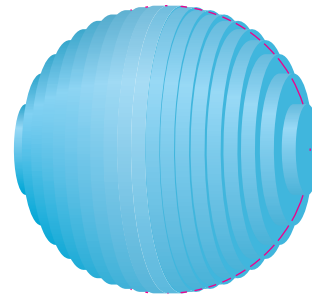
(a) Using 5 disks,  $V \approx 4.2726$ (b) Using 10 disks,  $V \approx 4.2097$ (c) Using 20 disks,  $V \approx 4.1940$ 

FIGURE 5

Approximating the volume of a sphere with radius 1

**EXAMPLE 2** Find the volume of the solid obtained by rotating about the  $x$ -axis the region under the curve  $y = \sqrt{x}$  from 0 to 1. Illustrate the definition of volume by sketching a typical approximating cylinder.

**SOLUTION** The region is shown in Figure 6(a). If we rotate about the  $x$ -axis, we get the solid shown in Figure 6(b). When we slice through the point  $x$ , we get a disk with radius  $\sqrt{x}$ . The area of this cross-section is

$$A(x) = \pi(\sqrt{x})^2 = \pi x$$

and the volume of the approximating cylinder (a disk with thickness  $\Delta x$ ) is

$$A(x) \Delta x = \pi x \Delta x$$

The solid lies between  $x = 0$  and  $x = 1$ , so its volume is

$$V = \int_0^1 A(x) dx = \int_0^1 \pi x dx = \pi \frac{x^2}{2} \Big|_0^1 = \frac{\pi}{2}$$

Did we get a reasonable answer in Example 2? As a check on our work, let's replace the given region by a square with base  $[0, 1]$  and height 1. If we rotate this square, we get a cylinder with radius 1, height 1, and volume  $\pi \cdot 1^2 \cdot 1 = \pi$ . We computed that the given solid has half this volume. That seems about right.

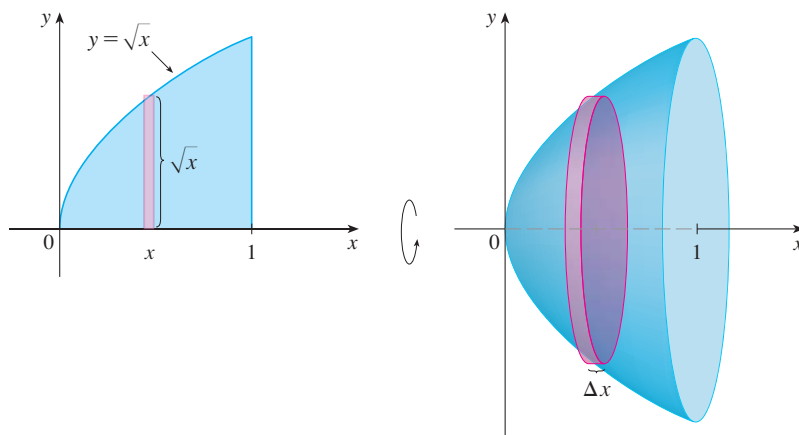


FIGURE 6

(a)

(b)

**EXAMPLE 3** Find the volume of the solid obtained by rotating the region bounded by  $y = x^3$ ,  $y = 8$ , and  $x = 0$  about the  $y$ -axis.

**SOLUTION** The region is shown in Figure 7(a) and the resulting solid is shown in Figure 7(b). Because the region is rotated about the  $y$ -axis, it makes sense to slice the solid perpendicular to the  $y$ -axis (obtaining circular cross-sections) and therefore to integrate with respect to  $y$ . If we slice at height  $y$ , we get a circular disk with radius  $x$ , where  $x = \sqrt[3]{y}$ . So the area of a cross-section through  $y$  is

$$A(y) = \pi x^2 = \pi (\sqrt[3]{y})^2 = \pi y^{2/3}$$

and the volume of the approximating cylinder pictured in Figure 7(b) is

$$A(y) \Delta y = \pi y^{2/3} \Delta y$$

Since the solid lies between  $y = 0$  and  $y = 8$ , its volume is

$$V = \int_0^8 A(y) dy = \int_0^8 \pi y^{2/3} dy = \pi \left[ \frac{3}{5} y^{5/3} \right]_0^8 = \frac{96\pi}{5}$$

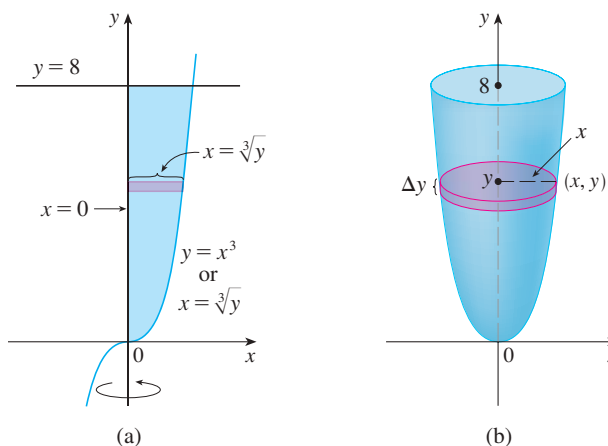


FIGURE 7

(a)

(b)



**EXAMPLE 4** The region  $\mathcal{R}$  enclosed by the curves  $y = x$  and  $y = x^2$  is rotated about the  $x$ -axis. Find the volume of the resulting solid.

**SOLUTION** The curves  $y = x$  and  $y = x^2$  intersect at the points  $(0, 0)$  and  $(1, 1)$ . The region between them, the solid of rotation, and a cross-section perpendicular to the  $x$ -axis are shown in Figure 8. A cross-section in the plane  $P_x$  has the shape of a *washer* (an annular ring) with inner radius  $x^2$  and outer radius  $x$ , so we find the cross-sectional area by subtracting the area of the inner circle from the area of the outer circle:

$$A(x) = \pi x^2 - \pi(x^2)^2 = \pi(x^2 - x^4)$$

Therefore we have

$$\begin{aligned} V &= \int_0^1 A(x) \, dx = \int_0^1 \pi(x^2 - x^4) \, dx \\ &= \pi \left[ \frac{x^3}{3} - \frac{x^5}{5} \right]_0^1 = \frac{2\pi}{15} \end{aligned}$$

**TEC** Visual 5.2B shows how solids of revolution are formed.

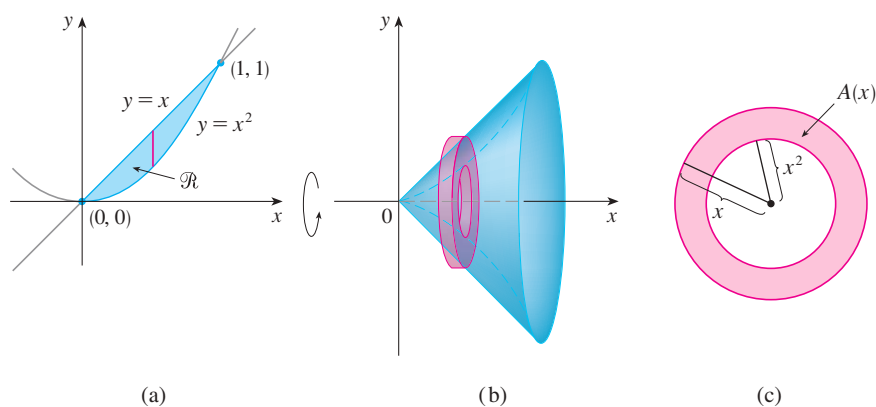


FIGURE 8

**EXAMPLE 5** Find the volume of the solid obtained by rotating the region in Example 4 about the line  $y = 2$ .

**SOLUTION** The solid and a cross-section are shown in Figure 9. Again the cross-section is a washer, but this time the inner radius is  $2 - x$  and the outer radius is  $2 - x^2$ .

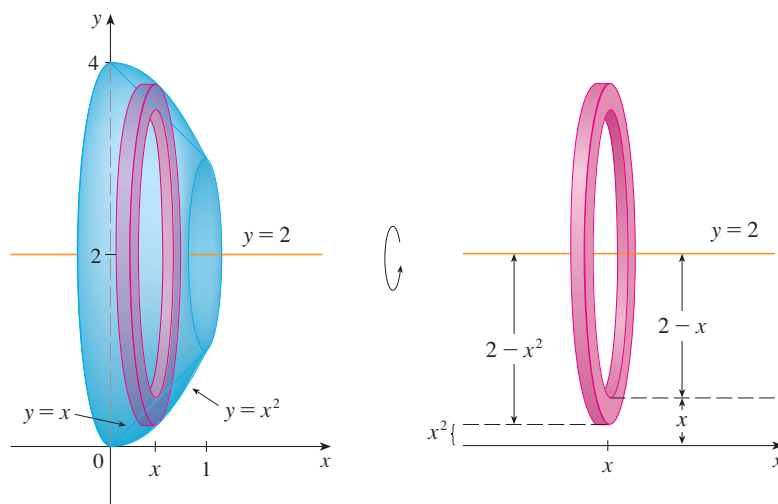


FIGURE 9

The cross-sectional area is

$$A(x) = \pi(2 - x^2)^2 - \pi(2 - x)^2$$

and so the volume of  $S$  is

$$\begin{aligned} V &= \int_0^1 A(x) dx \\ &= \pi \int_0^1 [(2 - x^2)^2 - (2 - x)^2] dx \\ &= \pi \int_0^1 (x^4 - 5x^2 + 4x) dx \\ &= \pi \left[ \frac{x^5}{5} - 5 \frac{x^3}{3} + 4 \frac{x^2}{2} \right]_0^1 \\ &= \frac{8\pi}{15} \end{aligned}$$

The solids in Examples 1–5 are all called **solids of revolution** because they are obtained by revolving a region about a line. In general, we calculate the volume of a solid of revolution by using the basic defining formula

$$V = \int_a^b A(x) dx \quad \text{or} \quad V = \int_c^d A(y) dy$$

and we find the cross-sectional area  $A(x)$  or  $A(y)$  in one of the following ways:

- If the cross-section is a disk (as in Examples 1–3), we find the radius of the disk (in terms of  $x$  or  $y$ ) and use

$$A = \pi(\text{radius})^2$$

- If the cross-section is a washer (as in Examples 4 and 5), we find the inner radius  $r_{\text{in}}$  and outer radius  $r_{\text{out}}$  from a sketch (as in Figures 8, 9, and 10) and compute the area of the washer by subtracting the area of the inner disk from the area of the outer disk:

$$A = \pi(\text{outer radius})^2 - \pi(\text{inner radius})^2$$

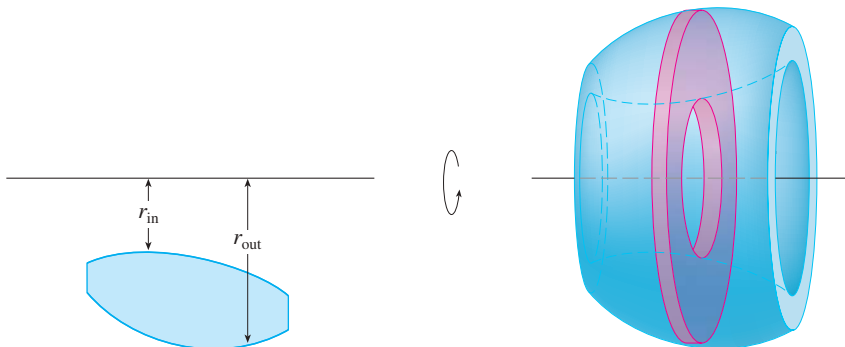


FIGURE 10

The next example gives a further illustration of the procedure.

**EXAMPLE 6** Find the volume of the solid obtained by rotating the region in Example 4 about the line  $x = -1$ .

**SOLUTION** Figure 11 shows a horizontal cross-section. It is a washer with inner radius  $1 + y$  and outer radius  $1 + \sqrt{y}$ , so the cross-sectional area is

$$\begin{aligned} A(y) &= \pi(\text{outer radius})^2 - \pi(\text{inner radius})^2 \\ &= \pi(1 + \sqrt{y})^2 - \pi(1 + y)^2 \end{aligned}$$

The volume is

$$\begin{aligned} V &= \int_0^1 A(y) dy = \pi \int_0^1 [(1 + \sqrt{y})^2 - (1 + y)^2] dy \\ &= \pi \int_0^1 (2\sqrt{y} - y - y^2) dy = \pi \left[ \frac{4y^{3/2}}{3} - \frac{y^2}{2} - \frac{y^3}{3} \right]_0^1 = \frac{\pi}{2} \end{aligned}$$

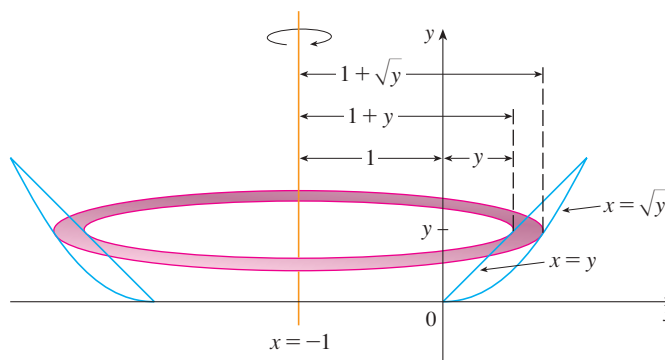


FIGURE 11

We now find the volumes of three solids that are *not* solids of revolution.

**EXAMPLE 7** Figure 12 shows a solid with a circular base of radius 1. Parallel cross-sections perpendicular to the base are equilateral triangles. Find the volume of the solid.

**SOLUTION** Let's take the circle to be  $x^2 + y^2 = 1$ . The solid, its base, and a typical cross-section at a distance  $x$  from the origin are shown in Figure 13.

Since  $B$  lies on the circle, we have  $y = \sqrt{1 - x^2}$  and so the base of the triangle  $ABC$  is  $|AB| = 2y = 2\sqrt{1 - x^2}$ . Since the triangle is equilateral, we see from Figure 13(c)

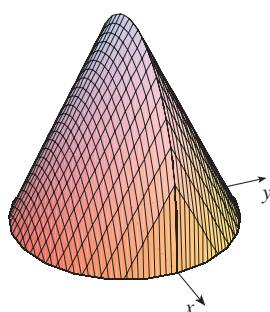


FIGURE 12  
Computer-generated picture  
of the solid in Example 7

**TEC** Visual 5.2C shows how the solid in Figure 12 is generated.

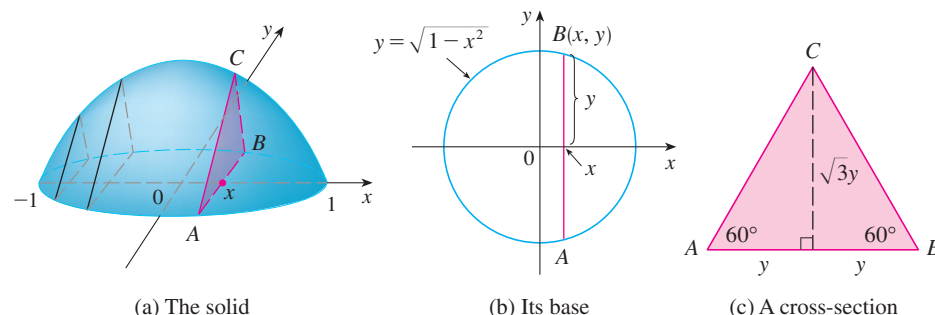


FIGURE 13

that its height is  $\sqrt{3}y = \sqrt{3}\sqrt{1-x^2}$ . The cross-sectional area is therefore

$$A(x) = \frac{1}{2} \cdot 2\sqrt{1-x^2} \cdot \sqrt{3}\sqrt{1-x^2} = \sqrt{3}(1-x^2)$$

and the volume of the solid is

$$\begin{aligned} V &= \int_{-1}^1 A(x) dx = \int_{-1}^1 \sqrt{3}(1-x^2) dx \\ &= 2 \int_0^1 \sqrt{3}(1-x^2) dx = 2\sqrt{3} \left[ x - \frac{x^3}{3} \right]_0^1 = \frac{4\sqrt{3}}{3} \end{aligned}$$

**EXAMPLE 8** Find the volume of a pyramid whose base is a square with side  $L$  and whose height is  $h$ .

**SOLUTION** We place the origin  $O$  at the vertex of the pyramid and the  $x$ -axis along its central axis as in Figure 14. Any plane  $P_x$  that passes through  $x$  and is perpendicular to the  $x$ -axis intersects the pyramid in a square with side of length  $s$ , say. We can express  $s$  in terms of  $x$  by observing from the similar triangles in Figure 15 that

$$\frac{x}{h} = \frac{s/2}{L/2} = \frac{s}{L}$$

and so  $s = Lx/h$ . [Another method is to observe that the line  $OP$  has slope  $L/(2h)$  and so its equation is  $y = Lx/(2h)$ .] Therefore the cross-sectional area is

$$A(x) = s^2 = \frac{L^2}{h^2} x^2$$

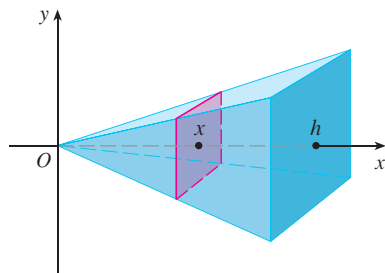


FIGURE 14

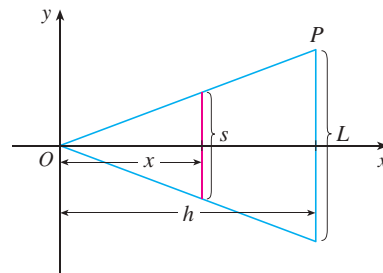


FIGURE 15

The pyramid lies between  $x = 0$  and  $x = h$ , so its volume is

$$V = \int_0^h A(x) dx = \int_0^h \frac{L^2}{h^2} x^2 dx = \frac{L^2}{h^2} \left[ \frac{x^3}{3} \right]_0^h = \frac{L^2 h}{3}$$

**NOTE** We didn't need to place the vertex of the pyramid at the origin in Example 8. We did so merely to make the equations simple. If, instead, we had placed the center of the base at the origin and the vertex on the positive  $y$ -axis, as in Figure 16, you can verify that we would have obtained the integral

$$V = \int_0^h \frac{L^2}{h^2} (h-y)^2 dy = \frac{L^2 h}{3}$$

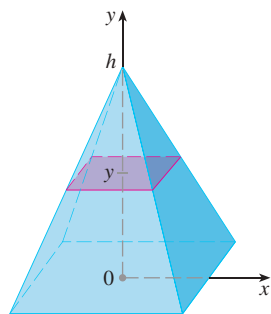


FIGURE 16

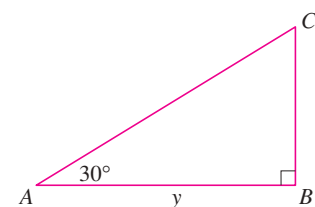
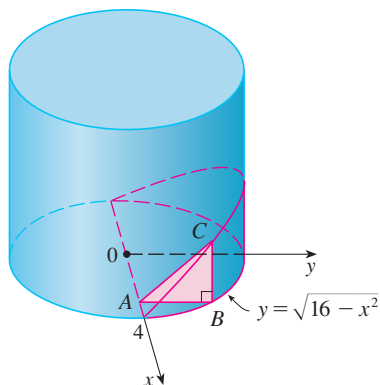


FIGURE 17

**EXAMPLE 9** A wedge is cut out of a circular cylinder of radius 4 by two planes. One plane is perpendicular to the axis of the cylinder. The other intersects the first at an angle of  $30^\circ$  along a diameter of the cylinder. Find the volume of the wedge.

**SOLUTION** If we place the  $x$ -axis along the diameter where the planes meet, then the base of the solid is a semicircle with equation  $y = \sqrt{16 - x^2}$ ,  $-4 \leq x \leq 4$ . A cross-section perpendicular to the  $x$ -axis at a distance  $x$  from the origin is a triangle  $ABC$ , as shown in Figure 17, whose base is  $y = \sqrt{16 - x^2}$  and whose height is  $|BC| = y \tan 30^\circ = \sqrt{16 - x^2}/\sqrt{3}$ . So the cross-sectional area is

$$A(x) = \frac{1}{2} \sqrt{16 - x^2} \cdot \frac{1}{\sqrt{3}} \sqrt{16 - x^2} = \frac{16 - x^2}{2\sqrt{3}}$$

and the volume is

$$\begin{aligned} V &= \int_{-4}^4 A(x) dx = \int_{-4}^4 \frac{16 - x^2}{2\sqrt{3}} dx \\ &= \frac{1}{\sqrt{3}} \int_0^4 (16 - x^2) dx = \frac{1}{\sqrt{3}} \left[ 16x - \frac{x^3}{3} \right]_0^4 \\ &= \frac{128}{3\sqrt{3}} \end{aligned}$$

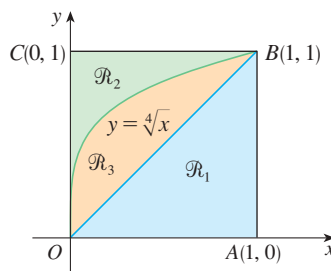
For another method see Exercise 64. ■

## 5.2 EXERCISES

**1–18** Find the volume of the solid obtained by rotating the region bounded by the given curves about the specified line. Sketch the region, the solid, and a typical disk or washer.

1.  $y = x + 1$ ,  $y = 0$ ,  $x = 0$ ,  $x = 2$ ; about the  $x$ -axis
2.  $y = 1/x$ ,  $y = 0$ ,  $x = 1$ ,  $x = 4$ ; about the  $x$ -axis
3.  $y = \sqrt{x - 1}$ ,  $y = 0$ ,  $x = 5$ ; about the  $x$ -axis
4.  $y = \sqrt{25 - x^2}$ ,  $y = 0$ ,  $x = 2$ ,  $x = 4$ ; about the  $x$ -axis
5.  $x = 2\sqrt{y}$ ,  $x = 0$ ,  $y = 9$ ; about the  $y$ -axis
6.  $2x = y^2$ ,  $x = 0$ ,  $y = 4$ ; about the  $y$ -axis
7.  $y = x^3$ ,  $y = x$ ,  $x \geq 0$ ; about the  $x$ -axis
8.  $y = 6 - x^2$ ,  $y = 2$ ; about the  $x$ -axis
9.  $y^2 = x$ ,  $x = 2y$ ; about the  $y$ -axis
10.  $x = 2 - y^2$ ,  $x = y^4$ ; about the  $y$ -axis
11.  $y = x^2$ ,  $x = y^2$ ; about  $y = 1$
12.  $y = x^3$ ,  $y = 1$ ,  $x = 2$ ; about  $y = -3$
13.  $y = 1 + \sec x$ ,  $y = 3$ ; about  $y = 1$
14.  $y = \sin x$ ,  $y = \cos x$ ,  $0 \leq x \leq \pi/4$ ; about  $y = -1$
15.  $y = x^3$ ,  $y = 0$ ,  $x = 1$ ; about  $x = 2$
16.  $y = x^2$ ,  $x = y^2$ ; about  $x = -1$
17.  $x = y^2$ ,  $x = 1 - y^2$ ; about  $x = 3$
18.  $y = x$ ,  $y = 0$ ,  $x = 2$ ,  $x = 4$ ; about  $x = 1$

**19–30** Refer to the figure and find the volume generated by rotating the given region about the specified line.



19.  $\mathcal{R}_1$  about  $OA$
20.  $\mathcal{R}_1$  about  $OC$
21.  $\mathcal{R}_1$  about  $AB$
22.  $\mathcal{R}_1$  about  $BC$

23.  $\mathcal{R}_2$  about  $OA$                       24.  $\mathcal{R}_2$  about  $OC$   
 25.  $\mathcal{R}_2$  about  $AB$                       26.  $\mathcal{R}_2$  about  $BC$   
 27.  $\mathcal{R}_3$  about  $OA$                       28.  $\mathcal{R}_3$  about  $OC$   
 29.  $\mathcal{R}_3$  about  $AB$                       30.  $\mathcal{R}_3$  about  $BC$

**31–34** Set up an integral for the volume of the solid obtained by rotating the region bounded by the given curves about the specified line. Then use your calculator to evaluate the integral correct to five decimal places.

31.  $y = \tan x$ ,  $y = 0$ ,  $x = \pi/4$   
 (a) About the  $x$ -axis                      (b) About  $y = -1$   
 32.  $y = 0$ ,  $y = \cos^2 x$ ,  $-\pi/2 \leq x \leq \pi/2$   
 (a) About the  $x$ -axis                      (b) About  $y = 1$   
 33.  $x^2 + 4y^2 = 4$   
 (a) About  $y = 2$                               (b) About  $x = 2$   
 34.  $y = x^2$ ,  $x^2 + y^2 = 1$ ,  $y \geq 0$   
 (a) About the  $x$ -axis                      (b) About the  $y$ -axis

 **35–36** Use a graph to find approximate  $x$ -coordinates of the points of intersection of the given curves. Then use your calculator to find (approximately) the volume of the solid obtained by rotating about the  $x$ -axis the region bounded by these curves.

35.  $y = 1 + x^4$ ,  $y = \sqrt{3 - x^3}$   
 36.  $y = \sqrt[3]{2x - x^2}$ ,  $y = x^2/(x^2 + 1)$

**CAS 37–38** Use a computer algebra system to find the exact volume of the solid obtained by rotating the region bounded by the given curves about the specified line.

37.  $y = \sin^2 x$ ,  $y = 0$ ,  $0 \leq x \leq \pi$ ; about  $y = -1$   
 38.  $y = x^2 - 2x$ ,  $y = x \cos(\pi x/4)$ ; about  $y = 2$

**39–42** Each integral represents the volume of a solid. Describe the solid.

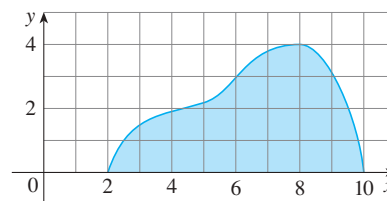
39.  $\pi \int_0^{\pi} \sin x \, dx$                       40.  $\pi \int_{-1}^1 (1 - y^2)^2 \, dy$   
 41.  $\pi \int_0^1 (y^4 - y^8) \, dy$                       42.  $\pi \int_1^4 [3^2 - (3 - \sqrt{x})^2] \, dx$

43. A CAT scan produces equally spaced cross-sectional views of a human organ that provide information about the organ otherwise obtained only by surgery. Suppose that a CAT scan of a human liver shows cross-sections spaced 1.5 cm apart. The liver is 15 cm long and the cross-sectional areas, in square centimeters, are 0, 18, 58, 79, 94, 106, 117, 128, 63, 39, and 0. Use the Midpoint Rule to estimate the volume of the liver.

44. A log 10 m long is cut at 1-meter intervals and its cross-sectional areas  $A$  (at a distance  $x$  from the end of the log) are listed in the table. Use the Midpoint Rule with  $n = 5$  to estimate the volume of the log.

| $x$ (m) | $A$ (m <sup>2</sup> ) | $x$ (m) | $A$ (m <sup>2</sup> ) |
|---------|-----------------------|---------|-----------------------|
| 0       | 0.68                  | 6       | 0.53                  |
| 1       | 0.65                  | 7       | 0.55                  |
| 2       | 0.64                  | 8       | 0.52                  |
| 3       | 0.61                  | 9       | 0.50                  |
| 4       | 0.58                  | 10      | 0.48                  |
| 5       | 0.59                  |         |                       |

45. (a) If the region shown in the figure is rotated about the  $x$ -axis to form a solid, use the Midpoint Rule with  $n = 4$  to estimate the volume of the solid.



- (b) Estimate the volume if the region is rotated about the  $y$ -axis. Again use the Midpoint Rule with  $n = 4$ .

- CAS 46.** (a) A model for the shape of a bird's egg is obtained by rotating about the  $x$ -axis the region under the graph of

$$f(x) = (ax^3 + bx^2 + cx + d)\sqrt{1 - x^2}$$

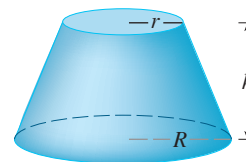
Use a CAS to find the volume of such an egg.

- (b) For a red-throated loon,  $a = -0.06$ ,  $b = 0.04$ ,  $c = 0.1$ , and  $d = 0.54$ . Graph  $f$  and find the volume of an egg of this species.

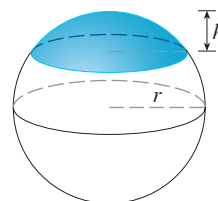
**47–61** Find the volume of the described solid  $S$ .

47. A right circular cone with height  $h$  and base radius  $r$

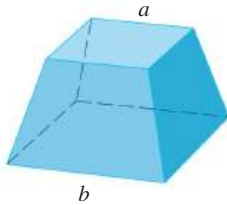
48. A frustum of a right circular cone with height  $h$ , lower base radius  $R$ , and top radius  $r$



49. A cap of a sphere with radius  $r$  and height  $h$

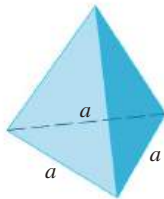


50. A frustum of a pyramid with square base of side  $b$ , square top of side  $a$ , and height  $h$



What happens if  $a = b$ ? What happens if  $a = 0$ ?

51. A pyramid with height  $h$  and rectangular base with dimensions  $b$  and  $2b$
52. A pyramid with height  $h$  and base an equilateral triangle with side  $a$  (a tetrahedron)

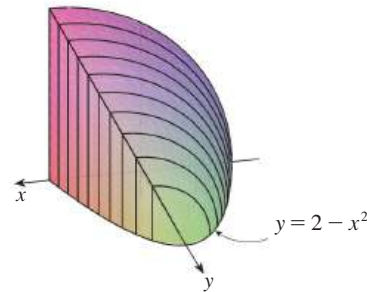


53. A tetrahedron with three mutually perpendicular faces and three mutually perpendicular edges with lengths 3 cm, 4 cm, and 5 cm
54. The base of  $S$  is a circular disk with radius  $r$ . Parallel cross-sections perpendicular to the base are squares.

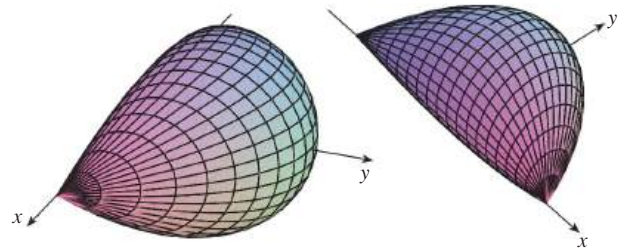


55. The base of  $S$  is an elliptical region with boundary curve  $9x^2 + 4y^2 = 36$ . Cross-sections perpendicular to the  $x$ -axis are isosceles right triangles with hypotenuse in the base.
56. The base of  $S$  is the triangular region with vertices  $(0, 0)$ ,  $(1, 0)$ , and  $(0, 1)$ . Cross-sections perpendicular to the  $y$ -axis are equilateral triangles.
57. The base of  $S$  is the same base as in Exercise 56, but cross-sections perpendicular to the  $x$ -axis are squares.
58. The base of  $S$  is the region enclosed by the parabola  $y = 1 - x^2$  and the  $x$ -axis. Cross-sections perpendicular to the  $y$ -axis are squares.
59. The base of  $S$  is the same base as in Exercise 58, but cross-sections perpendicular to the  $x$ -axis are isosceles triangles with height equal to the base.

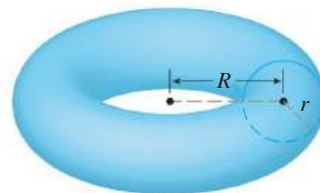
60. The base of  $S$  is the region enclosed by  $y = 2 - x^2$  and the  $x$ -axis. Cross-sections perpendicular to the  $y$ -axis are quarter-circles.



61. The solid  $S$  is bounded by circles that are perpendicular to the  $x$ -axis, intersect the  $x$ -axis, and have centers on the parabola  $y = \frac{1}{2}(1 - x^2)$ ,  $-1 \leq x \leq 1$ .



62. The base of  $S$  is a circular disk with radius  $r$ . Parallel cross-sections perpendicular to the base are isosceles triangles with height  $h$  and unequal side in the base.
- (a) Set up an integral for the volume of  $S$ .
- (b) By interpreting the integral as an area, find the volume of  $S$ .
63. (a) Set up an integral for the volume of a solid *torus* (the donut-shaped solid shown in the figure) with radii  $r$  and  $R$ .
- (b) By interpreting the integral as an area, find the volume of the torus.

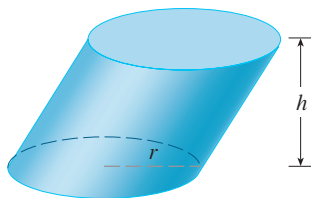


64. Solve Example 9 taking cross-sections to be parallel to the line of intersection of the two planes.
65. (a) Cavalieri's Principle states that if a family of parallel planes gives equal cross-sectional areas for two solids

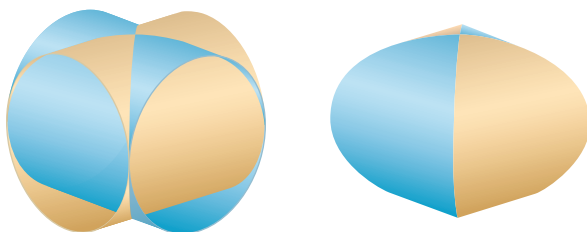


$S_1$  and  $S_2$ , then the volumes of  $S_1$  and  $S_2$  are equal. Prove this principle.

- (b) Use Cavalieri's Principle to find the volume of the oblique cylinder shown in the figure.



66. Find the volume common to two circular cylinders, each with radius  $r$ , if the axes of the cylinders intersect at right angles.



67. Find the volume common to two spheres, each with radius  $r$ , if the center of each sphere lies on the surface of the other sphere.
68. A bowl is shaped like a hemisphere with diameter 30 cm. A heavy ball with diameter 10 cm is placed in the bowl and water

is poured into the bowl to a depth of  $h$  centimeters. Find the volume of water in the bowl.

69. A hole of radius  $r$  is bored through the middle of a cylinder of radius  $R > r$  at right angles to the axis of the cylinder. Set up, but do not evaluate, an integral for the volume cut out.
70. A hole of radius  $r$  is bored through the center of a sphere of radius  $R > r$ . Find the volume of the remaining portion of the sphere.
71. Some of the pioneers of calculus, such as Kepler and Newton, were inspired by the problem of finding the volumes of wine barrels. (In fact Kepler published a book *Stereometria doliorum* in 1615 devoted to methods for finding the volumes of barrels.) They often approximated the shape of the sides by parabolas.
- (a) A barrel with height  $h$  and maximum radius  $R$  is constructed by rotating about the  $x$ -axis the parabola  $y = R - cx^2$ ,  $-h/2 \leq x \leq h/2$ , where  $c$  is a positive constant. Show that the radius of each end of the barrel is  $r = R - d$ , where  $d = ch^2/4$ .
- (b) Show that the volume enclosed by the barrel is

$$V = \frac{1}{3}\pi h(2R^2 + r^2 - \frac{2}{5}d^2)$$

72. Suppose that a region  $\mathcal{R}$  has area  $A$  and lies above the  $x$ -axis. When  $\mathcal{R}$  is rotated about the  $x$ -axis, it sweeps out a solid with volume  $V_1$ . When  $\mathcal{R}$  is rotated about the line  $y = -k$  (where  $k$  is a positive number), it sweeps out a solid with volume  $V_2$ . Express  $V_2$  in terms of  $V_1$ ,  $k$ , and  $A$ .

## 5.3 Volumes by Cylindrical Shells

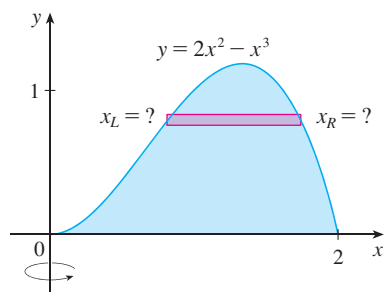


FIGURE 1

Some volume problems are very difficult to handle by the methods of the preceding section. For instance, let's consider the problem of finding the volume of the solid obtained by rotating about the  $y$ -axis the region bounded by  $y = 2x^2 - x^3$  and  $y = 0$ . (See Figure 1.) If we slice perpendicular to the  $y$ -axis, we get a washer. But to compute the inner radius and the outer radius of the washer, we'd have to solve the cubic equation  $y = 2x^2 - x^3$  for  $x$  in terms of  $y$ ; that's not easy.

Fortunately, there is a method, called the **method of cylindrical shells**, that is easier to use in such a case. Figure 2 shows a cylindrical shell with inner radius  $r_1$ , outer radius

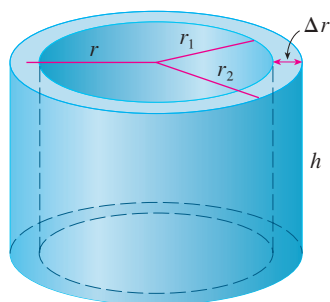


FIGURE 2

$r_2$ , and height  $h$ . Its volume  $V$  is calculated by subtracting the volume  $V_1$  of the inner cylinder from the volume  $V_2$  of the outer cylinder:

$$\begin{aligned} V &= V_2 - V_1 \\ &= \pi r_2^2 h - \pi r_1^2 h = \pi(r_2^2 - r_1^2)h \\ &= \pi(r_2 + r_1)(r_2 - r_1)h \\ &= 2\pi \frac{r_2 + r_1}{2} h(r_2 - r_1) \end{aligned}$$

If we let  $\Delta r = r_2 - r_1$  (the thickness of the shell) and  $r = \frac{1}{2}(r_2 + r_1)$  (the average radius of the shell), then this formula for the volume of a cylindrical shell becomes

1

$$V = 2\pi r h \Delta r$$

and it can be remembered as

$$V = [\text{circumference}][\text{height}][\text{thickness}]$$

Now let  $S$  be the solid obtained by rotating about the  $y$ -axis the region bounded by  $y = f(x)$  [where  $f(x) \geq 0$ ],  $y = 0$ ,  $x = a$ , and  $x = b$ , where  $b > a \geq 0$ . (See Figure 3.)

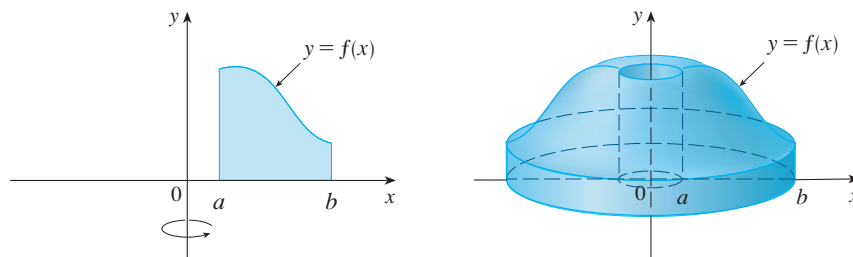


FIGURE 3

We divide the interval  $[a, b]$  into  $n$  subintervals  $[x_{i-1}, x_i]$  of equal width  $\Delta x$  and let  $\bar{x}_i$  be the midpoint of the  $i$ th subinterval. If the rectangle with base  $[x_{i-1}, x_i]$  and height  $f(\bar{x}_i)$  is rotated about the  $y$ -axis, then the result is a cylindrical shell with average radius  $\bar{x}_i$ , height  $f(\bar{x}_i)$ , and thickness  $\Delta x$ . (See Figure 4.) So by Formula 1 its volume is

$$V_i = (2\pi \bar{x}_i)[f(\bar{x}_i)] \Delta x$$

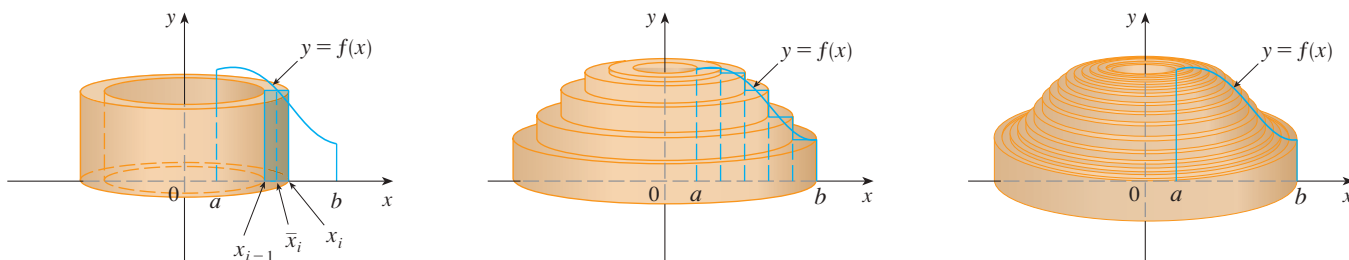


FIGURE 4

Therefore an approximation to the volume  $V$  of  $S$  is given by the sum of the volumes of

these shells:

$$V \approx \sum_{i=1}^n V_i = \sum_{i=1}^n 2\pi \bar{x}_i f(\bar{x}_i) \Delta x$$

This approximation appears to become better as  $n \rightarrow \infty$ . But, from the definition of an integral, we know that

$$\lim_{n \rightarrow \infty} \sum_{i=1}^n 2\pi \bar{x}_i f(\bar{x}_i) \Delta x = \int_a^b 2\pi x f(x) dx$$

Thus the following appears plausible:

**2** The volume of the solid in Figure 3, obtained by rotating about the  $y$ -axis the region under the curve  $y = f(x)$  from  $a$  to  $b$ , is

$$V = \int_a^b 2\pi x f(x) dx \quad \text{where } 0 \leq a < b$$

The argument using cylindrical shells makes Formula 2 seem reasonable, but later we will be able to prove it (see Exercise 7.1.73).

The best way to remember Formula 2 is to think of a typical shell, cut and flattened as in Figure 5, with radius  $x$ , circumference  $2\pi x$ , height  $f(x)$ , and thickness  $\Delta x$  or  $dx$ :

$$\int_a^b \underbrace{(2\pi x)}_{\text{circumference}} \underbrace{[f(x)]}_{\text{height}} \underbrace{dx}_{\text{thickness}}$$

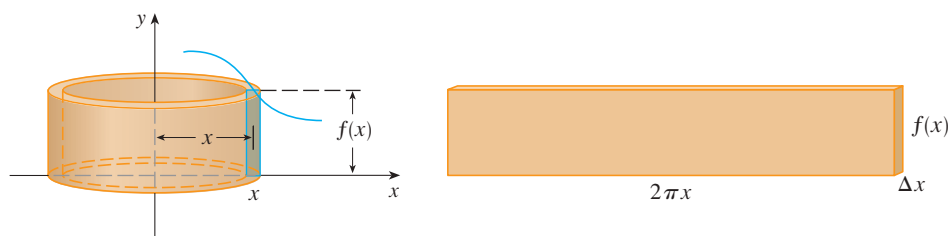


FIGURE 5

This type of reasoning will be helpful in other situations, such as when we rotate about lines other than the  $y$ -axis.

**EXAMPLE 1** Find the volume of the solid obtained by rotating about the  $y$ -axis the region bounded by  $y = 2x^2 - x^3$  and  $y = 0$ .

**SOLUTION** From the sketch in Figure 6 we see that a typical shell has radius  $x$ , circumference  $2\pi x$ , and height  $f(x) = 2x^2 - x^3$ . So, by the shell method, the volume is

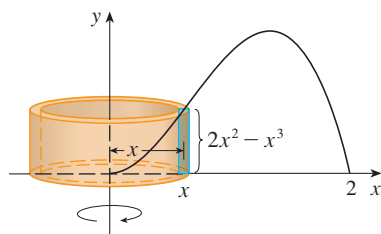


FIGURE 6

$$\begin{aligned} V &= \int_0^2 \underbrace{(2\pi x)}_{\text{circumference}} \underbrace{(2x^2 - x^3)}_{\text{height}} \underbrace{dx}_{\text{thickness}} \\ &= 2\pi \int_0^2 (2x^3 - x^4) dx = 2\pi \left[ \frac{1}{2}x^4 - \frac{1}{5}x^5 \right]_0^2 \\ &= 2\pi \left( 8 - \frac{32}{5} \right) = \frac{16}{5}\pi \end{aligned}$$

It can be verified that the shell method gives the same answer as slicing. ■

**TEC** Visual 5.3 shows how the solid and shells in Example 1 are formed.

Figure 7 shows a computer-generated picture of the solid whose volume we computed in Example 1.

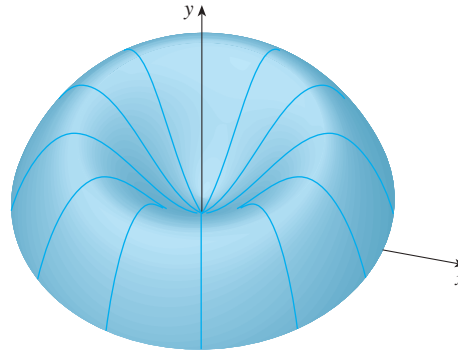


FIGURE 7

**NOTE** Comparing the solution of Example 1 with the remarks at the beginning of this section, we see that the method of cylindrical shells is much easier than the washer method for this problem. We did not have to find the coordinates of the local maximum and we did not have to solve the equation of the curve for  $x$  in terms of  $y$ . However, in other examples the methods of the preceding section may be easier.

**EXAMPLE 2** Find the volume of the solid obtained by rotating about the  $y$ -axis the region between  $y = x$  and  $y = x^2$ .

**SOLUTION** The region and a typical shell are shown in Figure 8. We see that the shell has radius  $x$ , circumference  $2\pi x$ , and height  $x - x^2$ . So the volume is

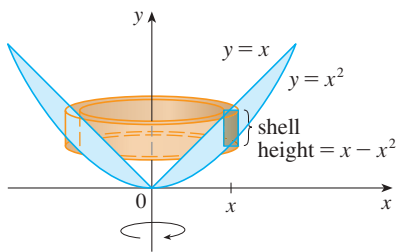


FIGURE 8

$$\begin{aligned} V &= \int_0^1 (2\pi x)(x - x^2) dx = 2\pi \int_0^1 (x^2 - x^3) dx \\ &= 2\pi \left[ \frac{x^3}{3} - \frac{x^4}{4} \right]_0^1 = \frac{\pi}{6} \end{aligned}$$

As the following example shows, the shell method works just as well if we rotate about the  $x$ -axis. We simply have to draw a diagram to identify the radius and height of a shell.

**EXAMPLE 3** Use cylindrical shells to find the volume of the solid obtained by rotating about the  $x$ -axis the region under the curve  $y = \sqrt{x}$  from 0 to 1.

**SOLUTION** This problem was solved using disks in Example 5.2.2. To use shells we relabel the curve  $y = \sqrt{x}$  (in the figure in that example) as  $x = y^2$  in Figure 9. For rotation about the  $x$ -axis we see that a typical shell has radius  $y$ , circumference  $2\pi y$ , and height  $1 - y^2$ . So the volume is

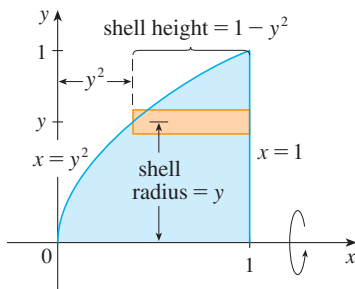


FIGURE 9

$$\begin{aligned} V &= \int_0^1 (2\pi y)(1 - y^2) dy = 2\pi \int_0^1 (y - y^3) dy \\ &= 2\pi \left[ \frac{y^2}{2} - \frac{y^4}{4} \right]_0^1 = \frac{\pi}{2} \end{aligned}$$

In this problem the disk method was simpler.

**EXAMPLE 4** Find the volume of the solid obtained by rotating the region bounded by  $y = x - x^2$  and  $y = 0$  about the line  $x = 2$ .

**SOLUTION** Figure 10 shows the region and a cylindrical shell formed by rotation about the line  $x = 2$ . It has radius  $2 - x$ , circumference  $2\pi(2 - x)$ , and height  $x - x^2$ .

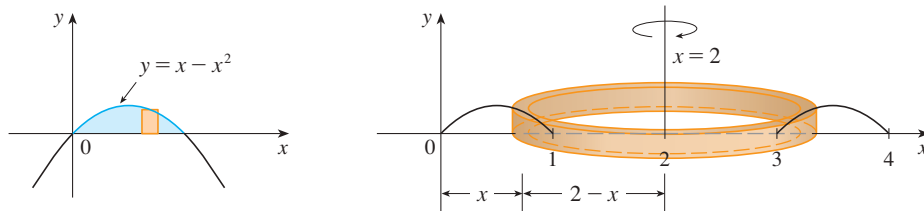


FIGURE 10

The volume of the given solid is

$$\begin{aligned} V &= \int_0^1 2\pi(2 - x)(x - x^2) dx \\ &= 2\pi \int_0^1 (x^3 - 3x^2 + 2x) dx \\ &= 2\pi \left[ \frac{x^4}{4} - x^3 + x^2 \right]_0^1 = \frac{\pi}{2} \end{aligned}$$

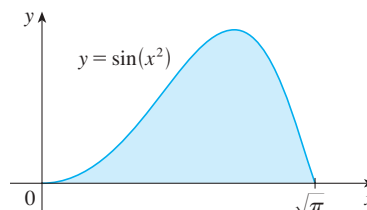
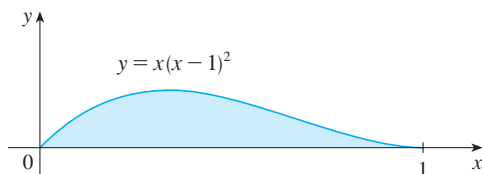
### Disks and Washers versus Cylindrical Shells

When computing the volume of a solid of revolution, how do we know whether to use disks (or washers) or cylindrical shells? There are several considerations to take into account: Is the region more easily described by top and bottom boundary curves of the form  $y = f(x)$ , or by left and right boundaries  $x = g(y)$ ? Which choice is easier to work with? Are the limits of integration easier to find for one variable versus the other? Does the region require two separate integrals when using  $x$  as the variable but only one integral in  $y$ ? Are we able to evaluate the integral we set up with our choice of variable?

If we decide that one variable is easier to work with than the other, then this dictates which method to use. Draw a sample rectangle in the region, corresponding to a cross-section of the solid. The thickness of the rectangle, either  $\Delta x$  or  $\Delta y$ , corresponds to the integration variable. If you imagine the rectangle revolving, it becomes either a disk (washer) or a shell.

## 5.3 EXERCISES

- Let  $S$  be the solid obtained by rotating the region shown in the figure about the  $y$ -axis. Explain why it is awkward to use slicing to find the volume  $V$  of  $S$ . Sketch a typical approximating shell. What are its circumference and height? Use shells to find  $V$ .
- Let  $S$  be the solid obtained by rotating the region shown in the figure about the  $y$ -axis. Sketch a typical cylindrical shell and find its circumference and height. Use shells to find the volume of  $S$ . Do you think this method is preferable to slicing? Explain.



**3–7** Use the method of cylindrical shells to find the volume generated by rotating the region bounded by the given curves about the  $y$ -axis.

3.  $y = \sqrt[3]{x}$ ,  $y = 0$ ,  $x = 1$

4.  $y = x^3$ ,  $y = 0$ ,  $x = 1$ ,  $x = 2$

5.  $y = x^2$ ,  $0 \leq x \leq 2$ ,  $y = 4$ ,  $x = 0$

6.  $y = 4x - x^2$ ,  $y = x$

7.  $y = x^2$ ,  $y = 6x - 2x^2$

8. Let  $V$  be the volume of the solid obtained by rotating about the  $y$ -axis the region bounded by  $y = \sqrt{x}$  and  $y = x^2$ . Find  $V$  both by slicing and by cylindrical shells. In both cases draw a diagram to explain your method.

**9–14** Use the method of cylindrical shells to find the volume of the solid obtained by rotating the region bounded by the given curves about the  $x$ -axis.

9.  $xy = 1$ ,  $x = 0$ ,  $y = 1$ ,  $y = 3$

10.  $y = \sqrt{x}$ ,  $x = 0$ ,  $y = 2$

11.  $y = x^{3/2}$ ,  $y = 8$ ,  $x = 0$

12.  $x = -3y^2 + 12y - 9$ ,  $x = 0$

13.  $x = 1 + (y - 2)^2$ ,  $x = 2$

14.  $x + y = 4$ ,  $x = y^2 - 4y + 4$

**15–20** Use the method of cylindrical shells to find the volume generated by rotating the region bounded by the given curves about the specified axis.

15.  $y = x^3$ ,  $y = 8$ ,  $x = 0$ ; about  $x = 3$

16.  $y = 4 - 2x$ ,  $y = 0$ ,  $x = 0$ ; about  $x = -1$

17.  $y = 4x - x^2$ ,  $y = 3$ ; about  $x = 1$

18.  $y = \sqrt{x}$ ,  $x = 2y$ ; about  $x = 5$

19.  $x = 2y^2$ ,  $y \geq 0$ ,  $x = 2$ ; about  $y = 2$

20.  $x = 2y^2$ ,  $x = y^2 + 1$ ; about  $y = -2$

## 21–26

- (a) Set up an integral for the volume of the solid obtained by rotating the region bounded by the given curve about the specified axis.  
 (b) Use your calculator to evaluate the integral correct to five decimal places.

21.  $y = \sin x$ ,  $y = 0$ ,  $x = 2\pi$ ,  $x = 3\pi$ ; about the  $y$ -axis

22.  $y = \tan x$ ,  $y = 0$ ,  $x = \pi/4$ ; about  $x = \pi/2$

23.  $y = \cos^4 x$ ,  $y = -\cos^4 x$ ,  $-\pi/2 \leq x \leq \pi/2$ ; about  $x = \pi$

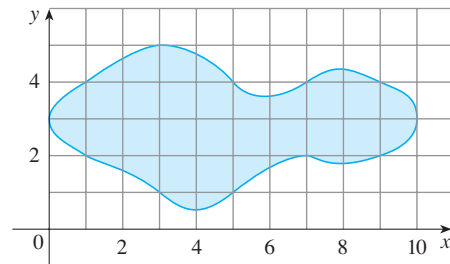
24.  $y = x$ ,  $y = 2x/(1 + x^3)$ ; about  $x = -1$

25.  $x = \sqrt{\sin y}$ ,  $0 \leq y \leq \pi$ ,  $x = 0$ ; about  $y = 4$

26.  $x^2 - y^2 = 7$ ,  $x = 4$ ; about  $y = 5$

27. Use the Midpoint Rule with  $n = 5$  to estimate the volume obtained by rotating about the  $y$ -axis the region under the curve  $y = \sqrt{1 + x^3}$ ,  $0 \leq x \leq 1$ .

28. If the region shown in the figure is rotated about the  $y$ -axis to form a solid, use the Midpoint Rule with  $n = 5$  to estimate the volume of the solid.



**29–32** Each integral represents the volume of a solid. Describe the solid.

29.  $\int_0^3 2\pi x^5 dx$

30.  $\int_1^5 2\pi y \sqrt{y-1} dy$

31.  $2\pi \int_1^4 \frac{y+2}{y^2} dy$

32.  $\int_0^{\pi/2} 2\pi(x+1)(2x - \sin x) dx$

 **33–34** Use a graph to estimate the  $x$ -coordinates of the points of intersection of the given curves. Then use this information and your calculator to estimate the volume of the solid obtained by rotating about the  $y$ -axis the region enclosed by these curves.

33.  $y = x^2 - 2x$ ,  $y = \frac{x}{x^2 + 1}$

34.  $y = 3 \sin x$ ,  $y = x^2 - 4x + 5$

 **35–36** Use a computer algebra system to find the exact volume of the solid obtained by rotating the region bounded by the given curves about the specified line.

35.  $y = \sin^2 x$ ,  $y = \sin^4 x$ ,  $0 \leq x \leq \pi$ ; about  $x = \pi/2$

36.  $y = x^3 \sin x$ ,  $y = 0$ ,  $0 \leq x \leq \pi$ ; about  $x = -1$

**37–43** The region bounded by the given curves is rotated about the specified axis. Find the volume of the resulting solid by any method.

**37.**  $y = -x^2 + 6x - 8$ ,  $y = 0$ ; about the  $y$ -axis

**38.**  $y = -x^2 + 6x - 8$ ,  $y = 0$ ; about the  $x$ -axis

**39.**  $y^2 - x^2 = 1$ ,  $y = 2$ ; about the  $x$ -axis

**40.**  $y^2 - x^2 = 1$ ,  $y = 2$ ; about the  $y$ -axis

**41.**  $x^2 + (y - 1)^2 = 1$ ; about the  $y$ -axis

**42.**  $x = (y - 3)^2$ ,  $x = 4$ ; about  $y = 1$

**43.**  $x = (y - 1)^2$ ,  $x - y = 1$ ; about  $x = -1$

**44.** Let  $T$  be the triangular region with vertices  $(0, 0)$ ,  $(1, 0)$ , and  $(1, 2)$ , and let  $V$  be the volume of the solid generated when  $T$  is rotated about the line  $x = a$ , where  $a > 1$ . Express  $a$  in terms of  $V$ .

**45–47** Use cylindrical shells to find the volume of the solid.

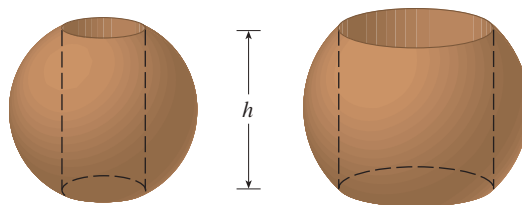
**45.** A sphere of radius  $r$

**46.** The solid torus of Exercise 5.2.63

**47.** A right circular cone with height  $h$  and base radius  $r$

**48.** Suppose you make napkin rings by drilling holes with different diameters through two wooden balls (which also have different diameters). You discover that both napkin rings have the same height  $h$ , as shown in the figure.

- Guess which ring has more wood in it.
- Check your guess: use cylindrical shells to compute the volume of a napkin ring created by drilling a hole with radius  $r$  through the center of a sphere of radius  $R$  and express the answer in terms of  $h$ .



## 5.4 Work

The term *work* is used in everyday language to mean the total amount of effort required to perform a task. In physics it has a technical meaning that depends on the idea of a *force*. Intuitively, you can think of a force as describing a push or pull on an object—for example, a horizontal push of a book across a table or the downward pull of the earth's gravity on a ball. In general, if an object moves along a straight line with position function  $s(t)$ , then the **force**  $F$  on the object (in the same direction) is given by Newton's Second Law of Motion as the product of its mass  $m$  and its acceleration  $a$ :

**1**

$$F = ma = m \frac{d^2s}{dt^2}$$

In the SI metric system, the mass is measured in kilograms (kg), the displacement in meters (m), the time in seconds (s), and the force in newtons ( $\text{N} = \text{kg} \cdot \text{m}/\text{s}^2$ ). Thus a force of 1 N acting on a mass of 1 kg produces an acceleration of  $1 \text{ m}/\text{s}^2$ . In the US Customary system the fundamental unit is chosen to be the unit of force, which is the pound.

In the case of constant acceleration, the force  $F$  is also constant and the work done is defined to be the product of the force  $F$  and the distance  $d$  that the object moves:

**2**

$$W = Fd \quad \text{work} = \text{force} \times \text{distance}$$

If  $F$  is measured in newtons and  $d$  in meters, then the unit for  $W$  is a newton-meter, which is called a joule (J). If  $F$  is measured in pounds and  $d$  in feet, then the unit for  $W$  is a foot-pound (ft-lb), which is about 1.36 J.



**EXAMPLE 1**

- (a) How much work is done in lifting a 1.2-kg book off the floor to put it on a desk that is 0.7 m high? Use the fact that the acceleration due to gravity is  $g = 9.8 \text{ m/s}^2$ .  
 (b) How much work is done in lifting a 20-lb weight 6 ft off the ground?

**SOLUTION**

(a) The force exerted is equal and opposite to that exerted by gravity, so Equation 1 gives

$$F = mg = (1.2)(9.8) = 11.76 \text{ N}$$

and then Equation 2 gives the work done as

$$W = Fd = (11.76 \text{ N})(0.7 \text{ m}) \approx 8.2 \text{ J}$$

(b) Here the force is given as  $F = 20 \text{ lb}$ , so the work done is

$$W = Fd = (20 \text{ lb})(6 \text{ ft}) = 120 \text{ ft}\cdot\text{lb}$$

Notice that in part (b), unlike part (a), we did not have to multiply by  $g$  because we were given the *weight* (which is a force) and not the mass of the object. ■

Equation 2 defines work as long as the force is constant, but what happens if the force is variable? Let's suppose that the object moves along the  $x$ -axis in the positive direction, from  $x = a$  to  $x = b$ , and at each point  $x$  between  $a$  and  $b$  a force  $f(x)$  acts on the object, where  $f$  is a continuous function. We divide the interval  $[a, b]$  into  $n$  subintervals with endpoints  $x_0, x_1, \dots, x_n$  and equal width  $\Delta x$ . We choose a sample point  $x_i^*$  in the  $i$ th subinterval  $[x_{i-1}, x_i]$ . Then the force at that point is  $f(x_i^*)$ . If  $n$  is large, then  $\Delta x$  is small, and since  $f$  is continuous, the values of  $f$  don't change very much over the interval  $[x_{i-1}, x_i]$ . In other words,  $f$  is almost constant on the interval and so the work  $W_i$  that is done in moving the particle from  $x_{i-1}$  to  $x_i$  is approximately given by Equation 2:

$$W_i \approx f(x_i^*) \Delta x$$

Thus we can approximate the total work by

**3**

$$W \approx \sum_{i=1}^n f(x_i^*) \Delta x$$

It seems that this approximation becomes better as we make  $n$  larger. Therefore we define the **work done in moving the object from  $a$  to  $b$**  as the limit of this quantity as  $n \rightarrow \infty$ . Since the right side of (3) is a Riemann sum, we recognize its limit as being a definite integral and so

**4**

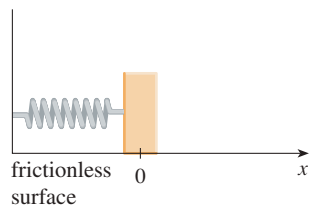
$$W = \lim_{n \rightarrow \infty} \sum_{i=1}^n f(x_i^*) \Delta x = \int_a^b f(x) dx$$

**EXAMPLE 2** When a particle is located a distance  $x$  feet from the origin, a force of  $x^2 + 2x$  pounds acts on it. How much work is done in moving it from  $x = 1$  to  $x = 3$ ?

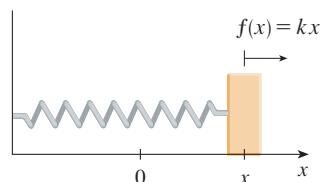
**SOLUTION**

$$W = \int_1^3 (x^2 + 2x) dx = \left[ \frac{x^3}{3} + x^2 \right]_1^3 = \frac{50}{3}$$

The work done is  $16\frac{2}{3}$  ft·lb. ■



(a) Natural position of spring



(b) Stretched position of spring

**FIGURE 1**  
Hooke's Law

In the next example we use a law from physics. **Hooke's Law** states that the force required to maintain a spring stretched  $x$  units beyond its natural length is proportional to  $x$ :

$$f(x) = kx$$

where  $k$  is a positive constant called the **spring constant** (see Figure 1). Hooke's Law holds provided that  $x$  is not too large.

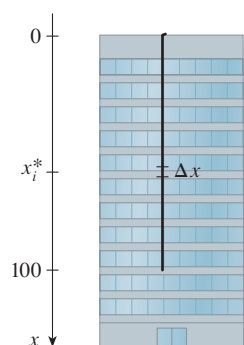
**EXAMPLE 3** A force of 40 N is required to hold a spring that has been stretched from its natural length of 10 cm to a length of 15 cm. How much work is done in stretching the spring from 15 cm to 18 cm?

**SOLUTION** According to Hooke's Law, the force required to hold the spring stretched  $x$  meters beyond its natural length is  $f(x) = kx$ . When the spring is stretched from 10 cm to 15 cm, the amount stretched is 5 cm = 0.05 m. This means that  $f(0.05) = 40$ , so

$$0.05k = 40 \quad k = \frac{40}{0.05} = 800$$

Thus  $f(x) = 800x$  and the work done in stretching the spring from 15 cm to 18 cm is

$$\begin{aligned} W &= \int_{0.05}^{0.08} 800x \, dx = 800 \left[ \frac{x^2}{2} \right]_{0.05}^{0.08} \\ &= 400[(0.08)^2 - (0.05)^2] = 1.56 \text{ J} \end{aligned}$$

**FIGURE 2**

**EXAMPLE 4** A 200-lb cable is 100 ft long and hangs vertically from the top of a tall building. How much work is required to lift the cable to the top of the building?

**SOLUTION** Here we don't have a formula for the force function, but we can use an argument similar to the one that led to Definition 4.

Let's place the origin at the top of the building and the  $x$ -axis pointing downward as in Figure 2. We divide the cable into small parts with length  $\Delta x$ . If  $x_i^*$  is a point in the  $i$ th such interval, then all points in the interval are lifted by approximately the same amount, namely,  $x_i^*$ . The cable weighs 2 pounds per foot, so the weight of the  $i$ th part is  $(2 \text{ lb/ft})(\Delta x \text{ ft}) = 2\Delta x \text{ lb}$ . Thus the work done on the  $i$ th part, in foot-pounds, is

$$\underbrace{(2\Delta x)}_{\text{force}} \cdot \underbrace{x_i^*}_{\text{distance}} = 2x_i^* \Delta x$$

We get the total work done by adding all these approximations and letting the number of parts become large (so  $\Delta x \rightarrow 0$ ):

$$\begin{aligned} W &= \lim_{n \rightarrow \infty} \sum_{i=1}^n 2x_i^* \Delta x = \int_0^{100} 2x \, dx \\ &= x^2 \Big|_0^{100} = 10,000 \text{ ft-lb} \end{aligned}$$

If we had placed the origin at the bottom of the cable and the  $x$ -axis upward, we would have gotten

$$W = \int_0^{100} 2(100 - x) \, dx$$

which gives the same answer.

**EXAMPLE 5** A tank has the shape of an inverted circular cone with height 10 m and base radius 4 m. It is filled with water to a height of 8 m. Find the work required to empty the tank by pumping all of the water to the top of the tank. (The density of water is  $1000 \text{ kg/m}^3$ .)

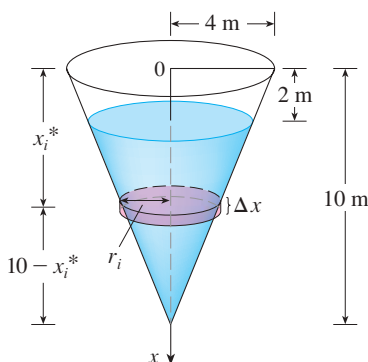


FIGURE 3

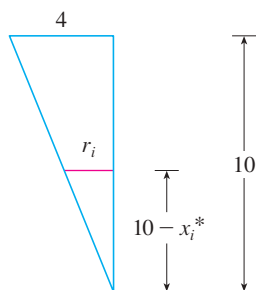


FIGURE 4

**SOLUTION** Let's measure depths from the top of the tank by introducing a vertical coordinate line as in Figure 3. The water extends from a depth of 2 m to a depth of 10 m and so we divide the interval  $[2, 10]$  into  $n$  subintervals with endpoints  $x_0, x_1, \dots, x_n$  and choose  $x_i^*$  in the  $i$ th subinterval. This divides the water into  $n$  layers. The  $i$ th layer is approximated by a circular cylinder with radius  $r_i$  and height  $\Delta x$ . We can compute  $r_i$  from similar triangles, using Figure 4, as follows:

$$\frac{r_i}{10 - x_i^*} = \frac{4}{10} \quad r_i = \frac{2}{5}(10 - x_i^*)$$

Thus an approximation to the volume of the  $i$ th layer of water is

$$V_i \approx \pi r_i^2 \Delta x = \frac{4\pi}{25} (10 - x_i^*)^2 \Delta x$$

and so its mass is

$$\begin{aligned} m_i &= \text{density} \times \text{volume} \\ &\approx 1000 \cdot \frac{4\pi}{25} (10 - x_i^*)^2 \Delta x = 160\pi (10 - x_i^*)^2 \Delta x \end{aligned}$$

The force required to raise this layer must overcome the force of gravity and so

$$\begin{aligned} F_i &= m_i g \approx (9.8) 160\pi (10 - x_i^*)^2 \Delta x \\ &= 1568\pi (10 - x_i^*)^2 \Delta x \end{aligned}$$

Each particle in the layer must travel a distance upward of approximately  $x_i^*$ . The work  $W_i$  done to raise this layer to the top is approximately the product of the force  $F_i$  and the distance  $x_i^*$ :

$$W_i \approx F_i x_i^* \approx 1568\pi x_i^* (10 - x_i^*)^2 \Delta x$$

To find the total work done in emptying the entire tank, we add the contributions of each of the  $n$  layers and then take the limit as  $n \rightarrow \infty$ :

$$\begin{aligned} W &= \lim_{n \rightarrow \infty} \sum_{i=1}^n 1568\pi x_i^* (10 - x_i^*)^2 \Delta x = \int_2^{10} 1568\pi x (10 - x)^2 dx \\ &= 1568\pi \int_2^{10} (100x - 20x^2 + x^3) dx = 1568\pi \left[ 50x^2 - \frac{20x^3}{3} + \frac{x^4}{4} \right]_2^{10} \\ &= 1568\pi \left( \frac{2048}{3} \right) \approx 3.4 \times 10^6 \text{ J} \end{aligned}$$

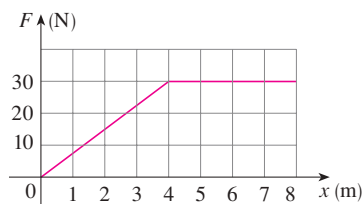
## 5.4 EXERCISES

1. A 360-lb gorilla climbs a tree to a height of 20 ft. Find the work done if the gorilla reaches that height in  
(a) 10 seconds (b) 5 seconds
2. How much work is done when a hoist lifts a 200-kg rock to a height of 3 m?
3. A variable force of  $5x^{-2}$  pounds moves an object along

a straight line when it is  $x$  feet from the origin. Calculate the work done in moving the object from  $x = 1$  ft to  $x = 10$  ft.

4. When a particle is located a distance  $x$  meters from the origin, a force of  $\cos(\pi x/3)$  newtons acts on it. How much work is done in moving the particle from  $x = 1$  to  $x = 2$ ? Interpret your answer by considering the work done from  $x = 1$  to  $x = 1.5$  and from  $x = 1.5$  to  $x = 2$ .

5. Shown is the graph of a force function (in newtons) that increases to its maximum value and then remains constant. How much work is done by the force in moving an object a distance of 8 m?



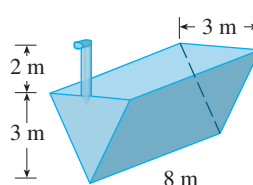
6. The table shows values of a force function  $f(x)$ , where  $x$  is measured in meters and  $f(x)$  in newtons. Use the Midpoint Rule to estimate the work done by the force in moving an object from  $x = 4$  to  $x = 20$ .

|        |   |     |     |     |     |     |     |     |     |
|--------|---|-----|-----|-----|-----|-----|-----|-----|-----|
| $x$    | 4 | 6   | 8   | 10  | 12  | 14  | 16  | 18  | 20  |
| $f(x)$ | 5 | 5.8 | 7.0 | 8.8 | 9.6 | 8.2 | 6.7 | 5.2 | 4.1 |

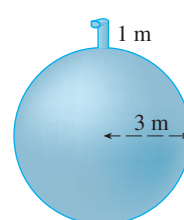
7. A force of 10 lb is required to hold a spring stretched 4 in. beyond its natural length. How much work is done in stretching it from its natural length to 6 in. beyond its natural length?
8. A spring has a natural length of 40 cm. If a 60-N force is required to keep the spring compressed 10 cm, how much work is done during this compression? How much work is required to compress the spring to a length of 25 cm?
9. Suppose that 2 J of work is needed to stretch a spring from its natural length of 30 cm to a length of 42 cm.
- How much work is needed to stretch the spring from 35 cm to 40 cm?
  - How far beyond its natural length will a force of 30 N keep the spring stretched?
10. If the work required to stretch a spring 1 ft beyond its natural length is 12 ft-lb, how much work is needed to stretch it 9 in. beyond its natural length?
11. A spring has natural length 20 cm. Compare the work  $W_1$  done in stretching the spring from 20 cm to 30 cm with the work  $W_2$  done in stretching it from 30 cm to 40 cm. How are  $W_2$  and  $W_1$  related?
12. If 6 J of work is needed to stretch a spring from 10 cm to 12 cm and another 10 J is needed to stretch it from 12 cm to 14 cm, what is the natural length of the spring?
- 13–22** Show how to approximate the required work by a Riemann sum. Then express the work as an integral and evaluate it.
13. A heavy rope, 50 ft long, weighs 0.5 lb/ft and hangs over the edge of a building 120 ft high.
- How much work is done in pulling the rope to the top of the building?
  - How much work is done in pulling half the rope to the top of the building?
14. A thick cable, 60 ft long and weighing 180 lb, hangs from a winch on a crane. Compute in two different ways the work done if the winch winds up 25 ft of the cable.
- Follow the method of Example 4.
  - Write a function for the weight of the remaining cable after  $x$  feet has been wound up by the winch. Estimate the amount of work done when the winch pulls up  $\Delta x$  ft of cable.
15. A cable that weighs 2 lb/ft is used to lift 800 lb of coal up a mine shaft 500 ft deep. Find the work done.
16. A chain lying on the ground is 10 m long and its mass is 80 kg. How much work is required to raise one end of the chain to a height of 6 m?
17. A leaky 10-kg bucket is lifted from the ground to a height of 12 m at a constant speed with a rope that weighs 0.8 kg/m. Initially the bucket contains 36 kg of water, but the water leaks at a constant rate and finishes draining just as the bucket reaches the 12-m level. How much work is done?
18. A bucket that weighs 4 lb and a rope of negligible weight are used to draw water from a well that is 80 ft deep. The bucket is filled with 40 lb of water and is pulled up at a rate of 2 ft/s, but water leaks out of a hole in the bucket at a rate of 0.2 lb/s. Find the work done in pulling the bucket to the top of the well.
19. A 10-ft chain weighs 25 lb and hangs from a ceiling. Find the work done in lifting the lower end of the chain to the ceiling so that it is level with the upper end.
20. A circular swimming pool has a diameter of 24 ft, the sides are 5 ft high, and the depth of the water is 4 ft. How much work is required to pump all of the water out over the side? (Use the fact that water weighs 62.5 lb/ft<sup>3</sup>.)
21. An aquarium 2 m long, 1 m wide, and 1 m deep is full of water. Find the work needed to pump half of the water out of the aquarium. (Use the fact that the density of water is 1000 kg/m<sup>3</sup>.)
22. A spherical water tank, 24 ft in diameter, sits atop a 60 ft tower. The tank is filled by a hose attached to the bottom of the sphere. If a 1.5 horsepower pump is used to deliver water up to the tank, how long will it take to fill the tank? (One horsepower = 550 ft-lb of work per second.)

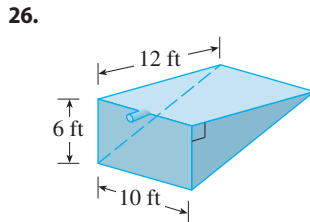
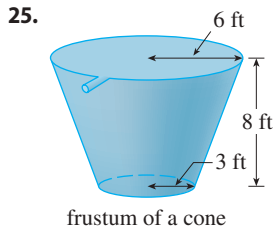
**23–26** A tank is full of water. Find the work required to pump the water out of the spout. In Exercises 25 and 26 use the fact that water weighs 62.5 lb/ft<sup>3</sup>.

23.



24.



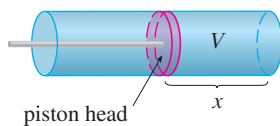


27. Suppose that for the tank in Exercise 23 the pump breaks down after  $4.7 \times 10^5$  J of work has been done. What is the depth of the water remaining in the tank?

28. Solve Exercise 24 if the tank is half full of oil that has a density of  $900 \text{ kg/m}^3$ .

29. When gas expands in a cylinder with radius  $r$ , the pressure at any given time is a function of the volume:  $P = P(V)$ . The force exerted by the gas on the piston (see the figure) is the product of the pressure and the area:  $F = \pi r^2 P$ . Show that the work done by the gas when the volume expands from volume  $V_1$  to volume  $V_2$  is

$$W = \int_{V_1}^{V_2} P \, dV$$



30. In a steam engine the pressure  $P$  and volume  $V$  of steam satisfy the equation  $PV^{1.4} = k$ , where  $k$  is a constant. (This is true for adiabatic expansion, that is, expansion in which there is no heat transfer between the cylinder and its surroundings.) Use Exercise 29 to calculate the work done by the engine during a cycle when the steam starts at a pressure of  $160 \text{ lb/in}^2$  and a volume of  $100 \text{ in}^3$  and expands to a volume of  $800 \text{ in}^3$ .
31. The kinetic energy KE of an object of mass  $m$  moving with velocity  $v$  is defined as  $\text{KE} = \frac{1}{2}mv^2$ . If a force  $f(x)$  acts on the object, moving it along the  $x$ -axis from  $x_1$  to  $x_2$ , the *Work-Energy Theorem* states that the net work done is equal to the change in kinetic energy:  $\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$ , where  $v_1$  is the velocity at  $x_1$  and  $v_2$  is the velocity at  $x_2$ .
- (a) Let  $x = s(t)$  be the position function of the object at time  $t$  and  $v(t)$ ,  $a(t)$  the velocity and acceleration functions. Prove the Work-Energy Theorem by first using the Substitution Rule for Definite Integrals (4.5.5) to show that

$$W = \int_{x_1}^{x_2} f(x) \, dx = \int_{t_1}^{t_2} f(s(t)) \, v(t) \, dt$$

Then use Newton's Second Law of Motion (force = mass  $\times$  acceleration) and the substitution  $u = v(t)$  to evaluate the integral.

- (b) How much work (in ft-lb) is required to hurl a 12-lb bowling ball at  $20 \text{ mi/h}$ ? (Note: Divide the weight in pounds by  $32 \text{ ft/s}^2$ , the acceleration due to gravity, to find the mass, measured in slugs.)

32. Suppose that when launching an 800-kg roller coaster car an electromagnetic propulsion system exerts a force of  $5.7x^2 + 1.5x$  newtons on the car at a distance  $x$  meters along the track. Use Exercise 31(a) to find the speed of the car when it has traveled 60 meters.

33. (a) Newton's Law of Gravitation states that two bodies with masses  $m_1$  and  $m_2$  attract each other with a force

$$F = G \frac{m_1 m_2}{r^2}$$

where  $r$  is the distance between the bodies and  $G$  is the gravitational constant. If one of the bodies is fixed, find the work needed to move the other from  $r = a$  to  $r = b$ .

- (b) Compute the work required to launch a 1000-kg satellite vertically to a height of 1000 km. You may assume that the earth's mass is  $5.98 \times 10^{24} \text{ kg}$  and is concentrated at its center. Take the radius of the earth to be  $6.37 \times 10^6 \text{ m}$  and  $G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$ .

34. The Great Pyramid of King Khufu was built of limestone in Egypt over a 20-year time period from 2580 BC to 2560 BC. Its base is a square with side length 756 ft and its height when built was 481 ft. (It was the tallest man-made structure in the world for more than 3800 years.) The density of the limestone is about  $150 \text{ lb/ft}^3$ .

- (a) Estimate the total work done in building the pyramid.
- (b) If each laborer worked 10 hours a day for 20 years, for 340 days a year, and did  $200 \text{ ft-lb/h}$  of work in lifting the limestone blocks into place, about how many laborers were needed to construct the pyramid?



## 5.5 Average Value of a Function

It is easy to calculate the average value of finitely many numbers  $y_1, y_2, \dots, y_n$ :

$$y_{\text{ave}} = \frac{y_1 + y_2 + \dots + y_n}{n}$$

But how do we compute the average temperature during a day if infinitely many temperature readings are possible? Figure 1 shows the graph of a temperature function  $T(t)$ , where  $t$  is measured in hours and  $T$  in  $^{\circ}\text{C}$ , and a guess at the average temperature,  $T_{\text{ave}}$ .

In general, let's try to compute the average value of a function  $y = f(x)$ ,  $a \leq x \leq b$ . We start by dividing the interval  $[a, b]$  into  $n$  equal subintervals, each with length  $\Delta x = (b - a)/n$ . Then we choose points  $x_1^*, \dots, x_n^*$  in successive subintervals and calculate the average of the numbers  $f(x_1^*), \dots, f(x_n^*)$ :

$$\frac{f(x_1^*) + \dots + f(x_n^*)}{n}$$

(For example, if  $f$  represents a temperature function and  $n = 24$ , this means that we take temperature readings every hour and then average them.) Since  $\Delta x = (b - a)/n$ , we can write  $n = (b - a)/\Delta x$  and the average value becomes

$$\begin{aligned} \frac{f(x_1^*) + \dots + f(x_n^*)}{\frac{b-a}{\Delta x}} &= \frac{1}{b-a} [f(x_1^*) + \dots + f(x_n^*)] \Delta x \\ &= \frac{1}{b-a} [f(x_1^*) \Delta x + \dots + f(x_n^*) \Delta x] \\ &= \frac{1}{b-a} \sum_{i=1}^n f(x_i^*) \Delta x \end{aligned}$$

If we let  $n$  increase, we would be computing the average value of a large number of closely spaced values. (For example, we would be averaging temperature readings taken every minute or even every second.) The limiting value is

$$\lim_{n \rightarrow \infty} \frac{1}{b-a} \sum_{i=1}^n f(x_i^*) \Delta x = \frac{1}{b-a} \int_a^b f(x) dx$$

by the definition of a definite integral.

Therefore we define the **average value of  $f$**  on the interval  $[a, b]$  as

$$f_{\text{ave}} = \frac{1}{b-a} \int_a^b f(x) dx$$

For a positive function, we can think of this definition as saying

$$\frac{\text{area}}{\text{width}} = \text{average height}$$

**EXAMPLE 1** Find the average value of the function  $f(x) = 1 + x^2$  on the interval  $[-1, 2]$ .

**SOLUTION** With  $a = -1$  and  $b = 2$  we have

$$f_{\text{ave}} = \frac{1}{b-a} \int_a^b f(x) dx = \frac{1}{2 - (-1)} \int_{-1}^2 (1 + x^2) dx = \frac{1}{3} \left[ x + \frac{x^3}{3} \right]_{-1}^2 = 2 \quad \blacksquare$$

If  $T(t)$  is the temperature at time  $t$ , we might wonder if there is a specific time when the temperature is the same as the average temperature. For the temperature function

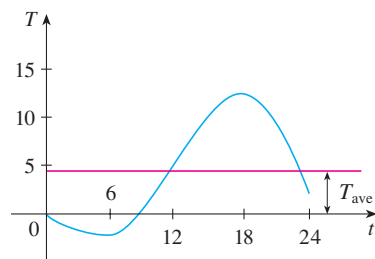


FIGURE 1

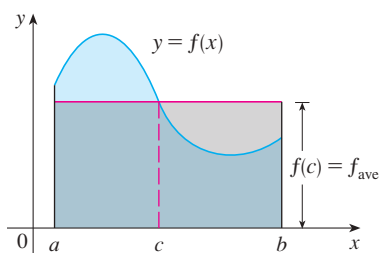


FIGURE 2

You can always chop off the top of a (two-dimensional) mountain at a certain height and use it to fill in the valleys so that the mountain becomes completely flat.

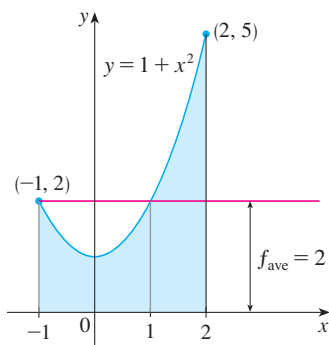


FIGURE 3

graphed in Figure 1, we see that there are two such times—just before noon and just before midnight. In general, is there a number  $c$  at which the value of a function  $f$  is exactly equal to the average value of the function, that is,  $f(c) = f_{\text{ave}}$ ? The following theorem says that this is true for continuous functions.

**The Mean Value Theorem for Integrals** If  $f$  is continuous on  $[a, b]$ , then there exists a number  $c$  in  $[a, b]$  such that

$$f(c) = f_{\text{ave}} = \frac{1}{b-a} \int_a^b f(x) \, dx$$

that is,

$$\int_a^b f(x) \, dx = f(c)(b-a)$$

The Mean Value Theorem for Integrals is a consequence of the Mean Value Theorem for derivatives and the Fundamental Theorem of Calculus. The proof is outlined in Exercise 23.

The geometric interpretation of the Mean Value Theorem for Integrals is that, for *positive* functions  $f$ , there is a number  $c$  such that the rectangle with base  $[a, b]$  and height  $f(c)$  has the same area as the region under the graph of  $f$  from  $a$  to  $b$ . (See Figure 2 and the more picturesque interpretation in the margin note.)

**EXAMPLE 2** Since  $f(x) = 1 + x^2$  is continuous on the interval  $[-1, 2]$ , the Mean Value Theorem for Integrals says there is a number  $c$  in  $[-1, 2]$  such that

$$\int_{-1}^2 (1 + x^2) \, dx = f(c)[2 - (-1)]$$

In this particular case we can find  $c$  explicitly. From Example 1 we know that  $f_{\text{ave}} = 2$ , so the value of  $c$  satisfies

$$f(c) = f_{\text{ave}} = 2$$

Therefore

$$1 + c^2 = 2 \quad \text{so} \quad c^2 = 1$$

So in this case there happen to be two numbers  $c = \pm 1$  in the interval  $[-1, 2]$  that work in the Mean Value Theorem for Integrals. ■

Examples 1 and 2 are illustrated by Figure 3.

**EXAMPLE 3** Show that the average velocity of a car over a time interval  $[t_1, t_2]$  is the same as the average of its velocities during the trip.

**SOLUTION** If  $s(t)$  is the displacement of the car at time  $t$ , then, by definition, the average velocity of the car over the interval is

$$\frac{\Delta s}{\Delta t} = \frac{s(t_2) - s(t_1)}{t_2 - t_1}$$

On the other hand, the average value of the velocity function on the interval is

$$\begin{aligned} v_{\text{ave}} &= \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} v(t) \, dt = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} s'(t) \, dt \\ &= \frac{1}{t_2 - t_1} [s(t_2) - s(t_1)] \quad (\text{by the Net Change Theorem}) \\ &= \frac{s(t_2) - s(t_1)}{t_2 - t_1} = \text{average velocity} \end{aligned}$$



## 5.5 EXERCISES

**1–8** Find the average value of the function on the given interval.

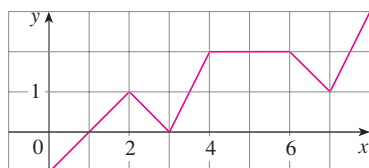
1.  $f(x) = 3x^2 + 8x$ ,  $[-1, 2]$
2.  $f(x) = \sqrt{x}$ ,  $[0, 4]$
3.  $g(x) = 3 \cos x$ ,  $[-\pi/2, \pi/2]$
4.  $g(t) = \frac{t}{\sqrt{3 + t^2}}$ ,  $[1, 3]$
5.  $f(t) = t^2(1 + t^3)^4$ ,  $[0, 2]$
6.  $f(x) = x^2/(x^3 + 3)^2$ ,  $[-1, 1]$
7.  $h(x) = \cos^4 x \sin x$ ,  $[0, \pi]$
8.  $h(t) = (1 + \sin t)^2 \cos t$ ,  $[\pi/2, 3\pi/2]$

## 9–12

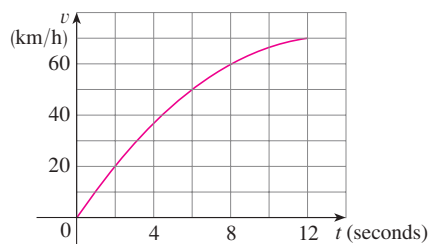
- (a) Find the average value of  $f$  on the given interval.
- (b) Find  $c$  such that  $f_{\text{ave}} = f(c)$ .
- (c) Sketch the graph of  $f$  and a rectangle whose area is the same as the area under the graph of  $f$ .

9.  $f(x) = (x - 3)^2$ ,  $[2, 5]$
10.  $f(x) = \sqrt[3]{x}$ ,  $[0, 8]$
11.  $f(x) = 2 \sin x - \sin 2x$ ,  $[0, \pi]$
12.  $f(x) = x\sqrt{4 - x^2}$ ,  $[0, 2]$

13. If  $f$  is continuous and  $\int_1^3 f(x) dx = 8$ , show that  $f$  takes on the value 4 at least once on the interval  $[1, 3]$ .
14. Find the numbers  $b$  such that the average value of  $f(x) = 2 + 6x - 3x^2$  on the interval  $[0, b]$  is equal to 3.
15. Find the average value of  $f$  on  $[0, 8]$ .



**16.** The velocity graph of an accelerating car is shown.



- (a) Use the Midpoint Rule to estimate the average velocity of the car during the first 12 seconds.
- (b) At what time was the instantaneous velocity equal to the average velocity?

- 17.** In a certain city the temperature (in  $^{\circ}\text{F}$ )  $t$  hours after 9 AM was modeled by the function

$$T(t) = 50 + 14 \sin \frac{\pi t}{12}$$

Find the average temperature during the period from 9 AM to 9 PM.

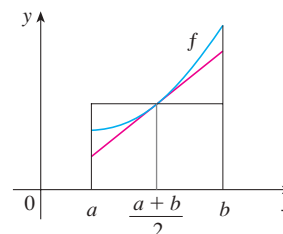
- 18.** The velocity  $v$  of blood that flows in a blood vessel with radius  $R$  and length  $l$  at a distance  $r$  from the central axis is

$$v(r) = \frac{P}{4\eta l} (R^2 - r^2)$$

where  $P$  is the pressure difference between the ends of the vessel and  $\eta$  is the viscosity of the blood (see Example 2.7.7). Find the average velocity (with respect to  $r$ ) over the interval  $0 \leq r \leq R$ . Compare the average velocity with the maximum velocity.

19. The linear density in a rod 8 m long is  $12/\sqrt{x + 1}$  kg/m, where  $x$  is measured in meters from one end of the rod. Find the average density of the rod.
20. If a freely falling body starts from rest, then its displacement is given by  $s = \frac{1}{2}gt^2$ . Let the velocity after a time  $T$  be  $v_T$ . Show that if we compute the average of the velocities with respect to  $t$  we get  $v_{\text{ave}} = \frac{1}{2}v_T$ , but if we compute the average of the velocities with respect to  $s$  we get  $v_{\text{ave}} = \frac{2}{3}v_T$ .
21. Use the result of Exercise 4.5.57 to compute the average volume of inhaled air in the lungs in one respiratory cycle.
22. Use the diagram to show that if  $f$  is concave upward on  $[a, b]$ , then

$$f_{\text{ave}} > f\left(\frac{a+b}{2}\right)$$





23. Prove the Mean Value Theorem for Integrals by applying the Mean Value Theorem for derivatives (see Section 3.2) to the function

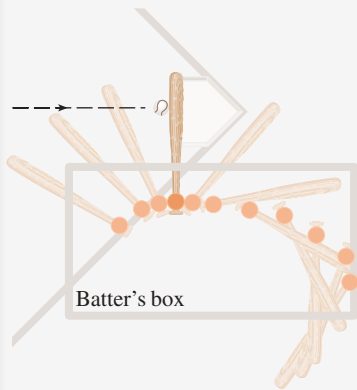
$$F(x) = \int_a^x f(t) dt$$

24. If  $f_{\text{ave}}[a, b]$  denotes the average value of  $f$  on the interval  $[a, b]$  and  $a < c < b$ , show that

$$f_{\text{ave}}[a, b] = \left( \frac{c-a}{b-a} \right) f_{\text{ave}}[a, c] + \left( \frac{b-c}{b-a} \right) f_{\text{ave}}[c, b]$$

## APPLIED PROJECT

## CALCULUS AND BASEBALL



An overhead view of the position of a baseball bat, shown every fiftieth of a second during a typical swing.  
(Adapted from *The Physics of Baseball*)

In this project we explore two of the many applications of calculus to baseball. The physical interactions of the game, especially the collision of ball and bat, are quite complex and their models are discussed in detail in a book by Robert Adair, *The Physics of Baseball*, 3d ed. (New York, 2002).

1. It may surprise you to learn that the collision of baseball and bat lasts only about a thousandth of a second. Here we calculate the average force on the bat during this collision by first computing the change in the ball's momentum.

The *momentum*  $p$  of an object is the product of its mass  $m$  and its velocity  $v$ , that is,  $p = mv$ . Suppose an object, moving along a straight line, is acted on by a force  $F = F(t)$  that is a continuous function of time.

- (a) Show that the change in momentum over a time interval  $[t_0, t_1]$  is equal to the integral of  $F$  from  $t_0$  to  $t_1$ ; that is, show that

$$p(t_1) - p(t_0) = \int_{t_0}^{t_1} F(t) dt$$

This integral is called the *impulse* of the force over the time interval.

- (b) A pitcher throws a 90-mi/h fastball to a batter, who hits a line drive directly back to the pitcher. The ball is in contact with the bat for 0.001 s and leaves the bat with velocity 110 mi/h. A baseball weighs 5 oz and, in US Customary units, its mass is measured in slugs:  $m = w/g$ , where  $g = 32 \text{ ft/s}^2$ .
- Find the change in the ball's momentum.
  - Find the average force on the bat.

2. In this problem we calculate the work required for a pitcher to throw a 90-mi/h fastball by first considering kinetic energy.

The *kinetic energy*  $K$  of an object of mass  $m$  and velocity  $v$  is given by  $K = \frac{1}{2}mv^2$ . Suppose an object of mass  $m$ , moving in a straight line, is acted on by a force  $F = F(s)$  that depends on its position  $s$ . According to Newton's Second Law

$$F(s) = ma = m \frac{dv}{dt}$$

where  $a$  and  $v$  denote the acceleration and velocity of the object.

- (a) Show that the work done in moving the object from a position  $s_0$  to a position  $s_1$  is equal to the change in the object's kinetic energy; that is, show that

$$W = \int_{s_0}^{s_1} F(s) ds = \frac{1}{2}mv_1^2 - \frac{1}{2}mv_0^2$$

where  $v_0 = v(s_0)$  and  $v_1 = v(s_1)$  are the velocities of the object at the positions  $s_0$  and  $s_1$ . *Hint:* By the Chain Rule,

$$m \frac{dv}{dt} = m \frac{dv}{ds} \frac{ds}{dt} = mv \frac{dv}{ds}$$

- (b) How many foot-pounds of work does it take to throw a baseball at a speed of 90 mi/h?

**NOTE** Another application of calculus to baseball can be found in Problem 16 on page 678.

## 5

## REVIEW

## CONCEPT CHECK

Answers to the Concept Check can be found on the back endpapers.

- Draw two typical curves  $y = f(x)$  and  $y = g(x)$ , where  $f(x) \geq g(x)$  for  $a \leq x \leq b$ . Show how to approximate the area between these curves by a Riemann sum and sketch the corresponding approximating rectangles. Then write an expression for the exact area.
  - Explain how the situation changes if the curves have equations  $x = f(y)$  and  $x = g(y)$ , where  $f(y) \geq g(y)$  for  $c \leq y \leq d$ .
- Suppose that Sue runs faster than Kathy throughout a 1500-meter race. What is the physical meaning of the area between their velocity curves for the first minute of the race?
- Suppose  $S$  is a solid with known cross-sectional areas. Explain how to approximate the volume of  $S$  by a Riemann sum. Then write an expression for the exact volume.
  - If  $S$  is a solid of revolution, how do you find the cross-sectional areas?
- What is the volume of a cylindrical shell?
  - Explain how to use cylindrical shells to find the volume of a solid of revolution.
  - Why might you want to use the shell method instead of slicing?
- Suppose that you push a book across a 6-meter-long table by exerting a force  $f(x)$  at each point from  $x = 0$  to  $x = 6$ . What does  $\int_0^6 f(x) dx$  represent? If  $f(x)$  is measured in newtons, what are the units for the integral?
- What is the average value of a function  $f$  on an interval  $[a, b]$ ?
  - What does the Mean Value Theorem for Integrals say? What is its geometric interpretation?

## EXERCISES

1–6 Find the area of the region bounded by the given curves.

- $y = x^2$ ,  $y = 4x - x^2$
- $y = \sqrt{x}$ ,  $y = -\sqrt[3]{x}$ ,  $y = x - 2$
- $y = 1 - 2x^2$ ,  $y = |x|$
- $x + y = 0$ ,  $x = y^2 + 3y$
- $y = \sin(\pi x/2)$ ,  $y = x^2 - 2x$
- $y = \sqrt{x}$ ,  $y = x^2$ ,  $x = 2$

7–11 Find the volume of the solid obtained by rotating the region bounded by the given curves about the specified axis.

- $y = 2x$ ,  $y = x^2$ ; about the  $x$ -axis
- $x = 1 + y^2$ ,  $y = x - 3$ ; about the  $y$ -axis
- $x = 0$ ,  $x = 9 - y^2$ ; about  $x = -1$
- $y = x^2 + 1$ ,  $y = 9 - x^2$ ; about  $y = -1$
- $x^2 - y^2 = a^2$ ,  $x = a + h$  (where  $a > 0$ ,  $h > 0$ ); about the  $y$ -axis

12–14 Set up, but do not evaluate, an integral for the volume of the solid obtained by rotating the region bounded by the given curves about the specified axis.

- $y = \tan x$ ,  $y = x$ ,  $x = \pi/3$ ; about the  $y$ -axis

13.  $y = \cos^2 x$ ,  $|x| \leq \pi/2$ ,  $y = \frac{1}{4}$ ; about  $x = \pi/2$

14.  $y = \sqrt{x}$ ,  $y = x^2$ ; about  $y = 2$

15. Find the volumes of the solids obtained by rotating the region bounded by the curves  $y = x$  and  $y = x^2$  about the following lines.

- The  $x$ -axis
- The  $y$ -axis
- $y = 2$

16. Let  $\mathcal{R}$  be the region in the first quadrant bounded by the curves  $y = x^3$  and  $y = 2x - x^2$ . Calculate the following quantities.

- The area of  $\mathcal{R}$
- The volume obtained by rotating  $\mathcal{R}$  about the  $x$ -axis
- The volume obtained by rotating  $\mathcal{R}$  about the  $y$ -axis

17. Let  $\mathcal{R}$  be the region bounded by the curves  $y = \tan(x^2)$ ,  $x = 1$ , and  $y = 0$ . Use the Midpoint Rule with  $n = 4$  to estimate the following quantities.

- The area of  $\mathcal{R}$
- The volume obtained by rotating  $\mathcal{R}$  about the  $x$ -axis

 18. Let  $\mathcal{R}$  be the region bounded by the curves  $y = 1 - x^2$  and  $y = x^6 - x + 1$ . Estimate the following quantities.

- The  $x$ -coordinates of the points of intersection of the curves
- The area of  $\mathcal{R}$
- The volume generated when  $\mathcal{R}$  is rotated about the  $x$ -axis
- The volume generated when  $\mathcal{R}$  is rotated about the  $y$ -axis

**19–22** Each integral represents the volume of a solid. Describe the solid.

19.  $\int_0^{\pi/2} 2\pi x \cos x \, dx$

20.  $\int_0^{\pi/2} 2\pi \cos^2 x \, dx$

21.  $\int_0^{\pi} \pi(2 - \sin x)^2 \, dx$

22.  $\int_0^4 2\pi(6 - y)(4y - y^2) \, dy$

23. The base of a solid is a circular disk with radius 3. Find the volume of the solid if parallel cross-sections perpendicular to the base are isosceles right triangles with hypotenuse lying along the base.

24. The base of a solid is the region bounded by the parabolas  $y = x^2$  and  $y = 2 - x^2$ . Find the volume of the solid if the cross-sections perpendicular to the  $x$ -axis are squares with one side lying along the base.

25. The height of a monument is 20 m. A horizontal cross-section at a distance  $x$  meters from the top is an equilateral triangle with side  $\frac{1}{4}x$  meters. Find the volume of the monument.

26. (a) The base of a solid is a square with vertices located at  $(1, 0)$ ,  $(0, 1)$ ,  $(-1, 0)$ , and  $(0, -1)$ . Each cross-section perpendicular to the  $x$ -axis is a semicircle. Find the volume of the solid.  
(b) Show that the volume of the solid of part (a) can be computed more simply by first cutting the solid and rearranging it to form a cone.

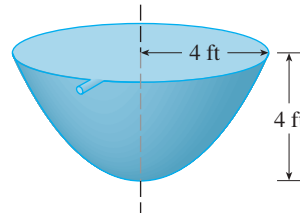
27. A force of 30 N is required to maintain a spring stretched from its natural length of 12 cm to a length of 15 cm. How much work is done in stretching the spring from 12 cm to 20 cm?

28. A 1600-lb elevator is suspended by a 200-ft cable that weighs 10 lb/ft. How much work is required to raise the elevator from the basement to the third floor, a distance of 30 ft?

29. A tank full of water has the shape of a paraboloid of revolution as shown in the figure; that is, its shape is obtained by rotating a parabola about a vertical axis.



- (a) If its height is 4 ft and the radius at the top is 4 ft, find the work required to pump the water out of the tank.  
(b) After 4000 ft-lb of work has been done, what is the depth of the water remaining in the tank?



30. A steel tank has the shape of a circular cylinder oriented vertically with diameter 4 m and height 5 m. The tank is currently filled to a level of 3 m with cooking oil that has a density of  $920 \text{ kg/m}^3$ . Compute the work required to pump the oil out through a 1-meter spout at the top of the tank.

31. Find the average value of the function  $f(t) = \sec^2 t$  on the interval  $[0, \pi/4]$ .

32. (a) Find the average value of the function  $f(x) = 1/\sqrt{x}$  on the interval  $[1, 4]$ .

(b) Find the value  $c$  guaranteed by the Mean Value Theorem for Integrals such that  $f_{\text{ave}} = f(c)$ .

(c) Sketch the graph of  $f$  on  $[1, 4]$  and a rectangle whose area is the same as the area under the graph of  $f$ .

33. If  $f$  is a continuous function, what is the limit as  $h \rightarrow 0$  of the average value of  $f$  on the interval  $[x, x + h]$ ?

34. Let  $\mathcal{R}_1$  be the region bounded by  $y = x^2$ ,  $y = 0$ , and  $x = b$ , where  $b > 0$ . Let  $\mathcal{R}_2$  be the region bounded by  $y = x^2$ ,  $x = 0$ , and  $y = b^2$ .

(a) Is there a value of  $b$  such that  $\mathcal{R}_1$  and  $\mathcal{R}_2$  have the same area?

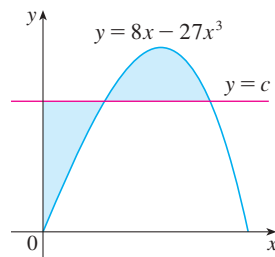
(b) Is there a value of  $b$  such that  $\mathcal{R}_1$  sweeps out the same volume when rotated about the  $x$ -axis and the  $y$ -axis?

(c) Is there a value of  $b$  such that  $\mathcal{R}_1$  and  $\mathcal{R}_2$  sweep out the same volume when rotated about the  $x$ -axis?

(d) Is there a value of  $b$  such that  $\mathcal{R}_1$  and  $\mathcal{R}_2$  sweep out the same volume when rotated about the  $y$ -axis?

## Problems Plus

- Find a positive continuous function  $f$  such that the area under the graph of  $f$  from 0 to  $t$  is  $A(t) = t^3$  for all  $t > 0$ .
  - A solid is generated by rotating about the  $x$ -axis the region under the curve  $y = f(x)$ , where  $f$  is a positive function and  $x \geq 0$ . The volume generated by the part of the curve from  $x = 0$  to  $x = b$  is  $b^2$  for all  $b > 0$ . Find the function  $f$ .
- There is a line through the origin that divides the region bounded by the parabola  $y = x - x^2$  and the  $x$ -axis into two regions with equal area. What is the slope of that line?
- The figure shows a horizontal line  $y = c$  intersecting the curve  $y = 8x - 27x^3$ . Find the number  $c$  such that the areas of the shaded regions are equal.



- A cylindrical glass of radius  $r$  and height  $L$  is filled with water and then tilted until the water remaining in the glass exactly covers its base.
  - Determine a way to “slice” the water into parallel rectangular cross-sections and then *set up* a definite integral for the volume of the water in the glass.
  - Determine a way to “slice” the water into parallel cross-sections that are trapezoids and then *set up* a definite integral for the volume of the water.
  - Find the volume of water in the glass by evaluating one of the integrals in part (a) or part (b).
  - Find the volume of the water in the glass from purely geometric considerations.
  - Suppose the glass is tilted until the water exactly covers half the base. In what direction can you “slice” the water into triangular cross-sections? Rectangular cross-sections? Cross-sections that are segments of circles? Find the volume of water in the glass.

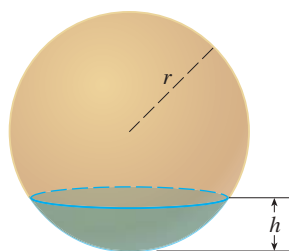
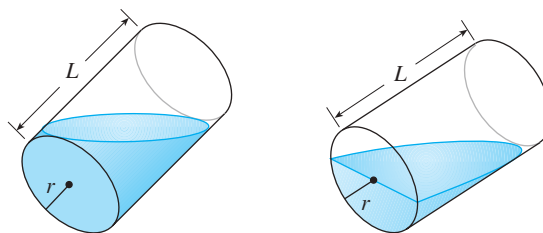


FIGURE FOR PROBLEM 5

- Show that the volume of a segment of height  $h$  of a sphere of radius  $r$  is

$$V = \frac{1}{3}\pi h^2(3r - h)$$

(See the figure.)

- Show that if a sphere of radius 1 is sliced by a plane at a distance  $x$  from the center in such a way that the volume of one segment is twice the volume of the other, then  $x$  is a solution of the equation

$$3x^3 - 9x + 2 = 0$$

where  $0 < x < 1$ . Use Newton's method to find  $x$  accurate to four decimal places.

- Using the formula for the volume of a segment of a sphere, it can be shown that the depth  $x$  to which a floating sphere of radius  $r$  sinks in water is a root of the equation

$$x^3 - 3rx^2 + 4r^3s = 0$$

where  $s$  is the specific gravity of the sphere. Suppose a wooden sphere of radius 0.5 m has specific gravity 0.75. Calculate, to four-decimal-place accuracy, the depth to which the sphere will sink.

- (d) A hemispherical bowl has radius 5 inches and water is running into the bowl at the rate of  $0.2 \text{ in}^3/\text{s}$ .
- How fast is the water level in the bowl rising at the instant the water is 3 inches deep?
  - At a certain instant, the water is 4 inches deep. How long will it take to fill the bowl?

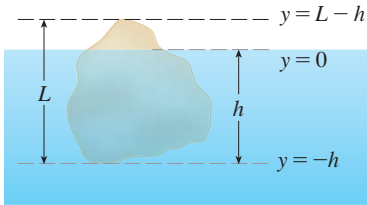


FIGURE FOR PROBLEM 6

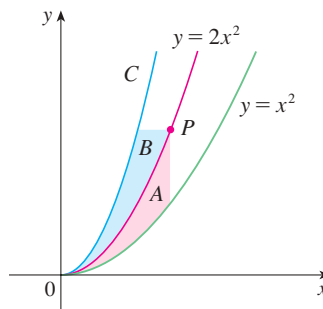
6. Archimedes' Principle states that the buoyant force on an object partially or fully submerged in a fluid is equal to the weight of the fluid that the object displaces. Thus, for an object of density  $\rho_0$  floating partly submerged in a fluid of density  $\rho_f$ , the buoyant force is given by  $F = \rho_f g \int_{-h}^0 A(y) dy$ , where  $g$  is the acceleration due to gravity and  $A(y)$  is the area of a typical cross-section of the object (see the figure). The weight of the object is given by

$$W = \rho_0 g \int_{-h}^{L-h} A(y) dy$$

- (a) Show that the percentage of the volume of the object above the surface of the liquid is

$$100 \frac{\rho_f - \rho_0}{\rho_f}$$

- The density of ice is  $917 \text{ kg/m}^3$  and the density of seawater is  $1030 \text{ kg/m}^3$ . What percentage of the volume of an iceberg is above water?
  - An ice cube floats in a glass filled to the brim with water. Does the water overflow when the ice melts?
  - A sphere of radius 0.4 m and having negligible weight is floating in a large freshwater lake. How much work is required to completely submerge the sphere? The density of the water is  $1000 \text{ kg/m}^3$ .
7. Water in an open bowl evaporates at a rate proportional to the area of the surface of the water. (This means that the rate of decrease of the volume is proportional to the area of the surface.) Show that the depth of the water decreases at a constant rate, regardless of the shape of the bowl.
8. A sphere of radius 1 overlaps a smaller sphere of radius  $r$  in such a way that their intersection is a circle of radius  $r$ . (In other words, they intersect in a great circle of the small sphere.) Find  $r$  so that the volume inside the small sphere and outside the large sphere is as large as possible.
9. The figure shows a curve  $C$  with the property that, for every point  $P$  on the middle curve  $y = 2x^2$ , the areas  $A$  and  $B$  are equal. Find an equation for  $C$ .



10. A paper drinking cup filled with water has the shape of a cone with height  $h$  and semi-vertical angle  $\theta$ . (See the figure.) A ball is placed carefully in the cup, thereby displacing some of the water and making it overflow. What is the radius of the ball that causes the greatest volume of water to spill out of the cup?

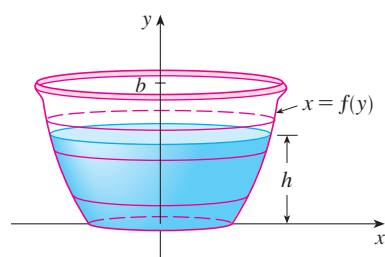
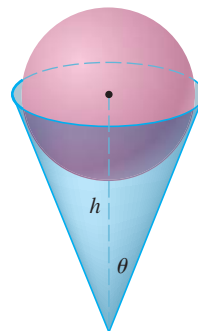


FIGURE FOR PROBLEM 11

11. A *clepsydra*, or water clock, is a glass container with a small hole in the bottom through which water can flow. The “clock” is calibrated for measuring time by placing markings on the container corresponding to water levels at equally spaced times. Let  $x = f(y)$  be continuous on the interval  $[0, b]$  and assume that the container is formed by rotating the graph of  $f$  about the  $y$ -axis. Let  $V$  denote the volume of water and  $h$  the height of the water level at time  $t$ .
- Determine  $V$  as a function of  $h$ .
  - Show that

$$\frac{dV}{dt} = \pi[f(h)]^2 \frac{dh}{dt}$$

- Suppose that  $A$  is the area of the hole in the bottom of the container. It follows from Torricelli's Law that the rate of change of the volume of the water is given by

$$\frac{dV}{dt} = kA\sqrt{h}$$

where  $k$  is a negative constant. Determine a formula for the function  $f$  such that  $dh/dt$  is a constant  $C$ . What is the advantage in having  $dh/dt = C$ ?

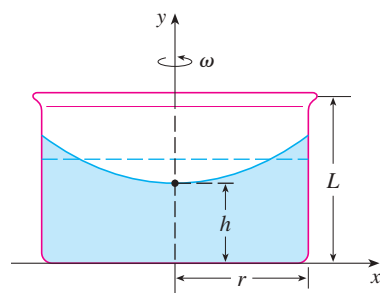


FIGURE FOR PROBLEM 12

12. A cylindrical container of radius  $r$  and height  $L$  is partially filled with a liquid whose volume is  $V$ . If the container is rotated about its axis of symmetry with constant angular speed  $\omega$ , then the container will induce a rotational motion in the liquid around the same axis. Eventually, the liquid will be rotating at the same angular speed as the container. The surface of the liquid will be convex, as indicated in the figure, because the centrifugal force on the liquid particles increases with the distance from the axis of the container. It can be shown that the surface of the liquid is a paraboloid of revolution generated by rotating the parabola

$$y = h + \frac{\omega^2 x^2}{2g}$$

about the  $y$ -axis, where  $g$  is the acceleration due to gravity.

- Determine  $h$  as a function of  $\omega$ .
- At what angular speed will the surface of the liquid touch the bottom? At what speed will it spill over the top?
- Suppose the radius of the container is 2 ft, the height is 7 ft, and the container and liquid are rotating at the same constant angular speed. The surface of the liquid is 5 ft below the top of the tank at the central axis and 4 ft below the top of the tank 1 ft out from the central axis.
  - Determine the angular speed of the container and the volume of the fluid.
  - How far below the top of the tank is the liquid at the wall of the container?

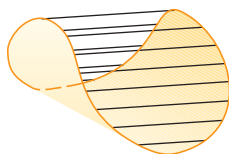
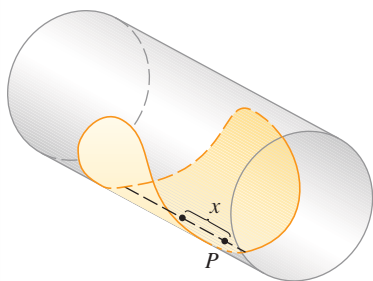


FIGURE FOR PROBLEM 14

13. Suppose the graph of a cubic polynomial intersects the parabola  $y = x^2$  when  $x = 0$ ,  $x = a$ , and  $x = b$ , where  $0 < a < b$ . If the two regions between the curves have the same area, how is  $b$  related to  $a$ ?

- CAS** 14. Suppose we are planning to make a taco from a round tortilla with diameter 8 inches by bending the tortilla so that it is shaped as if it is partially wrapped around a circular cylinder. We will fill the tortilla to the edge (but no more) with meat, cheese, and other ingredients. Our problem is to decide how to curve the tortilla in order to maximize the volume of food it can hold.
- (a) We start by placing a circular cylinder of radius  $r$  along a diameter of the tortilla and folding the tortilla around the cylinder. Let  $x$  represent the distance from the center of the tortilla to a point  $P$  on the diameter (see the figure). Show that the cross-sectional area of the filled taco in the plane through  $P$  perpendicular to the axis of the cylinder is

$$A(x) = r\sqrt{16 - x^2} - \frac{1}{2}r^2 \sin\left(\frac{2}{r}\sqrt{16 - x^2}\right)$$

and write an expression for the volume of the filled taco.

- (b) Determine (approximately) the value of  $r$  that maximizes the volume of the taco. (Use a graphical approach with your CAS.)
15. If the tangent at a point  $P$  on the curve  $y = x^3$  intersects the curve again at  $Q$ , let  $A$  be the area of the region bounded by the curve and the line segment  $PQ$ . Let  $B$  be the area of the region defined in the same way starting with  $Q$  instead of  $P$ . What is the relationship between  $A$  and  $B$ ?