

# Math 1080 Class notes Fall 2021

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## 5.5: Substitution Rule

### Theorem 5.6: Substitution Rule for Indefinite Integrals

Let  $u = g(x)$ , where  $g$  is differentiable on an interval, and let  $f$  be continuous on the corresponding range of  $g$ . On that interval,

$$\int f(g(x))g'(x) dx = \int f(u) du$$

**Example.** We know

$$\frac{d}{dx} \left[ \frac{(2x+1)^4}{4} \right] = 2(2x+1)^3$$

Thus, if  $f(x) = x^3$  and  $g(x) = 2x + 1$  then  $g'(x) = 2$ , so we let  $u = 2x + 1$ , then

$$\begin{aligned} \int 2(2x+1)^3 dx &= \int f(g(x))g'(x) dx \\ &= \int u^3 du \\ &= \frac{u^4}{4} + C \\ &= \frac{(2x+1)^4}{4} + C \end{aligned}$$

### Procedure: Substitution Rule (Change of Variables)

1. Given an indefinite integral involving a composite function  $f(g(x))$ , identify an inner function  $u = g(x)$  such that a constant multiple of  $g'(x)$  appears in the integrand.
2. Substitute  $u = g(x)$  and  $du = g'(x) dx$  in the integral.
3. Evaluate the new indefinite integral with respect to  $u$ .
4. Write the result in terms of  $x$  using  $u = g(x)$ .

**Example.** Evaluate the following integrals:

a)  $\int 2x(x^2 + 3)^4 dx$

b)  $\int (2x + 1)^3 dx$

c)  $\int x^2 \sqrt{x^3 + 1} dx$

d)  $\int \theta \sqrt[4]{1 - \theta^2} d\theta$

e)  $\int \sqrt{4 - t} dt$

f)  $\int (2 - x)^6 dx$

**Example.** Evaluate the following integrals:

a)  $\int \sec(2\theta) \tan(2\theta) d\theta$

b)  $\int \csc^2\left(\frac{t}{3}\right) dt$

c)  $\int \frac{\sin(x)}{1 + \cos^2(x)} dx$

d)  $\int \frac{\tan^{-1}(x)}{1 + x^2} dx$

The acceleration of a particle moving back and forth on a line is  $a(t) = \frac{d^2s}{dt^2} = \pi^2 \cos(\pi t) \text{ m/s}^2$  for all  $t$ . If  $s = 0$  and  $v = 8 \text{ m/s}$  when  $t = 0$ , find the value of  $s$  when  $t = 1$  sec.

**Example.** Evaluate the following integrals:

a)  $\int (6x^2 + 2) \sin(x^3 + x + 1) dx$

b)  $\int \frac{\sin(\theta)}{\cos^5(\theta)} d\theta$

c)  $\int \frac{e^{\sqrt{x}}}{\sqrt{x}} dx$

d)  $\int \frac{2^t}{2^t + 3} dt$

e)  $\int 6x^2 4^{x^3} dx$

f)  $\int \frac{dx}{\sqrt{36 - 4x^2}}$

g)  $\int \sin(t) \sec^2(\cos(t)) dt$

h)  $\int \frac{1}{\sqrt{x}(1 + \sqrt{x})^2} dx$

i)  $\int \frac{\sin(\sqrt{x})}{\sqrt{x}} dx$

j)  $\int 5 \cos(7x + 5) dx$

k)  $\int \frac{3}{\sqrt{1 - 25x^2}} dx$

l)  $\int \frac{dx}{\sqrt{1 - 9x^2}}$



**Example.** Evaluate the following integrals using the recommended substitution:

a)  $\int \sec^2(x) \tan(x) \, dx$   
where  $u = \tan(x)$ .

b)  $\int \sec^2(x) \tan(x) \, dx$   
where  $u = \sec(x)$ .

**Example.** Solve the initial value problem:  $\frac{dy}{dx} = 4x(x^2 + 8)^{-1/3}, y(0) = 0$ .

**Example.** Evaluate the following integrals:

a)  $\int x e^{-x^2} dx$

b)  $\int \frac{e^{1/x}}{x^2} dx$

c)  $\int \frac{dt}{8-3t}$

d)  $\int 5^t \sin(5^t) dt$

e)  $\int \frac{e^w}{36 + e^{2w}} dw$

**Theorem 5.7: Substitution Rule for Definite Integrals**

Let  $u = g(x)$ , where  $g'$  is continuous on  $[a, b]$ , and let  $f$  be continuous on the range of  $g$ . Then

$$\int_a^b f(g(x))g'(x) dx = \int_{g(a)}^{g(b)} f(u) du$$

**Example.** Evaluate the integrals:

a)  $\int_0^1 \frac{x^3}{\sqrt{x^4 + 9}} dx$

b)  $\int_1^3 \frac{dt}{(t - 4)^2}$

c)  $\int_0^3 \frac{v^2 + 1}{\sqrt{v^3 + 3v + 4}} dv$

d)  $\int_0^1 2x(4 - x^2) dx$

e)  $\int_2^3 \frac{x}{\sqrt[3]{x^2-1}} dx$

f)  $\int_0^{\frac{\pi}{2}} \frac{\sin(x)}{1+\cos(x)} dx$

g)  $\int_0^{\frac{\pi}{4}} \frac{\sin(x)}{\cos^2(x)} dx$

h)  $\int_{-\frac{\pi}{12}}^{\frac{\pi}{8}} \sec^2(2y) dy$

i)  $\int_0^1 (1 - 2x^9) dx$

j)  $\int_0^1 (1 - 2x)^9 dx$

k)  $\int_0^{\frac{1}{2}} \frac{1}{1 + 4x^2} dx$

l)  $\int_0^4 \frac{x}{x^2 + 1} dx$

m)  $\int_0^\pi 3 \cos^2(x) \sin(x) \, dx$

n)  $\int_0^{\frac{\pi}{8}} \sec(2\theta) \tan(2\theta) \, d\theta$

o)  $\int_0^1 (3t - 1)^{50} \, dt$

p)  $\int_0^3 \frac{1}{5x + 1} \, dx$

q)  $\int_0^1 x e^{-x^2} dx$

r)  $\int_e^{e^4} \frac{1}{x \sqrt{\ln(x)}} dx$

s)  $\int_0^{\frac{1}{2}} \frac{\sin^{-1}(x)}{\sqrt{1-x^2}} dx$

t)  $\int_0^1 \frac{e^z + 1}{e^z + z} dz$

$$\text{u) } \int_1^4 \frac{dy}{2\sqrt{y}(1+\sqrt{y})^2}$$

$$\text{v) } \int_{\ln(\frac{\pi}{4})}^{\ln(\frac{\pi}{2})} e^w \cos(e^w) dw$$

$$\text{w) } \int_0^{\frac{1}{8}} \frac{x}{\sqrt{1-16x^2}} dx$$

$$\text{x) } \int_1^{e^2} \frac{\ln(p)}{p} dp$$



$$\text{y) } \int_0^{\frac{\pi}{4}} e^{\sin^2(x)} \sin(2x) \, dx$$

$$\text{z) } \int_{-\pi}^{\pi} x^2 \sin(7x^3) \, dx$$

**Example. Average velocity:** An object moves in one dimension with a velocity in  $m/s$  given by  $v(t) = 8 \sin(\pi t) + 2t$ . Find its average velocity over the time interval from  $t = 0$  to  $t = 10$ , where  $t$  is measured in seconds.

**Example.** Prove  $\int \tan(x) \, dx = \ln |\sec(x)| + C$ .

**Example.** Evaluate the integrals:

a)  $\int \frac{x}{(x-2)^3} \, dx$

b)  $\int x\sqrt{x-1} \, dx$

c)  $\int x^3(1+x^2)^{\frac{3}{2}} dx$

d)  $\int \frac{y^2}{(y+1)^4} dy$

e)  $\int (z+1)\sqrt{3z+2} dz$

f)  $\int_0^1 \frac{x}{(x+2)^3} dx$

### Half-Angle Formulas

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

$$\sin^2(\theta) = \frac{1 - \cos(2\theta)}{2}$$

**Example.** Evaluate the integrals:

a)  $\int \cos^2(x) \, dx$

b)  $\int_0^{\frac{\pi}{2}} \cos^2(x) \, dx$

c)  $\int \frac{1}{x^2} \cos^2\left(\frac{1}{x}\right) dx$

d)  $\int x \sin^2(x^2) dx$

e)  $\int \sin^2\left(\theta + \frac{\pi}{6}\right) d\theta$

f)  $\int_0^{\frac{\pi}{4}} \cos^2(8\theta) d\theta$

**Example.** If  $f$  is continuous and  $\int_0^4 f(x) dx = 10$ , find  $\int_0^2 f(2x) dx$ .

**Example.** If  $f$  is continuous and  $\int_0^9 f(x) dx = 4$ , find  $\int_0^3 xf(x^2) dx$ .

**Example.** Suppose  $f$  is an even function with  $\int_0^8 f(x) dx = 9$ . Evaluate the following:

a)  $\int_{-1}^1 xf(x^2) dx$ .

b)  $\int_{-2}^2 x^2 f(x^3) dx$ .

**Example.** Evaluate the integrals:

a)  $\int \sec^2(10x) \, dx$

b)  $\int \tan^{10}(4x) \sec^2(4x) \, dx$

c)  $\int \left(x^{\frac{3}{2}} + 8\right)^5 \sqrt{x} \, dx$

d)  $\int \frac{2x}{\sqrt{3x+2}} \, dx$

e)  $\int \frac{7x^2 + 2x}{x} dx$

f)  $\int \frac{e^x - e^{-x}}{e^x + e^{-x}} dx$

g)  $\int_0^{\sqrt{3}} \frac{3}{9 + x^2} dx$

h)  $\int_0^{\frac{\pi}{6}} \frac{\sin(2y)}{\sin^2(y) + 2} dy$



i)  $\int \frac{\sec(z) \tan(z)}{\sqrt{\sec(z)}} dz$

j)  $\int \frac{1}{\sin^{-1}(x) \sqrt{1-x^2}} dx$

k)  $\int \frac{x}{\sqrt{4-9x^2}} dx$

l)  $\int \frac{x}{1+x^4} dx$

$$\text{m)} \int \frac{\cos \sqrt{\theta}}{\sqrt{\theta} \sin^2 \sqrt{\theta}} d\theta$$

$$\text{n)} \int x^2 \sqrt{2+x} dx$$

$$\text{o)} \int (\sin^5(x) + 3 \sin^3(x) - \sin(x)) \cos(x) dx$$

p)  $\int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} (x^3 + x^4 \tan(x)) \, dx$

q)  $\int_0^{\frac{\pi}{2}} \cos(x) \sin(\sin(x)) \, dx$

r)  $\int \frac{1+x}{1+x^2} \, dx$

**Example.** Evaluate these more challenging integrals:

a)  $\int \frac{dx}{\sqrt{1 + \sqrt{1 + x}}}$

b)  $\int x \sin^4(x^2) \cos(x^2) dx$

## 6.1: Velocity and Net Change

### Definition. (Position, Velocity, Displacement, and Distance)

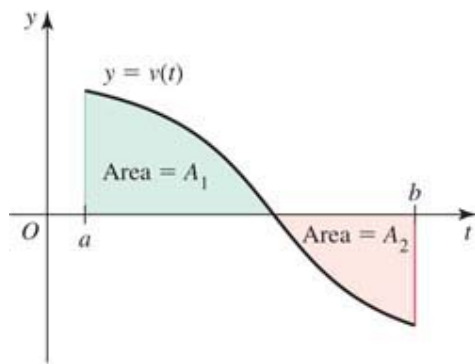
1. The **position** of an object moving along a line at time  $t$ , denoted  $s(t)$ , is the location of the object relative to the origin.
2. The **velocity** of an object at time  $t$  is  $v(t) = s'(t)$ .
3. The **displacement** of the object between  $t = a$  and  $t = b > a$  is

$$s(b) - s(a) = \int_a^b v(t) dt.$$

4. The **distance traveled** by the object between  $t = a$  and  $t = b > a$  is

$$\int_a^b |v(t)| dt$$

where  $|v(t)|$  is the **speed** of the object at time  $t$ .



$$\text{Displacement} = A_1 - A_2 = \int_a^b v(t) dt$$

(a)



$$\text{Distance traveled} = A_1 + A_2 = \int_a^b |v(t)| dt$$

(b)

**Example.** Suppose an object moves along a line with velocity (in ft/s)  $v(t) = 6 - 2t$ , for  $0 \leq t \leq 5$ , where  $t$  is measured in seconds.

- Find the displacement of the object on the interval  $0 \leq t \leq 5$ .

- Find the distance traveled by the object on the interval  $0 \leq t \leq 5$ .



**Example.** A cyclist rides down a long straight road at a velocity (in m/min) given by  $v(t) = 400 - 20t$ , for  $0 \leq t \leq 10$ .

- How far does the cyclists travel in the first 5 minutes?
- How far does the cyclists travel in the first 10 minutes?
- How far has the cyclist traveled when her velocity is 250 m/min?



**Example.** The population of a community of foxes is observed to fluctuate on a 10-year cycle due to variations in the availability of prey. When population measurements began ( $t = 0$ ), the population was 35 foxes. The growth rate in units of foxes/year was observed to be:

$$P'(t) = 5 + 10 \sin\left(\frac{\pi t}{5}\right)$$

- Find  $P(t)$ .
- Find the population of foxes after the first 5 years, rounded to the nearest whole number of foxes.

**Theorem 6.1: Position from Velocity**

Given the velocity  $v(t)$  of an object moving along a line and its initial position  $s(0)$ , the position function of the object for future times  $t \geq 0$  is

$$\underbrace{s(t)}_{\substack{\text{position} \\ \text{at } t}} = \underbrace{s(0)}_{\substack{\text{initial} \\ \text{position}}} + \underbrace{\int_0^t v(x) dx}_{\substack{\text{displacement} \\ \text{over } [0, t]}}.$$

**Theorem 6.2: Velocity from Acceleration**

Given the acceleration  $a(t)$  of an object moving along a line and its initial velocity  $v(0)$ , the velocity of the object for future times  $t \geq 0$  is

$$v(t) = v(0) + \int_0^t a(x) dx.$$

**Example.** At  $t = 0$ , a train approaching a station begins decelerating from a speed of 80 miles/hour according to the acceleration function  $a(t) = -1280(1 + 8t)^{-3}$ , where  $t \geq 0$  is measured in hours. The units of acceleration are mi/hr<sup>2</sup>.

- Find the velocity of the train at  $t = 0.25$ .
- How far does the train travel in the first 15 minutes (1/4 hour)?
- How long does it take the train to travel 9 miles?

**Theorem 6.3: Net Change and Future Value**

Suppose a quantity  $Q$  changes over time at a known rate  $Q'$ . Then the **net change** in  $Q$  between  $t = a$  and  $t = b > a$  is

$$\underbrace{Q(b) - Q(a)}_{\text{net change in } Q} = \int_a^b Q'(t) dt.$$

Given the initial value  $Q(0)$ , the **future value** of  $Q$  at time  $t \geq 0$  is

$$Q(t) = Q(0) + \int_0^t Q'(x) dx.$$

**Velocity-Displacement Problems**

Position  $s(t)$

Velocity:  $s'(t) = v(t)$

Displacement:  $s(b) - s(a) = \int_a^b v(t) dt$

Future position:  $s(t) = s(0) + \int_0^t v(x) dx$

**General Problems**

Quantity  $Q(t)$  (such as volume or population)

Rate of change:  $Q'(t)$

Net change:  $Q(b) - Q(a) = \int_a^b Q'(t) dt$

Future value of  $Q$ :  $Q(t) = Q(0) + \int_0^t Q'(x) dx$

## 6.2: Regions Between Curves

### Definition. (Area of a Region Between Two Curves)

Suppose  $f$  and  $g$  are continuous functions with  $f(x) \geq g(x)$  on the interval  $[a, b]$ . The area of the region bounded by the graphs of  $f$  and  $g$  on  $[a, b]$  is

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



**Example.** Consider the region bounded by the curves  $y = \cos(x)$  and  $y = 1 - \cos(x)$ ,  $0 \leq x \leq \pi$ . Set up the integral(s) representing the area of this region.



**Example.** Find the area of the region by integrating with respect to  $x$ .



**Example.** Find the volume of the solid whose base is bounded by the graphs of  $y = x + 1$  and  $y = x^2 - 1$ , with the cross sections in the shape of rectangles of height 2 taken perpendicular to the  $x$ -axis.



**Definition. (Area of a Region Between Two Curves with Respect to  $y$ )**

Suppose  $f$  and  $g$  are continuous functions with  $f(y) \geq g(y)$  on the interval  $[c, d]$ . The area of the region bounded by the graphs  $x = f(y)$  and  $x = g(y)$  on  $[c, d]$  is

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

**Example.** Find the area of the region bounded by  $x = 3y$ , and  $x = y^2 - 10$

by integrating with respect to  $x$

by integrating with respect to  $y$

**Example.** Find the area of the region bounded by  $y = x^3$ , and  $y = \sqrt{x}$   
by integrating with respect to  $x$

by integrating with respect to  $y$



**Example.** Find the area of the region bounded by  $y = 4\sqrt{2x}$ ,  $y = 2x^2$ , and  $y = -4x + 6$

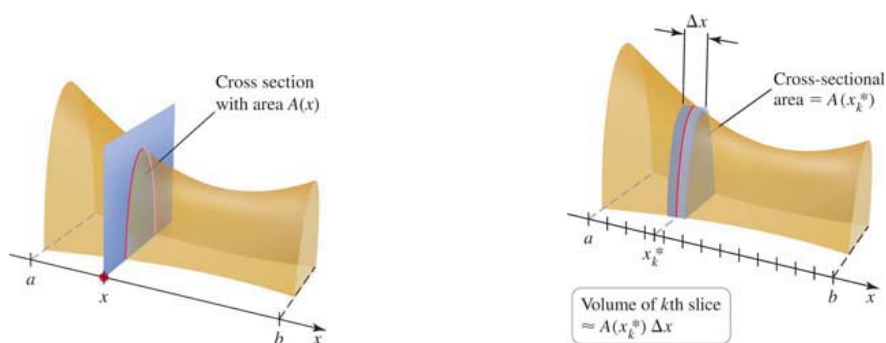


## 6.3: Volume by Slicing

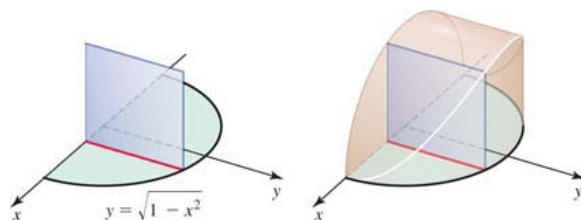
### General Slicing Method

Suppose a solid object extends from  $x = a$  to  $x = b$ , and the cross section of the solid perpendicular to the  $x$ -axis has an area given by a function  $A$  that is integrable on  $[a, b]$ . The volume of the solid is

$$V = \int_a^b A(x) dx.$$



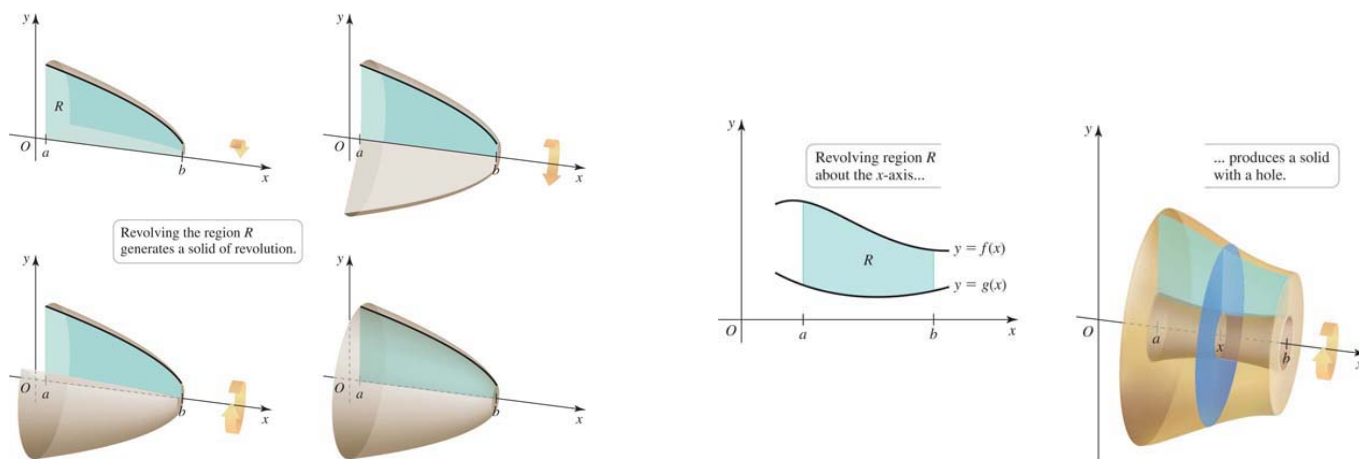
**Example.** Use the general slicing method to find the volume of the solid whose base is the region bounded by the semicircle  $y = \sqrt{1 - x^2}$  and the  $x$ -axis, and whose cross sections through the solid perpendicular to the  $x$ -axis are squares.



### Disk Method about the $x$ -Axis

Let  $f$  be continuous with  $f(x) \geq 0$  on the interval  $[a, b]$ . If the region  $R$  bounded by the graph of  $f$ , the  $x$ -axis, and the lines  $x = a$  and  $x = b$  is revolved about the  $x$ -axis, the volume of the resulting solid of revolution is

$$V = \int_a^b \underbrace{\pi f(x)^2}_{\text{disk radius}} dx.$$

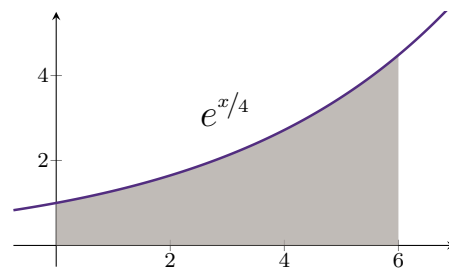


### Washer Method about the $x$ -Axis

Let  $f$  and  $g$  be continuous functions with  $f(x) \geq g(x) \geq 0$  on  $[a, b]$ . Let  $R$  be the region bounded by  $y = f(x)$ ,  $y = g(x)$ , and the lines  $x = a$  and  $x = b$ . When  $R$  is revolved about the  $x$ -axis, the volume of the resulting solid of revolution is

$$V = \int_a^b \pi \left( \underbrace{f(x)^2}_{\text{outer radius}} - \underbrace{g(x)^2}_{\text{inner radius}} \right) dx.$$

**Example.** Consider the region bounded by  $y = e^{x/4}$ ,  $y = 0$ ,  $x = 0$ , and  $x = 6$ . Find the volume of the solid generated by rotating the region about the  $x$ -axis.



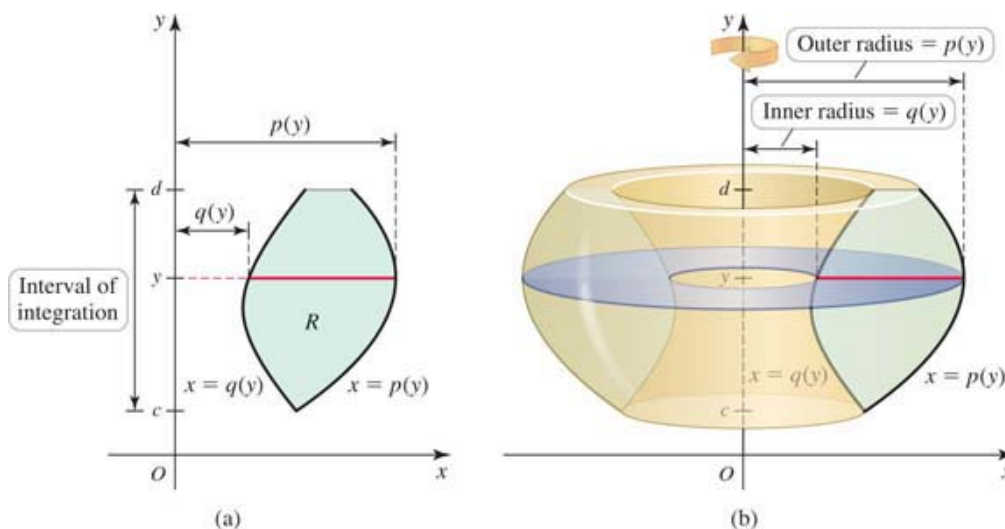
## Disk and Washer Methods about the $y$ -Axis

Let  $p$  and  $q$  be continuous functions with  $p(y) \geq q(y) \geq 0$  on  $[c, d]$ . Let  $R$  be the region bounded by  $x = p(y)$ ,  $x = q(y)$ , and the lines  $y = c$  and  $y = d$ . When  $R$  is revolved around the  $y$ -axis, the volume of the resulting solid of revolution is given by

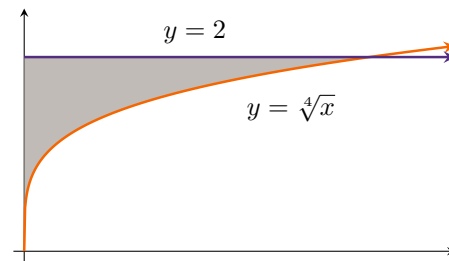
$$V = \int_c^d \pi \left( \underbrace{p(y)^2}_{\text{outer radius}} - \underbrace{q(y)^2}_{\text{inner radius}} \right) dy.$$

If  $q(y) = 0$ , the disk method results:

$$V = \int_c^d \pi \underbrace{p(y)^2}_{\text{disk radius}} dy.$$



**Example.** Consider the region bounded between  $y = \sqrt[4]{x}$ ,  $y = 2$ , and  $x = 0$ .

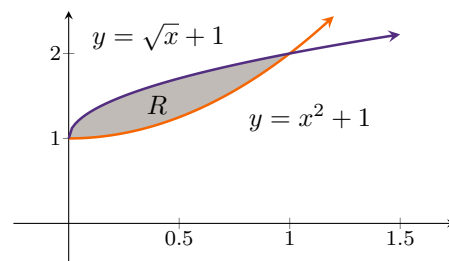


Setup the integral with respect to  $x$  that gives the area of the region.

Setup the integral with respect to  $y$  that gives the area of the region.

Use the disk/washer method to setup the that represents the volume of the solid generated by rotating the region about the  $x$ -axis.

**Example.** Consider the region  $R$  between  $y = \sqrt{x} + 1$  and  $y = x^2 + 1$ . Setup the integrals which find the volume of the solid obtained by rotating the region  $R$  as indicated below.



about the  $y$ -axis

about the  $x$ -axis

about the line  $x = 1$

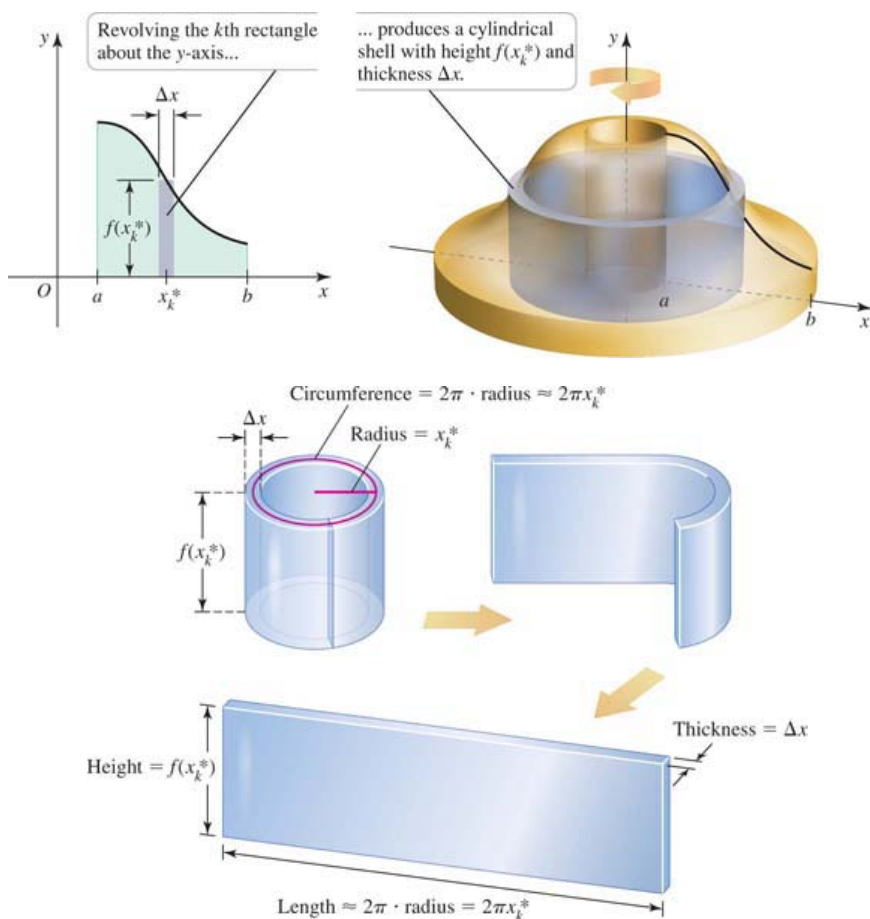
about the line  $y = -1$

## 6.4: Volume by Shells

### Volume by the Shell Method

Let  $f$  and  $g$  be continuous functions with  $f(x) \geq g(x)$  on  $[a, b]$ . If  $R$  is the region bounded by the curves  $y = f(x)$  and  $y = g(x)$  between the lines  $x = a$  and  $x = b$ , the volume of the solid generated when  $R$  is revolved about the  $y$ -axis is

$$V = \int_a^b \underbrace{2\pi x}_{\text{shell circumference}} \underbrace{(f(x) - g(x))}_{\text{shell height}} dx.$$





**Example.** Consider a general region  $R$  revolved around the  $y$ -axis.

When using the **disk/washer** method, we integrate with respect to \_\_\_\_\_

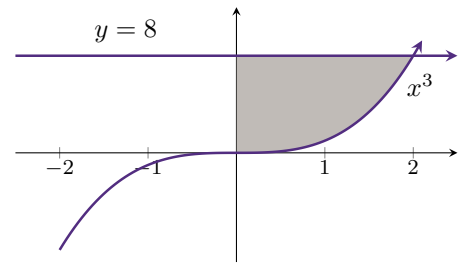
When using the **shell** method, we integrate with respect to \_\_\_\_\_

**Example.** Consider a general region  $R$  revolved around the  $x$ -axis.

When using the **disk/washer** method, we integrate with respect to \_\_\_\_\_

When using the **shell** method, we integrate with respect to \_\_\_\_\_

**Example.** Consider the region bounded between  $y = x^3$ ,  $y = 8$  and  $x = 0$ .



Use the disk/washer method to setup the integral that represents the volume of the solid generated by rotating the region about the  $x$ -axis.

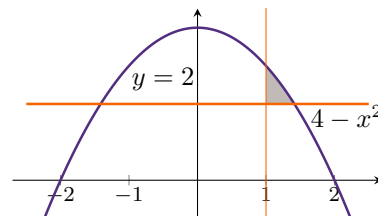
about the  $y$ -axis.

Use the disk/washer method to setup the integral that represents the volume of the solid generated by rotating the region about the line  $x = -1$ .

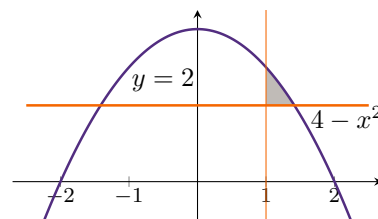
about the line  $y = 8$ .

**Example.** Consider the region  $R$  bounded by  $y = 4 - x^2$ ,  $y = 2$ , and  $x = 1$ . Use the shell method to setup the integral that represents the volume of the solid generated by rotating the region  $R$  about the indicated axis of rotation.

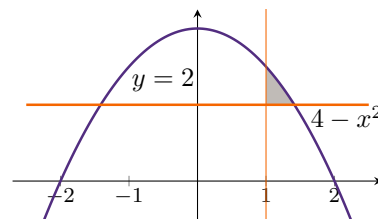
about  $x$ -axis,



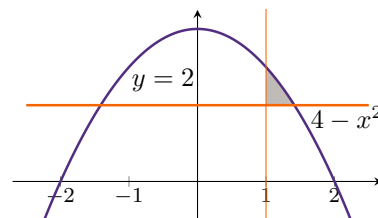
about  $y$ -axis,



about the line  $x = -2$ ,



about the line  $y = 2$ .



**Example.** Consider the region bounded by  $y = \frac{1}{x+1}$  and  $y = 1 - \frac{x}{3}$ . Use both the disk/washer method and shell method to find the volume of the solid generated when  $R$  is rotated about the  $x$ -axis.

**Example.** Determine if the following statements are true.

When using the shell method, the axis of the cylindrical shells is parallel to the axis of revolution.

If a region is revolved about the  $y$ -axis, then the shell method must be used.

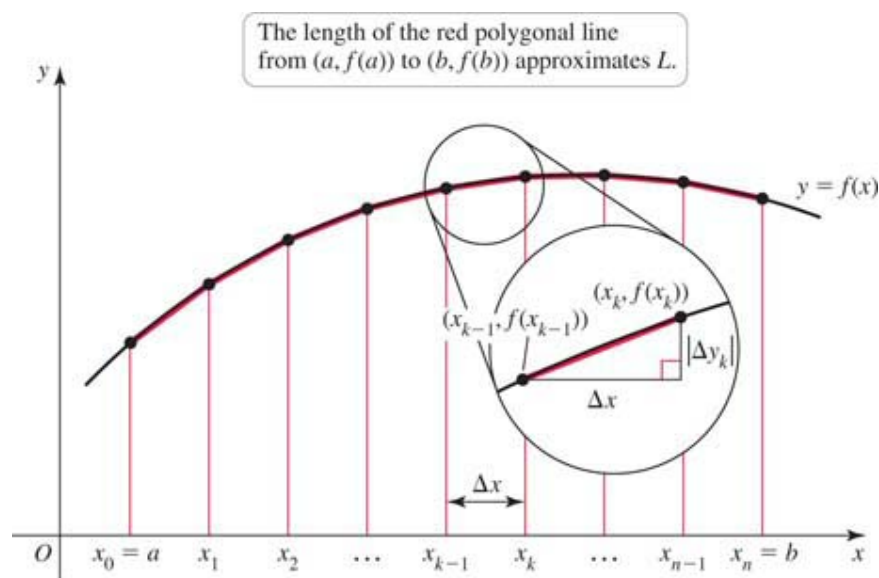
If a region is revolved about the  $x$ -axis, it is possible to use the disk/washer method and integrate with respect to  $x$ .

## 6.5: Length of Curves

### Definition. (Arc Length for $y = f(x)$ )

Let  $f$  have a continuous first derivative on the interval  $[a, b]$ . The length of the curve from  $(a, f(a))$  to  $(b, f(b))$  is

$$L = \int_a^b \sqrt{1 + f'(x)^2} dx.$$



### Definition. (Arc Length for $x = g(y)$ )

Let  $g$  have a continuous first derivative on the interval  $[c, d]$ . The length of the curve from  $(g(c), c)$  to  $(g(d), d)$  is

$$L = \int_c^d \sqrt{1 + g'(y)^2} dy.$$

**Example.** Using a geometric argument, we can see that the length of  $f(x) = -\frac{3}{4}x + \frac{7}{2}$  on the interval  $[-6, 2]$  is  $L = 10$ . Compute this using the arc-length formula.



**Example.** Find the arc length of the curve  $y = \frac{1}{4}x^2 - \frac{1}{2}\ln(x)$ , for  $1 \leq x \leq 2$ .



**Example.** Find the arc length of the curve  $y = \frac{1}{3}x^{3/2}$  on  $[0, 12]$ .

**Example.** Find a curve that passes through  $(1, 2)$  on  $[2, 6]$  whose arc length is computed using

$$\int_2^6 \sqrt{1 + 16x^{-2}} \, dx.$$

**Example.** Suppose  $f$  has length  $L$  on  $[a, b]$ . Evaluate

$$\int_{a/c}^{b/c} \sqrt{1 + f'(cx)^2} \, dx.$$

## 6.6: Surface Area

### Definition. (Area of a Surface of Revolution)

Let  $f$  be a nonnegative function with a continuous first derivative on the interval  $[a, b]$ . The area of the surface generated when the graph of  $f$  on the interval  $[a, b]$  is revolved around the  $x$ -axis is

$$S = \int_a^b 2\pi f(x) \sqrt{1 + f'(x)^2} dx.$$



**Example.** Find the exact area of the surface obtained by rotating the curve  $y = x^3$ ,  $0 \leq x \leq 2$  about the  $x$ -axis.

**Example.** Find the exact area of the surface obtained by rotating the curve  $y = \sqrt{8x - x^2}$ ,  $1 \leq x \leq 7$  about the  $x$ -axis.

**Example.** Find the exact area of the surface obtained by rotating the curve  $y = \frac{1}{2}(e^x + e^{-x})$ ,  $-\ln(2) \leq x \leq \ln(2)$  about the  $x$ -axis.

## 6.7: Physical Applications

**Definition. (Mass of a One-Dimensional Object)**

Suppose a thin bar or wire is represented by the interval  $a \leq x \leq b$  with a density function  $\rho$  (with units of mass per length). The **mass** of the object is

$$m = \int_a^b \rho(x) \, dx.$$

**Example.** A thin bar, represented by the interval  $0 \leq x \leq 4$ , has density in units of kg/m given by  $\rho(x) = 5e^{-2x}$ . What is the mass of the bar?

**Definition. (Work)**

The work done by a variable force  $F$  moving an object along a line from  $x = a$  to  $x = b$  in the direction of the force is

$$W = \int_a^b F(x) dx.$$

**Example.** According to **Hooke's Law**, the force required to keep a spring in a compressed or stretched position  $x$  units from the equilibrium position is  $F(x) = kx$ , where the positive spring constant  $k$  measures the stiffness of the spring.

Suppose a force of 40 N is required to stretch a spring 0.1 m from its equilibrium position. Assuming the spring obeys Hooke's Law, how much work is required to stretch the spring 0.4 m beyond its equilibrium position?

**Example (Work from force).** How much work is required to move an object from  $x = 1$  to  $x = 3$  (measured in meters) in the presence of a force (in N) given by  $F(x) = \frac{2}{x^2}$  acting along the  $x$ -axis?

**Example.** Imagine a chain of length  $L$  meters with constant density  $\rho$  kg/m is hanging vertically. Using  $g$  to represent the acceleration due to gravity, the work required to lift the chain is

$$W = \int_0^L \rho g(L - y) dy$$

A 50 meter long chain hangs vertically from a cylinder attached to a winch. Assume there is no friction in the system and the chain has a density of 3 kg/m. How much work is required to wind the entire chain onto the cylinder if a 60-kg load is attached to the end of the chain? Use  $g$  for the acceleration due to gravity.



**Example.** A 30-meter long rope hangs freely from a ledge. The rope has a density of 5 kg/m. How much work is done if the top  $1/3$  of the rope is pulled up to the ledge? Use  $g$  for the acceleration due to gravity.

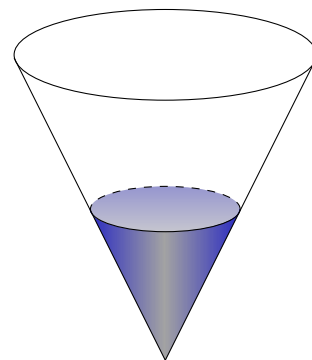
### Procedure: Solving Pumping Problems

1. Draw a  $y$ -axis in the vertical direction (parallel to gravity) and choose a convenient origin. Assume the interval  $[a, b]$  corresponds to the vertical extent of the fluid.
2. For  $a \leq y \leq b$ , find the cross-sectional area  $A(y)$  of the horizontal slices and the distance  $D(y)$  the slices must be lifted.
3. The work required to lift the water is

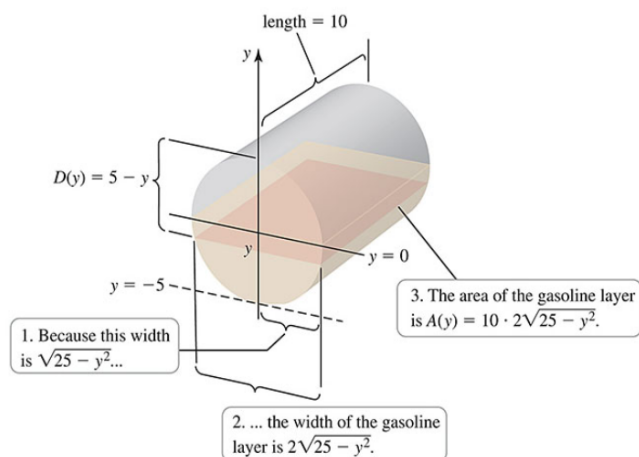
$$W = \int_a^b \rho g A(y) D(y) dy.$$

*Note:* Lifting problems are a special case of pumping problems where  $A(y) = 1$ .

**Example.** A water tank is shaped like an inverted cone with height 6 meters and base radius 1.5 meters. If the tank is full, how much work is required to pump the water to the level of the top of the tank and out of the tank? Use  $g$  for the acceleration due to gravity and note that the density of water is  $1000 \text{ kg/m}^3$ .



**Example.** (Pumping gasoline) A cylindrical tank with a length of 10 m and a radius of 5 m is on its side and half full of gasoline. How much work is required to empty the tank through an outlet pipe at the top of the tank? The density of gasoline is  $\rho = 737 \text{ kg/m}^3$

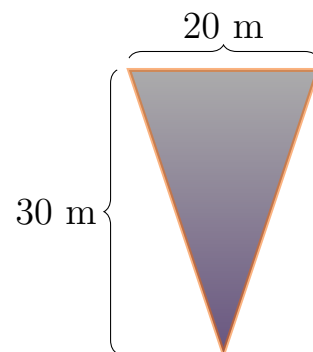


### Procedure: Solving Force-on-Dam Problems

1. Draw a  $y$ -axis on the face of the dam in the vertical direction and choose a convenient origin (often taken to be the base of the dam).
2. Find the width function  $w(y)$  for each value of  $y$  on the face of the dam.
3. If the base of the dam is at  $y = 0$  and the top of the dam is at  $y = a$ , then the total force on the dam is

$$F = \int_0^a \underbrace{\rho g (a - y)}_{\text{depth}} \underbrace{w(y)}_{\text{width}} dy.$$

**Example.** The figure to the right shows the shape and dimensions of a small dam. Assuming the water level is at the top of the dam, find the total force on the face of the dam. Use  $\rho$  for the density of the water and  $g$  for the acceleration due to gravity.



**Example.** Force on a building A large building shaped like a box is 50 m high with a face that is 80 m wide. A strong wind blows directly at the face of the building, exerting a pressure of  $150 \text{ N/m}^2$  at the ground and increasing with height according to  $P(y) = 150 + 2y$ , where  $y$  is the height above the ground. Calculate the total force on the building, which is a measure of the resistance that must be included in the design of the building.

## 8.1: Basic Approaches (to Integration)

**Example.** Derive the integral formula  $\int \sec(ax) \, dx = \frac{1}{a} \ln |\sec(ax) + \tan(ax)| + C$ .

**Example.** Evaluate  $\int \frac{dx}{e^{3x} + e^{-3x}}$ .

**Example.** Evaluate  $\int \frac{\sin(x) + \cos^4(x)}{\csc(x)} dx$ .

$$\text{Note: } \begin{cases} \cos^2(x) = \frac{1 + \cos(2x)}{2} \\ \sin^2(x) = \frac{1 - \cos(2x)}{2} \end{cases}$$

**Example.** Evaluate  $\int \frac{2x^2 + 3x - 4}{x - 2} dx$ .

**Example.** Evaluate  $\int \frac{dx}{\sqrt{7-6x-x^2}}$ .



## 8.2: Integration by Parts

### Integraton by Parts

Suppose  $u$  and  $v$  are differentiable functions. Then

$$\int u \, dv = uv - \int v \, du.$$

A good mnemonic is ILATE.

**Example.** Evaluate  $\int x e^{-\frac{x}{2}} dx$ .

## Integration by Parts for Definite Integrals

Let  $u$  and  $v$  be differentiable. Then

$$\int_a^b u(x)v'(x) dx = u(x)v(x) \Big|_a^b - \int_a^b v(x)u'(x) dx$$

**Example.** Find the area of the region between the  $x$ -axis and  $f(x) = \frac{\ln(x)}{x^2}$  on  $[1, e]$ .

**Example.** Evaluate  $\int x^2 \cos(2x) \, dx$ .

**Example.** Evaluate  $\int e^{-x} \sin(3x) dx$ .

**Example.** Evaluate  $\int e^{4x} \cos(3x) dx$ .

**Example.** Derive the integral formula

$$\int \ln(x) \, dx = x \ln(x) - x + C$$

**Example.** Evaluate  $\int 10 \cos(\sqrt{x}) \, dx$

**Example.** Evaluate  $\int_1^e \ln(2x) \, dx$ .



## 8.3: Trigonometric Integrals

### Important trigonometric identities

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Pythagorean Identities

$$\sin^2(\theta) + \cos^2(\theta) = 1$$

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Angle sum formulas

$$\sin(\alpha \pm \beta) = \sin(\alpha) \cos(\beta) \pm \cos(\alpha) \sin(\beta)$$

$$\cos(\alpha \pm \beta) = \cos(\alpha) \cos(\beta) \mp \sin(\alpha) \sin(\beta)$$

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Double angle formulas

$$\sin(2\theta) = 2 \sin(\theta) \cos(\theta)$$

$$\cos(2\theta) = \cos^2(\theta) - \sin^2(\theta)$$

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Half angle formulas

$$\sin^2(\theta) = \frac{1 - \cos(2\theta)}{2}$$

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

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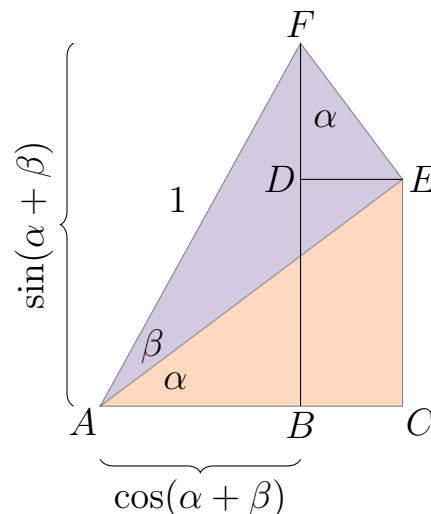
### Derivation of angle sum formulas

$$\sin(\alpha) = \frac{\overline{DE}}{\overline{EF}} = \frac{\overline{DE}}{\sin(\beta)} \Rightarrow \overline{DE} = \sin(\alpha) \sin(\beta)$$

$$\cos(\alpha) = \frac{\overline{DF}}{\overline{EF}} = \frac{\overline{DF}}{\sin(\beta)} \Rightarrow \overline{DF} = \cos(\alpha) \sin(\beta)$$

$$\sin(\alpha) = \frac{\overline{CE}}{\overline{AE}} = \frac{\overline{CE}}{\cos(\beta)} \Rightarrow \overline{CE} = \sin(\alpha) \cos(\beta)$$

$$\cos(\alpha) = \frac{\overline{AC}}{\overline{AE}} = \frac{\overline{AC}}{\cos(\beta)} \Rightarrow \overline{AC} = \cos(\alpha) \cos(\beta)$$



### Derivation of the double angle formulas

$$\sin(2\theta) = \sin(\theta + \theta) = \sin(\theta) \cos(\theta) + \cos(\theta) \sin(\theta) = 2 \sin(\theta) \cos(\theta)$$

$$\cos(2\theta) = \cos(\theta + \theta) = \cos(\theta) \cos(\theta) - \sin(\theta) \sin(\theta) = \cos^2(\theta) - \sin^2(\theta)$$

### Derivation of the half angle formulas

Start with the cosine double angle formula:

$$\cos(2\theta) = \cos^2(\theta) - \sin^2(\theta) = \boxed{2 \cos^2(\theta) - 1} = \boxed{1 - 2 \sin^2(\theta)}$$

Solve for either  $\sin^2(\theta)$  or  $\cos^2(\theta)$ :

$$\sin^2(\theta) = \frac{1 - \cos(2\theta)}{2}$$

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

**Example.** Evaluate the integral  $\int \cos^5(x) \, dx$ .

**Example.** Evaluate the integral  $\int \sin^3(x) \cos^{3/2}(x) dx$ .

**Example.** Evaluate the integral  $\int 20 \sin^2(x) \cos^2(x) dx$

**Example.** Evaluate the integral  $\int \sec^6(x) \tan^4(x) dx$ .

**Example.** Evaluate the integral  $\int 35 \tan^5(x) \sec^4(x) dx$ .

**Example.** Consider the region bounded by  $y = \sec(x)$  and  $y = \cos(x)$  for  $0 \leq x \leq \pi/3$ . Find the volume of the solid generated when rotating this region about the line  $y = -1$ .



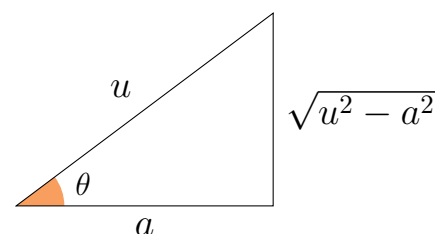
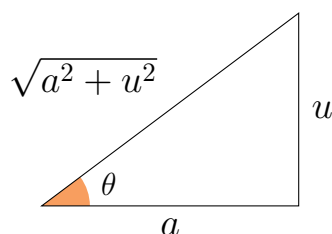
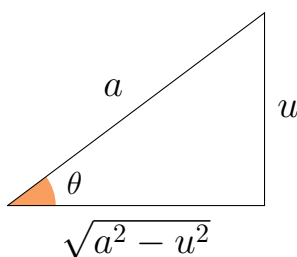
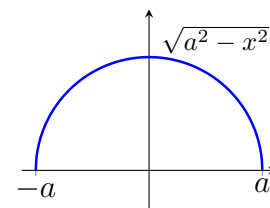


**Example.** Find the length of the curve  $y = \ln(2 \sec(x))$  on the interval  $[0, \pi/6]$ .

$\int \sin^m(x) \cos^n(x) dx$	<b>Strategy</b>
$m$ odd and positive, $n$ real	Split off $\sin(x)$ , rewrite the resulting even power of $\sin(x)$ in terms of $\cos(x)$ , and then use $u = \cos(x)$ .
$n$ odd and positive, $m$ real	Split off $\cos(x)$ , rewrite the resulting even power of $\cos(x)$ in terms of $\sin(x)$ , and then use $u = \sin(x)$ .
$m$ and $n$ both even, nonnegative integers	Use half-angle formulas to transform the integrand into a polynomial in $\cos(2x)$ , and apply the preceding strategies once again to powers of $\cos(2x)$ greater than 1.
$\int \tan^m(x) \sec^n(x) dx$	
$n$ even and positive, $m$ real	Split off $\sec^2(x)$ , rewrite the remaining even power of $\sec(x)$ in terms of $\tan(x)$ , and use $u = \tan(x)$ .
$m$ odd and positive, $n$ real	Split off $\sec(x) \tan(x)$ , rewrite the remaining even power of $\tan(x)$ in terms of $\sec(x)$ , and use $u = \sec(x)$ .
$m$ even and positive, $n$ odd and positive	Rewrite $\tan^m(x)$ in terms of $\sec(x)$
$\int \sec^n(x) dx$	
$n$ odd	Use integration by parts with $u = \sec^{n-2}(x)$ and $dv = \sec^2(x) dx$
$n$ even	Split off $\sec^2(x)$ , rewrite the remaining powers of $\sec(x)$ in terms of $\tan(x)$ , and use $u = \tan(x)$ .
$\int \tan^m(x) dx$	Split off $\tan^2(x)$ and rewrite in terms of $\sec(x)$ . Expand into difference of integrals substituting $u = \tan(x)$ . Repeat the process as needed for remaining powers of $\tan(x)$ .

## 8.4: Trigonometric Substitutions

**Example.** Verify the formula for the area of a circle with radius  $a$  by finding the area under  $f(x) = \sqrt{a^2 - x^2}$ .



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$a^2 - u^2$	$u = a \sin(\theta), \quad -\frac{\pi}{2} \leq \theta \leq \frac{\pi}{2}, \quad \text{for }  u  \leq a$	$a^2 - a^2 \sin^2(\theta) = a^2 \cos^2(\theta)$
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$a^2 + u^2$	$u = a \tan(\theta), \quad -\frac{\pi}{2} < \theta < \frac{\pi}{2},$	$a^2 + a^2 \tan^2(\theta) = a^2 \sec^2(\theta)$
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$u^2 - a^2$	$u = a \sec(\theta), \quad \begin{cases} 0 \leq \theta < \frac{\pi}{2}, & \text{for } u \geq a \\ \frac{\pi}{2} < \theta \leq \pi, & \text{for } u \leq -a \end{cases}$	$a^2 \sec^2(\theta) - a^2 = a^2 \tan^2(\theta)$
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**Example.**  $\int \frac{\sqrt{x^2 - 4}}{x^3} dx$

**Example.**  $\int \frac{\sqrt{16 - x^2}}{x} dx$

**Example.**  $\int \frac{x^2}{(25 - 4x^2)^{3/2}} dx$

**Example.**  $\int_0^{1/3} \frac{dx}{(9x^2 + 1)^{3/2}}$

**Example.**  $\int \frac{x}{\sqrt{x^2 - 2x + 10}}$



## 8.5: Partial Fractions

**Example.** Simplify  $f(x) = \frac{1}{x-2} + \frac{2}{x+4}$  by finding a common denominator.

### Procedure: Partial Fractions with Simple Linear Factors

Suppose  $f(x) = p(x)/q(x)$ , where  $p$  and  $q$  are polynomials with no common factors and with the degree of  $P$  less than the degree of  $q$ . Assume  $q$  is the product of simple linear factors. The partial fraction decomposition is obtained as follows.

**Step 1: Factor the denominator**  $q$  in the form  $(x - r_1)(x - r_2) \dots (x - r_n)$

**Step 2: Partial fraction decomposition**

$$\frac{p(x)}{q(x)} = \frac{A_1}{(x - r_1)} + \frac{A_2}{(x - r_2)} + \dots + \frac{A_n}{(x - r_n)}.$$

**Step 3: Clear denominators** Multiply both sides of the equation in Step 2 by  $q(x) = (x - r_1)(x - r_2) \dots (x - r_n)$

**Step 4: Solve for coefficients** Equate like powers of  $x$  in Step 3 to solve for the undetermined coefficients  $A_1, \dots, A_n$ .

**Example.** Perform partial fraction decomposition on  $f(x) = \frac{3x}{x^2 + 2x - 8}$ .

**Example.**  $\int \frac{28x^3 - 56x^2 + 9}{x^2 - 2x} dx$

**Procedure: Partial Fractions for Repeated Linear Factors**

Suppose the repeated linear factor  $(x - r)^m$  appears in the denominator of a proper rational function in reduced form. The partial fraction decomposition has a partial fraction for each power of  $(x - r)$  up to and including the  $m$ th power; that is, the partial fraction decomposition contains the sum

$$\frac{A_1}{(x - r)} + \frac{A_2}{(x - r)^2} + \frac{A_3}{(x - r)^3} + \cdots + \frac{A_m}{(x - r)^m}$$

where  $A_1, \dots, A_m$  are constants to be determined.

**Example.** Setup the partial fraction decomposition for  $f(x) = \frac{x^3 - 8x + 19}{x^4 + 3x^3}$ .

**Example.** Setup the partial fraction decomposition for  $g(x) = \frac{2}{x^5 - 6x^4 + 9x^3}$ .

**Example.** Evaluate  $\int \frac{x^2 + 1}{(2x - 3)(x - 2)^2} dx$ .

**Example.** Evaluate  $\int \frac{8}{3x^3 + 7x^2 + 4x} dx$ .

**Procedure: Partial Fractions with Simple Irreducible Quadratic Factors**

Suppose a simple irreducible factor  $ax^2+bx+c$  appears in the denominator of a proper rational function in reduced form. The partial fraction decomposition contains a term of the form

$$\frac{Ax+B}{ax^2+bx+c},$$

where  $A$  and  $B$  are unknown coefficients to be determined.

**Example.** Perform partial fraction decomposition on the following fractions or identify them as irreducible.

$$\frac{1}{x^2 - 13x + 43}$$

$$\frac{x^2}{(x-4)(x+5)}$$

**Example.** Perform partial fraction decomposition on the following fractions or identify them as irreducible.

$$\frac{7}{(x^2 + 1)^2}$$

$$\frac{1}{x^2 + 11x + 28}$$

**Example.** Evaluate  $\int \frac{4x}{(x+1)(x^2+1)} dx$



**Example.** Evaluate  $\int \frac{3x^2 + 2x + 12}{(x^2 + 4)^2} dx$

**Example.** Evaluate  $\int \frac{1}{x\sqrt{1+2x}} dx$  using the substitution  $u = \sqrt{1+2x}$ .

### Summary: Partial Fraction Decomposition

Let  $f(x) = p(x)/q(x)$  be a proper rational function in reduced form. Assume the denominator  $q$  has been factored completely over the real numbers and  $m$  is a positive integer.

1. **Simple linear factor:** A factor  $x - r$  in the denominator requires the partial fraction  $\frac{A}{x - r}$ .

2. **Repeated linear factor:** A factor  $(x - r)^m$  with  $m > 1$  in the denominator requires the partial fractions

$$\frac{A_1}{(x - r)} + \frac{A_2}{(x - r)^2} + \frac{A_3}{(x - r)^3} + \cdots + \frac{A_m}{(x - r)^m}.$$

3. **Simple irreducible quadratic factor:** An irreducible factor  $ax^2 + bx + c$  in the denominator requires the partial fraction

$$\frac{Ax + B}{ax^2 + bx + c}.$$

4. **Repeated irreducible quadratic factor:** An irreducible factor  $(ax^2 + bx + c)^m$  with  $m > 1$  in the denominator requires the partial fractions

$$\frac{A_1x + B_1}{ax^2 + bx + c} + \frac{A_2x + B_2}{(ax^2 + bx + c)^2} + \cdots + \frac{A_mx + B_m}{(ax^2 + bx + c)^m}.$$

## 8.6: Integration Strategies

**Example.** What integration methods can be used to evaluate the functions below?  
(No need to evaluate the integral)

$$\int \frac{1}{1-x^2} dx$$

$$\int x \sec^2(x) dx$$

$$\int \frac{x}{\sqrt{64-x^2}} dx$$

$$\int \frac{x^3}{\sqrt{64-x^2}} dx$$

**Example.** Identify two integration techniques which can be used to evaluate

$$\int \frac{4 - 3x^2}{x(x^2 - 4)} dx.$$

**Example.** Perform a substitution of variables to rewrite  $\int x \sin(\sqrt{x}) dx$ .

**Example.**  $\int_1^3 \frac{\tan^{-1}(\sqrt{x})}{x^{1/2} + x^{3/2}} dx$

## 8.9: Improper Integrals

### Definition. (Improper Integrals over Infinite Intervals)

1. If  $f$  is continuous on  $[a, \infty)$ , then

$$\int_a^{\infty} f(x) dx = \lim_{b \rightarrow \infty} \int_a^b f(x) dx.$$

2. If  $f$  is continuous on  $(-\infty, b]$ , then

$$\int_{-\infty}^b f(x) dx = \lim_{a \rightarrow -\infty} \int_a^b f(x) dx.$$

3. If  $f$  is continuous on  $(-\infty, \infty)$ , then

$$\int_{-\infty}^{\infty} f(x) dx = \lim_{a \rightarrow -\infty} \int_a^c f(x) dx + \lim_{b \rightarrow \infty} \int_c^b f(x) dx.$$

where  $c$  is any real number. It can be shown that the choice of  $c$  does not affect the value or convergence of the original integral.

If the limits in cases 1.– 3. exist, then the improper integrals **converge**; otherwise they **diverge**.

**Example.** Evaluate  $\int_1^{\infty} \frac{\ln(x)}{x} dx$  and determine if the integral converges or diverges.

**Example.** Evaluate  $\int_{-\infty}^{\infty} \frac{e^{3x}}{1 + e^{6x}} dx$ .



**Example.** For what values of  $p$  does  $\int_1^\infty \frac{1}{x^p} dx$  converge?

**Definition. (Improper Integrals with Unbounded Integrand)**

1. Suppose  $f$  is continuous on  $(a, b]$  with  $\lim_{x \rightarrow a^+} f(x) = \pm\infty$ . Then

$$\int_a^b f(x) dx = \lim_{c \rightarrow a^+} \int_c^b f(x) dx.$$

2. Suppose  $f$  is continuous on  $[a, b)$  with  $\lim_{x \rightarrow b^-} f(x) = \pm\infty$ . Then

$$\int_a^b f(x) dx = \lim_{c \rightarrow b^-} \int_a^c f(x) dx.$$

3. Suppose  $f$  is continuous on  $[a, b]$  except at the interior point  $p$  where  $f$  is unbounded. Then

$$\int_a^b f(x) dx = \lim_{c \rightarrow p^-} \int_a^c f(x) dx + \lim_{d \rightarrow p^+} \int_d^b f(x) dx.$$

If the limits in cases 1.– 3. exist, then the improper integrals **converge**; otherwise, they **diverge**.

**Example.** Determine which of the following integrals are improper integrals

$$\int_0^1 \sec(x) \, dx$$

$$\int_{\pi/2}^{3\pi/4} \tan(x) \, dx$$

$$\int_1^e \ln(x) \, dx$$

$$\int_0^1 \arctan(x) \, dx$$

$$\int_0^{0.5} \ln(x) \, dx$$

$$\int_{-10}^{-1} \frac{1}{x^{1/3}} \, dx$$

**Example.** Evaluate  $\int_1^9 \frac{dx}{(x-1)^{2/3}}$ . Does this integral converge or diverge?

**Example.** Evaluate  $\int_{-1}^1 \frac{e^{2/x}}{x^2} dx$ . Does this integral converge or diverge?

**Theorem 8.2: Comparison Test for Improper Integrals**

Suppose the functions  $f$  and  $g$  are continuous on the interval  $[a, \infty)$ , with  $f(x) \geq g(x) \geq 0$ , for  $x \geq a$ .

1. If  $\int_a^\infty f(x) dx$  converges, then  $\int_a^\infty g(x) dx$  converges.
2. If  $\int_a^\infty g(x) dx$  diverges, then  $\int_a^\infty f(x) dx$  diverges.

**Example.** Determine if the integral  $\int_2^\infty \frac{x^3}{x^4 - x^3 - 1} dx$  converges or diverges.

**Example** (Gabriel's Horn). Let  $R$  be the region bounded by the graph of  $y = 1/x$  and the  $x$ -axis for  $x \geq 1$ .

What is the volume of the solid generated when  $R$  is revolved around the  $x$ -axis?

What is the surface area of the solid generated when  $R$  is revolved about the  $x$ -axis?

## 10.1: An Overview of Sequences and Infinite Series

### Definition. (Sequence)

A **sequence**  $\{a_n\}$  is an ordered list of numbers of the form

$$\{a_1, a_2, a_3, \dots, a_n, \dots\}.$$

A sequence may be generated by a **recurrence relation** of the form  $a_{n+1} = f(a_n)$ , for  $n = 1, 2, 3, \dots$ , where  $a_1$  is given. A sequence may also be defined with an **explicit formula** of the form  $a_n = f(n)$ , for  $n = 1, 2, 3, \dots$ .

**Example.** Consider the sequence  $a_n = \frac{2^{n+1}}{2^n+1}$ ; Compute  $a_1$ ,  $a_2$ ,  $a_3$ , and  $a_4$ .



**Definition. (Limit of a Sequence)**

If the terms of a sequence  $\{a_n\}$  approach a unique number  $L$  as  $n$  increases— that is, if  $a_n$  can be made arbitrarily close to  $L$  by taking  $n$  sufficiently large— then we say  $\lim_{n \rightarrow \infty} a_n = L$  exists, and the sequence **converges** to  $L$ . If the terms of the sequence do not approach a single number as  $n$  increases, the sequence has no limit, and the sequence **diverges**.

**Example.** Determine if the sequence given by

$$a_n = \frac{3 + 5n^2}{n + n^2}$$

converges or diverges. If it converges, find the value that the sequence converges to.

**Example.** Determine if the sequence given by

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

converges or diverges. If it converges, find the value that the sequence converges to.

**Example.** A ball is thrown upward to a height of 10 meters. After each bounce, the ball rebounds to  $\frac{2}{3}$  of its previous height. Let  $h_n$  be the height after the  $n$ th bounce. Find an explicit formula for the  $n$ th term of the sequence  $\{h_n\}$ .

**Definition. (Infinite series)**

Given a sequence  $\{a_1, a_2, a_3, \dots\}$ , the sum of its terms

$$a_1 + a_2 + a_3 + \cdots = \sum_{k=1}^{\infty} a_k$$

is called an **infinite series**. The **sequence of partial sums**  $\{S_n\}$  associated with this series has the terms

$$S_1 = a_1$$

$$S_2 = a_1 + a_2$$

$$S_3 = a_1 + a_2 + a_3$$

$$\vdots$$

$$S_n = a_1 + a_2 + a_3 + \cdots + a_n = \sum_{k=1}^n a_k, \quad \text{for } n = 1, 2, 3, \dots$$

If the sequence of partial sums  $\{S_n\}$  has a limit  $L$ , the infinite series **converges** to that limit, and we write

$$\sum_{k=1}^{\infty} a_k = \lim_{n \rightarrow \infty} \underbrace{\sum_{k=1}^n a_k}_{S_n} = \lim_{n \rightarrow \infty} S_n = L.$$

If the sequence of partial sums diverges, the infinite series also **diverges**.

**Example.** Consider the infinite series  $4 + 0.9 + 0.09 + 0.009 + \dots$ . Compute  $S_1$ ,  $S_2$ ,  $S_3$ , and  $S_4$ . What is the value of this series?

**Example.** A sequence  $\{a_n\}$  has partial sums given by the formula  $S_n = 5 - \frac{1}{\sqrt{n}}$ .

What is the value of the series  $\sum_{n=1}^{\infty} a_n$ ?

What is the formula for  $a_n$ ?

What is the limit  $\lim_{n \rightarrow \infty} a_n$ ?

## 10.2: Sequences

### Theorem 10.1: Limits of Sequences from Limits of Functions

Suppose  $f$  is a function such that  $f(n) = a_n$ , for positive integers  $n$ . If  $\lim_{x \rightarrow \infty} f(x) = L$ , then the limit of the sequence  $\{a_n\}$  is also  $L$ , where  $L$  may be  $\pm\infty$ .

**Example.** Determine if the following sequences converge or diverge. If the sequence converges, find its limit.

$$\left\{ e^{2n/(n+2)} \right\}_{n=1}^{\infty}$$

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

$$\left\{ \frac{\arctan(n)}{n} \right\}_{n=1}^{\infty}$$

$$\left\{ \frac{e^{-n}}{42 \sin(e^{-n})} \right\}_{n=1}^{\infty}$$

## 10.2: Limit Laws for Sequences

Assume the sequences  $\{a_n\}$  and  $\{b_n\}$  have limits  $A$  and  $B$ , respectively. Then

1.  $\lim_{n \rightarrow \infty} (a_n \pm b_n) = A \pm B$
2.  $\lim_{n \rightarrow \infty} ca_n = cA$ , where  $c$  is a real number
3.  $\lim_{n \rightarrow \infty} a_nb_n = AB$
4.  $\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = \frac{A}{B}$ , provided  $B \neq 0$ .

**Example.** Consider the sequences  $\{a_n\}$ ,  $\{b_n\}$ ,  $\{c_n\}$ , and  $\{d_n\}$  where

$$a = \frac{1}{n}, \quad b_n = n, \quad c_n = e^n, \quad \text{and } d_n = \sqrt{n}.$$

Compute the following limits.

A.  $\lim_{n \rightarrow \infty} a_n$

B.  $\lim_{n \rightarrow \infty} b_n$

C.  $\lim_{n \rightarrow \infty} c_n$

D.  $\lim_{n \rightarrow \infty} d_n$

E.  $\lim_{n \rightarrow \infty} a_nb_n$

F.  $\lim_{n \rightarrow \infty} a_nc_n$

G.  $\lim_{n \rightarrow \infty} a_nd_n$

True or False: If for some sequence  $\{a_n\}$  and  $\{b_n\}$ ,  $\lim_{n \rightarrow \infty} a_n = 0$  and  $\lim_{n \rightarrow \infty} b_n = \infty$ , then  $\lim_{n \rightarrow \infty} a_nb_n = 0$ .

**Definition. (Terminology for Sequences)**

- $\{a_n\}$  is **increasing** if  $a_{n+1} > a_n$
- $\{a_n\}$  is **nondecreasing** if  $a_{n+1} \geq a_n$
- $\{a_n\}$  is **decreasing** if  $a_{n+1} < a_n$
- $\{a_n\}$  is **nonincreasing** if  $a_{n+1} \leq a_n$
- $\{a_n\}$  is **monotonic** if it is either nonincreasing or nondecreasing (it moves in one direction)
- $\{a_n\}$  is **bounded above** if there is a number  $M$  such that  $a_n \leq M$ , for all relevant values of  $n$
- $\{a_n\}$  is **bounded below** if there is a number  $N$  such that  $a_n \geq N$ , for all relevant values of  $n$ .
- If  $\{a_n\}$  is bounded above and bounded below, then we say that  $\{a_n\}$  is a **bounded** sequence.

**Example.** Consider the sequence  $\{-n^2\}_{n=1}^{\infty}$ . What can we say about this sequence?

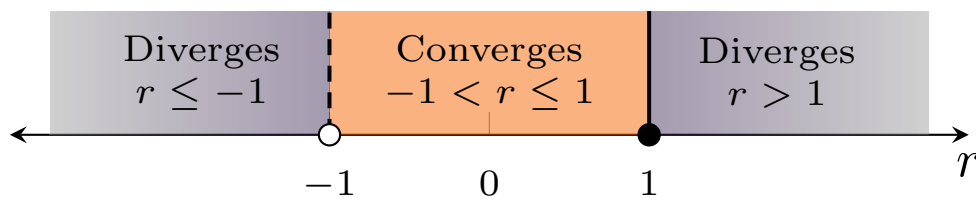


### Theorem 10.3: Geometric Sequences

Let  $r$  be a real number. Then

$$\lim_{n \rightarrow \infty} r^n = \begin{cases} 0 & \text{if } |r| < 1 \\ 1 & \text{if } r = 1 \\ \text{does not exist} & \text{if } r \leq -1 \text{ or } r > 1. \end{cases}$$

If  $r > 0$ , then  $\{r^n\}$  is a monotonic sequence. If  $r < 0$ , then  $\{r^n\}$  oscillates.



**Example.** Determine if the following sequences converge

$$\left\{ \frac{3^{n+1} + 3}{3^n} \right\}$$

$$\{2^{n+1}3^{-n}\}$$

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

$$\left\{ \frac{75^{n-1}}{99^n} + \frac{5^n \sin(n)}{8^n} \right\}$$

**Theorem 10.4: Squeeze Theorem for Sequences**

Let  $\{a_n\}$ ,  $\{b_n\}$ , and  $\{c_n\}$  be sequences with  $a_n \leq b_n \leq c_n$ , for all integers  $n$  greater than some index  $N$ . If  $\lim_{n \rightarrow \infty} a_n = \lim_{n \rightarrow \infty} c_n = L$ , then  $\lim_{n \rightarrow \infty} b_n = L$ .

**Example.** Find the limit of the sequence  $b_n = \frac{9 \cos(n)}{n^2 + 1}$ .

**Theorem 10.5: Bounded Monotonic Sequence**

A bounded monotonic sequence converges.

**Theorem 10.6: Growth Rates of Sequences**

The following sequences are ordered according to increasing growth rates as  $n \rightarrow \infty$ ; that is, if  $\{a_n\}$  appears before  $\{b_n\}$  in the list, then  $\lim_{n \rightarrow \infty} \frac{a_n}{b_n} = 0$  and  $\lim_{n \rightarrow \infty} \frac{b_n}{a_n} = \infty$ :

$$\{(\ln n)^q\} \ll \{n^p\} \ll \{n^p(\ln n)^r\} \ll \{n^{p+s}\} \ll \{b^n\} \ll \{n!\} \ll \{n^n\}$$

**Example.** Use growth rates to determine which of the following sequences converge.

$$\left\{ \frac{\ln(n^{10})}{0.00001n} \right\}$$

$$\left\{ \frac{n^8 \ln(n)}{n^{8.001}} \right\}$$

$$\left\{ \frac{n!}{10^n} \right\}$$

**Definition. (Limit of a Sequence)**

The sequence  $\{a_n\}$  converges to  $L$  provided the terms of  $a_n$  can be made arbitrarily close to  $L$  by taking  $n$  sufficiently large. More precisely,  $\{a_n\}$  has the unique limit  $L$  if, given any  $\varepsilon > 0$ , it is possible to find a positive integer  $N$  (depending only on  $\varepsilon$ ) such that

$$|a_n - L| < \varepsilon \quad \text{whenever } n > N.$$

If the **limit of a sequence** is  $L$ , we say the sequence **converges** to  $L$ , written

$$\lim_{n \rightarrow \infty} a_n = L.$$

A sequence that does not converge is said to **diverge**.

### 10.3: Infinite Series

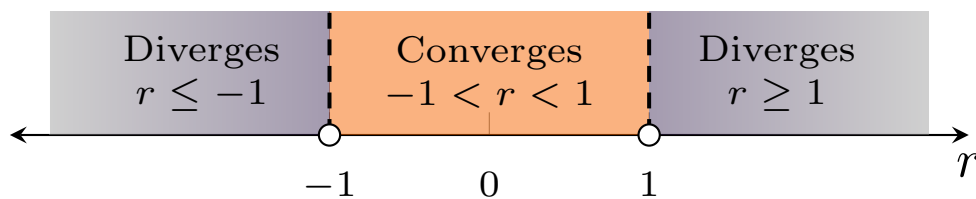
A **Geometric sum** with  $n$  terms has the form

$$S_n = a + ar + ar^2 + \cdots + ar^{n-1} = \sum_{k=0}^{n-1} ar^k$$

**Derivation of partial sum formula:**

#### Theorem 10.7: Geometric Series

Let  $a \neq 0$  and  $r$  be real numbers. If  $|r| < 1$ , then  $\sum_{k=0}^{\infty} ar^k = \frac{a}{1-r}$ . If  $|r| \geq 1$ , then the series diverges.



**Example.** Evaluate the following geometric series or state that the series diverges

$$\sum_{k=0}^{\infty} 1.1^k$$

$$\sum_{k=0}^{\infty} e^{-k}$$

$$\sum_{k=2}^{\infty} 3(-0.75)^k$$

$$\sum_{k=1}^{\infty} \frac{7}{10^k}$$

### Telescoping Series:

**Example.** Evaluate the following series

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

$$\sum_{k=3}^{\infty} \frac{1}{(k-2)(k-1)}$$

### Theorem 10.8: Properties of Convergent Series

1. Suppose  $\sum a_k$  converges to  $A$  and  $c$  is a real number. The series  $\sum ca_k$  converges, and  $\sum ca_k = c \sum a_k = cA$ .
2. Suppose  $\sum a_k$  diverges. Then  $\sum ca_k$  also diverges, for any real number  $c \neq 0$ .
3. Suppose  $\sum a_k$  converges to  $A$  and  $\sum b_k$  converges to  $B$ . The series  $\sum (a_k \pm b_k)$  converges and  $\sum (a_k \pm b_k) = \sum a_k \pm \sum b_k = A \pm B$ .
4. Suppose  $\sum a_k$  diverges and  $\sum b_k$  converges. Then  $\sum (a_k \pm b_k)$  diverges.
5. If  $M$  is a positive integer, then  $\sum_{k=1}^{\infty} a_k$  and  $\sum_{k=M}^{\infty} a_k$  either both converge or both diverge. In general, *whether* a series converges does not depend on a finite number of terms added to or removed from the series. However, the *value* of a convergent series does change if nonzero terms are added or removed.

**Example.** Evaluate

$$\sum_{k=1}^{\infty} \left[ \frac{1}{2} \left( \frac{2}{5} \right)^k + \frac{2}{3} \left( \frac{1}{6} \right)^k \right]$$



## 10.4: The Divergence and Integral Tests

### Theorem 10.9: Divergence Test

If  $\sum a_k$  converges, then  $\lim_{k \rightarrow \infty} a_k = 0$ . Equivalently, if  $\lim_{k \rightarrow \infty} a_k \neq 0$ , then the series diverges.

**Example.** If  $\lim_{k \rightarrow \infty} a_k = 1$ , what can we conclude about  $\sum_{k=1}^{\infty} a_k$ ?

**Example.** If  $\sum_{k=1}^{\infty} a_k = 42$ , what can we conclude about  $\lim_{k \rightarrow \infty} a_k$ ?

**Example.** If  $\lim_{k \rightarrow \infty} a_k = 0$ , what can we conclude about  $\sum_{k=1}^{\infty} a_k$ ?

**Example.** Determine which of the following series diverge by the divergence test.

$$\sum_{k=1}^{\infty} \frac{1}{\sqrt{k+1}}$$

$$\sum_{k=1}^{\infty} \frac{k^3 + 100}{3k^3 + k + 1}$$

$$\sum_{k=1}^{\infty} \frac{e^k}{k^2}$$

Table 1 Series Convergence				
Scenario	Sequence of Terms $\{a_1, a_2, a_3, \dots\}$	Sequence of Partial Sums $\{s_1, s_2, s_3, \dots\}$	Series $\sum_{n=1}^{\infty} a_n$	Possible or Impossible?
<b>A</b>	Converges	Diverges	Diverges	
<b>B</b>	Converges	Diverges	Converges	
<b>C</b>	Converges	Converges	Diverges	
<b>D</b>	Converges	Converges	Converges	
<b>E</b>	Diverges	Converges	Diverges	
<b>F</b>	Diverges	Converges	Converges	
<b>G</b>	Diverges	Diverges	Diverges	
<b>H</b>	Diverges	Diverges	Converges	

### Theorem 10.10: Harmonic Series

The harmonic series  $\sum_{k=1}^{\infty} \frac{1}{k} = 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \frac{1}{5} + \dots$  diverges—even though the terms of the series approach zero.

**Theorem 10.11: Integral Test**

Suppose  $f$  is a continuous, positive, decreasing function, for  $x \geq 1$ , and let  $a_k = f(k)$ , for  $k = 1, 2, 3, \dots$ . Then

$$\sum_{k=1}^{\infty} a_k \text{ and } \int_1^{\infty} f(x) dx$$

either both converge or both diverge. In the case of convergence, the value of the integral is *not* equal to the value of the series.

**Example.** Which of the following series below satisfy all the conditions to use the Integral Test?

$$\sum_{k=1}^{\infty} \arctan(k)$$

$$\sum_{k=1}^{\infty} \frac{(-1)^k}{k^2}$$

$$\sum_{k=1}^{\infty} \frac{1}{e^k}$$

**Example.** Consider the series

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

Use the integral test to show that the Harmonic Series diverges. For what values of  $p$  does this series converge?

**Theorem 10.12: Convergence of the  $p$ -series**

The  $p$ -series  $\sum_{k=1}^{\infty} \frac{1}{k^p}$  converges for  $p > 1$  and diverges for  $p \leq 1$ .

**Example.** Determine if the following  $p$ -series converge or diverge.

$$\sum_{k=1}^{\infty} \frac{1}{k^2}$$

$$\sum_{k=1}^{\infty} k^{-1/3}$$

$$\sum_{k=1}^{\infty} \frac{k^2}{k^{\pi}}$$

$$\sum_{k=1}^{\infty} \frac{2}{k}$$

$$\sum_{k=1}^{\infty} \frac{-3}{\sqrt[3]{k^4}}$$

$$\sum_{k=1}^{\infty} \frac{k^3 + 1}{k^5}$$

**Example.** Apply the Integral Test to determine if the series  $\sum_{k=1}^{\infty} \frac{1}{\sqrt{k+1}}$  converges or diverges.

**Theorem 10.13: Estimating Series with Positive Terms**

Let  $f$  be a continuous, positive, decreasing function, for  $x \geq 1$ , and let  $a_k = f(k)$ , for  $k = 1, 2, 3, \dots$ . Let  $S = \sum_{k=1}^{\infty} a_k$  be a convergent series and let  $S_n = \sum_{k=1}^n a_k$  be the sum of the first  $n$  terms of the series. The remainder  $R_n = S - S_n$  satisfies

$$R_n < \int_n^{\infty} f(x) dx.$$

Furthermore, the exact value of the series is bounded as follows:

$$L_n = S_n + \int_{n+1}^{\infty} f(x) dx < \sum_{k=1}^{\infty} a_k < S_n + \int_n^{\infty} f(x) dx = U_n.$$

**Example.** How many terms of the convergent  $p$ -series  $\sum_{k=1}^{\infty} \frac{1}{k^2}$  must be summed to obtain an approximation that is within  $10^{-3}$  of the exact value of the series?



## 10.5: Comparison Tests

**Theorem 10.14: Comparison Test**

Let  $\sum a_k$  and  $\sum b_k$  be series with positive terms where  $a_k \leq b_k$ .

1. If  $\sum b_k$  converges, then  $\sum a_k$  converges.
2. If  $\sum a_k$  diverges, then  $\sum b_k$  diverges.

**Example.** Use the comparison test to determine if the series  $\sum_{k=1}^{\infty} \frac{k^2}{k^3 - 3}$  converges or diverges.

**Theorem 10.15: Limit Comparison Test**

Let  $\sum a_k$  and  $\sum b_k$  be series with positive terms and let

$$\lim_{k \rightarrow \infty} \frac{a_k}{b_k} = L.$$

1. If  $0 < L < \infty$  (that is,  $L$  is a finite positive number), then  $\sum a_k$  and  $\sum b_k$  either both converge or both diverge.
2. If  $L = 0$  and  $\sum b_k$  converges, then  $\sum a_k$  converges.
3. If  $L = \infty$  and  $\sum b_k$  diverges, then  $\sum a_k$  diverges.

**Example.** Using either the Comparison Test or the Limit Comparison Test, determine if the series

$$\sum_{k=1}^{\infty} \frac{4k^2 - k}{k^3 + 9}$$

converges or diverges.

**Example.** Determine if the following series converge or diverge.

$$\sum_{k=1}^{\infty} \frac{1}{k\sqrt{k^2+1}}$$

$$\sum_{k=1}^{\infty} \frac{\ln(k)}{k^2}$$

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

$$\frac{1}{14^3} + \frac{2}{15^3} + \frac{3}{16^3} + \cdots$$

$$\sum_{k=1}^{\infty} \frac{\sin\left(\frac{\pi}{k}\right)}{k^3}$$

$$\sum_{k=1}^{\infty} \frac{\sqrt[3]{k^2 + 4}}{\sqrt{k^3 + 9}}$$