MTH 15: APPLIED CALCULUS I



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Introduction

Introduction

A Preview of Calculus

Calculus was first developed more than three hundred years ago by Sir Isaac Newton and Gottfried Leibniz to help them describe and understand the rules governing the motion of planets and moons. Since then, thousands of other men and women have refined the basic ideas of calculus, developed new techniques to make the calculations easier, and found ways to apply calculus to problems besides planetary motion. Perhaps most importantly, they have used calculus to help understand a wide variety of physical, biological, economic and social phenomena and to describe and solve problems in those areas.

Part of the beauty of calculus is that it is based on a few very simple ideas. Part of the power of calculus is that these simple ideas can help us understand, describe, and solve problems in a variety of fields.

About this book

Chapter 1 Review contains review material that you should recall before we begin calculus.

Chapter 2 The Derivative builds on the precalculus idea of the slope of a line to let us find and use rates of change in many situations.

Chapter 3 The Integral builds on the precalculus idea of the area of a rectangle to let us find accumulated change in more complicated and interesting settings.

Chapter 4 Functions of Two Variables extends the calculus ideas of chapter 2 to functions of more than one variable.

Supplements

An online course framework is available on MyOpenMath.com for this book. The course framework features:

- Links to individual sections of the e-text.
- Overview videos.
- Algorithmic, auto-grading online homework for each section of the text. Most problems have video help tied to the question.
- A collection of printable resources created by Shana Calaway for the Open Course Library project.

How is Applied Calculus Different?

Students who plan to go into science, engineering, or mathematics take a year-long sequence of classes that cover many of the same topics as we do in our one-quarter or one-semester course. Here are some of the differences:

No trigonometry

We will not be using trigonometry at all in this course. The scientists and engineers need trigonometry frequently, and so a great deal of the engineering calculus course is devoted to trigonometric functions and the situations they can model.

The applications are different

The scientists and engineers learn how to apply calculus to physics problems, such as work. They do a lot of geometric applications, like finding minimum distances, volumes of revolution, or arclengths. In this class, we will do only a few of these (distance/velocity problems, areas between curves). On the other hand, we will learn to apply calculus in some economic and business settings, like maximizing profit or minimizing average cost, finding elasticity of demand, or finding the present value of

a continuous income stream. Additionally we will apply calculus in life and social science settings, like determining the rate at which drug concentration in the body is changing, or exploring the rate at which a subject learns. These are applications that are seldom seen in a course for engineers.

Fewer theorems, no proofs

The focus of this course is applications rather than theory. In this course, we will use the results of some theorems, but we won't prove any of them. When you finish this course, you should be able to solve many kinds of problems using calculus, but you won't be prepared to go on to higher mathematics.

Less algebra

In this class, you will not need clever algebra. If you need to solve an equation, it will either be relatively simple, or you can use technology to solve it. In most cases, you won't need "exact answers;" calculator numbers will be good enough.

Simplification and Calculator Numbers

When you were in tenth grade, your math teacher may have impressed you with the need to simplify your answers. I'm here to tell you – she was wrong. The form your answer should be in depends entirely on what you will do with it next. In addition, the process of "simplifying," often messy algebra can ruin perfectly correct answers. From the teacher's point of view, "simplifying" obscures how a student arrived at his answer, and makes problems harder to grade. Moral: don't spend a lot of extra time simplifying your answer. Leave it as close to how you arrived at it as possible.

When should you simplify?

1. Simplify when it actually makes your life easier. For example, in Chapter 2 it's easier to find a second derivative if you simplify the first derivative.

2. Simplify your answer when you need to match it to an answer in the book. You may need to do some algebra to be sure your answer and the book answer are the same.

When you use your calculator

A calculator is required for this course, and it can be a wonderful tool. However, you should be careful not to rely too strongly on your calculator. Follow these rules of thumb:

1. Estimate your answers. If you expect an answer of about 4, and your calculator says 2500, you've made an error somewhere.
2. Don't round until the very end. Every time you make a calculation with a rounded number, your answer gets a little bit worse.
3. When you answer an applied problem, find a calculator number. It doesn't mean much to suggest that the company should produce $\frac{\sqrt{12100}(2.4)}{2.5}$ items; it's much more meaningful to report that they should produce about 106 items.
4. When you present your final answer, round it to something that makes sense. If you've found an amount of US money, round it to the nearest cent. If you've computed the number of people, round to the nearest person. If there's no obvious context, show your teacher at least two digits after the decimal place.
5. Occasionally in this course, you will need to find the "exact answer." That means – not a calculator approximation. (You can still use your calculator to check your answer.)

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1: PREREQUISITE REVIEW

1.1: Functions

1.2: Operations on Functions

1.3: Linear Functions

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1.5: Quadratic Functions

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1.1: Functions

What is a Function?

The natural world is full of relationships between quantities that change. When we see these relationships, it is natural for us to ask “If I know one quantity, can I then determine the other?” This establishes the idea of an input quantity, or independent variable, and a corresponding output quantity, or dependent variable. From this we get the notion of a functional relationship in which the output can be determined from the input.

For some quantities, like height and age, there are certainly relationships between these quantities. Given a specific person and any age, it is easy enough to determine their height, but if we tried to reverse that relationship and determine height from a given age that would be problematic, since most people maintain the same height for many years.

Function

A **function** is rule for a relationship between an input, or independent, quantity and an output, or dependent, quantity in which each input value uniquely determines one output value. We say “the output is a function of the input.”

Example 1.1.1

In the height and age example above, is height a function of age? Is age a function of height?

In the height and age example above, it would be correct to say that height is a function of age, since each age uniquely determines a height. For example, on my 18th birthday, I had exactly one height of 69 inches.

However, age is not a function of height, since one height input might correspond with more than one output age. For example, for an input height of 70 inches, there is more than one output of age since I was 70 inches at the age of 20 and 21.

Vimeo Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this Vimeo Video online

Function Notation

To simplify writing out expressions and equations involving functions, a simplified notation is often used. We also use descriptive variables to help us remember the meaning of the quantities in the problem.

Rather than write “height is a function of age,” we could use the descriptive variable h to represent height and we could use the descriptive variable a to represent age.

"height is a function of age"	if we name the function f we write
"h is f of a"	or more simply

"height is a function of age"	if we name the function f we write
$h = f(a)$	we could instead name the function h and write
$h(a)$	which is read "h of a"

Remember we can use any variable to name the function; the notation $h(a)$ shows us that h depends on a. The value "a" must be put into the function "h" to get a result. Be careful – the parentheses indicate that age is input into the function (Note: do not confuse these parentheses with multiplication!).

Function Notation

The notation output = f(input) defines a function named f. This would be read "output is f of input."

Example 1.1.2

A function $N = f(y)$ gives the number of police officers, N, in a town in year y. What does $f(2005) = 300$ tell us?

Solution

When we read $f(2005) = 300$, we see the input quantity is 2005, which is a value for the input quantity of the function, the year (y). The output value is 300, the number of police officers (N), a value for the output quantity. Remember $N = f(y)$. So this tells us that in the year 2005 there were 300 police officers in the town.

Tables as Functions

Functions can be represented in many ways: Words (as we did in the last few examples), tables of values, graphs, or formulas. Represented as a table, we are presented with a list of input and output values.

This table represents the age of children in years and their corresponding heights. While some tables show all the information we know about a function, this particular table represents just some of the data available for height and ages of children.

(input) a, age in years	4	5	6	7	8	9	10
(output) h, height in inches	40	42	44	47	50	52	54

Example 1.1.3

Which of these tables define a function (if any)?

Input	Output
2	1
5	3
8	6

Input	Output
-3	5
0	1
4	5

Input	Output
1	0
5	2
5	

Solution

The first and second tables define functions. In both, each input corresponds to exactly one output. The third table does not define a function since the input value of 5 corresponds with two different output values.

Solving and Evaluating Functions

When we work with functions, there are two typical things we do: evaluate and solve. Evaluating a function is what we do when we know an input, and use the function to determine the corresponding output. Evaluating will always produce one result, since each input of a function corresponds to exactly one output.

Solving equations involving a function is what we do when we know an output, and use the function to determine the inputs that would produce that output. Solving a function could produce more than one solution, since different inputs can produce the same output.

Example 1.1.4

Using the table shown, where $Q = g(n)$

n	1	2	3	4	5
Q	8	6	7	6	8

a. Evaluate $g(3)$
b. Solve $g(n) = 6$

Solution

Evaluating g(3) (read: “g of 3”) means that we need to determine the output value, Q, of the function g given the input value of n=3. Looking at the table, we see the output corresponding to n=3 is Q=7, allowing us to conclude g(3) = 7.

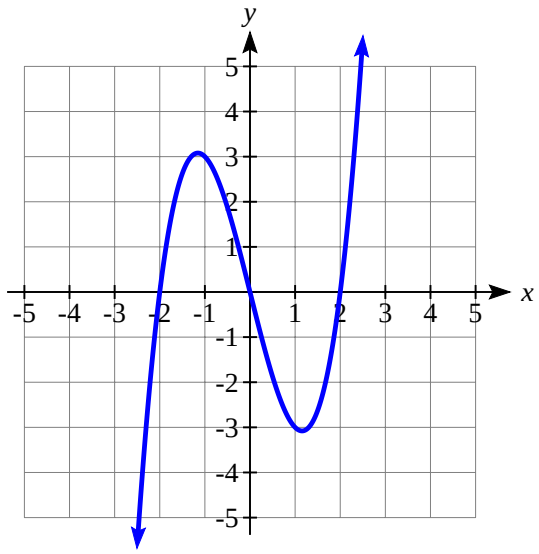
Solving g(n) = 6 means we need to determine what input values, n, produce an output value of 6. Looking at the table we see there are two solutions: n = 2 and n = 4. When we input 2 into the function g, our output is Q = 6 When we input 4 into the function g, our output is also Q = 6

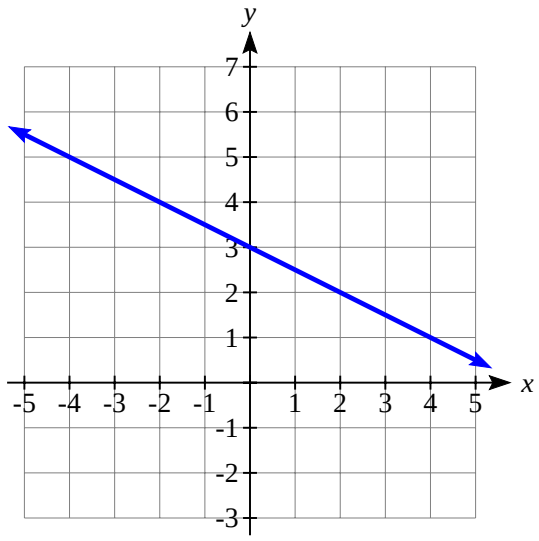
Graphs as Functions

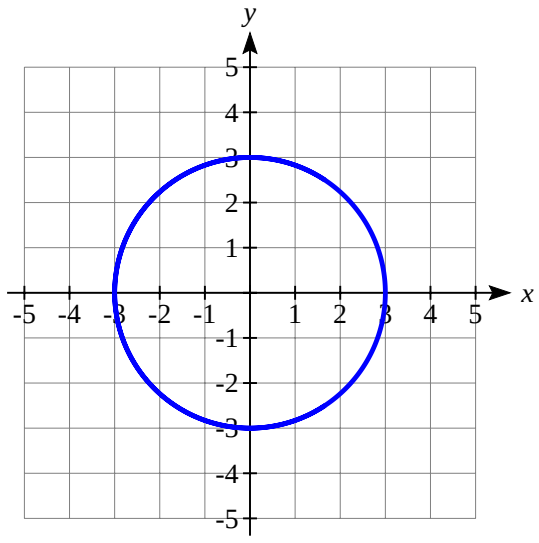
Oftentimes a graph of a relationship can be used to define a function. By convention, graphs are typically created with the input quantity along the horizontal axis and the output quantity along the vertical.

Example 1.1.5

Which of these graphs defines a function $y = f(x)$?


y
x
5
4
3
2
1
-1
-2
-3
-4
-5
-5 -4 -3 -2 -1 1 2 3 4 5


y
x
7
6
5
4
3
2
1
-1
-2
-3
-5 -4 -3 -2 -1 1 2 3 4 5


y
x
5
4
3
2
1
-1
-2
-3
-4
-5
-5 -4 -3 -2 -1 1 2 3 4 5

Solution

Looking at the three graphs above, the first two define a function y=f(x), since for each input value along the horizontal axis there is exactly one output value corresponding, determined by the y-value of the graph. The 3rd graph does not define a function y=f(x) since some input values, such as x=2, correspond with more than one output value.

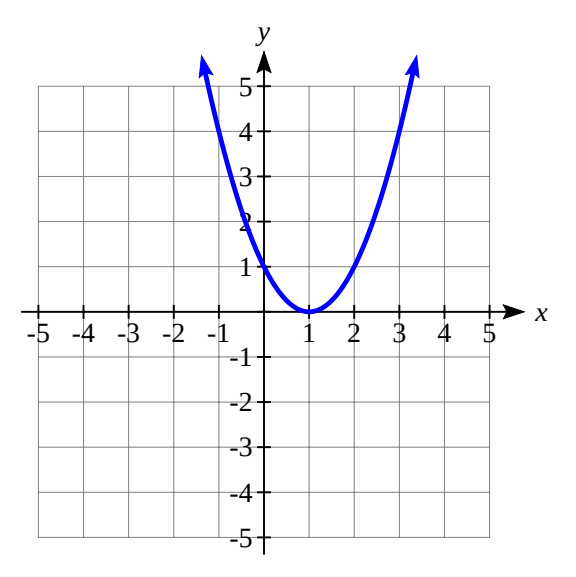
Vertical Line Test

The **vertical line test** is a handy way to think about whether a graph defines the vertical output as a function of the horizontal input. Imagine drawing vertical lines through the graph. If any vertical line would cross the graph more than once, then the graph does not define only one vertical output for each horizontal input.

Evaluating a function using a graph requires taking the given input and using the graph to look up the corresponding output. Solving a function equation using a graph requires taking the given output and looking on the graph to determine the corresponding input.

Example 1.1.6

Given the graph below,



a. Evaluate $f(2)$.
b. Solve $f(x) = 4$.

Solution

a) To evaluate f(2), we find the input of x=2 on the horizontal axis. Moving up to the graph gives the point (2, 1), giving an output of y=1. So f(2) = 1

b) To solve f(x) = 4, we find the value 4 on the vertical axis because if f(x) = 4 then 4 is the output. Moving horizontally across the graph gives two points with the output of 4: (-1,4) and (3,4). These give the two solutions to f(x) = 4: x = -1 or x = 3 This means f(-1)=4 and f(3)=4, or when the input is -1 or 3, the output is 4.

Notice that while the graph in the previous example is a function, getting two input values for the output value of 4 shows us that this function is not one-to-one.

Formulas as Functions

When possible, it is very convenient to define relationships using formulas. If it is possible to express the output as a formula involving the input quantity, then we can define a function.

Example 1.1.7

Express the relationship $2n + 6p = 12$ as a function $p = f(n)$ if possible.

Solution

To express the relationship in this form, we need to be able to write the relationship where p is a function of n, which means writing it as $p =$ [something involving n].

$$\begin{aligned} 2n + 6p &= 12 \quad \text{subtract } 2n \text{ from both sides} \\ 6p &= 12 - 2n \quad \text{divide both sides by 6 and simplify} \\ p &= \tfrac{12-2n}{6} = \tfrac{12}{6} - \tfrac{2n}{6} = 2 - \tfrac{1}{3}n \end{aligned}$$

Having rewritten the formula as $p =$, we can now express p as a function:

$$p = f(n) = 2 - \frac{1}{3}n$$

Not every relationship can be expressed as a function with a formula. As with tables and graphs, it is common to evaluate and solve functions involving formulas. Evaluating will require replacing the input variable in the formula with the value provided and calculating. Solving will require replacing the output variable in the formula with the value provided, and solving for the input(s) that would produce that output.

Example 1.1.8

Given the function $k(t) = t^3 + 2$:

a. Evaluate $k(2)$.
b. Solve $k(t) = 1$.

Solution

a) To evaluate $k(2)$, we plug in the input value 2 into the formula wherever we see the input variable t, then simplify

$$\begin{aligned} k(2) &= 2^3 + 2 \\ k(2) &= 8 + 2 \end{aligned}$$

So $k(2) = 10$

b) To solve $k(t) = 1$, we set the formula for $k(t)$ equal to 1 , and solve for the input value that will produce that output

$$k(t) = 1 \quad \text{substitute the original formula } k(t) = t^3 + 2$$

$t^3 + 2 = 1$ subtract 2 from each side
$t^3 = -1$ take the cube root of each side
$t = -1$

When solving an equation using formulas, you can check your answer by using your solution in the original equation to see if your calculated answer is correct.

We want to know if $k(t) = 1$ is true when $t = -1$.

$$\begin{aligned} k(-1) &= (-1)^3 + 2 \\ &= -1 + 2 \\ &= 1 \text{ which was the desired result.} \end{aligned} \tag{1.1.1}$$

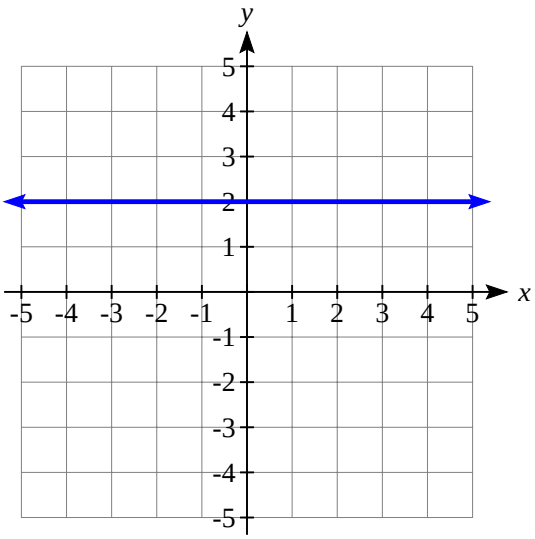
Basic Toolkit Functions

There are some basic functions that it is helpful to know the name and shape of. We call these the basic "toolkit of functions." For these definitions we will use x as the input variable and $f(x)$ as the output variable.

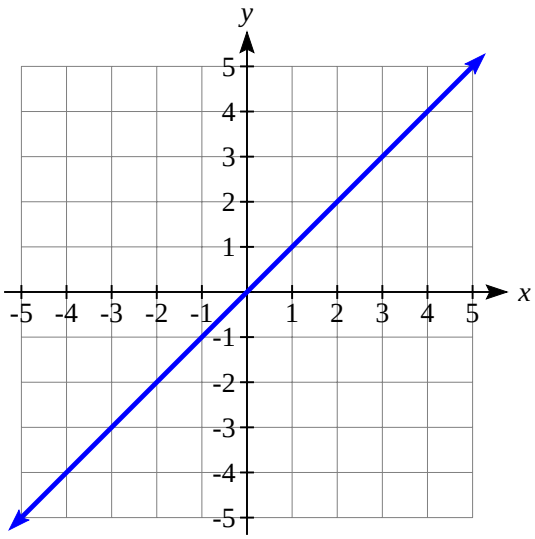
Toolkit Functions

Linear	
Constant:	$f(x) = c$, where c is a constant (number)
Identity:	$f(x) = x$
Absolute Value:	$f(x) = \|x\|$
Power	
Quadratic:	$f(x) = x^2$
Cubic:	$f(x) = x^3$
Reciprocal:	$f(x) = \frac{1}{x}$
Reciprocal squared:	$f(x) = \frac{1}{x^2}$
Square root:	$f(x) = \sqrt[2]{x} = \sqrt{x}$
Cube root:	$f(x) = \sqrt[3]{x}$

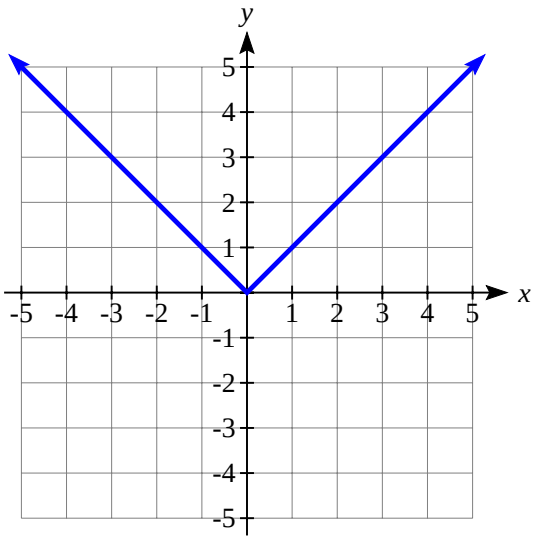
Graphs of the Toolkit Functions



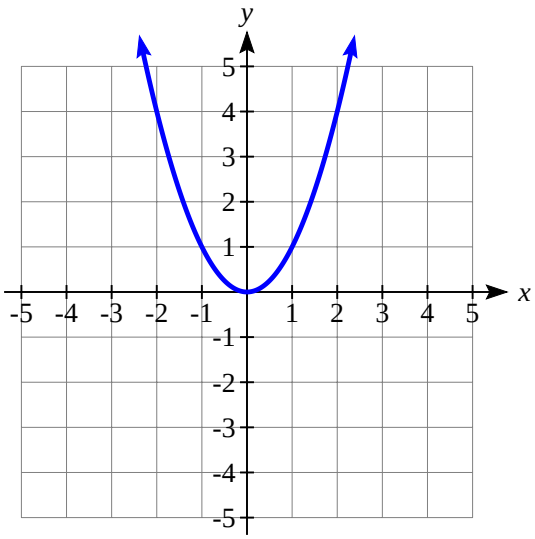
Constant: $f(x) = c$ (c is 2 in this picture).



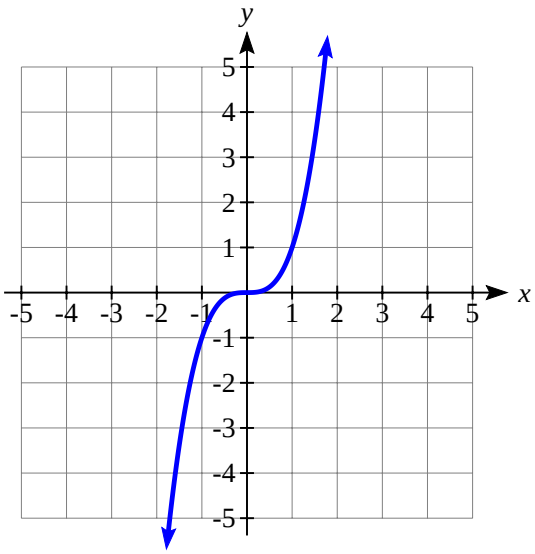
Identity: $f(x) = x$



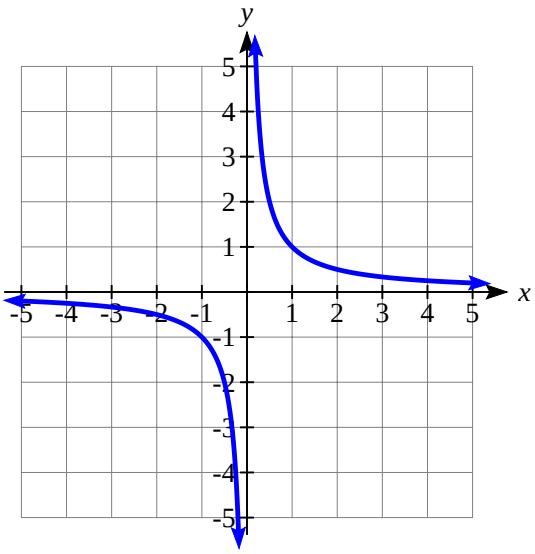
Absolute Value: $f(x) = |x|$



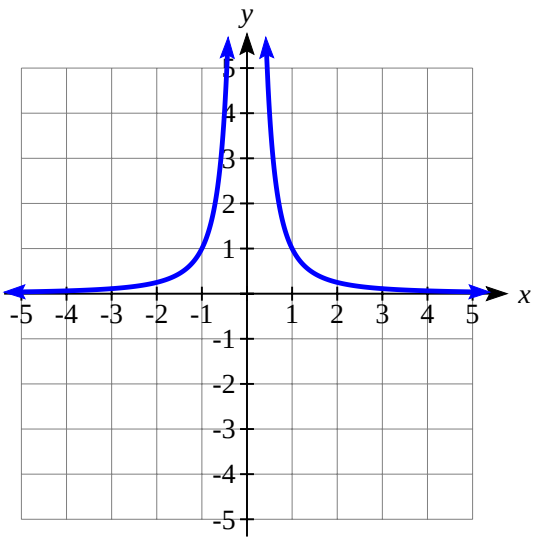
Quadratic: $f(x) = x^2$



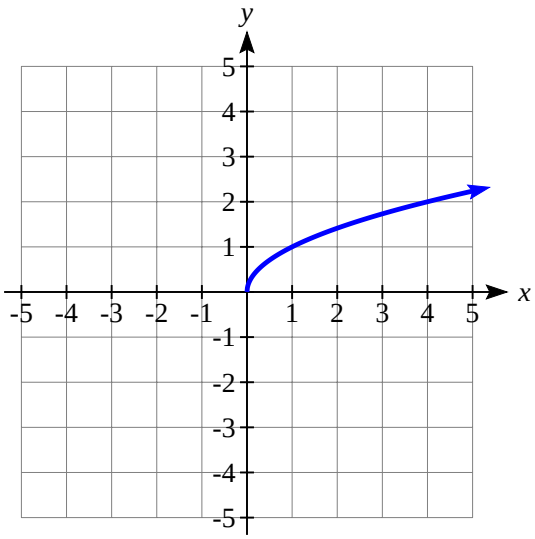
Cubic: $f(x) = x^3$



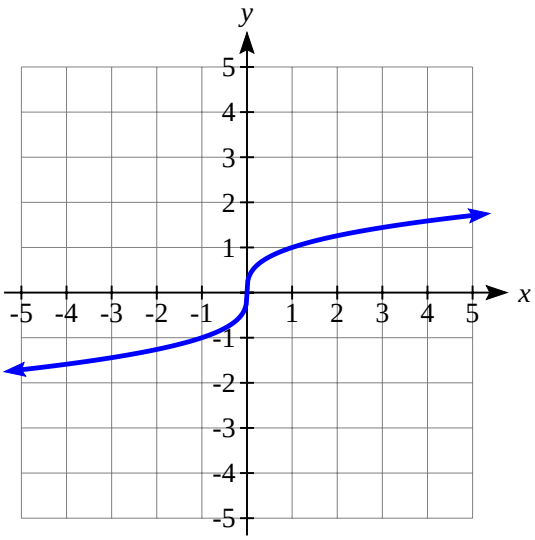
Reciprocal: $f(x) = \frac{1}{x}$



Reciprocal squared: $f(x) = \frac{1}{x^2}$



Square root: $f(x) = \sqrt[2]{x} = \sqrt{x}$



Cube root: $f(x) = \sqrt[3]{x}$

One of our main goals in mathematics is to model the real world with mathematical functions. In doing so, it is important to keep in mind the limitations of those models we create.

This table shows a relationship between circumference and height of a tree as it grows.

Circumference, c	1.7	2.5	5.5	8.2	13.7
Height, h	24.5	31	45.2	54.6	92.1

While there is a strong relationship between the two, it would certainly be ridiculous to talk about a tree with a circumference of -3 feet, or a height of 3000 feet. When we identify limitations on the inputs and outputs of a function, we are determining the domain and range of the function.

Domain and Range

- **Domain:** The set of possible input values to a function.
- **Range:** The set of possible output values of a function

Example 1.1.9

Using the tree table above, determine a reasonable domain and range.

Solution

We could combine the data provided with our own experiences and reason to approximate the domain and range of the function $h = f(c)$. For the domain, possible values for the input circumference c, it doesn't make sense to have negative values, so $c > 0$. We could make an educated guess at a maximum reasonable value, or look up that the maximum circumference measured is about 119 feet. With this information we would say a reasonable domain is feet.

Similarly for the range, it doesn't make sense to have negative heights, and the maximum height of a tree could be looked up to be 379 feet, so a reasonable range is feet.

A more compact alternative to inequality notation is **interval notation**, in which intervals of values are referred to by the starting and ending values. Curved parentheses are used for "strictly less than," and square brackets are used for "less than or equal to." Since infinity is not a number, we can't include it in the interval, so we always use curved parentheses with ∞ and $-\infty$. The table below will help you see how inequalities correspond to interval notation:

Inequality	Interval notation
$5 < h \leq 10$	(5, 10]
$5 \leq h < 10$	[5, 10)
$5 < h < 10$	(5, 10)
$h < 10$	$(-\infty, 10)$
$h \geq 10$	$[10, \infty)$
All real numbers ($\mathbb{R}$)	$(-\infty, \infty)$

Example 1.1.10

Describe the intervals of values shown on the line graph below using set builder and interval notations:



Solution

To describe the values, x, that lie in the intervals shown above we would say, "x is a real number greater than or equal to 1 and less than or equal to 3, or a real number greater than 5." As an inequality it is "$1 \leq x \leq 3$ or $x > 5$". In interval notation it is "$[1, 3] \cup (5, \infty)$".

Example 1.1.11

Find the domain of each function:

a. $f(x) = 2\sqrt{x+4}$
b. $g(x) = \dfrac{3}{6-3x}$

Solution

a. Since we cannot take the square root of a negative number, we need the inside of the square root to be non-negative. $x + 4 \geq 0$ when $x \geq -4$, so the domain of $f(x)$ is $[-4, \infty)$.
b. We cannot divide by zero, so we need the denominator to be non-zero. $6 - 3x = 0$ when $x = 2$, so we must exclude 2 from the domain. The domain of $g(x)$ is $(-\infty, 2) \cup (2, \infty)$.

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1.2: Operations on Functions

Composition of Functions

Suppose we wanted to calculate how much it costs to heat a house on a particular day of the year. The cost to heat a house will depend on the average daily temperature, and the average daily temperature depends on the particular day of the year. Notice how we have just defined two relationships: The temperature depends on the day, and the cost depends on the temperature. Using descriptive variables, we can notate these two functions.

The first function, $C(T)$, gives the cost C of heating a house when the average daily temperature is T degrees Celsius, and the second, $T(d)$, gives the average daily temperature of a particular city on day d of the year. If we wanted to determine the cost of heating the house on the fifth day of the year, we could do this by linking our two functions together, an idea called composition of functions. Using the function $T(d)$, we could evaluate $T(5)$ to determine the average daily temperature on the fifth day of the year. We could then use that temperature as the input to the $C(T)$ function to find the cost to heat the house on the fifth day of the year: $C(T(5))$.

Composition of Functions

When the output of one function is used as the input of another, we call the entire operation a **composition of functions**. We write $f(g(x))$, and read this as "f of g of x" or "f composed with g at x".

An alternate notation for composition uses the composition operator: $\circ$. $(f \circ g)(x)$ is read "f of g of x" or "f composed with g at x", just like $f(g(x))$.

Example 1.2.1

Suppose $c(s)$ gives the number of calories burned doing s sit-ups, and $s(t)$ gives the number of sit-ups a person can do in t minutes. Interpret $c(s(3))$.

Solution

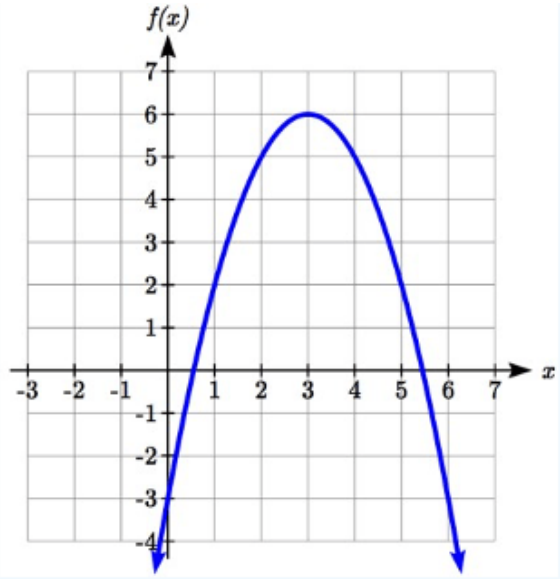
When we are asked to interpret, we are being asked to explain the meaning of the expression in words. The inside expression in the composition is $s(3)$. Since the input to the s function is time, the 3 is representing 3 minutes, and $s(3)$ is the number of sit-ups that can be done in 3 minutes. Taking this output and using it as the input to the $c(s)$ function will give us the calories that can be burned by the number of sit-ups that can be done in 3 minutes.

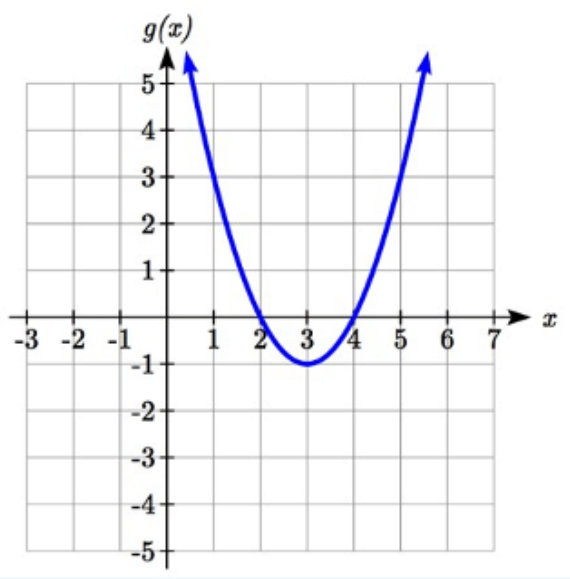
Composition of Functions using Tables and Graphs

When working with functions given as tables and graphs, we can look up values for the functions using a provided table or graph. We start evaluation from the provided input, and first evaluate the inside function. We can then use the output of the inside function as the input to the outside function. To remember this, always work from the inside out.

Example 1.2.2

Using the graphs below, evaluate $f(g(1))$.





Solution

To evaluate $f(g(1))$, we again start with the inside evaluation. We evaluate $g(1)$ using the graph of the $g(x)$ function, finding the input of 1 on the horizontal axis and finding the output value of the graph at that input. Here, $g(1) = 3$. Using this value as the input to the f function, $f(g(1)) = f(3)$. We can then evaluate this by looking to the graph of the $f(x)$ function, finding the input of 3 on the horizontal axis, and reading the output value of the graph at this input. Here, $f(3) = 6$, so $f(g(1)) = 6$.

Compositions using Formulas

When evaluating a composition of functions where we have either created or been given formulas, the concept of working from the inside out remains the same. First we evaluate the inside function using the input value provided, then use the resulting output as the input to the outside function.

Example 1.2.3

Given $f(t) = t^2 - t$ and $h(x) = 3x + 2$, evaluate $f(h(1))$.

Solution

Since the inside evaluation is $h(1)$ we start by evaluating the $h(x)$ function at 1:

$$h(1) = 3(1) + 2 = 5$$

Then $f(h(1)) = f(5)$, so we evaluate the $f(t)$ function at an input of 5:

$$f(h(1)) = f(5) = 5^2 - 5 = 20$$

We are not limited, however, to using a numerical value as the input to the function. We can put anything into the function: a value, a different variable, or even an algebraic expression, provided we use the input expression everywhere we see the input variable.

Example 1.2.4

Let $f(x) = x^2$ and $g(x) = \dfrac{1}{x} - 2x$. Find $f(g(x))$ and $g(f(x))$.

Solution

To find $f(g(x))$, we start by evaluating the inside, writing out the formula for $g(x)$:

$$g(x) = \frac{1}{x} - 2x$$

We then use the expression $\left(\frac{1}{x} - 2x\right)$ as the input for the function f:

$$f(g(x)) = f\left(\frac{1}{x} - 2x\right)$$

We then evaluate the function $f(x)$ using the formula for $g(x)$ as the input. Since $f(x) = x^2$ then

$$f\left(\frac{1}{x} - 2x\right) = \left(\frac{1}{x} - 2x\right)^2$$

This gives us the formula for the composition:

$$f(g(x)) = \left(\frac{1}{x} - 2x\right)^2$$

Likewise, to find $g(f(x))$, we evaluate the inside, writing out the formula for $f(x)$: $g(f(x)) = g(x^2)$.

Now we evaluate the function $g(x)$ using x^2 as the input:

$$g(f(x)) = \frac{1}{x^2} - 2x^2$$

Example 1.2.5

A city manager determines that the tax revenue, R, in millions of dollars collected on a population of p thousand people is given by the formula $R(p) = 0.03p + \sqrt{p}$, and that the city's population, in thousands, is predicted to follow the formula $p(t) = 60 + 2t + 0.3t^2$, where t is measured in years after 2010. Find a formula for the tax revenue as a function of the year.

Solution

Since we want tax revenue as a function of the year, we want year to be our initial input, and revenue to be our final output. To find revenue, we will first have to predict the city population, and then use that result as the input to the tax function. So we need to find $R(p(t))$. Evaluating this,

$$\begin{aligned} R(p(t)) &= R(60 + 2t + 0.3t^2) \\ &= 0.03(60 + 2t + 0.3t^2) + \sqrt{60 + 2t + 0.3t^2} \end{aligned}$$

This composition gives us a single formula which can be used to predict the tax revenue during a given year, without needing to find the intermediary population value.

For example, to predict the tax revenue in 2017, when $t = 7$ (because t is measured in years after 2010),

$$\begin{aligned} R(p(7)) &= 0.03\left(60 + 2(7) + 0.3\left(7^2\right)\right) + \sqrt{60 + 2(7) + 0.3\left(7^2\right)} \\ &\approx 12.079 \text{ million dollars} \end{aligned}$$

Later in this course, it will be desirable to decompose a function – to write it as a composition of two simpler functions.

Example 1.2.6

Write $f(x) = 3 + \sqrt{5 - x^2}$ as the composition of two functions.

Solution

We are looking for two functions, g and h, so $f(x) = g(h(x))$. To do this, we look for a function inside a function in the formula for $f(x)$. As one possibility, we might notice that $5 - x^2$ is the inside of the square root. We could then decompose the function as:

$$h(x) = 5 - x^2, \quad g(x) = 3 + \sqrt{x}$$

We can check our answer by recomposing the functions:

$$g(h(x)) = g(5 - x^2) = 3 + \sqrt{5 - x^2}$$

Note that this is not the only solution to the problem. Another non-trivial decomposition would be

$$h(x) = x^2, \quad g(x) = 3 + \sqrt{5 - x}.$$

Transformations of Functions

Transformations allow us to construct new equations from our basic toolkit functions. The most basic transformations are shifting the graph vertically or horizontally.

Vertical Shift

Given a function $f(x)$, if we define a new function $g(x)$ as $g(x) = f(x) + k$, where k is a constant, then $g(x)$ is a **vertical shift** of the function $f(x)$, where all the output values have been increased by k.

If k is positive, then the graph will shift up. If k is negative, then the graph will shift down.

Horizontal Shift

Given a function $f(x)$, if we define a new function $g(x)$ as $g(x) = f(x + k)$, where k is a constant, then $g(x)$ is a **horizontal shift** of the function $f(x)$, where all the output values have been increased by k.

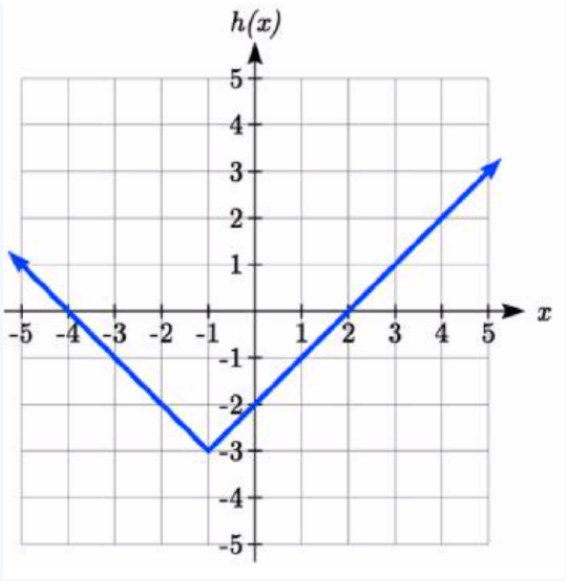
If k is positive, then the graph will shift left. If k is negative, then the graph will shift right.

Example 1.2.7

Given $f(x) = |x|$, sketch a graph of $h(x) = f(x + 1) - 3 = |x + 1| - 3$.

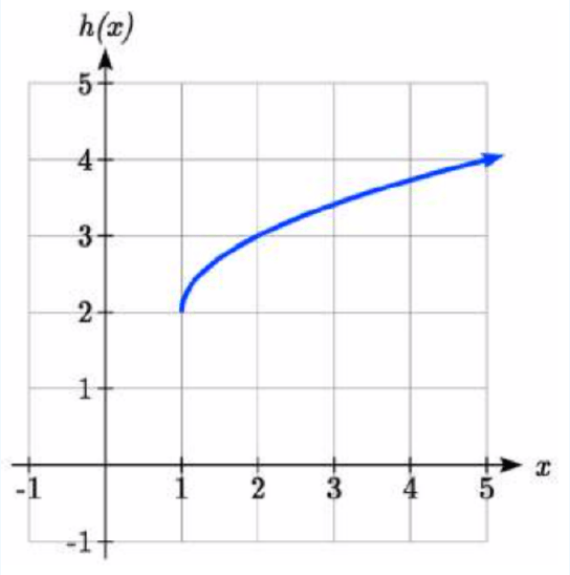
Solution

The function f is our toolkit absolute value function. We know that this graph has a V shape, with the point at the origin. The graph of h has transformed f in two ways: $f(x + 1)$ is a change on the inside of the function, giving a horizontal shift left by 1, then the subtraction by 3 in $f(x + 1) - 3$ is a change to the outside of the function, giving a vertical shift down by 3. Transforming the graph gives:



Example 1.2.8

Write a formula for the graph shown, a transformation of the toolkit square root function.



Solution

The graph of the toolkit function starts at the origin, so this graph has been shifted 1 to the right, and up 2. In function notation, we could write that as $h(x) = f(x-1) + 2$. Using the formula for the square root function we can write $h(x) = \sqrt{x-1} + 2$.

Note that this transformation has changed the domain and range of the function. This new graph has domain $[1, \infty)$ and range $[2, \infty)$.

Another transformation that can be applied to a function is a reflection over the horizontal or vertical axis.

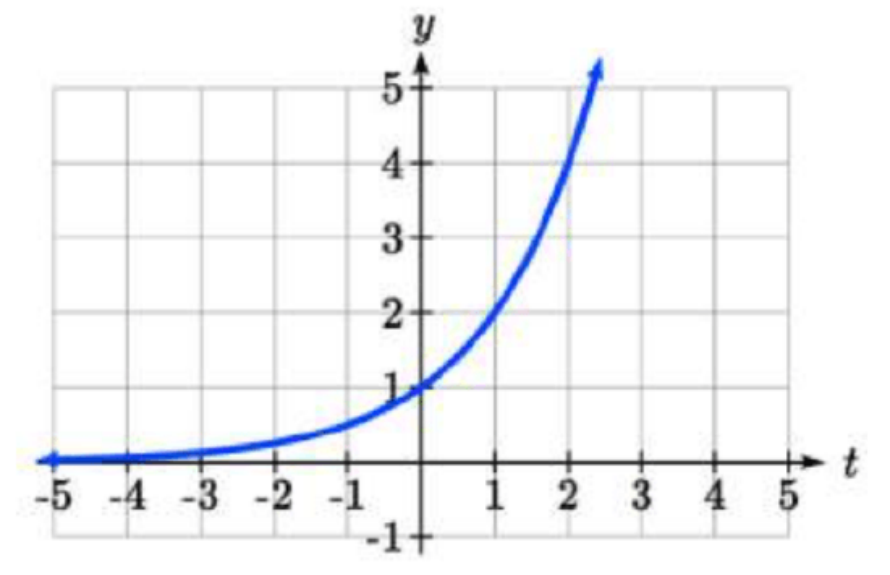
Reflections

Given a function $f(x)$, if we define a new function $g(x)$ as $-f(x)$, then $g(x)$ is a **vertical reflection** of the function $f(x)$, sometimes called a reflection about the x-axis

If we define a new function $g(x)$ as $f(-x)$, then $g(x)$ is a **horizontal reflection** of the function $f(x)$, sometimes called a reflection about the y-axis.

Example 1.2.9

A common model for learning has an equation similar to $k(t) = -2^t + 1$, where k is the percentage of mastery that can be achieved after t practice sessions. This is a transformation of the function $f(t) = 2^t$ shown here. Sketch a graph of $k(t)$.



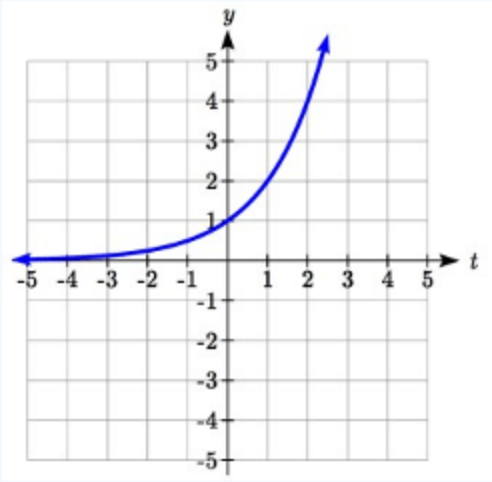
$f(t) = 2^t$

Solution

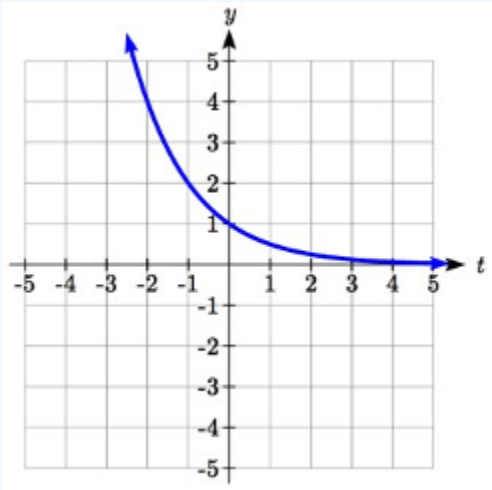
This equation combines three transformations into one equation.

A horizontal reflection:	$f(-t) = 2^{-t}$	combined with
a vertical reflection:	$-f(-t) = -2^{-t}$	combined with
a vertical shift up 1:	$-f(-t) + 1 = -2^{-t} + 1.$	

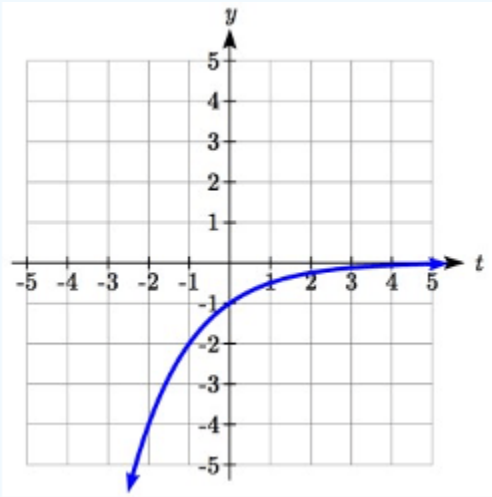
We can sketch a graph by applying these transformations one at a time to the original function:



The original graph



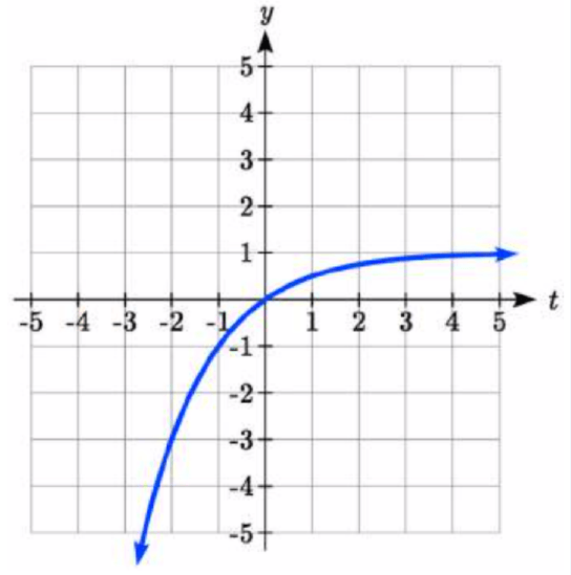
Horizontally reflected



Then vertically reflected

Then, after shifting up 1, we get the final graph:

$$k(t) = -f(-t) + 1 = -2^{-t} + 1$$



Final graph

Note: As a model for learning, this function would be limited to a domain of $t \geq 0$, with corresponding range $[0, 1)$.

With shifts, we saw the effect of adding or subtracting to the inputs or outputs of a function. We now explore the effects of multiplying the outputs.

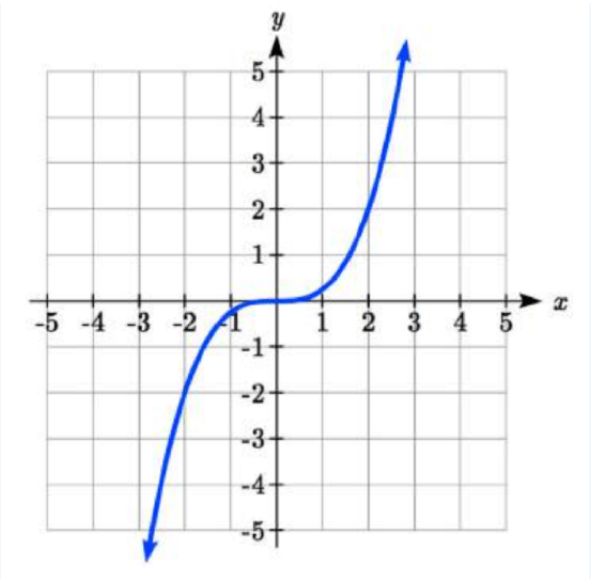
Vertical Stretch/Compression

Given a function $f(x)$, if we define a new function $g(x)$ as $g(x) = k \cdot f(x)$, where k is a constant, then $g(x)$ is a **vertical stretch or compression** of the function $f(x)$.

- If $k > 1$, then the graph will be stretched
- If $0 < k < 1$, then the graph will be compressed
- If $k < 0$, then there will be combination of a vertical stretch or compression with a vertical reflection

Example 1.2.10

The graph below is a transformation of the toolkit function $f(x) = x^3$. Relate this new function $g(x)$ to $f(x)$, then find a formula for $g(x)$.



Solution

When trying to determine a vertical stretch or shift, it is helpful to look for a point on the graph that is relatively clear. In this graph, it appears that $g(2) = 2$. With the basic cubic function at the same input, $f(2) = 2^3 = 8$. Based on that, it appears that the outputs of g are $\frac{1}{4}$ the outputs of the function f, since $g(2) = \frac{1}{4}f(x)$. From this we can fairly safely conclude that

$$g(x) = \frac{1}{4}f(x).$$

We can write a formula for g by using the definition of the function f:

$$g(x) = \frac{1}{4}f(x) = \frac{1}{4}x^3.$$

Combining Transformations

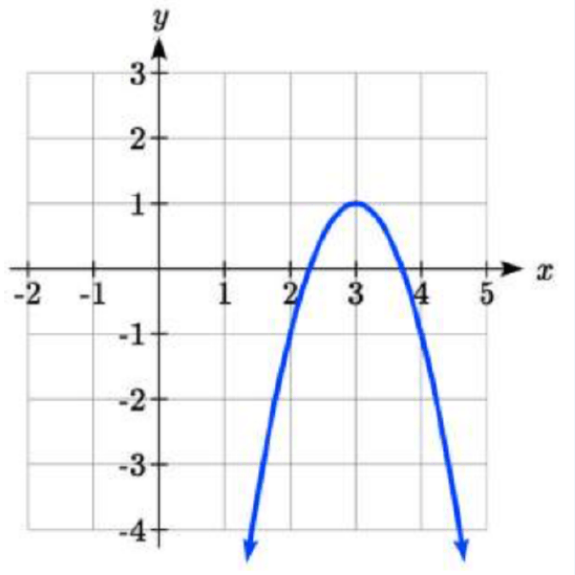
When combining vertical transformations, it is very important to consider the order of the transformations. For example, vertically shifting by 3 and then vertically stretching by 2 does not create the same graph as vertically stretching by 2 and then vertically shifting by 3. The order follows nicely from order of operations.

Combining Vertical Transformations

When combining vertical transformations written in the form $a \cdot f(x) + k$, first vertically stretch by a, then vertically shift by k.

Example 1.2.11

Write an equation for the transformed graph of the quadratic function shown.



Solution

Since this is a quadratic function, first consider what the basic quadratic tool kit function looks like and how this has changed. Observing the graph, we notice several transformations: The original tool kit function has been flipped over the x axis, some kind of stretch or compression has occurred, and we can see a shift to the right 3 units and a shift up 1 unit. In total there are four operations:

1. Vertical Reflection, requiring a negative sign outside the function.
2. Vertical Stretch
3. Horizontal Shift Right 3 units, which tells us to put x-3 on the inside of the function.
4. Vertical Shift up 1 unit, telling us to add 1 on the outside of the function.

By observation, the basic tool kit function has a vertex at (0, 0) and symmetrical points at (1, 1) and (-1, 1). These points are 1 unit up and 1 unit over from the vertex. The new points on the transformed graph are 1 unit away horizontally but 2 units away vertically. They have been stretched vertically by 2.

Not everyone can see this by simply looking at the graph. If you can, great, but if not we can solve for it. First, we will write the equation for this graph, with an unknown vertical stretch:

$f(x) = x^2$	The original function
$-f(x) = -x^2$	Vertically reflected
$-a \cdot f(x) = -ax^2$	Vertically stretched
$-a \cdot f(x-3) = -a(x-3)^2$	Shifted right 3
$-a \cdot f(x-3) + 1 = -a(x-3)^2 + 1$	Shifted up 1

We now know our graph is going to have an equation of the form $g(x) = -a(x-3)^2 + 1$. To find the vertical stretch, we can identify any point on the graph (other than the highest point), such as the point (2,-1), which tells us $g(2) = -1$. Using our general formula, and substituting 2 for x, and -1 for $g(x)$.

This tells us that to produce the graph we need a vertical stretch by two.

Thus the function that produces this graph is

$$g(x) = -2(x-3)^2 + 1.$$

Example 1.2.12

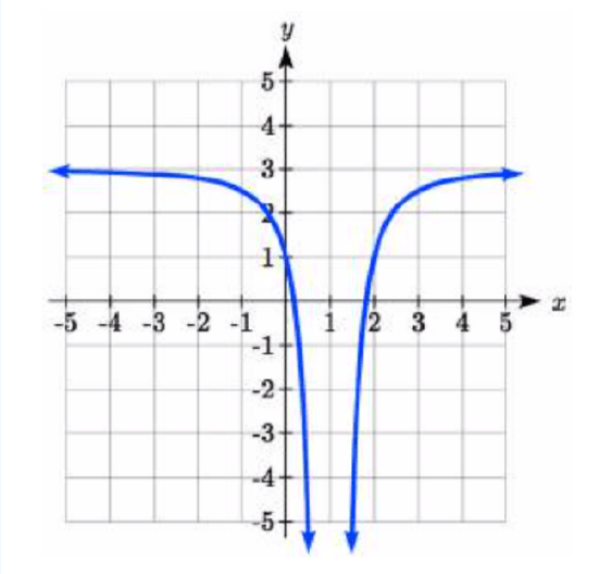
On what interval(s) is the function $g(x) = \dfrac{-2}{(x-1)^2} + 3$ increasing and decreasing?

Solution

This is a transformation of the toolkit reciprocal squared function, $f(x) = \dfrac{1}{x^2}$

$-2f(x) = \dfrac{-2}{x^2}$	A vertical flip and vertical stretch by 2
$-2f(x-1) = \dfrac{-2}{(x-1)^2}$	A shift right by 1
$-2f(x-1)+3 = \dfrac{-2}{(x-1)^2} + 3$	A shift up by 3

The basic reciprocal squared function is increasing on $(-\infty, 0)$ and decreasing on $(0, \infty)$. Because of the vertical flip, the $g(x)$ function will be decreasing on the left and increasing on the right. The horizontal shift right by 1 will also shift these intervals to the right one. From this, we can determine $g(x)$ will be increasing on $(1, \infty)$ and decreasing on $(-\infty, 1)$. We also could graph the transformation to help us determine these intervals.



Graph of the transformed function.

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1.3: Linear Functions

As you hop into a taxicab in Allentown, the meter will immediately read $3.30; this is the “drop” charge made when the taximeter is activated. After that initial fee, the taximeter will add $2.40 for each mile the taxi drives. In this scenario, the total taxi fare depends upon the number of miles ridden in the taxi, and we can ask whether it is possible to model this type of scenario with a function. Using descriptive variables, we choose m for miles and C for Cost in dollars as a function of miles: $C(m)$.

We know for certain that $C(0) = 3.30$, since the $3.30 drop charge is assessed regardless of how many miles are driven. Since $2.40 is added for each mile driven, we could write that if m miles are driven, $C(m) = 3.30 + 2.40m$ because we start with a $3.30 drop fee and then for each mile increase we add $2.40.

It is good to verify that the units make sense in this equation. The $3.30 drop charge is measured in dollars; the $2.40 charge is measured in dollars per mile. So

$$C(m) = 3.30 \text{ dollars} + \left(2.40\frac{\text{dollars}}{\text{mile}}\right)(m \text{ miles})$$

When dollars per mile are multiplied by a number of miles, the result is a number of dollars, matching the units on the 3.30, and matching the desired units for the C function.

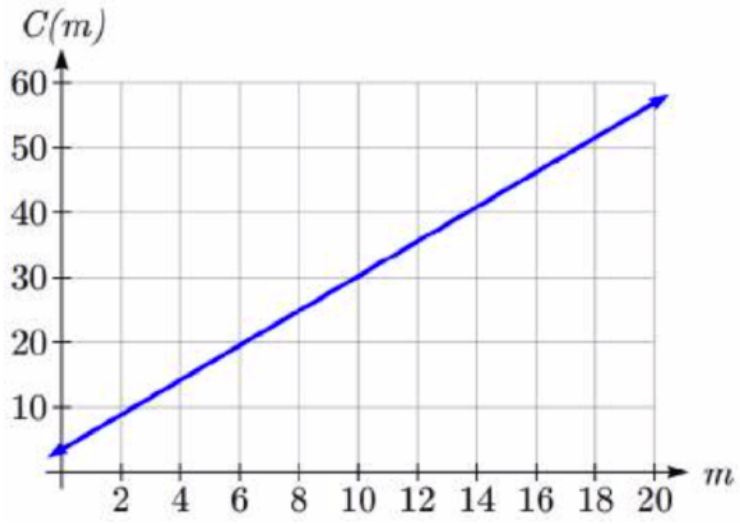
Notice this equation $C(m) = 3.30 + 2.40m$ consisted of two quantities. The first is the fixed $3.30 charge which does not change based on the value of the input. The second is the $2.40 dollars per mile value, which is a **rate of change**. In the equation this rate of change is multiplied by the input value.

Looking at this same problem in table format we can also see the cost changes by $2.40 for every 1 mile increase:

m	0	1	2	3
$C(m)$	3.30	5.70	8.10	10.50

It is important here to note that in this equation, the **rate of change is constant**; over any interval, the rate of change is the same.

Graphing this equation, $C(m) = 3.30 + 2.40m$ we see the shape is a line, which is how these functions get their name: **linear functions**.



When the number of miles is zero the cost is $3.30, giving the point (0, 3.30) on the graph. This is the vertical or $C(m)$ intercept. The graph is increasing in a straight line from left to right because for each mile the cost goes up by $2.40; this rate remains

consistent.

Linear Function

A **linear function** is a function whose graph produces a line. Linear functions can always be written in the form

$$f(x) = b + mx$$

or

$$f(x) = mx + b$$

where b is the initial or starting value of the function (with input $x = 0$), and m is the constant rate of change of the function.

This form of a line is called **slope-intercept form** of a line.

Many people like to write linear functions in the form $f(x) = b + mx$ because it corresponds to the way we tend to speak: "The output starts at b and increases at a rate of m."

For this reason alone we will use the $f(x) = b + mx$ form for many of the examples, but remember they are equivalent and can be written correctly both ways. While this is the book's convention, your instructor or videos you see might use $f(x) = mx + b$.

Slope and Increasing/Decreasing

m is the constant rate of change of the function (also called **slope**). The slope determines if the function is an increasing function or a decreasing function.

- $f(x) = b + mx$ is an **increasing** function if $m > 0$.
- $f(x) = b + mx$ is a **decreasing** function if $m < 0$.

If $m = 0$, the rate of change is 0, and the function $f(x) = b + 0x = b$ is just a horizontal line passing through the point (0, b), neither increasing nor decreasing.

Example 1.3.1

Marcus currently owns 200 songs in his iTunes collection. Every month, he adds 15 new songs. Write a formula for the number of songs, N, in his iTunes collection as a function of the number of months, m. How many songs will he own in a year?

Solution

The initial value for this function is 200, since he currently owns 200 songs, so $N(0) = 200$. The number of songs increases by 15 songs per month, so the rate of change is 15 songs per month. With this information, we can write the formula:

$$N(m) = 200 + 15m.$$

$N(m)$ is an increasing linear function.

With this formula we can predict how many songs he will have in 1 year (12 months):

$$N(12) = 200 + 15(12) = 200 + 180 = 380.$$

Marcus will have 380 songs in 12 months.

Calculating Rate of Change

Given two values for the input, x_1 and x_2, and two corresponding values for the output, y_1 and y_2, or a set of points, (x_1, y_1) and (x_2, y_2), if we wish to find a linear function that contains both points we can calculate the rate of change, m:

$$m = \frac{\text{change in output}}{\text{change in input}} = \frac{\Delta y}{\Delta x} = \frac{y_2 - y_1}{x_2 - x_1}.$$

Rate of change of a linear function is also called the **slope** of the line.

Note in function notation, $y_1 = f(x_1)$ and $y_2 = f(x_2)$, so we could equivalently write

$$m = \frac{f(x_2) - f(x_1)}{x_2 - x_1}.$$

Example 1.3.2

The population of a city increased from 23,400 to 27,800 between 2002 and 2006. Find the rate of change of the population during this time span.

Solution

The rate of change will relate the change in population to the change in time. The population increased by 27800-23400=4400 people over the 4 year time interval. To find the rate of change, the number of people per year the population changed by:

$$\frac{4400 \text{ people}}{4 \text{ years}} = 1100 \frac{\text{people}}{\text{year}} = 1100 \text{ people per year.}$$

Notice that we knew the population was increasing, so we would expect our value for m to be positive. This is a quick way to check to see if your value is reasonable.

Example 1.3.3

The pressure, P, in pounds per square inch (PSI) on a diver depends upon their depth below the water surface, d, in feet, following the equation $P(d) = 14.696 + 0.43d$. Interpret the components of this function.

Solution

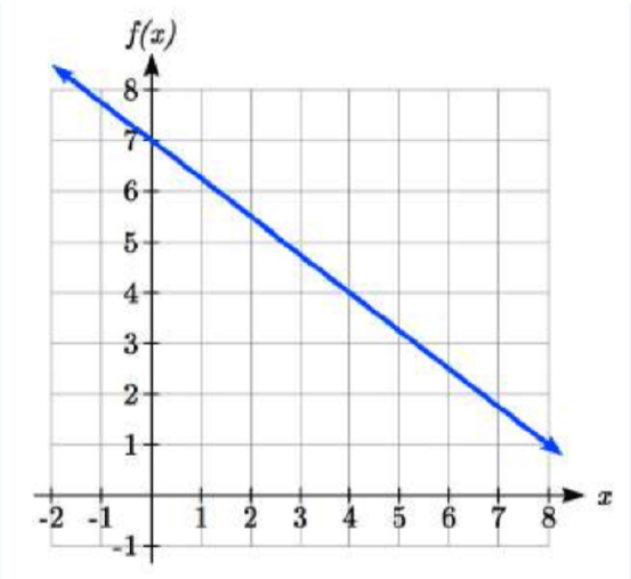
The rate of change, or slope, 0.434 would have units $\frac{\text{output}}{\text{input}} = \frac{\text{pressure}}{\text{depth}} = \frac{\text{PSI}}{\text{ft}}$. This tells us the pressure on the diver increases by 0.434 PSI for each foot their depth increases.

The initial value, 14.696, will have the same units as the output, so this tells us that at a depth of 0 feet, the pressure on the diver will be 14.696 PSI.

We can now find the rate of change given two input-output pairs, and could write an equation for a linear function if we had the rate of change and initial value. If we have two input-output pairs and they do not include the initial value of the function, then we will have to solve for it.

Example 1.3.4

Write an equation for the linear function graphed below.



Solution

Looking at the graph, we might notice that it passes through the points (0, 7) and (4, 4). From the first value, we know the initial value of the function is $b = 7$, so in this case we will only need to calculate the rate of change:

$$m = \frac{4-7}{4-0} = \frac{-3}{4}$$

This allows us to write the equation:

$$f(x) = 7 - \frac{3}{4}x$$

Example 1.3.5

If $f(x)$ is a linear function, $f(3) = -2$, and $f(8) = 1$, find an equation for the function.

Solution

In Example 1.3.3, we computed the rate of change to be $m = \frac{3}{5}$. In this case, we do not know the initial value $f(0)$, so we will have to solve for it. Using the rate of change, we know the equation will have the form $f(x) = b + \frac{3}{5}x$. Since we know the value of the function when $x = 3$, we can evaluate the function at 3: $f(x) = b + \frac{3}{5}(3)$.

Since we know that $f(3) = -2$, we can substitute on the left side: $-2 = b + \frac{3}{5}(3)$.

This leaves us with an equation we can solve for the initial value: $b = -2 - \frac{9}{5} = -\frac{19}{5}$.

Combining this with the value for the rate of change, we can now write a formula for this function:

$$f(x) = -\frac{19}{5} + \frac{3}{5}x.$$

As an alternative to the approach used above to find the initial value, b, we can use the **point-slope** form of a line instead.

Point-Slope Equation of a Line

An equation for the line passing through the point (x_1, y_1) with slope m can be written as

$$y - y_1 = m(x - x_1)$$

This is called the **point-slope form of a line**. It is a little easier to write if you know a point and the slope, but requires a bit of work to rewrite into slope-intercept form, and requires memorizing another formula.

Example 1.3.6

Working as an insurance salesperson, Ilya earns a base salary and a commission on each new policy, so Ilya's weekly income, I, depends on the number of new policies, n, he sells during the week. Last week he sold 3 new policies, and earned $760 for the week. The week before, he sold 5 new policies, and earned $920. Find an equation for $I(n)$, and interpret the meaning of the components of the equation.

Solution

The given information gives us two input-output pairs: (3,760) and (5,920). We start by finding the rate of change:

$$m = \frac{920 - 760}{5 - 3} = \frac{160}{2} = 80.$$

Keeping track of units can help us interpret this quantity. Income increased by $160 when the number of policies increased by 2, so the rate of change is $80 per policy; Ilya earns a commission of $80 for each policy sold during the week.

We can now write the equation using the point-slope form of the line, using the slope we just found and the point (3,760):

$$I - 760 = 80(n - 3)$$

If we wanted this in function form (slope intercept form), we could rewrite the equation into that form:

$$\begin{aligned} I - 760 &= 80(n - 3) \\ I - 760 &= 80n - 240 \\ I(n) &= 520 + 80n \end{aligned}$$

This form allows us to see the starting value for the function: 520. This is Ilya's income when $n = 0$, which means no new policies are sold. We can interpret this as Ilya's base salary for the week, which does not depend upon the number of policies sold.

Our final interpretation is: Ilya's base salary is $520 per week and he earns an additional $80 commission for each policy sold each week.

Graphs of Linear Functions

Graphical Interpretation of a Linear Equation

Graphically, in the equation $f(x) = b + mx$,

- b is the **vertical intercept** of the graph and tells us we can start our graph at $(0, b)$
- and m is the **slope of the line** and tells us how far to rise and run to get to the next point.

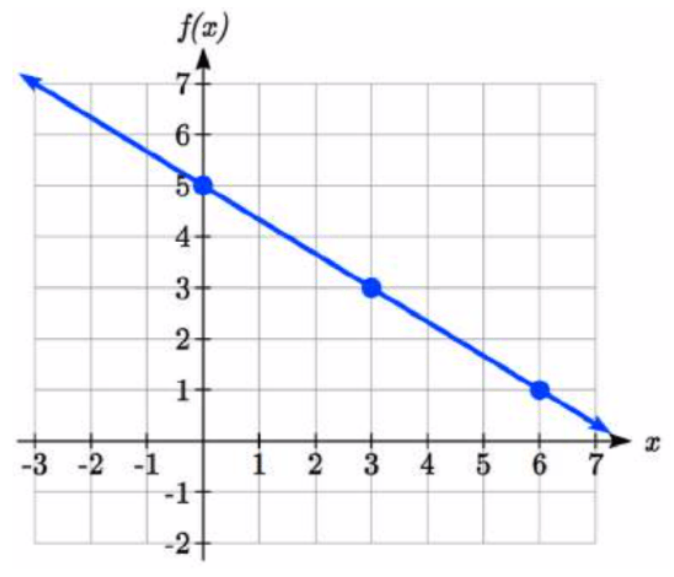
Once we have at least 2 points, we can extend the graph of the line to the left and right.

Example 1.3.7

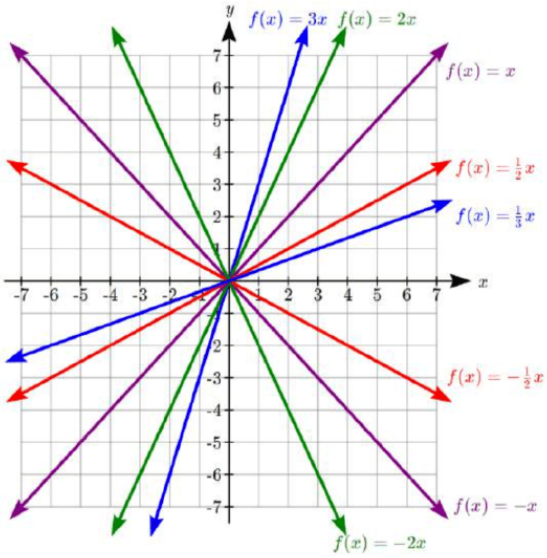
Graph $f(x) = 5 - \frac{2}{3}x$ using the vertical intercept and slope.

Solution

The vertical intercept of the function is (0, 5), giving us a point on the graph of the line. The slope is $-\frac{2}{3}$. This tells us that for every 3 units the graph "runs" in the horizontal, the vertical "rise" decreases by 2 units. In graphing, we can use this by first plotting our vertical intercept on the graph, then using the slope to find a second point. From the initial value (0, 5) the slope tells us that if we move to the right 3, we will move down 2, moving us to the point (3, 3). We can continue this again to find a third point at (6, 1). Finally, extend the line to the left and right, containing these points.

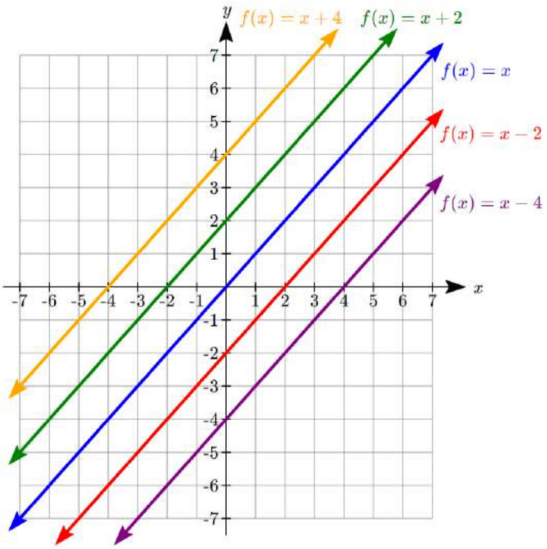


Another option for graphing is to use transformations of the identity function $f(x) = x$. In the equation $f(x) = mx$, the m is acting as the vertical stretch of the identity function. When m is negative, there is also a vertical reflection of the graph. Looking at some examples will also help show the effect of slope on the shape of the graph:



$f(x) = mx$ for several values of m.

In $f(x) = mx + b$, the b acts as the vertical shift, moving the graph up and down without affecting the slope of the line. Some examples:



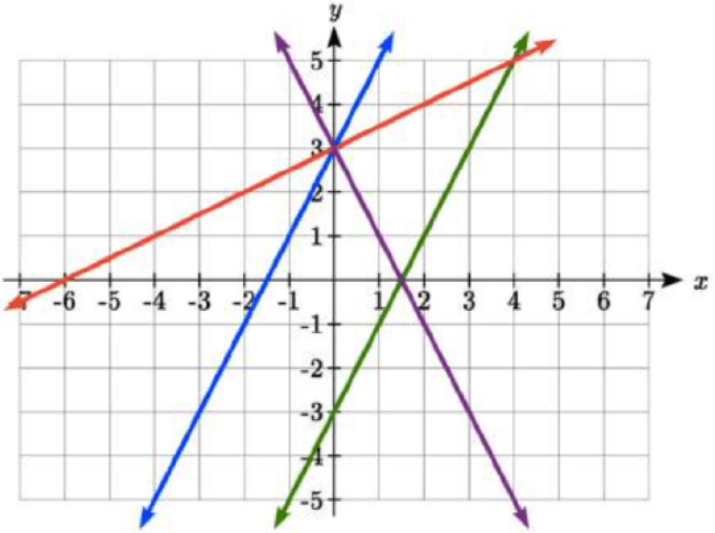
$f(x) = mx + b$ for several values of b.

Try it for yourself using this applet:

Example 1.3.8

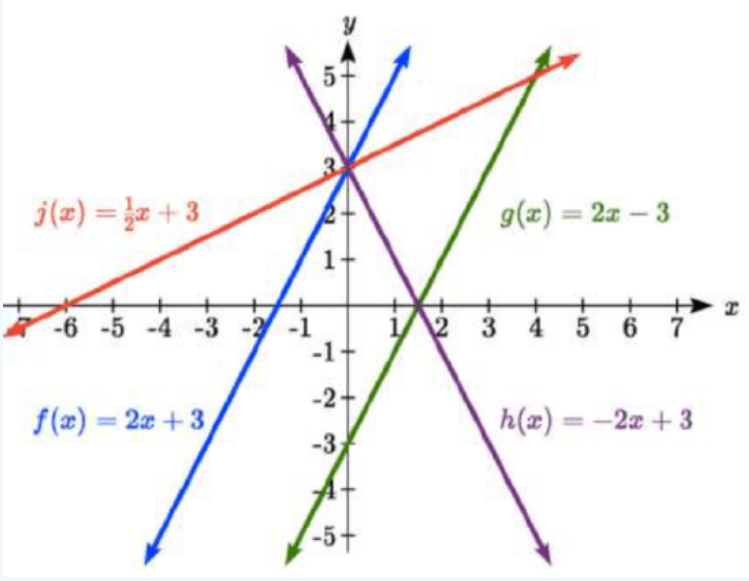
Match each equation with one of the lines in the graph below

$$f(x) = 2x + 3$$
$$g(x) = 2x - 3$$
$$h(x) = -2x + 3$$
$$j(x) = \frac{1}{2}x + 3$$



Solution

Only one graph has a vertical intercept of -3, so we can immediately match that graph with $g(x)$. For the three graphs with a vertical intercept at 3, only one has a negative slope, so we can match that line with $h(x)$. Of the other two, the steeper line would have a larger slope, so we can match that graph with equation $f(x)$, and the flatter line with the equation $j(x)$.



In addition to understanding the basic behavior of a linear function (increasing or decreasing, recognizing the slope and vertical intercept), it is often helpful to know the horizontal intercept of the function – where it crosses the horizontal axis.

Finding Horizontal Intercept

The **horizontal intercept** of the function is where the graph crosses the horizontal axis. If a function has a horizontal intercept, you can always find it by solving $f(x) = 0$.

Example 1.3.9

Find the horizontal intercept of $f(x) = -3 + \frac{1}{2}x$

Solution

Setting the function equal to zero to find what input will put us on the horizontal axis:

$$0 = -3 + \frac{1}{2}x$$
$$3 = \frac{1}{2}x$$
$$x = 6$$

Thus the graph crosses the horizontal axis at (6,0).

Intersections of Lines

The graphs of two lines will intersect if they are not parallel. They will intersect at the point that satisfies both equations. To find this point when the equations are given as functions, we can solve for an input value so that $f(x) = g(x)$. In other words, we can set the formulas for the lines equal, and solve for the input that satisfies the equation.

Economics tells us that in a free market, the price for an item is related to the quantity that producers will supply and the quantity that consumers will demand. Increases in prices will decrease demand, while supply tends to increase with prices. Sometimes supply and demand are modeled with linear functions.

Example 1.3.10

The supply, in thousands of items, for custom phone cases can be modeled by the equation $s(p) = 0.5 + 1.2p$ while the demand can be modeled by $d(p) = 8.7 - 0.7p$, where p is in dollars. Find the equilibrium price and quantity, the intersection of the supply and demand curves.

Solution

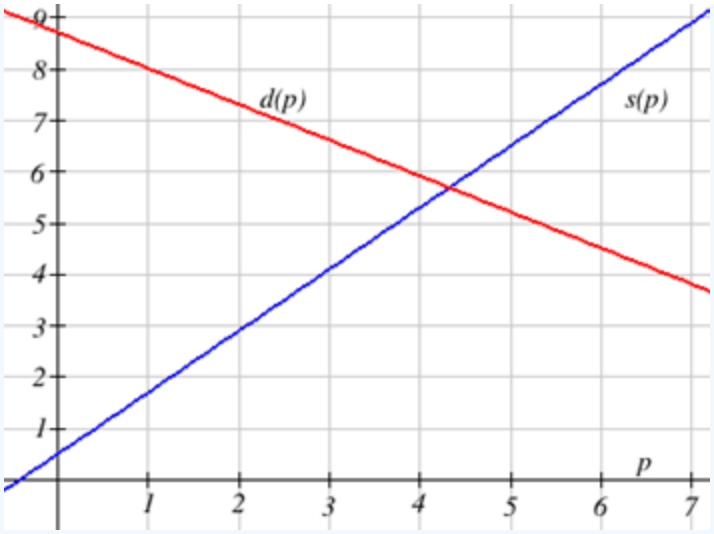
Setting $s(p) = d(p)$, we find

$$0.5 + 1.2p = 8.7 - 0.7p$$
$$1.9p = 8.2$$
$$p \approx \$4.32$$

We can find the output value of the intersection point by evaluating either function at this input:

$$s(4.32) = 0.5 + 1.2(4.32) \approx 5.68$$

These lines intersect at the point (4.32, 5.68). Looking at the graph, this result seems reasonable.



Business Applications

In business, a very common application of functions is to model cost, revenue, and profit.

Cost, Revenue, Profit

When a company produces q items, the **total cost** is the cost of total cost of producing those items. The total cost includes both **fixed costs**, which are startup costs, like equipment and buildings, and **variable costs**, which are costs that depend on the number of items produced, like materials and labor.

In the most simple case, **Total Cost = (Fixed Costs) + (Variable Costs)** $\cdot$ q

Revenue is the amount of money a company brings in from sales.

In the most simple case, **Revenue = (Price per item)** $\cdot$ q

Profit is the amount of money brings in, after expenses.

Profit = Revenue – Costs

We often talk about the **break-even** point. This is the level of production where Revenue equals Cost, or equivalently where Profit is zero. This is typically the minimum level of sales necessary for the company to make a profit.

Example 1.3.11

A tech startup is looking at developing and launching a new mobile app. Initial development of the app will cost $300,000, and they estimate marketing and support for each user will cost $0.50. While the app will be free, they estimate they will be able to bring in $2 per user on average from in-app purchases. How many users will the company need to break even?

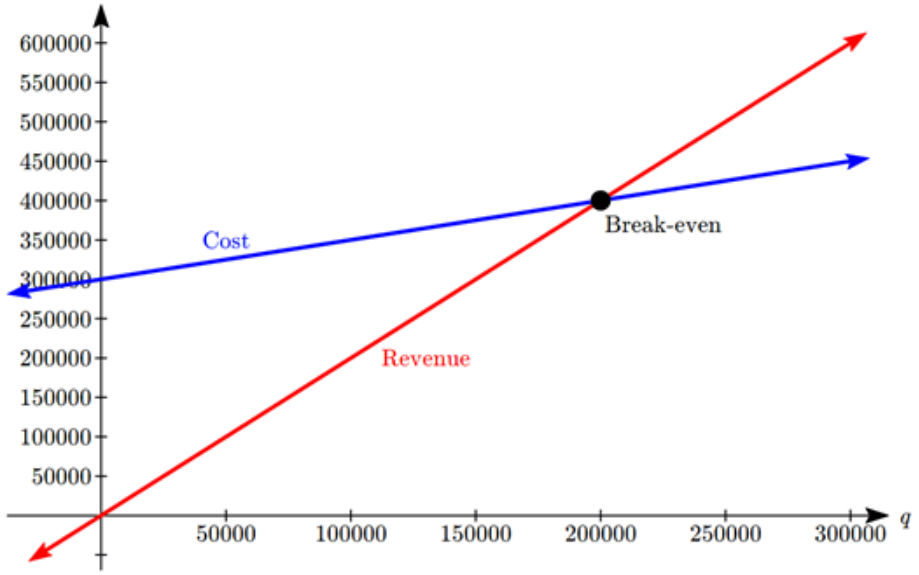
Solution

We start by modeling the cost, revenue, and profit. Let q = number of users.

The fixed (initial) costs are $300,000, and the variable (per-item) costs as $0.50 per user. We can write the total cost equation:
$TC(q) = 300,000 + 0.50q$

The revenue will be $2 per user, so the revenue equation will be:
$R(q) = 2q$

We could find the break-even point by setting the total cost equal to the revenue, which is equivalent to finding the intersection of the lines.



Alternatively, we could go ahead and find a profit equation first:
$P(q) = R(q) - TC(q) = 2q - (300,000 + 0.50q) = 1.5q - 300,000$

The break even point can be found by setting the profit equal to zero:

$$0 = 1.5q - 300,000$$
$$q = 200,000$$

The company will have to acquire 200,000 users to break even.

In economics, there is a model for how prices are determined in a free market which states that **supply and demand** for a product is related to the price. The demand relationship shows the quantity of a certain product that consumers are willing to buy at a certain price. Typically the quantity demanded will decrease for an item if the price increases. The supply relationship shows the quantity of a product that suppliers are willing to produce at a certain sales price. Typically the supply demanded will increase if the price increases. Economic theory says that supply and demand will interact, and the intersection will be the equilibrium price, or market price, where the quantity supplied and demanded will be equal.

Supply and Demand

If p is the price of a product, then

Q_d is the quantity demanded

Q_s is the quantity supplied

The demand curve is a decreasing function, while the supply curve is an increasing function.

The intersection of the curves is the **equilibrium price and quantity**, also called the **market price and quantity**. This point is often notated as p^*, Q^*.

Later in the course you will explore supply and demand curves that are non-linear, but in this section we will focus on linear supply and demand functions.

In most economic books, you will see the supply and demand curve written with price as the input and quantity as the output, like $Q_d = 140 - 2p$. However, supply and demand graphs are drawn with price on the vertical axis and quantity on the horizontal. We can write the equation in whichever way is more convenient for us.

Example 1.3.12

At a price of \$2.50 per gallon, there is a demand in a certain town for 42.5 thousand gallons of gas and a supply of 20 thousand gallons. At a price of \$3.50, there is demand for 25.5 thousand gallons and a supply of 28 thousand gallons. Assuming supply and demand are linear, find the equilibrium price and quantity.

Solution

We start by finding a linear equation for both supply and demand. We will use price, p in dollars, as the output and quantity, q in thousands of gallons, as the input.

For supply, we have the points (20, 2.50) and (28, 3.50).

Finding the slope: $m = \dfrac{3.50 - 2.50}{28 - 20} = \frac{1}{8}$

We know the equation will look like $p = \frac{1}{8}q + b$, so substituting in (20, 2.50)

$$\begin{aligned} 2.5 &= \frac{1}{8}(20) + b \\ 2.5 &= 2.5 + b \\ q &= 0 \end{aligned}$$

The supply equation is: $p = \frac{1}{8}q$

For demand, we have the points (42.5, 2.50) and (25.5, 3.50). Using a similar approach, we can find the demand equation is: $p = -\frac{1}{17}q + 5$

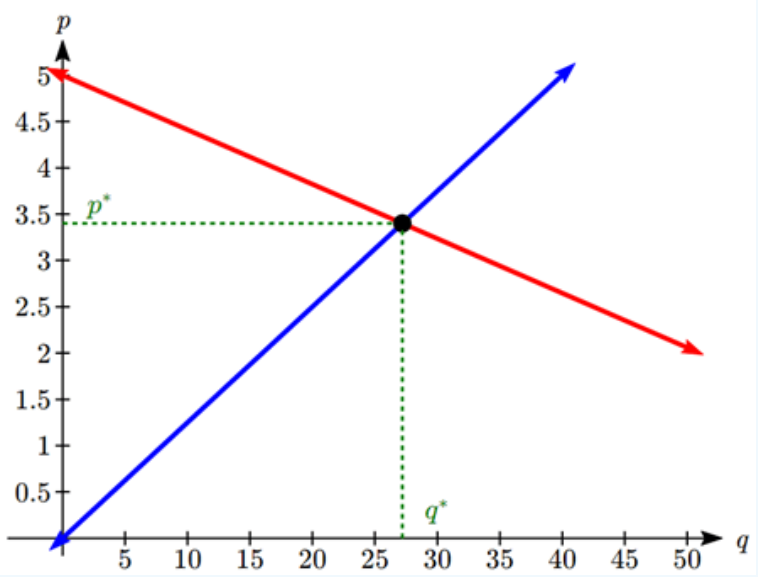
To find the equilibrium, we set the supply equal to the demand:
$\frac{1}{8}q = -\frac{1}{17}q + 5$

Multiplying through by 8(17) = 136 to clear the fractions,
$136\left(\frac{1}{8}q\right) = 136\left(-\frac{1}{17}q + 5\right)$
$17q = -8q + 680$

Now we solve for q
$25q = 680$
$q = 27.2$

To find the equilibrium price, we can substitute that value back into either equation:
$p = \frac{1}{8}(27.2) = 3.4$

The equilibrium quantity will be 27.2 thousand gallons of gas at a price of \$3.40.



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1.4: Exponents

The Laws of Exponents let you rewrite algebraic expressions that involve exponents. The last three listed here are really definitions rather than rules.

Laws of Exponents

All variables here represent real numbers and all variables in denominators are nonzero.

1. $x^a \cdot x^b = x^{a+b}$
2. $\dfrac{x^a}{x^b} = x^{a-b}$
3. $(x^a)^b = x^{ab}$
4. $(xy)^a = x^a y^a$
5. $\left(\dfrac{x}{y}\right)^b = \dfrac{x^b}{y^b}$
6. $x^0 = 1$, provided $x \neq 0$. [Although in some contexts 0^0 is still defined to be 1.]
7. $x^{-n} = \dfrac{1}{x^n}$, provided $x \neq 0$.
8. $x^{1/n} = \sqrt[n]{x}$, provided $x \neq 0$.

Example 1.4.1

Simplify $(2x^2)^3 (4x)$.

Solution

We'll begin by simplifying the $(2x^2)^3$ portion. Using Property 4, we can write

$2^3 (x^2)^3 (4x)$	
$8x^6(4x)$	Evaluate 2^3, and use Property 3.
$32x^7$	Multiply the constants, and use Property 1, recalling $x = x^1$.

Being able to work with negative and fractional exponents will be very important later in this course.

Example 1.4.2

Rewrite $\dfrac{5}{x^3}$ using negative exponents.

Solution

Since $x^{-n} = \dfrac{1}{x^n}$, then $x^{-3} = \dfrac{1}{x^3}$ and thus

$$\frac{5}{x^3} = 5x^{-3}.$$

Example 1.4.3

Simplify $\left(\frac{x^{-2}}{y^{-3}}\right)^2$ as much as possible and write your answer using only positive exponents.

Solution

$$\begin{aligned}\left(\frac{x^{-2}}{y^{-3}}\right)^2 &= \frac{\left(x^{-2}\right)^2}{\left(y^{-3}\right)^2} \\ &= \frac{x^{-4}}{y^{-6}} \\ &= \frac{y^6}{x^4}\end{aligned}$$

Example 1.4.4

Rewrite $4\sqrt{x} - \frac{3}{\sqrt{x}}$ using exponents.

Solution

A square root is a radical with index of two. In other words, $\sqrt{x} = \sqrt[2]{x}$. Using the exponent rule above, $\sqrt{x} = \sqrt[2]{x} = x^{1/2}$. Rewriting the square roots using the fractional exponent,

$$4\sqrt{x} - \frac{3}{\sqrt{x}} = 4x^{1/2} - \frac{3}{x^{1/2}}.$$

Now we can use the negative exponent rule to rewrite the second term in the expression:

$$4x^{1/2} - \frac{3}{x^{1/2}} = 4x^{1/2} - 3x^{-1/2}.$$

Example 1.4.5

Rewrite $\left(\sqrt{p^5}\right)^{-1/3}$ using only positive exponents.

Solution

$$\begin{aligned}\left(\sqrt{p^5}\right)^{-1/3} &= \left(\left(p^5\right)^{1/2}\right)^{-1/3} \\ &= p^{-5/6} \\ &= \frac{1}{p^{5/6}}\end{aligned}$$

Example 1.4.6

Rewrite $x^{-4/3}$as a radical.

Solution

$$
\begin{aligned}
x^{-4/3} &= \frac{1}{x^{4/3}} \\
&= \frac{1}{\left(x^{1/3}\right)^4} \quad \left(\text{since } \frac{4}{3} = 4 \cdot \frac{1}{3}\right) \\
&= \frac{1}{\left(\sqrt[3]{x}\right)^4} \quad \text{(using the radical equivalence)}
\end{aligned}
$$

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1.5: Quadratic Functions

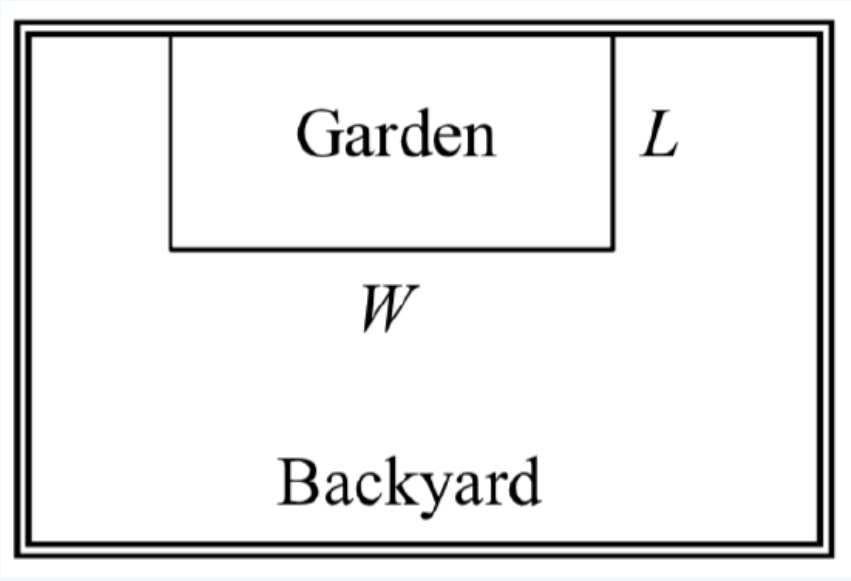
Quadratics are transformations of the function $f(x) = x^2$. Quadratics commonly arise from problems involving area and projectile motion, providing some interesting applications.

Example 1.5.1

A backyard farmer wants to enclose a rectangular space for a new garden. She has purchased 80 feet of wire fencing to enclose three sides, and will put the fourth side against the backyard fence. Find a formula for the area enclosed by the fence if the sides of fencing perpendicular to the existing fence have length L.

Solution

In a scenario like this involving geometry, it is often helpful to draw a picture. It might also be helpful to introduce a temporary variable, W, to represent the side of fencing parallel to the fourth side or backyard fence.



Since we know we only have 80 feet of fence available, we know that $L + W + L = 80$, or more simply, $2L + W = 80$. This allows us to represent the width, W, in terms of L: $W = 80 - 2L$

Now we are ready to write an equation for the area the fence encloses. We know the area of a rectangle is length multiplied by width, so $A = LW = L(80 - 2l)$, so

$$A(L) = 80L - 2L^2.$$

This formula represents the area of the fence in terms of the variable length L.

Example 1.5.2

A local newspaper currently has 84,000 subscribers, at a quarterly charge of \$30. Market research has suggested that if they raised the price to \$32, they would lose 5,000 subscribers. Assuming that subscriptions are linearly related to the price, create an equation to model their revenue as a function of the quarterly charge.

Solution

Revenue is the amount of money a company brings in. In this case, the revenue can be found by multiplying the charge per subscription times the number of subscribers. We can introduce variables, C for charge per subscription and S for the number subscribers, giving us the equation:

Revenue = CS

Since the number of subscribers changes with the price, we need to find a relationship between the variables.

We know that currently $S = 84,000$ and $C = 30$, and that if they raise the price to \$32 they would lose 5,000 subscribers, giving a second pair of values, $S = 79,000$ and $C = 32$. From this we can find a linear equation relating the two quantities. Treating C as the input and S as the output, the equation will have form $S = mC + b$. The slope will be

$$m = \frac{79,000 - 84,000}{32 - 30} = \frac{-5,000}{2} = -2,500$$

This tells us the paper will lose 2,500 subscribers for each dollar they raise the price. We can then solve for the vertical intercept.

$$S = -2500C + b$$

Plug in the point $S = 84,000$ and $C = 30$

$$84000 = -2500(30) + b$$

Solve for b

$$b = 159,000$$

This gives us the linear equation $S = -2,500C + 159,000$ relating cost and subscribers. Note this is a demand equation where C is the price and S is the quantity demanded. We now return to our revenue equation.

Revenue = CS

Substituting the equation for S from above:
Revenue = $C\left(-2,500C + 159,000\right)$

Expanding
Revenue = $-2,500C^2 + 159,000C$

We now have a quadratic equation for revenue as a function of the subscription charge. Later in the course we will use equations like this to determine the price to charge to maximize revenue.

Forms of Quadratic Functions

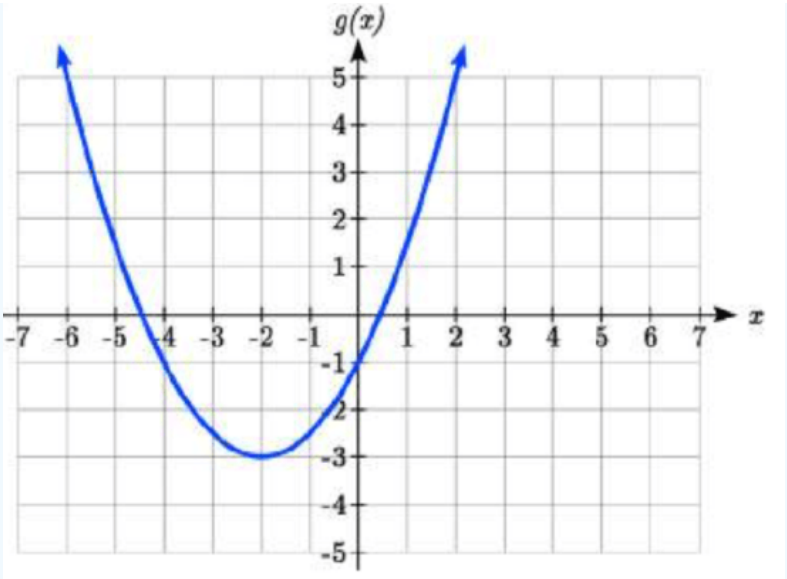
The **standard form** of a quadratic function is $f(x) = ax^2 + bx + c$.

The **transformation form** of a quadratic function is $f(x) = a(x - h)^2 + k$.

The **vertex** of the quadratic function is located at (h, k), where h and k are the numbers in the transformation form of the function. Because the vertex appears in the transformation form, it is often called the **vertex form**.

Example 1.5.3

Write an equation for the quadratic graphed below as a transformation of $f(x) = x^2$.



Solution

We can see the graph is the basic quadratic shifted to the left 2 and down 3, putting the vertex at $(-2,-3)$, giving a formula in the form $g(x)=a(x+2)^2-3$. By plugging in a point that falls on the grid, such as $(0,-1)$, we can solve for the stretch factor:

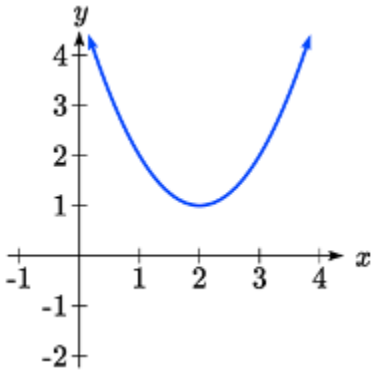
$$\begin{aligned} -1 &= a(0+2)^2-3 \\ 2 &= 4a \\ a &= \frac{1}{2} \end{aligned}$$

The equation for this formula is

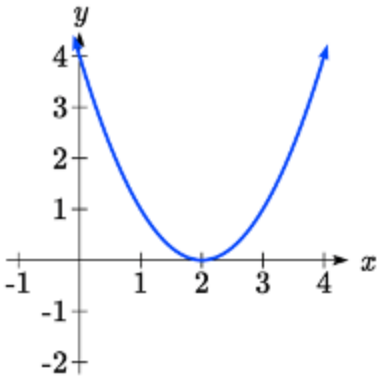
$$g(x)=\frac{1}{2}(x+2)^2-3$$

Short run Behavior: Intercepts

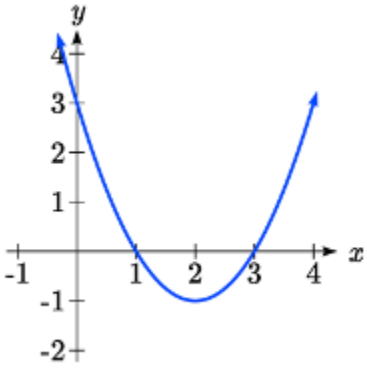
As with any function, we can find the vertical intercepts of a quadratic by evaluating the function at an input of zero, and we can find the horizontal intercepts by solving for when the output will be zero. Notice that depending upon the location of the graph, we might have zero, one, or two horizontal intercepts.



Zero horizontal intercepts



One horizontal intercept



Two horizontal intercepts

Notice that in the standard form of a quadratic, the constant term c reveals the vertical intercept of the graph, since $f(0) = a(0)^2 + b(0) + c = c$.

Example 1.5.4

Find the vertical and horizontal intercepts of the quadratic $f(x) = 3x^2 + 5x - 2$.

Solution

We can find the vertical intercept by evaluating the function at an input of zero:

$$f(0) = 3(0)^2 + 5(0) - 2 = -2$$

So the vertical intercept is at (0,-2)

For the horizontal intercepts, we solve for when the output will be zero:

$$0 = 3x^2 + 5x - 2.$$

In this case, the quadratic can be factored easily, providing the simplest method for solution.:

$$0 = (3x - 1)(x + 2),$$

so either

$$\begin{aligned} 0 &= 3x - 1 \\ x &= \frac{1}{3} \end{aligned}$$

or

$$\begin{aligned} 0 &= x + 2 \\ x &= -2 \end{aligned}$$

So the Horizontal intercepts are at $\left(\frac{1}{3}, 0\right)$ and $(-2, 0)$.

When a quadratic is not factorable or is hard to factor, we can turn to the quadratic formula.

Quadratic Formula

For a quadratic function given in standard form $f(x) = ax^2 + bx + c$, the **quadratic formula** gives the horizontal intercepts of the graph of this function:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

Example 1.5.5

A ball is thrown upwards from the top of a 40 foot high building at a speed of 80 feet per second. The ball's height above ground can be modeled by the equation

$$H(t) = -16t^2 + 80t + 40.$$

When does the ball hit the ground?

Solution

To find when the ball hits the ground, we need to determine when the height is zero, i.e., when $H(t) = 0$. While we could do this using the transformation form of the quadratic, we can also use the quadratic formula:

$$t = \frac{-80 \pm \sqrt{80^2 - 4(-16)(40)}}{2(-16)} = \frac{-80 \pm \sqrt{8960}}{-32}$$

Since the square root does not simplify nicely, we can use a calculator to approximate the values of the solutions:

$$t = \frac{-80 - \sqrt{8960}}{-32} \approx 5.458 \quad \text{or} \quad t = \frac{-80 + \sqrt{8960}}{-32} \approx -0.458$$

The second answer is outside the reasonable domain of our model, so we conclude the ball will hit the ground after about 5.458 seconds.

Example 1.5.6

The supply for a certain product can be modeled by $p = 3q^2$ and the demand can be modeled by $p = 1620 - 2q^2$, where p is the price in dollars, and q is the quantity in thousands of items. Find the equilibrium price and quantity.

Solution

Recall that the equilibrium price and quantity is found by finding where the supply and demand curve intersect. We can find that by setting the equations equal:

$$3q^2 = 1620 - 2q^2$$

Add $2q^2$ to both sides: $5q^2 = 1620$

Divide by 5 on both sides: $q^2 = 324$

Take the square root of both sides:

$$q = \pm\sqrt{324} = \pm 18$$

Since it doesn't make sense to talk about negative quantities, the equilibrium quantity is $q = 18$. To find the equilibrium price, we evaluate either function at the equilibrium quantity.

$$p = 3(18)^2 = 972$$

The equilibrium is 18 thousand items, at a price of $972.

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1.6: Polynomials and Rational Functions

Polynomial Functions

Terminology of Polynomial Functions

A **polynomial** is function that can be written as $f(x) = a_0 + a_1x + a_2x^2 + ... + a_nx^n$

Each of the a_i constants are called **coefficients** and can be positive, negative, or zero, and be whole numbers, decimals, or fractions.

A **term** of the polynomial is any one piece of the sum, that is any a_ix^i. Each individual term is a transformed power function.

The **degree** of the polynomial is the highest power of the variable that occurs in the polynomial.

The **leading term** is the term containing the highest power of the variable: the term with the highest degree.

The **leading coefficient** is the coefficient of the leading term.

Because of the definition of the "leading" term we often rearrange polynomials so that the powers are descending.

$$f(x) = a_nx^n + ... + a_2x^2 + a_1x + a_0$$

Example 1.6.1

Identify the degree, leading term, and leading coefficient of the polynomial

$$f(x) = 3 + 2x^2 - 4x^3$$

Solution

For the function $f(x)$, the degree is 3, the highest power on x. The leading term is the term containing that power, $-4x^3$. The leading coefficient is the coefficient of that term, -4.

Short run Behavior: Intercepts

As with any function, the vertical intercept can be found by evaluating the function at an input of zero. Since this is evaluation, it is relatively easy to do it for a polynomial of any degree. To find horizontal intercepts, we need to solve for when the output will be zero. For general polynomials, this can be a challenging prospect. Consequently, we will limit ourselves to three cases:

1. The polynomial can be factored using known methods: greatest common factor and trinomial factoring.
2. The polynomial is given in factored form.
3. Technology is used to determine the intercepts.

Example 1.6.2

Find the horizontal intercepts of $f(x) = x^6 - 3x^4 + 2x^2$.

Solution

We can attempt to factor this polynomial to find solutions for $f(x) = 0$.

$$x^6 - 3x^4 + 2x^2 = 0$$

$$\begin{aligned} x^2(x^4 - 3x^2 + 2) &= 0 && \text{Factoring out the greatest common factor} \\ x^2(x^2 - 1)(x^2 - 2) &= 0 && \text{Factoring the inside as a quadratic in } x^2 \end{aligned}$$

Then break apart to find solutions:

$$\begin{aligned} x^2 &= 0 \\ x &= 0 \end{aligned}$$

or

$$\begin{aligned} (x^2 - 1) &= 0 \\ x^2 &= 1 \\ x &= \pm 1 \end{aligned}$$

or

$$\begin{aligned} (x^2 - 2) &= 0 \\ x^2 &= 2 \\ x &= \pm\sqrt{2} \end{aligned}$$

This gives us 5 horizontal intercepts.

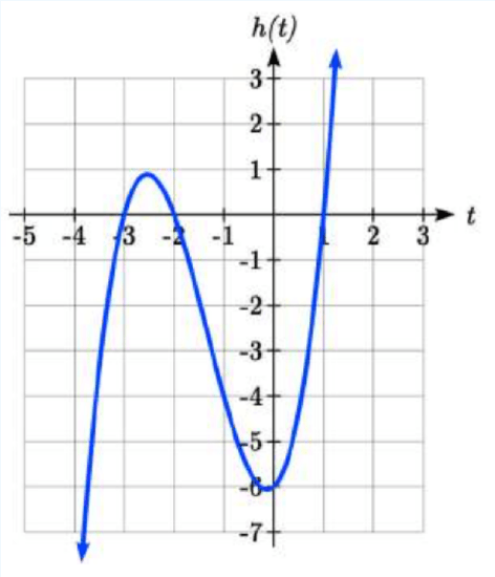
Example 1.6.3

Find the horizontal intercepts of $h(t) = t^3 + 4t^2 + t - 6$

Solution

Since this polynomial is not in factored form, has no common factors, and does not appear to be factorable using techniques we know, we can turn to technology to find the intercepts.

Graphing this function, it appears there are horizontal intercepts at t = -3, -2, and 1.



We could check these are correct by plugging in these values for t and verifying that $h(-3) = h(-2) = h(1) = 0$.

Solving Polynomial Inequalities

One application of our ability to find intercepts and sketch a graph of polynomials is the ability to solve polynomial inequalities. It is a very common question to ask when a function will be positive and negative, and one we will use later in this course.

Example 1.6.4

Solve $(x+3)(x+1)^2(x-4) > 0$

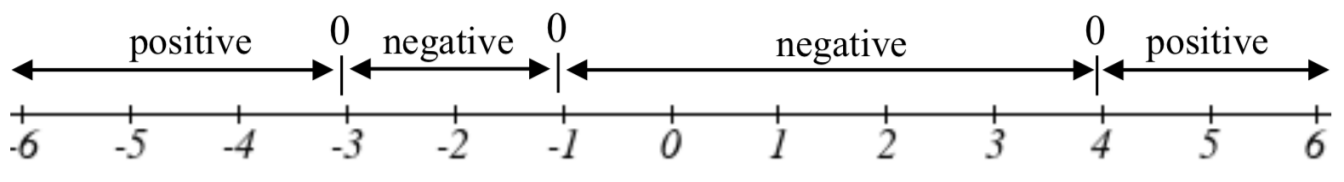
Solution

As with all inequalities, we start by solving the equality $(x+3)(x+1)^2(x-4) = 0$, which has solutions at x = -3, -1, and 4. We know the function can only change from positive to negative at these values, so these divide the inputs into 4 intervals.

We could choose a test value in each interval and evaluate the function $f(x) = (x+3)(x+1)^2(x-4)$ at each test value to determine if the function is positive or negative in that interval

Interval	Test x in interval	f(test value)	>0 or <0?
$x < -3$	-4	72	> 0
$-3 < x < -1$	-2	-6	< 0
$-1 < x < 4$	0	-12	< 0
$x > 4$	5	288	> 0

On a number line this would look like:



From our test values, we can determine this function is positive when $x < -3$ or $x > 4$, or in interval notation, $(-\infty, -3) \cup (4, \infty)$

Rational Functions

Rational functions are the ratios, or fractions, of polynomials. They can arise from both simple and complex situations.

Example 1.6.5

You plan to drive 100 miles. Find a formula for the time the trip will take as a function of the speed you drive.

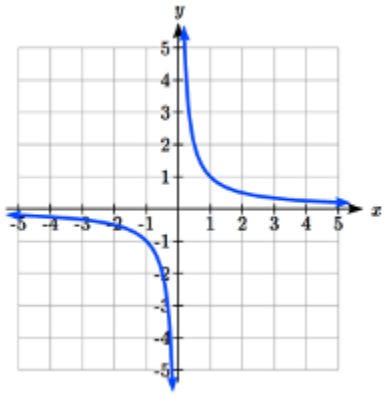
Solution

You may recall that multiplying speed by time will give you distance. If we let t represent the drive time in hours, and v represent the velocity (speed or rate) at which we drive, then $vt =$ distance. Since our distance is fixed at 100 miles, $vt = 100$. Solving this relationship for the time gives us the function we desired:

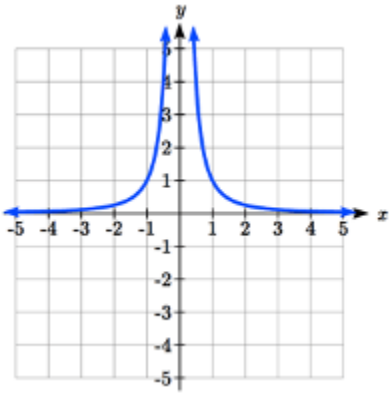
$$t(v) = \frac{100}{v}$$

Notice that this is a transformation of the reciprocal toolkit function, $f(x) = \frac{1}{x}$. Several natural phenomena, such as gravitational force and volume of sound, behave in a manner **inversely proportional to the square** of another quantity. For example, the volume, V, of a sound heard at a distance d from the source would be related by $V = \frac{k}{d^2}$ for some constant value k. These functions are transformations of the reciprocal squared toolkit function $f(x) = \frac{1}{x^2}$.

We have seen the graphs of the basic reciprocal function and the squared reciprocal function from our review of toolkit functions. These graphs have several important features.



$f(x) = \frac{1}{x}$



$f(x) = \frac{1}{x^2}$

Let's begin by looking at the reciprocal function, $f(x) = \frac{1}{x}$. As you well know, dividing by zero is not allowed and therefore zero is not in the domain, and so the function is undefined at an input of zero.

Short run behavior:

As the input values approach zero from the left side (taking on very small, negative values), the function values become very large

in the negative direction (in other words, they approach negative infinity).

We write: as $x \to 0^-, f(x) \to -\infty$.

As we approach zero from the right side (small, positive input values), the function values become very large in the positive direction (approaching infinity).

We write: as $x \to 0^+, f(x) \to \infty$.

This behavior creates a **vertical asymptote**. An asymptote is a line that the graph approaches. In this case the graph is approaching the vertical line $x = 0$ as the input becomes close to zero.

Long run behavior:

As the values of x approach infinity, the function values approach 0.

As the values of x approach negative infinity, the function values approach 0.

Symbolically: as $x \to \pm\infty, f(x) \to 0$

Based on this long run behavior and the graph we can see that the function approaches 0 but never actually reaches 0, it just "levels off" as the inputs become large. This behavior creates a **horizontal asymptote**. In this case the graph is approaching the horizontal line $f(x) = 0$ as the input becomes very large in the negative and positive directions.

Vertical and Horizontal Asymptotes

A **vertical asymptote** of a graph is a vertical line $x = a$ where the graph tends towards positive or negative infinity as the inputs approach a. As $x \to a, f(x) \to \pm\infty$.

A **horizontal asymptote** of a graph is a horizontal line $y = b$ where the graph approaches the line as the inputs get large. As $x \to \pm\infty, f(x) \to b$.

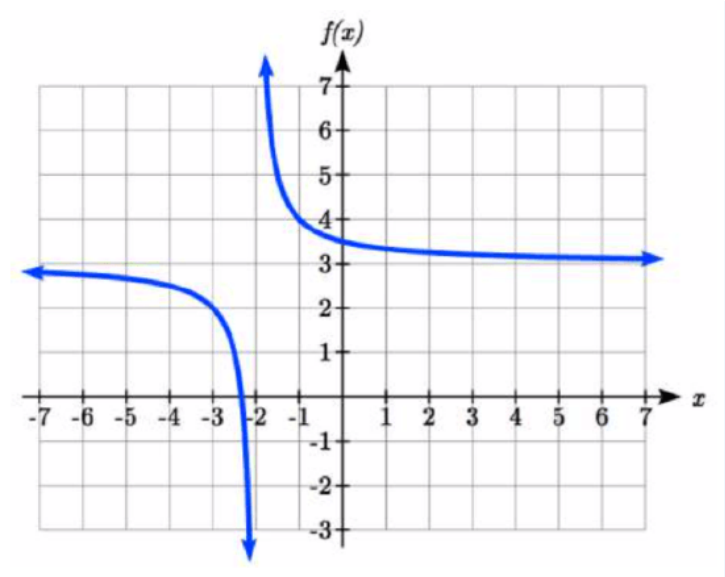
Example 1.6.6

Sketch a graph of the reciprocal function shifted two units to the left and up three units. Identify the horizontal and vertical asymptotes of the graph, if any.

Solution

Transforming the graph left 2 and up 3 would result in the function $f(x) = \frac{1}{x+2} + 3$, or equivalently, by giving the terms a common denominator, $f(x) = \frac{3x+7}{x+2}$

Shifting the toolkit function would give us this graph.



Notice that this equation is undefined at $x = -2$, and the graph also is showing a vertical asymptote at $x = -2$.

As $x \to -2^-$, $f(x) \to -\infty$, and as $x \to -2^+$, $f(x) \to \infty$

As the inputs grow large, the graph appears to be leveling off at output values of 3, indicating a horizontal asymptote at $y = 3$.

As $x \to \pm\infty$, $f(x) \to 3$.

Notice that horizontal and vertical asymptotes get shifted left 2 and up 3 along with the function.

A general rational function is the ratio of any two polynomials.

Rational Function

A **rational function** is a function that can be written as the ratio of two polynomials, $P(x)$ and $Q(x)$.

$$f(x) = \frac{P(x)}{Q(x)} = \frac{a_0 + a_1 x + a_2 x^2 + ... + a_p x^p}{b_0 + b_1 x + b_2 x^2 + ... + b_q x^q}$$

Rational functions can arise from real situations.

Example 1.6.7

A large mixing tank currently contains 100 gallons of water, into which 5 pounds of sugar have been mixed. A tap will open pouring 10 gallons per minute of water into the tank at the same time sugar is poured into the tank at a rate of 1 pound per minute. Find the concentration (pounds per gallon) of sugar in the tank after t minutes.

Solution

Notice that the amount of water in the tank is changing linearly, as is the amount of sugar in the tank. We can write an equation independently for each:

$$water = 100 + 10t$$
$$sugar = 5 + 1t$$

The concentration, C, will be the ratio of pounds of sugar to gallons of water

$$C(t) = \frac{5+t}{100+10t}$$

Vertical Asymptotes of Rational Functions

The **vertical asymptotes** of a rational function will occur where the denominator of the function is equal to zero and the numerator is not zero.

Horizontal Asymptote of Rational Functions

The **horizontal asymptote** of a rational function can be determined by looking at the degrees of the numerator and denominator.

Degree of denominator > degree of numerator: Horizontal asymptote at $y = 0$

Degree of denominator < degree of numerator: No horizontal asymptote

Degree of denominator = degree of numerator: Horizontal asymptote at ratio of leading coefficients.

Example 1.6.8

In the sugar concentration problem from earlier, we created the equation $C(t) = \frac{5+t}{100+10t}$.

Find the horizontal asymptote and interpret it in context of the scenario.

Solution

Both the numerator and denominator are linear (degree 1), so since the degrees are equal, there will be a horizontal asymptote at the ratio of the leading coefficients. In the numerator, the leading term is t, with coefficient 1. In the denominator, the leading term is $10t$, with coefficient 10. The horizontal asymptote will be at the ratio of these values: As $t \to \infty$, $C(t) \to \frac{1}{10}$. This function will have a horizontal asymptote at $y = \frac{1}{10}$.

This tells us that as the input gets large, the output values will approach 1/10. In context, this means that as more time goes by, the concentration of sugar in the tank will approach one tenth of a pound of sugar per gallon of water or 1/10 pounds per gallon.

Example 1.6.9

Find the horizontal and vertical asymptotes of the function

$$f(x) = \frac{(x-2)(x+3)}{(x-1)(x+2)(x-5)}$$

Solution

First, note this function has no inputs that make both the numerator and denominator zero, so there are no potential holes. The function will have vertical asymptotes when the denominator is zero, causing the function to be undefined. The denominator will be zero at x = 1, -2, and 5, indicating vertical asymptotes at these values.

The numerator has degree 2, while the denominator has degree 3. Since the degree of the denominator is greater than the degree of the numerator, the denominator will grow faster than the numerator, causing the outputs to tend towards zero as the inputs get large, and so as $x \to \pm\infty, f(x) \to 0$. This function will have a horizontal asymptote at $y = 0$.

As with all functions, a rational function will have a vertical intercept when the input is zero, if the function is defined at zero. It is possible for a rational function to not have a vertical intercept if the function is undefined at zero.

Likewise, a rational function will have horizontal intercepts at the inputs that cause the output to be zero (unless that input corresponds to a hole). It is possible there are no horizontal intercepts. Since a fraction is only equal to zero when the numerator is zero, horizontal intercepts will occur when the numerator of the rational function is equal to zero.

Example 1.6.10

Find the intercepts of $f(x) = \frac{(x-2)(x+3)}{(x-1)(x+2)(x-5)}$

Solution

We can find the vertical intercept by evaluating the function at zero

$$f(0) = \frac{(0-2)(0+3)}{(0-1)(0+2)(0-5)} = \frac{-6}{10} = -\frac{3}{5}$$

The horizontal intercepts will occur when the function is equal to zero:

$$0 = \frac{(x-2)(x+3)}{(x-1)(x+2)(x-5)}$$

This is zero when the numerator is zero.

$$0 = (x-2)(x+3)$$
$$x = 2, -3$$

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1.7: Exponential Functions

Consider these two companies:

- Company A has 100 stores, and expands by opening 50 new stores a year
- Company B has 100 stores, and expands by increasing the number of stores by 50% of their total each year.

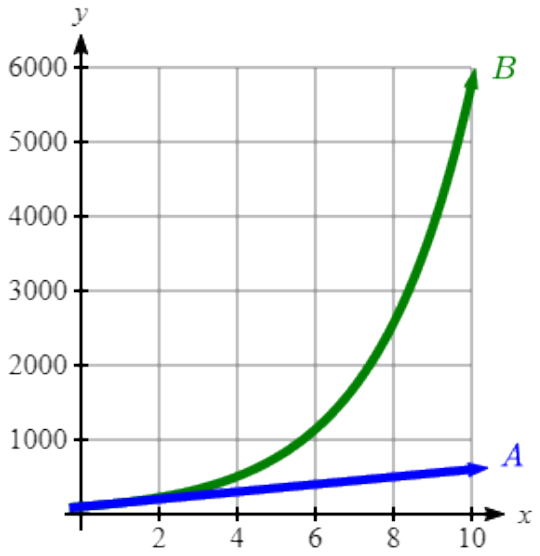
Company A is exhibiting linear growth. In linear growth, we have a constant rate of change – a constant *number* that the output increased for each increase in input. For company A, the number of new stores per year is the same each year.

Company B is different – we have a *percent* rate of change rather than a constant number of stores/year as our rate of change. To see the significance of this difference compare a 50% increase when there are 100 stores to a 50% increase when there are 1000 stores:

- 100 stores, a 50% increase is 50 stores in that year.
- 1000 stores, a 50% increase is 500 stores in that year.

Calculating the number of stores after several years, we can clearly see the difference in results.

Years	Company A	Company B
2	200	225
4	300	506
6	400	1139
8	500	2563
10	600	5767



Graphs of data from A and B, with B fit to a curve.

This percent growth can be modeled with an exponential function.

Exponential Function

An **exponential growth or decay function** is a function that grows or shrinks at a constant percent growth rate. The equation can be written in the form

$$f(x) = a(1+r)^x$$

or

$$f(x) = ab^x$$

where $b = 1 + r$.

Where

- a is the initial or starting value of the function,
- r is the percent growth or decay rate, written as a decimal,
- b is the growth factor or growth multiplier. Since powers of negative numbers behave strangely, we limit b to positive values.

Example 1.7.1

India's population was 1.14 billion in the year 2008 and is growing by about 1.34% each year. Write an exponential function for India's population, and use it to predict the population in 2020.

Solution

Using 2008 as our starting time ($t = 0$), our initial population will be 1.14 billion. Since the percent growth rate was 1.34%, our value for r is 0.0134.

Using the basic formula for exponential growth $f(x) = a(1+r)^x$ we can write the formula,

$$f(t) = 1.14(1 + 0.0134)^t$$

To estimate the population in 2020, we evaluate the function at $t = 12$, since 2020 is 12 years after 2008:

$$f(t) = 1.14(1 + 0.0134)^{12} \approx 1.337 \text{ billion people in } 2020.$$

Example 1.7.2

A certificate of deposit (CD) is a type of savings account offered by banks, typically offering a higher interest rate in return for a fixed length of time you will leave your money invested. If a bank offers a 24 month CD with an annual interest rate of 1.2% compounded monthly, how much will a $1000 investment grow to over those 24 months?

Solution

First, we must notice that the interest rate is an annual rate, but is compounded monthly, meaning interest is calculated and added to the account monthly. To find the monthly interest rate, we divide the annual rate of 1.2% by 12 since there are 12 months in a year: 1.2%/12 = 0.1%. Each month we will earn 0.1% interest. From this, we can set up an exponential function, with our initial amount of $1000 and a growth rate of $r = 0.001$, and our input m measured in months:

$$f(m) = 1000\left(1 + \frac{0.012}{12}\right)^m = 1000(1.001)^m$$

After 24 months, the account will have grown to $f(24) = 1000(1.001)^{24} \approx \$1024.28$.

Example 1.7.3

Bismuth-210 is an isotope that radioactively decays by about 13% each day, meaning 13% of the remaining Bismuth-210 transforms into another atom (polonium-210 in this case) each day. If you begin with 100 mg of Bismuth-210, how much remains after one week?

Solution

With radioactive decay, instead of the quantity increasing at a percent rate, the quantity is decreasing at a percent rate. Our initial quantity is $a = 100$ mg, and our growth rate will be negative 13%, since we are decreasing: $r = -0.13$. This gives the equation

$$Q(d) = 100(1 - 0.13)^d = 100(0.87)^d.$$

This can also be explained by recognizing that if 13% decays, then 87% remains.

After one week, 7 days, the quantity remaining would be $Q(7) = 100(0.87)^7 = 37.73$ mg of Bismuth-210 remains.

Example 1.7.4

$T(q)$ represents the total number of Android smart phone contracts, in thousands, held by a certain Verizon store region measured quarterly since January 1, 2010. Interpret all of the parts of the equation $T(2) = 86(1.64)^2 = 231.3056$.

Solution

Interpreting this from the basic exponential form, we know that 86 is our initial value. This means that on Jan. 1, 2010 this region had 86,000 Android smart phone contracts. Since $b = 1 + r = 1.64$, we know that every quarter the number of smart phone contracts grows by 64%. $T(2) = 231.3056$ means that in the second quarter (or at the end of the second quarter) there were approximately 231,305 Android smart phone contracts.

When working with exponentials, there is a special constant we must talk about. It arises when we talk about things growing continuously, such as continuous compounding, or natural phenomena like radioactive decay that happen continuously.

Euler's Number: e

$$e \approx 2.718282$$

Because e is often used as the base of an exponential, most scientific and graphing calculators have a button that can calculate powers of e, usually labeled e^x. Some computer software instead defines a function $exp(x)$, where exp(x) = e^x. Since calculus studies continuous change, we will almost always use the e-based form of exponential equations in this course.

Continuous Growth Formula

Continuous growth can be calculated using the formula

$$f(x) = ae^{rx}$$

where

- a is the starting amount,
- r is the continuous growth rate.

Example 1.7.5

Radon-222 decays at a continuous rate of 17.3% per day. How much will 100mg of Radon-222 decay to in 3 days?

Solution

Since we are given a continuous decay rate, we use the continuous growth formula. Since the substance is decaying, we know the growth rate will be negative: $r = -0.173$, $f(3) = 100e^{-0.173(3)} \approx 59.512$ mg of Radon-222 will remain.

Graphs of Exponential Functions

Graphical Features of Exponential Functions

Graphically, in the function $f(x) = ab^x$.

- a is the vertical intercept of the graph.
- b determines the rate at which the graph grows:
  - the function will increase if $b > 1$,
  - the function will decrease if $0 < b < 1$.
- The graph will have a horizontal asymptote at $y = 0$.
- The graph will be concave up if $a > 0$; concave down if $a < 0$.
- The domain of the function is all real numbers.
- The range of the function is $(0, \infty)$.

When sketching the graph of an exponential function, it can be helpful to remember that the graph will pass through the points $(0, a)$ and $(1, ab)$.

The value b will determine the function's long run behavior:

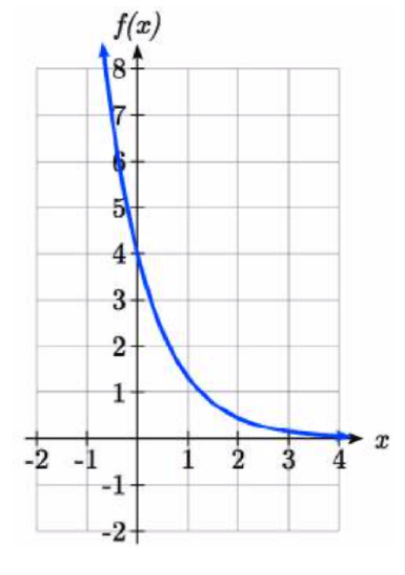
- If $b > 1$, as $x \to \infty$, $f(x) \to \infty$, and as $x \to -\infty$, $f(x) \to 0$.
- If $0 < b < 1$, as $x \to \infty$, $f(x) \to 0$, and as $x \to -\infty$, $f(x) \to \infty$.

Example 1.7.6

Sketch a graph of $f(x) = 4\left(\frac{1}{3}\right)^x$

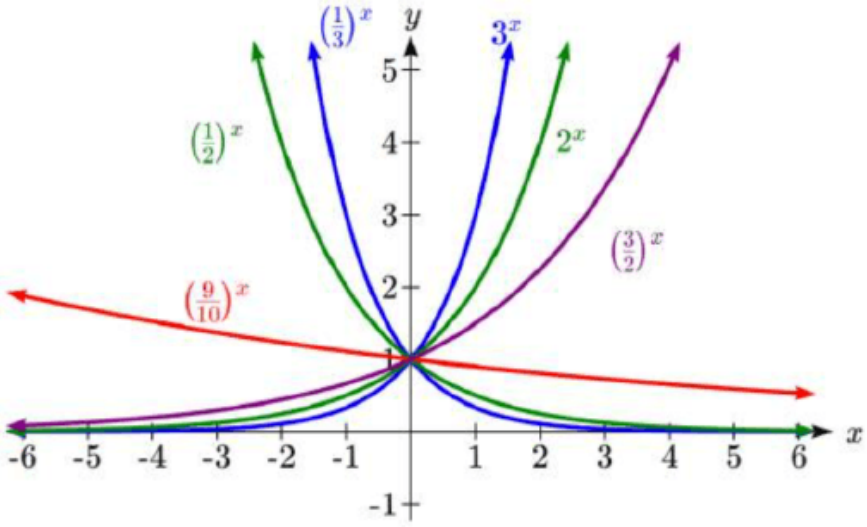
Solution

This graph will have a vertical intercept at (0,4), and pass through the point $\left(1, \frac{4}{3}\right)$. Since $b < 1$, the graph will be decreasing towards zero. Since $a > 0$, the graph will be concave up.



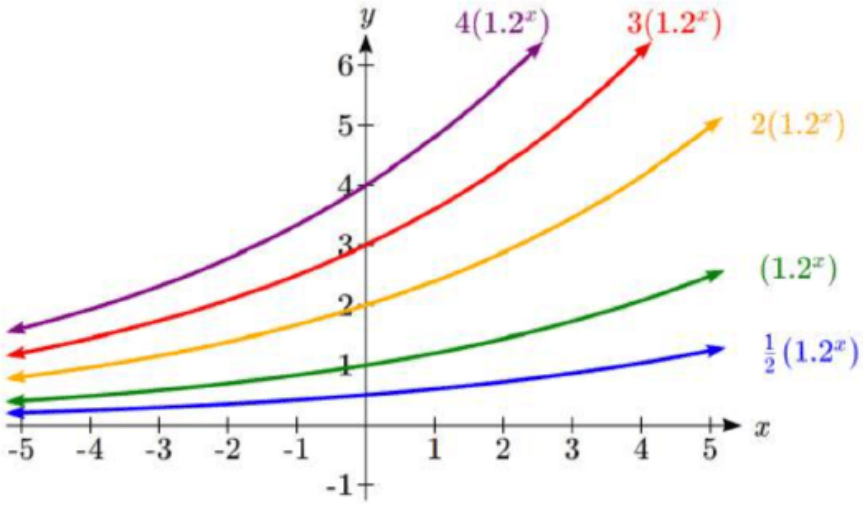
We can also see from the graph the long run behavior: as $x \to \infty$, $f(x) \to 0$, and as $x \to -\infty$, $f(x) \to \infty$.

To get a better feeling for the effect of a and b on the graph, examine the sets of graphs below. The first set shows various graphs, where a remains the same and we only change the value for b. Notice that the closer the value of b is to 1, the less steep the graph will be.



Changing the value of b.

In the next set of graphs, a is altered and our value for b remains the same.



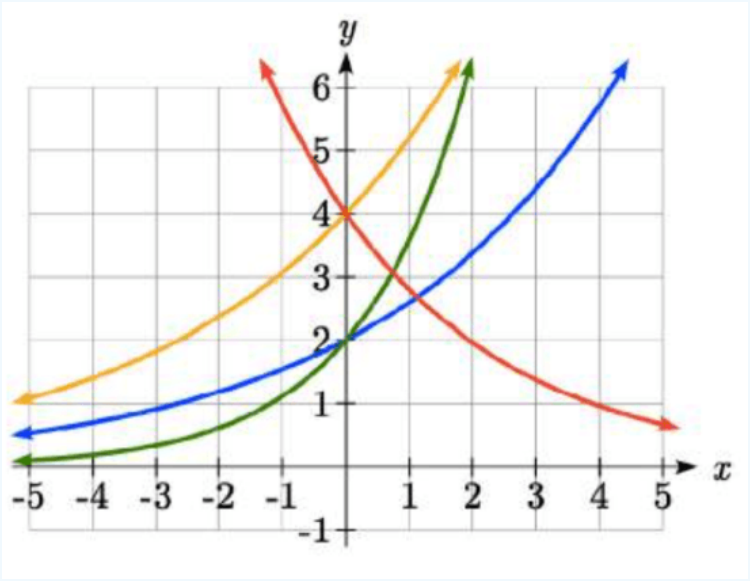
Changing the value of a.

Notice that changing the value for a changes the vertical intercept. Since a is multiplying the b^x term, a acts as a vertical stretch factor, not as a shift. Notice also that the long run behavior for all of these functions is the same because the growth factor did not change and none of these a values introduced a vertical flip.

Example 1.7.7

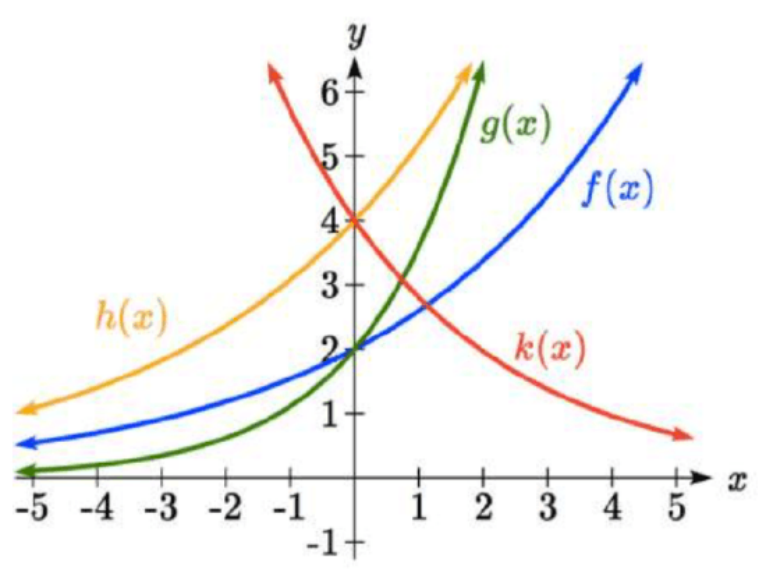
Match each equation with its graph.

- $f(x) = 2(1.3)^x$
- $g(x) = 2(1.8)^x$
- $h(x) = 4(1.3)^x$
- $k(x) = 4(0.7)^x$



Solution

The graph of $k(x)$ is the easiest to identify, since it is the only equation with a growth factor less than one, which will produce a decreasing graph. The graph of $h(x)$ can be identified as the only growing exponential function with a vertical intercept at (0,4). The graphs of $f(x)$ and $g(x)$ both have a vertical intercept at (0,2), but since $g(x)$ has a larger growth factor, we can identify it as the graph increasing faster.



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1.8: Logarithmic Functions

Logarithms are the inverse of exponential functions – they allow us to undo exponential functions and solve for the exponent. They are also commonly used to express quantities that vary widely in size.

Logarithm Equivalent to an Exponential

The logarithm (base b) function, written $\log_b(x)$, is the inverse of the exponential function (base b), b^x.

This means the statement $b^a = c$ is equivalent to the statement $\log_b(c) = a$.

Properties of Logs: Inverse Properties

- $\log_b(b^x) = x$
- $b^{\log_b(x)} = x$

Example 1.8.1

Write these exponential equations as logarithmic equations:

1. $2^3 = 8$
2. $5^2 = 25$
3. $10^{-4} = \frac{1}{10000}$

Solution

1. $2^3 = 8$ is equivalent to $\log_2(8) = 3$.
2. $5^2 = 25$ is equivalent to $\log_5(25) = 2$.
3. $10^{-4} = \frac{1}{10000}$ is equivalent to $\log_{10}\left(\frac{1}{10000}\right) = -4$.

Example 1.8.2

Solve $2^x = 10$ for x.

Solution

By rewriting this expression as a logarithm, we get $x = \log_2(10)$.

While this does define a solution, and an exact solution at that, you may find it somewhat unsatisfying since it is difficult to compare this expression to the decimal estimate we made earlier. Also, giving an exact expression for a solution is not always useful–often we really need a decimal approximation to the solution. Luckily, this is a task calculators and computers are quite adept at. Unluckily for us, most calculators and computers will only evaluate logarithms of two bases. Happily, this ends up not being a problem, as we'll see briefly.

Common and Natural Logarithms

The **common log** is the logarithm with base 10, and is typically written $\log(x)$.

The **natural log** is the logarithm with base e, and is typically written $\ln(x)$.

Example 1.8.3

Evaluate $\log(1000)$ using the definition of the common log.

Solution

To evaluate $\log(1000)$, we can say $x = \log(1000)$, then rewrite into exponential form using the common log base of 10:

$$10^x = 1000.$$

From this, we might recognize that 1000 is the cube of 10, so $x = 3$.

We also can use the inverse property of logs to write $log_{10}\left(10^3\right) = 3$.

Values of the common log

Number	Number as exponential	log(number)
1000	10^3	3
100	10^2	2
10	10^1	1
1	10^0	0
0.1	10^{-1}	-1
0.01	10^{-2}	-2
0.001	10^{-3}	-3

Example 1.8.4

Evaluate $\log(500)$ using you calculator or computer.

Solution

Using a computer or calculator, we can evaluate and find that $\log(500) \approx 2.69897$.

Another property provides the basis for solving exponential equations.

Properties of Logs: Exponent Property

$\log_b\left(A^r\right) = r \ \log_b(A)$

Solving exponential equations:

1. Isolate the exponential expressions when possible.
2. Take the logarithm of both sides.
3. Utilize the exponent property for logarithms to pull the variable out of the exponent.
4. Use algebra to solve for the variable.

Example 1.8.5

In the last section, we predicted the population (in billions) of India t years after 2008 by using the function $f(t) = 1.14(1 + 0.0134)^t$. If the population continues following this trend, when will the population reach 2 billion?

Solution

We need to solve for the t so that $f(t) = 2$

$2 = 1.14(1.0134)^t$	Initial equation.
$\frac{2}{1.14} = 1.0134^t$	Divide by 1.14 to isolate the exponential expression.
$\ln\left(\frac{2}{1.14}\right) = \ln\left(1.0134^t\right)$	Take the logarithm of both sides of the equation.
$\ln\left(\frac{2}{1.14}\right) = t\ \ln(1.0134)$	Apply the exponent property on the right side.
$t = \frac{\ln\left(\frac{2}{1.14}\right)}{\ln(1.0134)}$	Divide both sides by $\ln(1.0134)$
$t \approx 42.23$ years	

If this growth rate continues, the model predicts the population of India will reach 2 billion about 42 years after 2008, or approximately in the year 2050.

Example 1.8.6

Solve $5e^{-0.3t} = 2$ for t.

Solution

First we divide by 5 to isolate the exponential:

$$e^{-0.3t} = \frac{2}{5}.$$

Since this equation involves e, it makes sense to use the natural log:

$\ln\left(e^{-0.3t}\right) = \ln\left(\frac{2}{5}\right)$	Take the natural log of both sides.
$-0.3t = \ln\left(\frac{2}{5}\right)$	Utilizing the inverse property for logs.
$t = \frac{\ln\left(\frac{2}{5}\right)}{-0.3}$	Now dividing by -0.3.
$t \approx 3.054$	

In addition to solving exponential equations, logarithmic expressions are common in many physical situations.

Example 1.8.7

In chemistry, pH is a measure of the acidity or basicity of a liquid. The pH is related to the concentration of hydrogen ions, $[H^+]$, measured in moles per liter, by the equation

$$\text{pH} = -\log\left([H^+]\right)$$

If a liquid has concentration of 0.0001 moles per liter, determine the pH. Determine the hydrogen ion concentration of a liquid with pH of 7.

Solution

To answer the first question, we evaluate the expression $-\log(0.0001)$. While we could use our calculators for this, we do not really need them here, since we can use the inverse property of logs:

$$-\log(0.0001) = -\log\left(10^{-4}\right) = -(-4) = 4.$$

To answer the second question, we need to solve the equation $7 = -\log\left([H^+]\right)$. Begin by isolating the logarithm on one side of the equation by multiplying both sides by -1: $-7 = \log\left([H^+]\right)$. Rewriting into exponential form yields the answer:

$$[H^+] = 10^{-7} = 0.0000001 \text{ moles per liter.}$$

While we don't often need to sketch the graph of a logarithm, it is helpful to understand the basic shape.

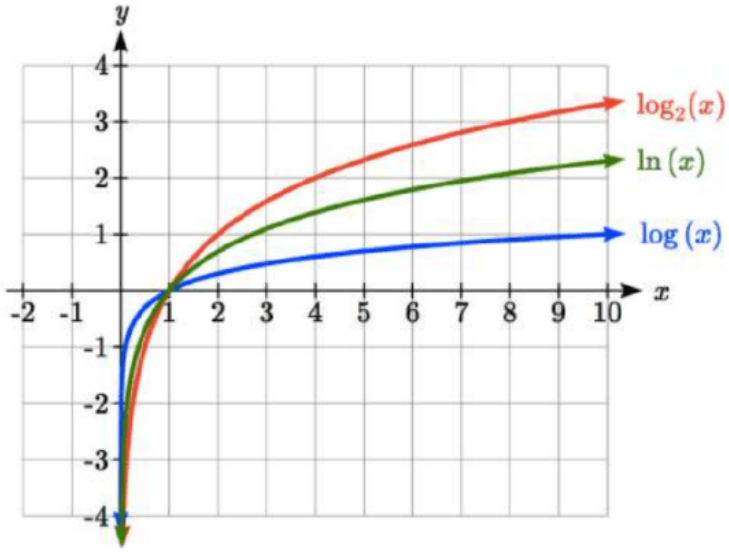
Graphical Features of the Logarithm

Graphically, given the function $g(x) = \log_b(x)$.

- The graph has a horizontal intercept at (1, 0).
- The graph has a vertical asymptote at $x = 0$.
- The graph is increasing and concave down.
- The domain of the function is $x > 0$, or $(0, \infty)$ in interval notation.
- The range of the function is all real numbers, or $(-\infty, \infty)$ in interval notation.

When sketching a general logarithm with base b, it can be helpful to remember that the graph will pass through the points $(1, 0)$ and $(b, 1)$.

To get a feeling for how the base affects the shape of the graph, examine the graphs below:



Another important observation made was the domain of the logarithm: $x > 0$. Like the reciprocal and square root functions, the logarithm has a restricted domain which must be considered when finding the domain of a composition involving a log.

Example 1.8.8

Find the domain of the function $f(x) = \log(5 - 2x)$.

Solution

The logarithm is only defined when the input is positive, so this function will only be defined when $5 - 2x > 0$. Solving this inequality, $-2x > -5$, so $x < \frac{5}{2}$.

The domain of this function is $x < \frac{5}{2}$, or, in interval notation, $\left(-\infty, \frac{5}{2}\right)$.

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1.E: Review (Exercises)

1.1 Exercises

Exercise $1.E.1$

The amount of garbage, G, produced by a city with population p is given by $G = f(p)$. G is measured in tons per week, and p is measured in thousands of people.

1. The town of Tola has a population of 40,000 and produces 13 tons of garbage each week. Express this information in terms of the function f.
2. Explain the meaning of the statement $f(5) = 2$.

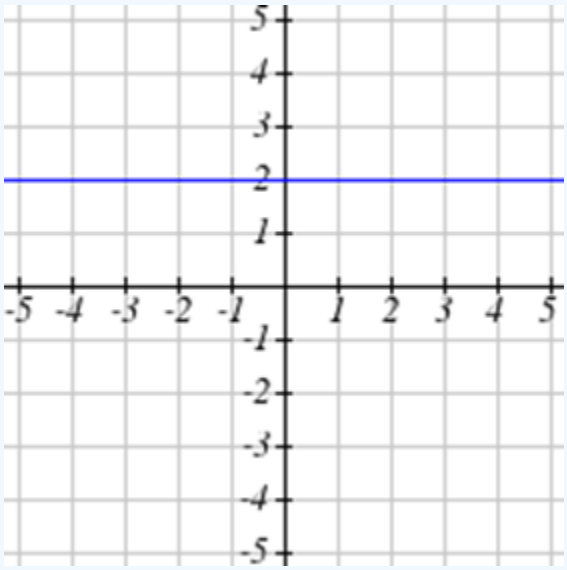
Exercise $1.E.2$

The number of cubic yards of dirt, D, needed to cover a garden with area a square feet is given by $D = g(a)$.

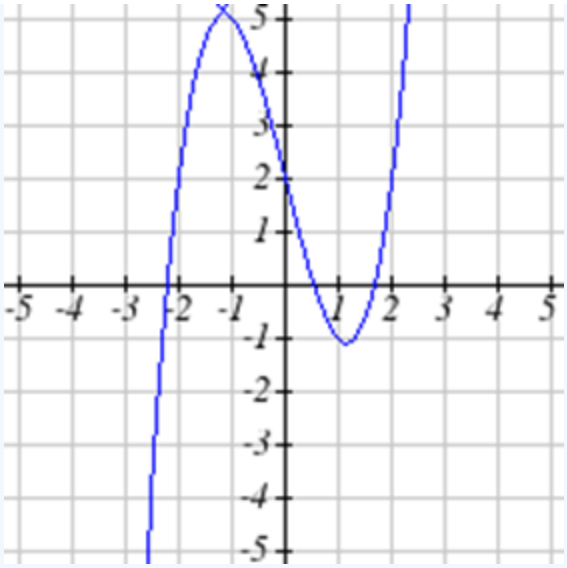
1. A garden with area 5000 ft^2 requires 50 cubic yards of dirt. Express this information in terms of the function g.
2. Explain the meaning of the statement $g(100) = 1$.

Exercise $1.E.3$

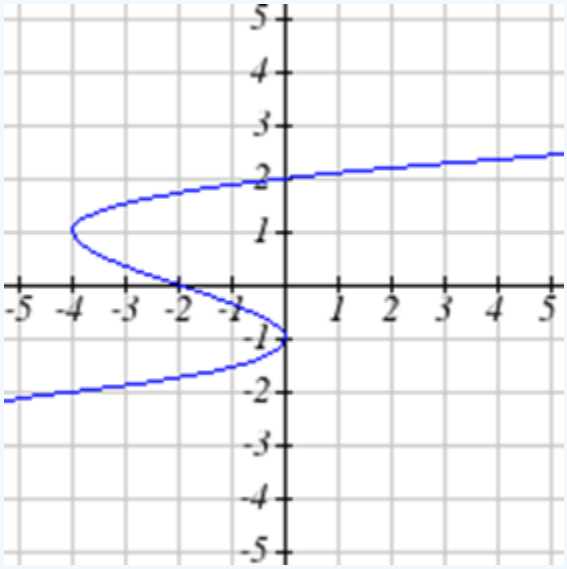
Select all of the following graphs which represent y as a function of x.



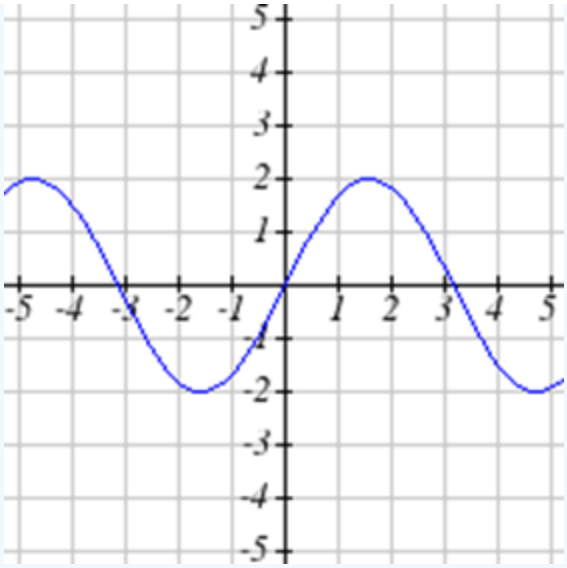
a.



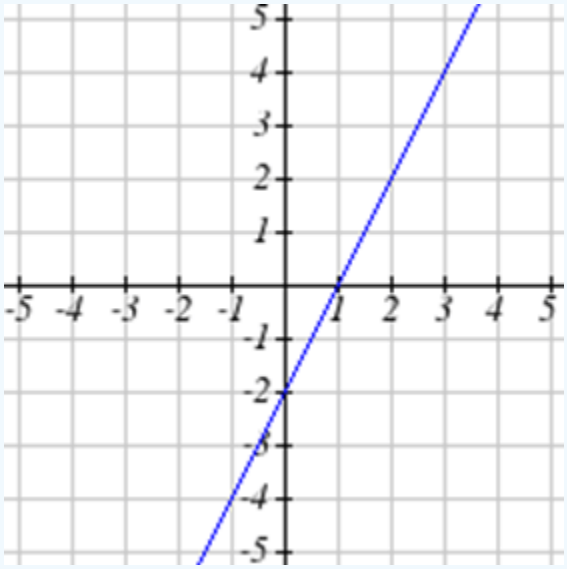
b.



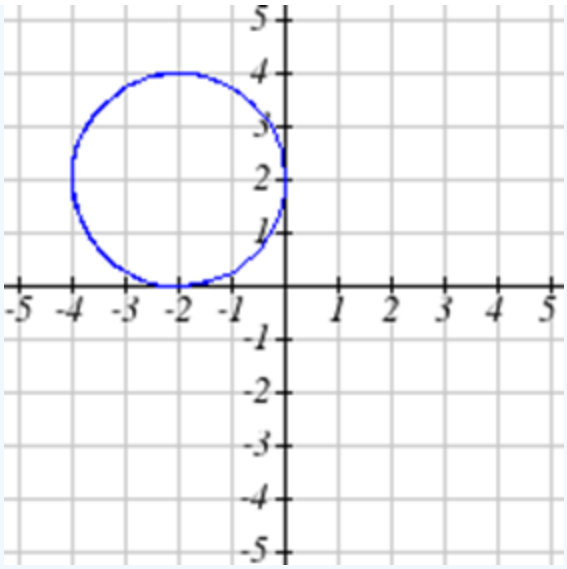
c.



d.



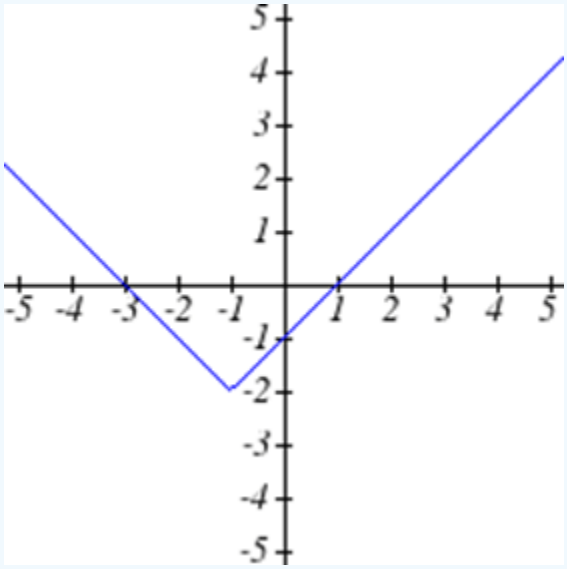
e.



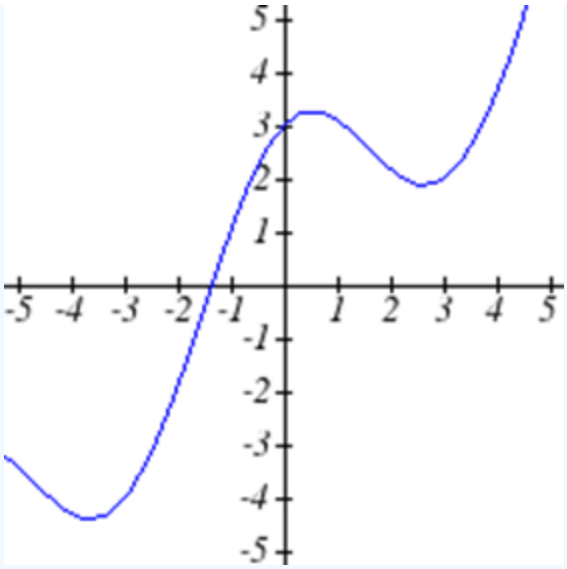
f.

Exercise $1.E.4$

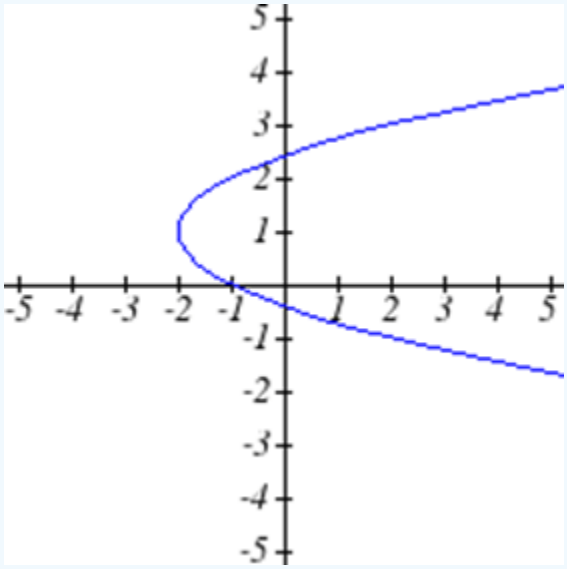
Select all of the following graphs which represent y as a function of x.



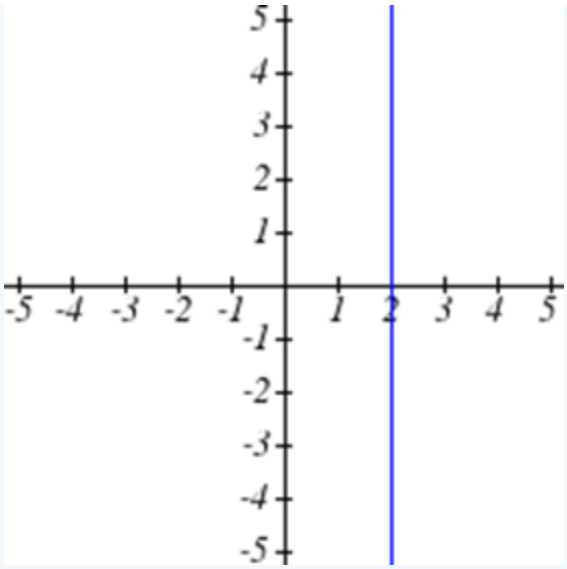
a.



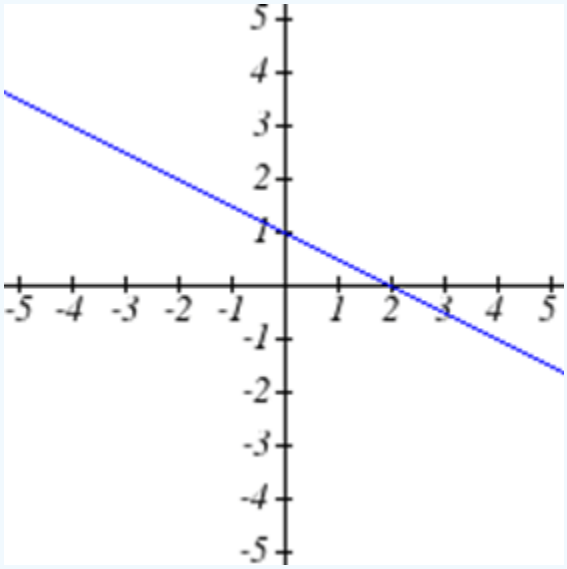
b.



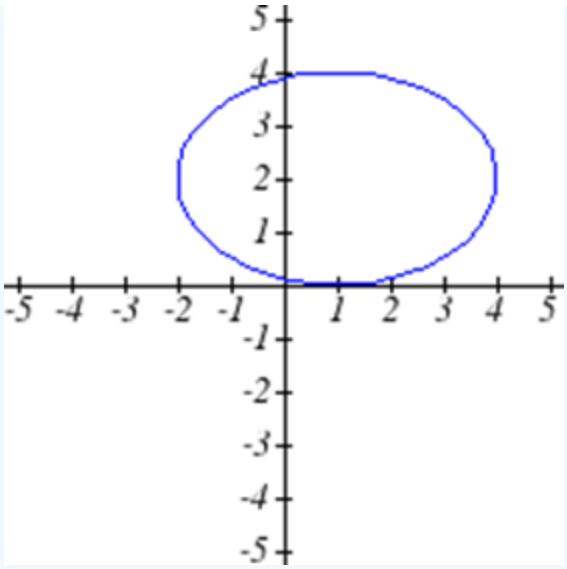
c.



d.



e.



f.

Exercise $1.E.5$

Select all of the following tables which represent y as a function of x.

a.

x	5	10	15
y	3	8	14

b.

x	5	10	15
y	3	8	8

c.

x	5	10	10
y	3	8	14

Exercise $1.E.6$

Select all of the following tables which represent y as a function of x.

a.

x	2	6	13
y	3	10	10

b.

x	2	6	6
y	3	10	14

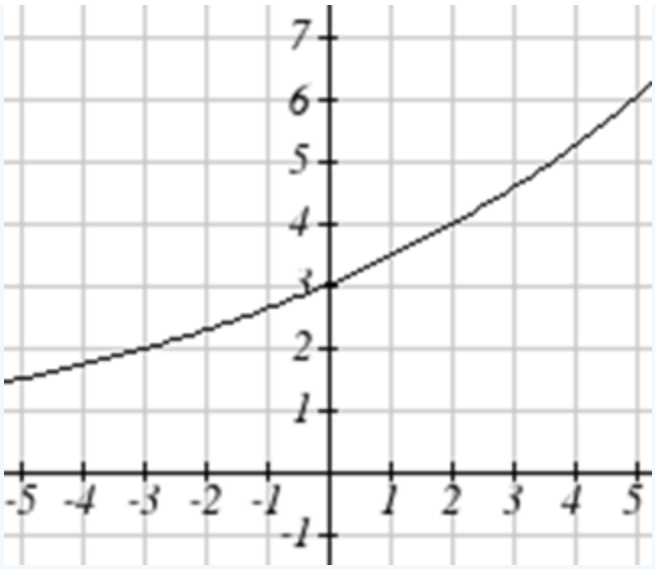
c.

x	2	6	13
y	3	10	14

Exercise $1.E.7$

Given the function $g(x)$ graphed here,

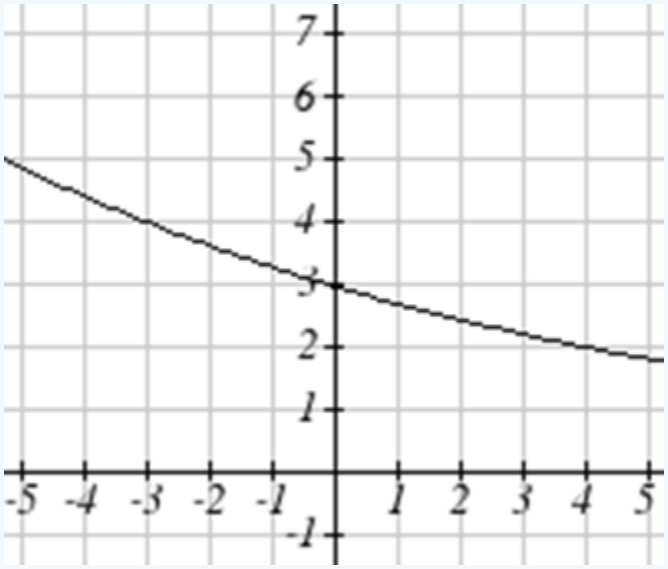
1. Evaluate $g(2)$
2. Solve $g(x) = 2$



Exercise $1.E.8$

Given the function $f(x)$ graphed here.

1. Evaluate $f(4)$
2. Solve $f(x) = 4$



Exercise $1.E.9$

Based on the table below,

1. Evaluate $f(3)$
2. Solve $f(x) = 1$

x	0	1	2	3	4	5	6	7	8	9

$f(x)$	74	28	1	53	56	3	36	45	14	47

Exercise $1.E.10$

Based on the table below,

1. Evaluate $f(8)$
2. Solve $f(x) = 7$

x	0	1	2	3	4	5	6	7	8	9
$f(x)$	62	8	7	38	86	73	70	39	75	34

Exercises $1.E.11 - 1.E.18$

For each of the following functions, evaluate: $f(-2)$, $f(-1)$, $f(0)$, $f(1)$, and $f(2)$

11. $f(x) = 4 - 2x$	12. $f(x) = 8 - 3x$
13. $f(x) = 8x^2 - 7x + 3$	14. $f(x) = 6x^2 - 7x + 4$
15. $f(x) = 3 + \sqrt{x+3}$	16. $f(x) = 4 - \sqrt[3]{x-2}$
17. $f(x) = \frac{x-3}{x+1}$	18. $f(x) = \frac{x-2}{x+2}$

Exercise $1.E.19$

Let $f(t) = 3t + 5$

1. Evaluate $f(0)$
2. Solve $f(t) = 0$

Exercise $1.E.20$

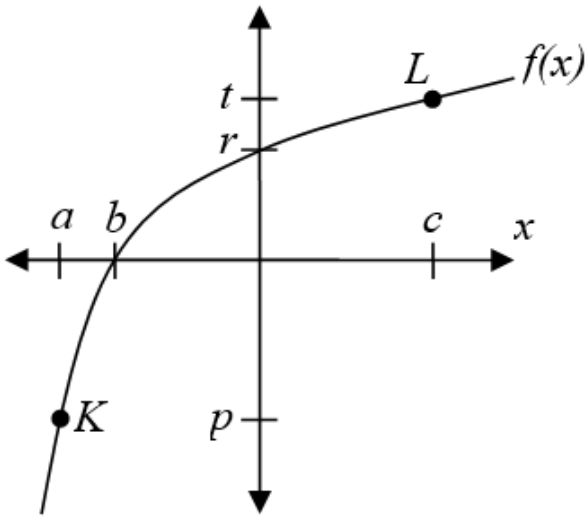
Let $g(p) = 6 - 2p$

1. Evaluate $g(0)$
2. Solve $g(p) = 0$

Exercise $1.E.21$

Using the graph shown,

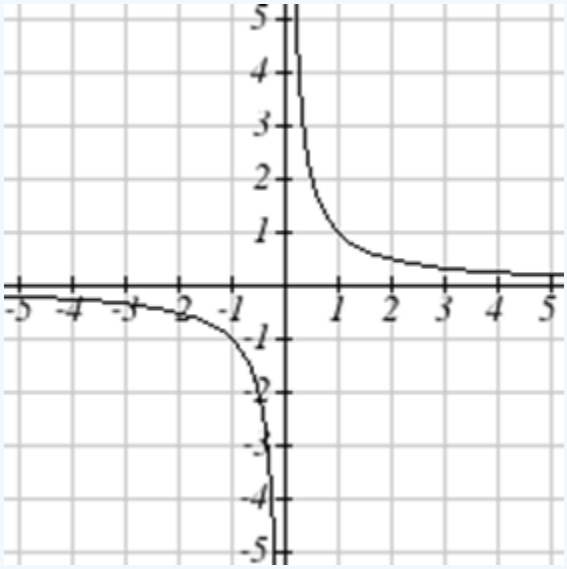
1. Evaluate $f(c)$
2. Solve $f(x) = p$
3. What are the coordinates of points L and K?



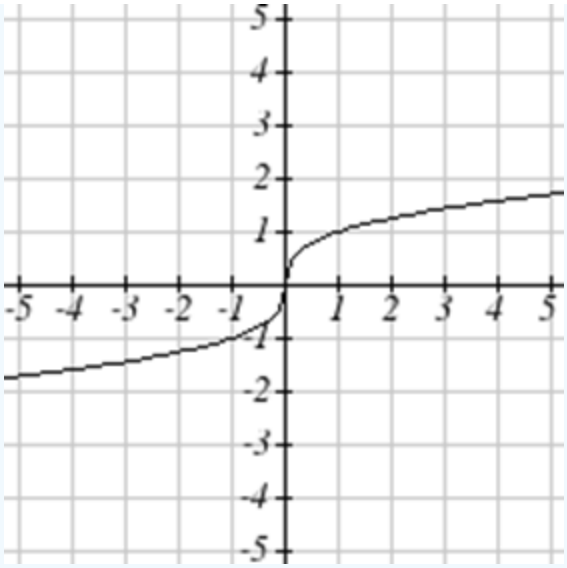
Exercise $1.E.22$

Match each graph with its equation.

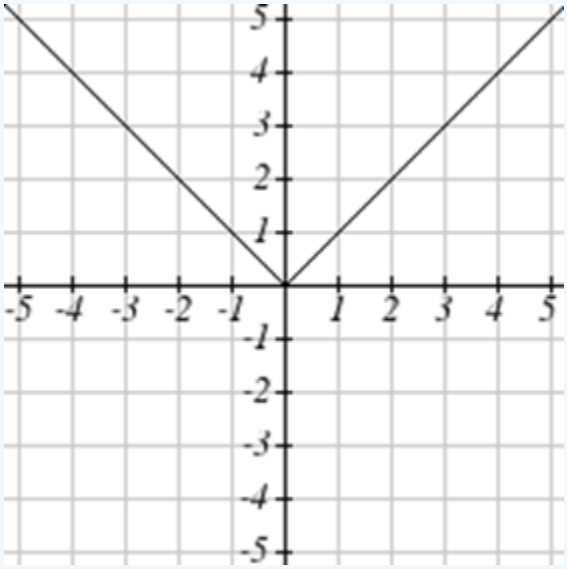
a. $y = x$	b. $y = x^3$	$y = \sqrt[3]{x}$	d. $y = \frac{1}{x}$
e. $y = x^2$	f. $y = \sqrt{x}$	g. $y = \lvert x \rvert$	h. $y = \frac{1}{x^2}$



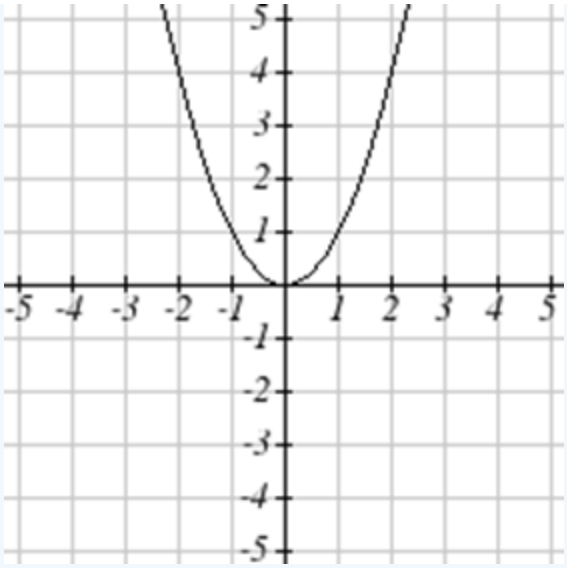
i.



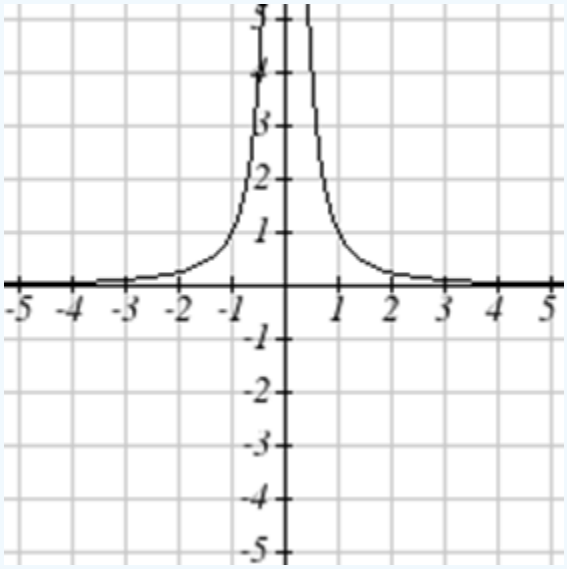
ii.



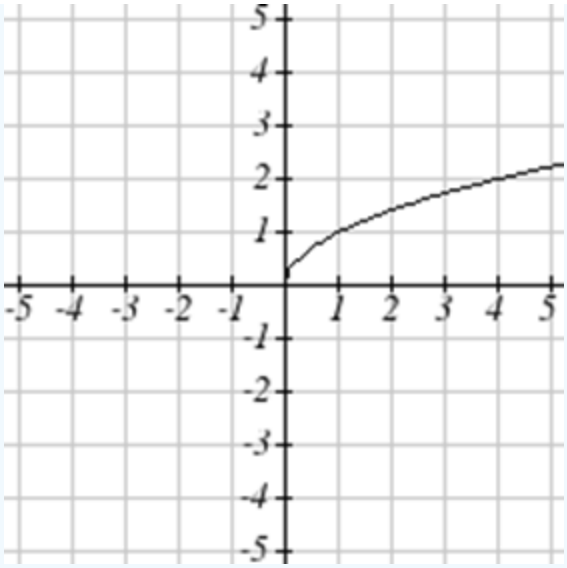
iii.



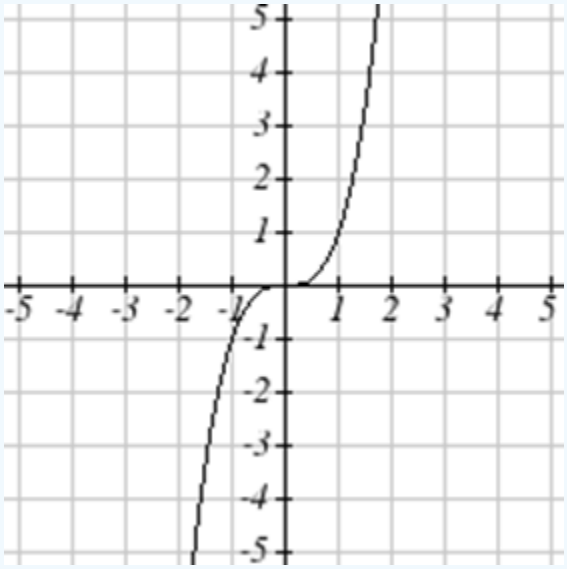
iv.



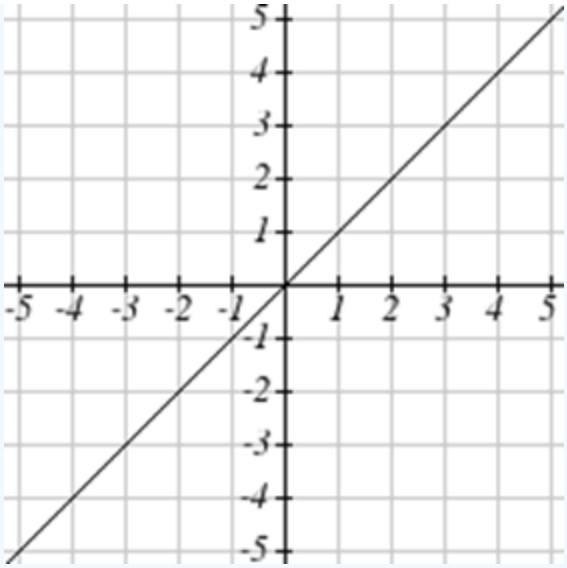
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vi.



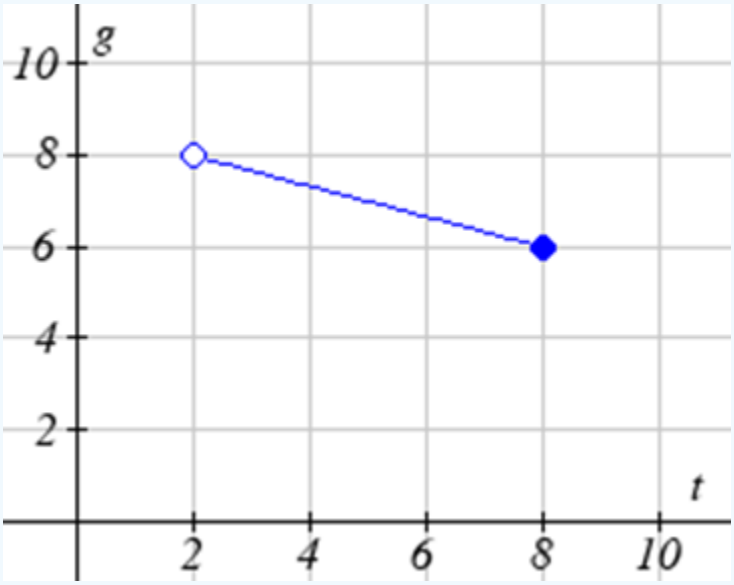
vii.



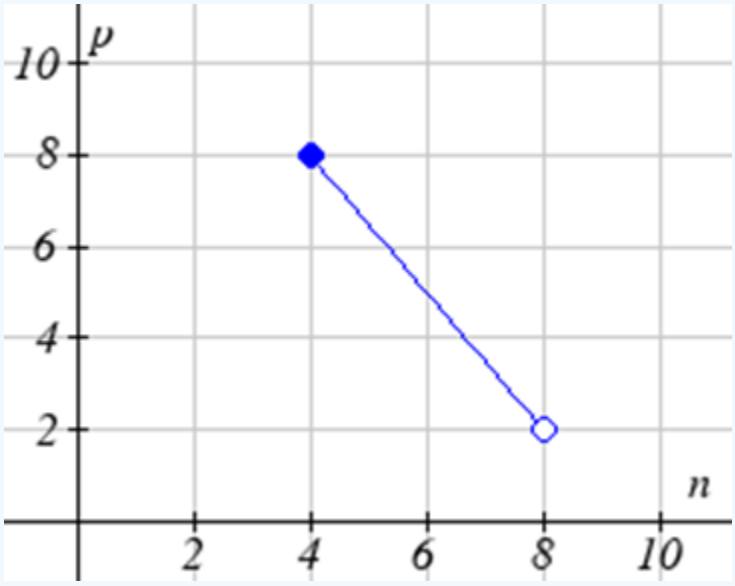
viii.

For Exercises $1.E.23 - 1.E.24$, write the domain and range of each graph as an inequality.

Exercise $1.E.23$



Exercise $1.E.24$



Exercise $1.E.25 - 1.E.30$

Find the domain of each function.

25. $f(x) = 3\sqrt{x-2}$	26. $f(x) = 5\sqrt{x+3}$
27. $f(x) = \frac{9}{x-6}$	28. $f(x) = \frac{6}{x-8}$
29. $f(x) = \frac{3x+1}{4x+2}$	30. $f(x) = \frac{5x+3}{4x-1}$

1.2 Exercises

Exercise $1.E.1 - 1.E.4$

Given each pair of functions, calculate $f(g(0))$ and $g(f(0))$.

1. $f(x) = 4x + 8, g(x) = 7 - x^2$	2. $f(x) = 5x + 7, g(x) = 4 - 2x^2$
3. $f(x) = \sqrt{x+4}, g(x) = 12 - x^3$	4. $f(x) = \frac{1}{x+2}, g(x) = 4x + 3$

Exercise $1.E.5 - 1.E.12$

Use this table of values to evaluate each expression below

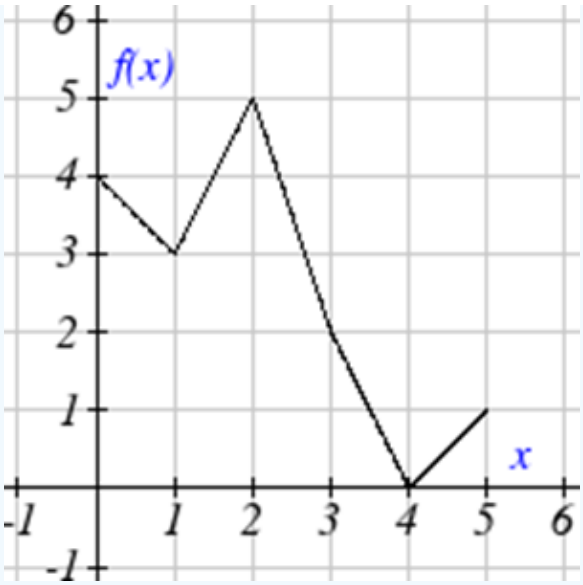
x	$f(x)$	$g(x)$
0	7	9

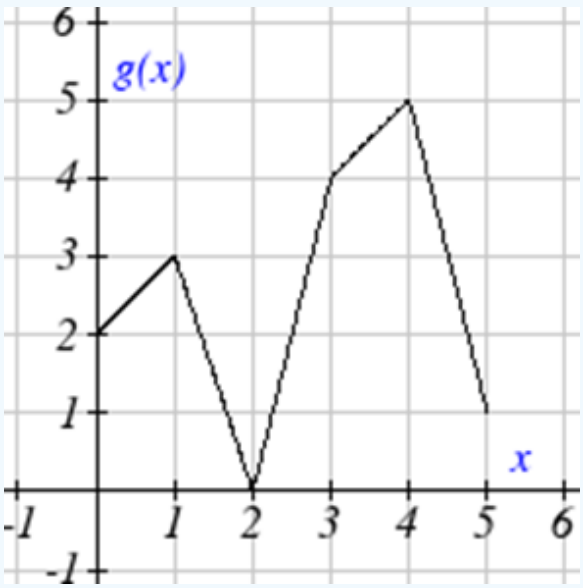
x	$f(x)$	$g(x)$
1	6	5
2	5	6
3	8	2
4	4	1
5	0	8
6	2	7
7	1	3
8	9	4
9	3	0

5. $f(g(8))$
6. $f(g(5))$
7. $g(f(5))$
8. $g(f(3))$
9. $f(f(4))$
10. $f(f(1))$
11. $g(g(2))$
12. $g(g(6))$

Exercise $1.E.13 - 1.E.20$

Use the graphs to evaluate the expressions below.





Use the graphs to evaluate the expressions below.

13. $f(g(3))$
14. $f(g(1))$
15. $g(f(1))$
16. $g(f(0))$
17. $f(f(5))$
18. $f(f(4))$
19. $g(g(2))$
20. $g(g(0))$

Exercise $1.E.21 - 1.E.26$

For each pair of functions, find $f(g(x))$ and $g(f(x))$. Simplify your answers.

21. $f(x) = \frac{1}{x-6}, g(x) = \frac{7}{x} + 6$	22. $f(x) = \frac{1}{x-4}, g(x) = \frac{2}{x} + 4$
23. $f(x) = x^2 + 1, g(x) = \sqrt{x+2}$	24. $f(x) = \sqrt{x} + 2, g(x) = x^2 + 3$
25. $f(x) = \lvert x \rvert, g(x) = 5x + 1$	26. $f(x) = \sqrt[3]{x}, g(x) = \frac{x+1}{x^3}$

Exercise $1.E.27$

If $f(x) = x^4 + 6$, $g(x) = x - 6$, and $h(x) = \sqrt{x}$, find $f(g(h(x)))$

Exercise $1.E.28$

If $f(x) = x^2 + 1$, $g(x) = \frac{1}{x}$, and $h(x) = x + 3$, find $f(g(h(x)))$

Exercise $1.E.29$

The function $D(p)$ gives the number of items that will be demanded when the price is p. The production cost, $C(x)$ is the cost of producing x items. To determine the cost of production when the price is \$6, you would do which of the following:

1. Evaluate $D(C(6))$
2. Solve $C(D(6))$
3. Evaluate $D(C(x)) = 6$
4. Solve $C(D(p)) = 6$

Exercise $1.E.30$

The function $A(d)$ gives the pain level on a scale of 0-10 experienced by a patient with d milligrams of a pain reduction drug in their system. The milligrams of drug in the patient's system after t minutes is modeled by $m(t)$. To determine when the patient will be at a pain level of 4, you would need to:

1. Evaluate $A(m(4))$
2. Solve $m(A(4))$
3. Evaluate $A(m(t)) = 4$
4. Solve $m(A(d)) = 4$

Exercise $1.E.31 - 1.E.36$

Find functions $f(x)$ and $g(x)$ so the given function can be expressed as $h(x) = f(g(x))$.

31. $h(x) = (x+2)^2$	32. $h(x) = (x-5)^3$
33. $h(x) = \frac{3}{x-5}$	34. $h(x) = \frac{4}{(x+2)^2}$
35. $h(x) = 3 + \sqrt{x-2}$	36. $h(x) = 4 + \sqrt[3]{x}$

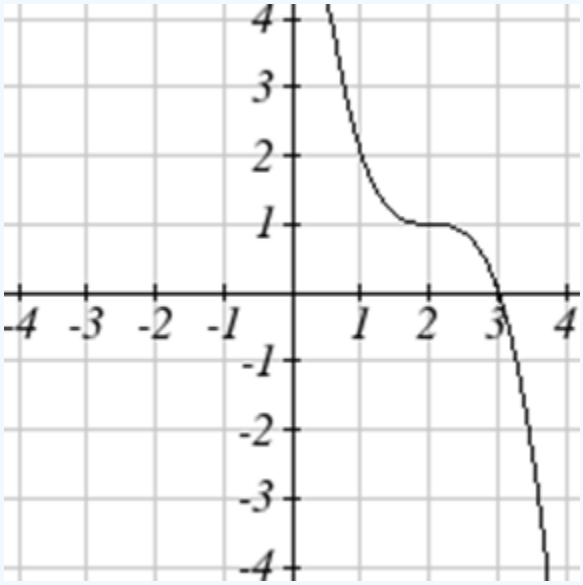
Exercise $1.E.37 - 1.E.44$

Sketch a graph of each function as a transformation of a toolkit function.

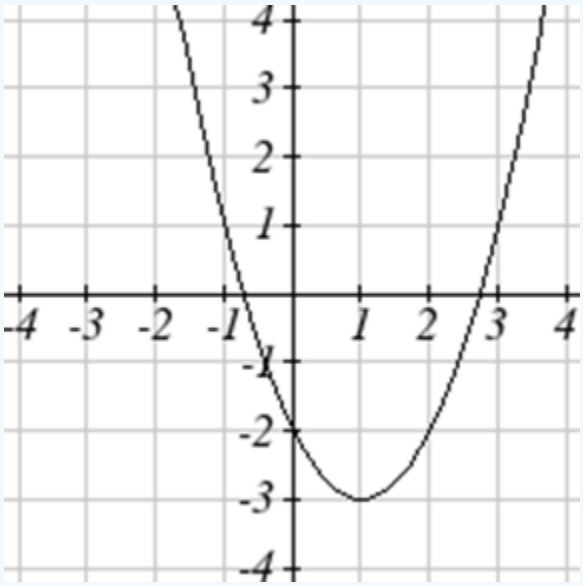
37. $f(t) = (t+1)^2 - 3$	38. $h(x) = \lvert x - 1 \rvert + 4$
39. $k(x) = (x-2)^3 - 1$	40. $m(t) = 3 + \sqrt{t+2}$
41. $f(x) = 4(x+1)^2 - 5$	42. $g(x) = 5(x+3)^2 - 2$
43. $h(x) = -2\lvert x - 4 \rvert + 3$	44. $k(x) = -3\sqrt{x} - 1$

Exercise $1.E.45 - 1.E.50$

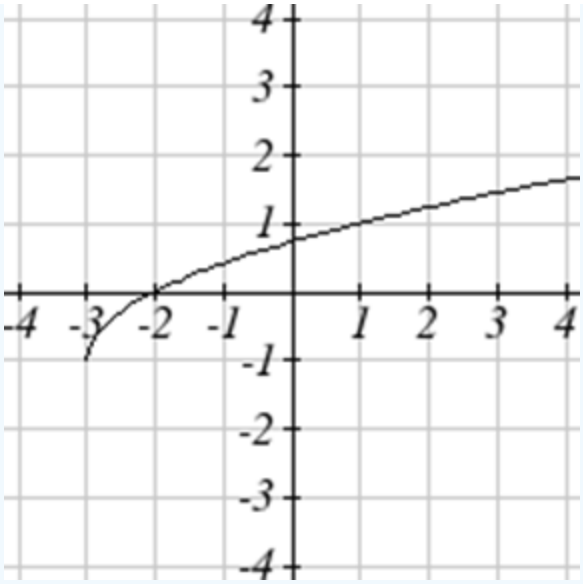
Write an equation for each function graphed below.



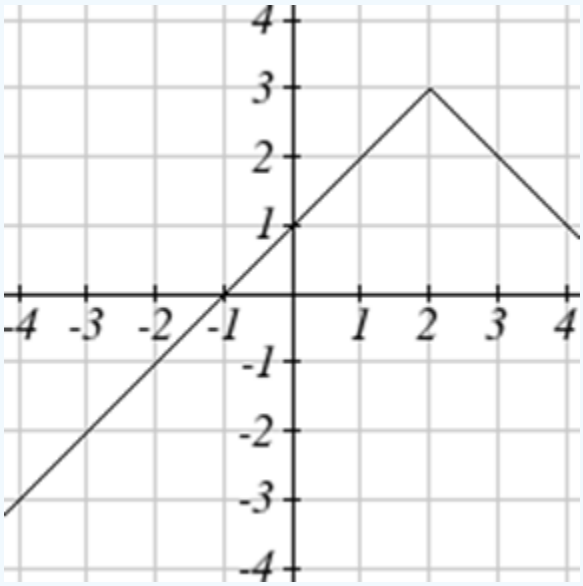
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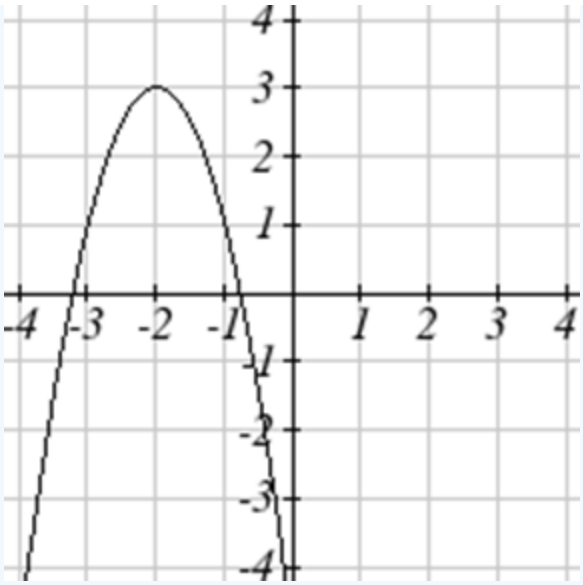
46.



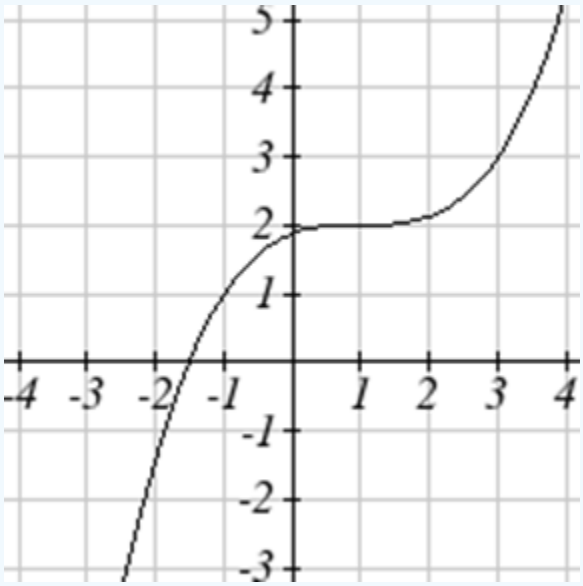
47.



48.



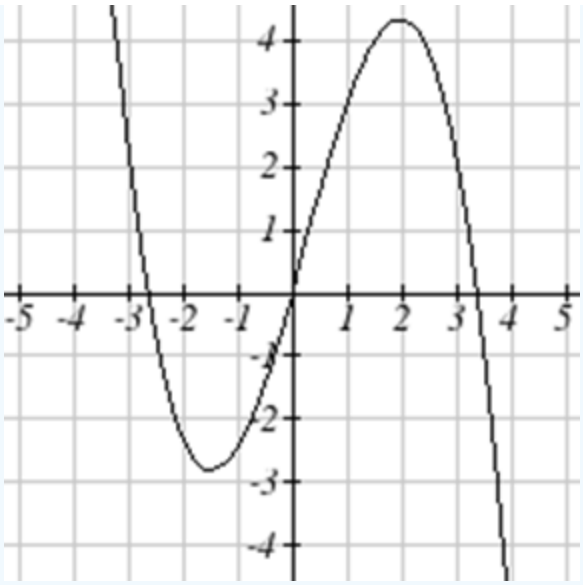
49.



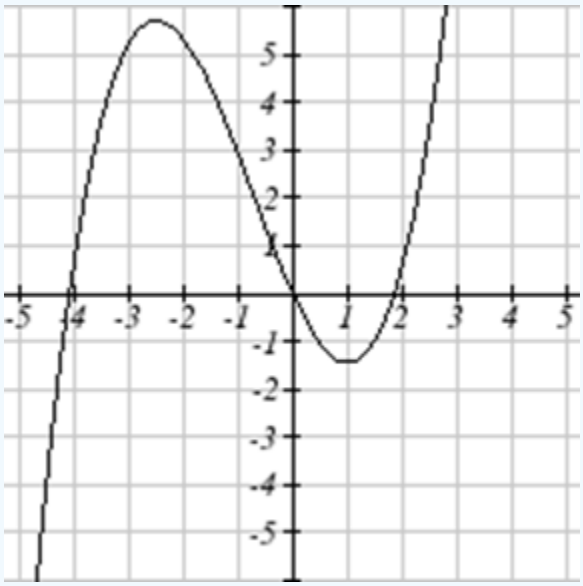
50.

Exercise $1.E.51 - 1.E.52$

For each function graphed, estimate the intervals on which the function is increasing and decreasing.



51.



52.

1.3 Exercises

Exercise $1.E.1$

A town's population has been growing linearly. In 2003, the population was 45,000, and the population has been growing by 1700 people each year. Write an equation, $P(t)$, for the population t years after 2003.

Exercise $1.E.2$

A town's population has been growing linearly. In 2005, the population was 69,000, and the population has been growing by 2500 people each year. Write an equation, $P(t)$, for the population t years after 2005.

Exercise $1.E.3$

Timmy goes to the fair with \$40. Each ride costs \$2. How much money will he have left after riding n rides?

Exercise $1.E.4$

At noon, a barista notices she has \$20 in her tip jar. If she makes an average of \$0.50 from each customer, how much will she have in her tip jar if she serves n more customers during her shift?

Exercise $1.E.5$

A phone company charges for service according to the formula: $C(n) = 24 + 0.1n$, where n is the number of minutes talked, and $C(n)$ is the monthly charge, in dollars.
Find and interpret the rate of change and initial value.

Exercise $1.E.6$

A phone company charges for service according to the formula: $C(n) = 26 + 0.04n$, where n is the number of minutes talked, and $C(n)$ is the monthly charge, in dollars.
Find and interpret the rate of change and initial value.

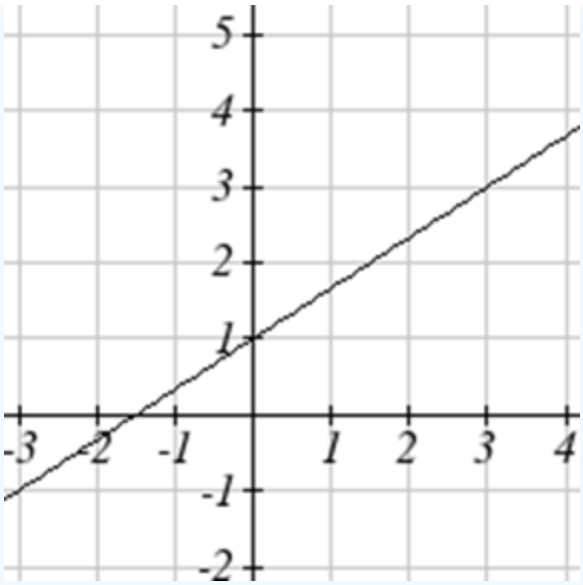
Exercise $1.E.7 - 1.E.14$

Given each set of information, find a linear equation satisfying the conditions, if possible.

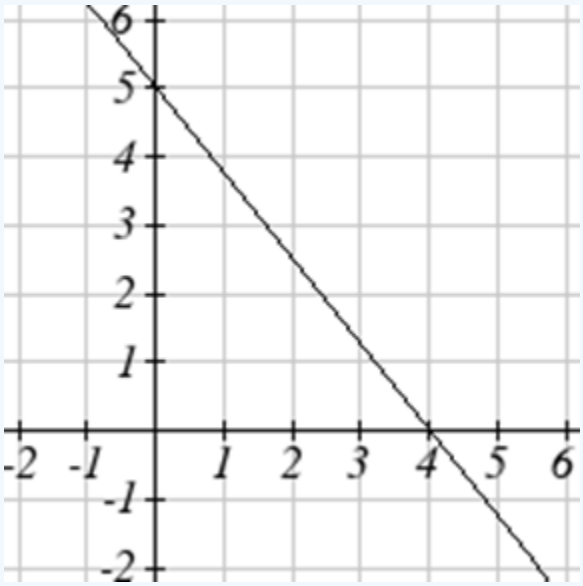
7. $f(-5) = -4$, and $f(5) = 2$	8. $f(-1) = 4$, and $f(5) = 1$
9. Passes through (2,4) and (4,10)	10. Passes through (1, 5) and (4, 11)
11. Passes through (-1,4) and (5, 2)	12. Passes through (-2, 8) and (4, 6)
13. x intercept at (-2, 0) and y intercept at (0, -3)	14. x intercept at (-5, 0) and y intercept at (0, 4)

Exercise $1.E.15 - 1.E.16$

Find an equation for the function graphed.



15.



16.

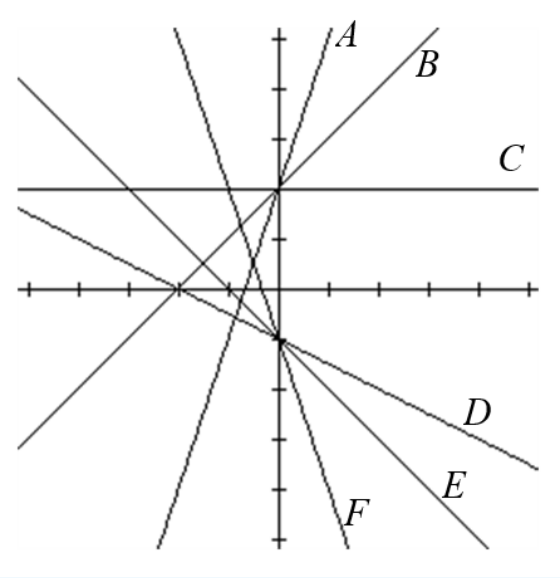
Exercise $1.E.17$

A clothing business finds there is a linear relationship between the number of shirts, n, it can sell and the price, p, it can charge per shirt. In particular, historical data shows that 1000 shirts can be sold at a price of \$30, while 3000 shirts can be sold at a price of \$22. Find a linear equation in the form $p = mn + b$ that gives the price p they can charge for n shirts.

Exercise $1.E.18$

A farmer finds there is a linear relationship between the number of bean stalks, n, she plants and the yield, y, each plant produces. When she plants 30 stalks, each plant yields 30 oz of beans. When she plants 34 stalks, each plant produces 28 oz of beans. Find a linear relationships in the form $y = mn + b$ that gives the yield when n stalks are planted.

Exercise $1.E.19 - 1.E.24$



Match each linear equation with its graph

19. $f(x) = -x - 1$
20. $f(x) = -2x - 1$
21. $f(x) = -\frac{1}{2}x - 1$
22. $f(x) = 2$
23. $f(x) = 2 + x$
24. $f(x) = 3x + 2$

Exercise $1.E.25 - 1.E.28$

Sketch the graph of each equation

25. $f(x) = -2x - 1$	26. $g(x) = -3x + 2$
27. $h(x) = \frac{1}{3}x + 2$	28. $k(x) = \frac{2}{3}x - 3$

Exercise $1.E.29$

Find the point at which the line $f(x) = -2x - 1$ intersects the line $g(x) = -x$

Exercise $1.E.30$

Find the point at which the line $f(x) = 2x + 5$ intersects the line $g(x) = -3x - 5$

Exercise $1.E.31$

A car rental company offers two plans for renting a car.

Plan A: 30 dollars per day and 18 cents per mile

Plan B: 50 dollars per day with free unlimited mileage

How many miles would you need to drive for plan B to save you money?

Exercise $1.E.32$

A cell phone company offers two data options for its prepaid phones

Pay per use: \$0.002 per Kilobyte (KB) used

Data Package: \$5 for 5 Megabytes (5120 Kilobytes) + \$0.002 per addition KB

Assuming you will use less than 5 Megabytes, under what circumstances will the data package save you money?

Exercise $1.E.33$

The Federal Helium Reserve held about 16 billion cubic feet of helium in 2010, and is being depleted by about 2.1 billion cubic feet each year.

1. Give a linear equation for the remaining federal helium reserves, R, in terms of t, the number of years since 2010.
2. In 2015, what will the helium reserves be?
3. If the rate of depletion doesn't change, when will the Federal Helium Reserve be depleted?

Exercise $1.E.34$

Suppose the world's current oil reserves are 1820 billion barrels. If, on average, the total reserves is decreasing by 25 billion barrels of oil each year:

1. Give a linear equation for the remaining oil reserves, R, in terms of t, the number of years since now.
2. Seven years from now, what will the oil reserves be?
3. If the rate of depletion isn't change, when will the world's oil reserves be depleted?

1.4 Exercises

Exercise $1.E.1 - 1.E.8$

Simplify each expression

1. x^3x^5	2. x^4x^2
3. $\left(x^3\right)^4$	4. $\left(x^7\right)^2$
5. $\left(2x^2\right)^3 x^4$	6. $\left(5x^4\right)^2 x^5$
7. $\frac{\left(3x^2\right)^2}{6x^3}$	8. $\frac{5x(4x)^2}{2x^2}$

Exercise $1.E.9 - 1.E.14$

Simplify, and rewrite without negative exponents

9. $4x^{-3}$	10. $2x^{-5}$
11. $x^{-4}x^2$	12. $x^{-2}x$
13. $\frac{5x^{-3}}{2x^{-6}}$	14. $\frac{2x^{-4}}{6x^{-2}}$

Exercise $1.E.15 - 1.E.20$

Rewrite using negative or fractional exponents

15. $\frac{4}{x^{-5}}$	16. $\frac{4}{x^{-3}}$
17. $3\sqrt{x}$	18. $\sqrt[4]{x}$
19. $\frac{4}{\sqrt[3]{x}}$	20. $\frac{1}{5\sqrt{x}}$

Exercise $1.E.21 - 1.E.24$

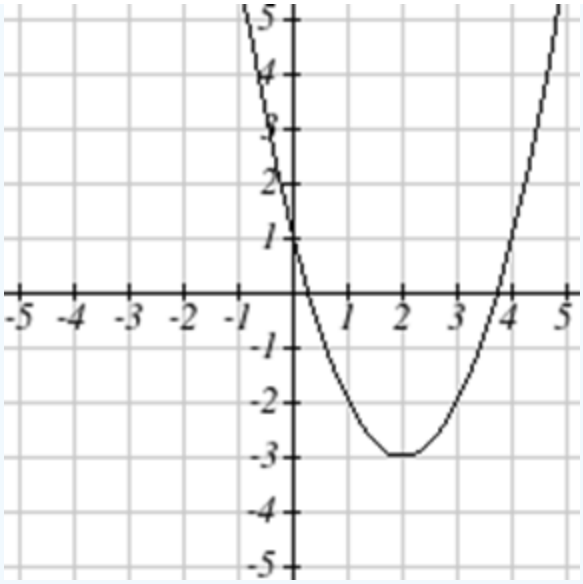
Rewrite as a radical

21. $4x^{-\frac{1}{2}}$	22. $5x^{-\frac{1}{3}}$
23. $2x^{\frac{1}{3}}$	24. $5x^{\frac{3}{2}}$

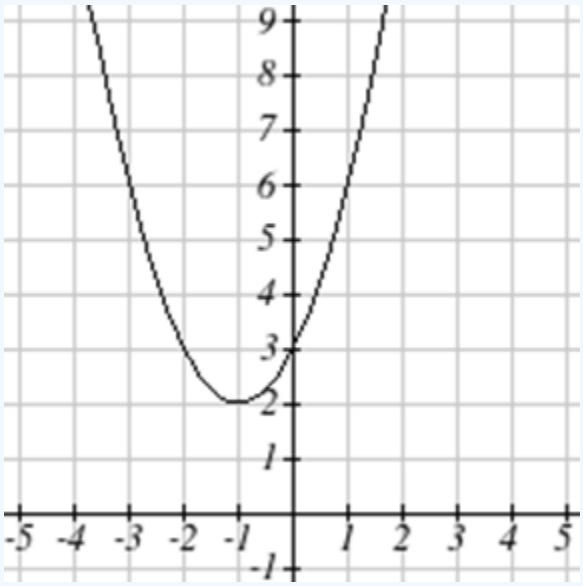
1.5 Exercises

Exercise $1.E.1 - 1.E.6$

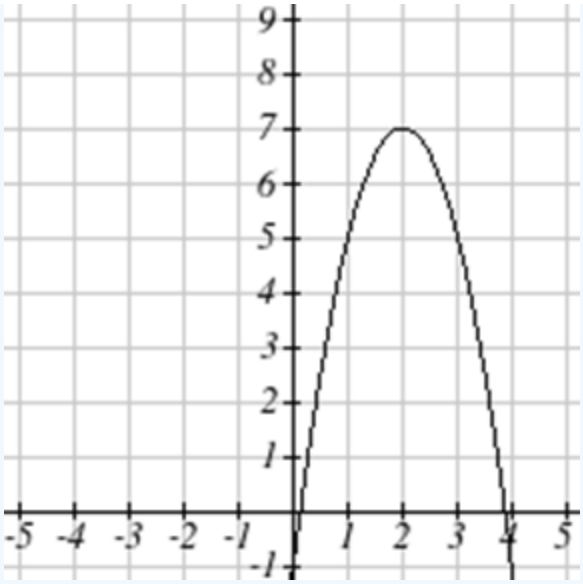
Write an equation for the quadratic function graphed.



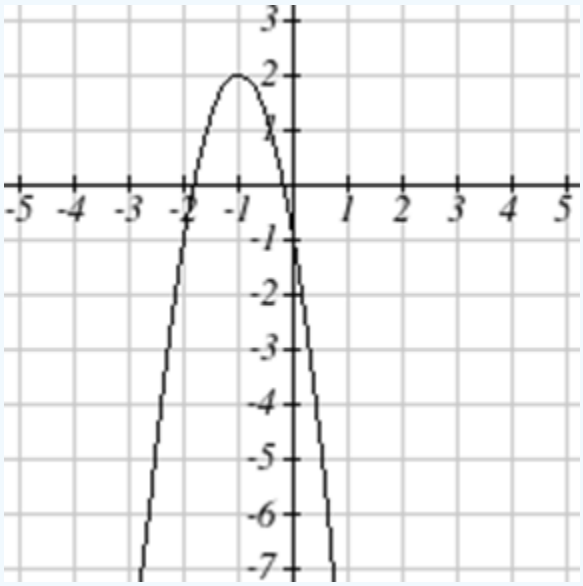
1.



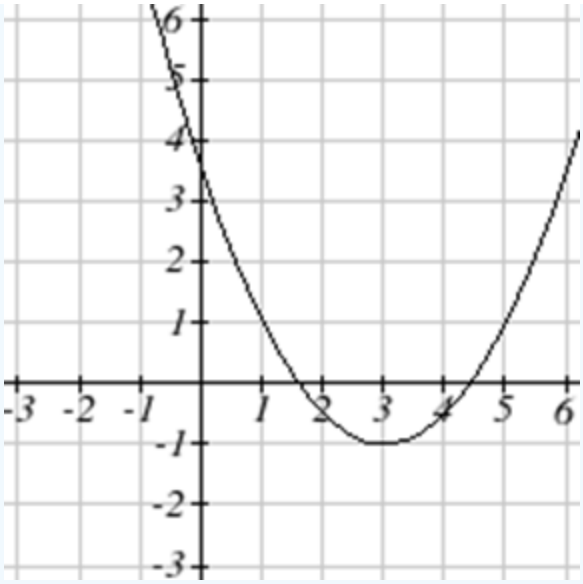
2.



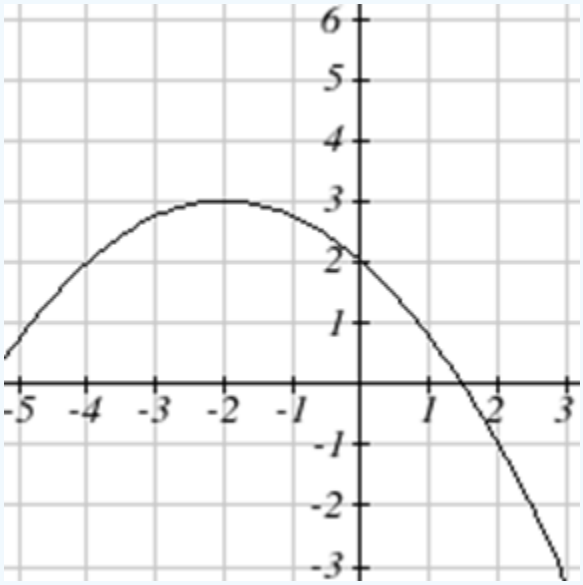
3.



4.



5.



6.

Exercise $1.E.7 - 1.E.12$

For each of the following quadratic functions, find a) the vertex, b) the vertical intercept, and c) the horizontal intercepts.

7. $y(x) = 2x^2 + 10x + 12$	8. $z(p) = 3x^2 + 6x - 9$
9. $f(x) = 2x^2 - 10x + 4$	10. $g(x) = -2x^2 - 14x + 12$
11. $h(t) = -4t^2 + 6t - 1$	12. $k(t) = 2x^2 + 4x - 15$

Exercise $1.E.13$

The height of a ball thrown in the air is given by $h(x) = -\frac{1}{12}x^2 + 6x + 3$, where x is the horizontal distance in feet from the point at which the ball is thrown.

1. How high is the ball when it was thrown?
2. What is the maximum height of the ball?
3. How far from the thrower does the ball strike the ground?

Exercise $1.E.14$

A javelin is thrown in the air. Its height is given by $h(x) = -\frac{1}{20}x^2 + 8x + 6$, where x is the horizontal distance in feet from the point at which the javelin is thrown.

1. How high is the javelin when it was thrown?
2. What is the maximum height of the javelin?
3. How far from the thrower does the javelin strike the ground?

1.6 Exercises

Exercise $1.E.1 - 1.E.6$

Find the degree and leading coefficient of each polynomial

1. $4x^7$	2. $5x^6$
3. $5 - x^2$	4. $6 + 3x - 4x^3$
5. $-2x^4 - 3x^2 + x - 1$	6. $6x^5 - 2x^4 + x^2 + 3$

Exercise $1.E.7 - 1.E.12$

Find the vertical and horizontal intercepts of each function.

7. $f(t) = 2(t-1)(t+2)(t-3)$	8. $f(x) = 3(x+1)(x-4)(x+5)$
9. $g(n) = -2(3n-1)(2n+1)$	10. $k(u) = -3(4-n)(4n+3)$
11. $C(t) = 2t^4 - 8t^3 + 6t^2$	12. $C(t) = 4t^4 + 12t^3 - 40t^2$

Exercise $1.E.13 - 1.E.14$

Use your calculator or other graphing technology to solve graphically for the zeros of the function.

13. $f(x) = x^3 - 7x^2 + 4x + 30$	14. $g(x) = x^3 - 6x^2 + x + 28$

Exercise $1.E.15 - 1.E.18$

Solve each inequality.

15. $(x-3)(x-2)^2 > 0$	16. $(x-5)(x+1)^2 > 0$
17. $(x-1)(x+2)(x-3) < 0$	18. $(x-4)(x+3)(x+6) < 0$

Exercise $1.E.19 - 1.E.26$

For each function, find the horizontal intercepts, the vertical intercept, the vertical asymptotes, and the horizontal asymptote.

19. $p(x) = \frac{2x-3}{x+4}$	20. $q(x) = \frac{x-5}{3x-1}$
21. $s(x) = \frac{4}{(x-2)^2}$	22. $r(x) = \frac{5}{(x+1)^2}$
23. $f(x) = \frac{3x^2-14x-5}{3x^2+8x-16}$	24. $g(x) = \frac{2x^2+7x-15}{3x^2-14+15}$
25. $h(x) = \frac{2x^2+x-1}{x-4}$	26. $k(x) = \frac{2x^2-3x-20}{x-5}$

Exercise $1.E.27$

A scientist has a beaker containing 20 mL of a solution containing 20% acid. To dilute this, she adds pure water.

1. Write an equation for the concentration in the beaker after adding n mL of water.
2. Find the concentration if 10 mL of water has been added.
3. How many mL of water must be added to obtain a 4% solution?
4. What is the behavior as $n \to \infty$, and what is the physical significance of this?

Exercise $1.E.28$

A scientist has a beaker containing 30 mL of a solution containing 3 grams of potassium hydroxide. To this, she mixes a solution containing 8 milligrams per mL of potassium hydroxide.

1. Write an equation for the concentration in the tank after adding n mL of the second solution.
2. Find the concentration if 10 mL of the second solution has been added.
3. How many mL of water must be added to obtain a 50 mg/mL solution?
4. What is the behavior as $n \to \infty$, and what is the physical significance of this?

1.7 Exercises

Exercise $1.E.1$

A population numbers 11,000 organisms initially and grows by 8.5% each year. Write an exponential model for the population.

Exercise $1.E.2$

A population is currently 6,000 and has been increasing by 1.2% each day. Write an exponential model for the population.

Exercise $1.E.3$

A vehicle purchased for $32,500 depreciates at a constant rate of 5% each year. Determine the approximate value of the vehicle 12 years after purchase.

Exercise $1.E.4$

A business purchases $125,000 of office furniture which depreciates at a constant rate of 12% each year. Find the residual value of the furniture 6 years after purchase.

Exercise $1.E.5$

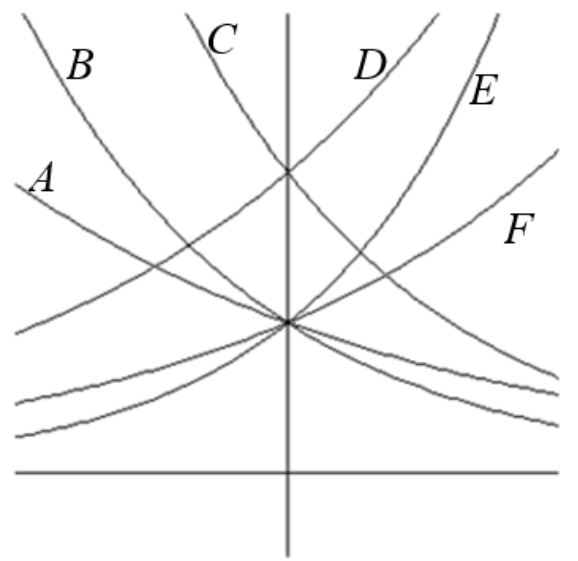
If $4,000 is invested in a bank account at an interest rate of 7 per cent per year, find the amount in the bank after 9 years if interest is compounded annually, quarterly, monthly, and continuously.

Exercise $1.E.6$

If $6,000 is invested in a bank account at an interest rate of 9 per cent per year, find the amount in the bank after 5 years if interest is compounded annually, quarterly, monthly, and continuously.

Exercise $1.E.7 - 1.E.12$

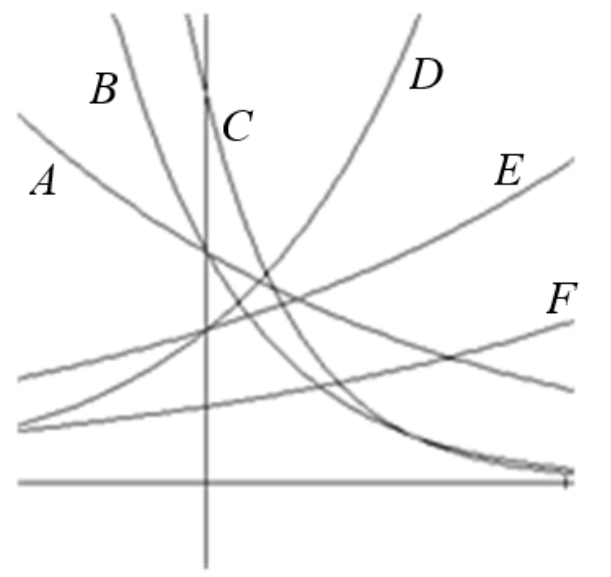
Match each function with one of the graphs below.



7. $f(x) = 2(0.69)^x$
8. $f(x) = 2(1.28)^x$
9. $f(x) = 2(0.81)^x$
10 $f(x) = 4(1.28)^x$
11. $f(x) = 2(1.59)^x$
12. $f(x) = 4(0.69)^x$

Exercise $1.E.13 - 1.E.16$

If all the graphs to the right have equations with form $f(t) = ae^{kt}$,



13. Which graph has the largest value for k?
14. Which graph has the smallest value for k?
15. Which graph has the largest value for a?
16. Which graph has the smallest value for a?

1.8 Exercises

Exercise $1.E.1 - 1.E.4$

Rewrite each equation in exponential form

1. $\log(v) = t$	2. $\log(r) = s$	3. $\ln(w) = n$	4. $\ln(x) = y$

Exercise $1.E.5 - 1.E.8$

Rewrite each equation in logarithmic form.

5. $10^a = b$	6. $10^p = v$	7. $e^k = h$	8. $e^y = x$

Exercise $1.E.9 - 1.E.24$

Solve each equation for the variable.

9. $5^x = 14$	10. $3^x = 23$	11. $7^x = \frac{1}{15}$	12. $3^x = \frac{1}{4}$
13. $e^{5x} = 17$	14. $e^{3x} = 12$	15. $3^{4x-5} = 38$	16. $4^{2x-3} = 44$

17. $1000(1.03)^t = 5000$	18. $200(1.06)^t = 550$
19. $3(1.04)^{3t} = 8$	20. $2(1.08)^{4t} = 7$
21. $50e^{-0.12t} = 10$	22. $10e^{-0.03t} = 4$
23. $10 - 8\left(\frac{1}{2}\right)^x = 5$	24. $100 - 100\left(\frac{1}{4}\right)^x = 70$

Exercise $1.E.25$

The population of Kenya was 39.8 million in 2009 and has been growing by about 2.6% each year. If this trend continues, when will the population exceed 45 million?

Exercise $1.E.26$

The population of Algeria was 34.9 million in 2009 and has been growing by about 1.5% each year. If this trend continues, when will the population exceed 45 million?

Exercise $1.E.27$

If $1000 is invested in an account earning 3% compounded monthly, how long will it take the account to grow in value to $1500?

Exercise $1.E.28$

If $1000 is invested in an account earning 2% compounded quarterly, how long will it take the account to grow in value to $1300?

Exercise $1.E.29$

Sketch a graph of: $f(x) = \log(x)$, $g(x) = \ln(x)$

Exercise $1.E.30 - 1.E.33$

Find the domain of each function.

30. $f(x) = \log(x - 5)$	31. $f(x) = \ln(3 - x)$
32. $f(x) = \ln(1 - 3x)$	33. $f(x) = \log(2x + 5)$

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2: LIMITS

2.1: Definitions of Limits

2.2: Techniques for Computing Limits

2.2E: Exercises for Section 2.3

2.3: Infinite Limits

2.3E: Exercises for Section 2.4

2.4: Continuity

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2.1: Definitions of Limits

Limits

In the last section, we saw that as the interval over which we calculated got smaller, the secant slopes approached the tangent slope. The **limit** gives us better language with which to discuss the idea of “approaches.”

The limit of a function describes the behavior of the function when the variable is near, **but does not equal**, a specified number (see the figure below).

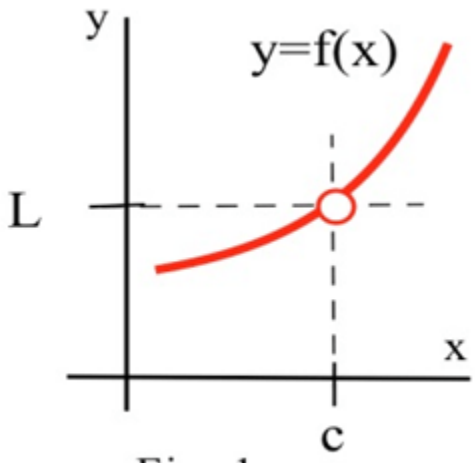


Fig. 1

Limit

If the values of $f(x)$ get closer and closer, as close as we want, to one number L as we take values of x very close to (but not equal to) a number c, then we say "**the limit of** $f(x)$ **as** x **approaches** c **is** L" and we write

$$\lim_{x \to c} f(x) = \mathbf{L}.$$

The symbol "$\to$" means "approaches" or, less formally, "gets very close to".

(This definition of the limit isn't stated as formally as it could be, but it is sufficient for our purposes in this course.)

Note:

- $\mathbf{f(c)}$ is a single number that describes the behavior (value) of $f(x)$ **AT** the point $x = c$.
- $\lim_{x \to c} f(x)$ is a single number that describes the behavior of $f(x)$ **NEAR, *BUT NOT AT***, the point $x = c$.

If we have a graph of the function near $x = c$, then it is usually easy to determine $\lim_{x \to c} f(x)$.

(Here is a link to the pictures used in the following video as well as elsewhere in this chapter: Graphs for Limits and Continuity Examples.)

Video

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Example 2.1.1

Use the graph of $y = f(x)$ in the figure below to determine the following limits:

1. $\lim_{x \to 1} f(x)$
2. $\lim_{x \to 2} f(x)$
3. $\lim_{x \to 3} f(x)$
4. $\lim_{x \to 4} f(x)$

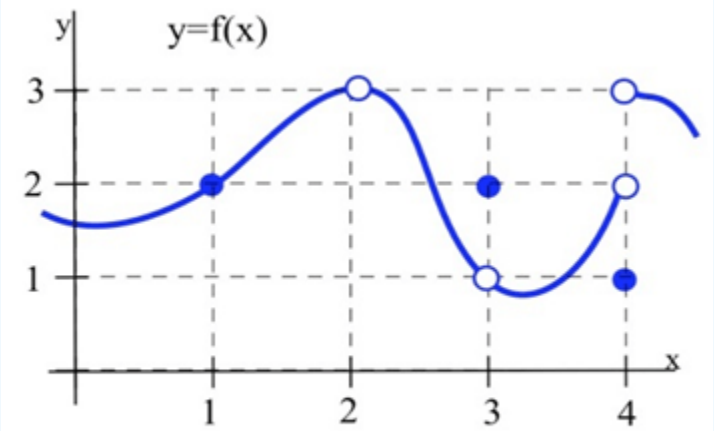


Fig. 2

Solution

1. $$\lim_{x \to 1} f(x) = 2$$

   When x is very close to 1, the values of $f(x)$ are very close to $y = 2$. In this example, it happens that $f(1) = 2$, but that is **irrelevant** for the limit. The only thing that matters is what happens for x *close to* 1 but $x \neq 1$.
2. $f(2)$ is undefined, but we only care about the behavior of $f(x)$ for x *close to* 2 but *not equal to* 2. When x is close to 2, the values of $f(x)$ are close to 3. If we restrict x close enough to 2, the values of y will be as close to 3 as we want, so $\lim_{x \to 2} f(x) = 3$.
3. When x is close to 3 (or "as x approaches the value 3"), the values of $f(x)$ are close to 1 (or "approach the value 1"), so $\lim_{x \to 3} f(x) = 1$. For this limit it is completely irrelevant that $f(3) = 2$, We only care about what happens to $f(x)$ for x close to and not equal to 3.
4. This one is harder and we need to be careful. When x is close to 4 and slightly **less than** 4 (x is just to the left of 4 on the x-axis), then the values of $f(x)$ are close to 2. But if x is close to 4 and slightly **larger than** 4 then the values of $f(x)$ are close to 3. If we only know that x is very close to 4, then we cannot say whether $y = f(x)$ will be close to 2 or close

to 3 – it depends on whether x is on the right or the left side of 4. In this situation, the $f(x)$ values are not close to a *single* number so we say $\lim_{x\to 4} f(x)$ **does not exist**. It is irrelevant that $f(4) = 1$. The limit, as x approaches 4, would still be undefined if $f(4)$ was 3 or 2 or anything else.

We can also explore limits using tables and using algebra.

Video

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Example 2.1.2

Find $\lim_{x\to 1} \dfrac{2x^2 - x - 1}{x - 1}$.

Solution

You might try to evaluate $f(x) = \frac{2x^2-x-1}{x-1}$ at $x = 1$, but $f(x)$ is not defined at $x = 1$. It is tempting, **but wrong**, to conclude that this function does not have a limit as x approaches 1.

Using tables: Trying some "test" values for x which get closer and closer to 1 from both the left and the right, we get

x	$f(x)$
0.9	2.82
0.9998	2.9996
0.999994	2.999988
0.9999999	2.9999998
$\to 1$	$\to 3$

x	$f(x)$
1.1	3.2
1.0003	3.0006
1.00001	3.00002
1.000007	3.000014
$\to 1$	$\to 3$

The function f is not defined at $x = 1$, but when x is **close to** 1, the values of $f(x)$ are getting very close to 3. We can get $f(x)$ as close to 3 as we want by taking x very close to 1 so

$$\lim_{x\to 1} \frac{2x^2 - x - 1}{x - 1} = 3.$$

Using algebra: We could have found the same result by noting that

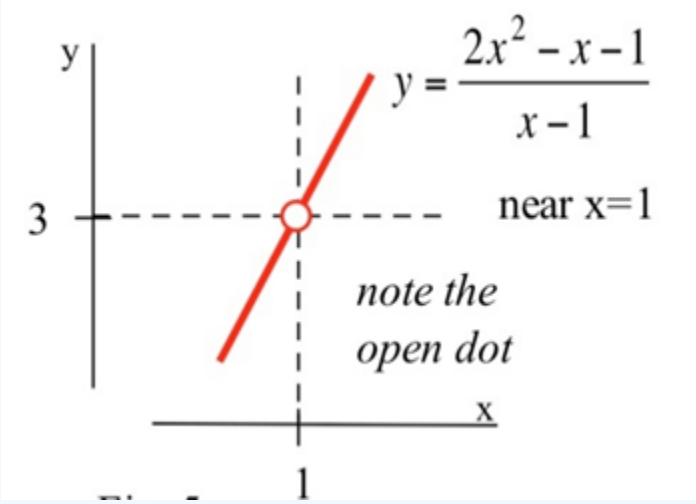
$$f(x) = \frac{2x^2 - x - 1}{x - 1} = \frac{(2x + 1)(x - 1)}{(x - 1)} = 2x + 1$$

as long as $x \neq 1$. (If $x \neq 1$, then $x–1 \neq 0$ so it is valid to divide the numerator and denominator by the factor $x–1$.) The "$x \to 1$" part of the limit means that x is close to 1 but **not equal to 1**, so our division step is valid and

$$\lim_{x \to 1} \frac{2x^2 - x - 1}{x - 1} = \lim_{x \to 1} 2x + 1 = 3,$$

which is our answer.

Using a graph: We can graph $y = f(x) = \frac{2x^2 - x - 1}{x - 1}$ for x close to 1:



Notice that whenever x is close to 1, the values of $y = f(x)$ are close to 3. Since f is not defined at $x = 1$, the graph has a hole above $x = 1$, but we only care about what $f(x)$ is doing for x close to but **not equal to** 1.

Example 2.1.3

Find $\lim_{x \to 3} \frac{\frac{1}{x} - \frac{1}{3}}{x - 3}$.

Solution

Notice that this function is not defined at $x = 3$. We can find the limit using algebra. Giving the two terms in the numerator a common denominator, we can simplify:

$$\frac{\frac{1}{x} - \frac{1}{3}}{x - 3} = \frac{\frac{1}{x} \cdot \frac{3}{3} - \frac{1}{3} \cdot \frac{x}{x}}{x - 3} = \frac{\frac{3}{3x} - \frac{x}{3x}}{x - 3} = \frac{\frac{3-x}{3x}}{x - 3}$$

Remember that dividing a fraction is the same as multiplying by the reciprocal, so

$$\frac{\frac{3-x}{3x}}{x - 3} = \frac{\frac{3-x}{3x}}{\frac{x-3}{1}}$$

is equivalent to

$$\frac{3 - x}{3x} \cdot \frac{1}{x - 3}$$

To simplify further, we need to factor a negative 1 out of the numerator. Then we can cancel the term $(x - 3)$

$\frac{-1(x - 3)}{3x} \cdot \frac{1}{x - 3} = \frac{-1}{3x}$ as long as $x \neq 3$

Now we can evaluate the limit using this simplified form.

$$\lim_{x\to 3}\frac{\frac{1}{x}-\frac{1}{3}}{x-3}=\lim_{x\to 3}\frac{-1}{3x}=-\frac{1}{9}$$

Video

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One Sided Limits

Sometimes, what happens to us at a place depends on the direction we use to approach that place. If we approach Niagara Falls from the upstream side, then we will be 182 feet higher and have different worries than if we approach from the downstream side. Similarly, the values of a function near a point may depend on the direction we use to approach that point.

Left and Right Limits

The **left limit** of $f(x)$ as x approaches c is L if the values of $f(x)$ get as close to L as we want when x is very close to and **left of** c (i.e., $x < \mathbf{c}$). We write

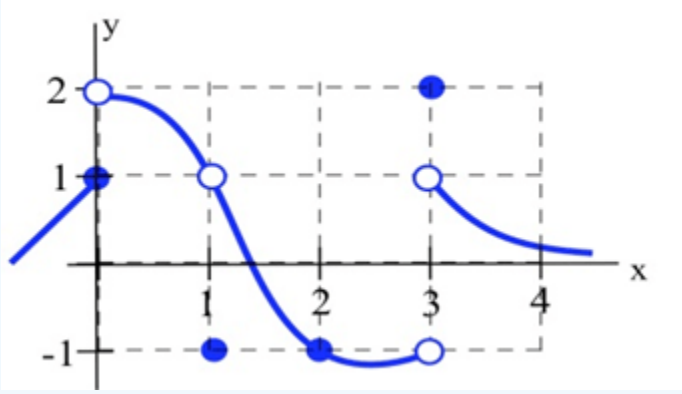
$$\lim_{x\to c^-} f(x)=L.$$

The **right limit** of $f(x)$ as x approaches c, written with $\mathbf{x\to c^+}$, is L if the values of $f(x)$ get as close to L as we want when x is very close to and **right of** c (i.e., $x > \mathbf{c}$). We write

$$\lim_{x\to c^+} f(x)=L.$$

Example 2.1.4

Evaluate the one sided limits of the function $f(x)$ graphed below at $x=0$ and $x=1$.



Solution

As x approach 0 from the *left*, the value of the function is getting closer to 1, so $\lim_{x\to 0^-} f(x)=1$.

As x approaches 0 from the *right*, the value of the function is getting closer to 2, so $\lim_{x \to 0^+} f(x) = 2$.

Notice that since the limit from the left and limit from the right are different, the general limit, $\lim_{x \to 0} f(x)$, does not exit.

At x approaches 1 from either direction, the value of the function is approaching 1, so

$$\lim_{x \to 1^-} f(x) = \lim_{x \to 1^+} f(x) = \lim_{x \to 1} f(x) = 1.$$

Video

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2.2: TECHNIQUES FOR COMPUTING LIMITS

Learning Objectives

- Recognize the basic limit laws.
- Use the limit laws to evaluate the limit of a function.
- Evaluate the limit of a function by factoring.
- Use the limit laws to evaluate the limit of a polynomial or rational function.
- Evaluate the limit of a function by factoring or by using conjugates.
- Evaluate the limit of a function by using the squeeze theorem.

In the previous section, we evaluated limits by looking at graphs or by constructing a table of values. In this section, we establish laws for calculating limits and learn how to apply these laws. In the Student Project at the end of this section, you have the opportunity to apply these limit laws to derive the formula for the area of a circle by adapting a method devised by the Greek mathematician Archimedes. We begin by restating two useful limit results from the previous section. These two results, together with the limit laws, serve as a foundation for calculating many limits.

Evaluating Limits with the Limit Laws

The first two limit laws were stated previosuly and we repeat them here. These basic results, together with the other limit laws, allow us to evaluate limits of many algebraic functions.

Basic Limit Results

For any real number a and any constant c,

I. $\lim\limits_{x \to a} x = a$
II. $\lim\limits_{x \to a} c = c$

Example 2.2.1: Evaluating a Basic Limit

Evaluate each of the following limits using Note.

a. $\lim\limits_{x \to 2} x$
b. $\lim\limits_{x \to 2} 5$

Solution

a. The limit of x as x approaches a is a: $\lim\limits_{x \to 2} x = 2$.
b. The limit of a constant is that constant: $\lim\limits_{x \to 2} 5 = 5$.

We now take a look at the **limit laws**, the individual properties of limits. The proofs that these laws hold are omitted here.

Limit Laws

Let $f(x)$ and $g(x)$ be defined for all $x \neq a$ over some open interval containing a. Assume that L and M are real numbers such that $\lim\limits_{x \to a} f(x) = L$ and $\lim\limits_{x \to a} g(x) = M$. Let c be a constant. Then, each of the following statements holds:

- **Sum law for limits**:

$$\lim_{x\to a}(f(x)+g(x))=\lim_{x\to a}f(x)+\lim_{x\to a}g(x)=L+M \tag{2.2.1}$$

- **Difference law for limits**:

$$\lim_{x\to a}(f(x)-g(x))=\lim_{x\to a}f(x)-\lim_{x\to a}g(x)=L-M \tag{2.2.2}$$

- **Constant multiple law for limits**:

$$\lim_{x\to a}cf(x)=c\cdot\lim_{x\to a}f(x)=cL \tag{2.2.3}$$

- **Product law for limits**:

$$\lim_{x\to a}(f(x)\cdot g(x))=\lim_{x\to a}f(x)\cdot\lim_{x\to a}g(x)=L\cdot M \tag{2.2.4}$$

- **Quotient law for limits**:

$$\lim_{x\to a}\frac{f(x)}{g(x)}=\frac{\lim_{x\to a}f(x)}{\lim_{x\to a}g(x)}=\frac{L}{M} \tag{2.2.5}$$

for $M\neq 0$.

- **Power law for limits**:

$$\lim_{x\to a}\big(f(x)\big)^n=\big(\lim_{x\to a}f(x)\big)^n=L^n \tag{2.2.6}$$

for every positive integer n.

- **Root law for limits**:

$$\lim_{x\to a}\sqrt[n]{f(x)}=\sqrt[n]{\lim_{x\to a}f(x)}=\sqrt[n]{L} \tag{2.2.7}$$

for all L if n is odd and for $L\geq 0$ if n is even.

We now practice applying these limit laws to evaluate a limit.

Example 2.2.2A: Evaluating a Limit Using Limit Laws

Use the limit laws to evaluate

$$\lim_{x\to -3}(4x+2).$$

Solution

Let's apply the limit laws one step at a time to be sure we understand how they work. We need to keep in mind the requirement that, at each application of a limit law, the new limits must exist for the limit law to be applied.

$$\begin{aligned}\lim_{x\to -3}(4x+2)&=\lim_{x\to -3}4x+\lim_{x\to -3}2 && \text{Apply the sum law.}\\ &=4\cdot\lim_{x\to -3}x+\lim_{x\to -3}2 && \text{Apply the constant multiple law.}\\ &=4\cdot(-3)+2=-10. && \text{Apply the basic limit results and simplify.}\end{aligned}$$

Example 2.2.2B: Using Limit Laws Repeatedly

Use the limit laws to evaluate

$$\lim_{x\to 2}\frac{2x^2-3x+1}{x^3+4}.$$

Solution

To find this limit, we need to apply the limit laws several times. Again, we need to keep in mind that as we rewrite the limit in terms of other limits, each new limit must exist for the limit law to be applied.

$$\begin{aligned}
\lim_{x\to 2}\frac{2x^2-3x+1}{x^3+4} &= \frac{\lim_{x\to 2}(2x^2-3x+1)}{\lim_{x\to 2}(x^3+4)} && \text{Apply the quotient law, make sure that } (2)^3+4\neq 0.\\
&= \frac{2\cdot\lim_{x\to 2}x^2-3\cdot\lim_{x\to 2}x+\lim_{x\to 2}1}{\lim_{x\to 2}x^3+\lim_{x\to 2}4} && \text{Apply the sum law and constant multiple law.}\\
&= \frac{2\cdot\left(\lim_{x\to 2}x\right)^2-3\cdot\lim_{x\to 2}x+\lim_{x\to 2}1}{\left(\lim_{x\to 2}x\right)^3+\lim_{x\to 2}4} && \text{Apply the power law.}\\
&= \frac{2(4)-3(2)+1}{(2)^3+4}=\frac{1}{4}. && \text{Apply the basic limit laws and simplify.}
\end{aligned}$$

Exercise 2.2.2

Use the limit laws to evaluate $\lim_{x\to 6}(2x-1)\sqrt{x+4}$. In each step, indicate the limit law applied.

Hint available at the end of this section.

Answer available at the end of this section.

Limits of Polynomial and Rational Functions

By now you have probably noticed that, in each of the previous examples, it has been the case that $\lim_{x\to a}f(x)=f(a)$. This is not always true, but it does hold for all polynomials for any choice of a and for all rational functions at all values of a for which the rational function is defined.

Limits of Polynomial and Rational Functions

Let $p(x)$ and $q(x)$ be polynomial functions. Let a be a real number. Then,

$$\lim_{x\to a}p(x)=p(a) \tag{2.2.8}$$

$$\lim_{x\to a}\frac{p(x)}{q(x)}=\frac{p(a)}{q(a)} \tag{2.2.9}$$

when $q(a)\neq 0$.

To see that this theorem holds, consider the polynomial

$$p(x)=c_nx^n+c_{n-1}x^{n-1}+\cdots+c_1x+c_0. \tag{2.2.10}$$

By applying the sum, constant multiple, and power laws, we end up with

$$\begin{aligned}\lim_{x\to a} p(x) &= \lim_{x\to a}(c_n x^n + c_{n-1}x^{n-1} + \cdots + c_1 x + c_0)\\ &= c_n\left(\lim_{x\to a} x\right)^n + c_{n-1}\left(\lim_{x\to a} x\right)^{n-1} + \cdots + c_1\left(\lim_{x\to a} x\right) + \lim_{x\to a} c_0\\ &= c_n a^n + c_{n-1}a^{n-1} + \cdots + c_1 a + c_0\\ &= p(a)\end{aligned}$$

It now follows from the quotient law that if $p(x)$ and $q(x)$ are polynomials for which $q(a) \neq 0$,

then

$$\lim_{x\to a}\frac{p(x)}{q(x)} = \frac{p(a)}{q(a)}. \tag{2.2.11}$$

Example 2.2.3: Evaluating a Limit of a Rational Function

Evaluate the $\lim_{x\to 3}\dfrac{2x^2-3x+1}{5x+4}$.

Solution

Since 3 is in the domain of the rational function $f(x) = \dfrac{2x^2-3x+1}{5x+4}$, we can calculate the limit by substituting 3 for x into the function. Thus,

$$\lim_{x\to 3}\frac{2x^2-3x+1}{5x+4} = \frac{10}{19}.$$

Exercise 2.2.3

Evaluate $\lim_{x\to -2}(3x^3 - 2x + 7)$.

Hint available at the end of this section.

Answer available at the end of this section.

Additional Limit Evaluation Techniques

As we have seen, we may evaluate easily the limits of polynomials and limits of some (but not all) rational functions by direct substitution. However, as we saw in the introductory section on limits, it is certainly possible for $\lim_{x\to a} f(x)$ to exist when $f(a)$ is undefined. The following observation allows us to evaluate many limits of this type:

If for all $x \neq a$, $f(x) = g(x)$ over some open interval containing a, then

$$\lim_{x\to a} f(x) = \lim_{x\to a} g(x). \tag{2.2.12}$$

To understand this idea better, consider the limit $\lim_{x\to 1}\dfrac{x^2-1}{x-1}$.

The function

$$f(x) = \frac{x^2-1}{x-1} = \frac{(x-1)(x+1)}{x-1}$$

and the function $g(x) = x + 1$ are identical for all values of $x \neq 1$. The graphs of these two functions are shown in Figure 2.2.1.

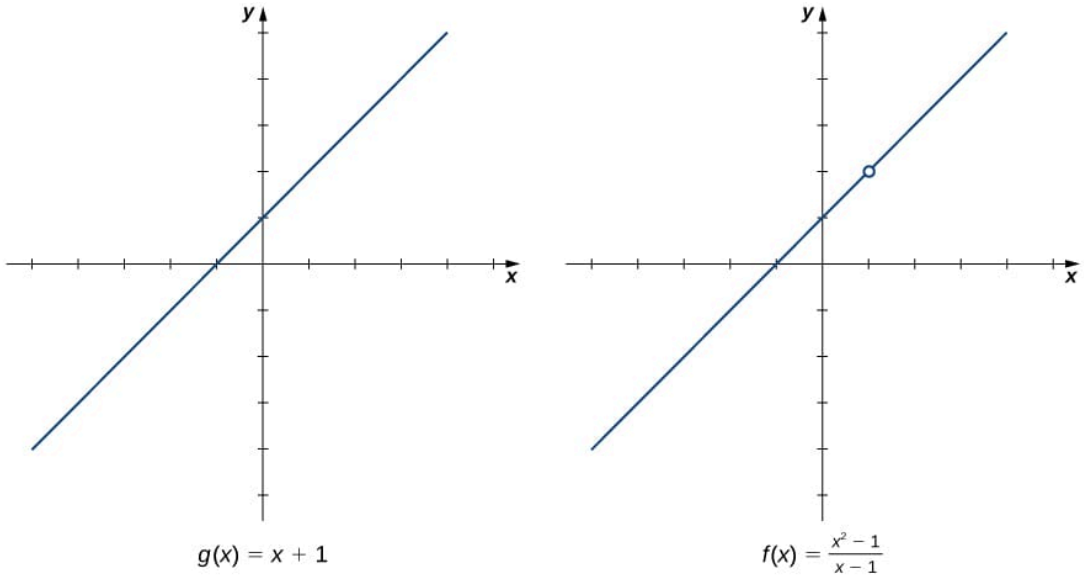


Figure 2.2.1: The graphs of $f(x)$ and $g(x)$ are identical for all $x \neq 1$. Their limits at 1 are equal.

We see that

$$\lim_{x\to 1} \frac{x^2-1}{x-1} = \lim_{x\to 1} \frac{(x-1)(x+1)}{x-1} = \lim_{x\to 1}(x+1) = 2.$$

The limit has the form $\lim_{x\to a} f(x)g(x)$, where $\lim_{x\to a} f(x) = 0$ and $\lim_{x\to a} g(x) = 0$. (In this case, we say that $f(x)/g(x)$ has the indeterminate form $0/0$.) The following Problem-Solving Strategy provides a general outline for evaluating limits of this type.

Problem-Solving Strategy: Calculating a Limit When $f(x)/g(x)$ has the Indeterminate Form $0/0$

1. First, we need to make sure that our function has the appropriate form and cannot be evaluated immediately using the limit laws.
2. We then need to find a function that is equal to $h(x) = f(x)/g(x)$ for all $x \neq a$ over some interval containing a. To do this, we may need to try one or more of the following steps:
   a. If $f(x)$ and $g(x)$ are polynomials, we should factor each function and cancel out any common factors.
   b. If the numerator or denominator contains a difference involving a square root, we should try multiplying the numerator and denominator by the conjugate of the expression involving the square root.
   c. If $f(x)/g(x)$ is a complex fraction, we begin by simplifying it.
3. Last, we apply the limit laws.

The next examples demonstrate the use of this Problem-Solving Strategy. Example 2.2.4 illustrates the factor-and-cancel technique; Example 2.2.5 shows multiplying by a conjugate. In Example 2.2.6, we look at simplifying a complex fraction.

Example 2.2.4: Evaluating a Limit by Factoring and Canceling

Evaluate $\lim_{x\to 3} \dfrac{x^2-3x}{2x^2-5x-3}$.

Solution

Step 1. The function $f(x) = \dfrac{x^2-3x}{2x^2-5x-3}$ is undefined for $x = 3$. In fact, if we substitute 3 into the function we get $0/0$, which is undefined. Factoring and canceling is a good strategy:

$$\lim_{x\to 3}\frac{x^2-3x}{2x^2-5x-3}=\lim_{x\to 3}\frac{x(x-3)}{(x-3)(2x+1)}$$

Step 2. For all $x\neq 3$, $\dfrac{x^2-3x}{2x^2-5x-3}=\dfrac{x}{2x+1}$. Therefore,

$$\lim_{x\to 3}\frac{x(x-3)}{(x-3)(2x+1)}=\lim_{x\to 3}\frac{x}{2x+1}.$$

Step 3. Evaluate using the limit laws:

$$\lim_{x\to 3}\frac{x}{2x+1}=\frac{3}{7}.$$

Exercise 2.2.4

Evaluate $\lim_{x\to -3}\dfrac{x^2+4x+3}{x^2-9}$.

Hint available at the end of this section.

Answer available at the end of this section.

Example 2.2.5: Evaluating a Limit by Multiplying by a Conjugate

Evaluate $\lim_{x\to -1}\dfrac{\sqrt{x+2}-1}{x+1}$.

Solution

Step 1. $\dfrac{\sqrt{x+2}-1}{x+1}$ has the form $0/0$ at –1. Let's begin by multiplying by $\sqrt{x+2}+1$, the conjugate of $\sqrt{x+2}-1$, on the numerator and denominator:

$$\lim_{x\to -1}\frac{\sqrt{x+2}-1}{x+1}=\lim_{x\to -1}\frac{\sqrt{x+2}-1}{x+1}\cdot\frac{\sqrt{x+2}+1}{\sqrt{x+2}+1}.$$

Step 2. We then multiply out the numerator. We don't multiply out the denominator because we are hoping that the $(x+1)$ in the denominator cancels out in the end:

$$=\lim_{x\to -1}\frac{x+1}{(x+1)(\sqrt{x+2}+1)}.$$

Step 3. Then we cancel:

$$=\lim_{x\to -1}\frac{1}{\sqrt{x+2}+1}.$$

Step 4. Last, we apply the limit laws:

$$\lim_{x\to -1}\frac{1}{\sqrt{x+2}+1}=\frac{1}{2}.$$

Exercise 2.2.5

Evaluate $\lim_{x\to 5}\dfrac{\sqrt{x-1}-2}{x-5}$.

Hint available at the end of this section.

Answer available at the end of this section.

Example 2.2.6: Evaluating a Limit by Simplifying a Complex Fraction

Evaluate $\lim_{x\to 1} \dfrac{\dfrac{1}{x+1}-\dfrac{1}{2}}{x-1}$.

Solution

Step 1. $\dfrac{\dfrac{1}{x+1}-\dfrac{1}{2}}{x-1}$ has the form $0/0$ at 1. We simplify the algebraic fraction by multiplying by $2(x+1)/2(x+1)$:

$$\lim_{x\to 1} \frac{\dfrac{1}{x+1}-\dfrac{1}{2}}{x-1} = \lim_{x\to 1} \frac{\dfrac{1}{x+1}-\dfrac{1}{2}}{x-1} \cdot \frac{2(x+1)}{2(x+1)}.$$

Step 2. Next, we multiply through the numerators. Do not multiply the denominators because we want to be able to cancel the factor $(x-1)$:

$$= \lim_{x\to 1} \frac{2-(x+1)}{2(x-1)(x+1)}.$$

Step 3. Then, we simplify the numerator:

$$= \lim_{x\to 1} \frac{-x+1}{2(x-1)(x+1)}.$$

Step 4. Now we factor out –1 from the numerator:

$$= \lim_{x\to 1} \frac{-(x-1)}{2(x-1)(x+1)}.$$

Step 5. Then, we cancel the common factors of $(x-1)$:

$$= \lim_{x\to 1} \frac{-1}{2(x+1)}.$$

Step 6. Last, we evaluate using the limit laws:

$$\lim_{x\to 1} \frac{-1}{2(x+1)} = -\frac{1}{4}.$$

Exercise 2.2.6

Evaluate $\lim_{x\to -3} \dfrac{\dfrac{1}{x+2}+1}{x+3}$.

Hint available at the end of this section.

Answer available at the end of this section.

Example does not fall neatly into any of the patterns established in the previous examples. However, with a little creativity, we can still use these same techniques.

Example 2.2.7: Evaluating a Limit When the Limit Laws Do Not Apply

Evaluate $\lim_{x\to 0}\left(\frac{1}{x}+\frac{5}{x(x-5)}\right)$.

Solution:

Both $1/x$ and $5/x(x-5)$ fail to have a limit at zero. Since neither of the two functions has a limit at zero, we cannot apply the sum law for limits; we must use a different strategy. In this case, we find the limit by performing addition and then applying one of our previous strategies. Observe that

$$\frac{1}{x}+\frac{5}{x(x-5)}=\frac{x-5+5}{x(x-5)}=\frac{x}{x(x-5)}.$$

Thus,

$$\lim_{x\to 0}\left(\frac{1}{x}+\frac{5}{x(x-5)}\right)=\lim_{x\to 0}\frac{x}{x(x-5)}=\lim_{x\to 0}\frac{1}{x-5}=-\frac{1}{5}.$$

Exercise 2.2.7

Evaluate $\lim_{x\to 3}\left(\frac{1}{x-3}-\frac{4}{x^2-2x-3}\right)$.

Hint available at the end of this section.

Answer available at the end of this section.

Let's now revisit one-sided limits. Simple modifications in the limit laws allow us to apply them to one-sided limits. For example, to apply the limit laws to a limit of the form $\lim_{x\to a^-}h(x)$, we require the function $h(x)$ to be defined over an open interval of the form (b,a); for a limit of the form $\lim_{x\to a^+}h(x)$, we require the function $h(x)$ to be defined over an open interval of the form (a,c). Example 2.2.8A illustrates this point.

Example 2.2.8A: Evaluating a One-Sided Limit Using the Limit Laws

Evaluate each of the following limits, if possible.

a. $\lim_{x\to 3^-}\sqrt{x-3}$
b. $\lim_{x\to 3^+}\sqrt{x-3}$

Solution

Figure illustrates the function $f(x)=\sqrt{x-3}$ and aids in our understanding of these limits.

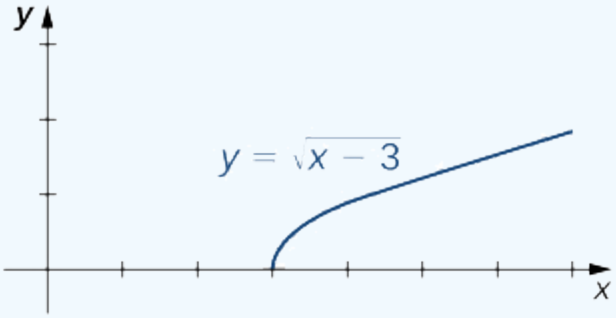


Figure 2.2.2: The graph shows the function $f(x) = \sqrt{x-3}$.

a. The function $f(x) = \sqrt{x-3}$ is defined over the interval $[3, +\infty)$. Since this function is not defined to the left of 3, we cannot apply the limit laws to compute $\lim\limits_{x \to 3^-} \sqrt{x-3}$. In fact, since $f(x) = \sqrt{x-3}$ is undefined to the left of 3, $\lim\limits_{x \to 3^-} \sqrt{x-3}$ does not exist.

b. Since $f(x) = \sqrt{x-3}$ is defined to the right of 3, the limit laws do apply to $\lim\limits_{x \to 3^+} \sqrt{x-3}$. By applying these limit laws we obtain $\lim\limits_{x \to 3^+} \sqrt{x-3} = 0$.

In Example $2.2.8B$ we look at one-sided limits of a piecewise-defined function and use these limits to draw a conclusion about a two-sided limit of the same function.

Example $2.2.8B$: Evaluating a Two-Sided Limit Using the Limit Laws

For $f(x) = \begin{cases} 4x-3, & \text{if } x < 2 \\ (x-3)^2, & \text{if } x \geq 2 \end{cases}$, evaluate each of the following limits:

a. $\lim\limits_{x \to 2^-} f(x)$
b. $\lim\limits_{x \to 2^+} f(x)$
c. $\lim\limits_{x \to 2} f(x)$

Solution

Figure illustrates the function $f(x)$ and aids in our understanding of these limits.

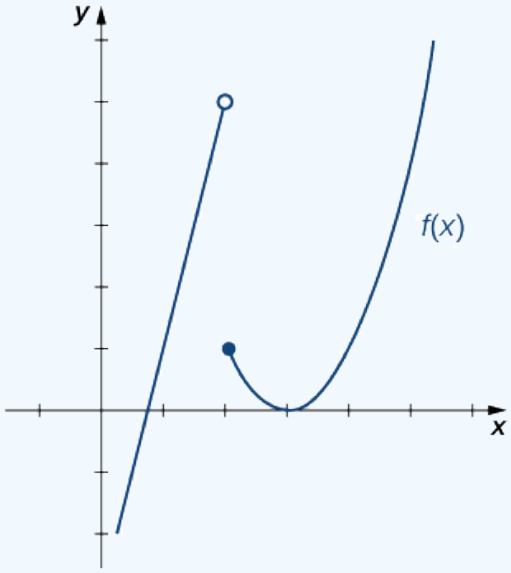


Figure 2.2.3: This graph shows a function $f(x)$.

a. Since $f(x) = 4x - 3$ for all x in $(-\infty, 2)$, replace $f(x)$ in the limit with $4x - 3$ and apply the limit laws:

$$\lim_{x \to 2^-} f(x) = \lim_{x \to 2^-} (4x - 3) = 5$$

b. Since $f(x) = (x - 3)^2$for all x in $(2, +\infty)$, replace $f(x)$ in the limit with $(x - 3)^2$ and apply the limit laws:

$$\lim_{x \to 2^+} f(x) = \lim_{x \to 2^-} (x - 3)^2 = 1.$$

c. Since $\lim_{x \to 2^-} f(x) = 5$ and $\lim_{x \to 2^+} f(x) = 1$, we conclude that $\lim_{x \to 2} f(x)$ does not exist.

Exercise 2.2.8

Graph $f(x) = \begin{cases} -x - 2, & \text{if } x < -1 \\ 2, & \text{if } x = -1 \\ x^3, & \text{if } x > -1 \end{cases}$ and evaluate $\lim_{x \to -1^-} f(x)$.

Hint available at the end of this section.

Answer available at the end of this section.

We now turn our attention to evaluating a limit of the form $\lim_{x \to a} \frac{f(x)}{g(x)}$, where $\lim_{x \to a} f(x) = K$, where $K \neq 0$ and $\lim_{x \to a} g(x) = 0$. That is, $f(x)/g(x)$ has the form $K/0, K \neq 0$ at a.

Example 2.2.9: Evaluating a Limit of the Form $K/0,\ K \neq 0$ Using the Limit Laws

Evaluate $\lim_{x \to 2^-} \frac{x - 3}{x^2 - 2x}$.

Solution

Step 1. After substituting in $x = 2$, we see that this limit has the form $-1/0$. That is, as x approaches 2 from the left, the numerator approaches -1; and the denominator approaches 0. Consequently, the magnitude of $\frac{x - 3}{x(x - 2)}$ becomes infinite. To get a better idea of what the limit is, we need to factor the denominator:

$$\lim_{x\to 2^-}\frac{x-3}{x^2-2x}=\lim_{x\to 2^-}\frac{x-3}{x(x-2)}$$

Step 2. Since $x-2$ is the only part of the denominator that is zero when 2 is substituted, we then separate $1/(x-2)$ from the rest of the function:

$$=\lim_{x\to 2^-}\frac{x-3}{x}\cdot\frac{1}{x-2}$$

Step 3. Using the Limit Laws, we can write:

$$=\left(\lim_{x\to 2^-}\frac{x-3}{x}\right)\cdot\left(\lim_{x\to 2^-}\frac{1}{x-2}\right).$$

Step 4. $\lim_{x\to 2^-}\frac{x-3}{x}=-\frac{1}{2}$ and $\lim_{x\to 2^-}\frac{1}{x-2}=-\infty$. Therefore, the product of $(x-3)/x$ and $1/(x-2)$ has a limit of $+\infty$:

$$\lim_{x\to 2^-}\frac{x-3}{x^2-2x}=+\infty.$$

Exercise 2.2.9

Evaluate $\lim_{x\to 1}\frac{x+2}{(x-1)^2}$.

Solution available at the end of this section.

Answer available at the end of this section.

The Squeeze Theorem

The techniques we have developed thus far work very well for algebraic functions, but we are still unable to evaluate limits of very basic trigonometric functions. The next theorem, called the **squeeze theorem,** proves very useful for establishing basic trigonometric limits. This theorem allows us to calculate limits by "squeezing" a function, with a limit at a point a that is unknown, between two functions having a common known limit at a. Figure 2.2.4 illustrates this idea.

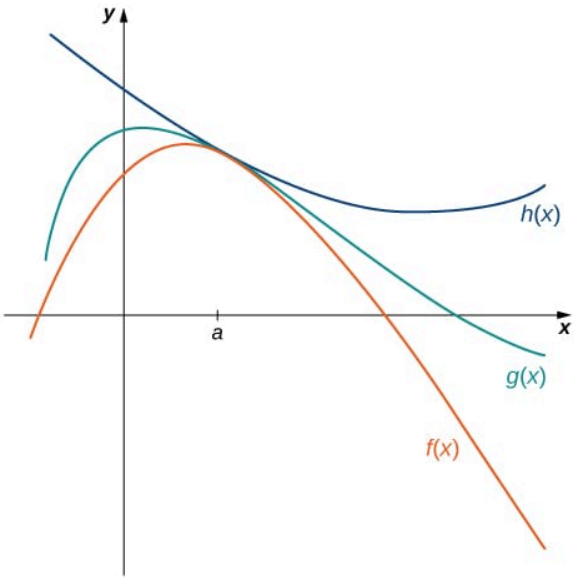


Figure 2.2.4: The Squeeze Theorem applies when $f(x)\le g(x)\le h(x)$ and $\lim_{x\to a}f(x)=\lim_{x\to a}h(x)$.

The Squeeze Theorem

Let $f(x), g(x)$, and $h(x)$ be defined for all $x \neq a$ over an open interval containing a. If

$$f(x) \leq g(x) \leq h(x) \tag{2.2.13}$$

for all $x \neq a$ in an open interval containing a and

$$\lim_{x \to a} f(x) = L = \lim_{x \to a} h(x) \tag{2.2.14}$$

where L is a real number, then $\lim_{x \to a} g(x) = L$.

Example 2.2.10: Applying the Squeeze Theorem

Apply the squeeze theorem to evaluate $\lim_{x \to 0} x \cos x$.

Solution

Because $-1 \leq \cos x \leq 1$ for all x, we have $-x \leq x \cos x \leq x$ for $x \geq 0$ and $-x \geq x \cos x \geq x$ for $x \leq 0$ (if x is negative the direction of the inequalities changes when we multiply). Since $\lim_{x \to 0}(-x) = 0 = \lim_{x \to 0} x$, from the squeeze theorem, we obtain $\lim_{x \to 0} x \cos x = 0$. The graphs of $f(x) = -x$, $g(x) = x \cos x$, and $h(x) = x$ are shown in Figure 2.2.5.

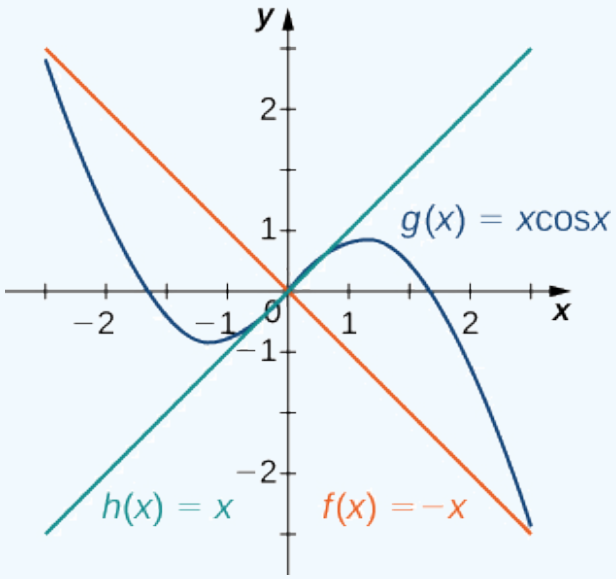


Figure 2.2.5: The graphs of $f(x)$, $g(x)$, and $h(x)$ are shown around the point $x = 0$.

Exercise 2.2.10

Use the squeeze theorem to evaluate $\lim_{x \to 0} x^2 \sin \frac{1}{x}$.

Hint available at the end of this section.

Answer available at the end of this section.

We now use the squeeze theorem to tackle several very important limits. Although this discussion is somewhat lengthy, these limits prove invaluable for the development of the material in both the next section and the next chapter. The first of these limits is $\lim_{\theta \to 0} \sin \theta$. Consider the unit circle shown in Figure 2.2.6. In the figure, we see that $\sin \theta$ is the y-coordinate on the unit circle and

it corresponds to the line segment shown in blue. The radian measure of angle θ is the length of the arc it subtends on the unit circle. Therefore, we see that for $0 < \theta < \frac{\pi}{2}, 0 < \sin\theta < \theta$.

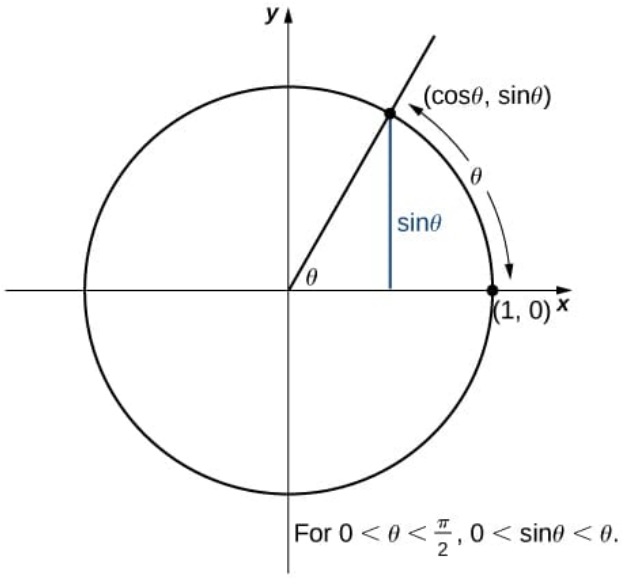


Figure 2.2.6: The sine function is shown as a line on the unit circle.

Because $\lim_{\theta \to 0^+} 0 = 0$ and $\lim_{x \to 0^+} \theta = 0$, by using the squeeze theorem we conclude that

$$\lim_{\theta \to 0^+} \sin\theta = 0.$$

To see that $\lim_{\theta \to 0^-} \sin\theta = 0$ as well, observe that for $-\frac{\pi}{2} < \theta < 0, 0 < -\theta < \frac{\pi}{2}$ and hence, $0 < \sin(-\theta) < -\theta$. Consequently, $0 < -\sin\theta < -\theta$. It follows that $0 > \sin\theta > \theta$. An application of the squeeze theorem produces the desired limit. Thus, since $\lim_{\theta \to 0^+} \sin\theta = 0$ and $\lim_{\theta \to 0^-} \sin\theta = 0$,

$$\lim_{\theta \to 0} \sin\theta = 0$$

Next, using the identity $\cos\theta = \sqrt{1 - \sin^2\theta}$ for $-\frac{\pi}{2} < \theta < \frac{\pi}{2}$, we see that

$$\lim_{\theta \to 0} \cos\theta = \lim_{\theta \to 0} \sqrt{1 - \sin^2\theta} = 1.$$

We now take a look at a limit that plays an important role in later chapters—namely, $\lim_{\theta \to 0} \frac{\sin\theta}{\theta}$. To evaluate this limit, we use the unit circle in Figure 2.2.6. Notice that this figure adds one additional triangle to Figure 2.2.7. We see that the length of the side opposite angle θ in this new triangle is $\tan\theta$. Thus, we see that for $0 < \theta < \frac{\pi}{2}$, $\sin\theta < \theta < \tan\theta$.

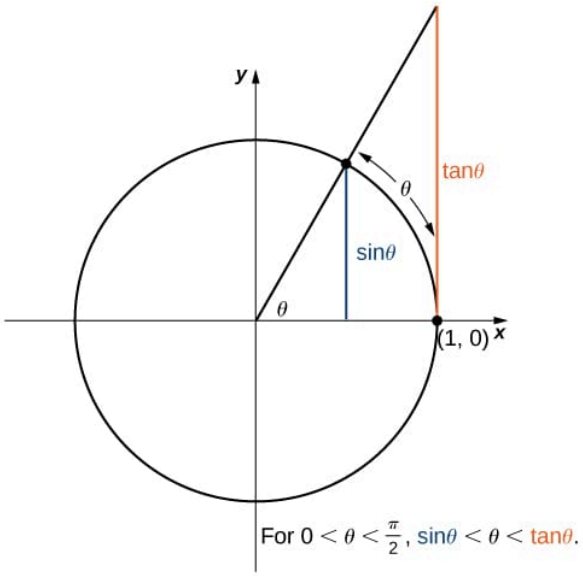


Figure 2.2.7: The sine and tangent functions are shown as lines on the unit circle.

By dividing by $\sin\theta$ in all parts of the inequality, we obtain

$$1 < \frac{\theta}{\sin\theta} < \frac{1}{\cos\theta}.$$

Equivalently, we have

$$1 > \frac{\sin\theta}{\theta} > \cos\theta.$$

Since $\lim\limits_{\theta\to 0^+} 1 = 1 = \lim\limits_{\theta\to 0^+} \cos\theta$, we conclude that $\lim\limits_{\theta\to 0^+} \dfrac{\sin\theta}{\theta} = 1$. By applying a manipulation similar to that used in demonstrating that $\lim\limits_{\theta\to 0^-} \sin\theta = 0$, we can show that $\lim\limits_{\theta\to 0^-} \dfrac{\sin\theta}{\theta} = 1$. Thus,

$$\lim_{\theta\to 0} \frac{\sin\theta}{\theta} = 1. \tag{2.2.15}$$

In Example 2.2.11, we use this limit to establish $\lim\limits_{\theta\to 0} \dfrac{1-\cos\theta}{\theta} = 0$. This limit also proves useful in later chapters.

Example 2.2.11: Evaluating an Important Trigonometric Limit

Evaluate $\lim\limits_{\theta\to 0} \dfrac{1-\cos\theta}{\theta}$.

Solution

In the first step, we multiply by the conjugate so that we can use a trigonometric identity to convert the cosine in the numerator to a sine:

$$\begin{aligned}\lim_{\theta\to 0}\frac{1-\cos\theta}{\theta} &= \lim_{\theta\to 0}\frac{1-\cos\theta}{\theta}\cdot\frac{1+\cos\theta}{1+\cos\theta}\\ &= \lim_{\theta\to 0}\frac{1-\cos^2\theta}{\theta(1+\cos\theta)}\\ &= \lim_{\theta\to 0}\frac{\sin^2\theta}{\theta(1+\cos\theta)}\\ &= \lim_{\theta\to 0}\frac{\sin\theta}{\theta}\cdot\frac{\sin\theta}{1+\cos\theta}\\ &= \left(\lim_{\theta\to 0}\frac{\sin\theta}{\theta}\right)\cdot\left(\lim_{\theta\to 0}\frac{\sin\theta}{1+\cos\theta}\right)\\ &= 1\cdot\frac{0}{2}=0.\end{aligned}$$

Therefore,

$$\lim_{\theta\to 0}\frac{1-\cos\theta}{\theta}=0. \tag{2.2.16}$$

Exercise 2.2.11

Evaluate $\lim_{\theta\to 0}\frac{1-\cos\theta}{\sin\theta}$.

Hint available at the end of this section.

Answer available at the end of this section.

Deriving the Formula for the Area of a Circle

Some of the geometric formulas we take for granted today were first derived by methods that anticipate some of the methods of calculus. The Greek mathematician *Archimedes* (ca. 287–212; BCE) was particularly inventive, using polygons inscribed within circles to approximate the area of the circle as the number of sides of the polygon increased. He never came up with the idea of a limit, but we can use this idea to see what his geometric constructions could have predicted about the limit.

We can estimate the area of a circle by computing the area of an inscribed regular polygon. Think of the regular polygon as being made up of n triangles. By taking the limit as the vertex angle of these triangles goes to zero, you can obtain the area of the circle. To see this, carry out the following steps:

1. Express the height h and the base b of the isosceles triangle in Figure $2.2.6$ in terms of θ and r.

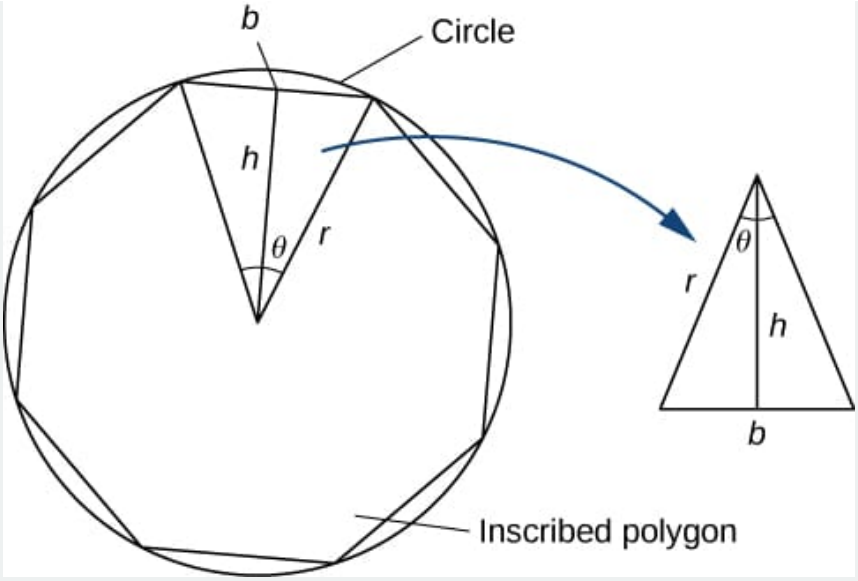


Figure 2.2.8

2. Using the expressions that you obtained in step 1, express the area of the isosceles triangle in terms of θ and r.

(Substitute $\frac{1}{2}\sin\theta$ for $\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{\theta}{2}\right)$ in your expression.)

3. If an n-sided regular polygon is inscribed in a circle of radius r, find a relationship between θ and n. Solve this for n. Keep in mind there are 2π radians in a circle. (Use radians, not degrees.)

4. Find an expression for the area of the n-sided polygon in terms of r and θ.

5. To find a formula for the area of the circle, find the limit of the expression in step 4 as θ goes to zero. (Hint: $\lim_{\theta\to 0}\frac{\sin\theta}{\theta} = 1$).

The technique of estimating areas of regions by using polygons is revisited in Introduction to Integration.

Key Concepts

- The limit laws allow us to evaluate limits of functions without having to go through step-by-step processes each time.
- For polynomials and rational functions,

$$\lim_{x\to a} f(x) = f(a). \tag{2.2.17}$$

- You can evaluate the limit of a function by factoring and canceling, by multiplying by a conjugate, or by simplifying a complex fraction.
- The squeeze theorem allows you to find the limit of a function if the function is always greater than one function and less than another function with limits that are known.

Key Equations

- **Basic Limit Results**

$$\lim_{x\to a} x = a \qquad \lim_{x\to a} c = c$$

- **Important Limits**

$$\lim_{\theta\to 0}\sin\theta = 0$$

$$\lim_{\theta \to 0} \cos\theta = 1$$

$$\lim_{\theta \to 0} \frac{\sin\theta}{\theta} = 1$$

$$\lim_{\theta \to 0} \frac{1-\cos\theta}{\theta} = 0$$

Glossary

constant multiple law for limits
the limit law

$$\lim_{x \to a} cf(x) = c \cdot \lim_{x \to a} f(x) = cL$$

difference law for limits
the limit law

$$\lim_{x \to a}(f(x) - g(x)) = \lim_{x \to a} f(x) - \lim_{x \to a} g(x) = L - M$$

limit laws
the individual properties of limits; for each of the individual laws, let $f(x)$ and $g(x)$ be defined for all $x \neq a$ over some open interval containing a; assume that L and M are real numbers so that $\lim_{x \to a} f(x) = L$ and $\lim_{x \to a} g(x) = M$; let c be a constant

power law for limits
the limit law

$$\lim_{x \to a}(f(x))^n = (\lim_{x \to a} f(x))^n = L^n$$

for every positive integer n

product law for limits
the limit law

$$\lim_{x \to a}(f(x) \cdot g(x)) = \lim_{x \to a} f(x) \cdot \lim_{x \to a} g(x) = L \cdot M$$

quotient law for limits
the limit law $\lim_{x \to a} \frac{f(x)}{g(x)} = \frac{\lim_{x \to a} f(x)}{\lim_{x \to a} g(x)} = \frac{L}{M}$ for M≠0

root law for limits
the limit law $\lim_{x \to a} \sqrt[n]{f(x)} = \sqrt[n]{\lim_{x \to a} f(x)} = \sqrt[n]{L}$ for all L if n is odd and for $L \geq 0$ if n is even

squeeze theorem
states that if $f(x) \leq g(x) \leq h(x)$ for all $x \neq a$ over an open interval containing a and $\lim_{x \to a} f(x) = L = \lim_{x \to a} h(x)$ where L is a real number, then $\lim_{x \to a} g(x) = L$

sum law for limits
The limit law $\lim_{x \to a}(f(x) + g(x)) = \lim_{x \to a} f(x) + \lim_{x \to a} g(x) = L + M$

Contributors and Attributions

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Answers

Exercise 2.2.2
Begin by applying the product law.

Exercise 2.2.2

$11\sqrt{10}$

Exercise 2.2.3

Use LIMITS OF POLYNOMIAL AND RATIONAL FUNCTIONS as reference

Exercise 2.2.3

–13

Exercise 2.2.4

Follow the steps in the Problem-Solving Strategy

Exercise 2.2.4

$\frac{1}{3}$

Exercise 2.2.5

Follow the steps in the Problem-Solving Strategy

Exercise 2.2.5

$\frac{1}{4}$

Exercise 2.2.6

Follow the steps in the Problem-Solving Strategy and

Exercise 2.2.6

–1

Exercise 2.2.7

Use the same technique as Example 2.2.7. Don't forget to factor $x^2 - 2x - 3$ before getting a common denominator.

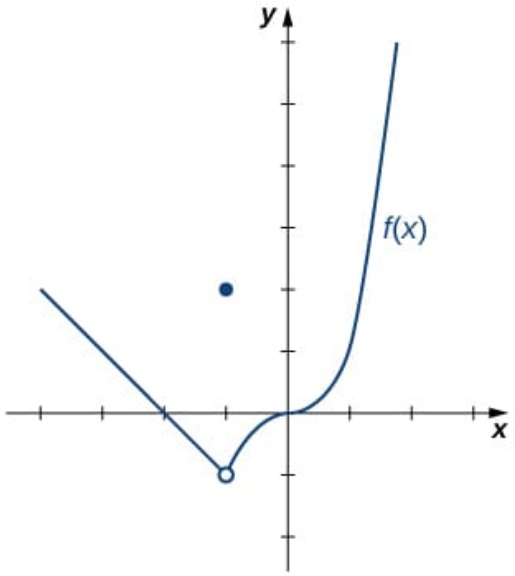
Exercise 2.2.7

$\frac{1}{4}$

Exercise 2.2.8

Use the method in Example $2.2.8B$ to evaluate the limit.

Exercise 2.2.8



$\lim_{x \to -1^-} f(x) = -1$

Exercise 2.2.9

Use the methods from Example 2.2.9.

Exercise 2.2.9

$+\infty$

Exercise 2.2.10

Use the fact that $-x^2 \leq x^2 \sin(1/x) \leq x^2$ to help you find two functions such that $x^2 \sin(1/x)$ is squeezed between them.

Exercise 2.2.10

0

Exercise 2.2.11

Multiply numerator and denominator by $1 + \cos\theta$.

Exercise 2.2.11

0

2.2E: Exercises for Section 2.3

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2.2E: Exercises for Section 2.3

In exercises 1 - 4, use the limit laws to evaluate each limit. Justify each step by indicating the appropriate limit law(s).

1) $\lim\limits_{x\to 0}\ (4x^2-2x+3)$

Answer

Use constant multiple law and difference law:

$$\lim_{x\to 0}\ (4x^2-2x+3)=4\lim_{x\to 0}x^2-2\lim_{x\to 0}x+\lim_{x\to 0}3=0+0+3=3$$

2) $\lim\limits_{x\to 1}\dfrac{x^3+3x^2+5}{4-7x}$

3) $\lim\limits_{x\to -2}\sqrt{x^2-6x+3}$

Answer

Use root law: $\lim\limits_{x\to -2}\sqrt{x^2-6x+3}=\sqrt{\lim\limits_{x\to -2}(x^2-6x+3)}=\sqrt{19}$

4) $\lim\limits_{x\to -1}\ (9x+1)^2$

In exercises 5 - 10, use direct substitution to evaluate the limit of each continuous function.

5) $\lim\limits_{x\to 7}x^2$

Answer

$$\lim_{x\to 7}x^2\ =\ 49$$

6) $\lim\limits_{x\to -2}(4x^2-1)$

7) $\lim\limits_{x\to 0}\dfrac{1}{1+\sin x}$

Answer

$$\lim_{x\to 0}\frac{1}{1+\sin x}\ =\ 1$$

8) $\lim\limits_{x\to 2}e^{2x-x^2}$

9) $\lim\limits_{x\to 1}\dfrac{2-7x}{x+6}$

Answer

$$\lim_{x\to 1}\frac{2-7x}{x+6}\ =\ -\frac{5}{7}$$

10) $\lim\limits_{x\to 3}\ln e^{3x}$

In exercises 11 - 20, use direct substitution to show that each limit leads to the indeterminate form $0/0$. Then, evaluate the limit analytically.

11) $\lim\limits_{x\to 4}\dfrac{x^2-16}{x-4}$

Answer

$$\lim_{x\to 4}\frac{x^2-16}{x-4}=\frac{16-16}{4-4}=\frac{0}{0};$$
$$\text{then, } \lim_{x\to 4}\frac{x^2-16}{x-4}=\lim_{x\to 4}\frac{(x+4)(x-4)}{x-4}=\lim_{x\to 4}(x+4)=4+4=8$$

12) $\lim_{x\to 2}\dfrac{x-2}{x^2-2x}$

13) $\lim_{x\to 6}\dfrac{3x-18}{2x-12}$

Answer

$$\lim_{x\to 6}\frac{3x-18}{2x-12}=\frac{18-18}{12-12}=\frac{0}{0};$$
$$\text{then, } \lim_{x\to 6}\frac{3x-18}{2x-12}=\lim_{x\to 6}\frac{3(x-6)}{2(x-6)}=\lim_{x\to 6}\frac{3}{2}=\frac{3}{2}$$

14) $\lim_{h\to 0}\dfrac{(1+h)^2-1}{h}$

15) $\lim_{t\to 9}\dfrac{t-9}{\sqrt{t}-3}$

Answer

$$\lim_{x\to 9}\frac{t-9}{\sqrt{t}-3}=\frac{9-9}{3-3}=\frac{0}{0};$$
$$\text{then, } \lim_{t\to 9}\frac{t-9}{\sqrt{t}-3}=\lim_{t\to 9}\frac{t-9}{\sqrt{t}-3}\frac{\sqrt{t}+3}{\sqrt{t}+3}=\lim_{t\to 9}\frac{(t-9)(\sqrt{t}+3)}{t-9}=\lim_{t\to 9}(\sqrt{t}+3)=\sqrt{9}+3=6$$

16) $\lim_{h\to 0}\dfrac{\dfrac{1}{a+h}-\dfrac{1}{a}}{h}$, where a is a real-valued constant

17) $\lim_{\theta\to\pi}\dfrac{\sin\theta}{\tan\theta}$

Answer

$$\lim_{\theta\to\pi}\frac{\sin\theta}{\tan\theta}=\frac{\sin\pi}{\tan\pi}=\frac{0}{0};$$
$$\text{then, } \lim_{\theta\to\pi}\frac{\sin\theta}{\tan\theta}=\lim_{\theta\to\pi}\frac{\sin\theta}{\frac{\sin\theta}{\cos\theta}}=\lim_{\theta\to\pi}\cos\theta=\cos\pi=-1$$

18) $\lim_{x\to 1}\dfrac{x^3-1}{x^2-1}$

19) $\lim_{x\to 1/2}\dfrac{2x^2+3x-2}{2x-1}$

Answer

$$\lim_{x\to 1/2}\frac{2x^2+3x-2}{2x-1}=\frac{\frac{1}{2}+\frac{3}{2}-2}{1-1}=\frac{0}{0};$$
$$\text{then, } \lim_{x\to 1/2}\frac{2x^2+3x-2}{2x-1}=\lim_{x\to 1/2}\frac{(2x-1)(x+2)}{2x-1}=\lim_{x\to 1/2}(x+2)=\frac{1}{2}+2=\frac{5}{2}$$

20) $\lim_{x\to -3}\dfrac{\sqrt{x+4}-1}{x+3}$

In exercises 25 - 32, assume that $\lim_{x\to 6}f(x)=4$, $\lim_{x\to 6}g(x)=9$, and $\lim_{x\to 6}h(x)=6$. Use these three facts and the limit laws to evaluate each limit.

25) $\lim_{x\to 6}2f(x)g(x)$

Answer

$$\lim_{x\to 6} 2f(x)g(x) = 2\left(\lim_{x\to 6} f(x)\right)\left(\lim_{x\to 6} g(x)\right) = 2(4)(9) = 72$$

26) $\lim\limits_{x\to 6} \dfrac{g(x)-1}{f(x)}$

27) $\lim\limits_{x\to 6} \left(f(x) + \dfrac{1}{3}g(x)\right)$

Answer

$$\lim_{x\to 6} \left(f(x) + \frac{1}{3}g(x)\right) = \lim_{x\to 6} f(x) + \frac{1}{3}\lim_{x\to 6} g(x) = 4 + \frac{1}{3}(9) = 7$$

28) $\lim\limits_{x\to 6} \dfrac{\left(h(x)\right)^3}{2}$

29) $\lim\limits_{x\to 6} \sqrt{g(x)-f(x)}$

Answer

$$\lim_{x\to 6} \sqrt{g(x)-f(x)} = \sqrt{\lim_{x\to 6} g(x) - \lim_{x\to 6} f(x)} = \sqrt{9-4} = \sqrt{5}$$

30) $\lim\limits_{x\to 6} x \cdot h(x)$

31) $\lim\limits_{x\to 6}[(x+1)\cdot f(x)]$

Answer

$$\lim_{x\to 6}[(x+1)f(x)] = \left(\lim_{x\to 6}(x+1)\right)\left(\lim_{x\to 6} f(x)\right) = 7(4) = 28$$

32) $\lim\limits_{x\to 6}(f(x)\cdot g(x) - h(x))$

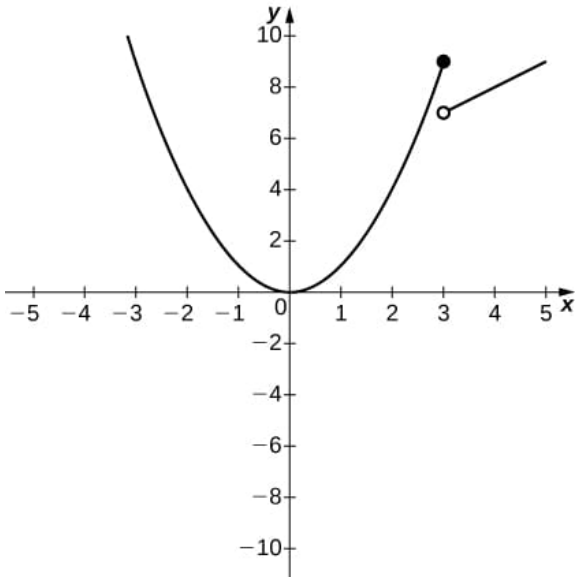
[T] In exercises 33 - 35, use a calculator to draw the graph of each piecewise-defined function and study the graph to evaluate the given limits.

33) $f(x) = \begin{cases} x^2, & x \le 3 \\ x+4, & x > 3 \end{cases}$

a. $\lim\limits_{x\to 3^-} f(x)$

b. $\lim\limits_{x\to 3^+} f(x)$

Answer



a. 9; b.7

34) $g(x) = \begin{cases} x^3 - 1, & x \leq 0 \\ 1, & x > 0 \end{cases}$

a. $\lim_{x \to 0^-} g(x)$

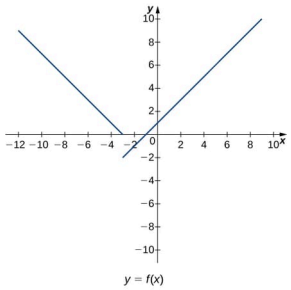
b. $\lim_{x \to 0^+} g(x)$

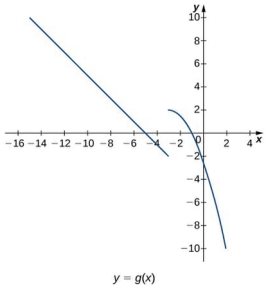
35) $h(x) = \begin{cases} x^2 - 2x + 1, & x < 2 \\ 3 - x, & x \geq 2 \end{cases}$

a. $\lim_{x \to 2^-} h(x)$

b. $\lim_{x \to 2^+} h(x)$

In exercises 36 - 43, use the following graphs and the limit laws to evaluate each limit.





36) $\lim_{x\to -3^+}(f(x)+g(x))$

37) $\lim_{x\to -3^-}(f(x)-3g(x))$

Answer

$$\lim_{x\to -3^-}(f(x)-3g(x))=\lim_{x\to -3^-}f(x)-3\lim_{x\to -3^-}g(x)=0+6=6$$

38) $\lim_{x\to 0}\dfrac{f(x)g(x)}{3}$

39) $\lim_{x\to -5}\dfrac{2+g(x)}{f(x)}$

Answer

$$\lim_{x\to -5}\frac{2+g(x)}{f(x)}=\frac{2+\left(\lim_{x\to -5}g(x)\right)}{\lim_{x\to -5}f(x)}=\frac{2+0}{2}=1$$

40) $\lim_{x\to 1}(f(x))^2$

41) $\lim_{x\to 1}\sqrt[3]{f(x)-g(x)}$

Answer

$$\lim_{x\to 1}\sqrt[3]{f(x)-g(x)}=\sqrt[3]{\lim_{x\to 1}f(x)-\lim_{x\to 1}g(x)}=\sqrt[3]{2+5}=\sqrt[3]{7}$$

42) $\lim_{x\to -7}(x\cdot g(x))$

43) $\lim_{x\to -9}[x\cdot f(x)+2\cdot g(x)]$

Answer

$$\lim_{x\to -9}(xf(x)+2g(x))=\left(\lim_{x\to -9}x\right)\left(\lim_{x\to -9}f(x)\right)+2\lim_{x\to -9}g(x)=(-9)(6)+2(4)=-46$$

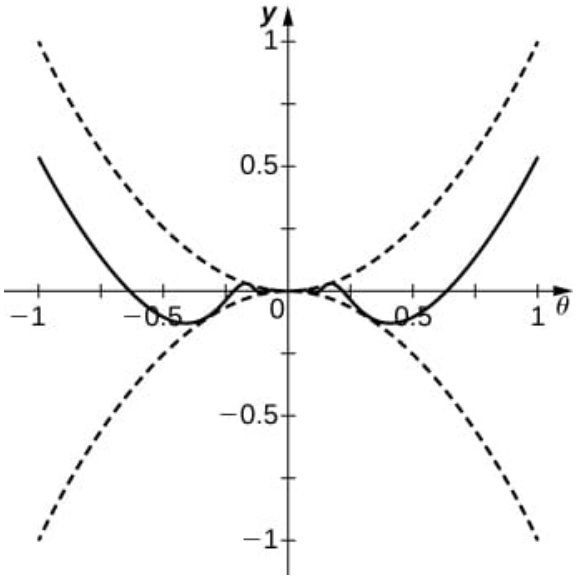
For exercises 44 - 46, evaluate the limit using the squeeze theorem. Use a calculator to graph the functions $f(x)$, $g(x)$, and $h(x)$ when possible.

44) [T] True or False? If $2x - 1 \leq g(x) \leq x^2 - 2x + 3$, then $\lim_{x \to 2} g(x) = 0$.

45) [T] $\lim_{\theta \to 0} \theta^2 \cos\left(\frac{1}{\theta}\right)$

Answer

The limit is zero.



46) $\lim_{x \to 0} f(x)$, where $f(x) = \begin{cases} 0, & x \text{ rational} \\ x^2, & x \text{ irrrational} \end{cases}$

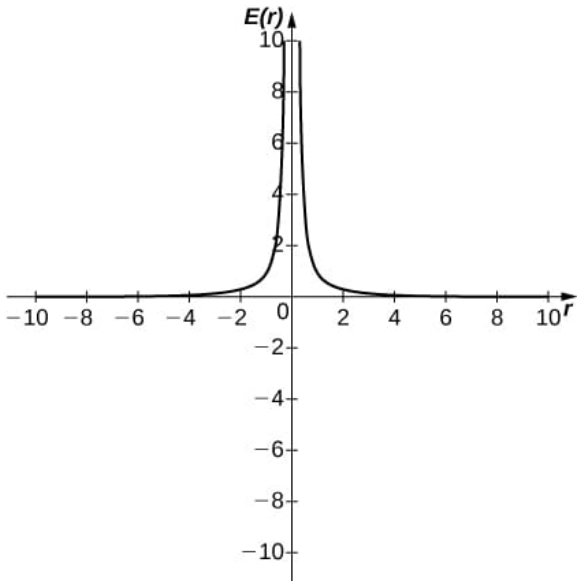
47) [T] In physics, the magnitude of an electric field generated by a point charge at a distance r in vacuum is governed by Coulomb's law: $E(r) = \frac{q}{4\pi\varepsilon_0 r^2}$, where E represents the magnitude of the electric field, q is the charge of the particle, r is the distance between the particle and where the strength of the field is measured, and $\frac{1}{4\pi\varepsilon_0}$ is Coulomb's constant: $8.988 \times 109N \cdot m^2/C^2$.

a. Use a graphing calculator to graph $E(r)$ given that the charge of the particle is $q = 10^{-10}$.

b. Evaluate $\lim_{r \to 0^+} E(r)$. What is the physical meaning of this quantity? Is it physically relevant? Why are you evaluating from the right?

Answer

a.



b. ∞. The magnitude of the electric field as you approach the particle q becomes infinite. It does not make physical sense to evaluate negative distance.

48) [T] The density of an object is given by its mass divided by its volume: $\rho = m/V$.

a. Use a calculator to plot the volume as a function of density $(V = m/\rho)$, assuming you are examining something of mass 8 kg $(m = 8)$.

b. Evaluate $\lim_{x \to 0^+} V(\rho)$ and explain the physical meaning.

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2.3: INFINITE LIMITS

Infinite Limits

Evaluating the limit of a function at a point or evaluating the limit of a function from the right and left at a point helps us to characterize the behavior of a function around a given value. As we shall see, we can also describe the behavior of functions that do not have finite limits.

We now turn our attention to $h(x) = 1/(x-2)^2$, the third and final function introduced at the beginning of this section (see Figure $2.3.1$(c)). From its graph we see that as the values of x approach 2, the values of $h(x) = 1/(x-2)^2$ become larger and larger and, in fact, become infinite. Mathematically, we say that the limit of $h(x)$ as x approaches 2 is positive infinity. Symbolically, we express this idea as

$$\lim_{x \to 2} h(x) = +\infty.$$

More generally, we define *infinite limits* as follows:

Definitions: Infinite Limits

We define three types of *infinite limits*.

Infinite limits from the left: Let $f(x)$ be a function defined at all values in an open interval of the form (b, a).

i. If the values of $f(x)$ increase without bound as the values of x (where $x < a$) approach the number a, then we say that the limit as x approaches a from the left is positive infinity and we write

$$\lim_{x \to a^-} f(x) = +\infty. \tag{2.3.1}$$

ii. If the values of $f(x)$ decrease without bound as the values of x (where $x < a$) approach the number a, then we say that the limit as x approaches a from the left is negative infinity and we write

$$\lim_{x \to a^-} f(x) = -\infty. \tag{2.3.2}$$

Infinite limits from the right: Let $f(x)$ be a function defined at all values in an open interval of the form (a, c).

i. If the values of $f(x)$ increase without bound as the values of x (where $x > a$) approach the number a, then we say that the limit as x approaches a from the left is positive infinity and we write

$$\lim_{x \to a^+} f(x) = +\infty. \tag{2.3.3}$$

ii. If the values of $f(x)$ decrease without bound as the values of x (where $x > a$) approach the number a, then we say that the limit as x approaches a from the left is negative infinity and we write

$$\lim_{x \to a^+} f(x) = -\infty. \tag{2.3.4}$$

Two-sided infinite limit: Let $f(x)$ be defined for all $x \neq a$ in an open interval containing a

i. If the values of $f(x)$ increase without bound as the values of x (where $x \neq a$) approach the number a, then we say that the limit as x approaches a is positive infinity and we write

$$\lim_{x \to a} f(x) = +\infty. \tag{2.3.5}$$

ii. If the values of $f(x)$ decrease without bound as the values of x (where $x \neq a$) approach the number a, then we say that the limit as x approaches a is negative infinity and we write

$$\lim_{x \to a} f(x) = -\infty. \tag{2.3.6}$$

It is important to understand that when we write statements such as $\lim_{x\to a} f(x) = +\infty$ or $\lim_{x\to a} f(x) = -\infty$ we are describing the behavior of the function, as we have just defined it. We are not asserting that a limit exists. For the limit of a function $f(x)$ to exist at a, it must approach a real number L as x approaches a. That said, if, for example, $\lim_{x\to a} f(x) = +\infty$, we always write $\lim_{x\to a} f(x) = +\infty$ rather than $\lim_{x\to a} f(x)$ DNE.

Example 2.3.5: Recognizing an Infinite Limit

Evaluate each of the following limits, if possible. Use a table of functional values and graph $f(x) = 1/x$ to confirm your conclusion.

a. $\lim_{x\to 0^-} \frac{1}{x}$
b. $\lim_{x\to 0^+} \frac{1}{x}$
c. $\lim_{x\to 0} \frac{1}{x}$

Solution

Begin by constructing a table of functional values.

Table 2.3.7

x	$\frac{1}{x}$	x	$\frac{1}{x}$
-0.1	-10	0.1	10
-0.01	-100	0.01	100
-0.001	-1000	0.001	1000
-0.0001	-10,000	0.0001	10,000
-0.00001	-100,000	0.00001	100,000
-0.000001	-1,000,000	0.000001	1,000,000

a. The values of $1/x$ decrease without bound as x approaches 0 from the left. We conclude that

$$\lim_{x\to 0^-} \frac{1}{x} = -\infty.$$

b. The values of $1/x$ increase without bound as x approaches 0 from the right. We conclude that

$$\lim_{x\to 0^+} \frac{1}{x} = +\infty.$$

c. Since $\lim_{x\to 0^-} \frac{1}{x} = -\infty$ and $\lim_{x\to 0^+} \frac{1}{x} = +\infty$ have different values, we conclude that

$$\lim_{x\to 0} \frac{1}{x} \quad \text{DNE.}$$

The graph of $f(x) = 1/x$ in Figure 2.3.8 confirms these conclusions.

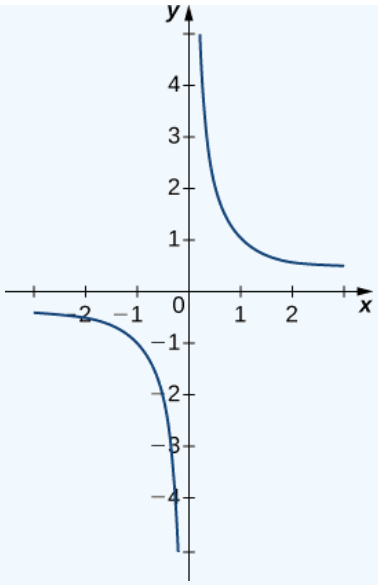


Figure 2.3.8: The graph of $f(x) = 1/x$ confirms that the limit as x approaches 0 does not exist.

Exercise 2.3.5

Evaluate each of the following limits, if possible. Use a table of functional values and graph $f(x) = 1/x^2$ to confirm your conclusion.

a. $\lim_{x \to 0^-} \frac{1}{x^2}$
b. $\lim_{x \to 0^+} \frac{1}{x^2}$
c. $\lim_{x \to 0} \frac{1}{x^2}$

Hint available at the end of this section.

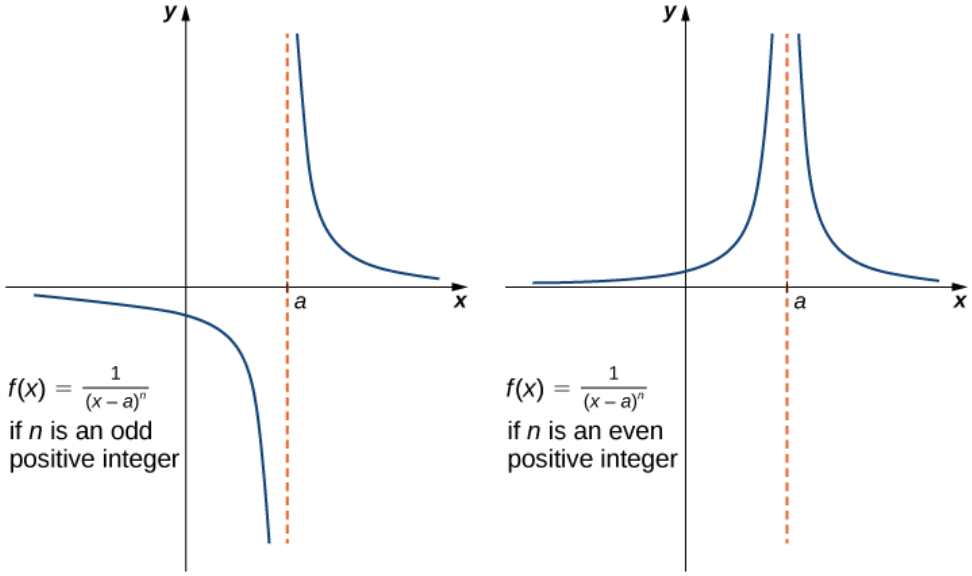


Figure 2.3.9: The function $f(x) = 1/(x-a)^n$ has infinite limits at a.

Infinite Limits from Positive Integers

If n is a positive even integer, then

$$\lim_{x\to a}\frac{1}{(x-a)^n}=+\infty. \tag{2.3.7}$$

If n is a positive odd integer, then

$$\lim_{x\to a^+}\frac{1}{(x-a)^n}=+\infty \tag{2.3.8}$$

and

$$\lim_{x\to a^-}\frac{1}{(x-a)^n}=-\infty. \tag{2.3.9}$$

We should also point out that in the graphs of $f(x)=1/(x-a)^n$, points on the graph having x-coordinates very near to a are very close to the vertical line $x=a$. That is, as x approaches a, the points on the graph of $f(x)$ are closer to the line $x=a$. The line $x=a$ is called a vertical asymptote of the graph. We formally define a *vertical asymptote* as follows:

Definition: Vertical Asymptotes

Let $f(x)$ be a function. If any of the following conditions hold, then the line $x=a$ is a vertical asymptote of $f(x)$.

$$\lim_{x\to a^-}f(x)=+\infty \tag{2.3.10}$$

$$\lim_{x\to a^-}f(x)=-\infty \tag{2.3.11}$$

$$\lim_{x\to a^+}f(x)=+\infty \tag{2.3.12}$$

$$\lim_{x\to a^+}f(x)=-\infty \tag{2.3.13}$$

$$\lim_{x\to a}f(x)=+\infty \tag{2.3.14}$$

$$\lim_{x\to a}f(x)=-\infty \tag{2.3.15}$$

Example 2.3.6: Finding a Vertical Asymptote

Evaluate each of the following limits using Equations 2.3.7, 2.3.8, and 2.3.9 above. Identify any vertical asymptotes of the function $f(x)=1/(x+3)^4$.

a. $\lim_{x\to -3^-}\frac{1}{(x+3)^4}$
b. $\lim_{x\to -3^+}\frac{1}{(x+3)^4}$
c. $\lim_{x\to -3}\frac{1}{(x+3)^4}$

Solution

We can use the above equations directly.

a. $\lim_{x\to -3^-}\frac{1}{(x+3)^4}=+\infty$
b. $\lim_{x\to -3^+}\frac{1}{(x+3)^4}=+\infty$

c. $\lim_{x\to -3} \dfrac{1}{(x+3)^4} = +\infty$

The function $f(x) = 1/(x+3)^4$ has a vertical asymptote of $x = -3$.

Exercise 2.3.6

Evaluate each of the following limits. Identify any vertical asymptotes of the function $f(x) = \dfrac{1}{(x-2)^3}$.

a. $\lim_{x\to 2^-} \dfrac{1}{(x-2)^3}$
b. $\lim_{x\to 2^+} \dfrac{1}{(x-2)^3}$
c. $\lim_{x\to 2} \dfrac{1}{(x-2)^3}$

Answer a available at the end of this section.

In the next example we put our knowledge of various types of limits to use to analyze the behavior of a function at several different points.

Example 2.3.7: Behavior of a Function at Different Points

Use the graph of $f(x)$ in Figure 2.3.10 to determine each of the following values:

a. $\lim_{x\to -4^-} f(x)$; $\lim_{x\to -4^+} f(x)$; $\lim_{x\to -4} f(x)$; $f(-4)$
b. $\lim_{x\to -2^-} f(x)$; $\lim_{x\to -2^+} f(x)$; $\lim_{x\to -2} f(x)$; $f(-2)$
c. $\lim_{x\to 1^-} f(x)$; $\lim_{x\to 1^+} f(x)$; $\lim_{x\to 1} f(x)$; $f(1)$
d. $\lim_{x\to 3^-} f(x)$; $\lim_{x\to 3^+} f(x)$; $\lim_{x\to 3} f(x)$; $f(3)$

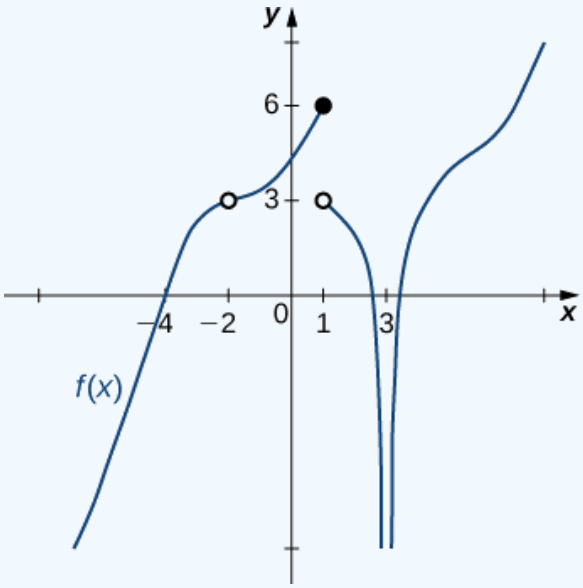


Figure 2.3.10: The graph shows $f(x)$.

Solution

Using the definitions above and the graph for reference, we arrive at the following values:

a. $\lim_{x\to -4^-} f(x) = 0$; $\lim_{x\to -4^+} f(x) = 0$; $\lim_{x\to -4} f(x) = 0$; $f(-4) = 0$
b. $\lim_{x\to -2^-} f(x) = 3$; $\lim_{x\to -2^+} f(x) = 3$; $\lim_{x\to -2} f(x) = 3$; $f(-2)$ is undefined
c. $\lim_{x\to 1^-} f(x) = 6$; $\lim_{x\to 1^+} f(x) = 3$; $\lim_{x\to 1} f(x)$ DNE; $f(1) = 6$
d. $\lim_{x\to 3^-} f(x) = -\infty$; $\lim_{x\to 3^+} f(x) = -\infty$; $\lim_{x\to 3} f(x) = -\infty$; $f(3)$ is undefined

Exercise 2.3.7

Evaluate $\lim_{x\to 1} f(x)$ for $f(x)$ shown here:

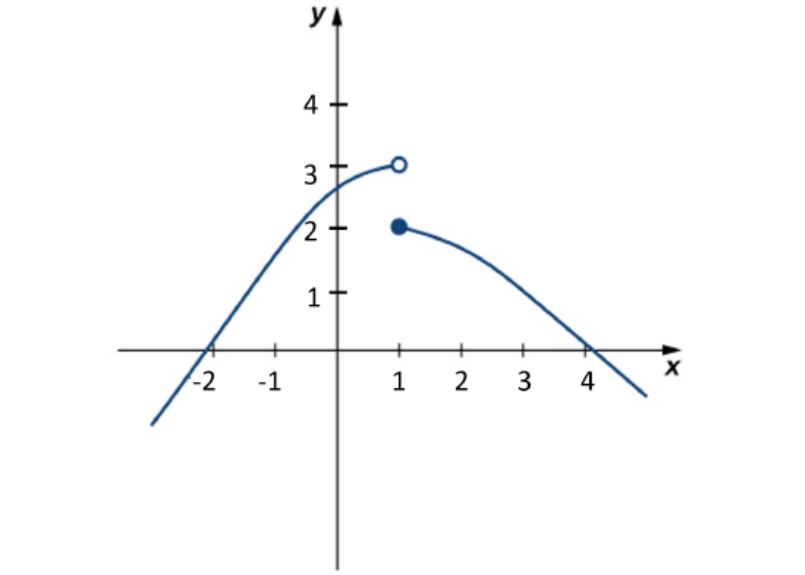


Figure 2.3.11. The graph of a piecewise function f.

Hint available at the end of this section.

Example 2.3.8: Einstein's Equation

In the Chapter opener we mentioned briefly how Albert Einstein showed that a limit exists to how fast any object can travel. Given Einstein's equation for the mass of a moving object

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}},$$

what is the value of this bound?

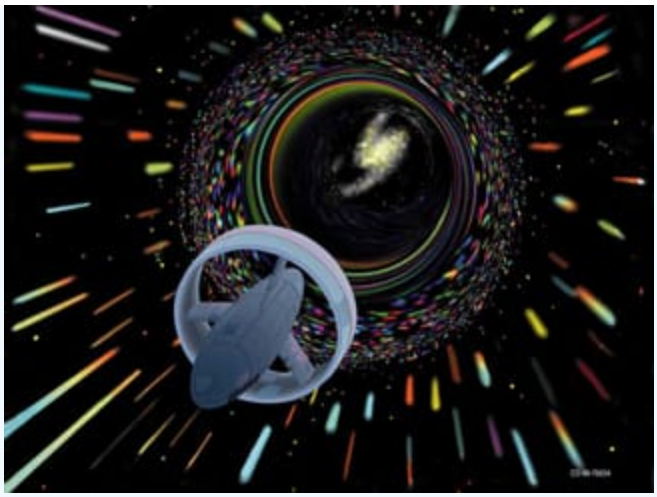


Figure 2.3.12. (Crefit:NASA)

Solution

Our starting point is Einstein's equation for the mass of a moving object,

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}},$$

where m_0 is the object's mass at rest, v is its speed, and c is the speed of light. To see how the mass changes at high speeds, we can graph the ratio of masses m/m_0 as a function of the ratio of speeds, v/c (Figure 2.3.13).

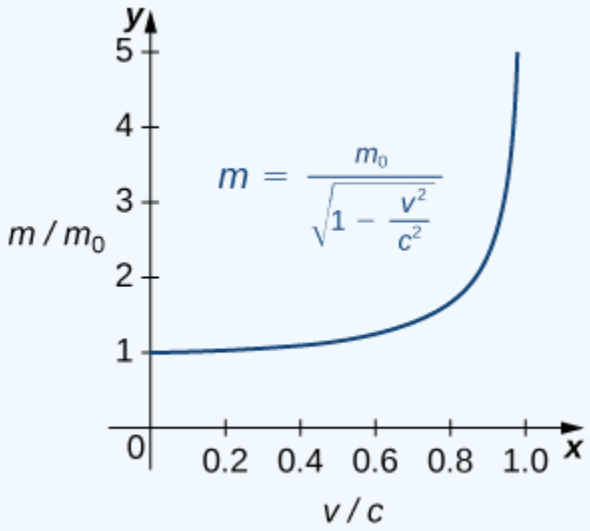


Figure 2.3.13: This graph shows the ratio of masses as a function of the ratio of speeds in Einstein's equation for the mass of a moving object.

We can see that as the ratio of speeds approaches 1—that is, as the speed of the object approaches the speed of light—the ratio of masses increases without bound. In other words, the function has a vertical asymptote at $v/c = 1$. We can try a few values of this ratio to test this idea.

Table 2.3.8

v/c	$\sqrt{1 - \frac{v^2}{c^2}}$	m/m_o
0.99	0.1411	7.089

v/c	$\sqrt{1-\frac{v^2}{c^2}}$	m/m_o
0.999	0.0447	22.37
0.9999	0.0141	70.7

Thus, according to Table 2.3.8:, if an object with mass 100 kg is traveling at 0.9999c, its mass becomes 7071 kg. Since no object can have an infinite mass, we conclude that no object can travel at or more than the speed of light.

We now turn our attention to evaluating a limit of the form $\lim\limits_{x\to a}\dfrac{f(x)}{g(x)}$, where $\lim\limits_{x\to a}f(x)=K$, where $K\neq 0$ and $\lim\limits_{x\to a}g(x)=0$. That is, $f(x)/g(x)$ has the form $K/0, K\neq 0$ at a.

Example 2.3.9: Evaluating a Limit of the Form $K/0,\ K\neq 0$ Using the Limit Laws

Evaluate $\lim\limits_{x\to 2^-}\dfrac{x-3}{x^2-2x}$.

Solution

Step 1. After substituting in $x=2$, we see that this limit has the form $-1/0$. That is, as x approaches 2 from the left, the numerator approaches -1; and the denominator approaches 0. Consequently, the magnitude of $\dfrac{x-3}{x(x-2)}$ becomes infinite. To get a better idea of what the limit is, we need to factor the denominator:

$$\lim_{x\to 2^-}\frac{x-3}{x^2-2x}=\lim_{x\to 2^-}\frac{x-3}{x(x-2)}$$

Step 2. Since $x-2$ is the only part of the denominator that is zero when 2 is substituted, we then separate $1/(x-2)$ from the rest of the function:

$$=\lim_{x\to 2^-}\frac{x-3}{x}\cdot\frac{1}{x-2}$$

Step 3. Using the Limit Laws, we can write:

$$=\left(\lim_{x\to 2^-}\frac{x-3}{x}\right)\cdot\left(\lim_{x\to 2^-}\frac{1}{x-2}\right).$$

Step 4. $\lim\limits_{x\to 2^-}\dfrac{x-3}{x}=-\dfrac{1}{2}$ and $\lim\limits_{x\to 2^-}\dfrac{1}{x-2}=-\infty$. Therefore, the product of $(x-3)/x$ and $1/(x-2)$ has a limit of $+\infty$:

$$\lim_{x\to 2^-}\frac{x-3}{x^2-2x}=+\infty.$$

Exercise 2.3.9

Evaluate $\lim\limits_{x\to 1}\dfrac{x+2}{(x-1)^2}$.

Solution available at the end of this section.

Answer available at the end of this section.

Answers

Exercise 2.3.5

Follow the procedures from Example 2.3.4.

a. $\lim_{x \to 0^-} \frac{1}{x^2} = +\infty$;

b. $\lim_{x \to 0^+} \frac{1}{x^2} = +\infty$;

c. $\lim_{x \to 0} \frac{1}{x^2} = +\infty$

It is useful to point out that functions of the form $f(x) = 1/(x-a)^n$, where n is a positive integer, have infinite limits as x approaches a from either the left or right (Figure 2.3.9). These limits are summarized in the above definitions.

Exercise 2.3.6

$\lim_{x \to 2^-} \frac{1}{(x-2)^3} = -\infty$

$\lim_{x \to 2^+} \frac{1}{(x-2)^3} = +\infty$

$\lim_{x \to 2} \frac{1}{(x-2)^3}$ DNE. The line $x = 2$ is the vertical asymptote of $f(x) = 1/(x-2)^3$.

Exercise 2.3.7

Compare the limit from the right with the limit from the left.

$\lim_{x \to 1} f(x)$ does not exist

Exercise 2.3.9

Use the methods from Example 2.3.9.

Exercise 2.3.9

$+\infty$

2.3E: Exercises for Section 2.4

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2.3E: Exercises for Section 2.4

Infinite Limits

[T] In exercises 1 - 3, set up a table of values to find the indicated limit. Round to eight significant digits.

1) $\lim_{x\to 2} \dfrac{x^2-4}{x^2+x-6}$

x	$\frac{x^2-4}{x^2+x-6}$	x	$\frac{x^2-4}{x^2+x-6}$
1.9	a.	2.1	e.
1.99	b.	2.01	f.
1.999	c.	2.001	g.
1.9999	d.	2.0001	h.

2) $\lim_{z\to 0} \dfrac{z-1}{z^2(z+3)}$

z	$\frac{z-1}{z^2(z+3)}$	z	$\frac{z-1}{z^2(z+3)}$
-0.1	a.	0.1	e.
-0.01	b.	0.01	f.
-0.001	c.	0.001	g.
-0.0001	d.	0.0001	h.

Answer

a. −37.931034; b. −3377.9264; c. −333,777.93; d. −33,337,778; e. −29.032258; f. −3289.0365; g. −332,889.04; h. −33,328,889

$\lim_{x\to 0} \dfrac{z-1}{z^2(z+3)} = -\infty$

3) $\lim_{t\to 0^+} \dfrac{\cos t}{t}$

t	$\frac{\cos t}{t}$
0.1	a.
0.01	b.
0.001	c.
0.0001	d.

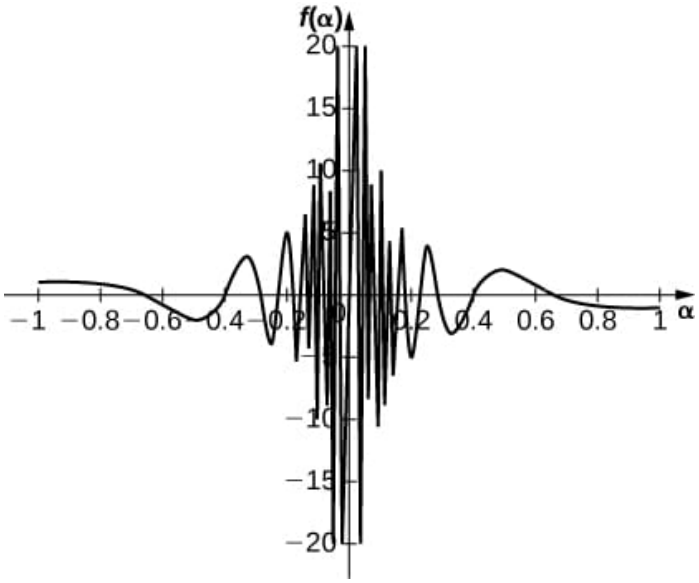
[T] In exercise 4, set up a table of values and round to eight significant digits. Based on the table of values, make a guess about what the limit is. Then, use a calculator to graph the function and determine the limit. Was the conjecture correct? If not, why does the method of tables fail?

4) $\lim_{\alpha\to 0^+} \dfrac{1}{\alpha}\cos\left(\dfrac{\pi}{\alpha}\right)$

a	$\frac{1}{\alpha}\cos\left(\frac{\pi}{\alpha}\right)$
0.1	a.
0.01	b.
0.001	c.
0.0001	d.

Answer

a. 10.00000; b. 100.00000; c. 1000.0000; d. 10,000.000;
Guess: $\lim_{\alpha\to 0^+}\frac{1}{\alpha}\cos\left(\frac{\pi}{\alpha}\right)=\infty$;
Actual: DNE , since the graph shows the function oscillates wildly between values approaching positive infinity and values approaching negative infinity, as the value of α approaches 0 from the positive side.



In exercises 5 - 8, use direct substitution to obtain an undefined expression. Then, simplify the function and determine the limit.

5) $\lim_{x\to -2^-}\dfrac{2x^2+7x-4}{x^2+x-2}$

Answer

$-\infty$

6) $\lim_{x\to -2^+}\dfrac{2x^2+7x-4}{x^2+x-2}$

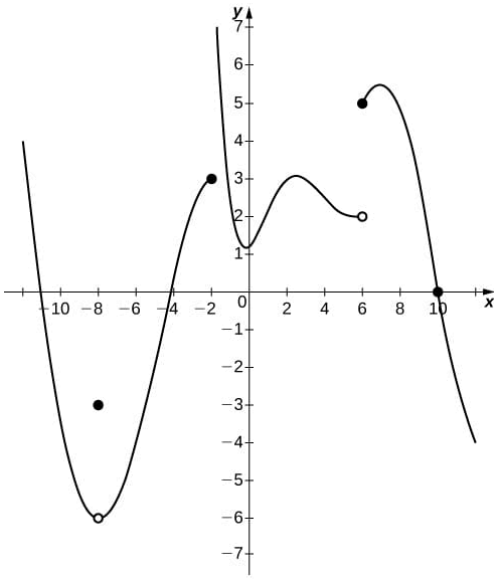
7) $\lim_{x\to 1^-}\dfrac{2x^2+7x-4}{x^2+x-2}$

Answer

$-\infty$

8) $\lim_{x\to 1^+}\dfrac{2x^2+7x-4}{x^2+x-2}$

In exercises 9 - 12, consider the graph of the function$y=f(x)$ shown here. Which of the statements about $y=f(x)$ are true and which are false? Explain why a statement is false.



9) $\lim_{x\to 10} f(x) = 0$

10) $\lim_{x\to -2^+} f(x) = 3$

Answer

False; $\lim_{x\to -2^+} f(x) = +\infty$

11) $\lim_{x\to -8} f(x) = f(-8)$

12) $\lim_{x\to 6} f(x) = 5$

Answer

False; $\lim_{x\to 6} f(x)$ DNE since $\lim_{x\to 6^-} f(x) = 2$ and $\lim_{x\to 6^+} f(x) = 5$.

Infinite Limits

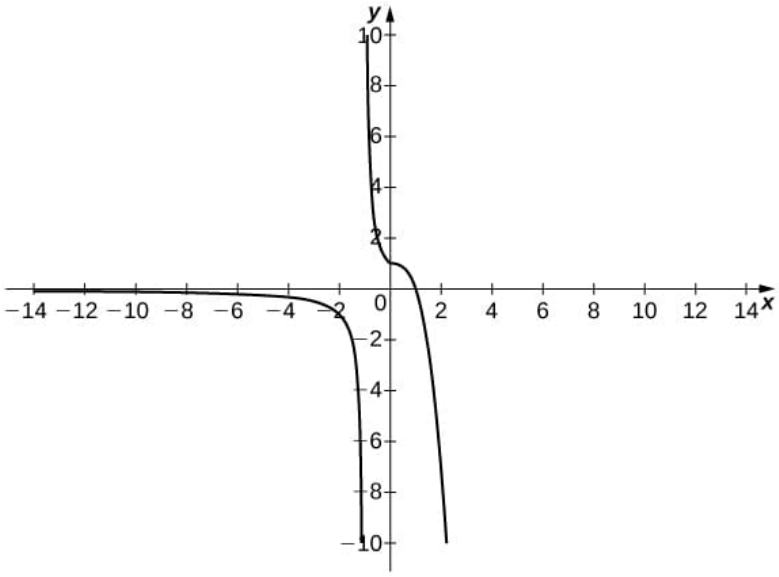
In exercises 13 - 17, sketch the graph of a function with the given properties.

13) $\lim_{x\to 2} f(x) = 1, \quad \lim_{x\to 4^-} f(x) = 3, \quad \lim_{x\to 4^+} f(x) = 6, \quad x = 4$ is not defined.

14) $\lim_{x\to -\infty} f(x) = 0, \quad \lim_{x\to -1^-} f(x) = -\infty, \quad \lim_{x\to -1^+} f(x) = \infty, \quad \lim_{x\to 0} f(x) = f(0), \quad f(0) = 1, \quad \lim_{x\to \infty} f(x) = -\infty$

Answer

Answers may vary

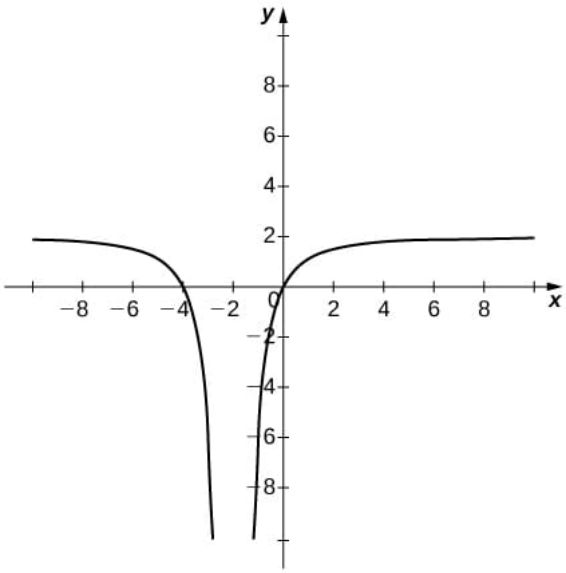


15) $\lim_{x\to-\infty} f(x) = 2, \quad \lim_{x\to3^-} f(x) = -\infty, \quad \lim_{x\to3^+} f(x) = \infty, \quad \lim_{x\to\infty} f(x) = 2, \quad f(0) = -\frac{1}{3}$

16) $\lim_{x\to-\infty} f(x) = 2, \quad \lim_{x\to-2} f(x) = -\infty, \quad \lim_{x\to\infty} f(x) = 2, \quad f(0) = 0$

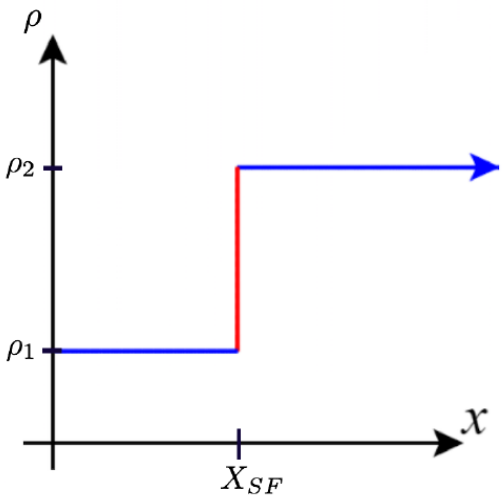
Answer

Answer may vary



17) $\lim_{x\to-\infty} f(x) = 0, \quad \lim_{x\to-1^-} f(x) = \infty, \quad \lim_{x\to-1^+} f(x) = -\infty, \quad f(0) = -1, \quad \lim_{x\to1^-} f(x) = -\infty, \quad \lim_{x\to1^+} f(x) = \infty, \quad \lim_{x\to\infty} f(x) = 0$

18) Shock waves arise in many physical applications, ranging from supernovas to detonation waves. A graph of the density of a shock wave with respect to distance, x, is shown here. We are mainly interested in the location of the front of the shock, labeled X_{SF} in the diagram.



a. Evaluate $\lim_{x \to X_{SF}^{+}} \rho(x)$.

b. Evaluate $\lim_{x \to X_{SF}^{-}} \rho(x)$.

c. Evaluate $\lim_{x \to X_{SF}} \rho(x)$. Explain the physical meanings behind your answers.

Answer

a. ρ_2 b. ρ_1 c. DNE unless $\rho_1 = \rho_2$. As you approach X_{SF} from the right, you are in the high-density area of the shock. When you approach from the left, you have not experienced the "shock" yet and are at a lower density.

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2.4: Continuity

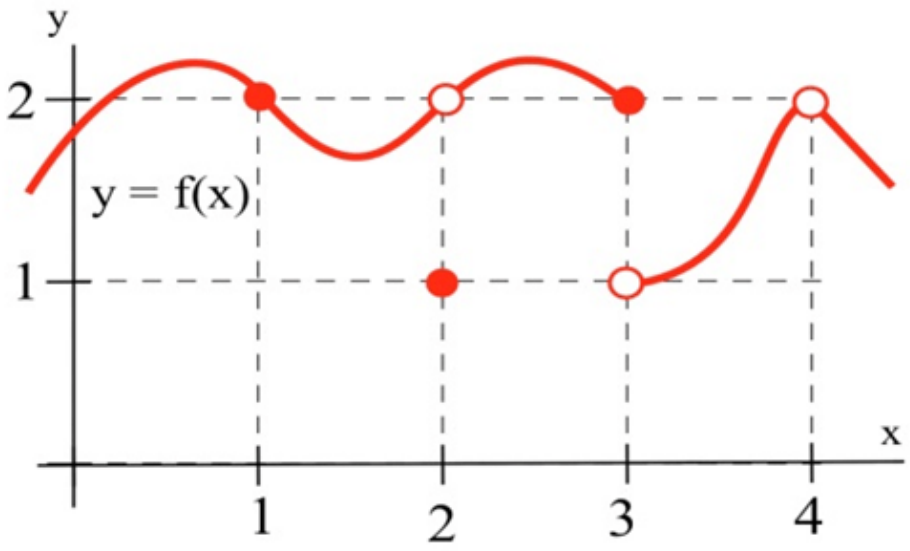
Continuity

A function that is "friendly" and doesn't have any breaks or jumps in it is called **continuous.** More formally,

Continuity at a Point

A function f **is continuous at** $\mathrm{x = a}$ if and only if $\lim\limits_{x \to a} \mathrm{f(x) = f(a)}$.

The graph below illustrates some of the different ways a function can behave at and near a point, and the table contains some numerical information about the function and its behavior.



a	$f(a)$	$\lim\limits_{x \to a} f(x)$
1	2	2
2	1	2
3	2	Does not exist (DNE)
4	Undefined	2

Based on the information in the table, we can conclude that f is continuous at 1 since $\lim\limits_{x \to 1} f(x) = 2 = f(1)$.

We can also conclude from the information in the table that f is not continuous at 2 or 3 or 4, because $\lim\limits_{x \to 2} f(x) \neq f(2)$, $\lim\limits_{x \to 3} f(x) \neq f(3)$, and $\lim\limits_{x \to 4} f(x) \neq f(4)$.

The behaviors at $x = 2$ and $x = 4$ exhibit a **hole** in the graph, sometimes called a **removable discontinuity**, since the graph could be made continuous by changing the value of a single point. The behavior at $x = 3$ is called a **jump discontinuity**, since the graph jumps between two values.

So which functions are continuous? It turns out pretty much every function you've studied is continuous where it is defined:

polynomial, radical, rational, exponential, and logarithmic functions are all continuous where they are defined. Moreover, **any combination of continuous functions is also continuous**.

This is helpful, because the definition of continuity says that for a continuous function, $\lim_{x\to a} f(x) = f(a)$. That means for a continuous function, we can find the limit by **direct substitution** (evaluating the function) if the function is continuous at a.

Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this Video online

Example 2.4.5

Evaluate using continuity, if possible:

1. $\lim_{x\to 2} x^3 - 4x$
2. $\lim_{x\to 2} \dfrac{x-4}{x+3}$
3. $\lim_{x\to 2} \dfrac{x-4}{x-2}$

Solution

1. The given function is polynomial, and is defined for all values of x, so we can find the limit by direct substitution:
$$\lim_{x\to 2} x^3 - 4x = 2^3 - 4(2) = 0.$$
2. The given function is rational. It is not defined at $x = -3$, but we are taking the limit as x approaches 2, and the function is defined at that point, so we can use direct substitution:
$$\lim_{x\to 2} \frac{x-4}{x+3} = \frac{2-4}{2+3} = -\frac{2}{5}.$$
3. This function is not defined at $x = 2$, and so is not continuous at $x = 2$. We cannot use direct substitution.

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3: THE DERIVATIVE

3.1: Introducing the Derivative
3.2: Techniques of Differentiation
3.3: Product and Quotient Rules
3.4: Chain Rule
3.5: Rates of Change and Marginal Analysis
3.5E: Exercises for Section 3.5
3.6: Implicit Differentiation and Related Rates

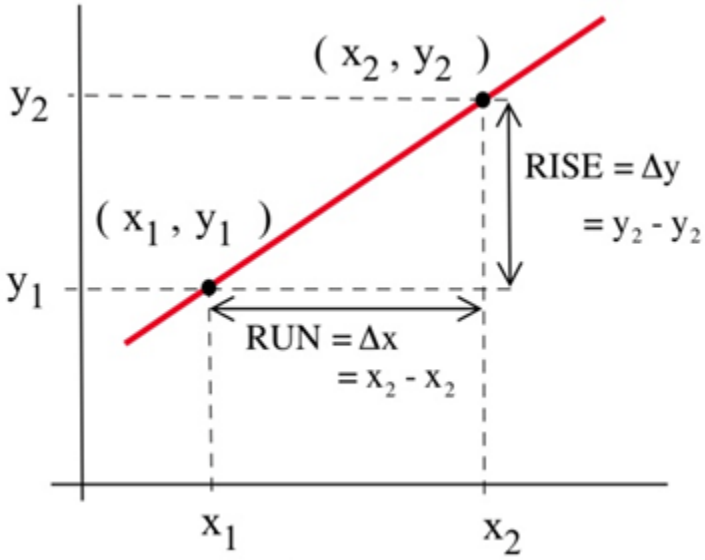
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3.1: Introducing the Derivative

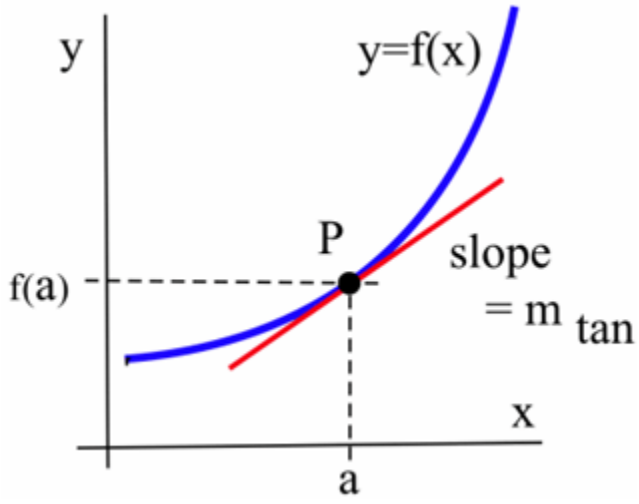
Precalculus Idea: Slope and Rate of Change

The slope of a line measures how fast a line rises or falls as we move from left to right along the line. It measures the rate of change of the y-coordinate with respect to changes in the x-coordinate. If the line represents the distance traveled over time, for example, then its slope represents the velocity. In the figure, you can remind yourself of how we calculate slope using two points on the line:



$$m = \text{Slope from } P \text{ to } Q = \frac{\text{rise}}{\text{run}} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{\Delta y}{\Delta x}$$

We would like to be able to get that same sort of information (how fast the curve rises or falls, velocity from distance) even if the graph is not a straight line. But what happens if we try to find the slope of a curve, as in the figure below?

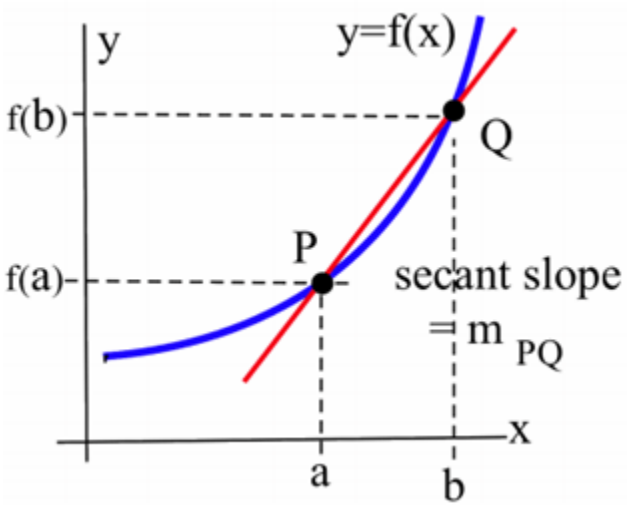


We need two points in order to determine the slope of a line. How can we find a slope of a curve, at just one point? The answer, as suggested in the figure, is to find the slope of the tangent line to the curve at that point. Most of us have an intuitive idea of what a tangent line is. Unfortunately, “tangent line” is hard to define precisely.

Definition: Secant Line

A **secant line** is a line between two points on a curve.

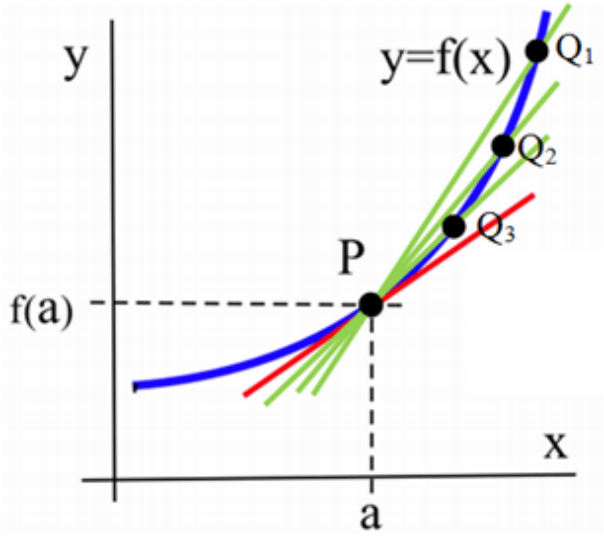
See the image below:



Can't-quite-do-it-yet Definition: Tangent Line

A **tangent line** is a line at one point on a curve... that does its best to be the curve at that point?

As you may be able to see in the image below, the closer the point Q is to the point P, the closer the secant slope gets to the tangent slope. This will be key to finding the tangent slope, but first we need to more carefully define the idea of "getting closer to."



Definition of the Derivative

When working with linear functions, we could find the slope of a line to determine the rate at which the function is changing. For an arbitrary function, we can determine the **average rate of change** of the function. This is the slope of the secant line through those two points on the graph.

Average Rate of Change

Average Rate of Change = $\dfrac{\Delta\text{output}}{\Delta\text{input}} = \dfrac{f(b)-f(a)}{b-a}$

= **the slope of the secant line through the two points** $(a, f(a))$ **and** $(b, f(b))$

Example 3.1.1

Suppose the total cost of producing x items is given by $TC(x) = 200 + 30x - 0.1x^2$. Determine the average rate of change of cost when increasing production from 25 units to 100 units.

Solution

The cost when producing 25 units is $TC(25) = 200 + 30(25) - 0.1(25)^2 = \$887.50$

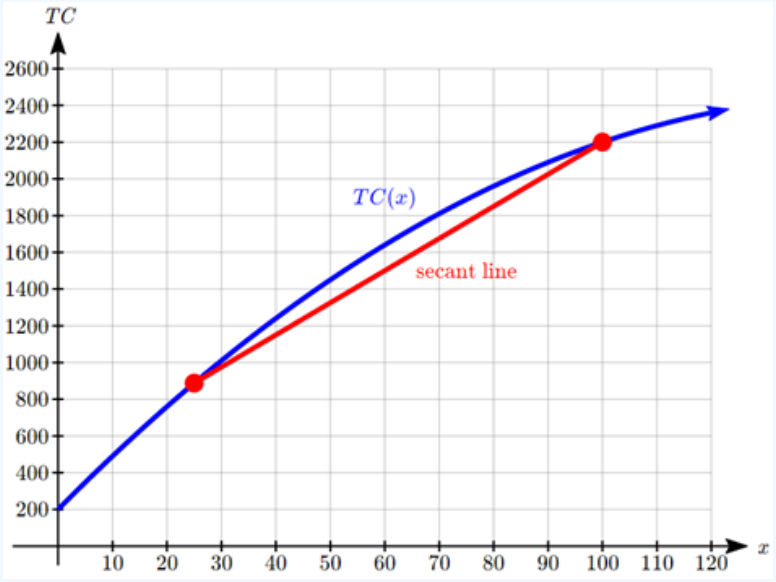
The cost when producing 100 units is $TC(100) = 200 + 30(100) - 0.1(100)^2 = \$2200$

The cost increased by \$2200-\$887.50 = \$1312.50 while production increased by 100 – 25 = 75 items. The average rate of change is:

$$\frac{TC(100)-TC(25)}{100-25} = \frac{2200-887.50}{100-25} = \frac{1312.50}{75} = 17.50 \text{ dollars per unit}$$

This tells us that on average the cost increases by \$17.50 for each unit produced.

The average rate of change is the slope of the secant line between (25, 887.50) and (100, 2200)



Thinking about the last example, suppose instead we asked the question "How fast are costs increasing when production is 25 units?" Notice this is a different kind of question. The question in the example asked for the rate of change over an interval, as production increased from one value to another. This question is again asking for a rate of change, but an **instantaneous rate of**

change, at a particular moment.

We don't yet have a way to calculated rate of change except over an interval. In the next example we will explore a couple ways to estimate the instantaneous rate of change.

Example 3.1.2

Suppose the total cost of producing x items is given by $TC(x) = 200 + 30x - 0.1x^2$. Estimate the instantaneous rate of change when 25 items are being produced.

Solution

We can see in the previous graph that the secant slope on the interval $25 \le x \le 100$ is not a particularly good estimate of the instantaneous rate of change since the cost function seems steeper at $x = 25$ then over the secant slope. We could improve the estimate by choosing a smaller interval.

Approach 1: Using smaller intervals

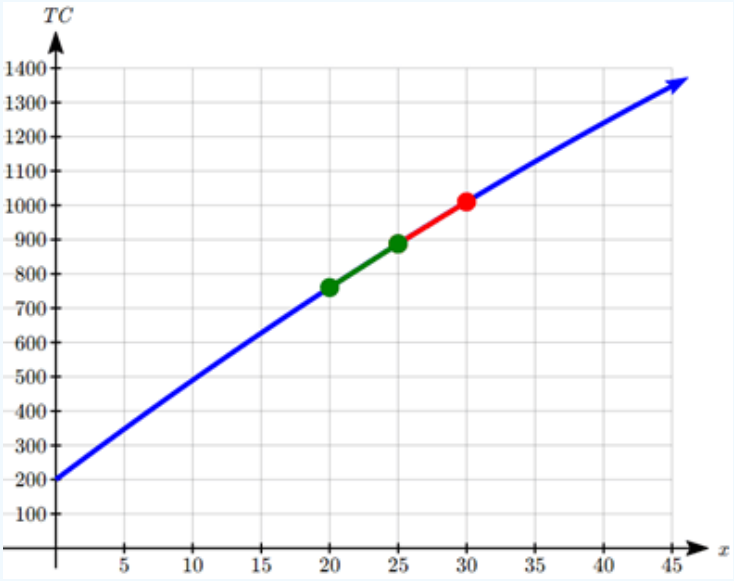
Using the interval $25 \le x \le 30$, the average rate of change would be:

$$\frac{TC(30) - TC(25)}{30 - 25} = \frac{1010 - 887.50}{30 - 25} = \frac{122.50}{5} = 24.50 \text{ dollars per unit}$$

Using an interval on the other side, $20 \le x \le 25$, the average rate of change would be:

$$\frac{TC(25) - TC(20)}{25 - 20} = \frac{887.50 - 760}{25 - 20} = \frac{127.5}{5} = 25.50 \text{ dollars per unit}$$

Visually, we can see both these secant lines seem to approximate the function pretty well.

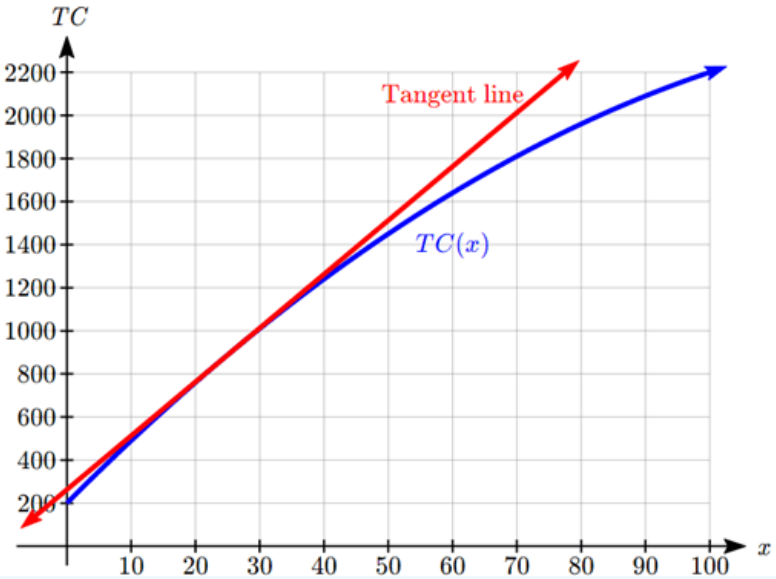


We would expect the instantaneous rate of change to be somewhere between these two values. Averaging them, we get an estimate of $25 per unit for the instantaneous rate of change.

Approach 2: Estimating from the graph.

This approach is more commonly used when we only have the graph of a function, and don't have a formula to evaluate, but we will illustrate it here using the same function.

The instantaneous rate of change is the slope of the tangent line, which is the line that just touches the graph at the point of interest, and has the same rate of change (slope) as the function does at the point. Given a graph, we can sketch in a **tangent line** by holding a ruler up to the graph, and drawing in a line that touches the graph when $x = 25$ and has the same slope.

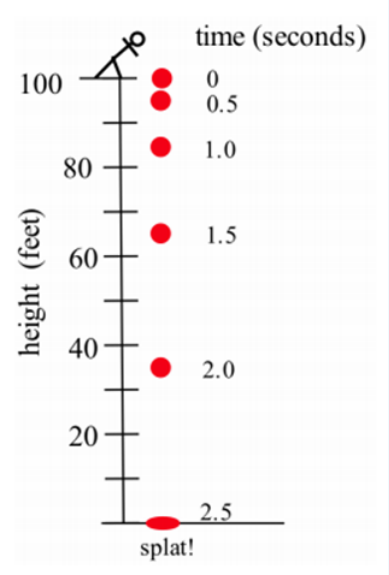


To estimate the instantaneous rate of change, we can now calculate the slope of this drawn-in line. Looking at the graph, the tangent line appears to pass approximately through (30, 1000) and (70, 2000) which would give a slope of $\frac{2000-1000}{70-30} = \frac{1000}{40} = 25$ dollars per unit.

Next we will explore the same ideas using a function defined in a table, and in another context.

Example 3.1.3

Suppose we drop a tomato from the top of a 100 foot building and time its fall.



Time (sec)	Height (ft)
0.0	100
0.5	96
1.0	84
1.5	64
2.0	36
2.5	0

1. How long did it take for the tomato to drop 100 feet?
2. How far did the tomato fall during the first second?
3. How far did the tomato fall during the last second?
4. How far did the tomato fall between $t = 0.5$ and $t = 1$?
5. What was the average velocity of the tomato during its fall?
6. What was the average velocity between $t = 1$ and $t = 2$ seconds?
7. How fast was the tomato falling 1 second after it was dropped?

Solution

Some of these questions are pretty easy to answer, while some are more complex.

1. From the table, it took 2.5 seconds for the tomato to drop 100 feet

2. During the first second, the tomato fell 100 – 84 = 16 feet
3. During the last second, the tomato fell 64 – 0 = 64 feet
4. Between $t = 0.5$ and $t = 1$ the tomato fell 96 – 84 = 12 feet
5. Velocity is similar to speed, and is a rate of change. We can calculate **average velocity** the same way we did average rate of change earlier.

$$\text{Average velocity} = \frac{\text{distance fallen}}{\text{total time}} = \frac{\Delta\text{position}}{\Delta\text{time}} = \frac{-100 \text{ ft}}{2.5 \text{ s}} = -40 \text{ ft/s}$$

6. Between $t = 1$ and $t = 2$ seconds,

$$\text{Average velocity} = \frac{\Delta\text{position}}{\Delta\text{time}} = \frac{36 \text{ ft} - 84 \text{ ft}}{2 \text{ s} - 1 \text{ s}} = \frac{-48 \text{ ft}}{1 \text{ s}} = -48 \text{ ft/s}$$

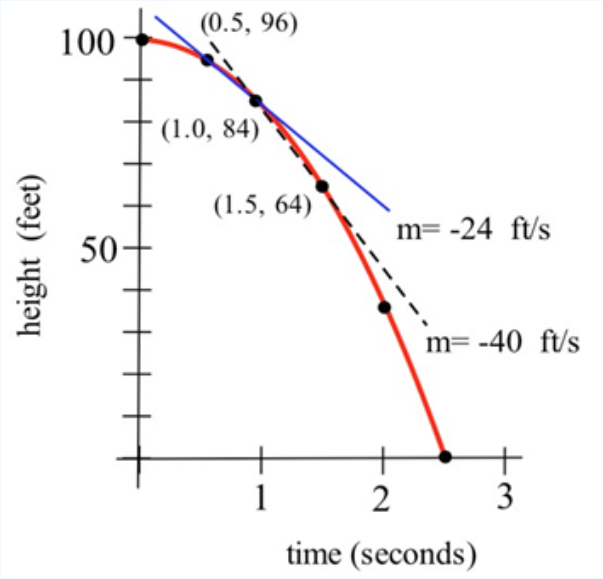
7. This question is significantly different from the previous two questions about average velocity. Here we want the **instantaneous velocity,** the velocity at an instant in time. Unfortunately the tomato is not equipped with a speedometer so we will have to give an approximate answer. Like in our Approach 1 in the previous example, we will estimate it using secant slopes.

One crude approximation of the instantaneous velocity after 1 second is simply the average velocity during the entire fall, -40 ft/s. But the tomato fell slowly at the beginning and rapidly near the end so the "-40 ft/s" estimate may or may not be a good answer.

We can get a better approximation of the instantaneous velocity at $t = 1$ by calculating the average velocities over a short time interval near $t = 1$. The average velocity between $t = 0.5$ and $t = 1$ is $\frac{-12 \text{ feet}}{0.5 \text{ s}} = -24 \text{ ft/s}$, and the average velocity between $t = 1$ and $t = 1.5$ is $\frac{-20 \text{ feet}}{0.5 \text{ s}} = -40 \text{ ft/s}$ so we can be reasonably sure that the instantaneous velocity is between -24 ft/s and -40 ft/s. The average, –32 ft/s, would be a good estimate for the instantaneous velocity.

In general, the shorter the time interval over which we calculate the average velocity, the better the average velocity will approximate the instantaneous velocity.

The average velocity over a time interval is $\frac{\Delta\text{position}}{\Delta\text{time}}$, which is the slope of the **secant line** through two points on the graph of height versus time. The instantaneous velocity at a particular time and height is the slope of the **tangent line** to the graph at the point given by that time and height.



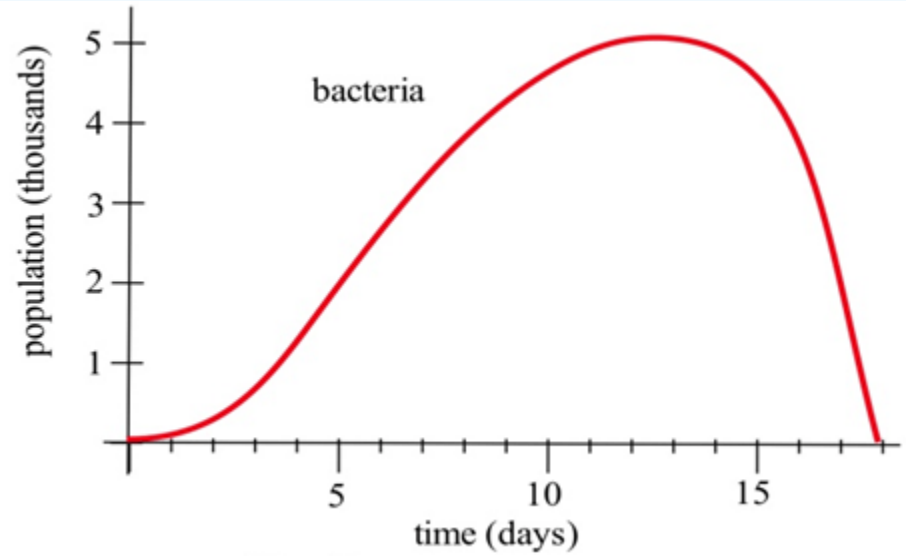
Average vs Instantaneous Velocity

Average velocity = $\frac{\Delta \text{position}}{\Delta \text{time}}$ = slope of the secant line through 2 points.

Instantaneous velocity = slope of the line tangent to the graph.

Example 3.1.4

Suppose we set up a machine to count the number of bacteria growing on a Petri plate. At first there are few bacteria so the population grows slowly. Then there are more bacteria to divide so the population grows more quickly. Later, there are more bacteria and less room and nutrients available for the expanding population, so the population grows slowly again. Finally, the bacteria have used up most of the nutrients, and the population declines as bacteria die.



Use the population graph to estimate the answer to the questions below.

1. What is the bacteria population at time $t = 3$ days?
2. What is the population increment from $t = 3$ to $t = 10$ days?
3. What is the **rate** of population growth from $t = 3$ to $t = 10$ days?
4. What is the **rate** of population growth on the third day, at $t = 3$?

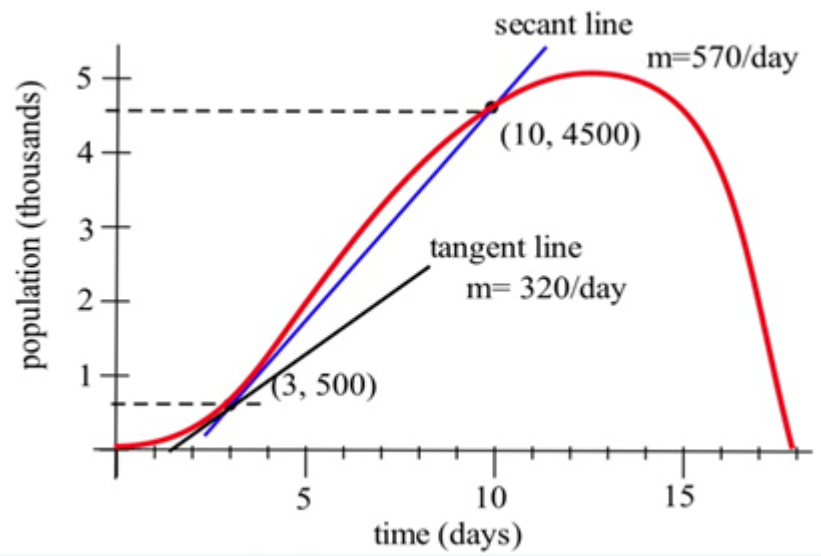
Solution

1. From the graph, at $t = 3$, the population is about 0.5 thousand, or 500 bacteria.
2. At $t = 10$, the population is about 4.5 thousand, so the increment is about 4000 bacteria.
3. The rate of growth from $t = 3$ to $t = 10$ is the average rate of change in population during that time:

$$\begin{aligned} \text{average change in population} &= \frac{\text{change in population}}{\text{change in time}} \\ &= \frac{\Delta \text{population}}{\Delta \text{time}} \\ &= \frac{4000 \text{ bacteria}}{7 \text{ days}} \\ &\approx 570 \text{ bacteria/day}. \end{aligned}$$

This is the slope of the secant line through the two points (3, 500) and (10, 4500).

4. This question is asking for the **instantaneous** rate of population change, the slope of the line which is **tangent** to the population curve at (3, 500). If we sketch a line approximately tangent to the curve at (3, 500) and pick two points near the ends of the tangent line segment, we can estimate that instantaneous rate of population growth is approximately 320 bacteria/day.



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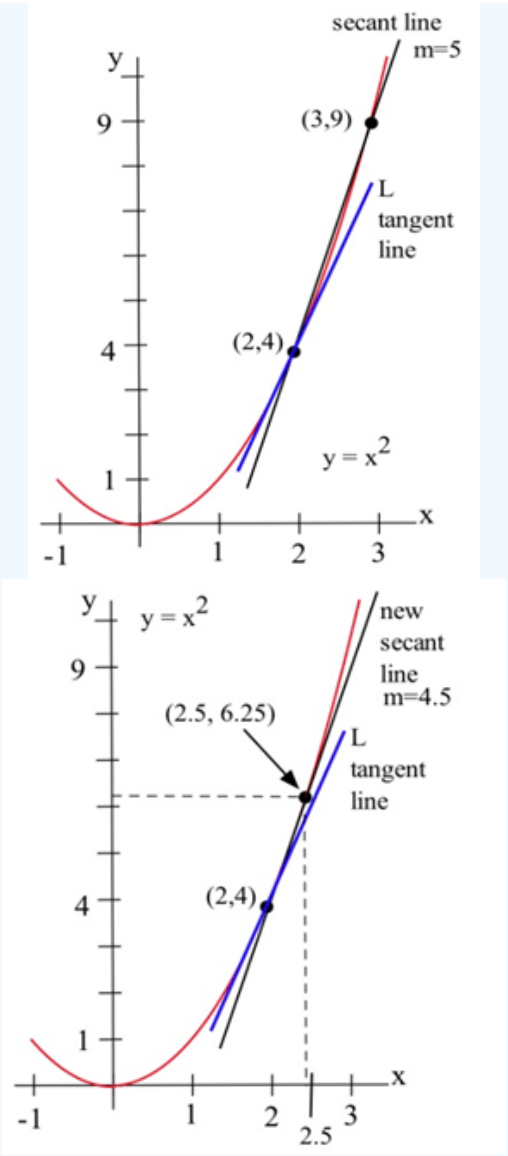
In the previous examples, we noticed that as the interval got smaller and smaller, the secant line got closer to the tangent line and its slope got closer to the slope of the tangent line. That's good news – we know how to find the slope of a secant line.

Let's explore further this idea of finding the tangent slope based on the secant slope.

Example 3.1.5

Find the slope of the line L in the graph below which is tangent to $f(x) = x^2$ at the point (2,4).

We could estimate the slope of L from the graph, but we won't. Instead, we will use the idea that secant lines over tiny intervals approximate the tangent line.



We can see that the line through (2,4) and (3,9) on the graph of f is an approximation of the slope of the tangent line, and we can calculate that slope exactly: $m = \frac{\Delta y}{\Delta x} = \frac{9-4}{3-2} = 5$. But $m = 5$ is only an estimate of the slope of the tangent line and not a very good estimate. It's too big. We can get a better estimate by picking a second point on the graph of f which is closer to (2,4). The point (2,4) is fixed and it must be one of the points we use.

From the second figure, we can see that the slope of the line through the points (2,4) and (2.5,6.25) is a better approximation of the slope of the tangent line at (2,4): $m = \frac{\Delta y}{\Delta x} = \frac{6.25-4}{2.5-2} = \frac{2.25}{0.5} = 4.5$, a better estimate, but still an approximation. We can continue picking points closer and closer to (2,4) on the graph of f, and then calculating the slopes of the lines through each of these points and the point (2,4):

Points to the left of (2,4)

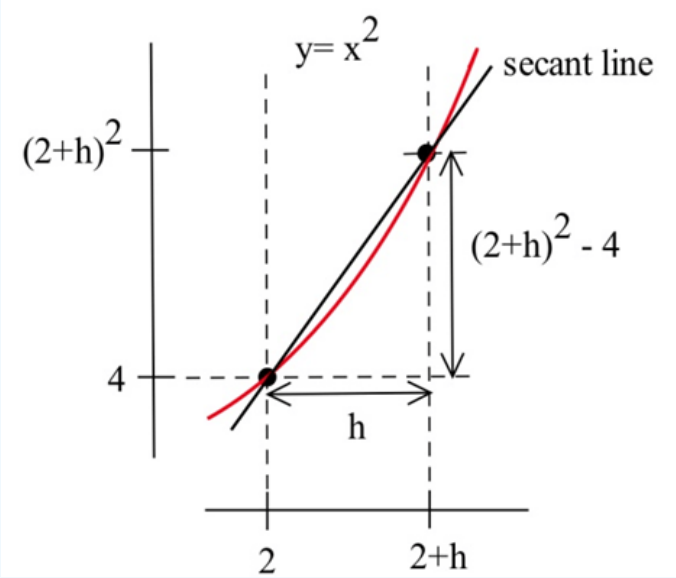
x	$y = x^2$	Slope of line through (x, y) and (2,4).
1.5	2.25	3.5
1.9	3.61	3.9
1.99	3.9601	3.99

Points to the right of (2,4)

x	$y = x^2$	Slope of line through (x, y) and (2,4).
3	9	5
2.5	6.25	4.5
2.01	4.0401	4.01

The only thing special about the x–values we picked is that they are numbers which are close, and very close, to $x = 2$. Someone else might have picked other nearby values for x. As the points we pick get closer and closer to the point (2,4) on the graph of $y = x^2$, the slopes of the lines through the points and (2,4) are better approximations of the slope of the tangent line, and these slopes are getting closer and closer to 4.

We can bypass much of the calculating by not picking the points one at a time: let's look at a general point near (2,4). Define $x = 2 + h$ so h is the increment from 2 to x. If h is small, then $x = 2 + h$ is close to 2 and the point $(2 + h, f(2 + h)) = (2 + h, (2 + h)^2)$ is close to (2,4). The slope m of the line through the points (2,4) and $(2 + h, (2 + h)^2)$ is a good approximation of the slope of the tangent line at the point (2,4):



We can calculate the secant slope for any value of h:

$$m = \frac{\Delta y}{\Delta x} = \frac{(2+h)^2 - 4}{(2+h) - 2} = \frac{(4 + 4h + h^2) - 4}{h} = \frac{4h + h^2}{h} = \frac{h(4+h)}{h} = 4 + h$$

The value $m = 4 + h$ is the slope of the secant line through the two points (2,4) and $(2 + h, (2 + h)^2)$. As h gets smaller and smaller, this slope approaches the slope of the tangent line to the graph of f at (2,4).

More formally, we could write:

$$\text{Slope of the tangent line} = \lim_{h \to 0} \frac{\Delta y}{\Delta x} = \lim_{h \to 0} (4 + h).$$

We can easily evaluate this limit using direct substitution, finding that as the interval h shrinks towards 0, the secant slope approaches the tangent slope, 4.

Use the applet below to explore this. You can drag the base point on the graph to explore the behavior at different locations on the graph. Once setting the base point, use the slider to see how the secant lines approach the tangent line as h approaches zero.

Finding tangent slopes and finding the instantaneous rate of change are the same problem. In each problem we wanted to know how rapidly something was **changing at an instant in time**, and the answer turned out to be finding the **slope of a tangent**

line, which we *approximated* with the **slope of a secant line**. This idea is the key to defining the slope of a curve.

Video

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The Derivative

We can view the derivative in different ways. Here are a three of them:

- The **derivative** of a function f at a point $(x, f(x))$ is the instantaneous rate of change.
- The **derivative** is the slope of the tangent line to the graph of f at the point $(x, f(x))$.
- The **derivative** is the slope of the curve $f(x)$ at the point $(x, f(x))$.

A function is called **differentiable** at $(x, f(x))$ if its derivative exists at $(x, f(x))$.

Notation for the Derivative

The **derivative of** $y = f(x)$ **with respect to** x is written as

$$f'(x)$$

(read aloud as "f prime of x"), or

$$y'$$

(read aloud as "why prime") or

$$\frac{dy}{dx}$$

(read aloud as "dee why dee ex"), or

$$\frac{df}{dx}.$$

The notation that resembles a fraction is called **Leibniz notation**. It displays not only the name of the function (f or y), but also the name of the variable (in this case, x). It looks like a fraction because the derivative is a slope. In fact, this is simply $\frac{\Delta y}{\Delta x}$ written in Roman letters instead of Greek letters.

Verb Forms

We **find the derivative** of a function, or **take the derivative** of a function, or **differentiate** a function.

We use an adaptation of the $\frac{df}{dx}$ notation to mean "find the derivative of $f(x)$:"

$$\frac{d}{dx}\left[f(x)\right] = \frac{df}{dx}.$$

[The book uses parentheses instead of brackets–both are acceptable forms of the notation.]

Formal Algebraic Definition

$$f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}$$

Practical Definition

The derivative can be approximated by looking at an average rate of change, or the slope of a secant line, over a very tiny interval. The tinier the interval, the closer this is to the true instantaneous rate of change, slope of the tangent line, or slope of the curve.

Looking Ahead

We will have methods for computing exact values of derivatives from formulas soon. If the function is given to you as a table or graph, you will still need to approximate this way.

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This is the foundation for the rest of this chapter. It's remarkable that such a simple idea (the slope of a tangent line) and such a simple definition (for the derivative $f'(x)$) will lead to so many important ideas and applications.

Example 3.1.6

Find the slope of the tangent line to $f(x) = \frac{1}{x}$ at $x = 3$.

Solution

The slope of the tangent line is the value of the derivative $f'(3)$. $f(3) = \frac{1}{3}$ and $f(3+h) = \frac{1}{3+h}$, so, using the formal limit definition of the derivative,

$$f'(3) = \lim_{h\to 0} \frac{f(3+h) - f(3)}{h} = \lim_{h\to 0} \frac{\frac{1}{3+h} - \frac{1}{3}}{h}.$$

We can simplify by giving the fractions a common denominator:

$$\begin{aligned}
\lim_{h\to 0} \frac{\frac{1}{3+h} - \frac{1}{3}}{h} &= \lim_{h\to 0} \frac{\frac{1}{3+h}\cdot\frac{3}{3} - \frac{1}{3}\cdot\frac{3+h}{3+h}}{h} \\
&= \lim_{h\to 0} \frac{\frac{3}{9+3h} - \frac{3+h}{9+3h}}{h} \\
&= \lim_{h\to 0} \frac{\frac{3-(3+h)}{9+3h}}{h} \\
&= \lim_{h\to 0} \frac{\frac{3-3-h}{9+3h}}{h} \\
&= \lim_{h\to 0} \frac{\frac{-h}{9+3h}}{h} \\
&= \lim_{h\to 0} \frac{-h}{9+3h}\cdot\frac{1}{h} \\
&= \lim_{h\to 0} \frac{-1}{9+3h}
\end{aligned}$$

and the evaluate using direct substitution:

$$\lim_{h\to 0} \frac{-1}{9+3h} = \frac{-1}{9+3(0)} = -\frac{1}{9}.$$

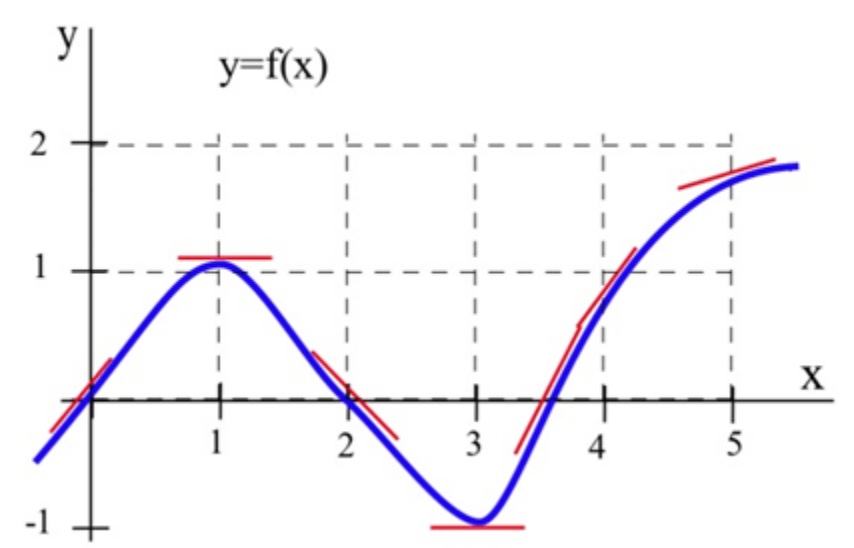
Thus, the slope of the tangent line to $f(x) = \frac{1}{x}$ at $x = 3$ is $-\frac{1}{9}$.

The Derivative as a Function

We now know how to find (or at least approximate) the derivative of a function for any x-value; this means we can think of the derivative as a function, too. The inputs are the same x's; the output is the value of the derivative at that x value.

Example 3.1.7

Below is the graph of a function $y = f(x)$. We can use the information in the graph to fill in a table showing values of $f'(x)$:



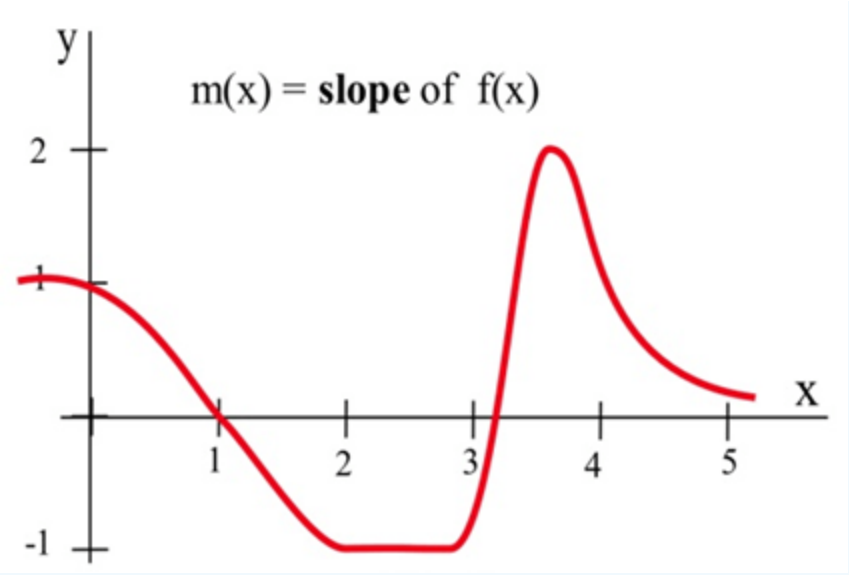
At various values of x, draw your best guess at the tangent line and measure its slope. You might have to extend your lines so you can read some points. In general, your estimate of the slope will be better if you choose points that are easy to read and far away from each other. Here are estimates for a few values of x (parts of the tangent lines used are shown above in the graph):

x	$y = f(x)$	$f'(x) =$ the estimated *slope* of the tangent line to the curve at the point (x, y).
0	0	1
1	1	0
2	0	-1
3	-1	0
3.5	0	2

We can estimate the values of $f'(x)$ at some non-integer values of x, too: $f'(0.5) \approx 0.5$ and $f'(1.3) \approx -0.3$.

We can even think about entire intervals. For example, if $0 < x < 1$, then $f(x)$ is increasing, all the slopes are positive, and so $f'(x)$ is positive.

The values of $f'(x)$ definitely depend on the values of x, and $f'(x)$ is a function of x. We can use the results in the table to help sketch the graph of $f'(x)$.



To get a better feel for this, explore the applet below. The top graph is the graph of the original function $g(x)$. The bottom graph shows the slopes of $g(x)$, so is a graph of the derivative, $g'(x)$. Drag the point *a* and notice how the slope of the tangent line corresponds to the value of the derivative $g'(x)$.

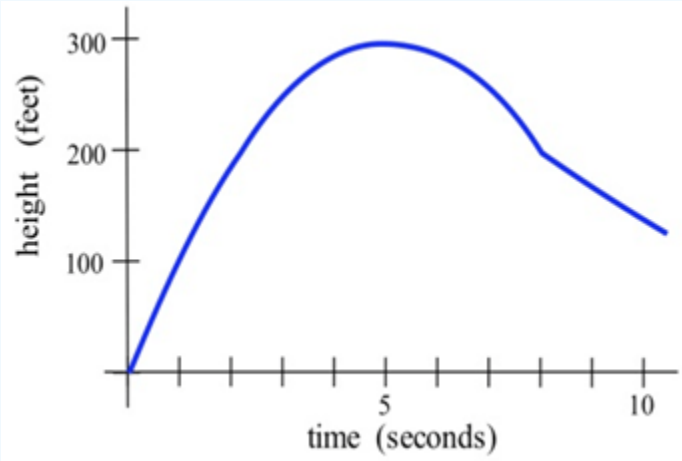
Video

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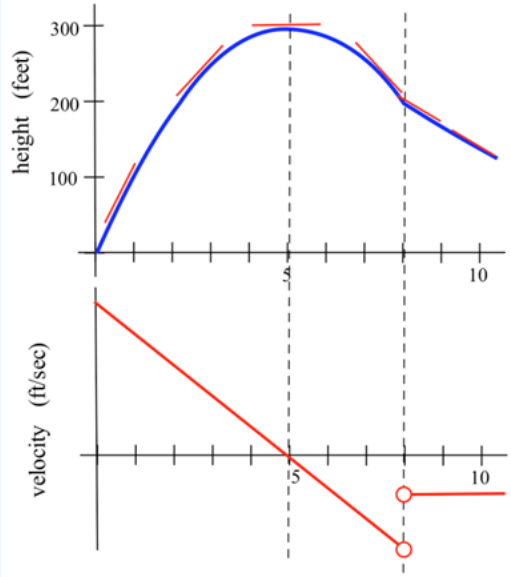
Example 3.1.8

Shown is the graph of the height $h(t)$ of a rocket at time t.



Sketch the graph of the **velocity** of the rocket at time t. (Velocity is the **derivative** of the height function, so it is the **slope of the tangent** to the graph of position or height.)

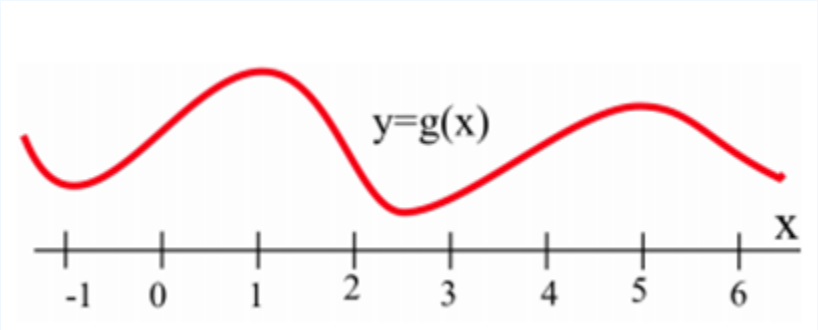
We can estimate the slope of the function at several points. The lower graph below shows the velocity of the rocket. This is $v(t) = h'(t)$.



In some applications, we need to know where the graph of a function $f(x)$ has horizontal tangent lines (slopes = 0).

Example 3.1.9

Below is the graph of $y = g(x)$. At what values of x does the graph of $g(x)$ have horizontal tangent lines?



The tangent lines to the graph of $g(x)$ are horizontal (slope = 0) when $x \approx -1, 1, 2.5, \text{ and } 5$.

We can also find derivative functions algebraically using limits.

Example 3.1.10

Find $\frac{d}{dx}(2x^2 - 4x - 1)$.

Setting up the derivative using a limit,

$$f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}.$$

We will start by simplifying $f(x + h)$ by expanding:

$$\begin{aligned} f(x+h) &= 2(x+h)^2 - 4(x+h) - 1 \\ &= 2(x^2 + 2xh + h^2) - 4(x+h) - 1 \\ &= 2x^2 + 4xh + 2h^2 - 4x - 4h - 1 \end{aligned}$$

Now finding the limit:

$$\begin{aligned} f'(x) &= \lim_{h\to 0} \frac{f(x+h) - f(x)}{h} \\ &= \lim_{h\to 0} \frac{(2x^2 + 4xh + 2h^2 - 4x - 4h - 1) - (2x^2 - 4x - 1)}{h} \\ &= \lim_{h\to 0} \frac{2x^2 + 4xh + 2h^2 - 4x - 4h - 1 - 2x^2 + 4x + 1}{h} \qquad \text{(Substitute in the formulas.)} \\ &= \lim_{h\to 0} \frac{4xh + 2h^2 - 4h}{h} \qquad \text{(Now simplify.)} \\ &= \lim_{h\to 0} \frac{h(4x + 2h - 4)}{h} \qquad \text{(Factor out the } h\text{, then cancel.)} \\ &= \lim_{h\to 0} (4x + 2h - 4) \end{aligned}$$

We can find the limit of this expression by direct substitution:

$$f'(x) = \lim_{h\to 0} (4x + 2h - 4) = 4x - 4$$

Notice that the derivative depends on x, and that this formula will tell us the slope of the tangent line to f at any value x. For example, if we wanted to know the tangent slope of f at $x = 3$, we would simply evaluate: $f'(3) = 4(3) - 4 = 8$.

A formula for the derivative function is very powerful, but as you can see, calculating the derivative using the limit definition is **very** time consuming. In the next section, we will identify some patterns that will allow us to start building a set of rules for finding derivatives without needing the limit definition.

Interpreting the Derivative

So far we have emphasized the derivative as the slope of the line tangent to a graph. That interpretation is very visual and useful when examining the graph of a function, and we will continue to use it. Derivatives, however, are used in a wide variety of fields and applications, and some of these fields use other interpretations. The following are a few interpretations of the derivative that are commonly used.

General

Rate of Change: $f'(x)$ is the **rate of change** of the function at x. If the units for x are years and the units for $f(x)$ are people, then the units for $\frac{df}{dx}$ are $\frac{\text{people}}{\text{year}}$, a rate of change in population.

Graphical

Slope: $f'(x)$ is the **slope of the line tangent to the graph of f at the point** $(x, f(x))$.

Physical

Velocity: If $f(x)$ is the position of an object at time x, then $f'(x)$ is the **velocity** of the object at time x. If the units for x are hours and $f(x)$ is distance measured in miles, then the units for $\mathbf{f'(x) = \frac{df}{dx}}$ are $\frac{\text{miles}}{\text{hour}}$, miles per hour, which is a measure of velocity.

Acceleration: If $f(x)$ is the velocity of an object at time x, then $f'(x)$ is the **acceleration** of the object at time x. If the units are for x are hours and $f(x)$ has the units $\frac{\text{miles}}{\text{hour}}$, then the units for the acceleration $\mathbf{f'(x) = \frac{df}{dx}}$ are $\frac{\text{miles/hour}}{\text{hour}} = \frac{\text{miles}}{\text{hour}^2}$, miles per hour per hour.

Business

Marginal Cost, Marginal Revenue, and Marginal Profit: We'll explore these terms in more depth later in the section. Basically, the marginal cost is approximately the *additional* cost of making one more object once we have already made x objects. If the units for x are bicycles and the units for $f(x)$ are dollars, then the units for $f'(x) = \frac{df}{dx}$ are $\frac{\text{dollars}}{\text{bicycle}}$, the cost per bicycle.

In business contexts, the word "**marginal**" usually means the derivative or rate of change of some quantity.

One of the strengths of calculus is that it provides a unity and economy of ideas among diverse applications. The vocabulary and problems may be different, but the ideas and even the notations of calculus are still useful.

Example 3.1.11

Suppose the demand curve for widgets was given by $D(p) = \frac{1}{p}$, where D is the quantity of widgets, in thousands, at a price of p dollars. Interpret the derivative of D at $p =$\$3.

Note that we calculated $D'(3)$ earlier to be $D'(3) = -\frac{1}{9} \approx -0.111$.

Since D has units “thousands of widgets” and the units for p is dollars of price, the units for D' will be $\frac{\text{thousands of widgets}}{\text{dollar of price}}$. In other words, it shows how the demand will change as the price increases.

Specifically, $D'(3) \approx -0.111$ tells us that when the price is \$3, the demand will *decrease* by about 0.111 thousand items for every dollar the price increases.

(Note: The screen shots in the following video are from an earlier version of the book, so some of the section numbers or titles may not look the same. However, much of the content is the same, and the comments still apply.)

Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

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3.2: Techniques of Differentiation

In the next few sections, we'll get the derivative rules that will let us find formulas for derivatives when our function comes to us as a formula. This is a very algebraic section, and you should get lots of practice. When you tell someone you have studied calculus, this is the one skill they will expect you to have.

Building Blocks

These are the simplest rules – rules for the basic functions. We won't prove these rules; we'll just use them. But first, let's look at a few so that we can see they make sense.

Example 3.2.1

Find the derivative of $y = f(x) = mx + b$.

Solution

This is a linear function, so its graph is its own tangent line! The slope of the tangent line, the derivative, is the slope of the line:

$$f'(x) = m$$

Rule

The derivative of a linear function is its slope.

Example 3.2.2

Find the derivative of $f(x) = 135$.

Solution

Think about this one graphically, too. The graph of $f(x)$ is a horizontal line. So its slope is zero:

$$f'(x) = 0$$

Rule

The derivative of a constant is zero.

Example 3.2.3

Find the derivative of $f(x) = x^2$.

Solution

Recall the formal definition of the derivative:

$$f'(x) = \lim_{h \to 0} \frac{f(x+h) - f(x)}{h}.$$

Using our function $f(x) = x^2$, $f(x+h) = (x+h)^2 = x^2 + 2xh + h^2$.

Then

$$\begin{aligned} f'(x) &= \lim_{h\to 0} \frac{f(x+h) - f(x)}{h} \\ &= \lim_{h\to 0} \frac{x^2 + 2xh + h^2 - x^2}{h} \\ &= \lim_{h\to 0} \frac{2xh + h^2}{h} \\ &= \lim_{h\to 0} \frac{h(2x+h)}{h} \\ &= \lim_{h\to 0} (2x+h) \\ &= 2x \end{aligned}$$

From all that, we find that $f'(x) = 2x$.

Luckily, there is a handy rule we use to skip using the limit:

Power Rule

The derivative of $f(x) = x^n$ is

$$f'(x) = nx^{n-1}.$$

Example 3.2.4

Find the derivative of $g(x) = 4x^3$.

Solution

Using the power rule, we know that if $f(x) = x^3$, then $f'(x) = 3x^2$. Notice that g is 4 times the function f. Think about what this change means to the graph of g – it's now 4 times as tall as the graph of f. If we find the slope of a secant line, it will be $\frac{\Delta g}{\Delta x} = \frac{4\Delta f}{\Delta x} = 4\frac{\Delta f}{\Delta x}$; each slope will be 4 times the slope of the secant line on the f graph. This property will hold for the slopes of tangent lines, too:

$$\frac{d}{dx}\left(4x^3\right) = 4\frac{d}{dx}\left(x^3\right) = 4 \cdot 3x^2 = 12x^2.$$

Rule

Constants come along for the ride, i.e., $\frac{d}{dx}(kf) = kf'$.

Here are all the basic rules in one place.

Derivative Rules: Building Blocks

In what follows, f and g are differentiable functions of x.

Constant Multiple Rule

$$\frac{d}{dx}(kf) = kf'$$

Sum and Difference Rule

$$\frac{d}{dx}(f \pm g) = f' \pm g'$$

Power Rule

$$\frac{d}{dx}(x^n) = nx^{n-1}$$

Special cases:

$$\frac{d}{dx}(k) = 0 \quad (\text{Because } k = kx^0.)$$
$$\frac{d}{dx}(x) = 1 \quad (\text{Because } x = x^1.)$$

Exponential Functions

$$\frac{d}{dx}(e^x) = e^x$$
$$\frac{d}{dx}(a^x) = \ln(a)\, a^x$$

Natural Logarithm

$$\frac{d}{dx}(\ln(x)) = \frac{1}{x}$$

The sum, difference, and constant multiple rule combined with the power rule allow us to easily find the derivative of any polynomial.

Example 3.2.5

Find the derivative of $p(x) = 17x^{10} + 13x^8 - 1.8x + 1003$.

Solution

$$\begin{aligned}\frac{d}{dx}\left(17x^{10} + 13x^8 - 1.8x + 1003\right) &= \frac{d}{dx}\left(17x^{10}\right) + \frac{d}{dx}\left(13x^8\right) - \frac{d}{dx}\left(1.8x\right) + \frac{d}{dx}\left(1003\right) \\ &= 17\frac{d}{dx}\left(x^{10}\right) + 13\frac{d}{dx}\left(x^8\right) - 1.8\frac{d}{dx}\left(x\right) + \frac{d}{dx}\left(1003\right) \\ &= 17\left(10x^9\right) + 13\left(8x^7\right) - 1.8\left(1\right) + 0 \\ &= 170x^9 + 104x^7 - 1.8\end{aligned}$$

You don't have to show every single step. Do be careful when you're first working with the rules, but pretty soon you'll be able to just write down the derivative directly:

Example 3.2.6

Find $\frac{d}{dx}(17x^2 - 33x + 12)$.

Solution

Writing out the rules, we'd write

$$\frac{d}{dx}\left(17x^2 - 33x + 12\right) = 17(2x) - 33(1) + 0 = 34x - 33.$$

Once you're familiar with the rules, you can, in your head, multiply the 2 times the 17 and the 33 times 1, and just write

$$\frac{d}{dx}\left(17x^2-33x+12\right)=34x-33.$$

The power rule works even if the power is negative or a fraction. In order to apply it, first translate all roots and basic rational expressions into exponents:

Example 3.2.7

Find the derivative of $y=3\sqrt{t}-\frac{4}{t^4}+5e^t$.

Solution

The first step is translate into exponents:

$$y=3\sqrt{t}-\frac{4}{t^4}+5e^t=3t^{1/2}-4t^{-4}+5e^t$$

Now you can take the derivative:

$$\begin{aligned}\frac{d}{dt}\left(3t^{1/2}-4t^{-4}+5e^t\right)&=3\left(\frac{1}{2}t^{-1/2}\right)-4\left(-4t^{-5}\right)+5\left(e^t\right)\\&=\frac{3}{2}t^{-1/2}+16t^{-5}+5e^t\end{aligned}$$

If there is a reason to, you can rewrite the answer with radicals and positive exponents:

$$y'=\frac{3}{2}t^{-1/2}+16t^{-5}+5e^t=\frac{3}{2\sqrt{t}}+\frac{16}{t^5}+5e^t$$

Be careful when finding the derivatives with negative exponents.

We can immediately apply these rules to solve the problem we started the chapter with - finding a tangent line.

Example 3.2.8

Find the equation of the line tangent to $g(t)=10-t^2$ when $t=2$.

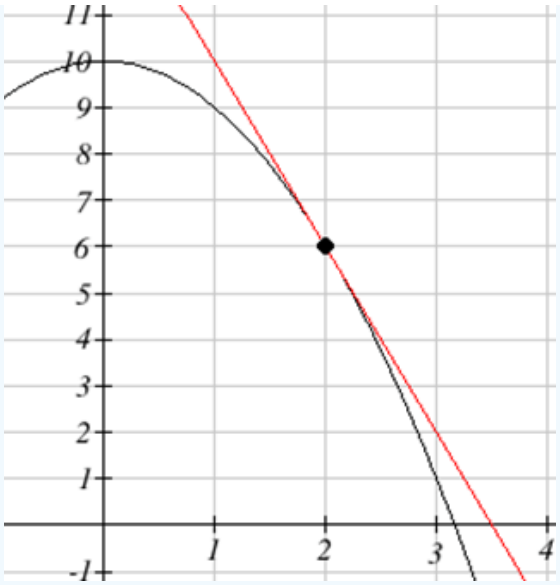
Solution

The slope of the tangent line is the value of the derivative. We can compute $g'(t)=-2t$. To find the slope of the tangent line when $t=2$, evaluate the derivative at that point. The slope of the tangent line is -4.

To find the equation of the tangent line, we also need a point on the tangent line. Since the tangent line touches the original function at $t=2$, we can find the point by evaluating the original function: $g(2)=10-2^2=6$. The tangent line must pass through the point (2, 6).

Using the point-slope equation of a line, the tangent line will have equation $y-6=-4(t-2)$. Simplifying to slope-intercept form, the equation is $y=-4t+14$.

Graphing, we can verify this line is indeed tangent to the curve:



We can also use these rules to help us find the derivatives we need to interpret the behavior of a function.

Example 3.2.9

In a memory experiment, a researcher asks the subject to memorize as many words from a list as possible in 10 seconds. Recall is tested, then the subject is given 10 more seconds to study, and so on. Suppose the number of words remembered after t seconds of studying could be modeled by $W(t) = 4t^{2/5}$. Find and interpret $W'(20)$.

Solution

$W'(t) = 4 \cdot \frac{2}{5}t^{-3/5} = \frac{8}{5}t^{-3/5}$, so $W'(20) = \frac{8}{5}(20)^{-3/5} \approx 0.2652$.

Since W is measured in words, and t is in seconds, W' has units words per second. $W'(20) \approx 0.2652$ means that after 20 seconds of studying, the subject is learning about 0.27 more words for each additional second of studying.

Business and Economics Terms

Next we will delve more deeply into some business applications. To do that, we first need to review some terminology.

Suppose you are producing and selling some item. The profit you make is the amount of money you take in minus what you have to pay to produce the items. Both of these quantities depend on how many you make and sell. (So we have functions here.) Here is a list of definitions for some of the terminology, together with their meaning in algebraic terms and in graphical terms.

Cost

Your **cost** is the money you have to spend to produce your items.

Fixed Cost

The **Fixed Cost** (**FC**) is the amount of money you have to spend regardless of how many items you produce. FC can include things like rent, purchase costs of machinery, and salaries for office staff. You have to pay the fixed costs even if you don't produce anything.

Total Variable Cost

The **Total Variable Cost** (**TVC**) for q items is the amount of money you spend to actually produce them. TVC includes things like the materials you use, the electricity to run the machinery, gasoline for your delivery vans, maybe the wages of your production workers. These costs will vary according to how many items you produce.

Total Cost

The **Total Cost** (**TC**, or sometimes just **C**) for q items is the total cost of producing them. It's the sum of the fixed cost and the total variable cost for producing q items.

Average Cost

The **Average Cost** (**AC**) for q items is the total cost divided by q, or

$$AC(q) = \frac{TC}{q}$$

You can also talk about the average fixed cost, $\frac{FC}{q}$, or the average variable cost, $\frac{TVC}{q}$.

Marginal Cost

The **Marginal Cost** (**MC**) at q items is the cost of producing the next item. Really, it's

$$MC(q) = TC(q+1) - TC(q).$$

In many cases, though, it's easier to approximate this difference using calculus (see Example 1 below). And some sources define the marginal cost directly as the derivative,

$$MC(q) = TC'(q).$$

In this course, we will use both of these definitions as if they were interchangeable.

The units on marginal cost is cost per item.

For the purposes of this course, if a question asks for marginal cost, revenue, profit, etc., compute it using the derivative if possible, unless specifically told otherwise.

Why is it okay that there are two definitions for Marginal Cost (and Marginal Revenue, and Marginal Profit)?

We have been using slopes of secant lines over tiny intervals to approximate derivatives. In this example, we'll turn that around – we'll use the derivative to approximate the slope of the secant line.

Notice that the "cost of the next item" definition is actually the slope of a secant line, over an interval of 1 unit:

$$MC(q) = C(q+1) - 1 = \frac{C(q+1) - 1}{1}.$$

So this is approximately the same as the derivative of the cost function at q:

$$MC(q) = C'(q).$$

In practice, these two numbers are so close that there's no practical reason to make a distinction. For our purposes, the marginal cost **is** the derivative **is** the cost of the next item.

Example 3.2.10

The table shows the total cost (TC) of producing q items.

Items, q	TC
0	$20,000
100	$35,000
200	$45,000
300	$53,000

1. What is the fixed cost?
2. When 200 items are made, what is the total variable cost? The average variable cost?
3. When 200 items are made, estimate the marginal cost.

Solution

1. The fixed cost is $20,000, the cost even when no items are made.
2. When 200 items are made, the total cost is $45,000. Subtracting the fixed cost, the total variable cost is $45,000 - $20,000 = $25,000.

   The average variable cost is the total variable cost divided by the number of items, so we would divide the $25,000 total variable cost by the 200 items made. $25,000/200 = $125. On average, each item had a variable cost of $125.

3. We need to estimate the value of the derivative, or the slope of the tangent line at $q = 200$. Finding the secant line from $q = 100$ to $q = 200$ gives a slope of

$$\frac{45,000 - 35,000}{200 - 100} = 100.$$

   Finding the secant line from $q = 200$ to $q = 300$ gives a slope of

$$\frac{53,000 - 45,000}{300 - 200} = 80.$$

   We could estimate the tangent slope by averaging these secant slopes, giving us an estimate of $90/item.

   This tells us that after 200 items have been made, it will cost about $90 to make one more item.

Example 3.2.11

The cost to produce x items is $C(x) = \sqrt{x}$ hundred dollars.

1. What is the cost for producing 100 items? 101 items? What is cost of the 101st item?
2. Calculate $C'(x)$ and evaluate C' at $x = 100$. How does $C'(100)$ compare with the last answer in Part a?

Solution

1. $C(100) = 10$ hundred dollars = $1000 and $C(101) = 10.0499$ hundred dollars = $1004.99, so it costs $4.99 for that 101st item. Using this definition, the marginal cost is $4.99.
2. $C'(x) = \frac{1}{2}x^{-1/2} = \frac{1}{2\sqrt{x}}$, so $C'(100) = \frac{1}{2\sqrt{100}} = \frac{1}{20}$ hundred dollars = $5.00.

Note how close these answers are! This shows (again) why it's OK that we use both definitions for marginal cost.

Demand

Demand is the functional relationship between the price p and the quantity q that can be sold (that is demanded). Depending on your situation, you might think of p as a function of q, or of q as a function of p

Revenue

Your **revenue** is the amount of money you actually take in from selling your products.

Total Revenue

The **Total Revenue** (**TR**, or just **R**) for q items is the total amount of money you take in for selling q items. Total Revenue is price multiplied by quantity,

$$TR = p \cdot q.$$

Average Revenue

The **Average Revenue** (**AR**) for q items is the total revenue divided by q, or

$$\frac{TR}{q}.$$

Marginal Revenue

The Marginal Revenue (MR) at q items is the revenue from producing the next item,

$$MR(q) = TR(q+1) - TR(q).$$

Just as with marginal cost, we will use both this definition and the derivative definition:

$$MR(q) = TR'(q).$$

Profit

Your **profit** is what's left over from total revenue after costs have been subtracted.

The **Profit** (**P**) for q items is

$$TR(q) - TC(q),$$

the difference between total revenue and total costs.

The **average profit** for q items is

$$\frac{P}{q}.$$

The **marginal profit** at q items is

$$P(q+1) – P(q),$$

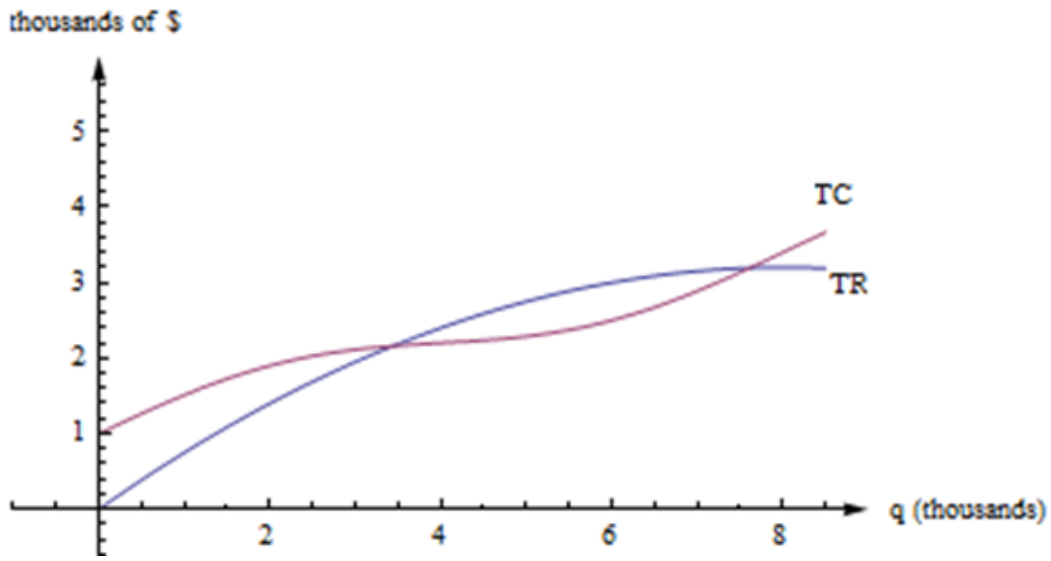
or

$$P'(q)$$

Graphical Interpretations of the Basic Business Math Terms

Illustration

Here are the graphs of TR and TC for producing and selling a certain item. The horizontal axis is the number of items, in thousands. The vertical axis is the number of dollars, also in thousands.



First, notice how to find the fixed cost and variable cost from the graph here. **FC is the y-intercept of the TC graph.** ($FC = TC(0)$.) The graph of TVC would have the same shape as the graph of TC, shifted down. ($TVC = TC - FC$.)

$MC(q) = TC(q+1) - TC(q)$, but that's impossible to read on this graph. How could you distinguish between TC(4022) and TC(4023)? On this graph, that interval is too small to see, and our best guess at the secant line is actually the tangent line to the TC curve at that point. (This is the reason we want to have the derivative definition handy.)

$MC(q)$ is the slope of the tangent line to the TC curve at $(q, TC(q))$.

$MR(q)$ is the slope of the tangent line to the TR curve at $(q, TR(q))$.

Profit is the distance between the TR and TC curve. If you experiment with a clear ruler, you'll see that the biggest profit occurs exactly when the tangent lines to the TR and TC curves are parallel. This is the rule **"profit is maximized when $MR = MC$"** which we'll explore later in the chapter.

Example 3.2.12

The demand, D, for a product at a price of p dollars is given by $D(p) = 200 - 0.2p^2$. Find the marginal revenue when the price is $10.

Solution

First we need to form a revenue equation. Since Revenue = Price$\times$Quantity, and the demand equation shows the quantity of product that can be sold, we have

$$R(p) = D(p) \cdot p = \left(200 - 0.2p^2\right) p = 200p - 0.2p^3.$$

Now we can find marginal revenue by finding the derivative:

$$R'(p) = 200(1) - 0.2(3p^2) = 200 - 0.6p^2$$

At a price of \$10, $R'(10) = 200 - 0.6(10)^2 = 140$.

Notice the units for R' are $\frac{\text{dollars of Revenue}}{\text{dollar of price}}$, so $R'(10) = 140$ means that when the price is \$10, the revenue will increase by \$140 for each dollar that the price was increased.

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3.3: Product and Quotient Rules

The basic rules will let us tackle simple functions. But what happens if we need the derivative of a combination of these functions?

Example 3.3.1

Find the derivative of $h(x) = \left(4x^3 - 11\right)(x + 3)$

This function is not a simple sum or difference of polynomials. It's a product of polynomials. We can simply multiply it out to find its derivative:

$$\begin{aligned} h(x) &= \left(4x^3 - 11\right)(x + 3) \\ &= 4x^4 - 11x + 12x^3 - 33 \\ h'(x) &= 16x^3 - 11 + 36x^2 \end{aligned}$$

Now suppose we wanted to find the derivative of

$$f(x) = \left(4x^5 + x^3 - 1.5x^2 - 11\right)\left(x^7 - 7.25x^5 + 120x + 3\right)$$

This function is not a simple sum or difference of polynomials. It's a product of polynomials. We could 'simply' multiply it out to find its derivative as before – who wants to volunteer? Nobody?

We'll need a rule for finding the derivative of a product so we don't have to multiply everything out.

It would be great if we can just take the derivatives of the factors and multiply them, but unfortunately that won't give the right answer. To see that, consider finding derivative of $h(x) = \left(4x^3 - 11\right)(x + 3)$. We already worked out the derivative, it is $h'(x) = 16x^3 - 11 + 36x^2$. What if we try differentiating the factors and multiplying them? We'd get $h'(x) = \left(12x^2\right)(1) = 12x^2$, which is radically different from the correct answer.

The rules for finding derivatives of products and quotients are a little complicated, but they save us the much more complicated algebra we might face if we were to try to multiply things out. They also let us deal with products where the factors are not polynomials. We can use these rules, together with the basic rules, to find derivatives of many complicated looking functions.

Derivative Rules: Product and Quotient Rules

In what follows, f and g are differentiable functions of x.

Product Rule

$\frac{d}{dx}(f \cdot g) = f' \cdot g + f \cdot g'$

The derivative of the first factor times the second left alone, plus the first left alone times the derivative of the second.

The product rule can extend to a product of several functions; the pattern continues – take the derivative of each factor in turn, multiplied by all the other factors left alone, and add them up:

$$\frac{d}{dx}(f \cdot g \cdot h) = f' \cdot g \cdot h + f \cdot g' \cdot h + f \cdot g \cdot h'$$

Quotient Rule

$$\frac{d}{dx}\left(\frac{f}{g}\right) = \frac{f' \cdot g - f \cdot g'}{g^2}$$

The numerator of the result resembles the product rule, but there is a minus instead of a plus; the minus sign goes with the g'. The denominator is simply the square of the original denominator – no derivatives there.

Example 3.3.2

Find the derivative of $h(x) = (4x^3 - 11)(x + 3)$

This is the same function we found the derivative of in Example 1, but let's use the product rule and check to see if we get the same answer. For this first example, we will provide a lot more detail and steps than one usually actually shows when working a problem like this.

Notice we can think of $h(x)$ as the product of two functions $f(x) = 4x^3 - 11$ and $g(x) = x + 3$. Finding the derivative of each of these,

$$f'(x) = 12x^2 \text{ and } g'(x) = 1.$$

Using the product rule,

$$\begin{aligned} h'(x) &= (f')(g) + (f)(g') \\ &= \left(12x^2\right)(x + 3) + \left(4x^3 - 11\right)(1) \end{aligned}$$

To check if this is equivalent to the answer we found in Example 1 we could simplify:

$$\begin{aligned} h'(x) &= \left(12x^2\right)(x + 3) + \left(4x^3 - 11\right)(1) \\ &= 12x^3 + 36x^2 + 4x^3 - 11 \\ &= 16x^3 + 36x^2 - 11 \end{aligned}$$

From this, we can see the answers are equivalent.

Example 3.3.3

Find the derivative of $F(t) = e^t \ln(t)$

This is a product, so we need to use the product rule. I like to put down empty parentheses to remind myself of the pattern; that way I don't forget anything:

$$F'(t) = (\ )(\ ) + (\ )(\ )$$

Then I fill in the parentheses – the first set gets the derivative of e^t, the second gets $\ln t$ left alone, the third gets e^t left alone, and the fourth gets the derivative of $\ln t$.

$$F'(t) = \left(e^t\right)(\ln(t)) + \left(e^t\right)\left(\frac{1}{t}\right) = e^t \ln(t) + \frac{e^t}{t}.$$

Notice that this was one we could *not* have done by "multiplying out."

Example 3.3.4

Find the derivative of $y = \frac{x^4+4^x}{3+16x^3}$.

This is a quotient, so we need to use the quotient rule. Again, you find it helpful to put down the empty parentheses as a template:

$$y' = \frac{(\ )(\ ) - (\ )(\ )}{(\ )^2}$$

We can find the derivative of the numerator and denominator separately:

For the numerator: $f(x) = x^4 + 4^x$ so $f'(x) = 4x^3 + \ln(4) \cdot 4^x$

For the denominator: $g(x) = 3 + 16x^3$ so $g'(x) = 48x^2$

Then fill in all the pieces:

$$y' = \frac{f' \cdot g - f \cdot g'}{g^2}$$

$$y' = \frac{\left(4x^3 + \ln(4) \cdot 4^x\right)\left(3 + 16x^3\right) - \left(x^4 + 4^x\right)\left(48x^2\right)}{\left(3 + 16x^3\right)^2}$$

Now for goodness' sake don't try to simplify that! Remember that "simple" depends on what you will do next; in this case, we were asked to find the derivative, and we've done that. I expect you to do any "basic" simplifications, such as multiplying constants together or doing obvious cancellations or combining of terms, but otherwise please STOP unless there is a reason to simplify further.

Example 3.3.5

Suppose a large tank contains 8 kg of a chemical dissolved in 50 liters of water. If a tap is opened and water is added to the tank at a rate of 5 liters per minute, at what rate is the concentration of chemical in the tank changing after 4 minutes?

First we need to set up a model for the concentration of chemical. The concentration would be measured as kg of chemical per liter of water, kg/L. The number of kg of chemical stays constant at 8 kg, but the quantity of water in the tank is increasing by 5 L/min. The total volume of water in the tank after t minutes is $50 + 5t$, so the concentration after t minutes is

$$c(t) = \frac{8}{50 + 5t}.$$

To find the rate at which the concentration is changing, we need the derivative:

$$\begin{aligned} c'(t) &= \frac{\frac{d}{dt}(8) \cdot (50 + 5t) - (8) \cdot \frac{d}{dt}(50 + 5t)}{(50 + 5t)^2} \\ &= \frac{(0) \cdot (50 + 5t) - (8)(5)}{(50 + 5t)^2} \\ &= -\frac{40}{(50 + 5t)^2} \end{aligned}$$

At $t = 4$,

$$c'(4) = -\frac{40}{(50 + 5(4))^2} \approx -0.00816.$$

Note that the units here are kg per liter, per minute, or $\frac{\text{kg/L}}{\text{min}}$. In other words, this tells us that after 4 minutes, the concentration of chemical is *decreasing* by 0.00816 kg/L each minute.

More Graphical Interpretations of the Basic Business Math Terms

Returning to our discussion of business and economics topics, in addition to total cost and marginal cost, we often also want to talk about average cost or average revenue.

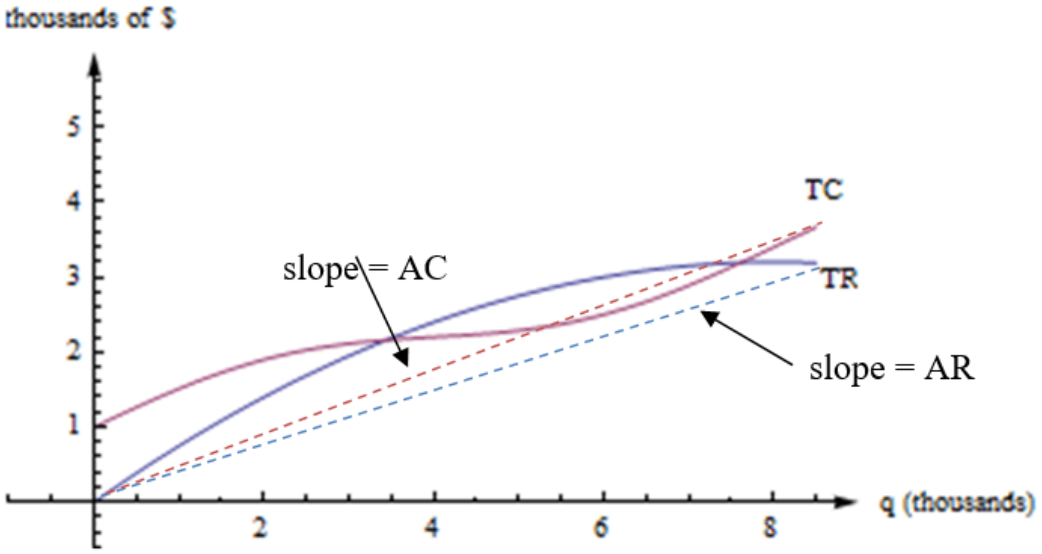
Recall from the previous section that the **Average Cost** (**AC**) for q items is the total cost divided by q, or $AC(q) = \frac{TC}{q}$. You can also talk about the average fixed cost, $\frac{FC}{q}$, or the average variable cost, $\frac{TVC}{q}$.

Also recall that the **Average Revenue** (**AR**) for q items is the total revenue divided by q, or $AR(q) = \frac{TR}{q}$.

We already know that we can find average rates of change by finding slopes of secant lines. AC, AR, MC, and MR are all rates of change, and we can find them with slopes, too.

$AC(q)$ is the slope of a diagonal line, from (0, 0) to $(q, TC(q))$.

$AR(q)$ is the slope of the line from (0, 0) to $(q, TR(q))$.



And just as we found marginal Total Cost, we can also find marginal Average Cost.

Example 3.3.6

The cost, in thousands of dollars, for producing x thousand cellphone cases is given by $C(x) = 22 + x - 0.004x^2$. Find

1. the Fixed Costs,
2. the Average Cost when 5 thousand, 10 thousand, or 20 thousand cases are produced,
3. the Marginal Average Cost when 5 thousand cases are produced.

1. The fixed costs are the costs when no items are produced: $C(0) = 22$ thousand dollars.
2. The average cost function is total cost divided by number of items, so

$$AC(x) = \frac{C(x)}{x} = \frac{22 + x - 0.004x^2}{x}.$$

Note the units are thousands of dollars per thousands of items, which simplifies to just dollars per item.

At a production of 5 thousand items: $AC(5) = \frac{22+5-0.004(5)^2}{5} = 5.38$ dollars per item.

At a production of 10 thousand items: $AC(10) = \frac{22+5-0.004(10)^2}{10} = 3.16$ dollars per item.

At a production of 20 thousand items: $AC(20) = \frac{22+5-0.004(20)^2}{20} = 2.02$ dollars per item.

Notice that while the total cost increases with production, the average cost per item decreases, because the initial fixed costs are being distributed across more items.

3. For the marginal average cost, we need to find the derivative of the average cost function. We can either calculate this using the quotient rule, or we could use algebra to simplify the equation first (this is the easier option – remember, simplifying before differentiating is almost always easier):

$$\begin{aligned} AC(x) &= \frac{22 + x - 0.004x^2}{x} \\ &= \frac{22}{x} + \frac{x}{x} - \frac{0.004x^2}{x} \\ &= \frac{22}{x} + 1 - 0.004x \\ &= 22x^{-1} + 1 - 0.004x \end{aligned}$$

(Note: we haven't differentiated yet, only simplified.)

Taking the derivative,

$$AC'(x) = -22x^{-2} - 0.004 = -\frac{22}{x^2} - 0.004.$$

When 5 thousand items are produced,

$$AC'(5) = -\frac{22}{5^2} - 0.004 = -0.884.$$

Since the units on AC are dollars per item, and the units on x are thousands of items, the units on AC' are dollars per item per thousands of items. This tells us that when 5 thousand items are produced, the average cost per item is *decreasing* by \$0.884 for each additional thousand items produced.

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3.4: Chain Rule

There is one more type of complicated function that we will want to know how to differentiate: composition. The Chain Rule will let us find the derivative of a composition. (This is the last derivative rule we will learn!)

Example 3.4.1

Find the derivative of $y = (4x^3 + 15x)^2$.

Solution

This is not a simple polynomial, so we can't use the basic building block rules yet. It is a product, so we could write it as $y = (4x^3 + 15x)^2 = (4x^3 + 15x)(4x^3 + 15x)$ and use the product rule. Or we could multiply it out and simply differentiate the resulting polynomial. I'll do it the second way:

$$\begin{aligned} y &= (4x^3 + 15x)^2 \\ &= 16x^6 + 120x^4 + 225x^2 \\ y' &= 96x^5 + 480x^3 + 450x \end{aligned}$$

Now suppose we want to find the derivative of $y = (4x^3 + 15x)^{20}$. We **could** write it as a product with 20 factors and use the product rule, or we **could** multiply it out. But I don't want to do that, do you?

We need an easier way, a rule that will handle a composition like this. The Chain Rule is a little complicated, but it saves us the much more complicated algebra of multiplying something like this out. It will also handle compositions where it wouldn't be possible to "multiply it out."

The Chain Rule is a common place for students to make mistakes. Part of the reason is that the notation takes a little getting used to. And part of the reason is that students often forget to use it when they should. When should you use the Chain Rule? Almost every time you take a derivative.

Derivative Rules: Chain Rule

In what follows, f and g are differentiable functions where $y = f(g(x))$. We could alternatively write $y = f(u)$ and $u = g(x)$.

Chain Rule (Leibniz notation)

$$\frac{dy}{dx} = \frac{dy}{du} \cdot \frac{du}{dx}$$

Notice that the du's seem to cancel. This is one advantage of the Leibniz notation – it can remind you of how the chain rule chains together.

Chain Rule (using prime notation)

$$\frac{d}{dx} f(g(x)) = f'(g(x)) \cdot g'(x)$$

Chain Rule (in words)

The derivative of a composition is the derivative of the outside (with the inside staying the same) TIMES the derivative of the inside.

I recite the version in words each time I take a derivative, especially if the function is complicated.

Example 3.4.2

Find the derivative of $y = (4x^3 + 15x)^2$.

Solution

This is the same one we did before by multiplying out. This time, let's use the Chain Rule: The inside function is what appears inside the parentheses: $4x^3 + 15x$. The outside function is the first thing we find as we come in from the outside – it's the square function, $(\text{inside})^2$.

The derivative of this outside function is $(2 \cdot \text{inside})$. Now using the chain rule, the derivative of our original function is $(2 \cdot \text{inside})$ TIMES the derivative of the inside (which is $12x^2 + 15$):

$$y' = 2\left(4x^3 + 15x\right)\left(12x^2 + 15\right)$$

If you multiply this out, you get the same answer we got before. Hurray! Algebra works!

Example 3.4.3

Find the derivative of $y = (4x^3 + 15x)^{20}$.

Solution

Now we have a way to handle this one. It's the derivative of the outside TIMES the derivative of the inside.

The outside function is $(\text{inside})^{20}$, which has derivative $20\,(\text{inside})^{19}$, so

$$y' = 20\left(4x^3 + 15x\right)^{19}\left(12x^2 + 15\right).$$

Example 3.4.4

Differentiate $y = e^{x^2+5}$.

Solution

This isn't a simple exponential function; it's a composition. Typical calculator or computer syntax can help you see what the "inside" function is here. On a TI calculator, for example, when you push the e^x key, it opens up parentheses: $\boxed{e\text{^(}}$. This tells you that the "inside" of the exponential function is the exponent. Here, the inside is the exponent $x^2 + 5$. Now we can use the Chain Rule: We want the derivative of the outside TIMES the derivative of the inside. The outside is the "e to the something" function, so its derivative is the same thing. The derivative of what's inside is $2x$. So

$$\frac{d}{dx}\left(e^{x^2+5}\right) = \left(e^{x^2+5}\right) \cdot (2x).$$

Example 3.4.5

The table gives values for f, f', g, and g' at a number of points. Use these values to determine $(f \circ g)(x)$ and $(f \circ g)'(x)$ at $x = -1$ and 0.

x	$f(x)$	$g(x)$	$f'(x)$	$g'(x)$	$(f \circ g)(x)$	$(g \circ f)(x)$
-1	2	3	1	0		
0	-1	1	3	2		
1	1	0	-1	3		

2	3	-1	0	1		
3	0	2	2	-1		

Solution

$$(f \circ g)(-1) = f\left(g(-1)\right) = f(3) = 0$$
$$(f \circ g)(0) = f\left(g(0)\right) = f(1) = 1$$
$$(f \circ g)'(-1) = f'\left(g(-1)\right) \cdot g'(-1) = f'(3) \cdot (0) = (2)(0) = 0 \text{ and}$$
$$(f \circ g)'(0) = f'\left(g(0)\right) \cdot g'(0) = f'(1) \cdot (2) = (-1)(2) = -2$$

Example 3.4.6

If 2400 people now have a disease, and the number of people with the disease appears to double every 3 years, then the number of people expected to have the disease in t years is $y = 2400 \cdot 2^{t/3}$.

1. How many people are expected to have the disease in 2 years?
2. When are 50,000 people expected to have the disease?
3. How fast is the number of people with the disease expected to grow now and 2 years from now?

1. In 2 years, $y = 2400 \cdot 2^{2/3} \approx 3,810$ people.
2. We know $y = 50,000$, and we need to solve $50,000 = 2400 \cdot 2^{t/3}$ for t. We could start by isolating the exponential by dividing both sides by 2400,
$$\frac{50000}{2400} = 2^{t/3}$$
$$\ln\left(\frac{50000}{2400}\right) = \ln\left(2^{t/3}\right) \qquad \text{(Taking the natural log of both sides.)}$$
$$\ln\left(\frac{50000}{2400}\right) = \frac{t}{3}\ln(2) \qquad \text{(Using the exponent property for logs.)}$$
$$t = \frac{3\ln\left(\frac{50000}{2400}\right)}{\ln(2)} \approx 13.14 \text{ years} \qquad \text{(Solving for } t\text{.)}$$
We expect 50,000 people to have the disease about 13.14 years from now.
3. This is asking for $\frac{dy}{dt}$ when $t = 0$ and 2 years. Using the chain rule,
$$\begin{aligned}\frac{dy}{dt} &= \frac{d}{dt}\left(2400 \cdot 2^{t/3}\right) \\ &= 2400 \cdot 2^{t/3} \cdot \ln(2) \cdot \frac{1}{3} \\ &\approx 554.5 \cdot 2^{t/3}\end{aligned}$$
So, at $t = 0$ the rate of growth of the disease is approximately $554.5 \cdot 2^0 \approx 554.5$ people/year. In 2 years the rate of growth will be approximately $554.5 \cdot 2^{2/3} \approx 880$ people/year.

Derivatives of Complicated Functions

You're now ready to take the derivative of some mighty complicated functions. But how do you tell what rule applies first? Work your way in from the outside – what do you encounter first? That's the first rule you need. Use the Product, Quotient, and Chain Rules to peel off the layers, one at a time, until you're all the way inside.

Example 3.4.7

Find $\frac{d}{dx}\left(e^{3x} \cdot \ln(5x+7)\right)$.

Solution

Coming in from the outside, we see that this is a product of two (complicated) functions. So we'll need the Product Rule first. we'll fill in the pieces we know, and then we can figure the rest as separate steps and substitute in at the end:

$$\frac{d}{dx}\left(e^{3x}\cdot\ln(5x+7)\right)=\left(\frac{d}{dx}\left(e^{3x}\right)\right)\cdot\ln(5x+7)+e^{3x}\cdot\left(\frac{d}{dx}\left(\ln(5x+7)\right)\right)$$

Now as separate steps, we'll find

$$\frac{d}{dx}\left(e^{3x}\right)=3e^{3x}\quad\text{(using the Chain Rule)}$$

and

$$\frac{d}{dx}\left(\ln(5x+7)\right)=\frac{1}{5x+7}\cdot 5\quad\text{(also using the Chain Rule).}$$

Finally, to substitute these in their places:

$$\frac{d}{dx}\left(e^{3x}\cdot\ln(5x+7)\right)=\left(3e^{3x}\right)\cdot\ln(5x+7)+e^{3x}\cdot\left(\frac{1}{5x+7}\cdot 5\right)$$

(We can stop here – we don't need to try to simplify any further.)

Example 3.4.8

Differentiate $z=\left(\dfrac{3t^3}{e^t(t-1)}\right)^4$.

Solution

Don't panic! As we come in from the outside, what's the first thing we encounter? It's that fourth power. That tells us that this is a composition, a (complicated) function raised to the fourth power.

Step One: Use the Chain Rule. The derivative of the outside TIMES the derivative of the inside:

$$\frac{dz}{dt}=\frac{d}{dt}\left(\frac{3t^3}{e^t(t-1)}\right)^4=4\left(\frac{3t^3}{e^t(t-1)}\right)^3\cdot\frac{d}{dt}\left(\frac{3t^3}{e^t(t-1)}\right)$$

Now we're one step inside, and we can concentrate on just the $\frac{d}{dt}\left(\frac{3t^3}{e^t(t-1)}\right)$ part. Now, as you come in from the outside, the first thing you encounter is a quotient – this is the quotient of two (complicated) functions.

Step Two: Use the Quotient Rule. The derivative of the numerator is straightforward, so we can just calculate it. The derivative of the denominator is a bit trickier, so we'll leave it for now:

$$\frac{d}{dt}\left(\frac{3t^3}{e^t(t-1)}\right)=\frac{\left(9t^2\right)\left(e^t(t-1)\right)-\left(3t^3\right)\left(\frac{d}{dt}\left(e^t(t-1)\right)\right)}{\left(e^t(t-1)\right)^2}$$

Now we've gone one more step inside, and we can concentrate on just the $\frac{d}{dt}\left(e^t(t-1)\right)$ part, which involves a product.

Step Three: Use the Product Rule:

$$\frac{d}{dt}\left(e^t(t-1)\right)=\left(e^t\right)(t-1)+\left(e^t\right)(1)$$

And now we're all the way in – no more derivatives to take!

Step Four: Now it's just a question of substituting back – be careful now!

$$\frac{d}{dt}\left(e^t(t-1)\right)=\left(e^t\right)(t-1)+\left(e^t\right)(1)$$

so

$$\frac{d}{dt}\left(\frac{3t^3}{e^t(t-1)}\right) = \frac{\left(9t^2\right)\left(e^t(t-1)\right) - \left(3t^3\right)\left(\left(e^t\right)(t-1) + \left(e^t\right)(1)\right)}{\left(e^t(t-1)\right)^2}$$

so

$$\frac{dz}{dt} = \frac{d}{dt}\left(\frac{3t^3}{e^t(t-1)}\right)^4 = 4\left(\frac{3t^3}{e^t(t-1)}\right)^3 \cdot \left(\frac{\left(9t^2\right)\left(e^t(t-1)\right) - \left(3t^3\right)\left(\left(e^t\right)(t-1) + \left(e^t\right)(1)\right)}{\left(e^t(t-1)\right)^2}\right)$$

Phew!

What if the Derivative Doesn't Exist?

Differentiable

A function is called **differentiable** at a point if its derivative exists at that point.

We've been acting as if derivatives exist everywhere for every function. This is true for most of the functions that you will run into in this class. But there are some common places where the derivative doesn't exist.

Remember that the derivative is the slope of the tangent line to the curve. That's what to think about.

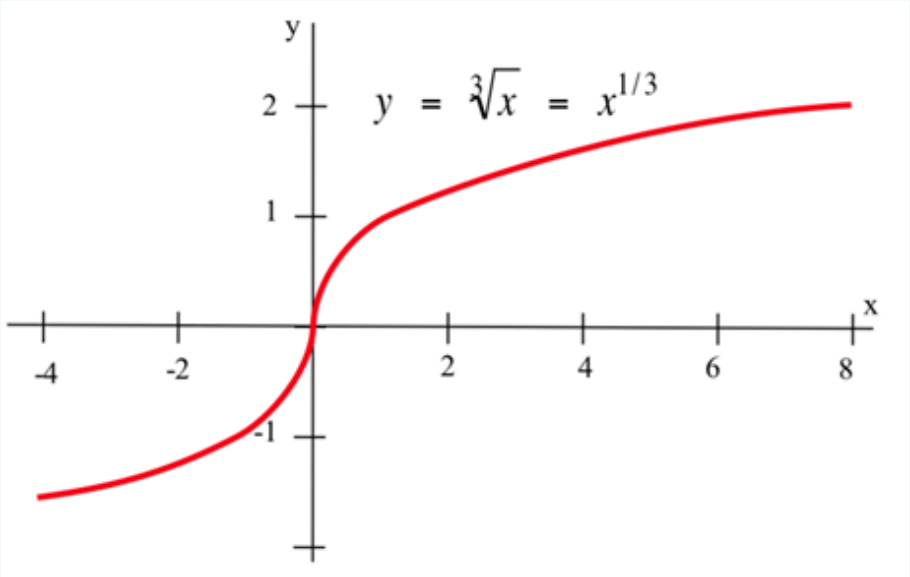
Where can a slope not exist? **If the tangent line is vertical, the derivative will not exist.**

Example 3.4.9

Show that $f(x) = \sqrt[3]{x} = x^{1/3}$ is not differentiable at $x = 0$.

Solution

Finding the derivative, $f(x) = \frac{1}{3}x^{-2/3} = \frac{1}{3x^{2/3}}$. At $x = 0$, this function is undefined. From the graph, we can see that the tangent line to this curve at $x = 0$ is vertical with undefined slope, which is why the derivative does not exist at $x = 0$.



Where can a tangent line not exist?

If there is a sharp corner (cusp) in the graph, the derivative will not exist at that point because there is no well-defined tangent line (a teetering tangent, if you will).

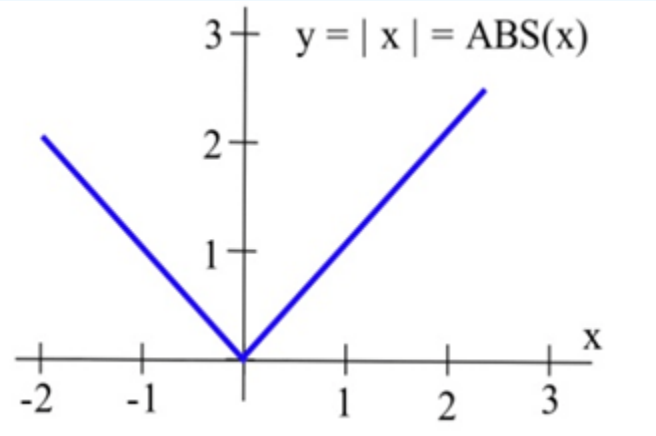
If there is a discontinuity in the graph (a jump, a break, a hole in the graph, or a vertical asymptote), the tangent line will be different on either side and **the derivative will not exist at that point**.

Example 3.4.10

Show that $f(x) = |x|$ is not differentiable at $x = 0$.

Solution

On the left side of the graph, the slope of the line is -1. On the right side of the graph, the slope is +1. There is no well-defined tangent line at the sharp corner at $x = 0$, so the function is not differentiable at that point.



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3.5: RATES OF CHANGE AND MARGINAL ANALYSIS

Learning Objectives

- Determine a new value of a quantity from the old value and the amount of change.
- Calculate the average rate of change and explain how it differs from the instantaneous rate of change.
- Apply rates of change to displacement, velocity, and acceleration of an object moving along a straight line.
- Predict the future population from the present value and the population growth rate.
- Use derivatives to calculate marginal cost and revenue in a business situation.

In this section we look at some applications of the derivative by focusing on the interpretation of the derivative as the rate of change of a function. These applications include **acceleration** and velocity in physics, **population growth rates** in biology, and marginal functions in economics.

Amount of Change Formula

One application for derivatives is to estimate an unknown value of a function at a point by using a known value of a function at some given point together with its rate of change at the given point. If $f(x)$ is a function defined on an interval $[a, a+h]$, then the **amount of change** of $f(x)$ over the interval is the change in the y values of the function over that interval and is given by

$$f(a+h)-f(a).$$

The **average rate of change** of the function f over that same interval is the ratio of the amount of change over that interval to the corresponding change in the x values. It is given by

$$\frac{f(a+h)-f(a)}{h}.$$

As we already know, the instantaneous rate of change of $f(x)$ at a is its derivative

$$f'(a)=\lim_{h\to 0}\frac{f(a+h)-f(a)}{h}.$$

For small enough values of h, $f\,'(a)\approx\frac{f(a+h)-f(a)}{h}$. We can then solve for $f(a+h)$ to get the amount of change formula:

$$f(a+h)\approx f(a)+f'(a)h. \tag{3.5.1}$$

We can use this formula if we know only $f(a)$and $f\,'(a)$ and wish to estimate the value of $f(a+h)$. For example, we may use the current population of a city and the rate at which it is growing to estimate its population in the near future. As we can see in Figure $3.5.1$, we are approximating $f(a+h)$ by the y coordinate at a+h on the line tangent to $f(x)$ at $x=a$. Observe that the accuracy of this estimate depends on the value of h as well as the value of $f\,'(a)$.

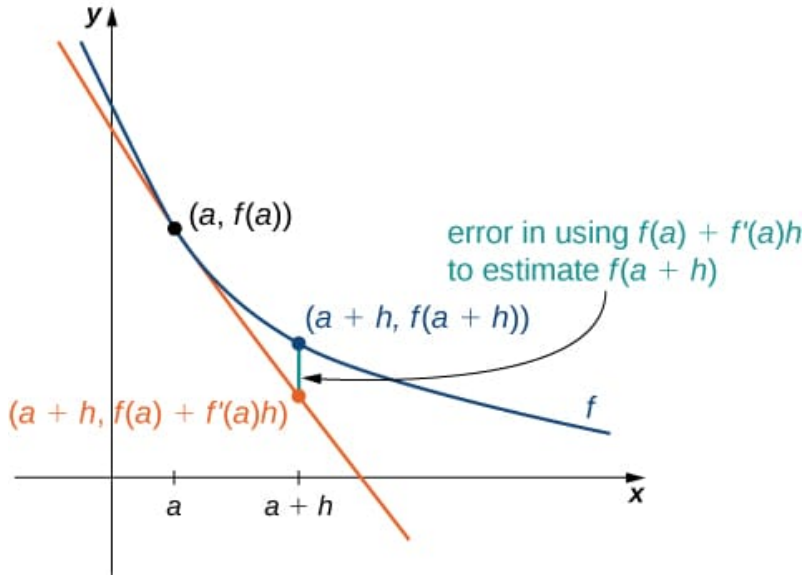


Figure 3.5.1: The new value of a changed quantity equals the original value plus the rate of change times the interval of change: $f(a+h) \approx f(a) + f\,'(a)h$.

Example 3.5.1: Estimating the Value of a Function

If $f(3) = 2$ and $f\,'(3) = 5$, estimate $f(3.2)$.

Solution

Begin by finding h. We have $h = 3.2 - 3 = 0.2$. Thus,

$$f(3.2) = f(3 + 0.2) \approx f(3) + (0.2)f\,'(3) = 2 + 0.2(5) = 3.$$

Exercise 3.5.1

Given $f(10) = -5$ and $f\,'(10) = 6$, estimate $f(10.1)$.

Hint available at the end of this section.

Answer available at the end of this section.

Motion along a Line

Another use for the derivative is to analyze motion along a line. We have described velocity as the rate of change of position. If we take the derivative of the velocity, we can find the acceleration, or the rate of change of velocity. It is also important to introduce the idea of **speed**, which is the magnitude of velocity. Thus, we can state the following mathematical definitions.

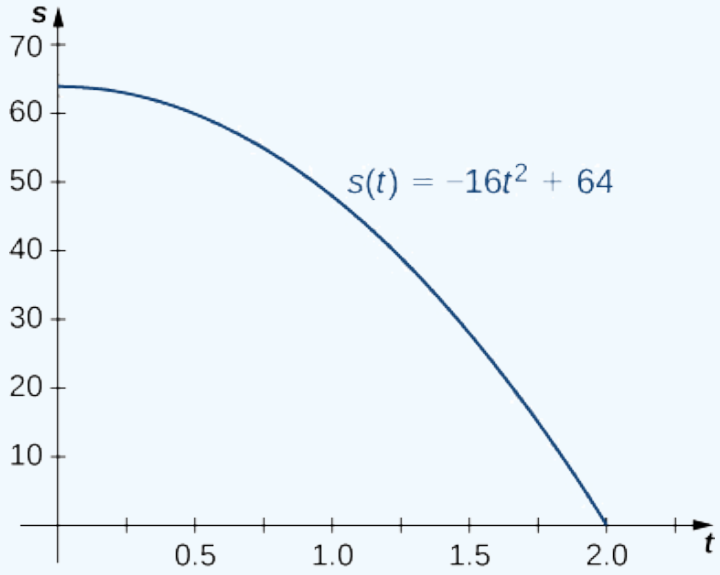
Definition

Let $s(t)$ be a function giving the position of an object at time t.

- The velocity of the object at time t is given by $v(t) = s\,'(t)$.
- The speed of the object at time t is given by $|v(t)|$.
- The acceleration of the object at t is given by $a(t) = v\,'(t) = s''(t)$.

Example 3.5.2: Comparing Instantaneous Velocity and Average Velocity

A ball is dropped from a height of 64 feet. Its height above ground (in feet) t seconds later is given by $s(t) = -16t^2 + 64$.



a. What is the instantaneous velocity of the ball when it hits the ground?
b. What is the average velocity during its fall?

Solution

The first thing to do is determine how long it takes the ball to reach the ground. To do this, set $s(t) = 0$. Solving $-16t^2 + 64 = 0$, we get $t = 2$, so it takes 2 seconds for the ball to reach the ground.

a. The instantaneous velocity of the ball as it strikes the ground is $v(2)$. Since $v(t) = s'(t) = -32t$, we obtain $v(t) = -64$ ft/s.
b. The average velocity of the ball during its fall is

$$v_{ave} = \frac{s(2)-s(0)}{2-0} = \frac{0-64}{2} = -32 \text{ ft/s.}$$

Example 3.5.3: Interpreting the Relationship between $v(t)$ and $a(t)$

A particle moves along a coordinate axis in the positive direction to the right. Its position at time t is given by $s(t) = t^3 - 4t + 2$. Find $v(1)$ and $a(1)$ and use these values to answer the following questions.

a. Is the particle moving from left to right or from right to left at time $t = 1$?
b. Is the particle speeding up or slowing down at time $t = 1$?

Solution

Begin by finding $v(t)$ and $a(t)$.

$v(t) = s'(t) = 3t^2 - 4$ and $a(t) = v'(t) = s''(t) = 6t$.

Evaluating these functions at $t = 1$, we obtain $v(1) = -1$ and $a(1) = 6$.

a. Because $v(1) < 0$, the particle is moving from right to left.

b. Because $v(1) < 0$ and $a(1) > 0$, velocity and acceleration are acting in opposite directions. In other words, the particle is being accelerated in the direction opposite the direction in which it is traveling, causing $|v(t)|$ to decrease. The particle is slowing down.

Example 3.5.4: Position and Velocity

The position of a particle moving along a coordinate axis is given by $s(t) = t^3 - 9t^2 + 24t + 4, \quad t \geq 0.$

a. Find $v(t)$.
b. At what time(s) is the particle at rest?
c. On what time intervals is the particle moving from left to right? From right to left?
d. Use the information obtained to sketch the path of the particle along a coordinate axis.

Solution

a. The velocity is the derivative of the position function:

$$v(t) = s\,'(t) = 3t^2 - 18t + 24.$$

b. The particle is at rest when $v(t) = 0$, so set $3t^2 - 18t + 24 = 0$. Factoring the left-hand side of the equation produces $3(t - 2)(t - 4) = 0$. Solving, we find that the particle is at rest at $t = 2$ and $t = 4$.

c. The particle is moving from left to right when $v(t) > 0$ and from right to left when $v(t) < 0$. Figure 3.5.2 gives the analysis of the sign of $v(t)$ for $t \geq 0$, but it does not represent the axis along which the particle is moving.



Figure 3.5.2:The sign of $v(t)$ determines the direction of the particle.

- Since $3t^2 - 18t + 24 > 0$ on $[0, 2) \cup (4, +\infty)$, the particle is moving from left to right on these intervals.
- Since $3t^2 - 18t + 24 < 0$ on $(2, 4)$, the particle is moving from right to left on this interval.

d. Before we can sketch the graph of the particle, we need to know its position at the time it starts moving $(t = 0)$ and at the times that it changes direction $(t = 2, 4)$. We have $s(0) = 4$, $s(2) = 24$, and $s(4) = 20$. This means that the particle begins on the coordinate axis at 4 and changes direction at 24 and 20 on the coordinate axis. The path of the particle is shown on a coordinate axis in Figure 3.5.3.

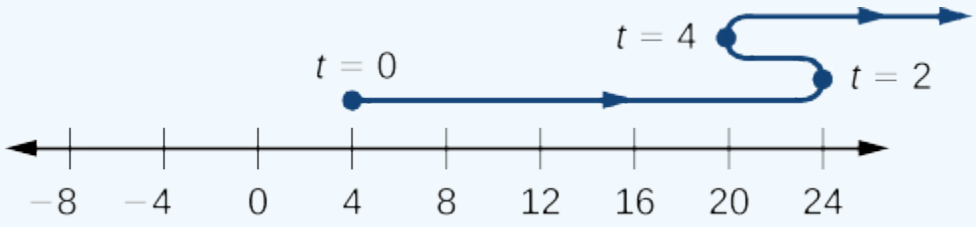


Figure 3.5.3: The path of the particle can be determined by analyzing $v(t)$.

Exercise 3.5.2

A particle moves along a coordinate axis. Its position at time t is given by $s(t) = t^2 - 5t + 1$. Is the particle moving from right to left or from left to right at time $t = 3$?

Hint available at the end of this section.

Answer available at the end of this section.

Population Change

In addition to analyzing velocity, speed, acceleration, and position, we can use derivatives to analyze various types of populations, including those as diverse as bacteria colonies and cities. We can use a current population, together with a growth rate, to estimate the size of a population in the future. The population growth rate is the rate of change of a population and consequently can be represented by the derivative of the size of the population.

Definition

If $P(t)$ is the number of entities present in a population, then the population growth rate of $P(t)$ is defined to be $P'(t)$.

Example 3.5.5: Estimating a Population

The population of a city is tripling every 5 years. If its current population is 10,000, what will be its approximate population 2 years from now?

Solution

Let $P(t)$ be the population (in thousands) t years from now. Thus, we know that $P(0) = 10$ and based on the information, we anticipate $P(5) = 30$. Now estimate $P'(0)$, the current growth rate, using

$$P'(0) \approx \frac{P(5)-P(0)}{5-0} = \frac{30-10}{5} = 4.$$

By applying Equation 3.5.1 to $P(t)$, we can estimate the population 2 years from now by writing

$$P(2) \approx P(0) + (2)P'(0) \approx 10 + 2(4) = 18;$$

thus, in 2 years the population will be 18,000.

Exercise 3.5.3

The current population of a mosquito colony is known to be 3,000; that is, $P(0) = 3,000$. If $P'(0) = 100$, estimate the size of the population in 3 days, where t is measured in days.

Hint available at the end of this section.

Answer available at the end of this section.

Changes in Cost and Revenue

In addition to analyzing motion along a line and population growth, derivatives are useful in analyzing changes in cost, revenue, and profit. The concept of a marginal function is common in the fields of business and economics and implies the use of derivatives. The marginal cost is the derivative of the cost function. The marginal revenue is the derivative of the revenue function. The marginal profit is the derivative of the profit function, which is based on the cost function and the revenue function.

Definition

- If $C(x)$ is the cost of producing x items, then the **marginal cost** $MC(x)$ is $MC(x) = C'(x)$.
- If $R(x)$ is the revenue obtained from selling x items, then the marginal revenue $MR(x)$ is $MR(x) = R'(x)$.
- If $P(x) = R(x) - C(x)$ is the profit obtained from selling x items, then the **marginal profit** $MP(x)$ is defined to be $MP(x) = P'(x) = MR(x) - MC(x) = R'(x) - C'(x)$.

We can roughly approximate

$$MC(x) = C'(x) = \lim_{h \to 0} \frac{C(x+h) - C(x)}{h}$$

by choosing an appropriate value for h. Since x represents objects, a reasonable and small value for h is 1. Thus, by substituting $h = 1$, we get the approximation $MC(x) = C\,'(x) \approx C(x+1) - C(x)$. Consequently, $C\,'(x)$ for a given value of x can be thought of as the change in cost associated with producing one additional item. In a similar way, $MR(x) = R\,'(x)$ approximates the revenue obtained by selling one additional item, and $MP(x) = P\,'(x)$ approximates the profit obtained by producing and selling one additional item.

Example 3.5.6: Applying Marginal Revenue

Assume that the number of barbeque dinners that can be sold, x, can be related to the price charged, p, by the equation $p(x) = 9 - 0.03x, 0 \leq x \leq 300$.

In this case, the revenue in dollars obtained by selling x barbeque dinners is given by

$$R(x) = xp(x) = x(9 - 0.03x) = -0.03x^2 + 9x \quad \text{for } 0 \leq x \leq 300.$$

Use the marginal revenue function to estimate the revenue obtained from selling the 101st barbeque dinner. Compare this to the actual revenue obtained from the sale of this dinner.

Solution

First, find the marginal revenue function: $MR(x) = R\,'(x) = -0.06x + 9$.

Next, use $R\,'(100)$ to approximate $R(101) - R(100)$, the revenue obtained from the sale of the 101st dinner. Since $R\,'(100) = 3$, the revenue obtained from the sale of the 101st dinner is approximately \$3.

The actual revenue obtained from the sale of the 101st dinner is

$$R(101) - R(100) = 602.97 - 600 = 2.97, \text{ or } \$2.97.$$

The marginal revenue is a fairly good estimate in this case and has the advantage of being easy to compute.

Exercise 3.5.4

Suppose that the profit obtained from the sale of x fish-fry dinners is given by $P(x) = -0.03x^2 + 8x - 50$. Use the marginal profit function to estimate the profit from the sale of the 101st fish-fry dinner.

Hint available at the end of this section.

Answer available at the end of this section.

Key Concepts

- Using $f(a+h) \approx f(a) + f\,'(a)h$, it is possible to estimate $f(a+h)$ given $f\,'(a)$ and $f(a)$.
- The rate of change of position is velocity, and the rate of change of velocity is acceleration. Speed is the absolute value, or magnitude, of velocity.
- The population growth rate and the present population can be used to predict the size of a future population.
- Marginal cost, marginal revenue, and marginal profit functions can be used to predict, respectively, the cost of producing one more item, the revenue obtained by selling one more item, and the profit obtained by producing and selling one more item.

Glossary

acceleration
: is the rate of change of the velocity, that is, the derivative of velocity

amount of change
: the amount of a function $f(x)$ over an interval $[x, x+h] is f(x+h)-f(x)$

average rate of change
: is a function $f(x)$ over an interval $[x, x+h]$ is $\frac{f(x+h)-f(a)}{b-a}$

marginal cost
: is the derivative of the cost function, or the approximate cost of producing one more item

marginal revenue
: is the derivative of the revenue function, or the approximate revenue obtained by selling one more item

marginal profit
: is the derivative of the profit function, or the approximate profit obtained by producing and selling one more item

population growth rate
: is the derivative of the population with respect to time

speed
: is the absolute value of velocity, that is, $|v(t)|$ is the speed of an object at time t whose velocity is given by $v(t)$

Answers

Exercise 3.5.1
Use the same process as in the preceding example.

Exercise 3.5.1
-4.4

Exercise 3.5.2
Find $v(3)$ and look at the sign.

Exercise 3.5.2
left to right

Exercise 3.5.3
Use $P(3) \approx P(0) + 3P'(0)$

Exercise 3.5.3
3,300

Exercise 3.5.4
Use $P'(100)$ to approximate $P(101) - P(100)$.

Exercise 3.5.4
$2

3.5E: Exercises for Section 3.5

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3.5E: Exercises for Section 3.5

In exercises 1 - 3, the given functions represent the position of a particle traveling along a horizontal line.

a. Find the velocity and acceleration functions.

b. Determine the time intervals when the object is slowing down or speeding up.

1) $s(t) = 2t^3 - 3t^2 - 12t + 8$

2) $s(t) = 2t^3 - 15t^2 + 36t - 10$

Answer

a. $v(t) = 6t^2 - 30t + 36, \quad a(t) = 12t - 30$;
b. speeds up for $(2, 2.5) \cup (3, \infty)$, slows down for $(0, 2) \cup (2.5, 3)$

3) $s(t) = \dfrac{t}{1 + t^2}$

4) A rocket is fired vertically upward from the ground. The distance s in feet that the rocket travels from the ground after t seconds is given by $s(t) = -16t^2 + 560t$.

a. Find the velocity of the rocket 3 seconds after being fired.

b. Find the acceleration of the rocket 3 seconds after being fired.

Answer

a. $464 \ \text{ft/s}^2$
b. $-32 \ \text{ft/s}^2$

5) A ball is thrown downward with a speed of 8 ft/s from the top of a 64-foot-tall building. After t seconds, its height above the ground is given by $s(t) = -16t^2 - 8t + 64$.

a. Determine how long it takes for the ball to hit the ground.

b. Determine the velocity of the ball when it hits the ground.

6) The position function $s(t) = t^2 - 3t - 4$ represents the position of the back of a car backing out of a driveway and then driving in a straight line, where s is in feet and t is in seconds. In this case, $s(t) = 0$ represents the time at which the back of the car is at the garage door, so $s(0) = -4$ is the starting position of the car, 4 feet inside the garage.

a. Determine the velocity of the car when $s(t) = 0$.

b. Determine the velocity of the car when $s(t) = 14$.

Answer

a. 5 ft/s
b. 9 ft/s

7) The position of a hummingbird flying along a straight line in t seconds is given by $s(t) = 3t^3 - 7t$ meters.

a. Determine the velocity of the bird at $t = 1$ sec.

b. Determine the acceleration of the bird at $t = 1$ sec.

c. Determine the acceleration of the bird when the velocity equals 0.

8) A potato is launched vertically upward with an initial velocity of 100 ft/s from a potato gun at the top of an 85-foot-tall building.

The distance in feet that the potato travels from the ground after t seconds is given by $s(t) = -16t^2 + 100t + 85$.

a. Find the velocity of the potato after 0.5 s and 5.75 s.

b. Find the speed of the potato at 0.5 s and 5.75 s.

c. Determine when the potato reaches its maximum height.

d. Find the acceleration of the potato at 0.5 s and 1.5 s.

e. Determine how long the potato is in the air.

f. Determine the velocity of the potato upon hitting the ground.

Answer

a. 84 ft/s, –84 ft/s
b. 84 ft/s
c. $\frac{25}{8}$ s
d. -32 ft/s^2 in both cases
e. $\frac{1}{8}(25 + \sqrt{965})$ s
f. $-4\sqrt{965}$ ft/s

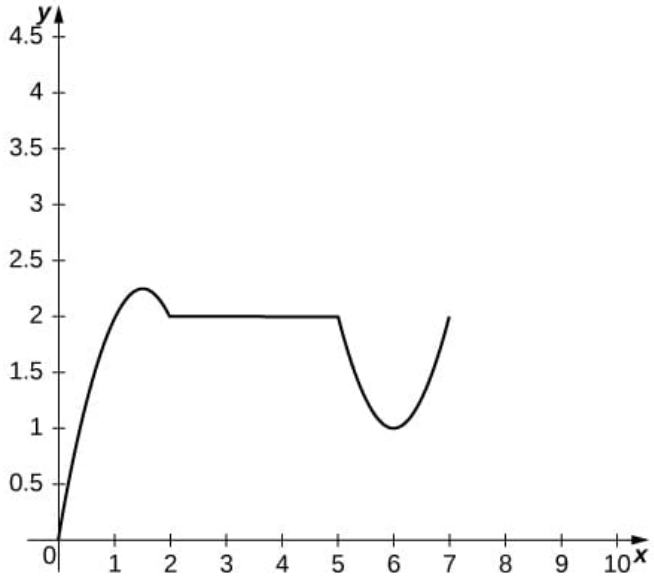
9) The position function $s(t) = t^3 - 8t$ gives the position in miles of a freight train where east is the positive direction and t is measured in hours.

a. Determine the direction the train is traveling when $s(t) = 0$.

b. Determine the direction the train is traveling when $a(t) = 0$.

c. Determine the time intervals when the train is slowing down or speeding up.

10) The following graph shows the position $y = s(t)$ of an object moving along a straight line.



a. Use the graph of the position function to determine the time intervals when the velocity is positive, negative, or zero.

b. Sketch the graph of the velocity function.

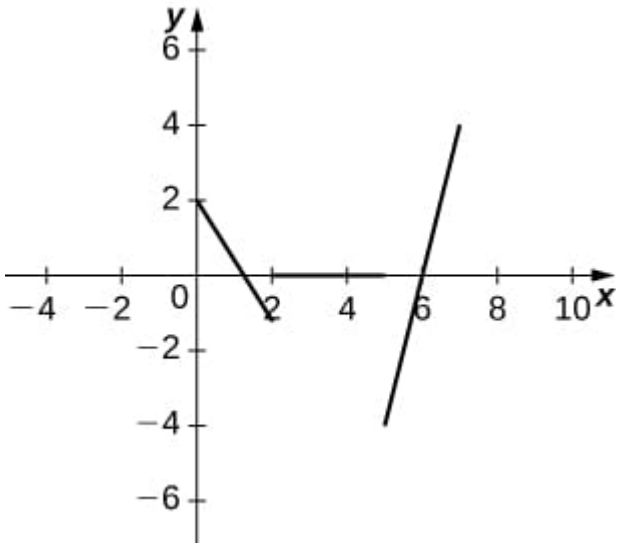
c. Use the graph of the velocity function to determine the time intervals when the acceleration is positive, negative, or zero.

d. Determine the time intervals when the object is speeding up or slowing down.

Answer

a. Velocity is positive on $(0, 1.5) \cup (6, 7)$, negative on $(1.5, 2) \cup (5, 6)$, and zero on $(2, 5)$.

b.



c. Acceleration is positive on $(5, 7)$, negative on $(0, 2)$, and zero on $(2, 5)$.
d. The object is speeding up on $(6, 7) \cup (1.5, 2)$ and slowing down on $(0, 1.5) \cup (5, 6)$.

11) The cost function, in dollars, of a company that manufactures food processors is given by $C(x) = 200 + \frac{7}{x} + \frac{x}{27}$, where x is the number of food processors manufactured.

a. Find the marginal cost function.

b. Find the marginal cost of manufacturing 12 food processors.

c. Find the actual cost of manufacturing the thirteenth food processor.

12) The price p (in dollars) and the demand x for a certain digital clock radio is given by the price–demand function $p = 10 - 0.001x$.

a. Find the revenue function $R(x)$

b. Find the marginal revenue function.

c. Find the marginal revenue at $x = 2000$ and 5000.

Answer

a. $R(x) = 10x - 0.001x^2$
b. $R'(x) = 10 - 0.002x$
c. \$6 per item, \$0 per item

13) [T] A profit is earned when revenue exceeds cost. Suppose the profit function for a skateboard manufacturer is given by $P(x) = 30x - 0.3x^2 - 250$, where x is the number of skateboards sold.

a. Find the exact profit from the sale of the thirtieth skateboard.

b. Find the marginal profit function and use it to estimate the profit from the sale of the thirtieth skateboard.

14) [T] In general, the profit function is the difference between the revenue and cost functions: $P(x) = R(x) - C(x)$.

Suppose the price-demand and cost functions for the production of cordless drills is given respectively by $p = 143 - 0.03x$ and $C(x) = 75,000 + 65x$, where x is the number of cordless drills that are sold at a price of p dollars per drill and $C(x)$ is the cost of producing x cordless drills.

a. Find the marginal cost function.

b. Find the revenue and marginal revenue functions.

c. Find $R\,'(1000)$ and $R\,'(4000)$. Interpret the results.

d. Find the profit and marginal profit functions.

e. Find $P\,'(1000)$ and $P\,'(4000)$. Interpret the results.

Answer

a. $C\,'(x) = 65$
b. $R(x) = 143x - 0.03x^2, R\,'(x) = 143 - 0.06x$
c. $R\,'(1000) = 83, \quad R\,'(4000) = -97$. At a production level of 1000 cordless drills, revenue is increasing at a rate of $83 per drill; at a production level of 4000 cordless drills, revenue is decreasing at a rate of $97 per drill.
d. $P(x) = -0.03x^2 + 78x - 75000, \quad P\,'(x) = -0.06x + 78$
e. $P\,'(1000) = 18, \quad P\,'(4000) = -162$. At a production level of 1000 cordless drills, profit is increasing at a rate of $18 per drill; at a production level of 4000 cordless drills, profit is decreasing at a rate of $162 per drill.

15) A small town in Ohio commissioned an actuarial firm to conduct a study that modeled the rate of change of the town's population. The study found that the town's population (measured in thousands of people) can be modeled by the function $P(t) = -\frac{1}{3}t^3 + 64t + 3000$, where t is measured in years.

a. Find the rate of change function $P\,'(t)$ of the population function.

b. Find $P\,'(1), \ P\,'(2), \ P\,'(3)$, and $P\,'(4)$. Interpret what the results mean for the town.

c. Find $P''(1), \ P''(2), \ P''(3)$, and $P''(4)$. Interpret what the results mean for the town's population.

16) [T] A culture of bacteria grows in number according to the function $N(t) = 3000(1 + \frac{4t}{t^2 + 100})$, where t is measured in hours.

a. Find the rate of change of the number of bacteria.

b. Find $N\,'(0), \ N\,'(10), \ N\,'(20)$, and $N\,'(30)$.

c. Interpret the results in (b).

d. Find $N''(0), \ N''(10), \ N''(20)$, and $N''(30)$. Interpret what the answers imply about the bacteria population growth.

Answer

a. $N\,'(t) = 3000\left(\frac{-4t^2 + 400}{(t^2 + 100)^2}\right)$
b. $120, 0, -14.4, -9.6$
c. The bacteria population increases from time 0 to 10 hours; afterwards, the bacteria population decreases.
d. $0, -6, 0.384, 0.432$. The rate at which the bacteria is increasing is decreasing during the first 10 hours. Afterwards, the bacteria population is decreasing at a decreasing rate.

17) The centripetal force of an object of mass m is given by $F(r) = \frac{mv^2}{r}$, where v is the speed of rotation and r is the distance from the center of rotation.

a. Find the rate of change of centripetal force with respect to the distance from the center of rotation.

b. Find the rate of change of centripetal force of an object with mass 1000 kilograms, velocity of 13.89 m/s, and a distance from the center of rotation of 200 meters.

The following questions concern the population (in millions) of London by decade in the 19th century, which is listed in the following table.

Year Since 1800	Population (millions)
1	0.8975
11	1.040
21	1.264
31	1.516
41	1.661
51	2.000
61	2.634
71	3.272
81	3.911
91	4.422

Population of LondonSource: http://en.Wikipedia.org/wiki/Demographics_of_London

18) [T]

a. Using a calculator or a computer program, find the best-fit linear function to measure the population.

b. Find the derivative of the equation in a. and explain its physical meaning.

c. Find the second derivative of the equation and explain its physical meaning.

Answer

a. $P(t) = 0.03983 + 0.4280$
b. $P'(t) = 0.03983$. The population is increasing.
c. $P''(t) = 0$. The rate at which the population is increasing is constant.

19) [T]

a. Using a calculator or a computer program, find the best-fit quadratic curve through the data.

b. Find the derivative of the equation and explain its physical meaning.

c. Find the second derivative of the equation and explain its physical meaning.

For the following exercises, consider an astronaut on a large planet in another galaxy. To learn more about the composition of this planet, the astronaut drops an electronic sensor into a deep trench. The sensor transmits its vertical position every second in relation to the astronaut's position. The summary of the falling sensor data is displayed in the following table.

Time after dropping (s)	Position (m)
0	0
1	–1
2	–2
3	–5
4	–7
5	–14

20) [T]

a. Using a calculator or computer program, find the best-fit quadratic curve to the data.

b. Find the derivative of the position function and explain its physical meaning.

c. Find the second derivative of the position function and explain its physical meaning.

Answer

a. $p(t) = -0.6071x^2 + 0.4357x - 0.3571$
b. $p\,'(t) = -1.214x + 0.4357$. This is the velocity of the sensor.
c. $p''(t) = -1.214$. This is the acceleration of the sensor; it is a constant acceleration downward.

21) [T]

a. Using a calculator or computer program, find the best-fit cubic curve to the data.

b. Find the derivative of the position function and explain its physical meaning.

c. Find the second derivative of the position function and explain its physical meaning.

d. Using the result from c. explain why a cubic function is not a good choice for this problem.

The following problems deal with the Holling type I, II, and III equations. These equations describe the ecological event of growth of a predator population given the amount of prey available for consumption.

22) [T] The **Holling type I equation** is described by $f(x) = ax$, where x is the amount of prey available and $a > 0$ is the rate at which the predator meets the prey for consumption.

a. Graph the Holling type I equation, given $a = 0.5$.

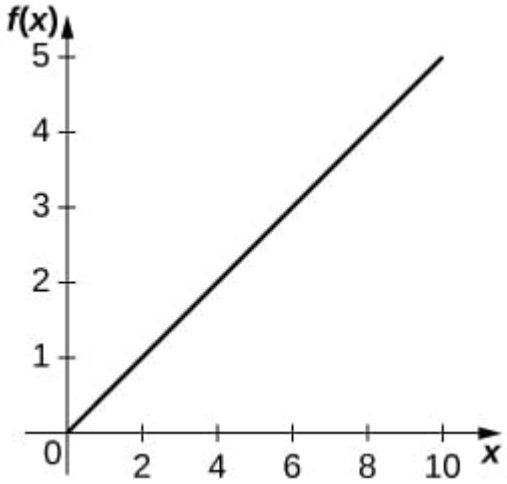
b. Determine the first derivative of the Holling type I equation and explain physically what the derivative implies.

c. Determine the second derivative of the Holling type I equation and explain physically what the derivative implies.

d. Using the interpretations from b. and c. explain why the Holling type I equation may not be realistic.

Answer

a.



b. $f\,'(x) = a$. The more increase in prey, the more growth for predators.
c. $f''(x) = 0$. As the amount of prey increases, the rate at which the predator population growth increases is

constant.
d. This equation assumes that if there is more prey, the predator is able to increase consumption linearly. This assumption is unphysical because we would expect there to be some saturation point at which there is too much prey for the predator to consume adequately.

23) [T] The Holling type II equation is described by $f(x) = \frac{ax}{n+x}$, where x is the amount of prey available and $a > 0$ is the maximum consumption rate of the predator.

a. Graph the Holling type II equation given $a = 0.5$ and $n = 5$. What are the differences between the Holling type I and II equations?

b. Take the first derivative of the Holling type II equation and interpret the physical meaning of the derivative.

c. Show that $f(n) = \frac{1}{2}a$ and interpret the meaning of the parameter n.

d. Find and interpret the meaning of the second derivative. What makes the Holling type II function more realistic than the Holling type I function?

24) [T] The Holling type III equation is described by $f(x) = \frac{ax^2}{n^2+x^2}$, where x is the amount of prey available and $a > 0$ is the maximum consumption rate of the predator.

a. Graph the Holling type III equation given $a = 0.5$ and $n = 5$. What are the differences between the Holling type II and III equations?

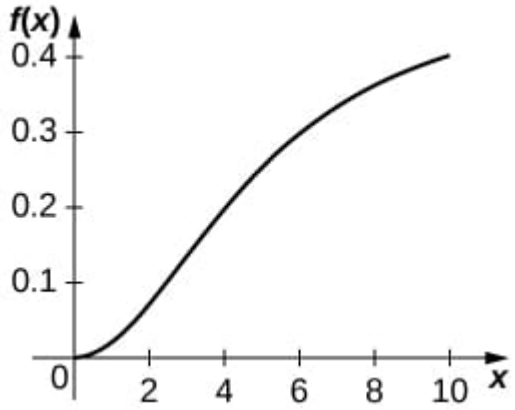
b. Take the first derivative of the Holling type III equation and interpret the physical meaning of the derivative.

c. Find and interpret the meaning of the second derivative (it may help to graph the second derivative).

d. What additional ecological phenomena does the Holling type III function describe compared with the Holling type II function?

Answer

a.



b. $f'(x) = \frac{2axn^2}{(n^2+x^2)^2}$. When the amount of prey increases, the predator growth increases.
c. $f''(x) = \frac{2an^2(n^2-3x^2)}{(n^2+x^2)^3}$. When the amount of prey is extremely small, the rate at which predator growth is increasing is increasing, but when the amount of prey reaches above a certain threshold, the rate at which predator growth is increasing begins to decrease.
d. At lower levels of prey, the prey is more easily able to avoid detection by the predator, so fewer prey individuals are consumed, resulting in less predator growth.

25) [T] The populations of the snowshoe hare (in thousands) and the lynx (in hundreds) collected over 7 years from 1937 to 1943 are shown in the following table. The snowshoe hare is the primary prey of the lynx.

Population of snowshoe hare (thousands)	Population of lynx (hundreds)
20	10
5	15
65	55
95	60

Snowshoe Hare and Lynx PopulationsSource: http://www.biotopics.co.uk/newgcse/predatorprey.html.

a. Graph the data points and determine which Holling-type function fits the data best.

b. Using the meanings of the parameters a and n, determine values for those parameters by examining a graph of the data. Recall that n measures what prey value results in the half-maximum of the predator value.

c. Plot the resulting Holling-type I, II, and III functions on top of the data. Was the result from part a. correct?

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3.6: Implicit Differentiation and Related Rates

Implicit Differentiation

In our work up until now, the functions we needed to differentiate were either given **explicitly**, such as $y = x^2 + e^x$, or it was possible to get an explicit formula for them, such as solving $y^3 - 3x^2 = 5$ to get $y = \sqrt[3]{5 + 3x^2}$. Sometimes, however, we will have an equation relating x and y which is either difficult or impossible to solve explicitly for y, such as $y + e^y = x^2$. In any case, we can still find $y' = f'(x)$ by using implicit differentiation.

The key idea behind implicit differentiation is to **assume that y is a function of x** even if we cannot explicitly solve for y. This assumption does not require any work, but we need to be very careful to treat y as a function when we differentiate and to use the Chain Rule.

Example 3.6.1

Assume that y is a function of x. Calculate

1. $\frac{d}{dx}\left(y^3\right)$
2. $\frac{d}{dx}\left(x^3y^2\right)$
3. $\frac{d}{dx}\left(\ln(y)\right)$

Solution

1. We need the chain rule since y is a function of x:
$$\frac{d}{dx}\left(y^3\right) = 3y^2\frac{dy}{dx} \overset{\text{or}}{=} 3y^2y'$$
2. We need to use the product rule and the Chain Rule:
$$\begin{aligned}\frac{d}{dx}\left(x^3y^2\right) &= x^3\frac{d}{dx}\left(y^2\right) + y^2\frac{d}{dx}\left(x^3\right)\\ &= x^3 2y\frac{dy}{dx} + y^2 3x^2\\ &\overset{\text{or}}{=} 2x^3yy' + 3y^2x^2\end{aligned}$$
3. We know $\frac{d}{dx}\left(\ln(x)\right) = \frac{1}{x}$, so we use that and the Chain Rule:
$$\frac{d}{dx}\left(\ln(y)\right) = \frac{1}{y}\cdot y'$$

Implicit Differentiation

To determine y', differentiate each side of the defining equation, **treating y as a function of x**, and then algebraically solve for y'.

Example 3.6.2

Find the slope of the tangent line to the circle $x^2 + y^2 = 25$ at the point (3,4) using implicit differentiation.

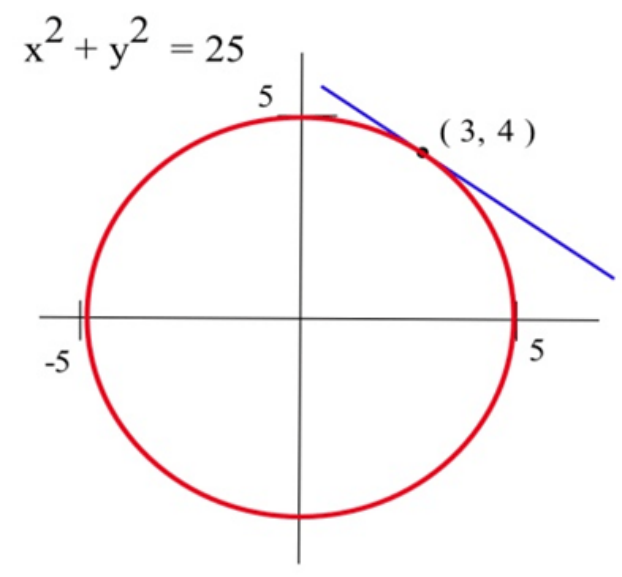
Solution

We differentiate each side of the equation $x^2 + y^2 = 25$ and then solve for y':

$$\frac{d}{dx}\left(x^2+y^2\right)=\frac{d}{dx}(25)$$
$$2x+2yy'=0$$

Solving for y', we have $y'=-\frac{2x}{2y}=-\frac{x}{y}$, and, at the point (3,4),

$$y'=-\frac{3}{4}.$$



In the previous example, it would have been easy to explicitly solve for y, and then we could differentiate y to get y'. Because we could explicitly solve for y, we had a choice of methods for calculating y'. Sometimes, however, we cannot explicitly solve for y, and the only way of determining y' is to use implicit differentiation.

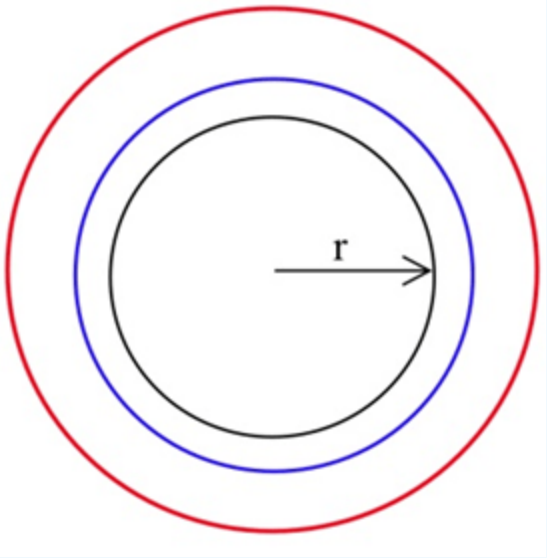
Related Rates

If several variables or quantities are related to each other and some of the variables are changing at a known rate, then we can use derivatives to determine how rapidly the other variables must be changing.

Example 3.6.3

Suppose the border of a town is roughly circular, and the radius of that circle has been increasing at a rate of 0.1 miles each year. Find how fast the area of the town has been increasing when the radius is 5 miles.

Solution



We could get an *approximate* answer by calculating the area of the circle when the radius is 5 miles ($A = \pi r^2 = \pi(5 \text{ miles})^2 \approx 78.6 \text{ miles}^2$) and 1 year later when the radius is 0.1 feet larger than before ($A = \pi r^2 = \pi(5.1 \text{ miles})^2 \approx 81.7 \text{ miles}^2$) and then finding

$$\frac{\Delta \text{Area}}{\Delta \text{time}} = \frac{81.7 \text{ mi}^2 - 78.6 \text{ mi}^2}{1 \text{ year}} = 3.1 \text{ mi}^2/\text{yr}.$$

This approximate answer represents the average change in area during the 1 year period when the radius increased from 5 miles to 5.1 miles, and would correspond to the secant slope on the area graph.

To find the exact answer, though, we need derivatives. In this case both radius and area are functions of time:

$$r(t) = \text{ radius at time } t \qquad A(t) = \text{ area at time } t$$

We know how fast the radius is changing, which is a statement about the derivative: $\frac{dr}{dt} = 0.1 \frac{\text{mile}}{\text{year}}$. We also know that $r = 5$ at our moment of interest.

We are looking for how fast the area is increasing, which is $\frac{dA}{dt}$.

Now we need an equation relating our variables, which is the area equation:

$$A = \pi r^2.$$

Taking the derivative of both sides of that equation with respect to t, we can use implicit differentiation:

$$\frac{d}{dt}(A) = \frac{d}{dt}(\pi r^2)$$
$$\frac{dA}{dt} = \pi 2r \frac{dr}{dt}$$

Plugging in the values we know for r and $\frac{dr}{dt}$,

$$\frac{dA}{dt} = \pi 2(5 \text{ miles}) \left(0.1 \frac{\text{miles}}{\text{year}}\right) = \pi \frac{\text{miles}^2}{\text{year}}$$

So the area of the town is increasing by approximately 3.14 square miles per year when the radius is 5 miles.

Related Rates

When working with a related rates problem,

1. Draw a picture (if possible).
2. Identify the quantities that are changing, and assign them variables.
3. Find an equation that relates those quantities.
4. Differentiate both sides of that equation with respect to time.
5. Plug in any known values for the variables or rates of change.
6. Solve for the desired rate.

Example 3.6.4

A company has determined the demand curve for their product is $q = \sqrt{5000 - p^2}$, where p is the price in dollars, and q is the quantity in millions. If weather conditions are driving the price up \$2 a week, find the rate at which demand is changing when the price is \$40.

Solution

The quantities changing are p and q, and we assume they are both functions of time, t, in weeks. We already have an equation relating the quantities, so we can implicitly differentiate it.

$$\begin{aligned}\frac{d}{dt}(q) &= \frac{d}{dt}\left(5000 - p^2\right)^{1/2} \\ \frac{dq}{dt} &= \frac{1}{2}\left(5000 - p^2\right)^{-1/2}\frac{d}{dt}\left(5000 - p^2\right) \\ \frac{dq}{dt} &= \frac{1}{2}\left(5000 - p^2\right)^{-1/2}\left(-2p\frac{dp}{dt}\right)\end{aligned}$$

Using the given information, we know the price is increasing by \$2 per week when the price is \$40, giving $\frac{dp}{dt} = 2$ when $p = 40$. Plugging in these values,

$$\frac{dq}{dt} = \frac{1}{2}\left(5000 - 40^2\right)^{-1/2}(-2(40)(2)) \approx -1.37$$

Demand is falling by 1.37 million items per week.

Example 3.6.5

The total daily cost for producing x items in a day is $TC(x) = 300,000 + 4x + \frac{200,000}{x}$. If production has been ramping up by 20 items a day, find the rate at which total daily cost is increasing, if they are currently producing 2,000 items.

Solution

The quantities changing are x and TC, and we assume they are both functions of time, t, in days. We already have an equation relating the quantities, so we can implicitly differentiate it.

$$\begin{aligned}\frac{d}{dt}(TC) &= \frac{d}{dt}\left(300,000 + 4x + 200,000x^{-1}\right) \\ \frac{dTC}{dt} &= 4\frac{dx}{dt} - 200,000x^{-2}\frac{dx}{dt} \\ \frac{dTC}{dt} &= \left(4 - \frac{200,000}{x^2}\right)\frac{dx}{dt}\end{aligned}$$

We know the quantity produced is increasing by 20 items per week when the production is 2,000 items, giving $\frac{dx}{dt} = 20$ when $x = 2000$. Plugging in these values,

$$\frac{dTC}{dt} = \left(4 - \frac{200,000}{2000^2}\right)(20) = 79$$

Total daily cost is increasing by \$79 each day.

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4: APPLICATIONS OF DIFFERENTIATION

4.1: Curve Sketching
4.2: Second Derivative and Concavity
4.3: Optimization
4.4: Applied Optimization
4.5: Implicit Differentiation and Related Rates

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4.1: Curve Sketching

This section examines some of the interplay between the shape of the graph of f and the behavior of f'. If we have a graph of f, we will see what we can conclude about the values of f'. If we know values of f', we will see what we can conclude about the graph of f. We will also utilize the information from f'' that we learning in the last section.

First Derivative Information

Definitions

The function $f(x)$ is **increasing** on (a,b) if $a < x_1 < x_2 < b$ implies $f(x_1) < f(x_2)$.

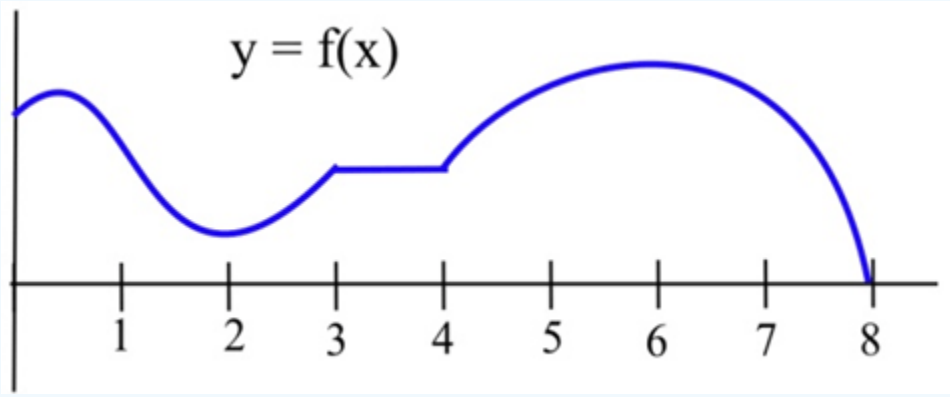
The function $f(x)$ is **decreasing** on (a,b) if $a < x_1 < x_2 < b$ implies $f(x_1) > f(x_2)$.

Graphically, f is **increasing** (decreasing) if, as we move from left to right along the graph of f, the height of the graph **increases** (decreases).

These same ideas make sense if we consider $h(t)$ to be the height (in feet) of a rocket at time t seconds. We naturally say that the rocket is rising or that its height is increasing if the height $h(t)$ increases over a period of time, as t increases.

Example 4.1.1

List the intervals on which the function shown is increasing or decreasing.



f is increasing on the intervals [0,0.5], [2,3] and [4,6].

f is decreasing on [0.5,2] and [6,8].

On the interval [3,4] the function is not increasing or decreasing – it is constant.

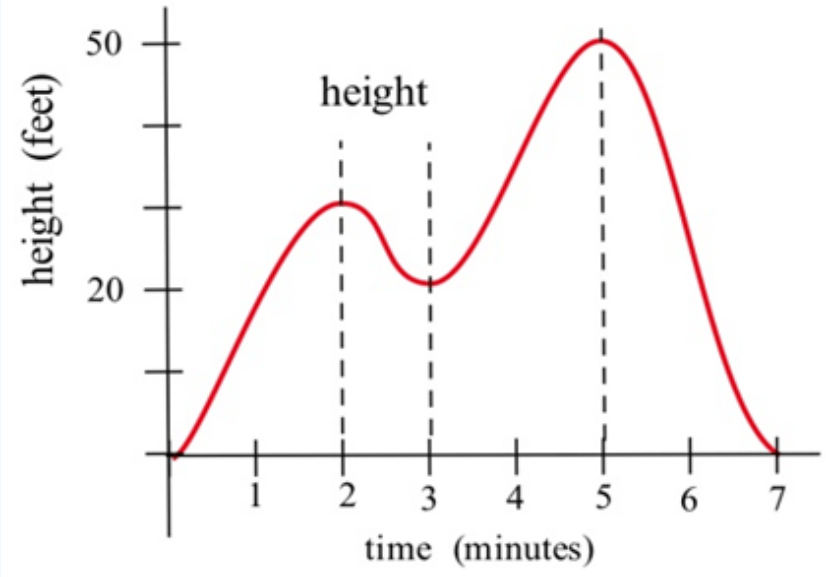
First Derivative Information about Shape

For a function f which is differentiable on an interval (a,b);

- if f is increasing on (a,b), then $f'(x) \geq 0$ for all x in (a,b).
- if f is decreasing on (a,b), then $f'(x) \leq 0$ for all x in (a,b).
- if f is constant on (a,b), then $f'(x) = 0$ for all x in (a,b).

Example 4.1.2

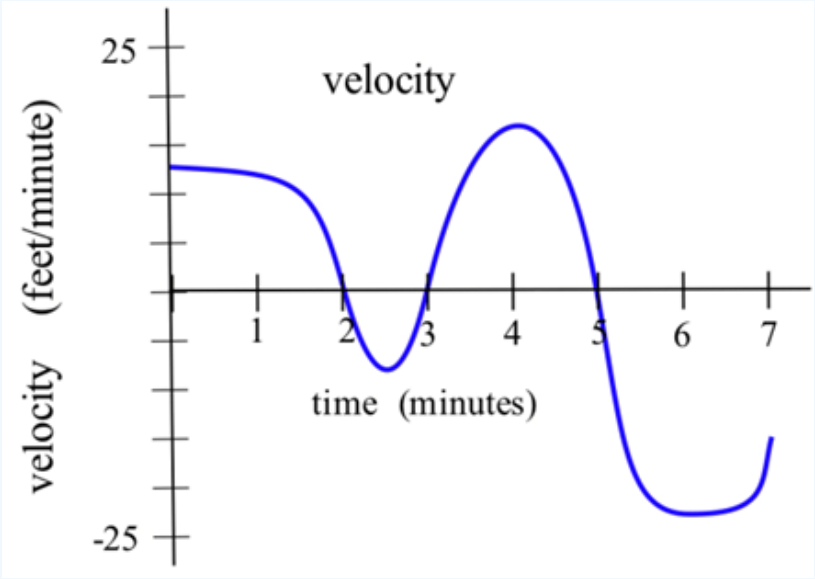
The graph shows the height of a helicopter during a period of time. Sketch the graph of the upward velocity of the helicopter, $\frac{dh}{dt}$.



Notice that the $h(t)$ has a local maximum when $t = 2$ and $t = 5$, and so $v(2) = 0$ and $v(5) = 0$. Similarly, $h(t)$ has a local minimum when $t = 3$, so $v(3) = 0$.

When h is increasing, v is positive. When h is decreasing, v is negative.

Using this information, we can sketch a graph of $v(t) = \frac{dh}{dt}$.



The next theorem is almost the converse of the First Shape Theorem and explains the relationship between the values of the derivative and the graph of a function from a different perspective. It says that if we know something about the values of f', then we can draw some conclusions about the shape of the graph of f.

First Derivative Information about Shape (part 2)

For a function f which is differentiable on an interval I;

- if $f'(x) > 0$ for all x in the interval I, then f is increasing on I.
- if $f'(x) < 0$ for all x in the interval I, then f is decreasing on I.
- if $f'(x) = 0$ for all x in the interval I, then f is constant on I.

Example 4.1.3

Use information about the values of f' to help graph $f(x) = x^3 - 6x^2 + 9x + 1$.

Solution

$f'(x) = 3x^2 - 12x + 9 = 3(x-1)(x-3)$ so $f'(x) = 0$ only when $x = 1$ or $x = 3$. f' is a polynomial so it is always defined.

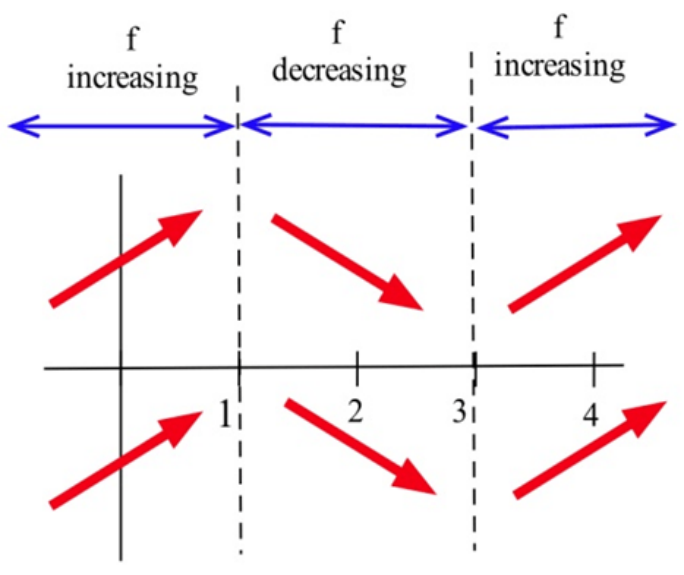
The only critical numbers for f are $x = 1$ and $x = 3$, and they divide the real number line into three intervals: $(-\infty, 1)$, $(1, 3)$, and $(3, \infty)$. On each of these intervals, the function is either always increasing or always decreasing.

If $x < 1$, then $f'(x) =$ 3(negative number)(negative number) > 0 so f is increasing.

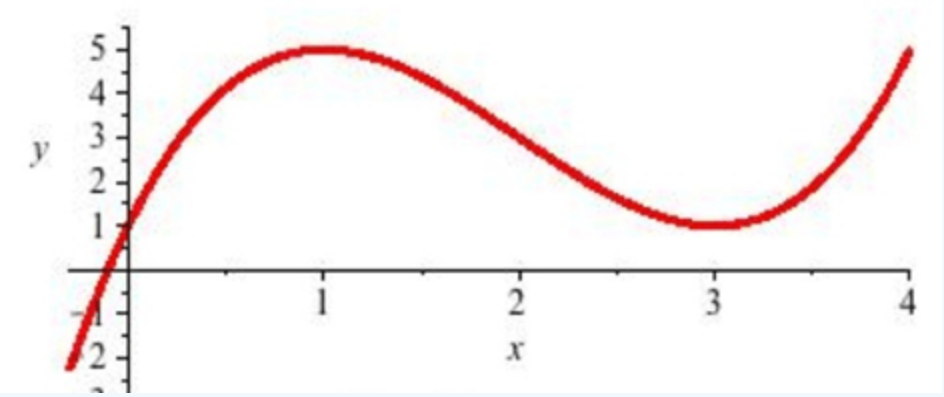
If $1 < x < 3$, then $f'(x) =$ 3(positive number)(negative number) < 0 so f is decreasing.

If $x > 3$, then $f'(x) =$ 3(positive number)(positive number) > 0 so f is increasing.

Even though we don't know the value of f anywhere yet, we do know a lot about the shape of the graph of f: as we move from left to right along the x-axis, the graph of f increases until $x = 1$, then the graph decreases until $x = 3$, and then the graph increases again. The graph of f makes "turns" when $x = 1$ and $x = 3$; it has a local maximum at $x = 1$, and a local minimum at $x = 3$.



To plot the graph of f, we still need to evaluate f at a few values of x, but only at a very few values. $f(1) = 5$, and (1,5) is a local maximum of f. $f(3) = 1$, and (3,1) is a local minimum of f. The resulting graph of f is shown here.



Second Derivative Information

Until now, we've only used first derivative information, but we could also use information from the second derivative to provide more information about the shape of the function.

Second Derivative Information about Shape

- If f is concave up on (a, b), then $f''(x) \geq 0$ for all x in (a, b).
- If f is concave down on (a, b), then $f''(x) \leq 0$ for all x in (a, b).

The converse of both of these are also true:

- If $f''(x) \geq 0$ for all x in (a, b), then f is concave up on (a, b).
- If $f''(x) \leq 0$ for all x in (a, b), then f is concave down on (a, b).

Example 4.1.4

Use information about the values of f'' to help determine the intervals on which the function $f(x) = x^3 - 6x^2 + 9x + 1$ is concave up and concave down.

Solution

For concavity, we need the second derivative: $f'(x) = 3x^2 - 12x + 9$, so $f''(x) = 6x - 12$.

To find possible inflection points, set the second derivative equal to zero. $6x - 12 = 0$, so $x = 2$. This divides the real number line into two intervals: $(-\infty, 2)$ and $(2, \infty)$.

For $x < 2$, the second derivative is negative (for example, $f''(0) = 6(0) - 12 = -12$), so f is concave down. For $x > 2$, the second derivative is positive, so f is concave up.

We could have incorporated this concavity information when sketching the graph for the previous example, and indeed we can see the concavity reflected in the graph shown.

Example 4.1.5

Use information about the values of f' and f'' to help graph $f(x) = x^{2/3}$.

Solution

$f'(x) = \frac{2}{3}x^{-1/3}$. This is undefined at $x = 0$.

$f''(x) = -\frac{2}{9}x^{-4/3}$. This is also undefined at $x = 0$.

This creates two intervals: $x < 0$, and $x > 0$.

On the interval $x < 0$, we could test out a value like $x = -1$:

$$f'(-1) = \frac{2}{3}(-1)^{-1/3} = -\frac{2}{3}$$

and

$$f''(-1) = -\frac{2}{9}(-1)^{-4/3} = -\frac{2}{9}.$$

$f'(x)$ is negative and $f''(x)$ is negative, so we can conclude that the function is decreasing and concave down on this interval.

On the interval $x > 0$, we could test out a value like $x = 1$:

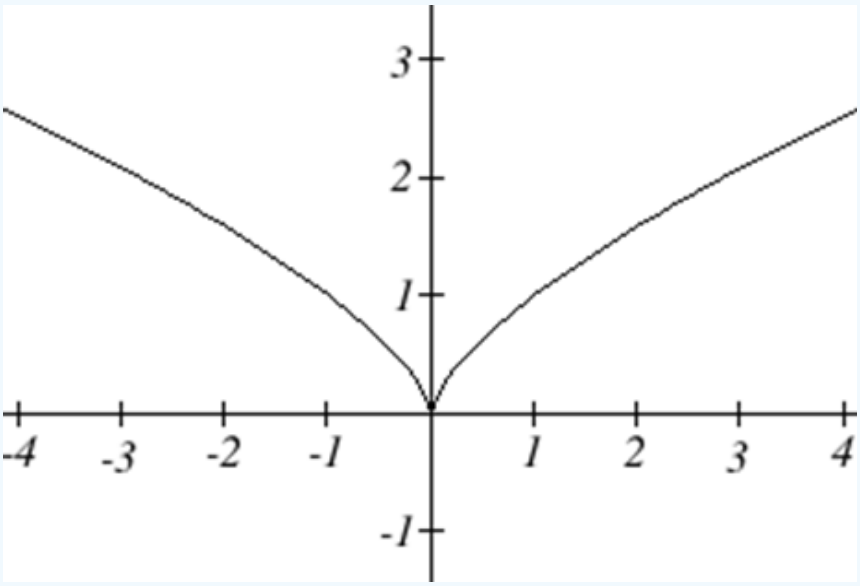
$$f'(1) = \frac{2}{3}(1)^{-1/3} = \frac{2}{3}$$

and

$$f''(1) = -\frac{2}{9}(1)^{-4/3} = -\frac{2}{9}.$$

$f'(x)$ is positive and $f''(x)$ is negative, so we can conclude that the function is increasing and concave down on this interval.

We can also calculate that $f(0) = 0$, giving us a base point for the graph. Using this information, we can conclude the graph must look like this:



Sketching without an Equation

Of course, graphing calculators and computers are great at graphing functions. Calculus provides a way to illuminate what may be hidden or out of view when we graph using technology. More importantly, calculus gives us a way to look at the derivatives of functions for which there is no equation given. We already saw the idea of this back in Section 2.3 where we sketched the derivative of two graphs by estimating slopes on the curves.

We can summarize all the derivative information about shape in a table.

Summary of Derivative Information about the Graph

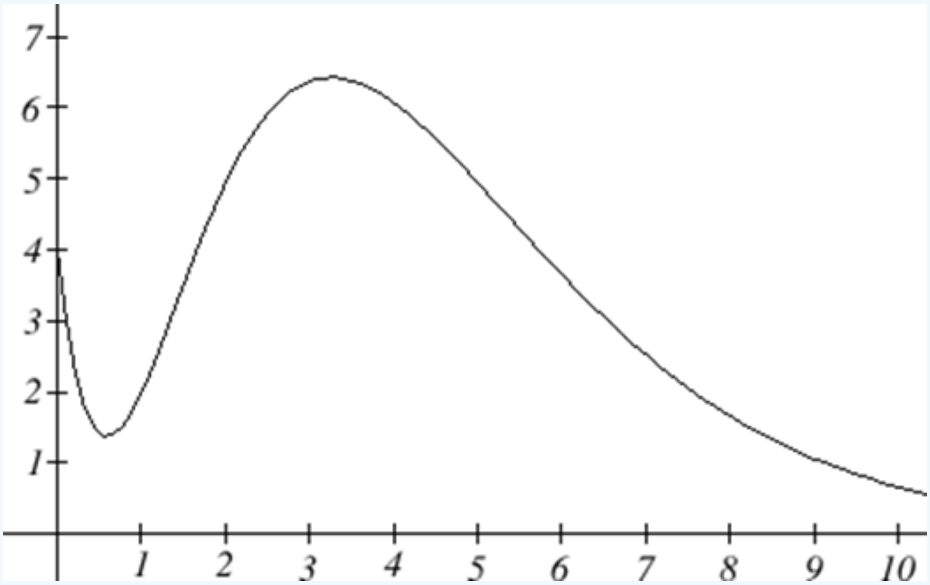
$f(x)$	Increasing	Decreasing	Concave Up	Concave Down
$f'(x)$	$+$	$-$	Increasing	Decreasing
$f''(x)$			$+$	$-$

When $f'(x) = 0$, the graph of f may have a local max or min.

When $f''(x) = 0$, the graph of f may have an inflection point.

Example 4.1.6

A company's bank balance, B, in millions of dollars, t weeks after releasing a new product is shown in the graph below. Sketch a graph of the marginal balance – the rate at which the bank balance was changing over time.



Solution

Notice that since the tangent line will be horizontal at about $t = 0.6$ and $t = 3.2$, the derivative will be 0 at those points.

We can then identifying intervals on which the original function is increasing or decreasing. This will tell us when the derivative function is positive or negative.

Interval	$B(t)$	$B'(t)$
$0 < t < 0.6$	Decreasing	Negative
$0.6 < t < 3.2$	Increasing	Positive
$t > 3.2$	Decreasing	Negative

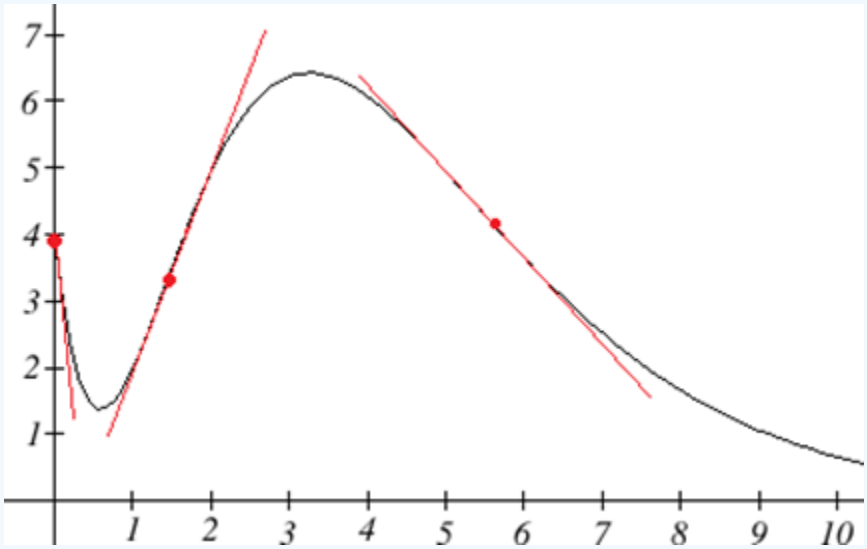
There appear to be inflection points at about $t = 1.5$ and $t = 5.5$. At these points, the derivative will be changing from increasing to decreasing or vice versa, so the derivative will have a local max or min at those points.

Looking at the intervals of concavity:

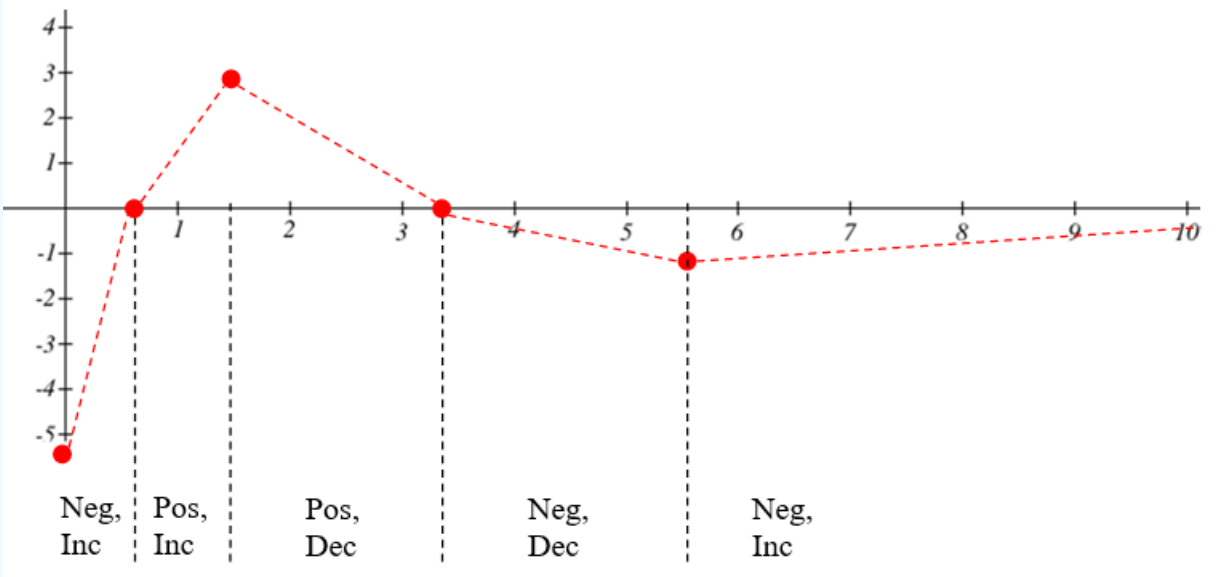
Interval	$B(t)$	$B'(t)$
$0 < t < 1.5$	Concave Up	Increasing
$1.5 < t < 5.5$	Concave Down	Decreasing
$t > 5.5$	Concave Up	Increasing

If we wanted a more accurate sketch of the derivative function, we could also estimate the derivative at a few points:

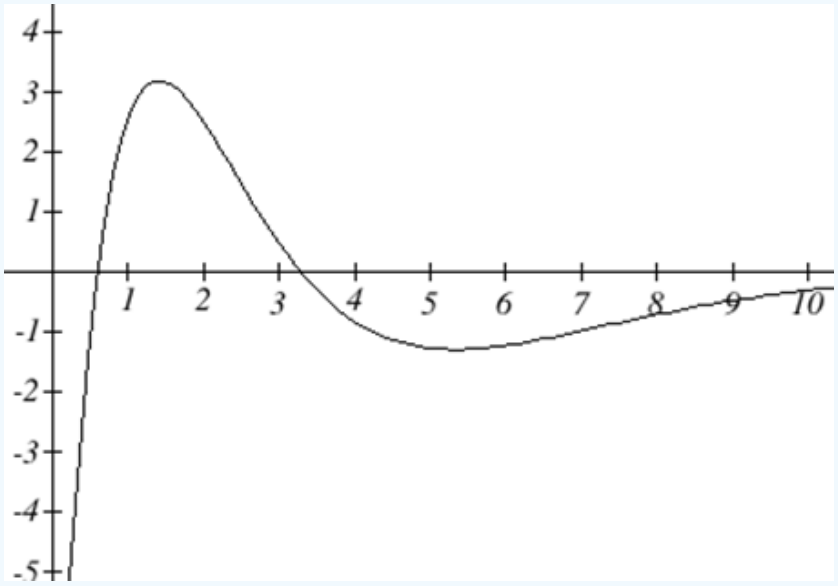
t	$B'(t)$
0	-10
1.5	3
6	-1



Now we can sketch the derivative. We know a few values for the derivative function, and on each interval we know the shape we need. We can use this to create a rough idea of what the graph should look like.



Smoothing this out gives us a good estimate for the graph of the derivative.



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4.2: Second Derivative and Concavity

Second Derivative and Concavity

Graphically, a function is **concave up** if its graph is curved with the opening upward (Figure $4.2.1a$). Similarly, a function is **concave down** if its graph opens downward (Figure $4.2.1b$).

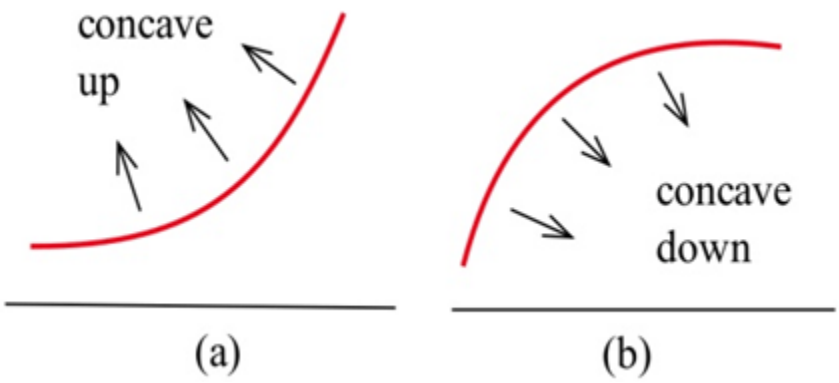
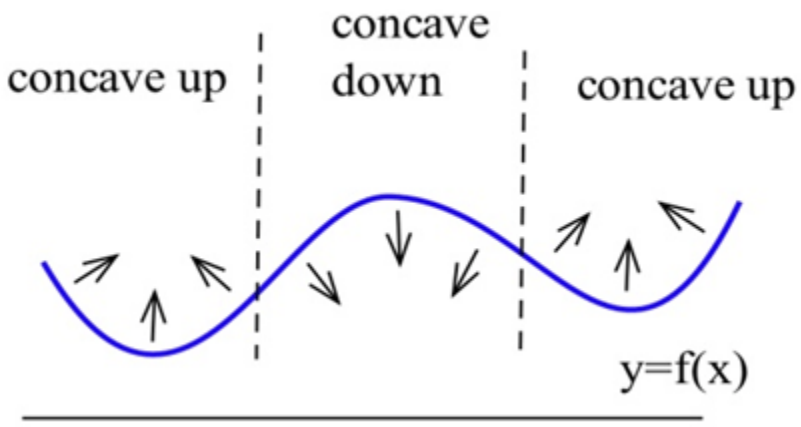


Figure $4.2.1$

This figure shows the concavity of a function at several points. Notice that a function can be concave up regardless of whether it is increasing or decreasing.



For example, **an epidemic**: Suppose an epidemic has started, and you, as a member of congress, must decide whether the current methods are effectively fighting the spread of the disease or whether more drastic measures and more money are needed. In Figure $4.2.2$ below, $f(x)$ is the number of people who have the disease at time x, and two different situations are shown. In both Figure $4.2.2a$ and Figure $4.2.2b$, the number of people with the disease, $f(\text{now})$, and the rate at which new people are getting sick, $f'(\text{now})$, are the same. The difference in the two situations is the concavity of f, and that difference in concavity might have a big effect on your decision.

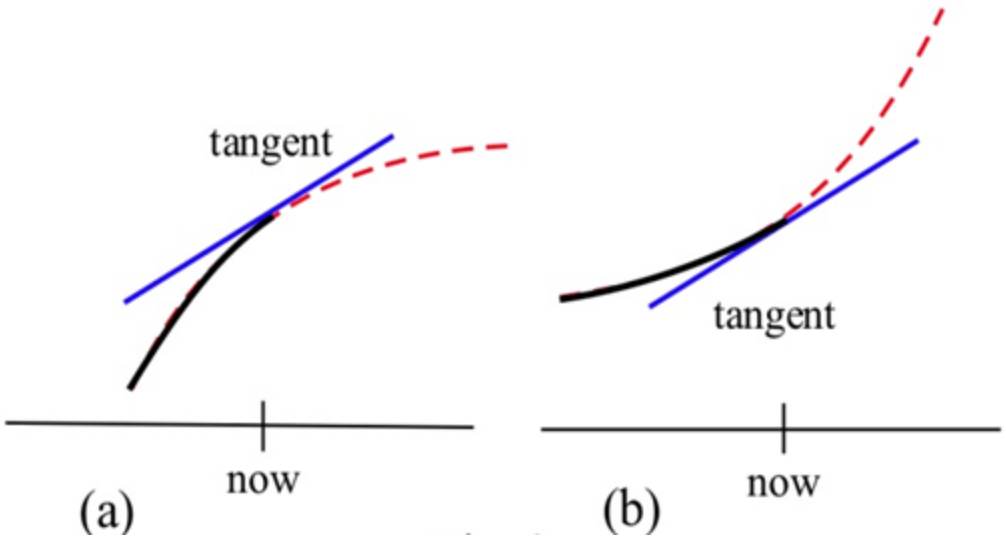


Figure $4.2.2$

In Figure $4.2.2a$, f is concave down at "now", the slopes are decreasing, and it looks as if it is tailing off. We can say "f is increasing at a decreasing rate." It appears that the current methods are starting to bring the epidemic under control.

In Figure $4.2.2b$, f is concave up, the slopes are increasing, and it looks as if it will keep increasing faster and faster. It appears that the epidemic is still out of control.

The differences between the graphs come from whether the *derivative* is increasing or decreasing

The derivative of a function f is a function that gives information about the slope of f. **The derivative tells us if the original function is increasing or decreasing**.

Because f' is a function, we can take its derivative. This second derivative also gives us information about our original function f. The second derivative gives us a mathematical way to tell how the graph of a function is curved. **The second derivative tells us if the original function is concave up or down**.

Second Derivative

Let $y = f(x)$. The **second derivative of** f is the derivative of $y' = f'(x)$.

Using prime notation, this is $f''(x)$ or y''. You can read this aloud as "f double prime of x" or "y double prime."

Using Leibniz notation, the second derivative is written $\frac{d^2y}{dx^2}$ or $\frac{d^2f}{dx^2}$. This is read aloud as "the second derivative of y (or f)."

Derivatives and the Graph of a Function

The first derivative tells us if a function is increasing or decreasing

If $f'(x)$ is positive on an interval, the graph of $y = f(x)$ is **increasing** on that interval.

If $f'(x)$ is negative on an interval, the graph of $y = f(x)$ is **decreasing** on that interval.

The second derivative tells us if a function is concave up or concave down

If $f''(x)$ is positive on an interval, the graph of $y = f(x)$ is **concave up** on that interval. We can say that f is increasing (or decreasing) **at an increasing rate**.

If $f''(x)$ is negative on an interval, the graph of $y = f(x)$ is **concave down** on that interval. We can say that f is increasing (or decreasing) **at a decreasing rate**.

Example 4.2.1

Find $f''(x)$ for $f(x) = 3x^7$.

First, we need to find the first derivative:

$$f'(x) = 21x^6.$$

Then we take the derivative of that function:

$$f''(x) = \frac{d}{dx}\left(f'(x)\right) = \frac{d}{dx}\left(21x^6\right) = 126x^5.$$

If $f(x)$ represents the position of a particle at time x, then $v(x) = f'(x)$ will represent the velocity (rate of change of the position) of the particle and $a(x) = v'(x) = f''(x)$ will represent the acceleration (the rate of change of the velocity) of the particle.

You are probably familiar with acceleration from driving or riding in a car. The speedometer tells you your velocity (speed). When you leave from a stop and press down on the accelerator, you are accelerating – increasing your speed.

Example 4.2.2

The height (feet) of a particle at time t seconds is $f(t) = t^3–4t^2 + 8t$. Find the height, velocity and acceleration of the particle when $t = 0$, 1, and 2 seconds.

$f(t) = t^3–4t^2 + 8t$ so $f(0) = 0$ feet, $f(1) = 5$ feet, and $f(2) = 8$ feet.

The velocity is $v(t) = f'(t) = 3t^2–8t + 8$ so $v(0) = 8$ ft/s, $v(1) = 3$ ft/s, and $v(2) = 4$ ft/s. At each of these times the velocity is positive and the particle is moving upward, increasing in height.

The acceleration is $a(t) = f''(t) = 6t–8$ so $a(0) = –8$ ft/s^2, $a(1) = –2$ ft/s^2 and $a(2) = 4$ ft/s^2.

At time 0 and 1, the acceleration is negative, so the particle's velocity would be decreasing at those points - the particle was slowing down. At time 2, the velocity is positive, so the particle was increasing in speed.

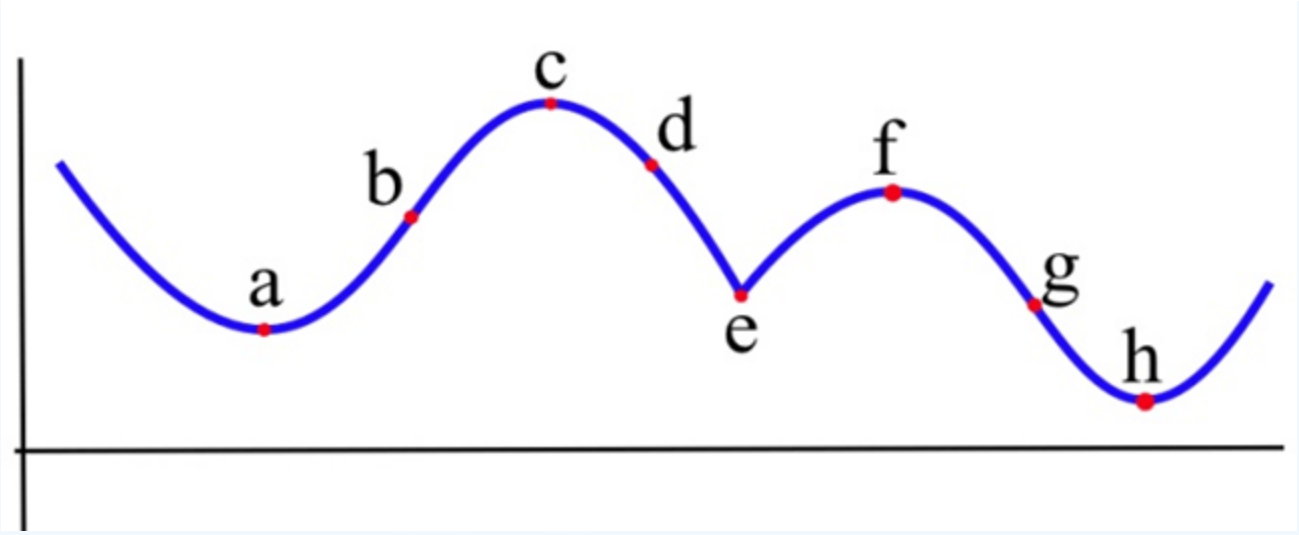
Inflection Points

Inflection Point

An **inflection point** is a point on the graph of a function where the concavity of the function changes, from concave up to down or from concave down to up.

Example 4.2.3

Which of the labeled points in the graph below are inflection points?



The concavity changes at points b and g. At points a and h, the graph is concave up on both sides, so the concavity does not change. At points c and f, the graph is concave down on both sides. At point e, even though the graph looks strange there, the graph is concave down on both sides – the concavity does not change.

Inflection points happen when the concavity changes. Because we know the connection between the concavity of a function and the sign of its second derivative, we can use this to find inflection points.

Working Definition: Inflection Point

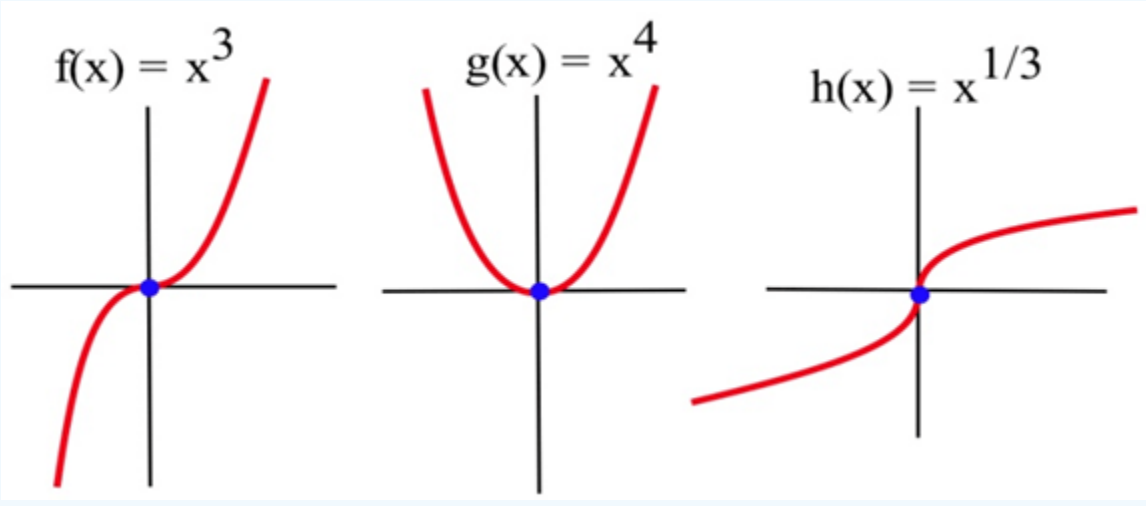
An **inflection point** is a point on the graph where the second derivative changes sign.

In order for the second derivative to change signs, it must either be zero or be undefined. So to find the inflection points of a function we only need to check the points where $f''(x)$ is 0 or undefined.

Note that it is not enough for the second derivative to be zero or undefined. We still need to check that the sign of f'' changes sign. The functions in the next example illustrate what can happen.

Example 4.2.4

Let $f(x) = x^3$, $g(x) = x^4$ and $h(x) = x^{1/3}$. For which of these functions is the point (0,0) an inflection point?



Graphically, it is clear that the concavity of $f(x) = x^3$ and $h(x) = x^{1/3}$ changes at (0,0), so (0,0) is an inflection point for f and h. The function $g(x) = x^4$ is concave up everywhere so (0,0) is not an inflection point of g.

We can also compute the second derivatives and check the sign change.

If $f(x) = x^3$, then $f'(x) = 3x^2$ and $f''(x) = 6x$. The only point at which $f''(x) = 0$ or is undefined (f' is not differentiable) is at $x = 0$. If $x < 0$, then $f''(x) < 0$ so f is concave down. If $x > 0$, then $f''(x) > 0$ so f is concave up. At $x = 0$ the concavity changes so the point $(0, f(0)) = (0, 0)$ is an inflection point of $f(x) = x^3$.

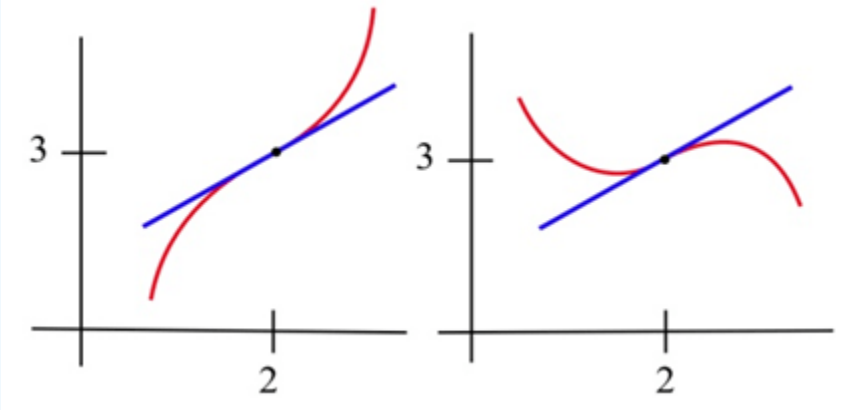
If $g(x) = x^4$, then $g'(x) = 4x^3$ and $g''(x) = 12x^2$. The only point at which $g''(x) = 0$ or is undefined is at $x = 0$. If $x < 0$, then $g''(x) > 0$ so g is concave up. If $x > 0$, then $g''(x) > 0$ so g is also concave up. At $x = 0$ the concavity **does not change** so the point $(0, g(0)) = (0, 0)$ is **not an inflection point** of $g(x) = x^4$. Keep this example in mind!

If $h(x) = x^{1/3}$, then $h'(x) = \frac{1}{3}x^{-2/3}$ and $h''(x) = -\frac{2}{9}x^{-5/3}$. h'' is not defined if $x = 0$, but $h''(\text{negative number}) > 0$ and $h''(\text{positive number}) < 0$ so h changes concavity at (0,0) and (0,0) is an inflection point of h.

Example 4.2.5

Sketch the graph of a function with $f(2) = 3$, $f'(2) = 1$, and an inflection point at (2,3).

Two possible solutions are shown here.



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4.3: Optimization

In theory and applications, we often want to maximize or minimize some quantity. An engineer may want to maximize the speed of a new computer or minimize the heat produced by an appliance. A manufacturer may want to maximize profits and market share or minimize waste. A student may want to maximize a grade in calculus or minimize the hours of study needed to earn a particular grade.

Without calculus, we only know how to find the optimum points in a few specific examples (for example, we know how to find the vertex of a parabola). But what if we need to optimize an unfamiliar function?

The best way we have without calculus is to examine the graph of the function, perhaps using technology. But our view depends on the viewing window we choose – we might miss something important. In addition, we'll probably only get an approximation this way. (In some cases, that will be good enough.)

Calculus provides ways of drastically narrowing the number of points we need to examine to find the exact locations of maximums and minimums, while at the same time ensuring that we haven't missed anything important.

Local Maxima and Minima

Before we examine how calculus can help us find maximums and minimums, we need to define the concepts we will develop and use.

Definition: Local Maxima and Minima

$f(x)$ has a **local maximum** at $x = a$ if $f(a) \geq f(x)$ for all x near a.

$f(x)$ has a **local minimum** at $x = a$ if $f(a) \leq f(x)$ for all x near a.

$f(x)$ has a **local extreme** at $x = a$ if $f(a)$ is a **local maximum or minimum**.

The plurals of these are maxima and minima. We often simply say "max" or "min;" it saves a lot of syllables.

Some books say "relative" instead of "local."

The process of finding maxima or minima is called **optimization**.

A point is a local max (or min) if it is higher (lower) than all the **nearby points**. These points come from the shape of the graph.

Definition: Global Maxima and Minima

$f(x)$ has a **global maximum** at $x = a$ if $f(a) \geq f(x)$ for all x in the domain of $f(x)$.

$f(x)$ has a **global minimum** at $x = a$ if $f(a) \leq f(x)$ for all x in the domain of $f(x)$.

$f(x)$ has a **global extreme** at $x = a$ if $f(a)$ is a **global maximum or minimum**.

Some books say "absolute" instead of "global."

A point is a global max (or min) if it is higher (lower) than every point on the graph. These points come from the shape of the graph **and** the window through which we view the graph.

The local and global extremes of the function in Figure 1 are labeled. You should notice that every global extreme is also a local extreme, but there are local extremes that are not global extremes.

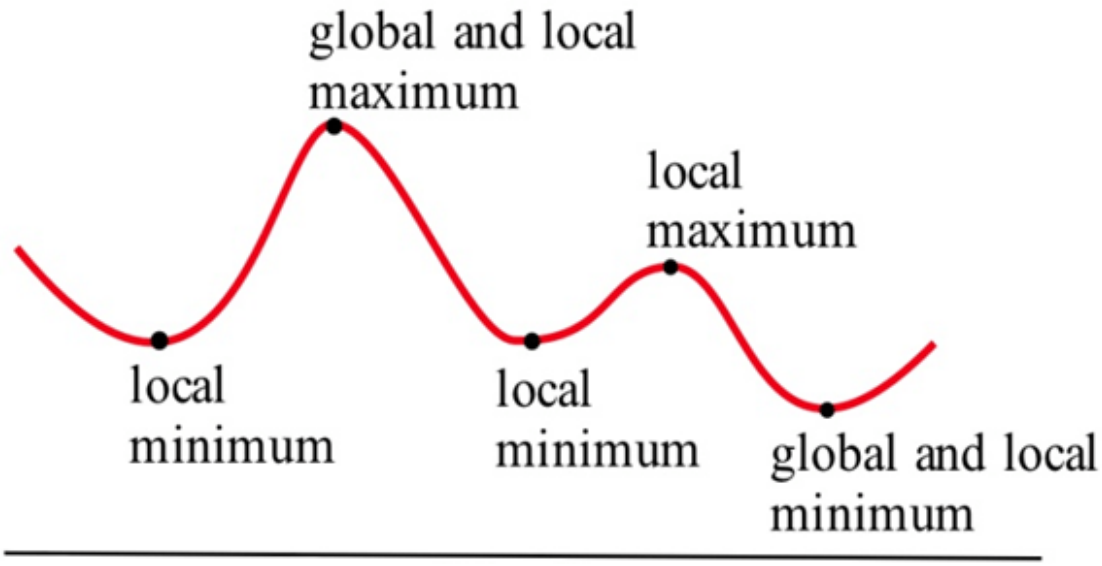


Figure 1

If $h(x)$ is the height of the earth above sea level at the location x, then the global maximum of h is h(summit of Mt. Everest) = 29,028 feet. The local maximum of h for the United States is h(summit of Mt. McKinley) = 20,320 feet. The local minimum of h for the United States is h(Death Valley) = -282 feet.

Example 4.3.1

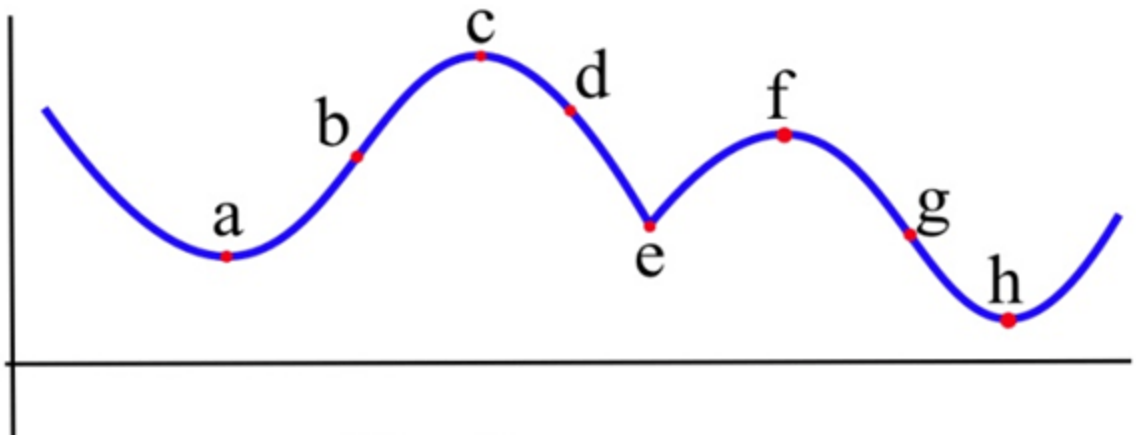
The table shows the annual calculus enrollments at a large university. Which years had local maximum or minimum calculus enrollments? What were the global maximum and minimum enrollments in calculus?

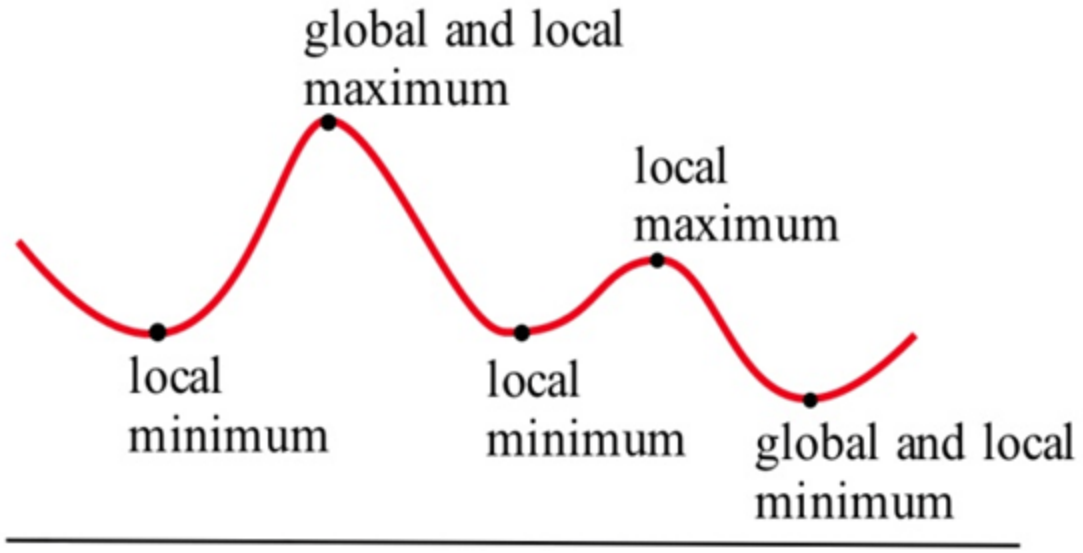
Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Enrollment	1257	1324	1378	1336	1389	1450	1523	1582	1567	1545	1571

There were local maxima in 2002 and 2007; the global maximum was 1582 students in 2007. There were local minima in 2003 and 2009; the global minimum was 1257 students in 2000. We choose not to think of 2000 as a local minimum or 2010 as a local maximum; however, some books would include the endpoints. We are allowed to have a global maximum or global minimum at an endpoint.

Finding Maxima and Minima of a Function

What must the tangent line look like at a local max or min? Look at these two graphs again – you'll see that at all the extreme points, the tangent line is horizontal (so $f' = 0$). There is one cusp in the blue graph – the tangent line is vertical there (so f' is undefined).





That gives us the clue how to find extreme values.

Critical number

A **critical number** for a function f is a value $x = a$ in the domain of f where either $f'(a) = 0$ **or** $f'(a)$ **is undefined.**

Critical point

A **critical point** for a function f is a point $(a, f(a))$ where a is a critical number of f.

A local max or min of f can only occur at a critical point.

Example 4.3.2

Find the critical points of $f(x) = x^3 - 6x^2 + 9x + 2$.

A critical number of f can occur only where $f'(x) = 0$ or where f' does not exist.

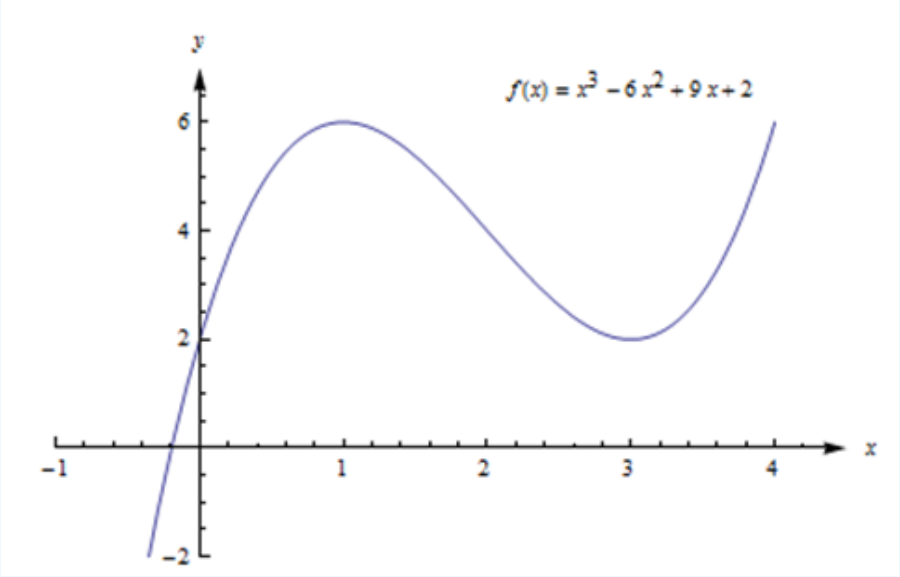
$$f'(x) = 3x^2 - 12x + 9 = 3(x^2 - 4x + 3) = 3(x - 1)(x - 3)$$

So $f'(x) = 0$ at $x = 1$ and $x = 3$ (and no other values of x). There are no places where f' is undefined.

The critical numbers are $x = 1$ and $x = 3$. So the critical points are (1, 6) and (3, 2).

These are the only possible locations of local extremes of f. We haven't discussed yet how to tell whether either of these points is actually a local extreme of f, or which kind it might be. But we can be certain that no other point is a local extreme.

The graph of f below shows that $(1, f(1)) = (1, 6)$ is a local maximum and $(3, f(3)) = (3, 2)$ is a local minimum. This function does not have a global maximum or minimum.



Example 4.3.3

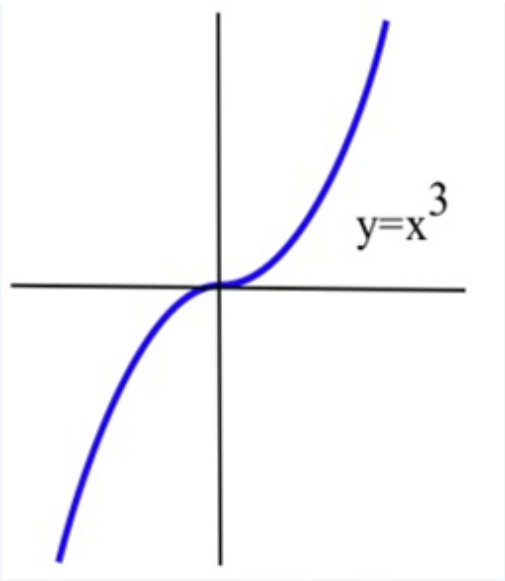
Find all local extremes of $f(x) = x^3$.

$f(x) = x^3$ is differentiable for all x, and $f'(x) = 3x^2$. The only place where $f'(x) = 0$ is at $x = 0$, so the only candidate is the critical point (0,0).

If $x > 0$ then $f(x) = x^3 > 0 = f(0)$, so $f(0)$ is not a local maximum.

Similarly, if $x < 0$ then $f(x) = x^3 < 0 = f(0)$ so $f(0)$ is not a local minimum.

The critical point (0,0) is the only candidate to be a local extreme of f, and, based on the graph, this candidate did not turn out to be a local extreme of f. The function $f(x) = x^3$ does not have any local extremes.



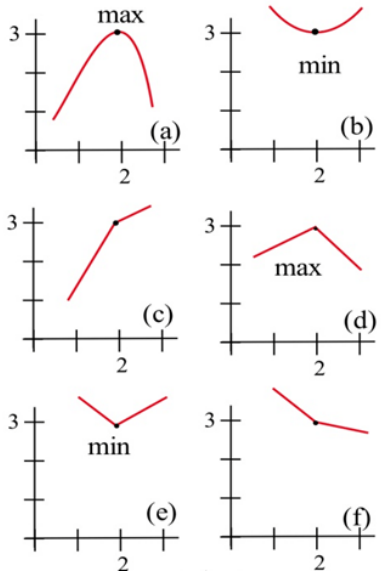
Remember this example! It is not enough to find the critical points – we can only say that f *might* have a local extreme at the critical points.

First and Second Derivative Tests

Is that critical point a Maximum or Minimum (or Neither)?

Once we have found the critical points of f, we still have the problem of determining whether these points are maxima, minima or neither.

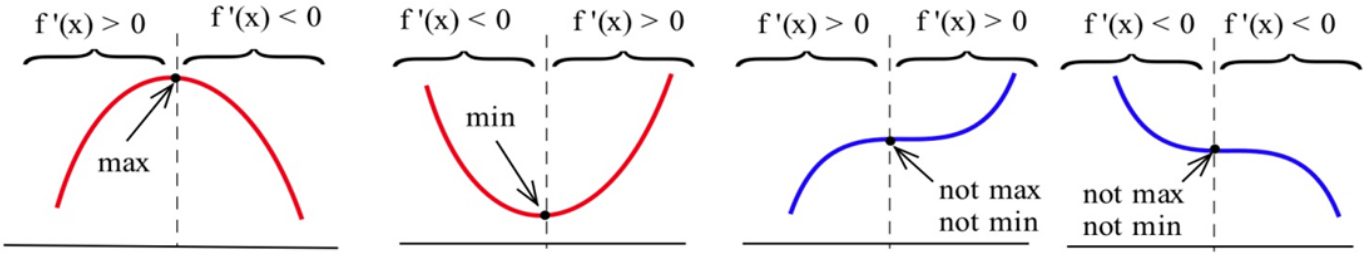
All of the graphs in the figure below have a critical point at (2, 3). It is clear from the graphs that the point (2,3) is a local maximum in (a) and (d), (2,3) is a local minimum in (b) and (e), and (2,3) is not a local extreme in (c) and (f).



The critical numbers only give the *possible* locations of extremes, and some critical numbers are not the locations of extremes. The critical numbers are the *candidates* for the locations of maxima and minima.

f' and Extreme Values of f

Four possible shapes of graphs are shown here – in each graph, the point marked by an arrow is a critical point, where $f'(x) = 0$. What happens to the derivative near the critical point?



At a local max, such as in the graph on the left, the function increases on the left of the local max, then decreases on the right. The derivative is first positive, then negative at a local max. At a local min, the function decreases to the left and increases to the right, so the derivative is first negative, then positive. When there isn't a local extreme, the function continues to increase (or decrease) right past the critical point – the derivative doesn't change sign.

The First Derivative Test for Extremes

Find the critical points of f.

For each critical number c, examine the sign of f' to the left and to the right of c. What happens to the sign as you move from left to right?

- If $f'(x)$ **changes from positive to negative** at $x = c$, then f has a **local maximum** at $(c, f(c))$.
- If $f'(x)$ **changes from negative to positive** at $x = c$, then f has a **local minimum** at $(c, f(c))$.
- If $f'(x)$ **does not change sign** at $x = c$, then $(c, f(c))$ is **neither** a local maximum nor a local minimum.

Example 4.3.4

Find the critical points of $f(x) = x^3 - 6x^2 + 9x + 2$ and classify them as local max, local min, or neither.

We already found the critical points; they are (1, 6) and (3, 2).

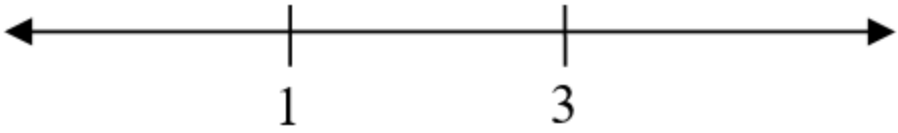
Now we can use the first derivative test to classify each. Recall that $f'(x) = 3x^2 - 12x + 9 = 3(x^2 - 4x + 3) = 3(x - 1)(x - 3)$. The factored form is easiest to work with here, so let's use that.

At (1, 6) we could choose a number slightly less than 1 to plug into the formula for f' – perhaps use $x = 0$, or $x = 0.9$. Then we could examine its sign. But we don't care about the numerical value, all we are interested in is its sign. And for that, we don't have to do any plugging in:

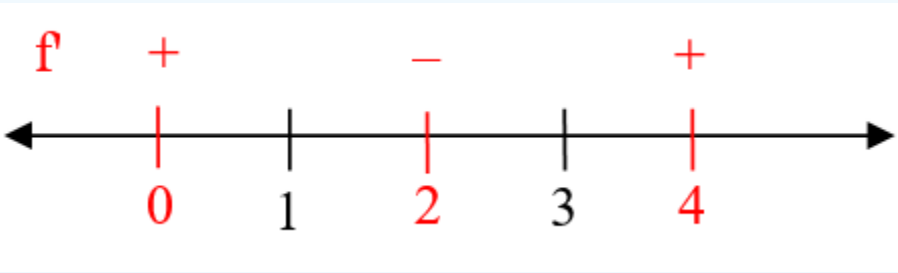
- If x is a little less than 1, then $x - 1$ is negative, and $x - 3$ is negative. So $f' = 3(x - 1)(x - 3)$ will be pos(neg)(neg) = positive.
- For x a little more than 1, we can evaluate f' at a number more than 1 (but less than 3, we don't want to go past the next critical point!) – perhaps $x = 2$. Or we can make a quick sign argument like what we did above: for x a little more than 1, $f' = 3(x - 1)(x - 3)$ will be pos(pos)(neg) = negative.

So f' changes from positive to negative, which means there is a local max at (1, 6).

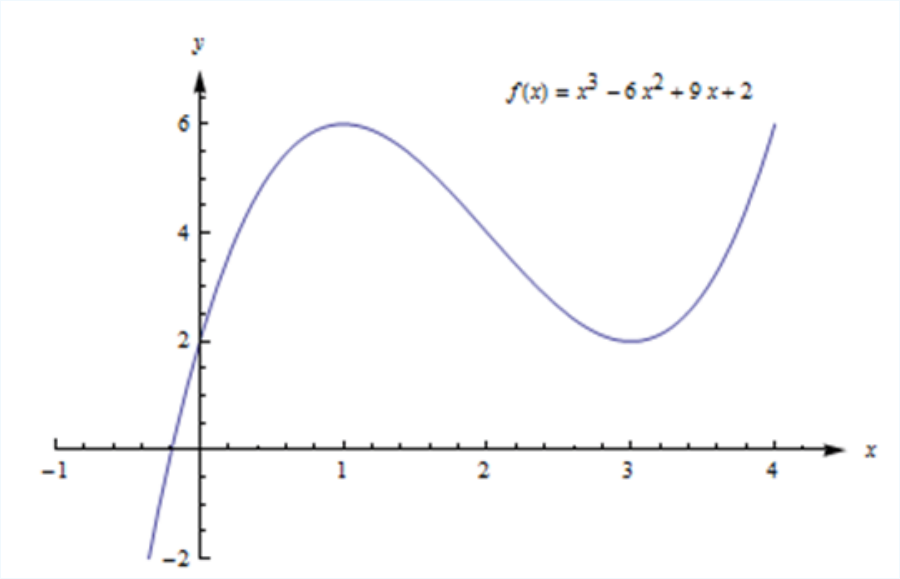
As another approach, we could draw a number line, and mark the critical numbers:



We already know the derivative is zero or undefined at the critical numbers. On each interval between these values, the derivative will stay the same sign. To determine the sign, we could pick a test value in each interval, and evaluate the derivative at those points (or use the sign approach used above).

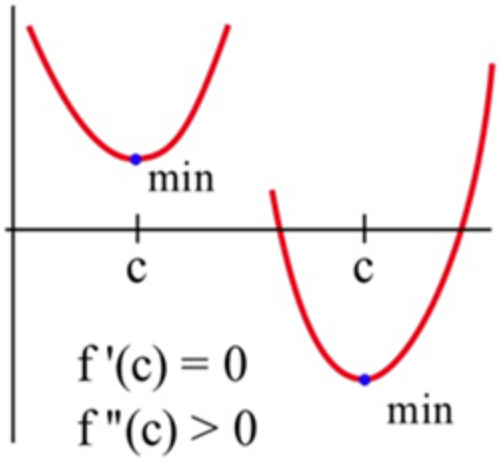


At (3, 2) f' changes from negative to positive, so there is a local min at (3, 2). This confirms what we saw before in the graph.



f'' and Extreme Values of f

The concavity of a function can also help us determine whether a critical point is a maximum or minimum or neither. For example, if a point is at the bottom of a concave up function, then the point is a minimum.



The Second Derivative Test for Extremes

Find all critical points of f. For those critical points where $f'(c) = 0$, find $f''(c)$.

- If $f''(c) < 0$ (negative) then f is concave down and has a local maximum at $x = c$.
- If $f''(c) > 0$ (positive) then f is concave up and has a local minimum at $x = c$.
- If $f''(c) = 0$ then f may have a local maximum, a minimum or neither at $x = c$.

The cartoon faces can help you remember the Second Derivative Test.





Example 4.3.5

$f(x) = 2x^3 - 15x^2 + 24x - 7$ has critical numbers $x = 1$ and 4. Use the Second Derivative Test for Extremes to determine whether $f(1)$ and $f(4)$ are maximums or minimums or neither.

We need to find the second derivative:

$$\begin{aligned} f(x) &= 2x^3 - 15x^2 + 24x - 7 \\ f'(x) &= 6x^2 - 30x + 24 \\ f''(x) &= 12x - 30 \end{aligned}$$

Then we just need to evaluate f'' at each critical number:

$x = 1$: $f''(1) = 12(1) - 30 < 0$, so there is a local maximum at $x = 1$.

$x = 4$: $f''(4) = 12(4) - 30 > 0$, so there is a local minimum at $x = 4$.

Many students like the Second Derivative Test. The Second Derivative Test is often easier to use than the First Derivative Test. You only have to find the sign of one number for each critical number rather than two. And if your function is a polynomial, its second derivative will probably be a simpler function than the derivative.

However, if you needed a product rule, quotient rule, or chain rule to find the first derivative, finding the second derivative can be a lot of work. Also, even if the second derivative is easy, the Second Derivative Test doesn't always give an answer. The First Derivative Test will always give you an answer.

Use whichever test you want to. But remember – you have to do some test to be sure that your critical point actually is a local max or min.

Global Maxima and Minima

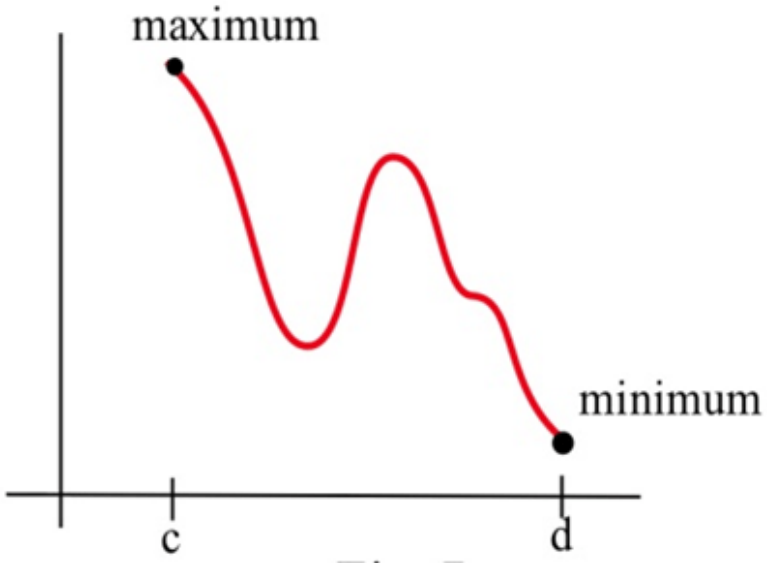
In applications, we often want to find the global extreme; knowing that a critical point is a local extreme is not enough.

For example, if we want to make the greatest profit, we want to make the absolutely greatest profit of all. How do we find global max and min?

There are just a few additional things to think about.

Endpoint Extremes

The local extremes of a function occur at critical points – these are points in the function that we can find by thinking about the shape (and using the derivative to help us). But if we're looking at a function on a closed interval, the endpoints could be extremes. These endpoint extremes are not related to the shape of the function; they have to do with the interval, the window through which we're viewing the function.



In the graph above, it appears that there are three critical points – one local min, one local max, and one that is neither one. But the global max, the highest point of all, is at the left endpoint. The global min, the lowest point of all, is at the right endpoint.

How do we decide if endpoints are global max or min? It's easier than you expected – simply plug in the endpoints, along with all the critical numbers, and compare y-values.

To find Global Extremes

This technique can be used when you are trying to find global extrema over a limited interval.

The only places where a function can have a global extreme on a limited interval are at critical points or endpoints.

- If the function has only one critical point, and it's a local extreme, then it is also the global extreme.
- If there are endpoints, find the global extremes by comparing y-values at all the critical points and at the endpoints.
- When in doubt, graph the function to be sure. (However, unless the problem explicitly tells you otherwise, it is **not** enough to just use the graph to get your answer.)

Example 4.3.6

Find the global max and min of $f(x) = x^3 - 3x^2 - 9x + 5$ for $-2 \leq x \leq 6$.

$f'(x) = 3x^2 - 6x - 9 = 3(x+1)(x-3)$. We need to find critical points, and we need to check the endpoints.

$f'(x) = 3(x+1)(x-3) = 0$ when $x = -1$ and $x = 3$. The endpoints of the interval are $x = -2$ and $x = 6$.

Now we simply compare the values of f at these four values of x:

x	$f(x)$
-2	3
-1	10
3	-22
6	59

The global minimum of f on $[-2, 6]$ is -22, when $x = 3$, and the global maximum of f on $[-2, 6]$ is 59, when $x = 6$.

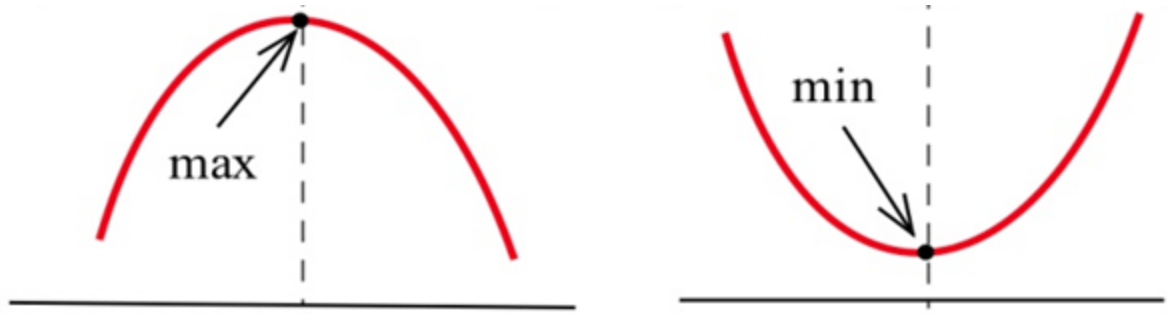
Caution

Be careful! You can **only** use this technique (evaluating the function at endpoints and critical values) to determine **global** extrema over a limited interval.

If a question asks for **local** extrema, you **must** use the first or second derivative test described earlier in the section.

If there's only one critical point

If the function has only one critical point and it's a local max (or min), then it must be the global max (or min). To see this, think about the geometry. Look at the graph on the left – there is a local max, and the graph goes down on either side of the critical point. Suppose there was some other point that was higher – then the graph would have to turn around. But that turning point would have shown up as another critical point. If there's only one critical point, then the graph can never turn back around.



When in doubt, graph it and look.

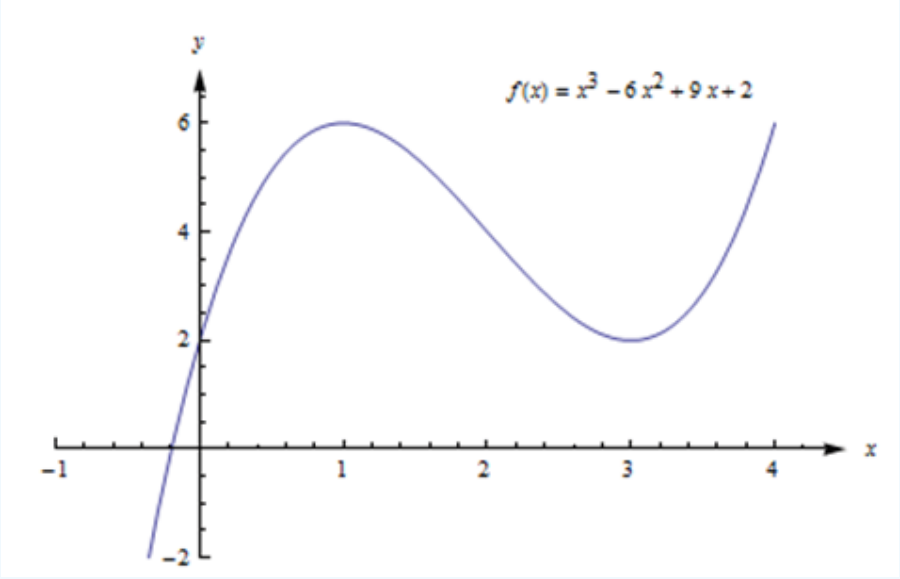
If you are trying to find a global max or min on an open interval (or the whole real line), and there is more than one critical point, then you need to look at the graph to decide whether there is a global max or min. Be sure that all your critical points show in your graph, and that you graph beyond them – that will tell you what you want to know.

Example 4.3.7

Find the global max and min of $f(x) = x^3 - 6x^2 + 9x + 2$.

We have previously found that (1, 6) is a local max and (3, 2) is a local min. This is not a closed interval, and there are two critical points, so we must turn to the graph of the function to find global max and min.

The graph of f shows that points to the left of $x = 4$ have y-values greater than 6, so (1, 6) is not a global max. Likewise, if x is negative, y is less than 2, so (3, 2) is not a global min. There are no endpoints, so we've exhausted all the possibilities. This function does not have a global maximum or minimum.



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4.4: Applied Optimization

We have used derivatives to help find the maximums and minimums of some functions given by equations, but it is very unlikely that someone will simply hand you a function and ask you to find its extreme values. More typically, someone will describe a problem and ask your help in maximizing or minimizing something: “What is the largest volume package which the post office will take?”; “What is the quickest way to get from here to there?”; or “What is the least expensive way to accomplish some task?” In this section, we’ll discuss how to find these extreme values using calculus.

Max/Min Applications

Example

The manager of a garden store wants to build a 600 square foot rectangular enclosure on the store’s parking lot in order to display some equipment. Three sides of the enclosure will be built of redwood fencing, at a cost of $7 per running foot. The fourth side will be built of cement blocks, at a cost of $14 per running foot. Find the dimensions of the least costly such enclosure.

The process of finding maxima or minima is called optimization. The function we're optimizing is called the **objective function** (or **objective equation**). The objective function can be recognized by its proximity to “est” words (greatest, least, highest, farthest, most, ...). Look at the garden store example; the cost function is the objective function.

In many cases, there are two (or more) variables in the problem. In the garden store example again, the length and width of the enclosure are both unknown. If there is an equation that relates the variables we can solve for one of them in terms of the others, and write the objective function as a function of just one variable. Equations that relate the variables in this way are called **constraint equations**. The constraint equations are always equations, so they will have equals signs. For the garden store, the fixed area relates the length and width of the enclosure. This will give us our constraint equation.

Max-Min Story Problem Technique

1. Translate the English statement of the problem line by line into a picture (if that applies) and into math. This is often the hardest step!
2. Identify the objective function. Look for words indicating a largest or smallest value.
    1. If you seem to have two or more variables, find the constraint equation. Think about the English meaning of the word “constraint”, and remember that the constraint equation will have an equals sign.
    2. Solve the constraint equation for one variable and substitute into the objective function. Now you have an equation of one variable.
3. Use calculus to find the optimum values. (Take derivative, find critical points, test. Don't forget to check the endpoints!)
4. Look back at the question to make sure you answered what was asked. Translate your number answer back into English.

Example 4.4.1

The manager of a garden store wants to build a 600 square foot rectangular enclosure on the store's parking lot in order to display some equipment. Three sides of the enclosure will be built of redwood fencing, at a cost of $7 per running foot. The fourth side will be built of cement blocks, at a cost of $14 per running foot. Find the dimensions of the least costly such enclosure.

First, translate line by line into math and a picture:

Text	Translation

The manager of a garden store wants to build a 600 *square foot rectangular* enclosure on the store's parking lot in order to display some equipment.

Three sides of the enclosure will be built of redwood fencing, at a *cost of $7 per running foot*. The *fourth side* will be built of cement blocks, at a *cost of $14 per running foot*.

Find the dimensions of the least costly such enclosure.

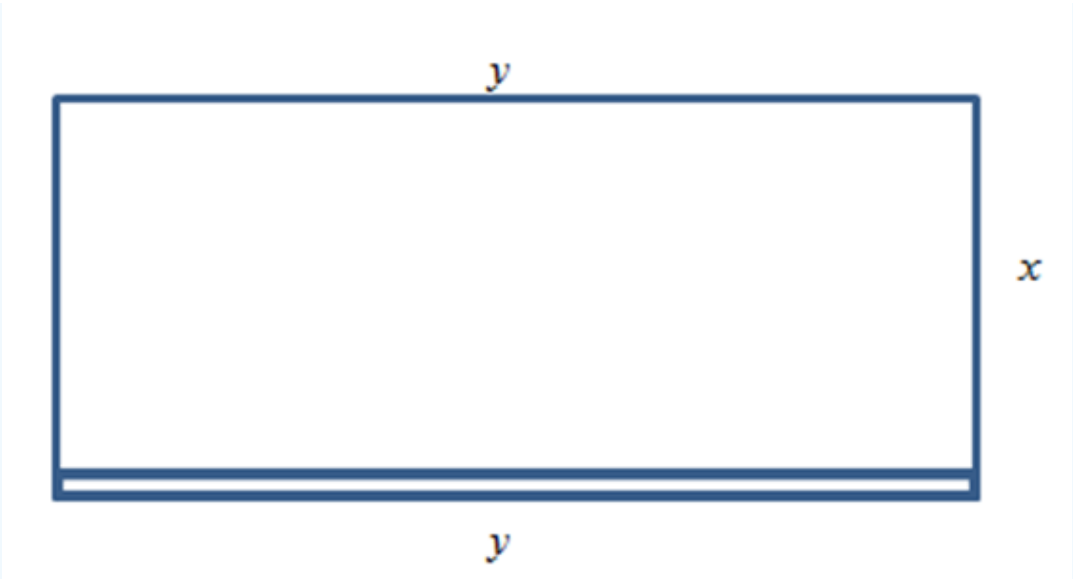
Let x and y be the dimensions of the enclosure, with y being the length of the side made of blocks. The

$$\text{Area} = A = xy = 600.$$

$2x + y$ costs $7 per foot, y costs $14 per foot, so

$$\text{Cost} = C = 7(2x + y) + 14y = 14x + 21y.$$

Find x and y so that C is minimized.



The objective function is the cost function, and we want to minimize it. As it stands, though, it has two variables, so we need to use the constraint equation. The constraint equation is the fixed area $A = xy = 600$. Solve A for x to get $x = \frac{600}{y}$, and then substitute into C:

$$C = 14\left(\frac{600}{y}\right) + 21y = \frac{8400}{y} + 21y.$$

Now we have a function of just one variable, so we can find the minimum using calculus.

$$C' = -\frac{8400}{y^2} + 21$$

C' is undefined for $y = 0$, and $C' = 0$ when $y = 20$ or $y = -20$.

Of these three critical numbers, only $y = 20$ makes sense (is in the domain of the actual function) – remember that y is a length, so it can't be negative, and $y = 0$ would mean there was no enclosure at all, so it couldn't have an area of 600 square feet.

Test $y = 20$ (here we chose the second derivative test):

$$C'' = \frac{16800}{y^3} > 0,$$

so this is a local minimum.

Since this is the only critical point in the domain, this must be the global minimum. Going back to our constraint function, we can find that when $y = 20$, $x = 30$. The dimensions of the enclosure that minimize the cost are 20 feet by 30 feet.

When trying to maximize their revenue, businesses also face the constraint of consumer demand. While a business would love to see lots of products at a very high price, typically demand decreases as the price of goods increases. In simple cases, we can construct that demand curve to allow us to maximize revenue.

Example 4.4.2

A concert promoter has found that if she sells tickets for \$50 each, she can sell 1200 tickets, but for each \$5 she raises the price, 50 less people attend. What price should she sell the tickets at to maximize her revenue?

We are trying to maximize revenue, and we know that $R = pq$, where p is the price per ticket, and q is the quantity of tickets sold.

The problem provides information about the demand relationship between price and quantity – as price increases, demand decreases. We need to find a formula for this relationship. To investigate, let's calculate what will happen to attendance if we raise the price:

Price, p	50	55	60	65
Quantity, q	1200	1150	1100	1050

You might recognize this as a linear relationship. We can find the slope for the relationship by using two points:

$$m = \frac{1150 - 1200}{55 - 50} = \frac{-50}{5} = -10.$$

You may notice that the second step in that calculation corresponds directly to the statement of the problem: the attendance drops 50 people for every $5 the price increases.

Using the point-slope form of the line, we can write the equation relating price and quantity:

$$q - 1200 = -10(p - 50).$$

Simplifying to slope-intercept form gives the demand equation

$$q = 1700 - 10p.$$

Substituting this into our revenue equation, we get an equation for revenue involving only one variable:

$$R = pq = p(1700 - 10p) = 1700p - 10p^2.$$

Now, we can find the maximum of this function by finding critical numbers. $R' = 1700 - 20p$, so $R' = 0$ when $p = 85$.

Using the second derivative test, $R'' = -20 < 0$ (for any value of p), so the critical number is a local maximum. Since it is the only critical number, we can also conclude that it is the global maximum.

The promoter will be able to maximize revenue by charging $85 per ticket. At this price, she will sell $q = 1700 - 10(85) = 850$ tickets, generating $72,250 in revenue.

"Marginal Revenue = Marginal Cost"

You may have heard before that "profit is maximized when marginal cost and marginal revenue are equal." Now you can see why people say that! (Even though it's not completely true.)

Example 4.4.3

Suppose we want to maximize profit.

Now we know what to do – find the profit function, find its critical points, test them, etc.

But remember that Profit = Revenue - Cost. So Profit' = Revenue' - Cost'. That is, the derivative of the profit function is $MR - MC$.

Now let's find the critical points – those will be where Profit' = 0 or is undefined. Profit' = 0 when $MR - MC = 0$, or where $MR = MC$.

Profit has critical points when Marginal Revenue and Marginal Cost are equal.

In all the cases we'll see in this class, Profit will be very well behaved, and we won't have to worry about looking for critical points where Profit' is undefined. But remember that not all critical points are local max! The places where $MR = MC$ could represent local max, local min, or neither one.

Example 4.4.4

A company sells q ribbon winders per year at $\$p$ per ribbon winder. The demand function for ribbon winders is given by: $p = 300 - 0.02q$. The ribbon winders cost $30 apiece to manufacture, plus there are fixed costs of $9000 per year. Find the quantity where profit is maximized.

We want to maximize profit, but there isn't a formula for profit given. So let's make one. We can find a function for Revenue = pq using the demand function for p.

$$R(q) = (300 - 0.02q)q = 300q - 0.02q^2.$$

We can also find a function for Cost, using the variable cost of $30 per ribbon winder, plus the fixed cost:

$$C(q) = 9000 + 30q.$$

Putting them together, we get a function for Profit:

$$P(q) = R(q) - C(q) = \left(300q - 0.02q^2\right) - (9000 + 30q) = -0.02q^2 + 270q - 9000$$

Now we have two choices. We can find the critical points of Profit by taking the derivative of $P(q)$ directly, or we can find MR and MC and set them equal. (Naturally, we'll get the same answer either way.)

Let's use $MR = MC$ this time.

$$\begin{aligned} MR &= 300 - 0.04q \\ MC &= 30 \\ 300 - 0.04q &= 30 \\ 270 &= 0.04q \\ q &= 6750 \end{aligned}$$

The only critical point is at $q = 6750$. Now we need to be sure this is a local max and not a local min. In this case, we'll look to the graph of $P(q)$ – it's a downward opening parabola, so this must be a local max. And since it's the only critical point, it must also be the global max.

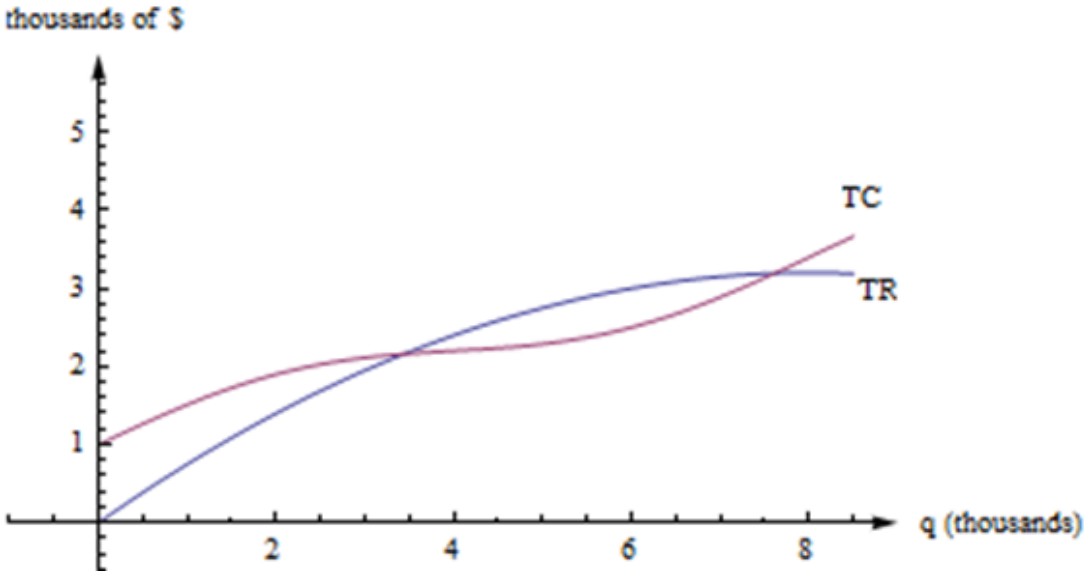
Profit is maximized when they sell 6750 ribbon winders.

"Average Cost = Marginal Cost"

"Average cost is minimized when average cost = marginal cost" is another saying that isn't quite true; in this case, the correct statement is:

Average Cost has critical points when Average Cost and Marginal Cost are equal.

Let's look at a geometric argument here. Remember that the average cost is the slope of the diagonal line, the line from the origin to the point on the total cost curve. If you move your clear plastic ruler around, you'll see (and feel) that the slope of the diagonal line is smallest when the diagonal line just touches the cost curve – when the diagonal line is actually a tangent line – when the average cost is equal to the marginal cost.



Example 4.4.5

The cost in dollars to produce q gift baskets is given by $C(q) = 160 + 2q + .1q^2$. Find the quantity where the average cost is minimum.

Solution

$A(q) = \frac{C(q)}{q} = \frac{160}{q} + 2 + .1q$. We could find the critical points by finding A', or by setting average cost to marginal cost; we'll do the latter this time.

$$MC(q) = 2 + .2q.$$

So we want to solve:

$$\begin{aligned} \frac{160}{q} + 2 + .1q &= 2 + .2q \\ \frac{160}{q} &= .1q \\ 1600 &= q^2 \\ q &= 40 \end{aligned}$$

The critical point of average cost is when $q = 40$.

Notice that we still have to confirm that the critical point is a minimum. For this, we can use the first or second derivative test on $A(q)$.

$$\begin{aligned} A'(q) &= \frac{-160}{q^2} + .1 \\ A''(q) &= \frac{320}{q^3} > 0 \end{aligned}$$

The second derivative is positive for all positive q, so that means this is a local min. Average cost is minimized when they produce 40 gift baskets; at that quantity, the average cost is $10 per basket.

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4.5: Implicit Differentiation and Related Rates

Implicit Differentiation

In our work up until now, the functions we needed to differentiate were either given **explicitly**, such as $y = x^2 + e^x$, or it was possible to get an explicit formula for them, such as solving $y^3 - 3x^2 = 5$ to get $y = \sqrt[3]{5 + 3x^2}$. Sometimes, however, we will have an equation relating x and y which is either difficult or impossible to solve explicitly for y, such as $y + e^y = x^2$. In any case, we can still find $y' = f'(x)$ by using implicit differentiation.

The key idea behind implicit differentiation is to **assume that y is a function of x** even if we cannot explicitly solve for y. This assumption does not require any work, but we need to be very careful to treat y as a function when we differentiate and to use the Chain Rule.

Example 4.5.1

Assume that y is a function of x. Calculate

1. $\frac{d}{dx}\left(y^3\right)$
2. $\frac{d}{dx}\left(x^3y^2\right)$
3. $\frac{d}{dx}\left(\ln(y)\right)$

Solution

1. We need the chain rule since y is a function of x:
$$\frac{d}{dx}\left(y^3\right) = 3y^2\frac{dy}{dx} \overset{\text{or}}{=} 3y^2y'$$
2. We need to use the product rule and the Chain Rule:
$$\begin{aligned}\frac{d}{dx}\left(x^3y^2\right) &= x^3\frac{d}{dx}\left(y^2\right) + y^2\frac{d}{dx}\left(x^3\right)\\ &= x^3 2y\frac{dy}{dx} + y^2 3x^2\\ &\overset{\text{or}}{=} 2x^3yy' + 3y^2x^2\end{aligned}$$
3. We know $\frac{d}{dx}\left(\ln(x)\right) = \frac{1}{x}$, so we use that and the Chain Rule:
$$\frac{d}{dx}\left(\ln(y)\right) = \frac{1}{y}\cdot y'$$

Implicit Differentiation

To determine y', differentiate each side of the defining equation, **treating y as a function of x**, and then algebraically solve for y'.

Example 4.5.2

Find the slope of the tangent line to the circle $x^2 + y^2 = 25$ at the point (3,4) using implicit differentiation.

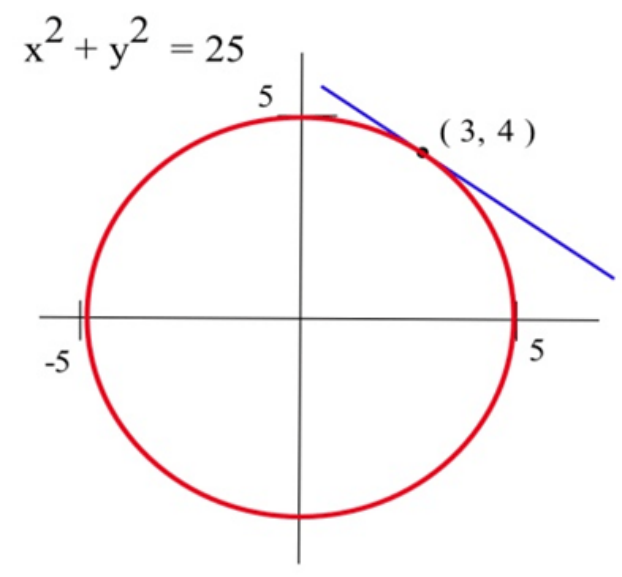
Solution

We differentiate each side of the equation $x^2 + y^2 = 25$ and then solve for y':

$$\frac{d}{dx}\left(x^2+y^2\right)=\frac{d}{dx}(25)$$
$$2x+2yy'=0$$

Solving for y', we have $y'=-\frac{2x}{2y}=-\frac{x}{y}$, and, at the point (3,4),

$$y'=-\frac{3}{4}.$$



In the previous example, it would have been easy to explicitly solve for y, and then we could differentiate y to get y'. Because we could explicitly solve for y, we had a choice of methods for calculating y'. Sometimes, however, we cannot explicitly solve for y, and the only way of determining y' is to use implicit differentiation.

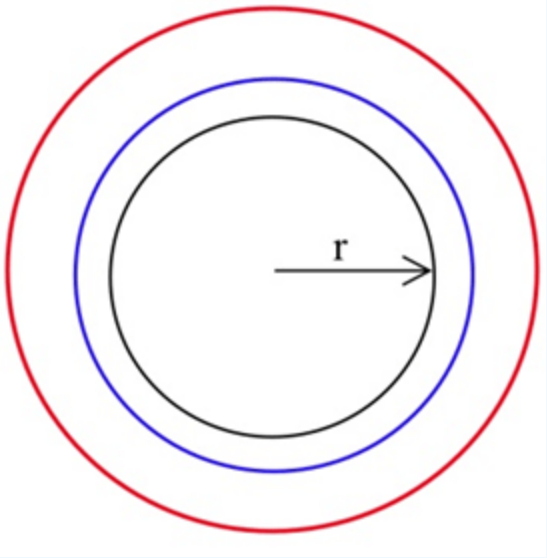
Related Rates

If several variables or quantities are related to each other and some of the variables are changing at a known rate, then we can use derivatives to determine how rapidly the other variables must be changing.

Example 4.5.3

Suppose the border of a town is roughly circular, and the radius of that circle has been increasing at a rate of 0.1 miles each year. Find how fast the area of the town has been increasing when the radius is 5 miles.

Solution



We could get an *approximate* answer by calculating the area of the circle when the radius is 5 miles ($A = \pi r^2 = \pi(5 \text{ miles})^2 \approx 78.6 \text{ miles}^2$) and 1 year later when the radius is 0.1 feet larger than before ($A = \pi r^2 = \pi(5.1 \text{ miles})^2 \approx 81.7 \text{ miles}^2$) and then finding

$$\frac{\Delta \text{Area}}{\Delta \text{time}} = \frac{81.7 \text{ mi}^2 - 78.6 \text{ mi}^2}{1 \text{ year}} = 3.1 \text{ mi}^2/\text{yr}.$$

This approximate answer represents the average change in area during the 1 year period when the radius increased from 5 miles to 5.1 miles, and would correspond to the secant slope on the area graph.

To find the exact answer, though, we need derivatives. In this case both radius and area are functions of time:

$$r(t) = \text{ radius at time } t \qquad A(t) = \text{ area at time } t$$

We know how fast the radius is changing, which is a statement about the derivative: $\frac{dr}{dt} = 0.1 \frac{\text{mile}}{\text{year}}$. We also know that $r = 5$ at our moment of interest.

We are looking for how fast the area is increasing, which is $\frac{dA}{dt}$.

Now we need an equation relating our variables, which is the area equation:

$$A = \pi r^2.$$

Taking the derivative of both sides of that equation with respect to t, we can use implicit differentiation:

$$\frac{d}{dt}(A) = \frac{d}{dt}(\pi r^2)$$
$$\frac{dA}{dt} = \pi 2r \frac{dr}{dt}$$

Plugging in the values we know for r and $\frac{dr}{dt}$,

$$\frac{dA}{dt} = \pi 2(5 \text{ miles}) \left(0.1 \frac{\text{miles}}{\text{year}}\right) = \pi \frac{\text{miles}^2}{\text{year}}$$

So the area of the town is increasing by approximately 3.14 square miles per year when the radius is 5 miles.

Related Rates

When working with a related rates problem,

1. Draw a picture (if possible).
2. Identify the quantities that are changing, and assign them variables.
3. Find an equation that relates those quantities.
4. Differentiate both sides of that equation with respect to time.
5. Plug in any known values for the variables or rates of change.
6. Solve for the desired rate.

Example 4.5.4

A company has determined the demand curve for their product is $q = \sqrt{5000 - p^2}$, where p is the price in dollars, and q is the quantity in millions. If weather conditions are driving the price up \$2 a week, find the rate at which demand is changing when the price is \$40.

Solution

The quantities changing are p and q, and we assume they are both functions of time, t, in weeks. We already have an equation relating the quantities, so we can implicitly differentiate it.

$$\begin{aligned}\frac{d}{dt}(q) &= \frac{d}{dt}\left(5000 - p^2\right)^{1/2} \\ \frac{dq}{dt} &= \frac{1}{2}\left(5000 - p^2\right)^{-1/2}\frac{d}{dt}\left(5000 - p^2\right) \\ \frac{dq}{dt} &= \frac{1}{2}\left(5000 - p^2\right)^{-1/2}\left(-2p\frac{dp}{dt}\right)\end{aligned}$$

Using the given information, we know the price is increasing by \$2 per week when the price is \$40, giving $\frac{dp}{dt} = 2$ when $p = 40$. Plugging in these values,

$$\frac{dq}{dt} = \frac{1}{2}\left(5000 - 40^2\right)^{-1/2}(-2(40)(2)) \approx -1.37$$

Demand is falling by 1.37 million items per week.

Example 4.5.5

The total daily cost for producing x items in a day is $TC(x) = 300,000 + 4x + \frac{200,000}{x}$. If production has been ramping up by 20 items a day, find the rate at which total daily cost is increasing, if they are currently producing 2,000 items.

Solution

The quantities changing are x and TC, and we assume they are both functions of time, t, in days. We already have an equation relating the quantities, so we can implicitly differentiate it.

$$\begin{aligned}\frac{d}{dt}(TC) &= \frac{d}{dt}\left(300,000 + 4x + 200,000x^{-1}\right) \\ \frac{dTC}{dt} &= 4\frac{dx}{dt} - 200,000x^{-2}\frac{dx}{dt} \\ \frac{dTC}{dt} &= \left(4 - \frac{200,000}{x^2}\right)\frac{dx}{dt}\end{aligned}$$

We know the quantity produced is increasing by 20 items per week when the production is 2,000 items, giving $\frac{dx}{dt} = 20$ when $x = 2000$. Plugging in these values,

$$\frac{dTC}{dt} = \left(4 - \frac{200,000}{2000^2}\right)(20) = 79$$

Total daily cost is increasing by \$79 each day.

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5: THE INTEGRAL

5.1: Prelude to the Integral

5.2: The Definite Integral

5.3: The Fundamental Theorem and Antidifferentiation

5.4: Antiderivatives of Formulas

5.5: Substitution

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5.8: Applications to Business

5.9: Differential Equations

5.E: The Integral (Exercises)

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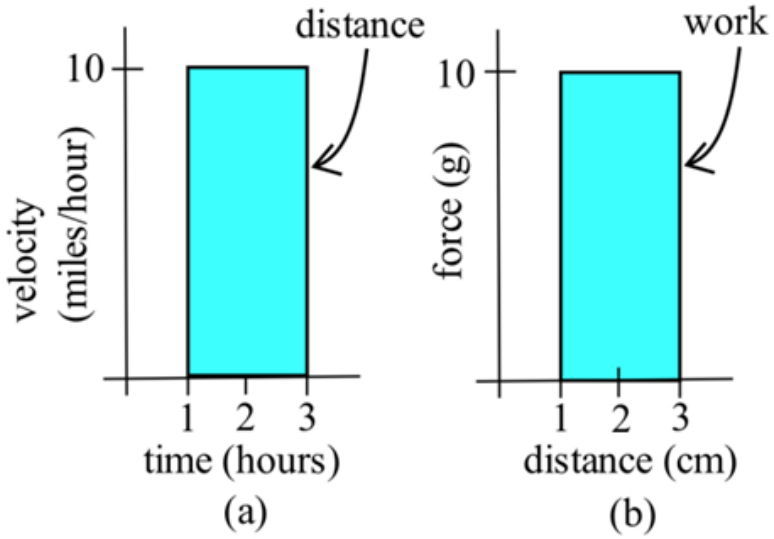
5.1: Prelude to the Integral

The previous chapters dealt with **Differential Calculus**. We started with the "simple" geometrical idea of the **slope of a tangent line** to a curve, developed it into a combination of theory about derivatives and their properties, techniques for calculating derivatives, and applications of derivatives. This chapter deals with **Integral Calculus** and starts with the "simple" geometric idea of **area**. This idea will be developed into another combination of theory, techniques, and applications.

PreCalculus Idea – The Area of a Rectangle

If you look on the inside cover of nearly any traditional math book, you will find a bunch of area and volume formulas – the area of a square, the area of a trapezoid, the volume of a right circular cone, and so on. Some of these formulas are pretty complicated. But you still won't find a formula for the area of a jigsaw puzzle piece or the volume of an egg. There are lots of things for which there is no formula. Yet we might still want to find their areas.

One reason areas are so useful is that they can represent quantities other than simple geometric shapes. If the units for each side of the rectangle are *meters*, then the area will have the units $meters \cdot meters = square\ meters = \mathrm{m}^2$. But if the units of the base of a rectangle are *hours* and the units of the height are *miles/hour*, then the units of the area of the rectangle are $hours \cdot (miles/hour) = miles$, a measure of distance. Similarly, if the base units are *centimeters* and the height units are *grams*, then the area units are *gram-centimeters*, a measure of work.



The basic shape we will use is the rectangle; the area of a rectangle is base·height. You should also know the area formulas for triangles, $A = \frac{1}{2}bh$, and for circles, $A = \pi r^2$.

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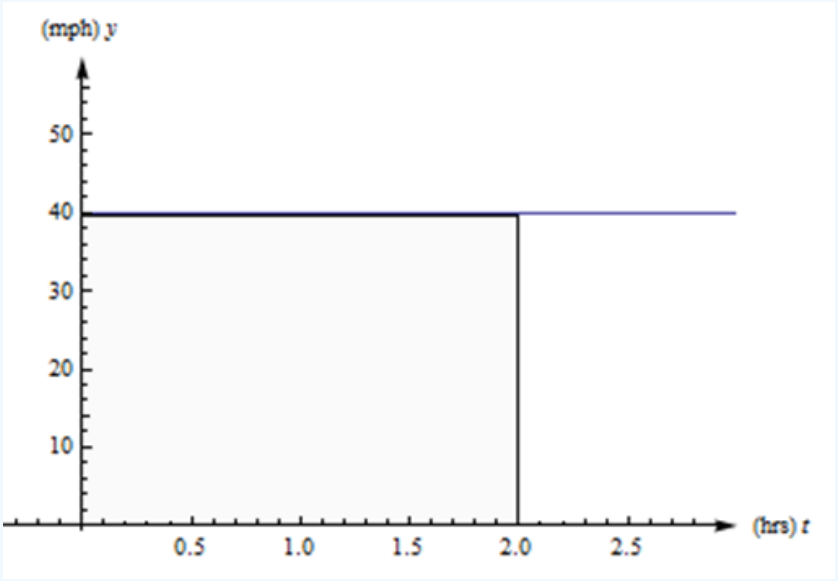
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5.2: The Definite Integral

Distance from Velocity

Example 5.2.1

Suppose a car travels on a straight road at a constant speed of 40 miles per hour for two hours. See the graph of its velocity below. How far has it gone?

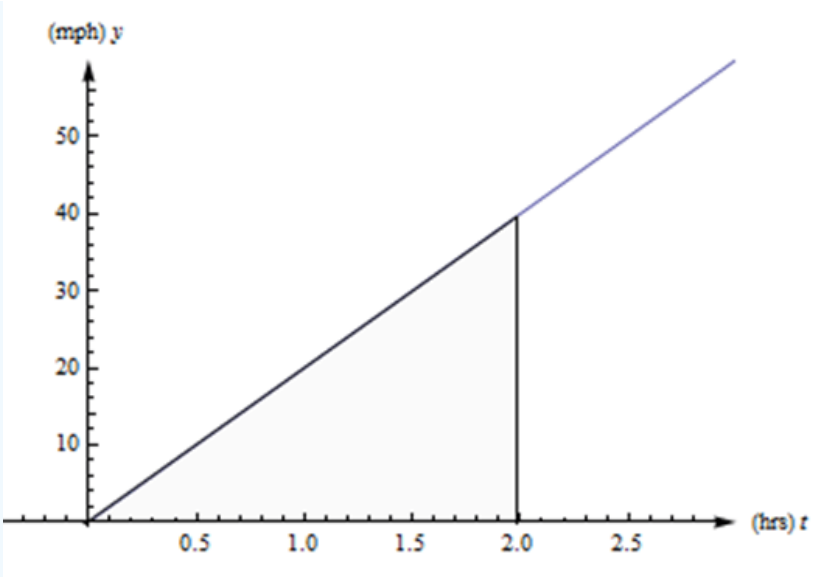


Solution

We all remember **distance = rate·time**, so this one is easy. The car has gone (40 miles/hour)·(2 hours) = 80 miles.

Example 5.2.2

Now suppose that a car travels so that its speed increases steadily from 0 to 40 miles per hour, for two hours. (Just be grateful you weren't stuck behind this car on the highway.) See the graph of its velocity in below. How far has this car gone?



Solution

The trouble with our old reliable **distance = rate·time** relationship is that it only works if the rate is constant. If the rate is changing, there isn't a good way to use this formula.

But look at the graph from the last example again. Notice that **distance = rate·time** also describes the area between the velocity graph and the t-axis, between $t = 0$ and $t = 2$ hours. The **rate** is the height of the rectangle, the **time** is the length of the rectangle, and the **distance** is the **area** of the rectangle. This is the way we can extend our simple formula to handle more complicated velocities: And this is the way we can answer the second example.

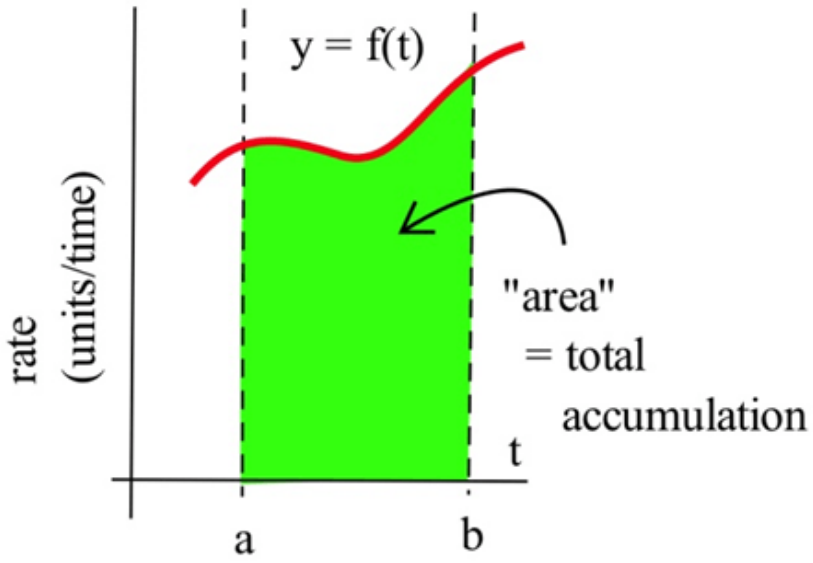
The distance the car travels is the area between its velocity graph, the t-axis, $t = 0$ and $t = 2$. This region is a triangle, so its area is

$$\frac{1}{2}bh = \frac{1}{2}(2 \text{ hours})(40 \text{ miles per hour}) = 40 \text{ miles}.$$

So the car travels 40 miles during its annoying trip.

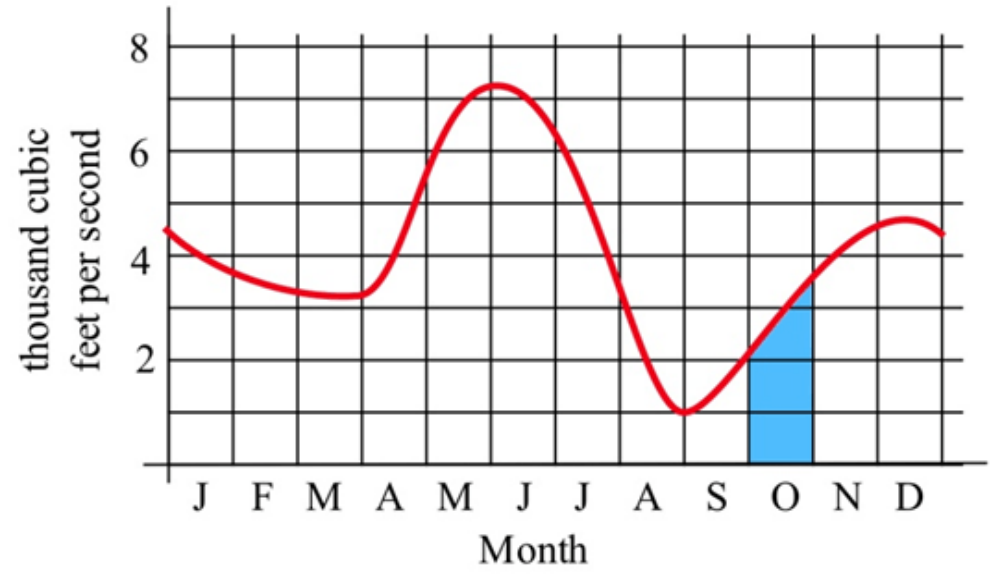
In our distance/velocity examples, the function represented a **rate** of travel (miles per hour), and the area represented the **total** distance traveled. This principle works more generally:

For functions representing other **rates** such as the production of a factory (bicycles per day), or the flow of water in a river (gallons per minute) or traffic over a bridge (cars per minute), or the spread of a disease (newly sick people per week), the area will still represent the **total** amount of something.



Example 5.2.3

The graph below shows the flow rate (cubic feet per second) of water in the Skykomish river at the town of Goldbar in Washington state.



Solution

The area of the shaded region represents the total volume (cubic feet or ft^3) of water flowing past the town during the month of October. We can approximate this area to approximate the total water by thinking of the shaded region as a rectangle with a triangle on top.

$$\begin{aligned}\text{Total water} &= \text{total area}\\ &\approx \text{area of rectangle} + \text{area of the "triangle"}\\ &\approx \left(2000\frac{\text{ft}^3}{\text{s}}\right)(30\text{ days}) + \frac{1}{2}\left(1500\frac{\text{ft}^3}{\text{s}}\right)(30\text{ days})\\ &= \left(2570\frac{\text{ft}^3}{\text{s}}\right)(30\text{ days})\end{aligned}$$

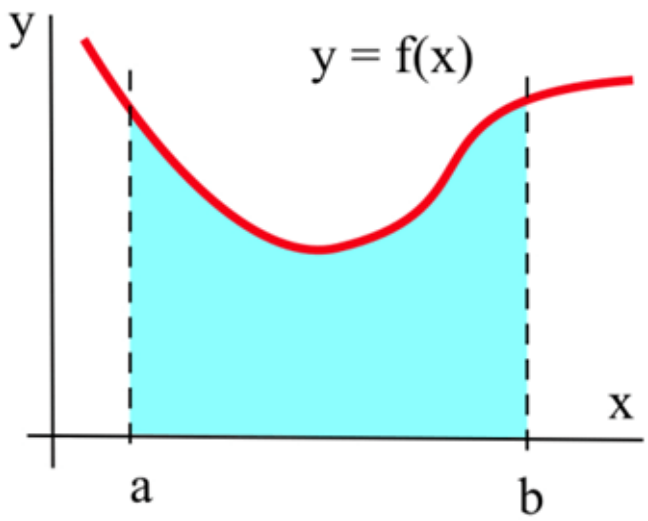
Note that we need to convert the units to make sense of our result:

$$\begin{aligned}\text{Total water} &\approx \left(2570\frac{\text{ft}^3}{\text{s}}\right)(30 \text{ days}) \\ &= \left(2570\frac{\text{ft}^3}{\text{s}}\right)(2{,}592{,}000 \text{ sec}) \\ &\approx 7.128 \cdot 10^9 \text{ ft}^3\end{aligned}$$

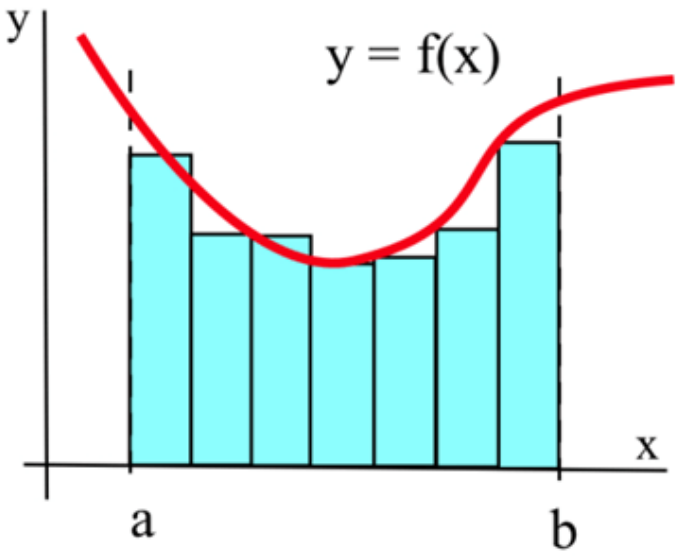
About 7 billion cubic feet of water flowed past Goldbar in October.

Approximating with Rectangles

How do we approximate the area if the rate curve is, well, "curvy"? We could use rectangles and triangles, like we did in the last example. But it turns out to be more useful (and easier) to simply use rectangles. The more rectangles we use, the better our approximation is.

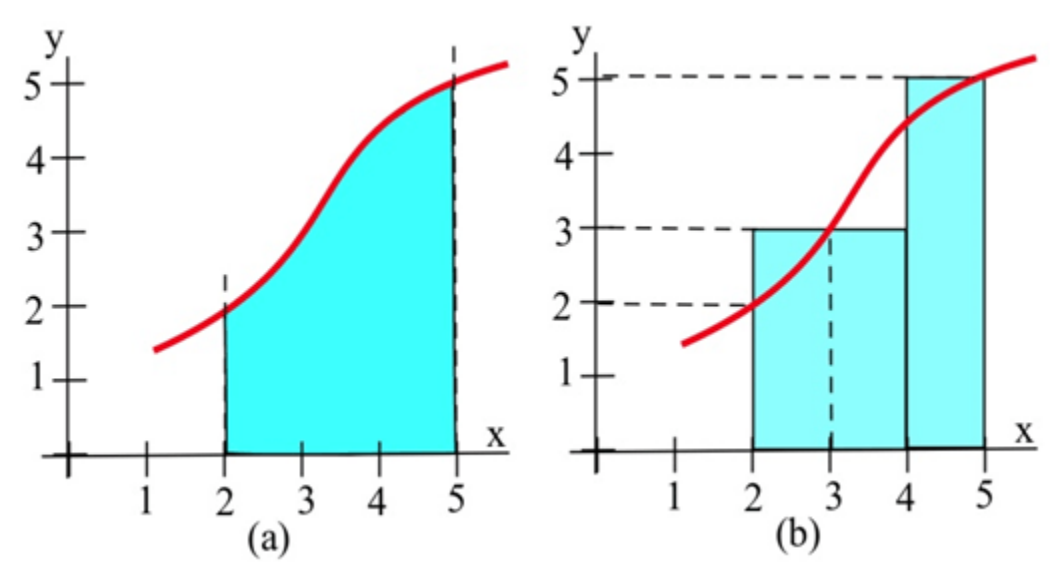


Suppose we want to calculate the area between the graph of a positive function f and the x-axis on the interval $[a, b]$ (graphed above). The **Riemann Sum method** is to build several rectangles with bases on the interval $[a, b]$ and sides that reach up to the graph of f (see below). Then the areas of the rectangles can be calculated and added together to get a number called a Riemann Sum of f on $[a, b]$. The area of the region formed by the rectangles is an **approximation** of the area we want.



Example 5.2.4

Approximate the area in the graph on the left between the graph of f and the x-axis on the interval [2, 5] by summing the areas of the rectangles in the graph on the right.



Solution

The total area of rectangles is

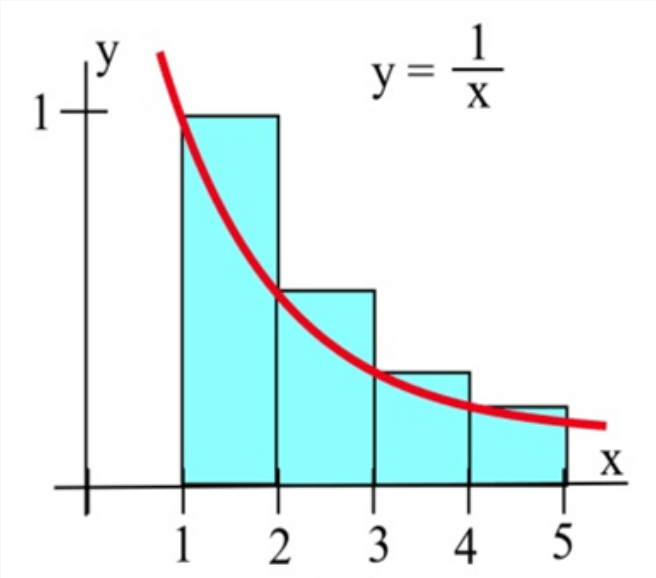
$$(2)(3) + (1)(5) = 11 \text{ units}^2.$$

Example 5.2.5

Let A be the region bounded by the graph of $f(x) = \frac{1}{x}$, the x-axis, and vertical lines at $x = 1$ and $x = 5$. We can't find the area exactly (with what we know now), but we can approximate it using rectangles.

When we make our rectangles, we have a lot of choices. We could pick any (non-overlapping) rectangles whose bottoms lie within the interval on the x-axis, and whose tops intersect with the curve somewhere. But it is easiest to choose rectangles that (a) have all the same width and (b) take their heights from the function at one edge. Below are graphs showing two ways to use four rectangles to approximate this area. In the first graph, we used left-endpoints; the height of each rectangle comes from the function value at its left edge. In the second graph on the next page, we used right-hand endpoints.

Left-hand endpoints: The area is approximately the sum of the areas of the rectangles. Each rectangle gets its height from the function $f(x) = \frac{1}{x}$ and each rectangle has a width of 1.



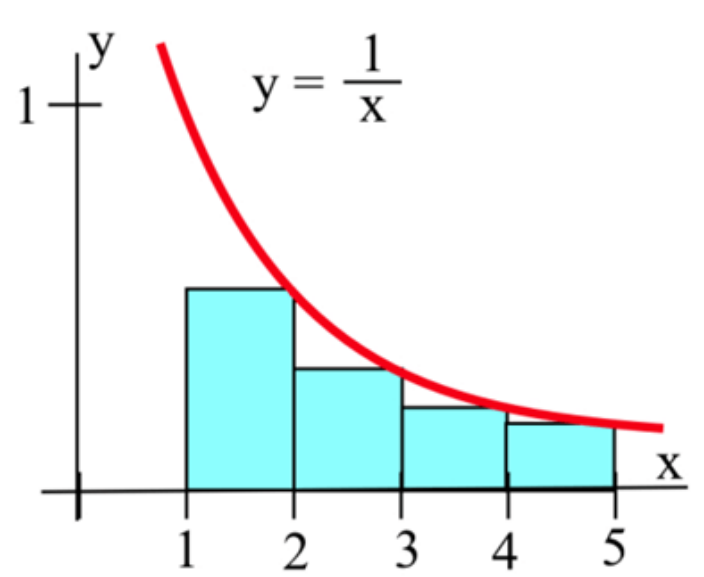
You can find the area of each rectangle using area = height·width. So the total area of the rectangles, the left-hand estimate of the area under the curve, is

$$f(1) \cdot 1 + f(2) \cdot 1 + f(3) \cdot 1 + f(4) \cdot 1 = 1 + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} = \frac{25}{12} \approx 2.08.$$

Notice that because this function is decreasing, all the left endpoint rectangles stick out above the region we want – using left-hand endpoints will overestimate the area.

Right-hand endpoints: The right-hand estimate of the area is

$$f(2) \cdot 1 + f(3) \cdot 1 + f(4) \cdot 1 + f(5) \cdot 1 = \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \frac{1}{5} = \frac{77}{60} \approx 1.28.$$



All the right-hand rectangles lie completely under the curve, so this estimate will be an underestimate.

We can see that the true area is actually in between these two estimates. So we could take their average:

$$\text{Average} = \frac{\frac{25}{12} + \frac{77}{60}}{2} = \frac{101}{60} \approx 1.68$$

In general, the average of the left-hand and right-hand estimates will be closer to the real area than either individual estimate.

Our estimate of the area under the curve is about 1.68. (The actual area is about 1.61.)

This applet will allow you to see how the approximation changes if you use more rectangles; change the “position” slider to switch between using the left endpoints, right endpoints, and midpoints:

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this GeoGebra Interactive online

If we wanted a better answer, we could use even more and even narrower rectangles. But there is a limit to how much work we want to do by hand. In practice, choose a manageable number of rectangles. We will have better methods to get more accurate answers before long.

These sums of areas of rectangles are called **Riemann sums**. You may see a shorthand notation used when people talk about sums. We won't use it much in this book, but you should know what it means.

Riemann sum and Sigma Notation

Riemann Sum

A Riemann sum for a function $f(x)$ over an interval $[a, b]$ is a sum of areas of rectangles that approximates the area under the curve. Start by dividing the interval $[a, b]$ into n subintervals; each subinterval will be the base of one rectangle. We usually make all the rectangles the same width Δx. The height of each rectangle comes from the function evaluated at some point in its sub interval. Then the Riemann sum is

$$f(x_1)\Delta x + f(x_2)\Delta x + f(x_3)\Delta x + \cdots + f(x_n)\Delta x$$

or, factoring out the Δx,

$$\Delta x \left(f(x_1) + f(x_2) + f(x_3) + \cdots + f(x_n)\right).$$

Sigma Notation

The upper-case Greek letter Sigma $\sum$ is used to stand for "sum". Sigma notation is a way to compactly represent a sum of many similar terms, such as a Riemann sum.

Using the Sigma notation, the Riemann sum can be written

$$\sum_{i=1}^{n} f\left(x_i\right) \Delta x.$$

This is read aloud as "the sum as i goes from 1 to n of f of x sub i times Delta x." The "i" is a counter or index, like you might have seen in a programming class.

Definition of the Definite Integral

Because the area under the curve is so important, it has a special vocabulary and notation.

The Definite Integral

The **definite integral** of a positive function $f(x)$ over an interval $[a, b]$ is the area between f, the x-axis, $x = a$ and $x = b$.

The **definite integral** of a positive function $f(x)$ from a to b is the area under the curve between a and b.

If $f(t)$ represents a positive rate (in y-units per t-units), then the definite integral of $f(t)$ from a to b is the total y-units that accumulate between $t = a$ and $t = b$.

Notation for the Definite Integral

The definite integral of $f(x)$ from a to b is written

$$\int_a^b f(x)\, dx.$$

The $\int$ symbol is called the **integral sign**; it is an elongated letter S, standing for "sum". (The $\int$ corresponds to the $\sum$ from the Riemann sum)

The dx on the end *must* be included! The dx tells what the variable is – in this example, the variable is x. (The dx corresponds to the Δx from the Riemann sum)

The function f is called the **integrand**.

The a and b are called the **limits of integration**.

Verb forms

We **integrate**, or **find the definite integral** of a function. This process is called **integration**.

Formal Algebraic Definition

$$\int_a^b f(x)\, dx = \lim_{n\to\infty} \sum_{i=1}^{n} f(x_i)\Delta x.$$

Practical Definition

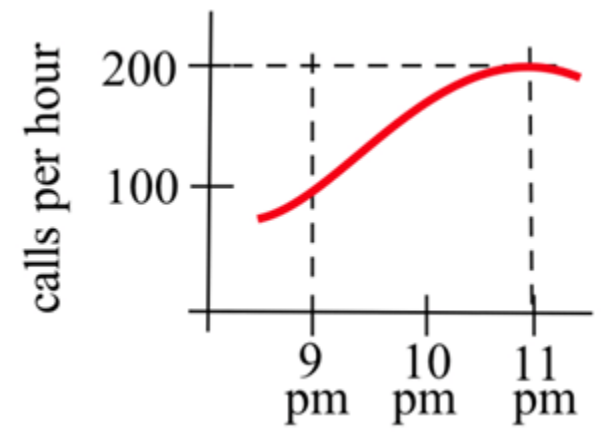
The definite integral can be approximated with a Riemann sum (dividing the area into rectangles where the height of each rectangle comes from the function, computing the area of each rectangle, and adding them up). The more rectangles we use, the narrower the rectangles are, the better our approximation will be.

Looking Ahead

We will have methods for computing exact values of some definite integrals from formulas soon. In many cases, including when the function is given to you as a table or graph, you will still need to approximate the definite integral with rectangles.

Example 5.2.6

The graph below shows $y = r(t)$, the number of telephone calls made per hours on a Tuesday. Approximately how many calls were made between 9 pm and 11 pm? Express this as a definite integral and approximate with a Riemann sum.

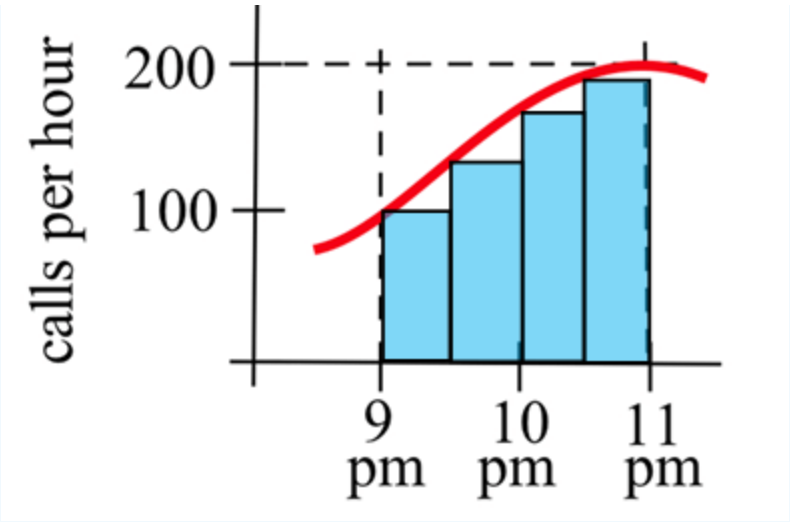


Solution

We know that the accumulated calls will be the area under this rate graph over that two-hour period, the definite integral of this rate from $t = 9$ to $t = 11$.

The total number of calls will be $\int_9^{11} r(t)\ dt$.

The top here is a curve, so we can't get an exact answer. But we can approximate the area using rectangles. Let's choose to use four rectangles and left-endpoints:



$$\int_9^{11} r(t)\,dt \approx 0.5(100+150+180+195) = 312.5$$

The units are *calls per hour·hours* = *calls*. Our estimate is that about 312 calls were made between 9 pm and 11 pm. Is this an under-estimate or an over-estimate?

Example 5.2.7

Describe the area between the graph of $f(x) = \frac{1}{x}$, the x-axis, and the vertical lines at $x = 1$ and $x = 5$ as a definite integral.

Solution

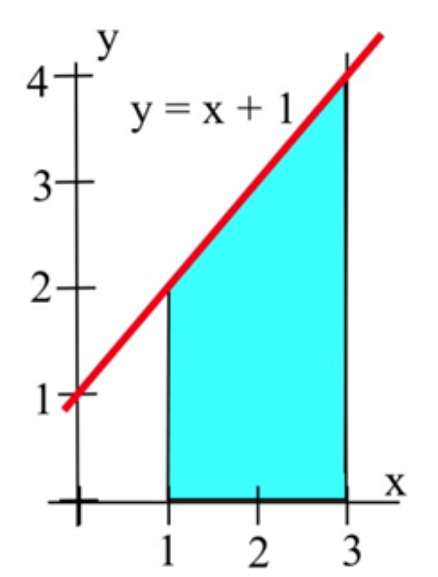
This is the same area we estimated to be about 1.68 before. Now we can use the notation of the definite integral to describe it. Our estimate of $\int_1^5 \frac{1}{x}\,dx$ was 1.68. The true value of $\int_1^5 \frac{1}{x}\,dx$ is about 1.61.

Example 5.2.8

Using the idea of area, determine the value of $\int_1^3 1+x\,dx$.

Solution

$\int_1^3 1+x\,dx$ represents the area between the graph of $f(x) = 1+x$, the x-axis, and the vertical lines at 1 and 3.



Since this area can be broken into a rectangle and a triangle, we can find the area exactly. The area equals

$$4 + \frac{1}{2}(2)(2) = 6 \text{ units}^2.$$

Example 5.2.9

The table shows rates of population growth for Berrytown for several years. Use this table to estimate the total population growth from 1970 to 2000:

Year, t	1970	1980	1990	2000
Rate of population growth $R(t)$ in thousands of people per year	1.5	1.9	2.2	2.4

Solution

The definite integral of this rate will give the total change in population over the thirty-year period. We only have a few pieces of information, so we can only estimate. Even though we haven't made a graph, we're still approximating the area under the rate curve, using rectangles. How wide are the rectangles? We have information every 10 years, so the rectangles have a width of 10 years. How many rectangles? Be careful here – this is a thirty-year span, so there are three rectangles.

- Using left-hand endpoints: (1.5)(10) + (1.9)(10) + (2.2)(10) = 56
- Using right-hand endpoints: (1.9)(10) + (2.2)(10) + (2.4)(10) = 65

Taking the average of these two:

$$\frac{56 + 65}{2} = 60.5$$

Our best estimate of the total population growth from 1970 to 2000 is **60.5 thousand people**.

Signed Area

You may have noticed that until this point, we've insisted that the integrand (the function we're integrating) be positive. That's because we've been talking about area, which is always positive.

If the “height” (from the function) is a negative number, then multiplying it by the width doesn't give us actual area, it gives us the area with a negative sign.

But it turns out to be useful to think about the possibility of negative area. We'll expand our idea of a definite integral now to include integrands that might not always be positive. The “heights” of the rectangles, the values from the function, now might not always be positive.

The Definite Integral and Signed Area

The **definite integral** of a function $f(x)$ over an interval $[a, b]$ is the **signed area** between f, the x-axis, $x = a$ and $x = b$.

The **definite integral** of a function $f(x)$ from a to b is the **signed area** under the curve between a and b.

If the function is positive, the signed area is positive, as before (and we can call it area.)

If the function dips below the x-axis, the areas of the regions below the x-axis come in with a negative sign. In this case, we cannot call it simply “area.” These negative areas take away from the definite integral.

$\int_a^b f(x)\ dx =$ (Area above x-axis) $-$ (Area below x-axis)

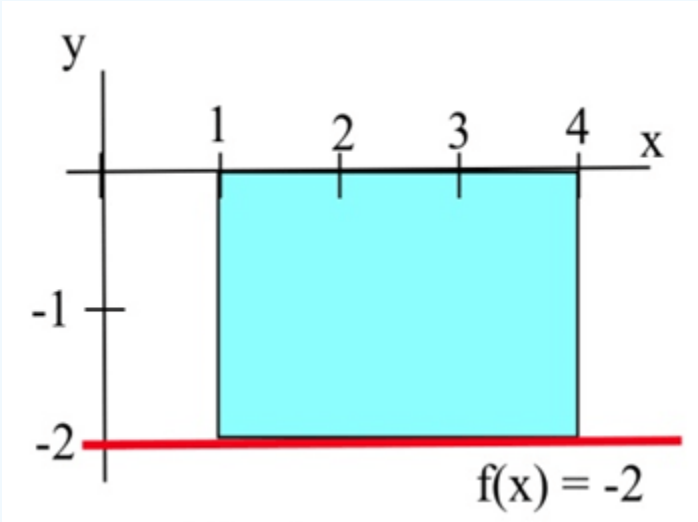
If $f(t)$ represents a positive rate (in y-units per t-units), then the **definite integral** of f from a to b is the **total** y-units that accumulate between $t = a$ and $t = b$.

If $f(t)$ represents any rate (in y-units per t-units), then the **definite integral** of f from a to b is the **net** y-units that accumulate between $t = a$ and $t = b$.

Example 5.2.10

Find the definite integral of $f(x) = -2$ on the interval [1,4].

Solution



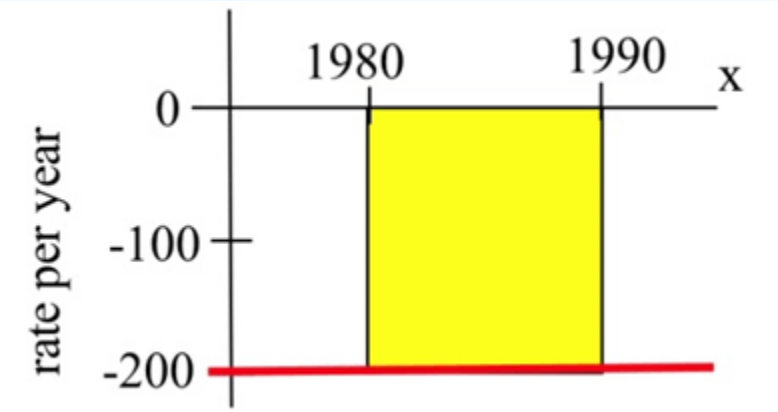
$\int_1^4 -2\ dx$ is the signed area of the region shown to the right. The region lies below the x-axis, so the area, 6, comes in with a negative sign. So the definite integral is $\int_1^4 -2\ dx = -6$.

Negative rates indicate that the amount is decreasing. For example, if $f(t)$ is the velocity of a car in the positive direction along a straight line at time t (miles/hour), then negative values of f indicate that the car is traveling in the negative direction, backwards. The definite integral of f is the change in position of the car during the time interval. If the velocity is positive, positive distance accumulates. If the velocity is negative, distance in the negative direction accumulates.

This is true of any rate. For example, if $f(t)$ is the rate of population change (people/year) for a town, then negative values of f would indicate that the population of the town was getting smaller, and the definite integral (now a negative number) would be the **change** in the population, a decrease, during the time interval.

Example 5.2.11

In 1980 there were 12,000 ducks nesting around a lake, and the **rate** of population change (in ducks per year) is shown in the figure below. Write a definite integral to represent the total change in the duck population from 1980 to 1990, and estimate the population in 1990.



Solution

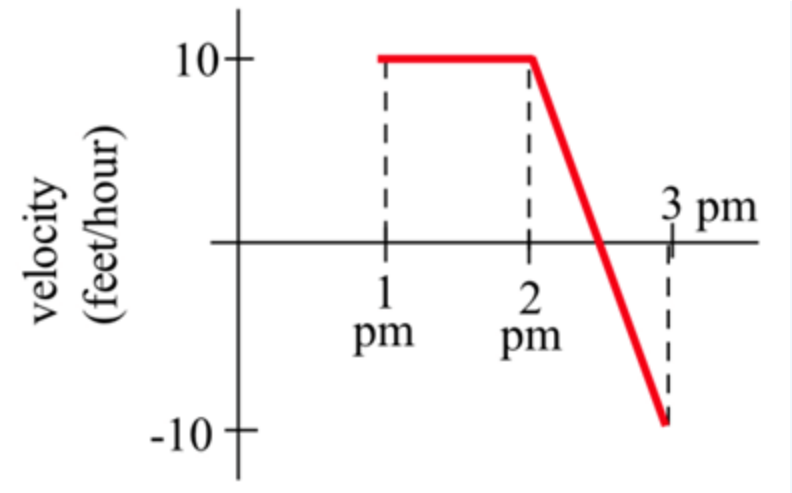
The change in population is:

$$\begin{aligned}\int_{1980}^{1990} f(t)\,dt &= -(\text{area between } f \text{ and axis}) \\ &\approx -(200 \text{ ducks/year}) \cdot (10 \text{ years}) \\ &= -2000 \text{ ducks}\end{aligned}$$

Then (1990 duck population) = (1980 population) + (change from 1980 to 1990) = (12,000) + (-2000) = 10,000 ducks.

Example 5.2.12

A bug starts at the location $x = 12$ on the x-axis at 1 pm walks along the axis with the velocity $v(x)$ shown in the graph. How far does the bug travel between 1 pm and 3 pm, and where is the bug at 3 pm?



Solution

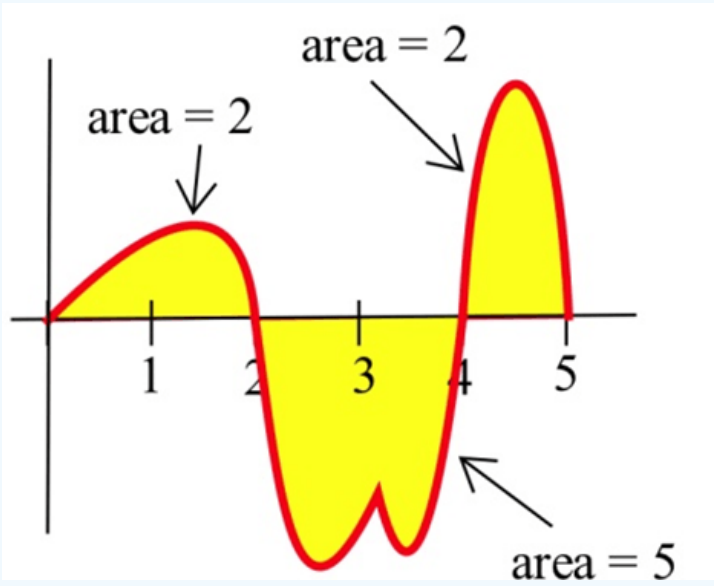
Note that the velocity is positive from 1 until 2:30, then becomes negative. So the bug moves in the positive direction from 1 until 2:30, then turns around and moves back toward where it started. The area under the velocity curve from 1 to 2:30 shows the total distance traveled by the bug in the positive direction; the bug moved 12.5 feet in the positive direction. The **area** between the velocity curve and the x-axis, between 2:30 and 3, shows the total distance traveled by the bug in the negative direction, back toward home; the bug traveled 2.5 feet in the negative direction. The definite integral of the velocity curve, $\int_1^3 v(t)\ dt$, shows the net change in distance:

$$\int_1^3 v(t)\,dt = 12.5 - 2.5 = 10.$$

The bug ended up 10 feet farther in the positive direction than he started. At 3 pm, the bug is at $x = 22$.

Example 5.2.13

Use the graph below to calculate $\int_0^2 f(x)\ dx$, $\int_2^4 f(x)\ dx$, $\int_4^5 f(x)\ dx$, and $\int_0^5 f(x)\ dx$.



Solution

Using the given areas, $\int_0^2 f(x)\ dx = 2$, $\int_2^4 f(x)\ dx = -5$, $\int_4^5 f(x)\ dx = 2$, and $\int_0^5 f(x)\ dx$ =(area above)−(area below) $= (2 + 2) - (5) = -1$.

Approximating with Technology

If your function is given as a graph or table, you will still have to approximate definite integrals using areas, usually of rectangles. But if your function is given as a formula, you can turn to technology to get a better approximate answer. For example, most graphing calculators have some kind of numerical integration tool built in. You can also find many online tools that can do this; type numerical integration into any search engine to see a selection of these.

Most numerical integration tools use rectangles to estimate the signed area, just as you would do by hand. But they use many more rectangles than you would have the patience for, so they get a better answer. Some of them use computer algebra systems to find exact answers; we will learn how to do this ourselves later in this chapter.

When you turn to technology to find the value of a definite integral, be careful. Not every tool will be able to give you a correct answer for every integral. You should make an estimate of the answer yourself first so you can judge whether the answer you get makes sense.

Example 5.2.14

Use technology to approximate the definite integral $\int_1^5 \frac{1}{x}\ dx$. (This is the same definite integral we approximated with rectangles before.)

Solution

We could use the following command in GeoGebra to approximate this integral:

```
Integral[1 / x, 1, 5]
```

Or click this link to see how to evaluate this integral using Wolfram|Alpha.

Example 5.2.15

Use technology to approximate the definite integral $\int_1^2 e^{x^2+x}\ dx$.

Solution

The function here is positive, so there must be some area under the curve here. There isn't an algebraic way to find the exact answer, so some programs may just return the original integral rather than try to approximate it.

We could use the following command in GeoGebra to approximate this integral:

```
Integral[e^(x^2 + x), 1, 2]
```

Or click this link to see how to approximate this integral using Wolfram|Alpha. Although it looks like Wolfram|Alpha can evaluate the integral, the "Erfi" function that it shows in its answer is actually defined in terms of another integral, so it still hasn't found an algebraic answer.

Accumulation in Real Life

We have already seen that the "area" under a graph can represent quantities whose units are not the usual geometric units of square meters or square feet. For example, if t is a measure of time in seconds and $f(t)$ is a velocity with units feet/second, then the definite integral has units (feet/second)·(seconds) = feet.

In general, the units for the definite integral $\int_a^b f(x)\ dx$ are (y-units)·(x-units). A quick check of the units can help avoid errors in setting up an applied problem.

In previous examples, we looked at a function that represented a **rate** of travel (miles per hour); in that case, the area represented the **total** distance traveled. For functions representing other **rates** such as the production of a factory (bicycles per day), or the flow of water in a river (gallons per minute) or traffic over a bridge (cars per minute), or the spread of a disease (newly sick people per week), the area will still represent the **total** amount of something.

Example 5.2.16

Suppose $MR(q)$ is the marginal revenue in dollars/item for selling q items. What does $\int_0^{150} MR(q)\ dq$ represent?

Solution

$\int_0^{150} MR(q)\ dq$ has units (dollars/item)·(items) = dollars, and represents the accumulated dollars for selling from 0 to 150 items. That is, $\int_0^{150} MR(q)\ dq = TR(150)$, the total revenue from selling 150 items.

Example 5.2.17

Suppose $r(t)$, in centimeters per year, represents how the diameter of a tree changes with time. What does $\int_{T_1}^{T_2} r(t)\ dt$ represent?

Solution

$\int_{T_1}^{T_2} r(t)\ dt$ has units of (centimeters per year)·(years) = centimeters, and represents the accumulated growth of the tree's diameter from T_1 to T_2. That is, $\int_{T_1}^{T_2} r(t)\ dt$ is the change in the diameter of the tree over this period of time.

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5.3: The Fundamental Theorem and Antidifferentiation

The Fundamental Theorem of Calculus

This section contains the most important and most used theorem of calculus, the Fundamental Theorem of Calculus. Discovered independently by Newton and Leibniz in the late 1600s, it establishes the connection between derivatives and integrals, provides a way of easily calculating many integrals, and was a key step in the development of modern mathematics to support the rise of science and technology. Calculus is one of the most significant intellectual structures in the history of human thought, and the Fundamental Theorem of Calculus is a most important brick in that beautiful structure.

The Fundamental Theorem of Calculus

If $F(x)$ is a function where $F'(x) = f(x)$, then

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

This is actually not new for us; we've been using this relationship for some time; we just haven't written it this way. This says what we've said before: the definite integral of a rate from a to b is the net y-units, the change in y, that accumulate between $t = a$ and $t = b$. Here we've just made it plain that that the rate is a derivative.

Thinking about the relationship this way gives us the key to finding exact answers for some definite integrals. If the integrand is the derivative of some F, then maybe we could simply find F and subtract – that would be easier than approximating with rectangles. Going backwards through the differentiation process will help us evaluate definite integrals.

Example 5.3.1

Find $f(x)$ if $f'(x) = 2x$.

Solution

Oooh, I know this one. It's $f(x) = x^2 + 3$. Oh, wait, you were thinking something else? Yes, I guess you're right, $f(x) = x^2$ works too. So does $f(x) = x^2 - \pi$, and $f(x) = x^2 + 104{,}589.2$. In fact, there are lots of answers.

In fact, there are infinitely many functions that all have the same derivative. And that makes sense – the derivative tells us about the shape of the function, but it doesn't tell about the location. We could shift the graph up or down and the shape wouldn't be affected, so the derivative would be the same.

This leads to one of the trickier definitions – pay careful attention to the articles ("the" versus "an"), because they're important.

Antiderivatives

An **antiderivative** of a function $f(x)$ is any function $F(x)$ where $F'(x) = f(x)$.

The antiderivative of a function $f(x)$ is a whole family of functions, written $F(x) + C$, where $F'(x) = f(x)$ and C represents any constant.

The antiderivative is also called the **indefinite integral**.

Notation for the Antiderivative

The antiderivative of f is written

$$\int f(x)\,dx$$

This notation resembles the definite integral, because the Fundamental Theorem of Calculus says antiderivatives and definite integrals are intimately related. But in this notation, there are no limits of integration.

The $\int$ symbol is still called an **integral sign**; the dx on the end still must be included; you can still think of $\int$ and dx as left and right parentheses. The function f is still called the **integrand**.

Verb Forms

We **antidifferentiate**, or **integrate**, or **find the indefinite integral** of a function. This process is called **antidifferentiation** or **integration**.

There are no small families in the world of antiderivatives: if f has one antiderivative F, then f has an infinite number of antiderivatives and every one of them has the form $F(x)+C$.

Example 5.3.2

Find **an** antiderivative of $2x$.

Solution

We can choose any function we like as long as its derivative is $2x$, so we can pick, say, $F(x)=x^2-5.2$.

Example 5.3.3

Find **the** antiderivative of $2x$.

Solution

Now we need to write the entire family of functions whose derivatives are $2x$. We can use the $\int$ notation:

$$\int 2x\,dx = x^2 + C.$$

(Don't forget the "$+C$"!)

Example 5.3.4

Find $\int e^x\ dx$.

Solution

This is likely one you remember: e^x is its own derivative, so it is also its own antiderivative. The integral sign tells us that we need to include the entire family of functions, so we need that "$+C$" on the end:

$$\int e^x\,dx = e^x + C.$$

Antiderivatives Graphically or Numerically

Another way to think about the Fundamental Theorem of Calculus is to solve the expression for $F(b)$:

The Fundamental Theorem of Calculus (restated): Net Change

$$\int_a^b F'(x)\,dx = F(b) - F(a)$$

The definite integral of a derivative from a to b gives the net change in the original function.

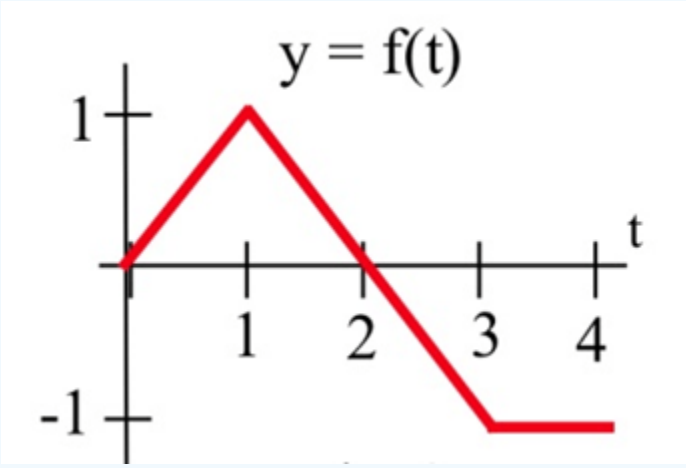
$$F(b) = F(a) + \int_a^b F'(x)\,dx$$

The amount we end up is the amount we start with plus the net change in the function.

This lets us get values for the antiderivative – as long as we have a starting point, and we know something about the area.

Example 5.3.5

Suppose $F(t)$ has the derivative $f(t)$ shown below, and suppose that we know $F(0) = 5$. Find values for $F(1),\ F(2),\ F(3)$, and $F(4)$.



Solution

Using the second way to think about the Fundamental Theorem of Calculus, $F(b) = F(a) + \int_a^b F'(x)\ dx$, we can see that $F(1) = F(0) + \int_0^1 f(x)\ dx$. We know the value of $F(0)$, and we can easily find $\int_0^1 f(x)\ dx$ from the graph – it's just the area of a triangle. So

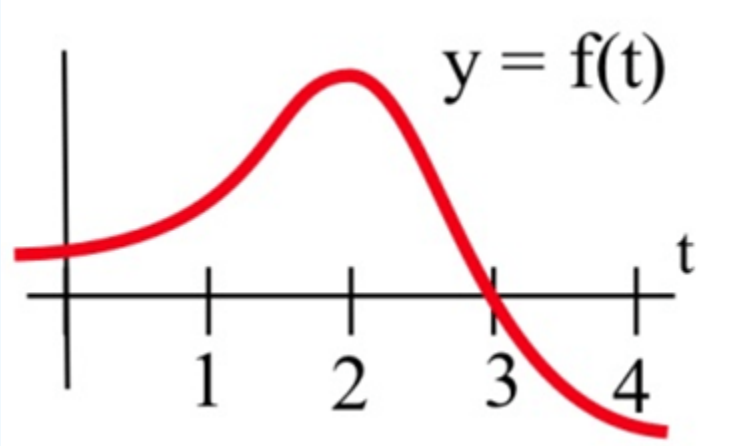
$$\begin{aligned} F(1) &= \\ &= 5 + 0.5 = 5.5 \\ F(2) &= F(0) + \int_0^2 f(x)\,dx \\ &= 5 + 1 = 6 \end{aligned}$$

Note that we can start from any place of which we know the value; for example, now that we know $F(2)$, we can use that to find

$$F(3) = F(2) + \int_2^3 f(x)\,dx$$
$$= 6 - 0.5 = 5.5$$
$$F(4) = F(3) + \int_3^4 f(x)\,dx$$
$$= 5.5 - 1 = 4.5$$

Example 5.3.6

$F'(t) = f(t)$ is shown below. Where does $F(t)$ have maximum and minimum values on the interval [0, 4]?



Solution

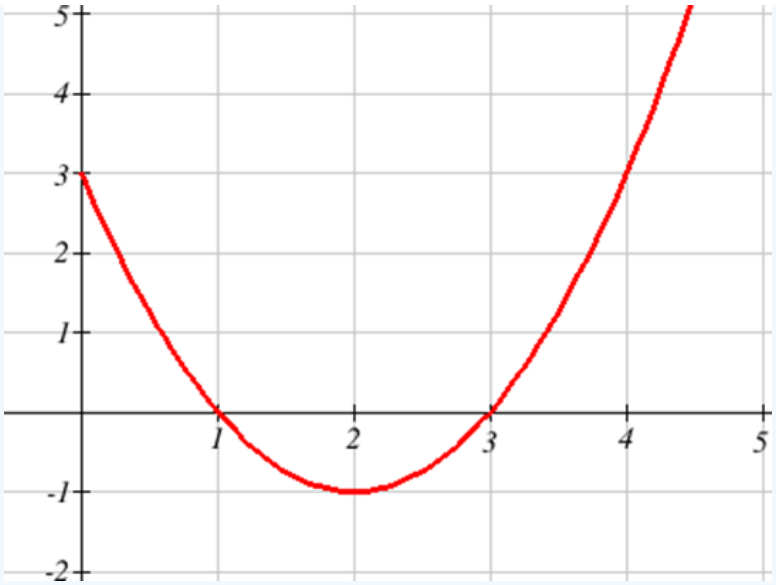
Since $F(b) = F(a) + \int_a^b F'(x)\ dx$, we know that F is increasing as long as the area accumulating under $F' = f$ is positive (until $t = 3$), and then decreases when the curve dips below the x-axis so that negative area starts accumulating. The area between $t = 3$ and $t = 4$ is much smaller than the positive area that accumulates between 0 and 3, so we know that $F(4)$ must be larger than $F(0)$. The maximum value is when $t = 3$; the minimum value is when $t = 0$.

Note that this is a different way to look at a problem we already knew how to solve – in Chapter 2, we would have found critical points of F, where $f = 0$: there's only one, when $t = 3$. $f = F'$ goes from positive to negative there, so F has a local max at that point. It's the only critical point, so it must be a global max. Then we would look at the values of F at the endpoints to find which was the global min.

We can also attempt to sketch a function based on the graph of the derivative.

Example 5.3.7

The graph below shows $f'(x)$ – the rate of change of $f(x)$. Use it to sketch a graph of $f(x)$ that satisfies $f(0) = 0$.



Solution

Recall from the last chapter the relationships between the function graph and the derivative graph:

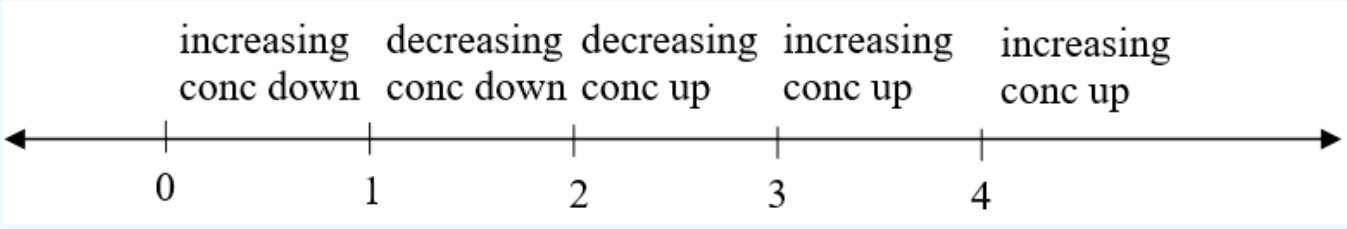
$f(x)$	Increasing	Decreasing	Concave Up	Concave Down
$f'(x)$	$+$	$-$	Increasing	Decreasing

In the graph shown, we can see the derivative is positive on the interval (0, 1) and $(3, \infty)$, so the graph of f should be increasing on those intervals. Likewise, f should be decreasing on the interval (1,3).

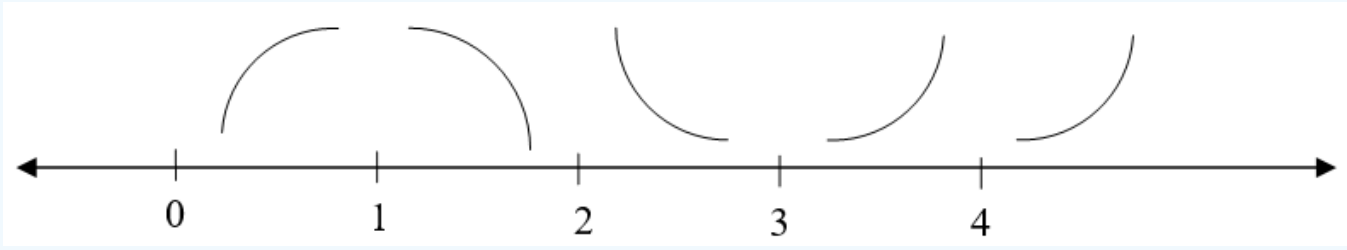
In the graph, f' is decreasing on the interval (0, 2), so f should be concave down on that interval. Likewise, f should be concave up on the interval $(2, \infty)$.

The derivative itself is not enough information to know where the function f starts, since there are a family of antiderivatives, but in this case we are given a specific point at which to start.

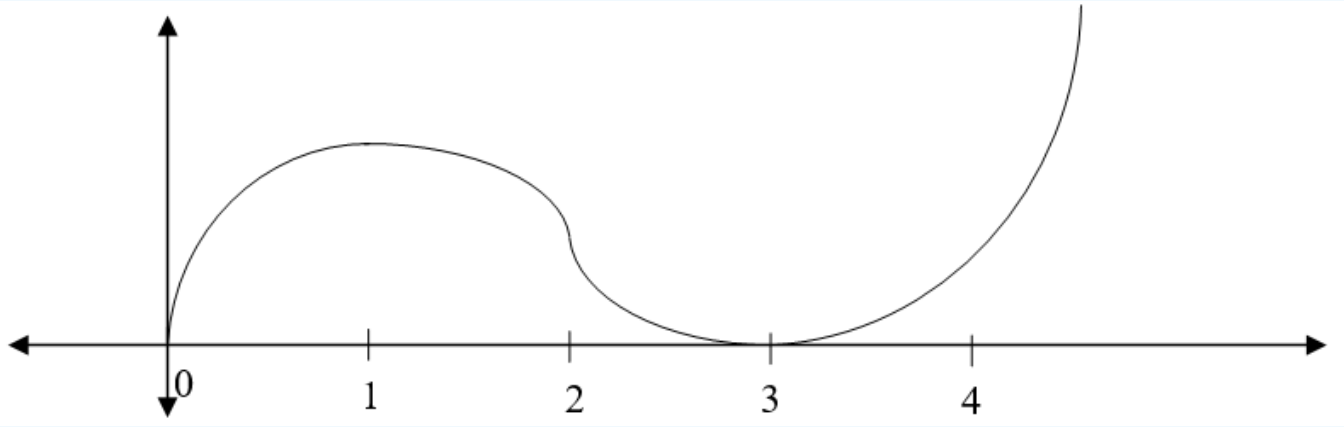
To start the sketch, we might note first the shapes we need:



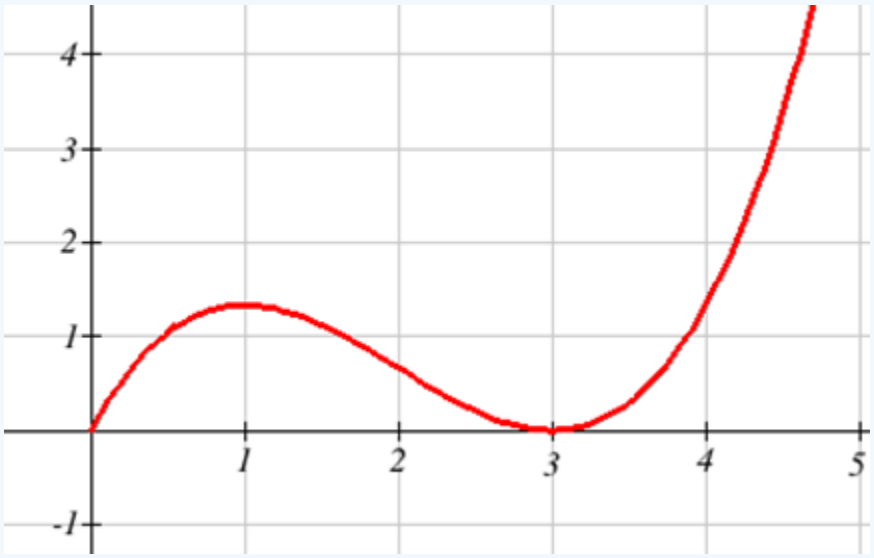
then sketch the basic shapes:



Now we can attempt to sketch the graph, starting at the point (0, 0). Notice we are very roughly sketching this, as we don't have much information to work with. We can tell, though, from the graph that the area from $x = 0$ to $x = 1$ is about the same as the area from $x = 1$ to $x = 3$, so we would expect the net area from $x = 0$to $x = 3$ to be close to 0.



It turns out this graph isn't horribly bad. Smoothing it out would give a graph closer to the actual antiderivative graph, shown below.



Derivative of the Integral

There is another important connection between the integral and derivative.

The Fundamental Theorem of Calculus (part 2)

If

$$A(x) = \int_a^x f(t)\,dt$$

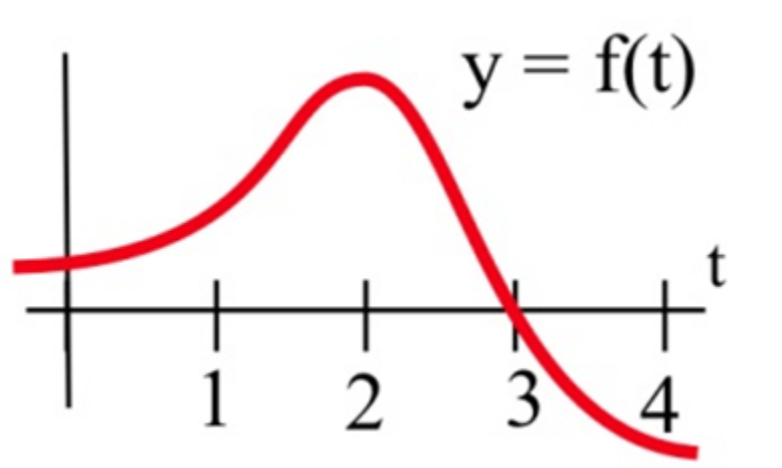
then

$$A'(x) = \frac{d}{dx}\int_a^x f(t)\,dt = f(x).$$

I.e., the derivative of the *accumulation function* is the original function.

Example 5.3.8

Let $F(x) = \int_0^x f(t)\ dt$, where f is graphed below. Estimate $F'(3)$.



Solution

The function $F(x)$ measures the area from $t = 0$ to some $t = x$. To estimate $F'(3)$, we want to estimate how much the area is increasing when $t = 3$. Since the value of the function $f(t)$ is 0 at $t = 3$, the area will not be increasing or decreasing, so we can estimate $F'(3) = 0$.

Directly using the fundamental theorem of calculus part 2,

$$F'(x) = \frac{d}{dx}\int_a^x f(t)\,dt = f(x)$$

so

$$F'(x) = f(3) = 0.$$

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5.4: Antiderivatives of Formulas

Now we can put the ideas of areas and antiderivatives together to get a way of evaluating definite integrals that is exact and often easy. To evaluate a definite integral $\int_a^b f(t)\ dt$, we can find any antiderivative $F(t)$ of $f(t)$ and evaluate $F(b) - F(a)$. The problem of finding the exact value of a definite integral reduces to finding some (any) antiderivative F of the integrand and then evaluating $F(b) - F(a)$. Even finding one antiderivative can be difficult, and we will stick to functions that have easy antiderivatives.

Building Blocks

Antidifferentiation is going backwards through the derivative process. So the easiest antiderivative rules are simply backwards versions of the easiest derivative rules. Recall from Chapter 2:

Derivative Rules: Building Blocks

In what follows, f and g are differentiable functions of x.

Constant Multiple Rule

$$\frac{d}{dx}(kf) = kf'$$

Sum and Difference Rule

$$\frac{d}{dx}(f \pm g) = f' \pm g'$$

Power Rule

$$\frac{d}{dx}(x^n) = nx^{n-1}$$

Special cases:

$$\frac{d}{dx}(k) = 0 \quad (\text{Because } k = kx^0.)$$
$$\frac{d}{dx}(x) = 1 \quad (\text{Because } x = x^1.)$$

Exponential Functions

$$\frac{d}{dx}(e^x) = e^x$$
$$\frac{d}{dx}(a^x) = \ln(a)\, a^x$$

Natural Logarithm

$$\frac{d}{dx}(\ln(x)) = \frac{1}{x}$$

Thinking about these basic rules was how we came up with the antiderivatives of $2x$ and e^x before.

The corresponding rules for antiderivatives are next – each of the antiderivative rules is simply rewriting the derivative rule. All of these antiderivatives can be verified by differentiating.

There is one surprise – the antiderivative of $\frac{1}{x}$ is actually not simply $\ln(x)$, it's $\ln|x|$. This is a good thing – the antiderivative has

a domain that matches the domain of $\frac{1}{x}$, which is bigger than the domain of $\ln(x)$, so we don't have to worry about whether our x's are positive or negative. But we *must* be careful to include those absolute values – otherwise, we could end up with domain problems.

Antiderivative Rules: Building Blocks

In what follows, f and g are differentiable functions of x, and k, n, and C are constants.

Constant Multiple Rule

$$\int k \cdot f(x)\,dx = k \cdot \int f(x)\,dx$$

Sum and Difference Rule

$$\int (f(x) \pm g(x))\;dx = \int f(x)\,dx \pm \int g(x)\,dx$$

Power Rule

$$\int x^n\,dx = \frac{x^{n+1}}{n+1} + C, \text{ provided that } n \neq -1$$

Special case:

$$\int k\,dx = kx + C \quad (\text{Because } k = kx^0.)$$

(The other special case ($n = -1$) is covered next.)

Natural Logarithm

$$\int x^{-1}\,dx = \int \frac{1}{x}\,dx = \ln|x| + C$$

Exponential Functions

$$\int e^x\,dx = e^x + C$$
$$\int a^x\,dx = \frac{a^x}{\ln(a)} + C$$

Example 5.4.1

Find the antiderivative of $y = 3x^7 - 15\sqrt{x} + \frac{14}{x^2}$.

Solution

$$\begin{aligned}\int \left(3x^7 - 15\sqrt{x} + \frac{14}{x^2}\right)\,dx &= \int \left(3x^7 - 15x^{1/2} + 14x^{-2}\right)\,dx \\ &= 3\frac{x^8}{8} - 15\frac{x^{3/2}}{3/2} + 14\frac{x^{-1}}{-1} + C \\ &= \frac{3}{8}x^8 - 10x^{3/2} - 14x^{-1} + C\end{aligned}$$

Example 5.4.2

Find $\int \left(e^x + 12 - \frac{16}{x}\right)\;dx$.

Solution

$$\int \left(e^x + 12 - \frac{16}{x}\right)\, dx = e^x + 12x - 16\ln|x| + C$$

Example 5.4.3

Find $F(x)$ so that $F'(x) = e^x$ and $F(0) = 10$.

Solution

This time we are looking for a particular antiderivative; we need to find exactly the right constant. Let's start by finding the antiderivative:

$$\int e^x\, dx = e^x + C$$

So we know that $F(x) = e^x + (\text{some constant})$, now we just need to find which one. To do that, we'll use the other piece of information (the initial condition):

$$\begin{aligned} F(x) &= e^x + C \\ F(0) &= e^0 + C = 1 + C = 10 \\ C &= 9 \end{aligned}$$

The particular constant we need is 9; thus, $F(x) = e^x + 9$.

The reason we are looking at antiderivatives right now is so we can evaluate definite integrals exactly. Recall the Fundamental Theorem of Calculus:

Fundamental Theorem of Calculus

If $F(x)$ is a function where $F'(x) = f(x)$, then

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

If we can find an antiderivative for the integrand, we can use that to evaluate the definite integral. The evaluation $F(b) - F(a)$ is represented as $F(x)]_a^b$ or $F(x)|_a^b$.

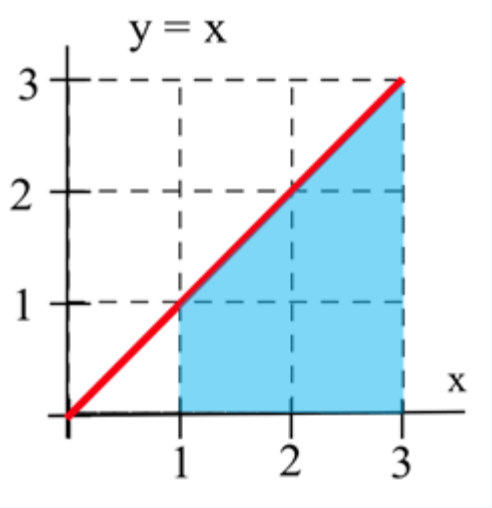
Example 5.4.4

Evaluate $\int_1^3 x\ dx$ in two ways:

1. By sketching the graph of $y = x$ and geometrically finding the area.
2. By finding an antiderivative of $F(x)$ of the integrand and evaluating $F(3) - F(1)$.

Solution

1. The graph of $y = x$ is shown below, and the shaded region corresponding to the integral has area 4.



2. One antiderivative of x is $F(x) = \frac{1}{2}x^2$, and

$$\begin{aligned}\int_1^3 x\,dx &= \left[\frac{1}{2}x^2\right]_1^3 \\ &= \left(\frac{1}{2}(3)^2\right) - \left(\frac{1}{2}(1)^2\right) \\ &= \frac{9}{2} - \frac{1}{2} \\ &= 4.\end{aligned}$$

Note that this answer agrees with the answer we got geometrically.

If we had used another antiderivative of x, say $F(x) = \frac{1}{2}x^2 + 7$, then

$$\begin{aligned}\int_1^3 x\,dx &= \left[\frac{1}{2}x^2 + 7\right]_1^3 \\ &= \left(\frac{1}{2}(3)^2 + 7\right) - \left(\frac{1}{2}(1)^2 + 7\right) \\ &= \frac{9}{2} + 7 - \frac{1}{2} - 7 \\ &= 4.\end{aligned}$$

In general, **whatever constant we choose gets subtracted away during the evaluation**, so we might as well always choose the easiest one, where the constant is 0.

Example 5.4.5

Find the area between the graph of $y = 3x^2$ and the horizontal axis for x between 1 and 2.

Solution

This is

$$\int_1^2 3x^2\,dx = x^3\Big|_1^2 = 2^3 - 1^3 = 7.$$

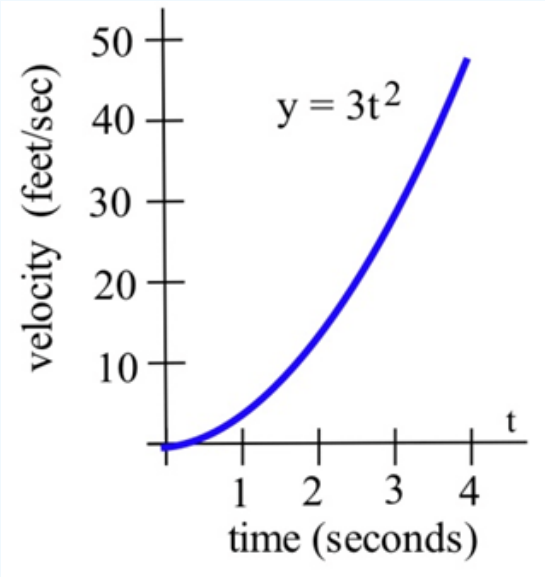
Example 5.4.6

A robot has been programmed so that when it starts to move, its velocity after t seconds will be $3t^2$ feet/second.

1. How far will the robot travel during its first 4 seconds of movement?
2. How far will the robot travel during its next 4 seconds of movement?

Solution

1. The distance during the first 4 seconds will be the area under the graph of velocity, from $t = 0$ to $t = 4$.



That area is the definite integral $\int_0^4 3t^2\ dt$. An antiderivative of $3t^2$ is t^3, so $\int_0^4 3t^2\ dt = t^3]_0^4 = 4^3 - 0^3 = 64$ feet.

2. $\int_4^8 3t^2\ dt = t^3]_4^8 = 8^3 - 4^3 = 512 - 64 = 448$ feet.

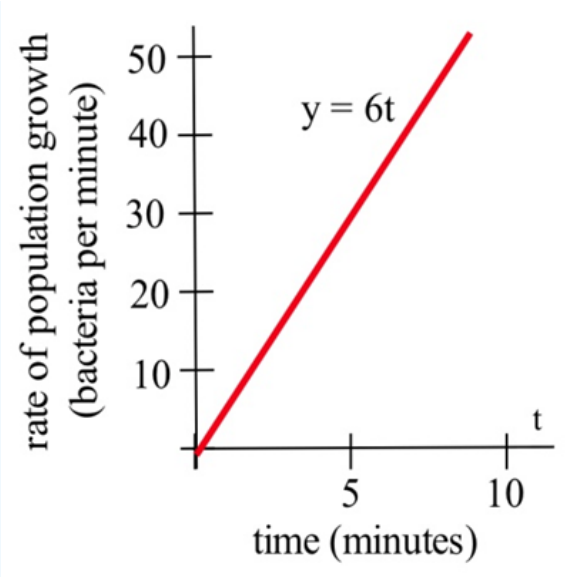
Example 5.4.7

Suppose that t minutes after putting 1000 bacteria on a Petri plate the rate of growth of the population is $6t$ bacteria per minute.

1. How many new bacteria are added to the population during the first 7 minutes?
2. What is the total population after 7 minutes?

Solution

1. The number of new bacteria is the area under the rate of growth graph, and one antiderivative of $6t$ is $3t^2$.



So

$$\text{new bacteria} = \int_0^7 6t\,dt = 3t^2\big|_0^7 = 3(7)^2 - 3(0)^2 = 147$$

2. The new population = (old population) + (new bacteria) = 1000 + 147 = 1147 bacteria.

Example 5.4.8

A company determines their marginal cost for production, in dollars per item, is $MC(x) = \frac{4}{\sqrt{x}} + 2$ when producing x thousand items. Find the cost of increasing production from 4 thousand items to 5 thousand items.

Solution

Remember that marginal cost is the rate of change of cost, and so the fundamental theorem tells us that $\int_a^b MC(x)\ dx = \int_a^b C'(x)\ dx = C(b) - C(a)$. In other words, the integral of marginal cost will give us a net change in cost. To find the cost of increasing production from 4 thousand items to 5 thousand items, we need to integrate $\int_4^5 MC(x)\ dx$.

We can write the marginal cost as $MC(x) = 4x^{-1/2} + 2$. We can then use the basic rules to find an antiderivative:

$$C(x) = 4\frac{x^{1/2}}{1/2} + 2x = 8\sqrt{x} + 2x.$$

Using this,

$$\begin{aligned}\text{Net change in cost} &= \int_4^5 \left(4x^{-1/2} + 2\right)\,dx \\ &= \left[8\sqrt{x} + 2x\right]_4^5 \\ &= \left(8\sqrt{5} + 2(5)\right) - \left(8\sqrt{4} + 2(4)\right) \\ &\approx 3.889\end{aligned}$$

It will cost 3.889 thousand dollars to increase production from 4 thousand items to 5 thousand items. (The final answer would be better written as $3889.)

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5.5: Substitution

We don't have many integration rules. For quite a few of the problems we see, the rules won't directly apply; we'll have to do some algebraic manipulation first. In practice, it is much harder to write down the antiderivative of a function than it is to find a derivative. (In fact, it's very easy to write a function that doesn't have any antiderivative you can find with algebra, although *proving* that it doesn't have an antiderivative is much more difficult.)

The Substitution Method (also called u-Substitution) is one way of algebraically manipulating an integrand so that the rules apply. This is a way to unwind or undo the Chain Rule for derivatives. When you find the derivative of a function using the Chain Rule, you end up with a product of something like the original function *times* a derivative. We can reverse this to write an integral:

$$\frac{d}{dx} f\left(g(x)\right) = f'\left(g(x)\right) g'(x)$$

so

$$f\left(g(x)\right) = \int f'\left(g(x)\right) g'(x)\, dx$$

With substitution, we will substitute $u = g(x)$ (hence the name "u-substitution"). This means $\frac{du}{dx} = g'(x)$, so $du = g'(x)dx$. Making these substitutions, $\int f'\left(g(x)\right) g'(x)\ dx$ becomes $\int f'(u)\ du$, which will probably be easier to integrate.

Try u-Substitution when you see a product in your integral, especially if you recognize one factor as the derivative of some part of the other factor.

The u-Substitution Method for Antiderivatives

The goal is to turn $\int f\left(g(x)\right)\ dx$ into $\int f(u)\ du$, where $f(u)$ is much less messy than $f\left(g(x)\right)$.

1. Let u be some part of the integrand. A good first choice is "one step inside the messiest bit."
2. Compute $du = \frac{du}{dx}\ dx$.
3. Translate all your x's into u's everywhere in the integral, including the dx. When you're done, you should have a new integral that is entirely in u. If you have any x's left, then that's an indication that the substitution didn't work or isn't complete; you may need to go back to step 1 and try a different choice for u.
4. Integrate the new u-integral, if possible. If you still can't integrate it, go back to step 1 and try a different choice for u.
5. Finally, substitute back x's for u's everywhere in your answer.

Example 5.5.1

Evaluate $\int \frac{x}{\sqrt{4-x^2}}\ dx$.

Solution

This integrand is more complicated than anything in our list of basic integral formulas, so we'll have to try something else. The only tool we have is substitution, so let's try that!

1. Let u be some part of the integrand. A good first choice is "one step inside the messiest bit":

   Let $u = 4 - x^2$.

2. Compute $du = \frac{du}{dx}\ dx$:

   $du = -2x\ dx$. There is $x\ dx$ in the integrand, so that's a good sign; that will be $-\frac{1}{2}\ du$.

3. Translate all your x's into u's everywhere in the integral, including the dx:

$$\begin{aligned}\int \frac{x}{\sqrt{4-x^2}}\,dx &= \int \frac{1}{\sqrt{4-x^2}}(x\,dx)\\ &= \int \frac{1}{\sqrt{u}}\left(-\frac{1}{2}du\right)\\ &= -\frac{1}{2}\int \frac{1}{\sqrt{u}}\,du\\ &= -\frac{1}{2}\int u^{-1/2}\,du\end{aligned}$$

Alternatively, we could have solved for dx and substituted that and simplified: $dx = \frac{du}{-2x}$, so

$$\begin{aligned}\int \frac{x}{\sqrt{4-x^2}}\,dx &= \int \frac{x}{\sqrt{u}}\left(\frac{du}{-2x}\right)\\ &= \int \frac{1}{\sqrt{u}}\left(-\frac{1}{2}du\right)\\ &= -\frac{1}{2}\int \frac{1}{\sqrt{u}}\,du\\ &= -\frac{1}{2}\int u^{-1/2}\,du\end{aligned}$$

4. Integrate the new u-integral, if possible:

$$-\frac{1}{2}\int u^{-1/2}\,du = -\frac{1}{2}\frac{u^{1/2}}{1/2} + C = -u^{1/2} + C$$

5. Finally, substitute back x's for u's everywhere in the answer:

   Undoing our $u = 4 - x^2$ substitution yields

$$-u^{1/2} + C = -\sqrt{4-x^2} + C.$$

Thus we have found

$$\int \frac{x}{\sqrt{4-x^2}}\,dx = -\sqrt{4-x^2} + C$$

How would we check this? By differentiating:

$$\begin{aligned}\frac{d}{dx}\left(-\sqrt{4-x^2}+C\right) &= \frac{d}{dx}\left(-\left(4-x^2\right)^{1/2}+C\right)\\ &= -\frac{1}{2}\left(4-x^2\right)^{-1/2}(-2x)\\ &= x\left(4-x^2\right)^{-1/2}\\ &= \frac{x}{\sqrt{4-x^2}}\end{aligned}$$

Example 5.5.2

Evaluate $\int \frac{e^x\,dx}{(e^x+15)^3}$.

Solution

This integral is not in our list of building blocks. But notice that the derivative of $e^x + 15$ (which we see in the denominator) is just e^x (which we see in the numerator), so substitution will be a good choice for this.

Let $u = e^x + 15$. Then $du = e^x\ dx$, and this integral becomes $\int \frac{du}{u^3} = \int u^{-3}\ du$.

Luckily, that is on our list of building block formulas: $\int \frac{du}{u^3} = \frac{u^{-2}}{-2} + C = -\frac{1}{2u^2} + C$.

Finally, translating back:

$$\int \frac{e^x\,dx}{(e^x+15)^3} = -\frac{1}{2(e^x+15)^2} + C.$$

Example 5.5.3

Evaluate

a. $\int \frac{x^2}{x^3+5}\,dx$
b. $\int \frac{x^3+5}{x^2}\,dx$

Solution

1. This is not a basic integral, but the composition is less obvious. Here, we can treat the denominator as the inside of the $\frac{1}{x}$ function.

   Let $u = x^3+5$. Then $du = 3x^2\ dx$. Solving for dx, $dx = \frac{du}{3x^2}$. Substituting,

   $$\int \frac{x^2}{x^3+5}\,dx = \int \frac{x^2}{u}\frac{du}{3x^2} = \int \frac{1}{u}\frac{du}{3} = \frac{1}{3}\int \frac{1}{u}\,du$$

   Using our basic formulas,

   $$\frac{1}{3}\int \frac{1}{u}\,du = \frac{1}{3}\ln|u| + C.$$

   Undoing the substitution,

   $$\int \frac{x^2}{x^3+5}\,dx = \frac{1}{3}\ln|x^3+5| + C.$$

2. It is tempting to start this problem the same way we did the last, but if we try it will not work, since the numerator of this fraction is not the derivative of the denominator. Instead, we need to try a different approach. For this problem, we can use some basic algebra:

   $$\begin{aligned}\int \frac{x^3+5}{x^2}\,dx &= \int \left(\frac{x^3}{x^2} + \frac{5}{x^2}\right)dx \\ &= \int \left(x + 5x^{-2}\right)dx.\end{aligned}$$

   We can integrate this using our basic rules, without needing substitution:

   $$\begin{aligned}\int \left(x+5x^{-2}\right)dx &= \frac{x^2}{2} + 5\frac{x^{-1}}{-1} + C \\ &= \frac{1}{2}x^2 - \frac{5}{x} + C.\end{aligned}$$

Substitution and Definite Integrals

When you use substitution to help evaluate a definite integral, you have a choice for how to handle the limits of integration. You can do either of these, whichever seems better to you. The important thing to remember is that the original limits of integration were values of the original variable (say, x), not values of the new variable (say, u).

1. You can solve the antiderivative as a side problem, translating back to x's, and then use the antiderivative with the original limits of integration.

   Or...

2. You can substitute for the limits of integration at the same time as you're substituting for everything inside the integral, and then skip the "translate back into x" step.

   If the original integral had endpoints $x = a$ and $x = b$, and we make the substitution $u = g(x)$ and $du = g'(x)\ dx$, then the new integral will have endpoints $u = g(a)$ and $u = g(b)$ and

   $$\int_{x=a}^{x=b} (\text{original integrand})\, dx$$

   becomes

   $$\int_{u=g(a)}^{u=g(b)} (\text{new integrand})\, du.$$

Method 1 seems more straightforward for most students, but it can involve some messy algebra. Method 2 is often neater and usually involves fewer steps.

Example 5.5.4

Evaluate $\int_0^1 (3x-1)^4\ dx$.

Solution

We'll need substitution to find an antiderivative, so we'll need to handle the limits of integration carefully. Let's solve this example both ways.

1. Step One – find the antiderivative, using substitution:

   Let $u = 3x - 1$. Then $du = 3\ dx$ and

   $$\int (3x-1)^4\, dx = \int u^4 \left(\frac{1}{3}\, du\right) = \frac{1}{3}\frac{u^5}{5} + C.$$

   Translating back to x:

   $$\frac{1}{3}\frac{u^5}{5} + C = \frac{(3x-1)^5}{15} + C.$$

   Step Two – evaluate the definite integral:

   $$\int_0^1 (3x-1)^4\, dx = \frac{(3x-1)^5}{15}\Bigg]_0^1 = \frac{(3(1)-1)^5}{15} - \frac{(3(0)-1)^5}{15} = \frac{32}{15} - \frac{-1}{15} = \frac{33}{15}.$$

2. Let $u = 3x - 1$. Then $du = 3\ dx$ and, substituting for the limits of integration, when $x = 0$, $u = -1$, and when $x = 1$, $u = 2$.

   So,

   $$\begin{aligned}\int_{x=0}^{x=1} (3x-1)^4\, dx &= \int_{u=-1}^{u=2} u^4 \left(\frac{1}{3}\, du\right) \\ &= \frac{u^5}{15}\Bigg]_{u=-1}^{u=2} \\ &= \frac{(2)^5}{15} - \frac{(-1)^5}{15} \\ &= \frac{32}{15} - \frac{-1}{15} \\ &= \frac{33}{15}\end{aligned}$$

Example 5.5.5

Evaluate $\int_2^{10} \frac{(\ln(x))^6}{x}\, dx$.

Solution

I can see the derivative of $\ln(x)$ in the integrand, so I can tell that substitution is a good choice.

Let $u = \ln(x)$. Then $du = \frac{1}{x}\, dx$. When $x = 2$, $u = \ln(2)$. When $x = 10$, $u = \ln(10)$. So the new definite integral is

$$\begin{aligned}\int_{x=2}^{x=10} \frac{(\ln(x))^6}{x}\, dx &= \int_{u=\ln(2)}^{u=\ln(10)} u^6\, du \\ &= \frac{u^7}{7}\Big]_{u=\ln(2)}^{u=\ln(10)} \\ &= \frac{1}{7}\left((\ln(10))^7 - (\ln(2))^7\right) \\ &\approx 49.01.\end{aligned}$$

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5.6: Additional Integration Techniques

Integration By Parts

Integration by parts is an integration method which enables us to find antiderivatives of some new functions such as $\ln(x)$ as well as antiderivatives of products of functions such as $x^2\ln(x)$ and xe^x.

If the function we're trying to integrate can be written as a product of two functions, u, and dv, then integration by parts lets us trade out a complicated integral for hopefully simpler one.

Integration by Parts Formula

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

For definite integrals:

$$\int_a^b u\,dv = uv\Big]_a^b - \int_a^b v\,du$$

Example 5.6.1

Integrate $\int xe^x\ dx$.

Solution

To use the Integration by Parts method, we break apart the product into two parts:

$$u = x \qquad \text{and} \qquad dv = e^x\,dx.$$

We now calculate du, the derivative of u, and v, the integral of dv:

$$du = \left(\frac{d}{dx}x\right)dx \qquad \text{and} \qquad v = \int e^x\,dx = e^x.$$

Using the Integration by Parts formula,

$$\int xe^x\,dx = uv - \int v\,du = xe^x - \int e^x\,dx.$$

Notice the remaining integral is simpler that the original, and one which we can easily evaluate:

$$xe^x - \int e^x\,dx = xe^x - e^x + C.$$

In the last example we could have chosen either x or e^x as our u, but had we chosen $u = e^x$, the second integral would have become messier, rather than simpler.

Rule of Thumb

When selecting the u for Integration by Parts, select a logarithmic expression if one is present. If not, select an algebraic expression (like x or dx).

(There is a larger decision tree that can be written down for choosing u and dv, but since we're not looking at any trigonometric functions in this course the rule above is sufficient for the functions we're integrating.)

Example 5.6.2

Integrate $\int_1^4 6x^2 \ln(x)\ dx$.

Solution

Since this contains a logarithmic expression, we'll use it for our u:

$$u = \ln(x) \qquad \text{and} \qquad dv = 6x^2\,dx$$

We now calculate du and v:

$$du = \frac{1}{x}dx \qquad \text{and} \qquad v = \int 6x^2\,dx = 6\frac{x^3}{3} = 2x^3$$

Using the By Parts formula:

$$\int_1^4 6x^2 \ln(x)\,dx = 2x^3 \ln(x)\Big]_1^4 - \int_1^4 6x^2 \frac{1}{x}\,dx$$

We can simplify the expression in the integral on the right:

$$\int_1^4 6x^2 \ln(x)\,dx = 2x^3 \ln(x)\Big]_1^4 - \int_1^4 6x\,dx$$

The remaining integral is a basic one we can now evaluate:

$$\int_1^4 6x^2 \ln(x)\,dx = 2x^3 \ln(x)\Big]_1^4 - 3x^2\Big]_1^4$$

Finally, we can evaluate the expressions:

$$\begin{aligned}\int_1^4 6x^2 \ln(x)\,dx &= \left(\left(2\cdot 4^3 \ln(4)\right) - \left(2\cdot 1^3 \ln(1)\right)\right) - \left(\left(3\cdot 4^2\right) - \left(3\cdot 1^2\right)\right)\\ &= 128\ln(4) - 45\\ &\approx 132.446\end{aligned}$$

Integration Using Tables of Integrals

There are many techniques of integration we will not be studying. Many of them lead to general formulas which can be compiled into a Table of Integrals – a type of cheat-sheet for integration.

For example, here are two entries you might find in a table of integrals:

Table of Integral Examples

$$\int \frac{1}{x^2 - a^2}\,dx = \frac{1}{2a}\ln\left|\frac{x-a}{x+a}\right| + C$$

$$\int \frac{1}{\sqrt{x^2 + a^2}}\,dx = \ln\left|x + \sqrt{x^2 + a^2}\right| + C$$

Example 5.6.3

Integrate $\int \frac{5}{x^2 - 9}\ dx$.

Solution

This integral looks very similar to the form of the first integral in the examples table. By employing the rule that allows us to pull out constants, and by rewriting 9 as 3^2, we can better see the match.

$$\int \frac{5}{x^2-9}\,dx = 5\int \frac{1}{x^2-3^2}\,dx$$

Now we simply use the formula from the table, with $a=3$.

$$\begin{aligned}\int \frac{5}{x^2-9}\,dx =& 5\int \frac{1}{x^2-3^2}\,dx \\ &= 5\left(\frac{1}{2\cdot 3}\ln\left|\frac{x-3}{x+3}\right|\right)+C \\ &= \frac{5}{6}\ln\left|\frac{x-3}{x+3}\right|+C\end{aligned}$$

Sometimes we have to combine the table with other techniques we've learned, like substitution.

Example 5.6.4

Integrate $\int \frac{x^2}{\sqrt{x^6+16}}\,dx$.

Solution

This integral looks somewhat like the second integral in the example table, but the power of x is incorrect, and there is an x^2 in the numerator which does not match. Trying to utilize this rule, we can try to rewrite the x^6 in the denominator to look like (something)^2. Luckily, $x^6=\left(x^3\right)^2$.

$$\int \frac{x^2}{\sqrt{x^6+16}}\,dx = \int \frac{x^2}{\sqrt{\left(x^3\right)^2+16}}\,dx$$

Now we can use substitution, letting $u=x^3$, so $du=3x^2\ dx$.

Making the subsitution:

$$\int \frac{x^2}{\sqrt{\left(x^3\right)^2+16}}\,dx = \int \frac{1}{\sqrt{u^2+16}}\,\frac{du}{3} = \frac{1}{3}\int \frac{1}{\sqrt{u^2+16}}\,du$$

Now we can use the table entry:

$$\frac{1}{3}\int \frac{1}{\sqrt{u^2+16}}\,du = \frac{1}{3}\ln\left|u+\sqrt{u^2+16}\right|+C$$

Undoing the substitution yields the final answer:

$$\int \frac{x^2}{\sqrt{x^6+16}}\,dx = \frac{1}{3}\ln\left|x^3+\sqrt{x^6+16}\right|+C$$

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5.7: Area, Volume, and Average Value

Average Value

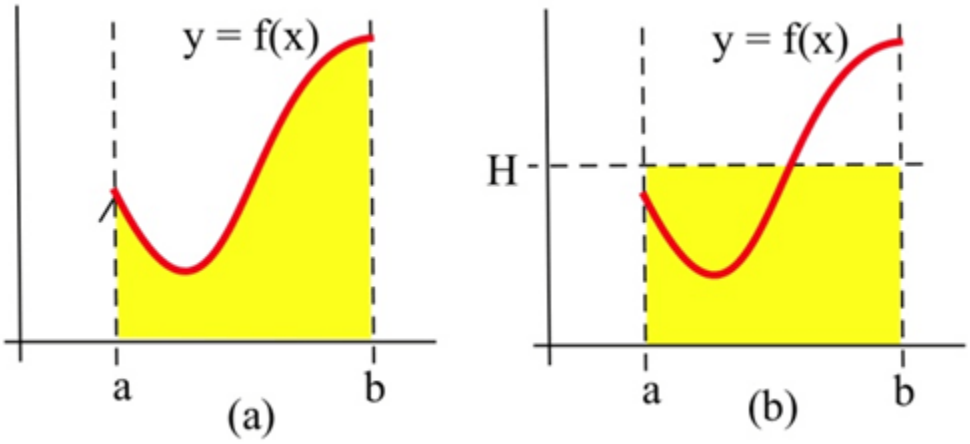
We know the average of n numbers $a_1, a_2, \ldots, a_n$ is their sum divided by n. But what if we need to find the average temperature over a day's time – there are too many possible temperatures to add them up! This is a job for the definite integral.

Average Value

The average value of a function $f(x)$ on the interval $[a, b]$ is given by

$$\frac{1}{b-a}\int_a^b f(x)\,dx.$$

The average value of a positive f has a nice geometric interpretation. Imagine that the area under f (graph (a) below) is a liquid that can "leak" through the graph to form a rectangle with the same area (graph (b) below).



If the height of the rectangle is H, then the area of the rectangle is $H \cdot (b-a)$. We know the area of the rectangle is the same as the area under f so $H \cdot (b-a) = \int_a^b f(x)\ dx$. Then

$$H = \frac{1}{b-a}\int_a^b f(x)\,dx,$$

the average value of f on $[a, b]$.

The average value of a positive function f is the height H of the rectangle whose area is the same as the area under f.

Example 5.7.1

During a 9 hour work day, the production rate at time t hours after the start of the shift was given by the function $r(t) = 5 + \sqrt{t}$ cars per hour. Find the average hourly production rate.

Solution

The average hourly production is $\frac{1}{9-0}\int_0^9 \left(5+\sqrt{t}\right)\ dt = 7$ cars per hour.

A note about the units – remember that the definite integral has units (cars per hour)·(hours) = cars. But the $\frac{1}{b-a}$ in front has units $\frac{1}{\text{hours}}$ so the units of the average value are cars per hour, just what we expect an average rate to be.

In general...

...the average value of a function will have the same units as the integrand.

Function averages, involving means and more complicated averages, are used to "smooth" data so that underlying patterns are more obvious and to remove high frequency "noise" from signals. In these situations, the original function f is replaced by some "average of f." If f is rather jagged time data, then the ten year average of f is the integral $g(x) = \frac{1}{10}\int_{x-5}^{x+5} f(t)\ dt$, an average of f over 5 units on each side of x.

For example, the figure below shows the graphs of a Monthly Average (rather "noisy" data) of surface temperature data, an Annual Average (still rather "jagged"), and a Five Year Average (a much smoother function).

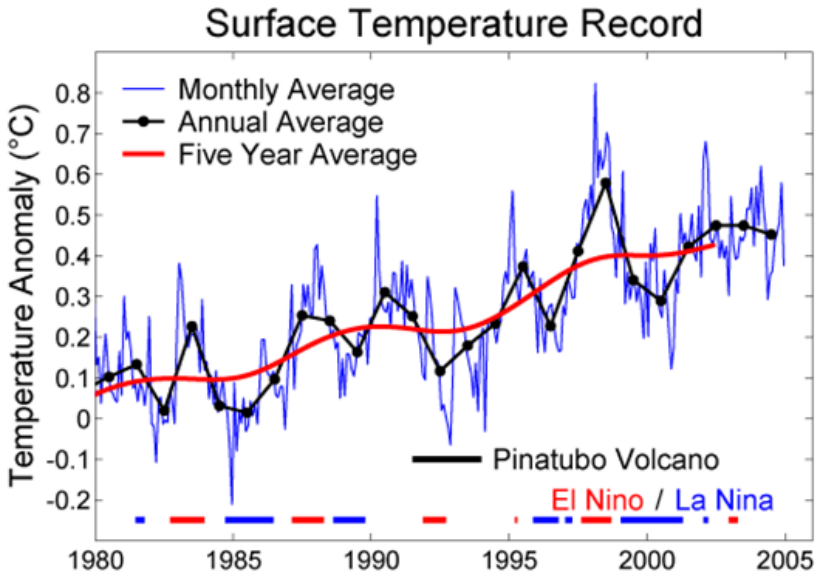
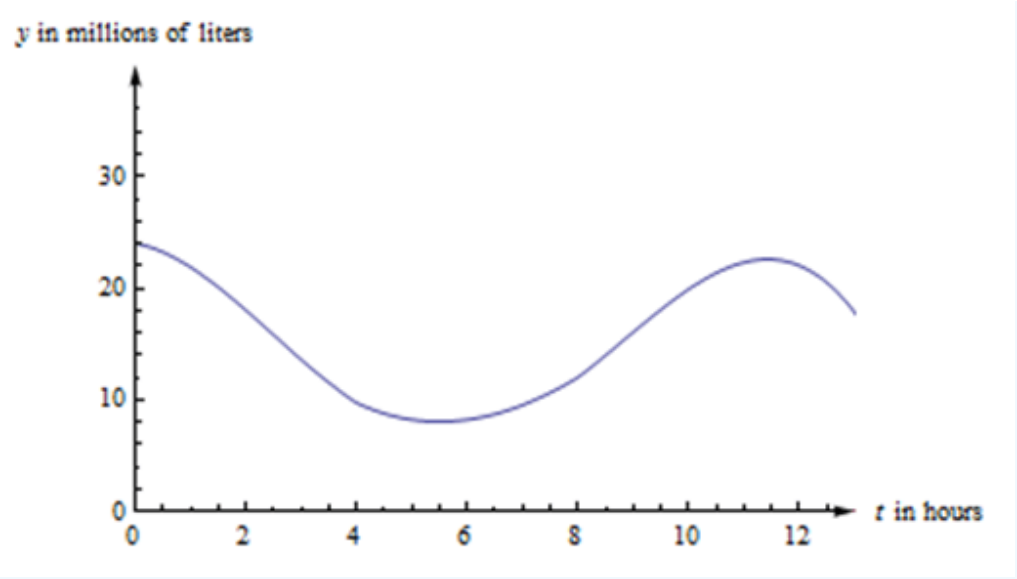


Image prepared by Robert A. Rohde, http://commons.wikimedia.org/wiki/File:Short_Instrumental_Temperature_Record.png.

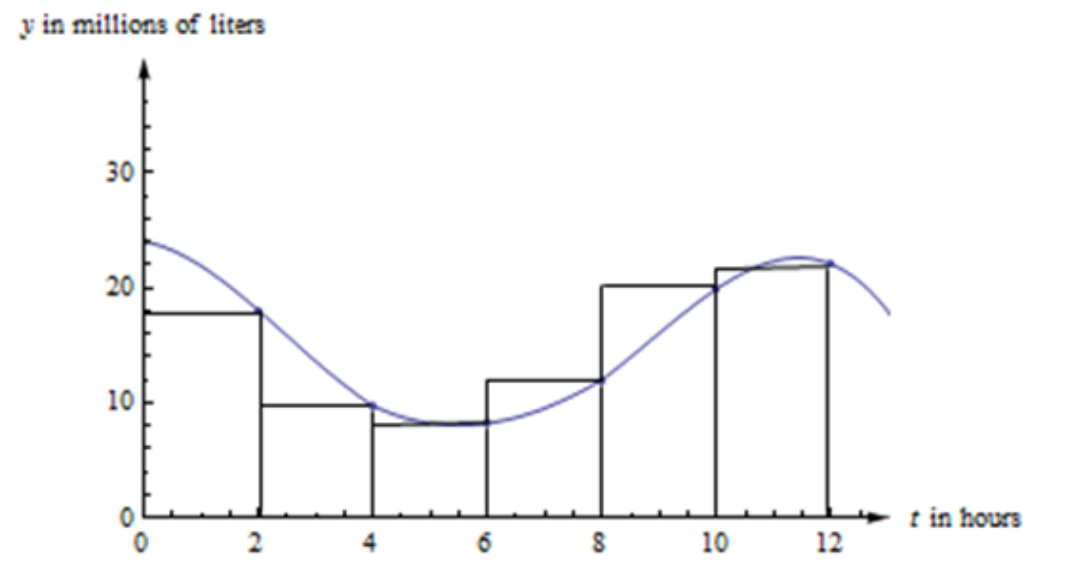
Typically the average function reveals the pattern much more clearly than the original data. This use of a "moving average" value of "noisy" data (weather information, stock prices) is a very common.

Example 5.7.2

The graph below shows the amount of water in a reservoir over a 12 hour period. Estimate the average amount of water in the reservoir over this period.



If $V(t)$ is the volume of the water (in millions of liters) after t hours, then the average amount is $\frac{1}{12}\ \int_0^{12} V(t)\ dt$. In order to find the definite integral, we'll have to estimate. Let's use 6 rectangles and take the heights from their right edges (there's nothing special about using 6 rectangles or right edges – other choices would still give you a valid estimate).



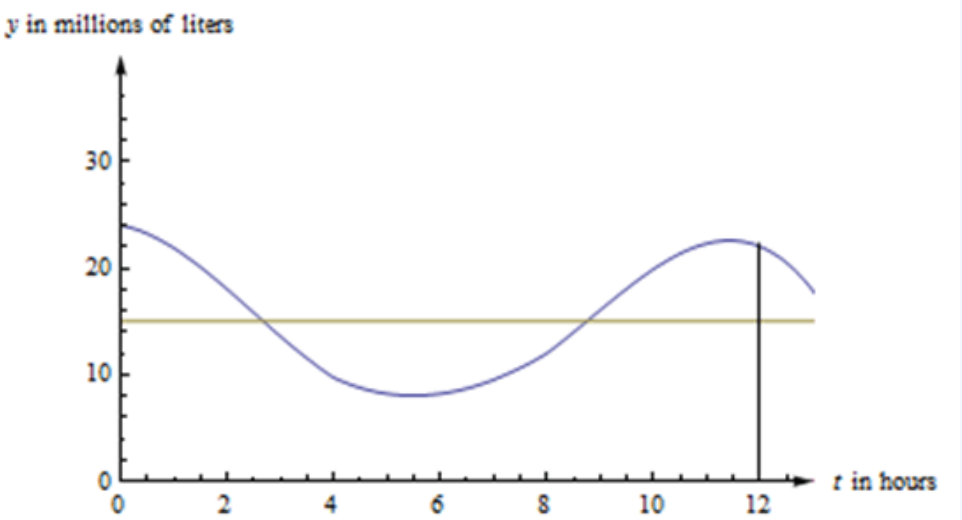
The estimate of the integral is

$$\int_0^{12} V(t)\,dt \approx (18)(2) + (9.7)(2) + (8.2)(2) + (12)(2) + (19.9)(2) + (22)(2) = 179.6.$$

Solution

The units of this integral are (millions of liters)·(feet). So our estimate of the average volume is $\frac{1}{12} \cdot 179.6 \approx 15$ millions of liters. (The estimate might change a little depending on how we estimate the function values from the graph.)

In the figure below, you can see the same graph with the line $y = 15$ drawn in. The area under the curve and the area under the rectangle are (approximately) the same.

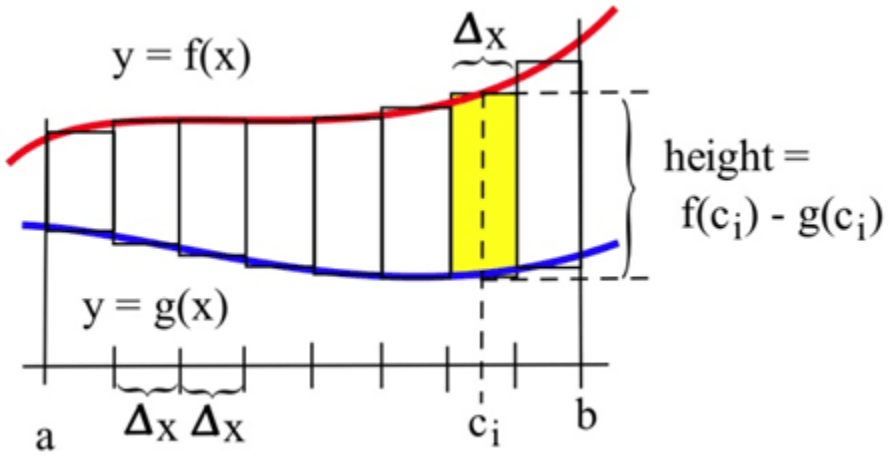


In fact, that would be a different way to estimate the average value. We could have estimated the placement of the horizontal line so that the area under the curve and under the line were equal.

Area

We have already used integrals to find the area between the graph of a function and the horizontal axis. Integrals can also be used to find the area between two graphs.

If $f(x) \geq g(x)$ for all x in $[a, b]$, then we can approximate the area between f and g by partitioning the interval $[a, b]$ and forming a Riemann sum, as shown in the picture. The height of each rectangle is top - bottom, $f(c_i) - g(c_i)$ so the area of the i-th rectangle is (height)·(base) = $(f(c_i) - g(c_i)) \cdot \Delta x$. Adding up these rectangles gives an approximation of the total area as $\sum_{i=1}^{n} (f(c_i) - g(c_i)) \cdot \Delta x$, a Riemann sum.



The limit of this Riemann sum, as the number of rectangles gets larger and their width gets smaller, is the definite integral $\int_a^b (f(x) - g(x))\ dx$.

Area Between Two Curves

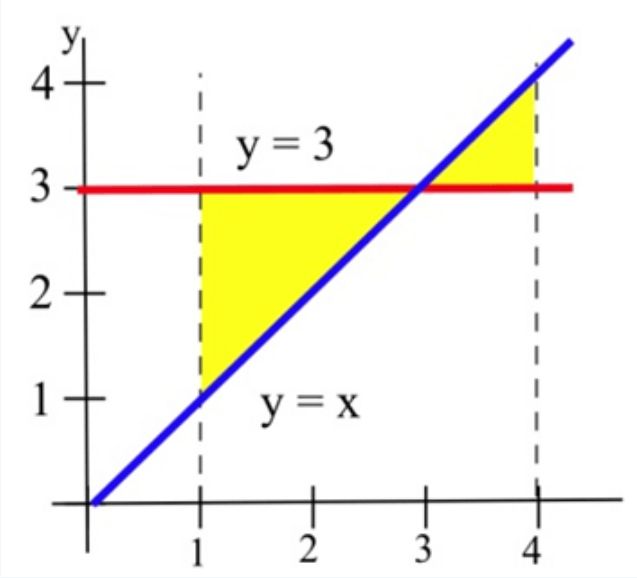
The area between two curves $f(x)$ and $g(x)$, where $f(x) \geq g(x)$, between $x = a$ and $x = b$ is

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

The integrand is “top - bottom.” Make a graph or use test values to be sure which curve is which.

Example 5.7.3

Find the area bounded between the graphs of $f(x) = x$ and $g(x) = 3$ for $1 \le x \le 4$.



Solution

Always start with a graph so you can see which graph is the top and which is the bottom. In this example, the two curves cross, and they change positions; we'll need to split the area into two pieces. Geometrically, we can see that the area is 2 + 0.5 = 2.5.

Writing the area as a sum of definite integrals, we get

$$\text{Area } = \int_1^3 (3 - x)\, dx + \int_3^4 (x - 3)\, dx.$$

These integrals are easy to evaluate using antiderivatives:

$$\begin{aligned}\int_1^3 (3 - x)\, dx &= \left[3x - \frac{x^2}{2}\right]_1^3 \\ &= \left(9 - \frac{9}{2}\right) - \left(3 - \frac{1}{2}\right) \\ &= 2\end{aligned}$$

$$\begin{aligned}\int_3^4 (x - 3)\, dx &= \left[\frac{x^2}{2} - 3x\right]_3^4 \\ &= \left(\frac{16}{2} - 12\right) - \left(\frac{9}{2} - 9\right) \\ &= \frac{1}{2}\end{aligned}$$

The sum of these two integrals tells us that the total area between f and g is 2.5 square units, which we already knew from the picture.

Note that the single integral $\int_1^4 (3 - x)\ dx = 1.5$ is not the **area** we want in the last example. The value of **the integral is 1.5**, and

the value of **the area is 2.5**. That's because for the triangle on the right, the graph of $y = x$ is above the graph of $y = 3$, so the integrand $3 - x$ is negative; in the definite integral, the area of that triangle comes in with a negative sign.

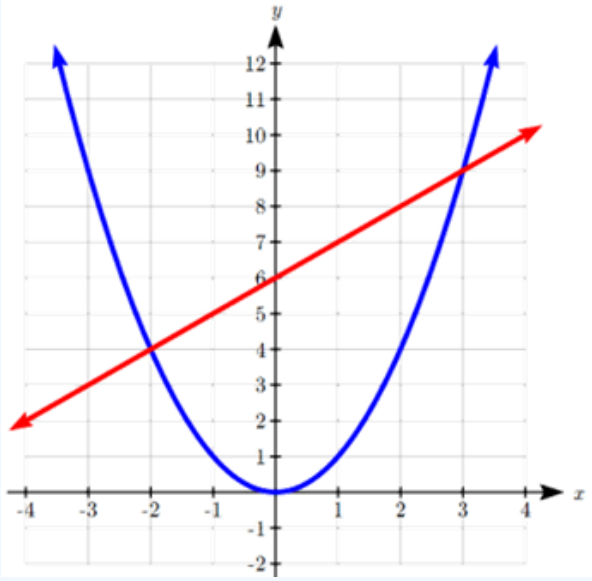
In this example, it was easy to see exactly where the two curves crossed so we could break the region into the two pieces to figure separately. In other examples, you might need to solve an equation to find where the curves cross.

Example 5.7.4

Find the area bounded by the graphs of $f(x) = x^2$ and $g(x) = x + 6$.

Solution

To begin, it will help to sketch a graph of the functions to see the area enclosed.



To set up the integral for the area, we need to determine where the line intersects the parabola. While the points look fairly clear in the graph, it will be good to verify the points algebraically:

$$\begin{aligned} x^2 &= x + 6 \\ x^2 - x - 6 &= 0 \\ (x - 3)(x + 2) &= 1 \\ x &= -2, 3 \end{aligned}$$

Over this interval $-2 \leq x \leq 3$ notice the linear function is on top, so if we were to draw a rectangle between the curves, the height would be (top function) – (bottom function) = $(x + 6) - x^2$.

Setting up a definite integral for this area:

$$\text{Area } = \int_{-2}^{3} (x + 6 - x^2)\, dx$$

We can evaluate this integral using antiderivatives:

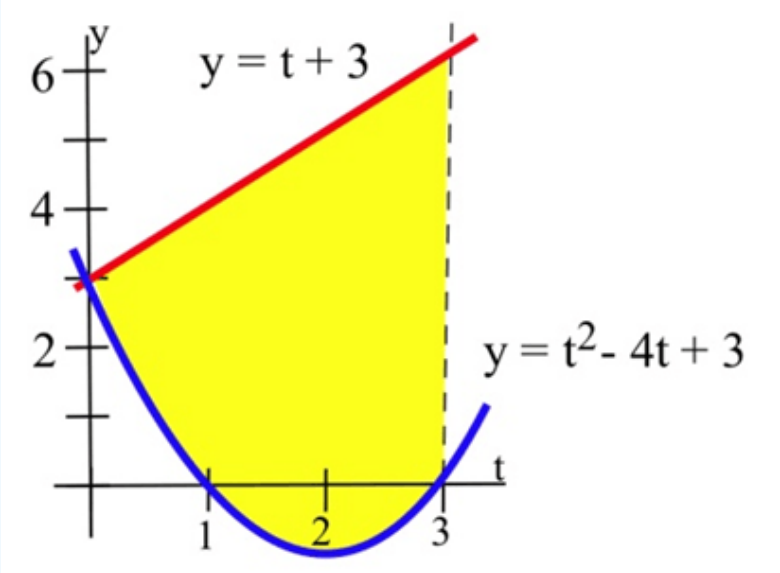
$$\begin{aligned}\int_{-2}^{3}(x+6-x^2)\,dx &= \left[\frac{x^2}{2}+6x-\frac{x^3}{3}\right]_{-2}^{3}\\ &= \left(\frac{3^2}{2}+6\cdot 3-\frac{3^3}{3}\right)-\left(\frac{(-2)^2}{2}+6\cdot(-2)-\frac{(-2)^3}{3}\right)\\ &= \left(\frac{9}{2}+18-\frac{27}{3}\right)-\left(\frac{4}{2}-12+\frac{8}{3}\right)\\ &= \left(\frac{9}{2}+18-9\right)-\left(2-12+\frac{8}{3}\right)\\ &= \left(\frac{9}{2}+9\right)-\left(-10+\frac{8}{3}\right)\\ &= \frac{9}{2}+9+10-\frac{8}{3}\\ &= \frac{125}{6}\end{aligned}$$

The area between the curves is $\frac{125}{6}\approx 20.833$ square units.

Example 5.7.5

Two objects start from the same location and travel along the same path with velocities $v_A(t)=t+3$ and $v_B(t)=t^2-4t+3$ meters per second. How far ahead is A after 3 seconds?

Solution



Since $v_A(t)\geq v_B(t)$, the "area" between the graphs of v_A and v_B represents the distance between the objects.

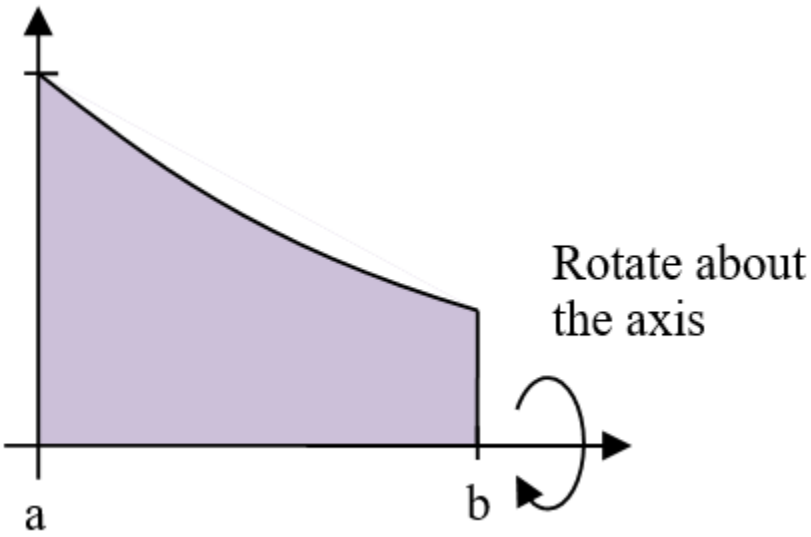
After 3 seconds, the distance apart is

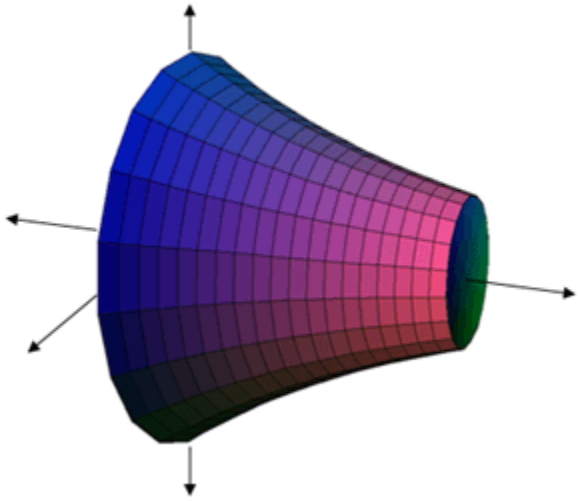
$$\begin{aligned}\int_0^3 \left(v_A(t)-v_B(t)\right)\,dt &= \int_0^3 \left((t+3)-\left(t^2-4t+3\right)\right)\,dt\\ &= \int_0^3 \left(5t-t^2\right)\,dt\\ &= \left[5\frac{t^2}{2}-\frac{t^3}{3}\right]_0^3\\ &= \left(5\frac{9}{2}-\frac{27}{3}\right)-(0)\\ &= 13.5 \text{ meters.}\end{aligned}$$

Volume

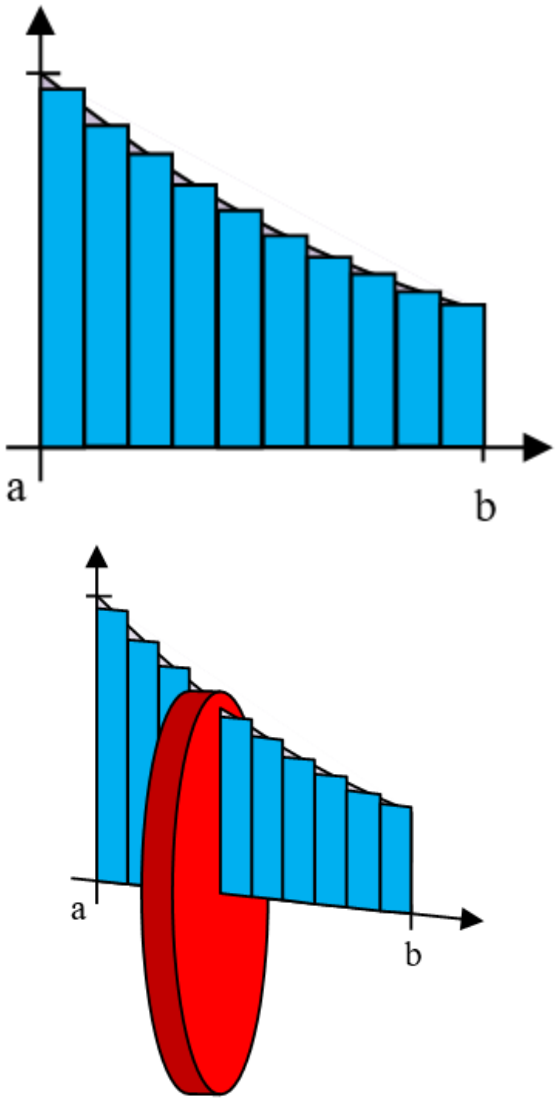
Just as we can partition an interval and imagine approximating an area with rectangles to find a formula for the area between curves, we can partition an interval and imagine approximating a volume with simple shapes to find a formula for the volume of a solid. While this approach works for a variety of shapes, our focus will be on shapes formed by revolving a curve around the horizontal axis.

We start with an area, the region below a function on the interval $a \leq x \leq b$. We are going to take that region, and rotate it around the x-axis, creating the solid shape shown.





To find the volume of this solid, we can start by partitioning the interval [0,1] and approximating the area with rectangles. As before, the width of each rectangle would be Δx and the height $f(c_i)$.



If we took just one of these rectangles and rotated it about the horizontal axis, it would form a cylindrical shape. The radius of that cylinder would be $f(c_i)$, so the volume would be

$$V = \pi r^2 h = \pi \left(f(c_i)\right)^2 \Delta x.$$

The volume of the whole solid could be approximated by rotating each of the rectangles about the x axis. Adding up the volume of each of the little cylindrical discs gives an approximation of the total volume as $\sum_{i=1}^{n} \pi \left(f(c_i)\right)^2 \Delta x$, a Riemann sum.

The limit of this sum as the width of the rectanges becomes small is the definite integral $\int_a^b \pi \left(f(c_i)\right)^2 \ dx$

Volume

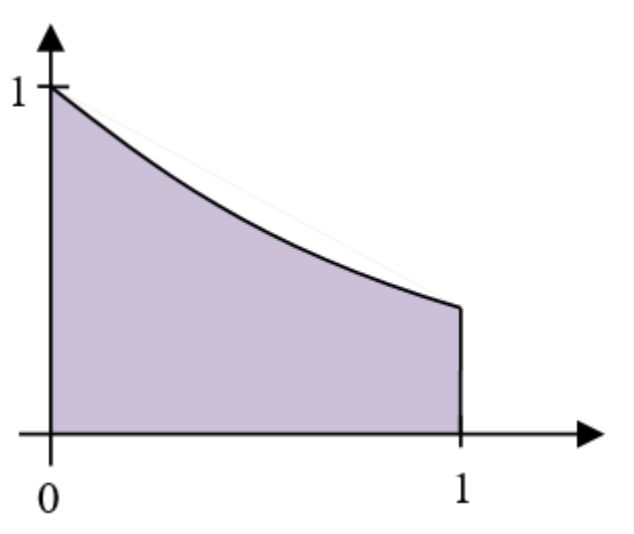
The volume of the solid obtained by rotating about the x-axis the area bounded by the curve $f(x)$, the x-axis, $x = a$, and $x = b$ is

$$\int_a^b \pi \left(f(c_i)\right)^2 \ dx$$

Example 5.7.6

Find the volume of the solid formed by rotating the area under $f(x) = e^{-x}$ on the interval [0,1] about the x-axis.

Solution



This is the region pictured in the earlier example. We substitute in the function and bounds into the formula we derived to set up the definite integral:

$$\text{Volume} = \int_0^1 \pi \left(e^{-x}\right)^2 \, dx.$$

Using exponent rules, the integrand can be simplified. The constant π can be pulled out of the integral:

$$\text{Volume} = \pi \int_0^1 e^{-2x} \, dx.$$

Using the substitution $u = -2x$, we can integrate this function.

$$\begin{aligned} \pi \int_0^1 e^{-2x} \, dx &= (u\text{-substitution}) \\ &= -\frac{1}{2}\pi e^{-2x}\Big]_0^1 \\ &= \left(-\frac{1}{2}\pi e^{-2(1)}\right) - \left(-\frac{1}{2}\pi e^{-2(0)}\right) \\ &\approx 1.358 \text{ cubic units.} \end{aligned}$$

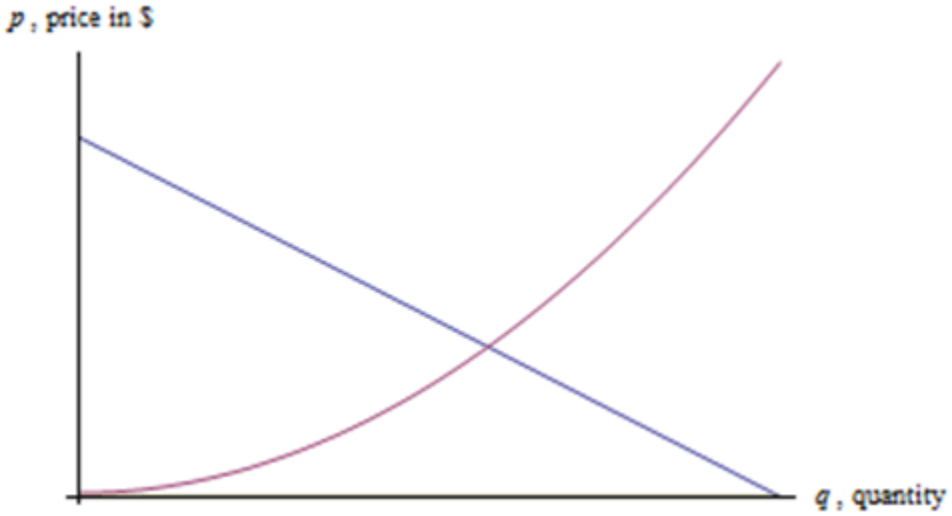
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5.8: Applications to Business

Consumer and Producer Surplus

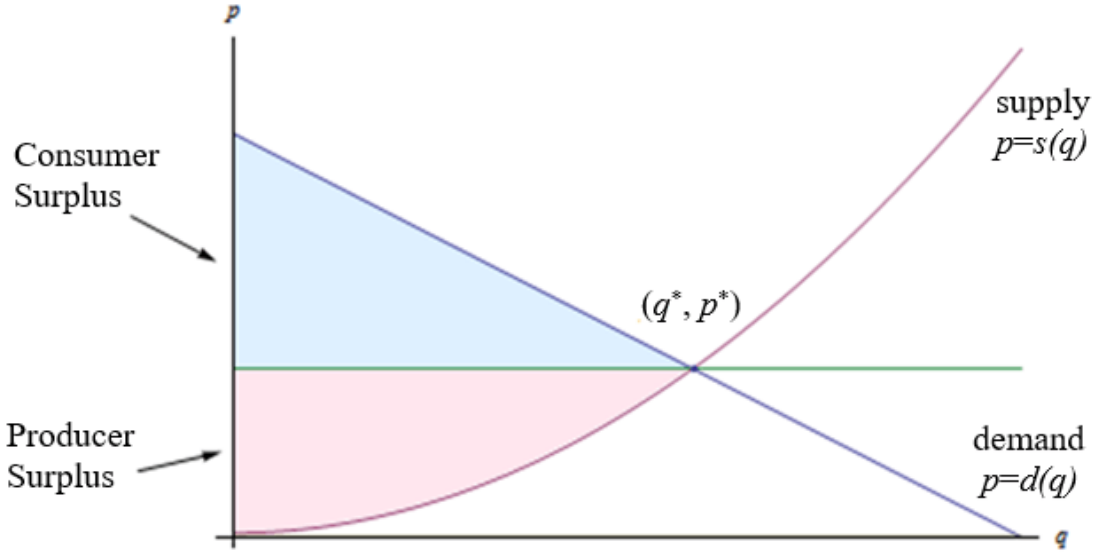
Here are a demand and a supply curve for a product. Which is which?



The demand curve is decreasing – lower prices are associated with higher quantities demanded, higher prices are associated with lower quantities demanded. Demand curves are often shown as if they were linear, but there's no reason they have to be.

The supply curve is increasing – lower prices are associated with lower supply, and higher prices are associated with higher quantities supplied.

The point where the demand and supply curve cross is called the equilibrium point (q^*, p^*).



Suppose that the price is set at the equilibrium price, so that the quantity demanded equals the quantity supplied. Now think about the folks who are represented on the left of the equilibrium point. The consumers on the left would have been willing to pay

a higher price than they ended up having to pay, so the equilibrium price saved them money. On the other hand, the producers represented on the left would have been willing to supply these goods for a lower price – they made more money than they expected to. Both of these groups ended up with extra cash in their pockets!

Graphically, the amount of extra money that ended up in consumers' pockets is the area between the demand curve and the horizontal line at p^*. This is the difference in price, summed up over all the consumers who spent less than they expected to – a definite integral. Notice that since the area under the horizontal line is a rectangle, we can simplify the area integral:

$$\int_0^{q^*} (d(q) - p^*)\, dq = \int_0^{q^*} d(q)\, dq - \int_0^{q^*} p^*\, dq = \int_0^{q^*} d(q)\, dq - p^*q^*.$$

The amount of extra money that ended up in producers' pockets is the area between the supply curve and the horizontal line at p^*. This is the difference in price, summed up over all the producers who received more than they expected to. Similar to consumer surplus, this integral can be simplified:

$$\int_0^{q^*} (p^* - s(q))\, dq = \int_0^{q^*} p^*\, dq - \int_0^{q^*} s(q)\, dq = p^*q^* - \int_0^{q^*} s(q)\, dq.$$

Consumer and Producer Surplus

Given a demand function $p = d(q)$ and a supply function $p = s(q)$, and the equilibrium point (q^*, p^*)

- The **consumer surplus** is
$$\int_0^{q^*} d(q)\, dq - p^*q^*.$$
- The **producer surplus** is
$$p^*q^* - \int_0^{q^*} s(q)\, dq.$$
- The sum of the consumer surplus and producer surplus is the **total gains from trade**.

What are the units of consumer and producer surplus? The units are (price per item)(quantity of items) = money!

Example 5.8.1

Suppose the demand for a product is given by $p = d(q) = -0.8q + 150$ and the supply for the same product is given by $p = s(q) = 5.2q$. For both functions, q is the quantity and p is the price, in dollars.

1. Find the equilibrium point.
2. Find the consumer surplus at the equilibrium price.
3. Find the producer surplus at the equilibrium price.

Solution

1. The equilibrium point is where the supply and demand functions are equal.
$$\begin{aligned} -0.8q + 150 &= 5.2q \\ 150 &= 6.0q \\ q &= \frac{150}{6} \\ q &= 25 \end{aligned}$$

The equilibrium quantity is 25 items. To find the corresponding equilibrium price we can use either the demand or supply equation.

$s(25) = 5.2(25) = 130$. The equilibrium price is $130.

2. The consumer surplus is

$$\begin{aligned}\int_0^{25} (-0.8q + 150)\,dq - (130)(25) &= \left[-0.8\frac{q^2}{2} + 150q\right]_0^{25} - 3250 \\ &= \left(-0.4\left(25^2\right) + 150(25)\right) - \left(-0.4\left(0^2\right) + 150(0)\right) - 3250 \\ &= 3500 - 0 - 3250 \\ &= \$250\end{aligned}$$

3. The producer surplus is

$$\begin{aligned}(130)(25) - \int_0^{25} 5.2q\,dq &= 3250 - \left[5.2\frac{q^2}{2}\right]_0^{25} \\ &= 3250 - \left(\left(2.6\left(25^2\right)\right) - \left(2.6\left(0^2\right)\right)\right) \\ &= 3250 - (1625 - 0) \\ &= \$1625\end{aligned}$$

Example 5.8.2

Suppose the demand for a product is given by $p = d(q) = 300 - 5q$ and the supply for the same product is given by $p = s(q) = q^2$. For both functions, q is the quantity and p is the price, in dollars.

1. Find the equilibrium point.
2. Find the consumer surplus at the equilibrium price.
3. Find the producer surplus at the equilibrium price.

Solution

1. This is quadratic, so we can rearrange the equation so one side is zero: $q^2 + 5q - 300 = 0$.

   We could solve this using the quadratic equation: $q = \frac{-5 \pm \sqrt{5^2 - 4(1)(-300)}}{2(1)}$

   or we could factor: $(q + 20)(q - 15) = 0$, so $q = -20$ or $q = 15$.

   We want the positive solution. The equilibrium quantity is 15 items. The equilibrium price is $s(15) = 15^2 = \$225$.

2. The consumer surplus is

$$\begin{aligned}\int_0^{15} (300 - 5q)\,dq - (225)(15) &= \left[300q - 5\frac{q^2}{2}\right]_0^{15} - 3375 \\ &= \left(300(15) - 2.5\left(15^2\right)\right) - \left(300(0) - 2.5\left(0^2\right)\right) - 3375 \\ &= 3937.5 - 0 - 3375 \\ &= \$562.50\end{aligned}$$

3. The producer surplus is

$$\begin{aligned}(225)(15) - \int_0^{15} q^2\,dq &= 3375 - \left[\frac{q^3}{3}\right]_0^{15} s \\ &= 3375 - \left(\left(\frac{15^3}{3}\right) - \left(\frac{0^3}{3}\right)\right) \\ &= 3375 - (1125 - 0) \\ &= \$2250\end{aligned}$$

Example 5.8.3

The tables below show information about the demand and supply functions for a product. For both functions, q is the quantity and p is the price, in dollars.

q	0	100	200	300	400	500	600	700
p	70	61	53	46	40	35	31	28

q	0	100	200	300	400	500	600	700
p	14	21	28	33	40	47	54	61

1. Which is which? That is, which table represents demand and which represents supply?
2. What is the equilibrium price and quantity?
3. Find the consumer and producer surplus at the equilibrium price.

Solution

1. The first table shows decreasing price associated with increasing quantity; that is the demand function.
2. For both functions, $q = 400$ is associated with $p = 40$; the equilibrium price is $40 and the equilibrium quantity is 400 units. Notice that we were lucky here, because the equilibrium point is actually one of the points shown. In many cases with a table, we would have to estimate.
3. The consumer surplus uses the demand function, which comes from the first table. We'll have to approximate the value of the integral using rectangles. There are 4 rectangles, and let's choose to use left endpoints.

   The consumer surplus is

$$\int_0^{400} (\text{demand})\, dq - (40)(400) \approx$$
$$(100)(70 + 61 + 53 + 46) - (40)(400) = \$7000$$

   So the consumer surplus is about $7000.

   The producer surplus uses the supply function, which comes from the second table. Let's choose to use left endpoints for this integral also.

   The producer surplus is

$$(40)(400) - \int_0^{400} (\text{supply})\, dq \approx$$
$$(40)(400) - (100)(14 + 21 + 28 + 33) = \$6400$$

   So the producer surplus is about $6400.

Continuous Income Stream

In precalculus, you learned about compound interest in that really simple situation where you made a single deposit into an interest-bearing account and let it sit undisturbed, earning interest, for some period of time. Recall:

Compound Interest Formulas

Let P be the principal (initial investment), r be the annual interest rate expressed as a decimal, and $A(t)$ be the amount in the account at the end of t years.

Compounding n times per year

$$A(t) = P\left(1 + \frac{r}{n}\right)^{nt}$$

Compounded continuously

$$A(t) = Pe^{rt}$$

If you're using this formula to find what an account will be worth in the future, $t > 0$ and $A(t)$ is called the **future value**.

If you're using the formula to find what you need to deposit today to have a certain value P sometime in the future, $t < 0$ and $A(t)$ is called the **present value**.

You may also have learned somewhat more complicated annuity formulas to deal with slightly more complicated situations – where you make equal deposits equally spaced in time.

But real life is not usually so neat.

Calculus allows us to handle situations where "deposits" are flowing continuously into an account that earns interest. As long as we can model the flow of income with a function, we can use a definite integral to calculate the present and future value of a continuous income stream. The idea here is that each little bit of income in the future needs to be multiplied by the exponential function to bring it back to the present, and then we'll add them all up (a definite integral).

Continuous Income Stream

Suppose money can earn interest at an annual interest rate of r, compounded continuously. Let $F(t)$ be a continuous income function (in dollars per year) that applies between year 0 and year T.

Then the present value of that income stream is given by

$$PV = \int_0^T F(t)e^{-rt}\,dt.$$

The future value can be computed by the ordinary compound interest formula

$$FV = PVe^{rt}.$$

This is a useful way to compare two investments – find the present value of each to see which is worth more today.

Example 5.8.4

You have an opportunity to buy a business that will earn \$75,000 per year continuously over the next eight years. Money can earn 2.8% per year, compounded continuously. Is this business worth its purchase price of \$630,000?

Solution

First, please note that we still have to make some simplifying assumptions. We have to assume that the interest rates are going to remain constant for that entire eight years. We also have to assume that the \$75,000 per year is coming in continuously, like a faucet dripping dollars into the business. Neither of these assumptions might be accurate.

But moving on: The present value of the \$630,000 is, well, \$630,000. This is one investment, where we put our \$630,000 in the bank and let it sit there.

To find the present value of the business, we think of it as an income stream. The function $F(t)$ in this case is a constant \$75,000 dollars per year, so $F(t) = 75{,}000$. The interest rate is 2.8% and the term we're interested in is 8 years, so $r = .028$, and $T = 8$:

$$PV = \int_0^8 75000e^{-0.028t}\,dt \approx 537{,}548.75$$

The present value of the business is about $537,500, which is less than the $630,000 asking price, so this is not a good deal.

While this integral could have been done using substitution, for many of the integrals in this section we don't have the techniques to use antiderivatives or, in some cases, no antiderivative exists. Technology will work quickly, and it will give you an answer that is good enough.

Example 5.8.5

A company is considering purchasing a new machine for its production floor. The machine costs $65,000. The company estimates that the additional income from the machine will be a constant $7000 for the first year, then will increase by $800 each year after that. In order to buy the machine, the company needs to be convinced that it will pay for itself by the end of 8 years with this additional income. Money can earn 1.7% per year, compounded continuously. Should the company buy the machine?

Solution

We'll assume that the income will come in continuously over the 8 years. We'll also assume that interest rates will remain constant over that 8-year time period.

We're interested in the present value of the machine, which we will compare to its $65,000 price tag. Let t be the time, in years, since the purchase of the machine. The income from the machine is different depending on the time.

From $t = 0$ to $t = 1$ (the first year), the income is constant $7000 per year. From $t = 1$ to $t = 8$, the income is increasing by $800 each year; the income flow function $F(t)$ will be $F(t) = 7000 + 800(t - 1) = 6200 + 800t$. To find the present value, we'll have to divide the integral into the two pieces, one for each of the functions:

$$PV = \int_0^1 7000e^{-0.017t}\,dt + \int_1^8 (6200 + 800t)e^{-0.017t}\,dt \approx 70166.$$

The present value is greater than the cost of the machine, so the company should buy the machine.

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5.9: Differential Equations

A **differential equation** is an equation involving the derivative of a function. They allow us to express with a simple equation the relationship between a quantity and it's rate of change.

Example 5.9.1

A bank pays 2% interest on its certificate of deposit accounts, but charges a \$20 annual fee. Write an equation for the rate of change of the balance, $B'(t)$.

Solution

If the balance $B(t)$ has units of dollars, then $B'(t)$ has units of dollars per year. When we think of what is changing the balance of the account, there are two factors:

1. The interest, which increases the balance, and
2. The fee, which decreases the balance.

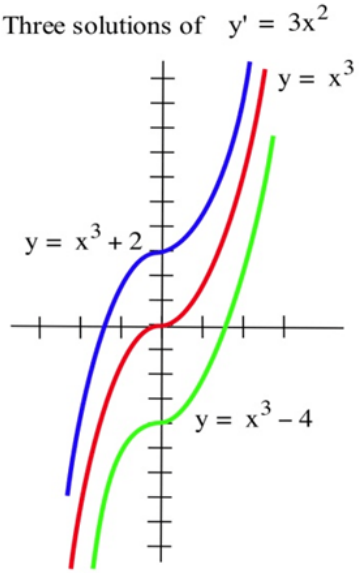
Considering the interest, we know each year the balance will increase by 2%, but 2% of what? Each year that will change, since we earn interest on whatever the current balance is. We can represent the amount of increase as 2% of the balance: $0.02B(t)$ dollars/year.

The fee already has the units of dollars/year. Since everything now has the same units, we can put the two together, and create the equation:

$$B'(t) = 0.02B(t) - 20.$$

The result is an example of a differential equation. Notice this particular equation involves both the derivative *and* the original function, and so we can't simply find $B(t)$ using basic integration.

Algebraic equations contain constants and variables, and the solutions of an algebraic equation are typically numbers. For example, $x = 3$ and $x = -2$ are solutions of the algebraic equation $x^2 = x + 6$. Differential equations contain derivatives or differentials of functions. Solutions of differential equations are functions. The differential equation $y' = 3x^2$ has infinitely many solutions, and two of those solutions are the functions $y = x^3 + 2$ and $y = x^3 - 4$.



You have already solved lots of differential equations: every time you found an antiderivative of a function $f(x)$, you solved

the differential equation $y' = f(x)$ to get a solution y. The differential equation $y' = f(x)$, however, is just the beginning. Other applications generate different differential equations, like in the bank balance example above.

Checking Solutions of Differential Equations

Whether a differential equation is easy or difficult to solve, it is important to be able to check that a possible solution really satisfies the differential equation.

A possible solution of an algebraic equation can be checked by putting the solution into the equation to see if the result is true: $x = 3$ is a solution of $5x + 1 = 16$ since $5(3) + 1 = 16$ is true. Similarly, a solution of a differential equation can be checked by substituting the function and the appropriate derivatives into the equation to see if the result is true: $y = x^2$ is a solution of $xy' = 2y$ since $y' = 2x$ and $x(2x) = 2\left(x^2\right)$ is true.

Example 5.9.2

1. Check that $y = x^2 + 5$ is a solution of $y'' + y = x^2 + 7$ and
2. Check that $y = x + \frac{5}{x}$ is a solution of $y' + \frac{y}{x} = 2$.

Solution

1. $y = x^2 + 5$ so $y' = 2x$ and $y'' = 2$. Substituting these functions for y and y'' into the differential equation $y'' + y = x^2 + 7$, we have
$$y'' + y = (2) + \left(x^2 + 5\right) = x^2 + 7,$$
so $y = x^2 + 5$ is a solution of the differential equation.
2. $y = x + \frac{5}{x}$ so $y' = 1 - \frac{5}{x^2}$. Substituting these functions for y and y' in the differential equation $y' + \frac{y}{x} = 2$, we have
$$y' + \frac{y}{x} = \left(1 - \frac{5}{x^2}\right) + \frac{1}{x}\left(x + \frac{5}{x}\right) = 1 - \frac{5}{x^2} + 1 + \frac{5}{x^2} = 2,$$
the result we wanted to verify.

Separable Differential Equations

A differential equation is called **separable** if the variables can be separated algebraically so that all the x's and dx are one one side of the equation, and all the y's and dy are on the other side of the equation. In other words, so the equation has the form $f(x)\ dx = g(y)\ dy$.

Once separated, separable differential equations can be solved by integrating both sides of the equation.

Example 5.9.3

Find the solution of
$$y' = \frac{6x + 1}{2y}.$$

Solution

Rewriting y' is a helpful first step:
$$\frac{dy}{dx} = \frac{6x + 1}{2y}$$

Now we can multiply both sides by dx and by $2y$ to separate the variables:
$$2y\,dy = (6x + 1)\,dx$$

Integrating each side, we have

$$\int 2y\,dy = \int (6x+1)\,dx$$
$$y^2 + C_1 = 3x^2 + x + C_2$$

Notice that we can combine the two constants to create a new, consolidated constant C, so we usually only bother to put a constant on the right side:

$$y^2 = 3x^2 + x + C.$$

As expected, there is a whole family of solutions to this differential equation.

Initial Value Problem (IVT)

An **initial value problem** is a differential equation that provides additional information about the initial, or starting, value of the function. This allows us to then solve for the constant and find a single solution.

Example 5.9.4

Find the solution of $y' = \frac{6x+1}{2y}$ which satisfies $y(2) = 3$.

Solution

In the previous example we found the general solution, $y^2 = 3x^2 + x + C$.

Substituting in the initial condition, $y = 3$ when $x = 2$,

$$3^2 = 3(2)^2 + 2 + C,$$

so $9 = 12 + 2 + C$, giving $C = -5$.

The solution is

$$y^2 = 3x^2 + x - 5.$$

Sometimes it is desirable to solve for y, which would yield $y = \pm\sqrt{3x^2 + x - 5}$, but since the initial condition had a positive y value, we isolate the positive solution:

$$y = \sqrt{3x^2 + x - 5}.$$

Example 5.9.5

A bank pays 2% interest on its certificate of deposit accounts, but charges a $20 annual fee. If you initially invest $3,000, how much will you have after 10 years?

Solution

You may recognize this as the example from the beginning of the section, for which we set up the equation $B'(t) = 0.02B(t) - 20$ or, more simply,

$$\frac{dB}{dt} = 0.02B - 20.$$

We can separate this equation by multiply by dt and dividing by the entire expression on the right:

$$\frac{dB}{0.02B - 20} = dt.$$

Integrating the left side of this equation requires substitution. Let $u = 0.02B - 20$, so $du = 0.02\ dB$. Making the substitution,

$$\begin{aligned}\int \frac{dB}{0.02B-20} &= \int \frac{du/0.02}{u} \\ &= \int \frac{1}{u}\frac{du}{0.02} \\ &= \frac{1}{0.02}\int \frac{1}{u}\,du \\ &= \frac{1}{0.02}\ln|u| + C_1 \\ &= \frac{1}{0.02}\ln|0.02B-20| + C_1\end{aligned}$$

Integrating on the right side of the differential equation is easier:

$$\int dt = t + C_2$$

Together, this gives us the general solution to the differential equation (we're also combining the C's in this step):

$$\frac{1}{0.02}\ln|0.02B-20| = t + C$$

Now we would like to solve for B. Start by multiplying by 0.02.

$$\begin{aligned}\ln|0.02B-20| &= 0.02t + 0.02C && \\ \ln|0.02B-20| &= 0.02t + D && \text{We can rename } D = 0.02C \text{ for simplicity.} \\ e^{\ln|0.02B-20|} &= e^{0.02t+D} && \text{Exponentiate both sides: } e^{\text{left}} = e^{\text{right}}. \\ |0.02B-20| &= e^{0.02t+D} && \text{Use the log rule } e^{\ln(A)} = A. \\ 0.02B-20 &= e^{0.02t+D} && \text{Since the RHS is always positive, we can drop the abs value.} \\ 0.02B-20 &= e^{0.02t}e^{D} && \text{Using the rule } e^{A+B} = e^A e^B. \\ 0.02B-20 &= ke^{0.02t} && \text{Rename } k = e^D. \\ B &= \frac{ke^{0.02t}+20}{0.02} = \frac{ke^{0.02t}}{0.02} + 1000 && \text{Add 20 and divide by 0.02.} \\ B &= Ae^{0.02t} + 1000 && \text{Rename } A = \frac{k}{0.02}.\end{aligned}$$

Finally, we can substitute our initial value of $B = 3000$ when $t = 0$ to solve for the constant A:

$$\begin{aligned}3000 &= Ae^{0.02(0)} + 1000 \\ A &= 2000\end{aligned}$$

This gives us the equation for the account balance after t years:

$$B(t) = 2000e^{0.02t} + 1000.$$

To find the balance after 10 years, we can evaluate this equation at $t = 10$:

$$B(10) = 2000e^{0.02(10)} + 1000 \approx \$3442.81.$$

It's worth noting that this answer isn't exactly right. Differential equations assume *continuous* changes, and it is unlikely interest is compounded continuously or the fee is extracted continuously. However, the answer is probably close to the actual answer, and differential equations provide a relatively simple model of a complicated situation.

Models of Growth

The bank account example demonstrated one basic model of growth: growth proportional to the existing quantity. Bank accounts and populations both tend to grow this way if not constrained. This type of growth is called **unlimited growth**.

Unlimited Growth

If a quantity or population y grows at a rate proportional that quantity's size, it can be modeled with **unlimited growth**, which has the differential equation:

$$y' = ry,$$

where r is a constant.

Example 5.9.6

A population grows by 8% each year. If the current population is 5,000, find an equation for the population after t years.

Solution

$$\begin{aligned} \frac{dy}{dt} &= 0.08y \\ \frac{1}{y}\,dy &= 0.08\,dt && \text{Separate the variables.} \\ \ln|y| &= 0.08t + C && \text{Integrate both sides.} \\ e^{\ln|y|} &= e^{0.08t+C} && \text{Exponentiate both sides.} \\ y &= Ae^{0.08t} && \text{Simplify both sides, using the tricks we used in the bank example.} \end{aligned}$$

Now substitute in the initial condition: $5000 = Ae^{0.08(0)}$, so $A = 5000$.

The population will grow following the equation

$$y = 5000e^{0.08t}.$$

Notice that the solution to the unlimited growth equation is an exponential equation.

When a product is advertised heavily, sales will tend to grow very quickly, but eventually the market will reach saturation, and sales will slow. In this type of growth, called **limited growth**, the population grows at a rate proportional to the distance from the maximum value.

Limited Growth

If a quantity grows at a rate proportional to the distance from the maximum value, M, it can be modeled with **limited growth**, which has the differential equation

$$y' = k(M - y),$$

where k is a constant, and M is the maximum size of y.

Example 5.9.7

A new cell phone is introduced. The company estimates they will sell 200 thousand phones. After 1 month they have sold 20 thousand. How many will they have sold after 9 months?

Solution

In this case there is a maximum amount of phones they expect to sell, so $M = 200$ thousand. Modeling the sales, y, in thousands of phones, we can write the differential equation

$$y' = k(200 - y).$$

Since it was a new phone, $y(0) = 0$. We also know the sales after one month, $y(1) = 20$.

Solving the differential equation:

$$\begin{aligned} \frac{dy}{dt} &= k(200-y) && \\ \frac{dy}{200-y} &= k\,dt && \text{Separate the variables.} \\ -\ln|200-y| &= kt + C && \text{Integrate both sides. On the left use the substitution.} \\ e^{\ln|200-y|} &= e^{-kt+C} && \text{Multiply both sides by -1, and exponentiate both sides.} \\ 200-y &= Be^{-kt} && \text{Simplify.} \\ y &= Ae^{-kt} + 200 && \text{Subtract 200, divide by -1, and simplify.} \end{aligned}$$

Using the initial condition $y(0) = 0$,

$$0 = Ae^{-k(0)} + 200,$$

so $0 = A + 200$, giving $A = -200$.

Using the value $y(1) = 20$:

$$\begin{aligned} 20 &= -200e^{-k(t)} + 200 && \\ \frac{=180}{-200} &= 0.9 = e^{-k} && \text{Subtract 200 and divide -200.} \\ \ln(0.9) &= \ln\left(e^{-k}\right) = -k && \text{Take the ln of both sides.} \\ k &= -\ln(0.9) \approx 0.105 && \text{Divide by -1.} \end{aligned}$$

As a quick sanity check, this value is positive as we would expect, indicating that the sales are growing over time. We now have the equation for the sales of phones over time:

$$A = -200e^{-0.105t} + 200.$$

Finally, we can evaluate this at $t = 9$ to find the sales after 9 months:

$$A(9) = -200e^{-0.105(9)} + 200 \approx 122.26 \text{ thousand phones.}$$

Limited growth is also commonly used for learning models, since when learning a new skill, people typically learn quickly at first, then their rate of improvement slows down as they approach mastery.

Example 5.9.8

Jim is learning a new set of product codes for work. Each day he studies, and tests his recall. Suppose that after 4 days, Jim has mastered 70% of the new codes. How long will it take for him to master 95% of the codes, if the limited growth model applies.

Solution

In this case there is a maximum amount of mastery possible, so M = 100%. Modeling his learning, L, as percent of mastery, we can write the differential equation $L' = k(100 - L)$

Solving as we did in the previous example, we obtain $L = Ae^{-kt} + 100$.

Since he started not knowing any of the codes $L(0) = 0$, so $0 = Ae^{-k(0)} + 100$, so $A = -100$.

Using that Jim mastered 70 of the codes in 4 days, $L(4) = 70$, so

$$\begin{aligned} 70 &= -100e^{-k(4)} + 100 \\ -30 &= -100e^{-k(4)} \\ 0.3 &= e^{-k(4)} \\ \ln(0.3) &= \ln\left(e^{-k(4)}\right) = -4k \\ k &= \frac{\ln(0.3)}{-4} \approx 0.301 \end{aligned}$$

Now we have the equation $L = -100e^{-0.301t} + 100$, we can solve for when $L = 95$.

$$\begin{aligned} 95 &= -100e^{-0.301t} + 100 \\ -5 &= -100e^{-0.301t} \\ 0.05 &= e^{-0.301t} \\ \ln(0.3) = \ln\left(e^{-0.301t}\right) &= -0.301t \\ t &= \frac{\ln(0.05)}{-0.301} \approx 9.95 \end{aligned}$$

Jim will have reached 95% mastery after about 10 days.

Earlier we used unlimited growth to model a population, but often a population will be constrained by food, space, and other resources. When a population grows both proportional to its size, and relative to the distance from some maximum, that is called **logistic growth**. This leads to the differential equation $y' = ky(M - y)$, which is accurate but not always convenient to use. We will use a slight modification. Since solving this differential equation requires integration techniques we haven't learned, the solution form is given.

Logistic Growth

If a quantity grows at a rate proportional to its size and to the distance from the maximum value, M, it can be modeled with **logistic growth**, which has the differential equation:

$$y' = ry\left(1 - \frac{y}{M}\right).$$

r can be interpreted as "the growth rate absent constraints", i.e., how the population would grow if there wasn't a maximum value.

This differential equation has solutions of the form

$$y = \frac{M}{1 + Ae^{-rt}}.$$

Example 5.9.9

A colony of 100 rabbits is introduced to a reclaimed forest. After 1 year, the population has grown to 300. It is estimated the forest can sustain 5000 rabbits. The forest service plans to reintroduce wolves to the forest when the rabbit population reaches 3000 rabbits. When will that occur?

Solution

The maximum sustainable population was given as $M = 5000$. Using the solution form

$$y = \frac{M}{1 + Ae^{-rt}}$$

and the initial condition $y(0) = 100$ we can solve for A:

$$\begin{aligned} 100 &= \frac{5000}{1 + Ae^{-r(0)}} \\ 100 &= \frac{5000}{1 + A} && \text{Simplify.} \\ 100(1 + A) &= 5000 && \text{Multiply both sides by } 1 + A. \\ 1 + A &= 50 && \text{Divide by } 100. \\ A &= 49 \end{aligned}$$

Now, using $y(1) = 300$, we can solve for r:

$$\begin{aligned} 300 &= \frac{5000}{1+49e^{-r(1)}} \\ 300\left(1+49e^{-r}\right) &= 5000 \\ 1+49e^{-r} &= \frac{5000}{300} \\ e^{-r} &= \frac{\frac{50}{3}-1}{49} \approx 0.3197 \\ -r &= \ln(0.3197) \\ r &= -\ln(0.3197) \approx 1.1404 \end{aligned}$$

We now have the equation for the population after t years:

$$y = \frac{5000}{1+49e^{-1.1404t}}.$$

To answer the original equation, of when the rabbit population will reach 3000, we need to solve for t when $y = 3000$:

$$\begin{aligned} 3000 &= \frac{5000}{1+49e^{-1.1404t}} \\ 3000\left(1+49e^{-1.1404t}\right) &= 5000 \\ e^{-1.1404t} &= \frac{\frac{5}{3}-1}{49} \approx 0.01361 \\ t &= \frac{\ln(0.01361)}{-1.1404} \approx 3.77 \text{ years.} \end{aligned}$$

Logistic growth is also a good model for unadvertised sales. A new product that is not advertised will have sales increase slowly at first, then grow as word of mouth spreads and people become familiar with the product. Sales will level off as they approach market saturation.

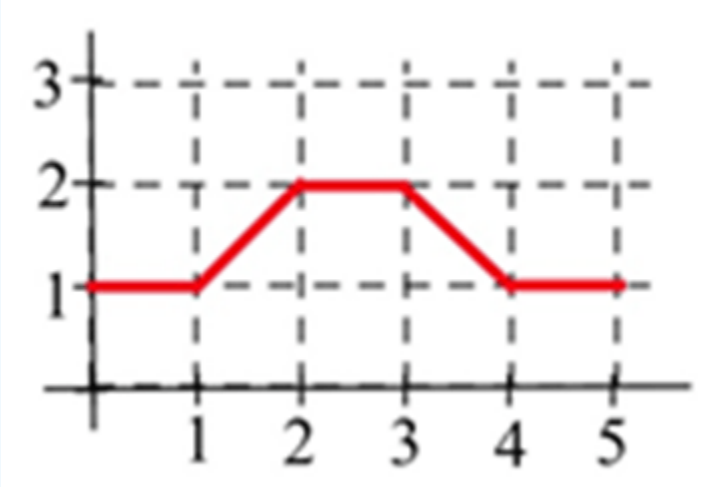
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5.E: The Integral (Exercises)

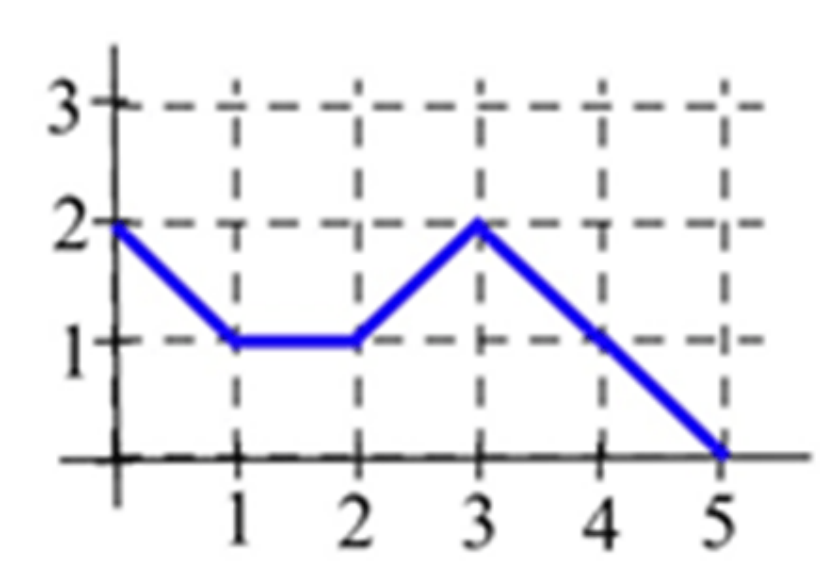
3.2 Exercises

Exercise $5.E.1$



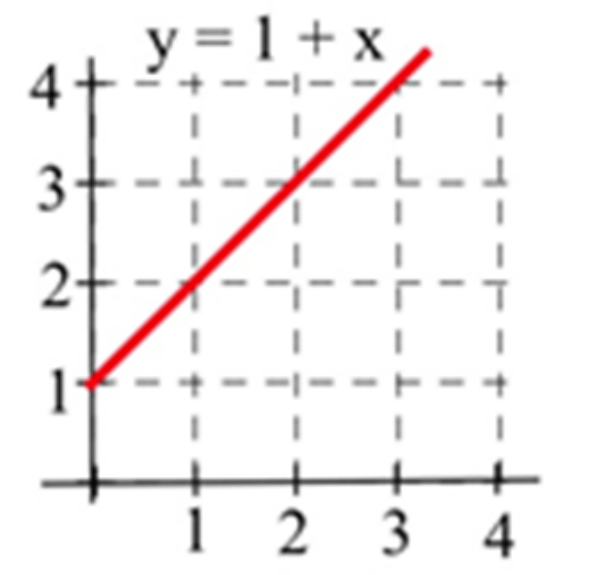
Let $A(x)$ represent the area bounded by the graph and the horizontal axis and vertical lines at $t = 0$ and $t = x$ for the graph shown. Evaluate $A(x)$ for $x =$ 1, 2, 3, 4, and 5.

Exercise $5.E.2$



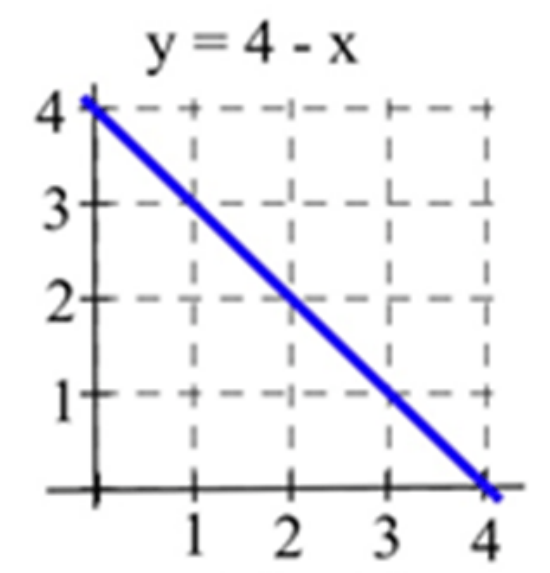
Let $B(x)$ represent the area bounded by the graph and the horizontal axis and vertical lines at $t = 0$ and $t = x$ for the graph shown. Evaluate $B(x)$ for $x =$ 1, 2, 3, 4, and 5.

Exercise $5.E.3$



Let $C(x)$ represent the area bounded by the graph and the horizontal axis and vertical lines at $t = 0$ and $t = x$ for the graph shown. Evaluate $C(x)$ for $x =$ 1, 2, and 3 and find a formula for $C(x)$.

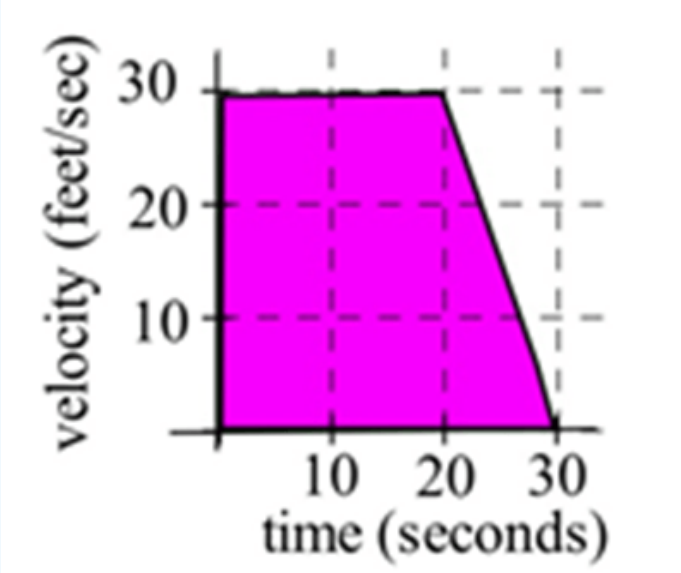
Exercise $5.E.4$



Let $A(x)$ represent the area bounded by the graph and the horizontal axis and vertical lines at $t = 0$ and $t = x$ for the graph shown. Evaluate $A(x)$ for $x =$ 1, 2, and 3 and find a formula for $A(x)$.

Exercise $5.E.5$

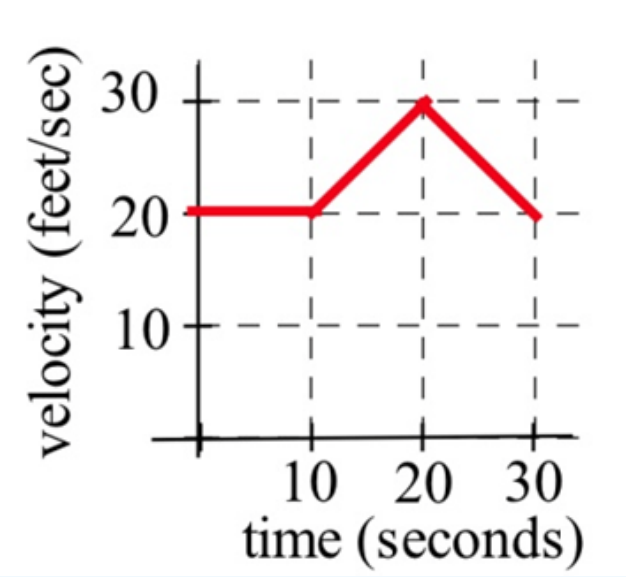
A car had the velocity shown in the graph to the right.



A car had the velocity shown in the graph to the right. How far did the car travel from $t = 0$ to $t = 30$ seconds?

Exercise $5.E.6$

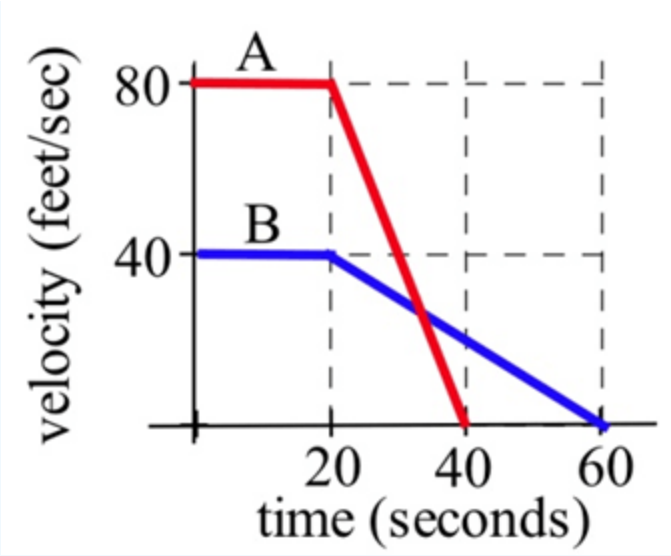
A car had the velocity shown below.



How afar did the car travel from $t = 0$ to $t = 30$ seconds?

Exercise $5.E.7$

The velocities of two cars are shown in the graph.

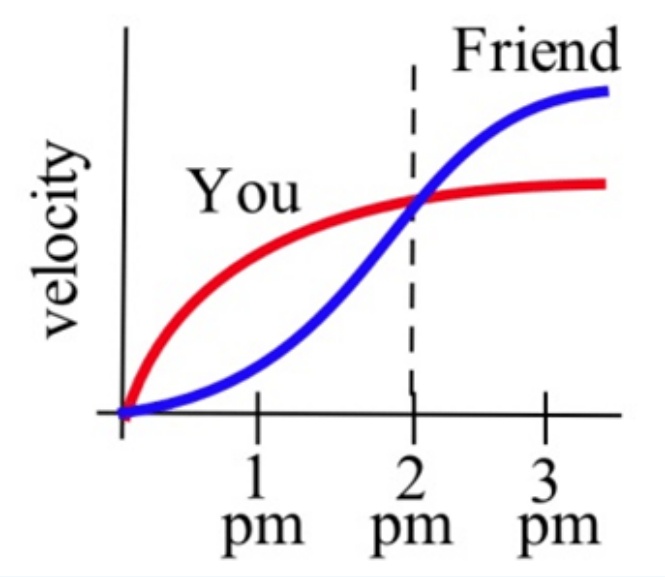


(a) From the time the brakes were applied, how many seconds did it take each car to stop?

(b) From the time the brakes were applied, which car traveled farther until it came to a complete stop?

Exercise $5.E.8$

You and a friend start off at noon and walk in the same direction along the same path at the rates shown.

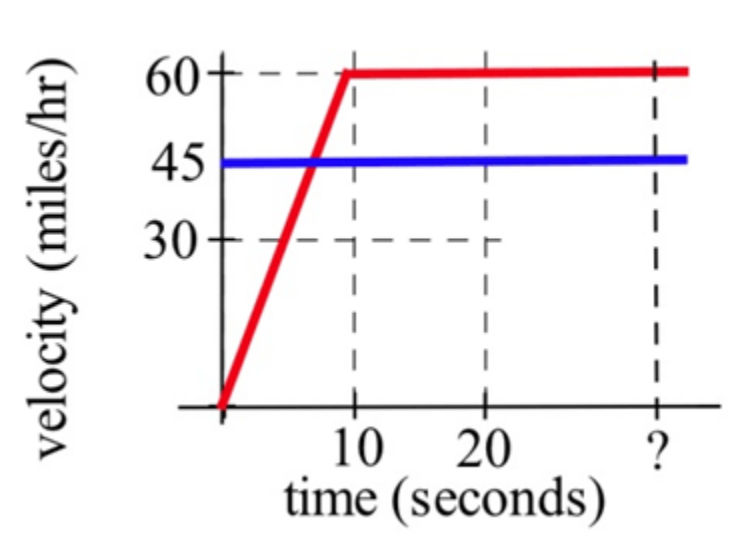


(a) Who is walking faster at 2 pm? Who is ahead at 2 pm?

(b) Who is walking faster at 3 pm? Who is ahead at 3 pm?

(c) When will you and your friend be together? (Answer in words.)

Exercise 5.E.9



Police chase: A speeder traveling 45 miles per hour (in a 25 mph zone) passes a stopped police car which immediately takes off after the speeder. If the police car speeds up steadily to 60 miles/hour in 20 seconds and then travels at a steady 60 miles/hour, **how long** and **how far** before the police car catches the speeder who continued traveling at 45 miles/hour?

Exercise 5.E.10

Water is flowing into a tub. The table shows the rate at which the water flows, in gallons per minute. The tub is initially empty.

t, in minutes	0	1	2	3	4	5	6	7	8	9	10
Flow rate, in gal/min	0.5	1.0	1.2	1.4	1.7	2.0	2.3	1.8	0.7	0.5	0.2

Use the table to estimate how much water is in the tub after

a. five minutes

b. ten minutes

Exercise 5.E.11

The table shows the speedometer readings for a short car trip.

t, in minutes	0	5	10	15	20
Speed, in mph	0	30	40	65	40

a. Use the table to estimate how far the car traveled over the twenty minutes shown.

b. How accurate would you expect your estimate to be?

Exercise 5.E.12

The table shows values of $f(t)$. Use the table to estimate $\int_0^{40} f(t)dt$.

t	0	10	20	30	40
$f(t)$	17	22	18	11	35

Exercise 5.E.13

The table shows values of $g(x)$.

x	0	1	2	3	4	5	6
$g(x)$	140	142	144	152	154	165	200

Use the table to estimate

a. $\int_0^3 g(x)dx$	b $\int_3^6 g(x)dx$	c. $\int_0^6 g(x)dx$

Exercise 5.E.14

What are the units for the "area" of a rectangle with the given base and height units?

Base units	Height units	"Area" units
miles per second	seconds	
hours	dollars per hour	
square feet	feet	
kilowatts	hours	
houses	people per house	

meals	meals	

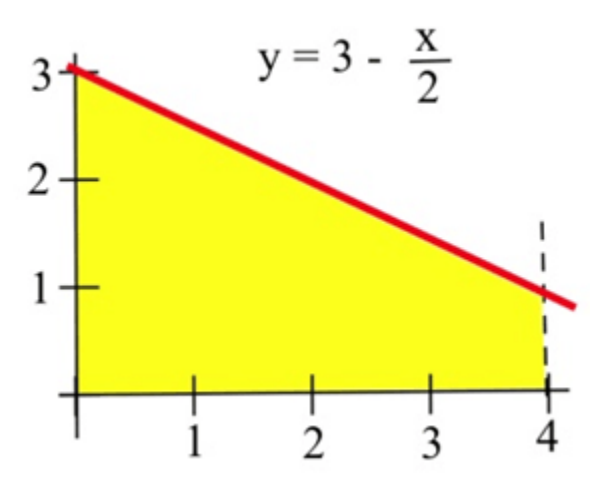
Exercise $5.E.15 - 5.E.17$

In problems 15 – 17, represent the area of each bounded region as a definite integral, and use geometry to determine the value of the definite integral.

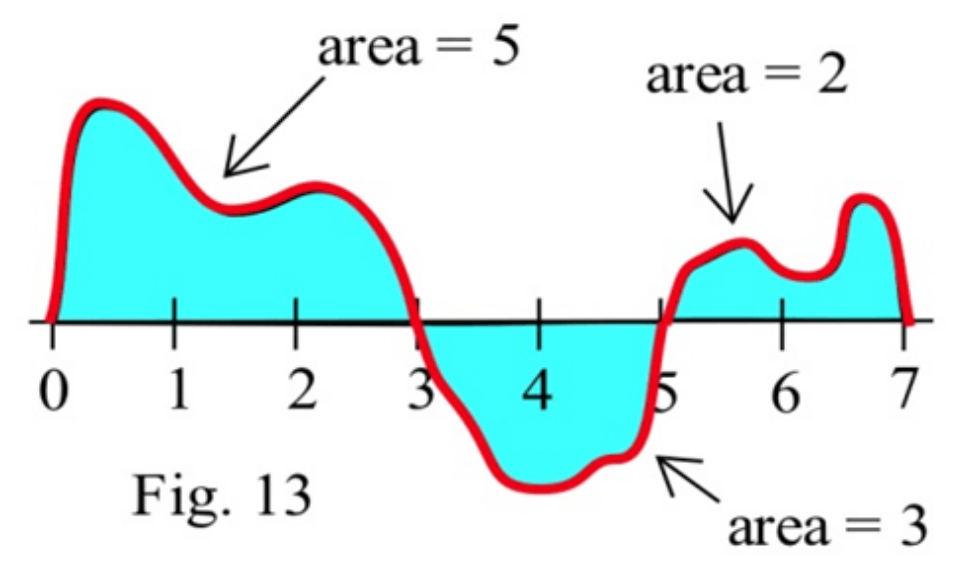
15. The region bounded by $y = 2x$, the x–axis, the line $x = 1$, and $x = 3$.

16. The region bounded by $y = 4–2x$, the x–axis, and the y–axis.

17. The shaded region in the graph to the right.



Exercise $5.E.18$



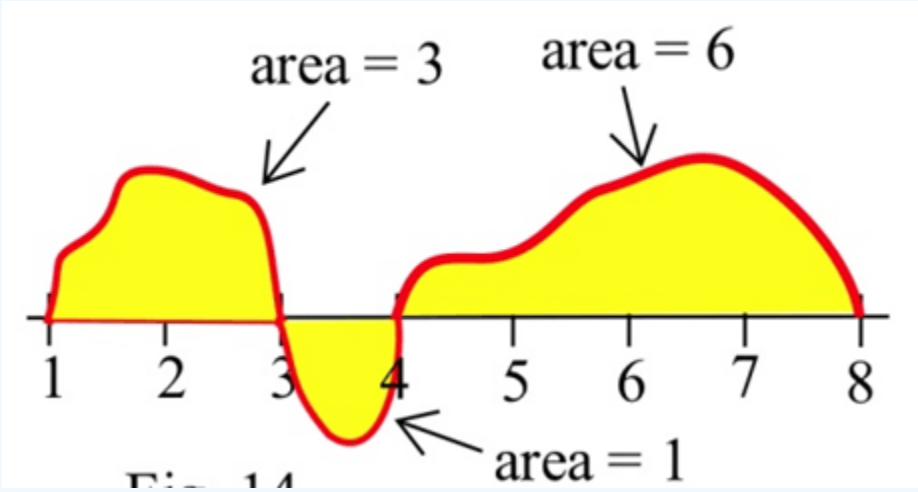
Using the graph of f shown and the given areas of several regions, evaluate:

(a) $\int_0^3 f(x)dx$

(b) $\int_3^5 f(x)dx$

(c) $\int_5^7 f(x)dx$

Exercise $5.E.19$



Using the graph of f shown and the given areas of several regions, evaluate:

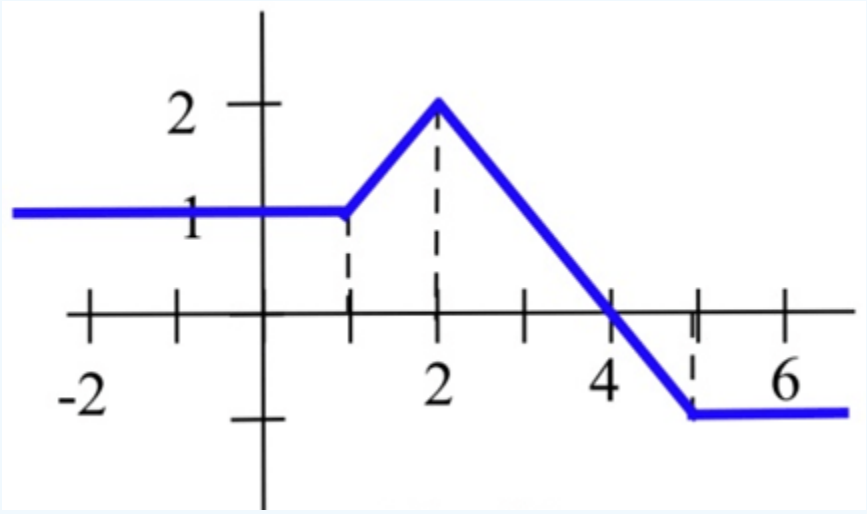
(a) $\int_1^3 g(x)dx$

(b) $\int_3^4 g(x)dx$

(c) $\int_4^8 g(x)dx$

(d) $\int_1^8 g(x)dx$

Exercise $5.E.20$



Use the graph to evaluate:

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

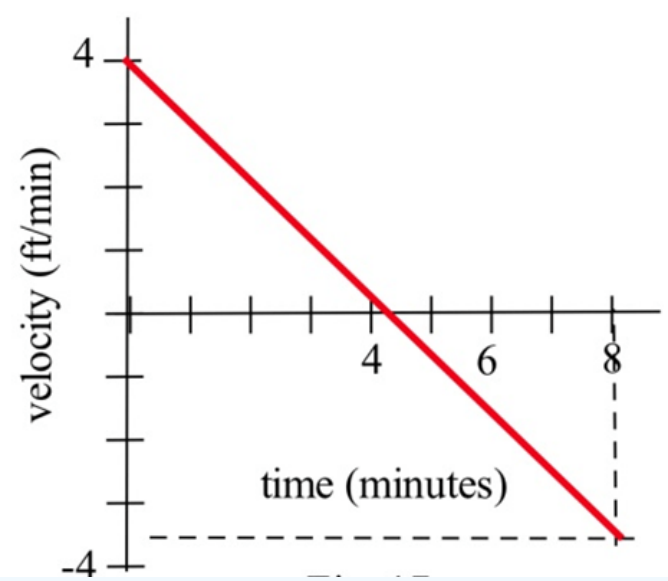
(b) $\int_4^6 h(x)dx$

(c) $\int_{-2}^6 h(x)dx$

(d) $\int_{-2}^4 h(x)dx$

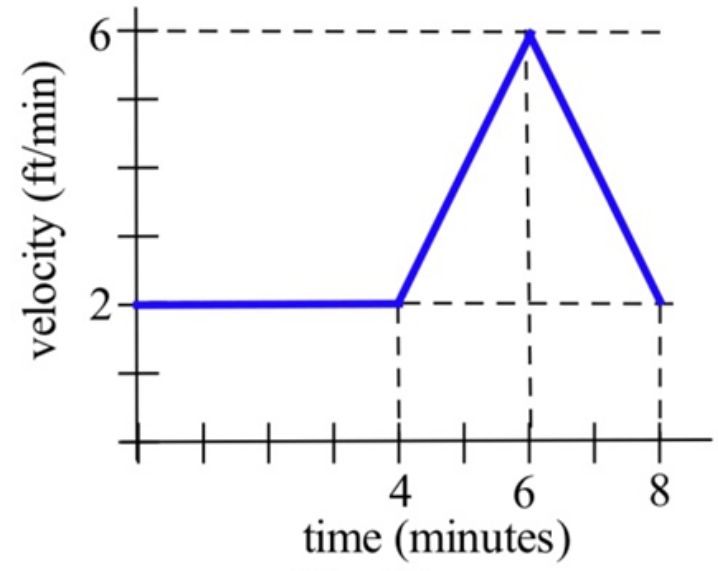
Exercise $5.E.21$

Your velocity along a straight road is shown to the right. How far did you travel in 8 minutes?



Exercise $5.E.22$

Your velocity along a straight road is shown below. How many feet did you walk in 8 minutes?



Exercise $5.E.23 - 5.E.26$

In problems 23 - 26, the units are given for x and for $f(x)$. Give the units of $\int_a^b f(x)dx$.

23. x is time in "seconds", and $f(x)$ is velocity in "meters per second."

24. x is time in "hours", and $f(x)$ is a flow rate in "gallons per hour."

25. x is a position in "feet", and $f(x)$ is an area in "square feet."

26. x is a position in "inches", and $f(x)$ is a density in "pounds per inch."

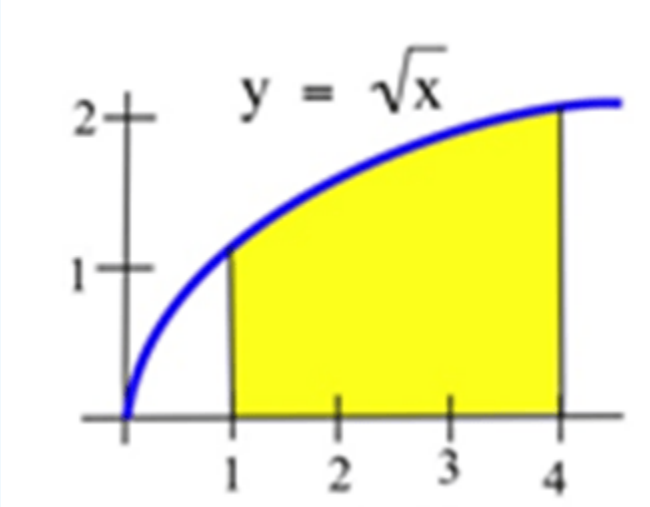
Exercise $5.E.27 - 5.E.31$

In problems 27 – 31, represent the area with a definite integral and use technology to find the approximate answer.

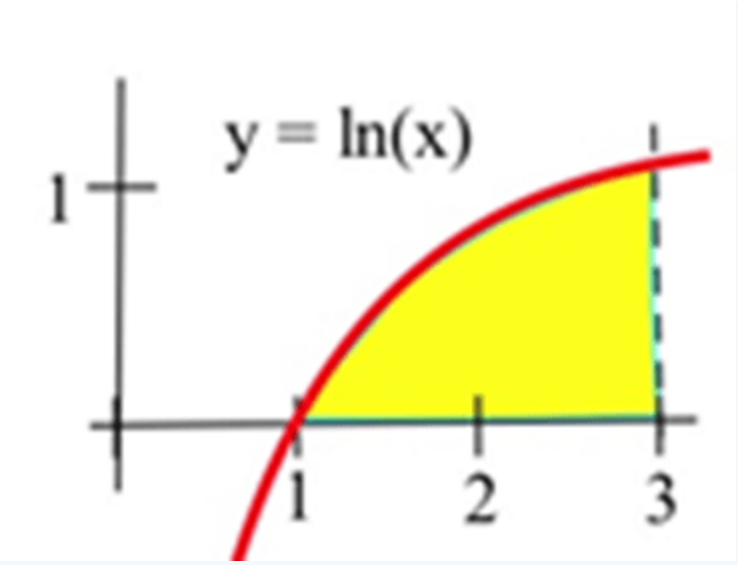
27. The region bounded by $y = x^3$, the x–axis, the line $x = 1$, and $x = 5$.

28. The region bounded by $y = \sqrt{x}$, the x–axis, and the line $x = 9$.

29. The shaded region shown to the right.



30. The shaded region below.



31. Consider the definite integral $\int_0^3 (3+x)dx$.

(a) Using six rectangles, find the left-hand Riemann sum for this definite integral.

(b) Using six rectangles, find the right-hand Riemann sum for this definite integral.

(c) Using geometry, find the exact value of this definite integral.

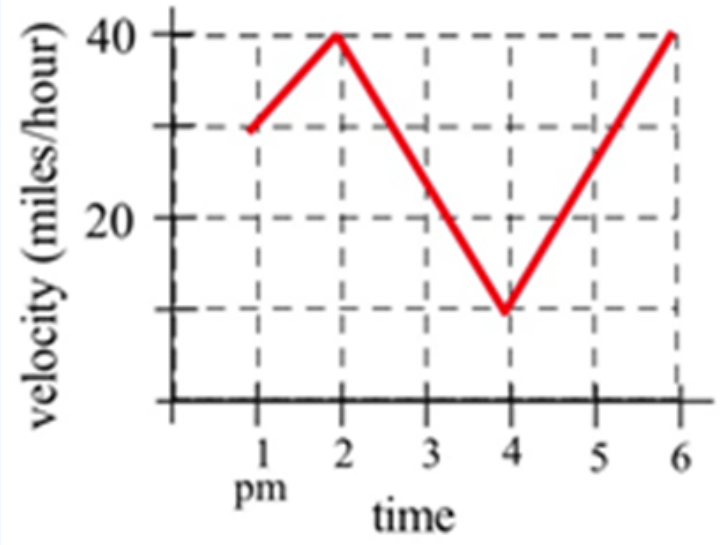
Exercise $5.E.32$

Consider the definite integral $\int_0^2 x^3 dx$.

(a) Using four rectangles, find the left-hand Riemann sum for this definite integral.

(b) Using four rectangles, find the right-hand Riemann sum for this definite integral.

Exercise $5.E.33$



Write the total distance traveled by the car in the graph between 1 pm and 4 pm as a definite integral and estimate the value of the integral.

Exercise $5.E.34 - 5.E.41$

Problems 34 – 41 refer to the graph of f shown.

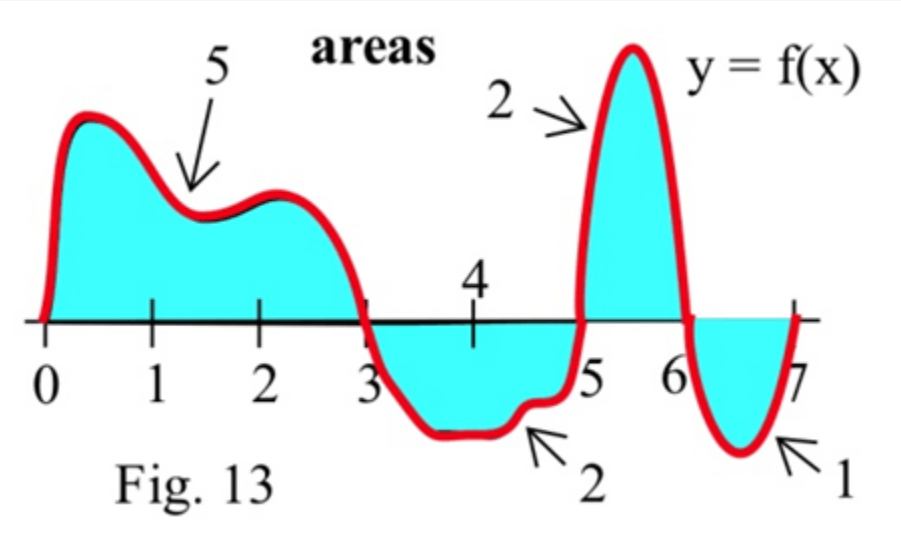


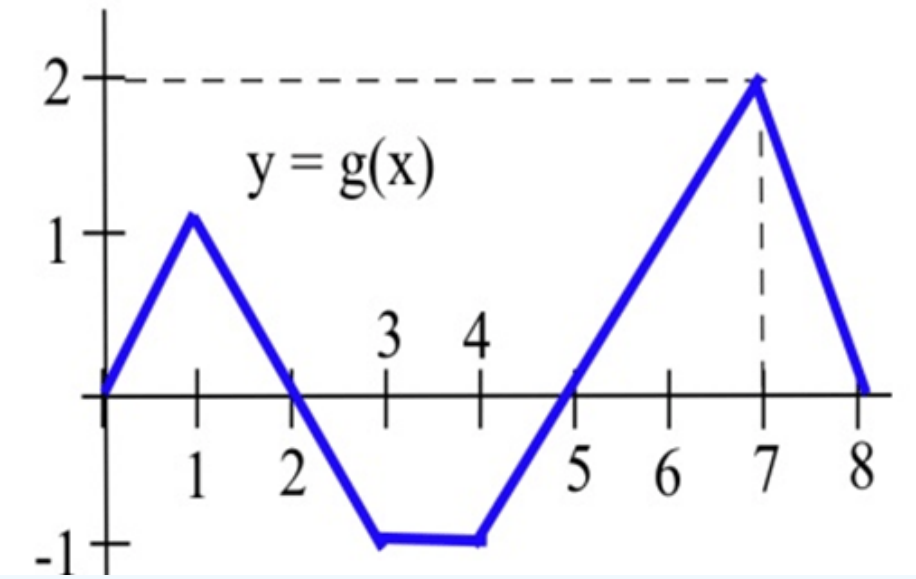
Fig. 13

Use the graph to determine the values of the definite integrals. (The bold numbers represent the **area** of each region.)

34. $\int_0^3 f(x)dx$	35. $\int_3^5 f(x)dx$	36. $\int_2^2 f(x)dx$	37. $\int_6^7 f(w)dw$
38. $\int_0^5 f(x)dx$	39. $\int_0^7 f(x)dx$	40. $\int_3^6 f(t)dt$	41. $\int_5^7 f(x)dx$

Exercise $5.E.42 - 5.E.47$

Problems 42 – 47 refer to the graph of g shown.



Use the graph to evaluate the integrals.

42. $\int_0^2 g(x)dx$	43. $\int_1^3 g(t)dt$	44. $\int_0^5 g(x)dx$
45. $\int_0^8 g(s)ds$	46. $\int_0^3 2g(t)dt$	47. $\int_5^8 1+g(x)dx$

3.3 Exercises

Exercise $5.E.1 - 5.E.5$

In problems 1 – 5, verify that $F(x)$ is an antiderivative of the integrand $f(x)$ and use Part 2 of the Fundamental Theorem to evaluate the definite integrals.

1. $\int_0^1 2xdx, F(x) = x^2 + 5$	2. $\int_1^4 3x^2dx, F(x) = x^3 + 2$	3. $\int_1^3 x^2dx, F(x) = \frac{1}{3}x^3$
4. $\int_0^3 (x^2 + 4x - 3)dx, F(x) = \frac{1}{3}x^3 + 2x^2 – 3x$	5. $\int_1^5 \frac{1}{x}dx, F(x) = \ln(x)$	

Exercise $5.E.6$

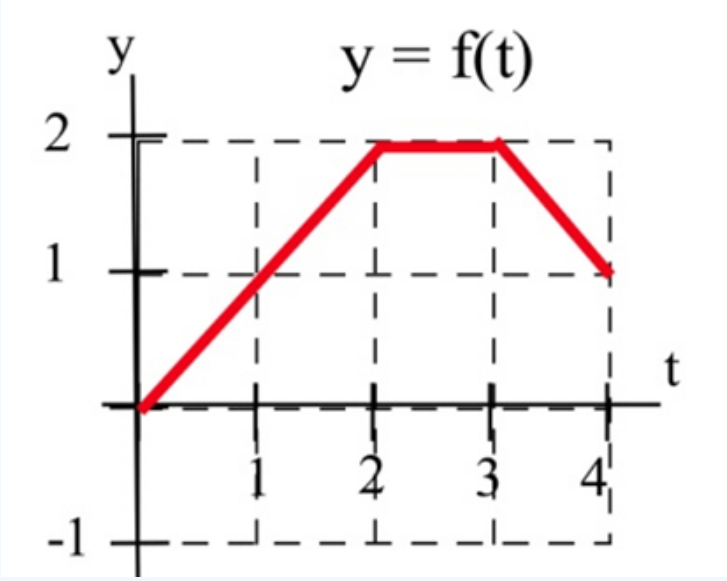
Given $A(x) = \int_0^x 2tdt$, find $A'(x)$

Exercise $5.E.7$

Given $A(x) = \int_0^x (3 - t^2)dt$, find $A'(x)$

Exercise $5.E.8$

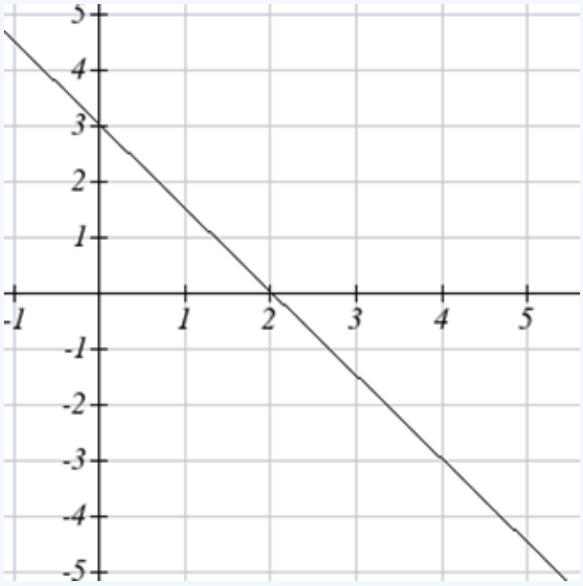
Let $A(x) = \int_0^x f(t)dt$ for the function graphed here.



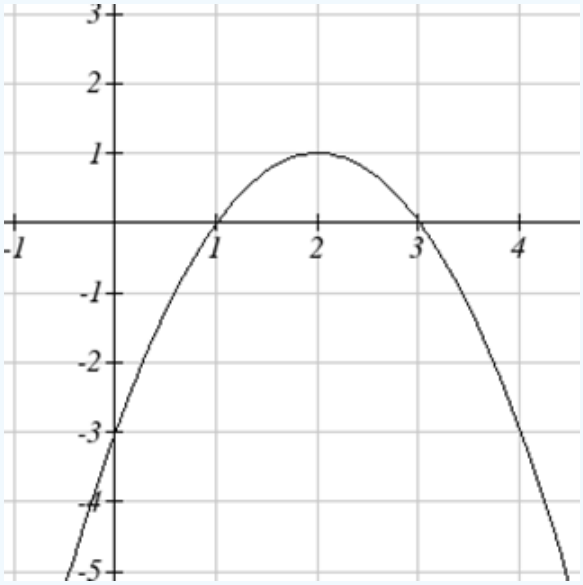
Evaluate $A'(1)$, $A'(2)$, $A'(3)$.

Exercise $5.E.9 - 5.E.10$

For problems 9-10, the graph provided shows $g'(x)$. Use it sketch a graph of $g(x)$ that satisfies $g(0) = 0$.



9.



10.

3.4 Exercises

Exercise $5.E.1 - 5.E.10$

For problems 1-10, find the indicated antiderivative.

1. $\int (x^3 - 14x + 5)dx$	2. $\int (2.5x^5 - x - 1.25)dx$
3. $\int 12.3dy$	4. $\int \pi^2 dw$
5. $\int e^P dP$	6. $\int \left(\sqrt{x} + e^x - \frac{1}{4x^3}\right) dx$
7. $\int \frac{1}{x} dx$	8. $\int \frac{1}{x^2} dx$
9. $\int (x-2)(x+2)dx$	10. $\int \frac{t^5 - t^2}{t} dt$

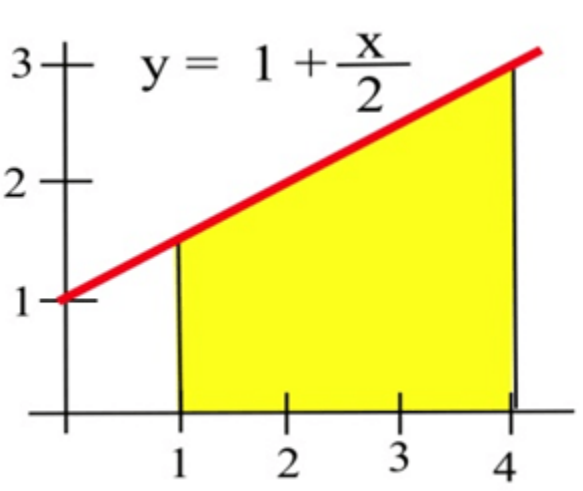
Exercise $5.E.11 - 5.E.18$

For problems 11-18, find an antiderivative of the integrand and use the Fundamental Theorem to evaluate the definite integral.

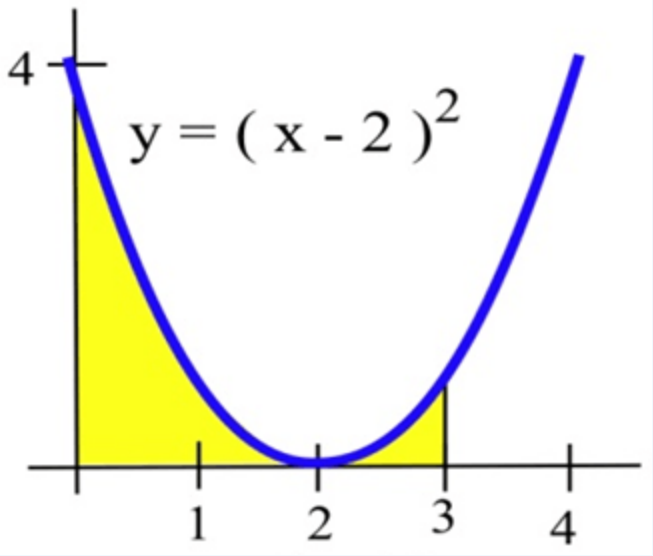
11. $\int_2^5 3x^2 dx$	12. $\int_{-1}^2 x^2 dx$	13. $\int_1^3 (x^2 + 4x - 3)dx$	14. $\int_1^e \frac{1}{x} dx$
15. $\int_{25}^{100} \sqrt{x} dx$	16. $\int_3^5 \sqrt{x} dx$	17. $\int_1^{10} \frac{1}{x^2} dx$	18. $\int_1^{1000} \frac{1}{x^2} dx$

Exercise $5.E.19 - 5.E.21$

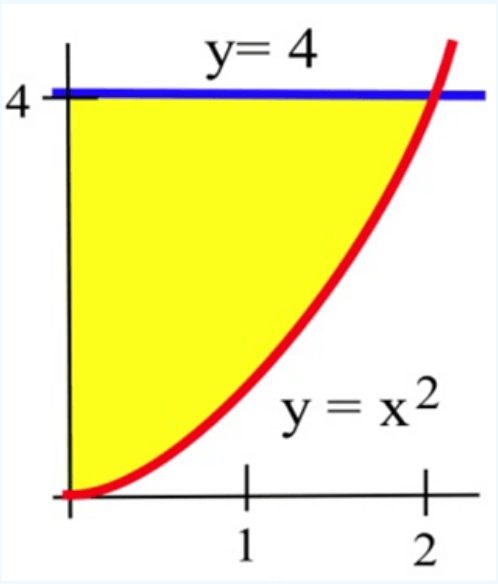
For problems 19 - 21 find the area shown in the figure.



19.



20.



21.

3.5 Exercises

Exercise $5.E.1 - 5.E.8$

For problems 1-8, find the indicated antiderivative.

1. $\int \frac{1}{(4x+1)^3} dx$	2. $\int e^{100x} dx$
3. $\int (1.0003)^{12t} dt$	4. $\int \frac{e^{10/x}}{x^2} dx$
5. $\int \sqrt{w+5} dw$	6. $\int 6x^2\sqrt{3x^3-1} dx$
7. $\int \frac{dx}{x \ln x}$	8. $\int \frac{x-3}{x^2-6x+5} dx$

Exercise $5.E.9 - 5.E.12$

For problems 9-12, find an antiderivative of the integrand and use the Fundamental Theorem to evaluate the definite integral.

9. $\int_{-2}^{2} \frac{2x}{1+x^2} dx$	10. $\int_{0}^{1} e^{2x} dx$	11. $\int_{2}^{4} (x-2)^3 dx$	12. $\int_{0}^{1} x\sqrt{1-x^2} dx$

3.6 Exercises

Exercise $5.E.1 - 5.E.4$

In problems 1–4, a function u or dv is given. Find the piece u or dv which is not given, calculate du and v, and apply the Integration by Parts Formula.

1. $\int 12x \cdot \ln(x) dx$	$u = \ln(x)$	2. $\int x \cdot e^{-x} dx$	$u = x$
3. $\int x^4 \ln(x) dx$	$dv = x^4 dx$	4. $\int x \cdot (5x+1)^{19} dx$	$u = x$

Exercise $5.E.5 - 5.E.10$

In problems 5 - 10 evaluate the integrals

5. $\int_{0}^{1} \frac{x}{e^{3x}} dx$	6. $\int_{0}^{1} 10x \cdot e^{3x} dx$	7. $\int_{1}^{3} \ln(2x+5) dx$
8. $\int x^3 \ln(5x) dx$	9. $\int x \ln(x+1) dx$	10. $\int_{1}^{2} \frac{\ln(x)}{x^2} dx$

Exercise $5.E.11 - 5.E.14$

For problems 11 - 14 integrate each function.

11. $\int \frac{1}{4-x^2}$	12. $\int \frac{2}{9-x^2}$	13. $\int \sqrt{4+x^2}$	14. $\int \sqrt{9+x^2}$

3.7 Exercises

Exercise $5.E.1 - 5.E.4$

In problems 1 – 4, use the values in the table to estimate the areas.

x	$f(x)$	$g(x)$	$h(x)$
0	5	2	5
1	6	1	6
2	6	2	8

3	4	2	6
4	3	3	5
5	2	4	4
6	2	0	2

1. Estimate the area between f and g, between $x = 0$ and $x = 4$.

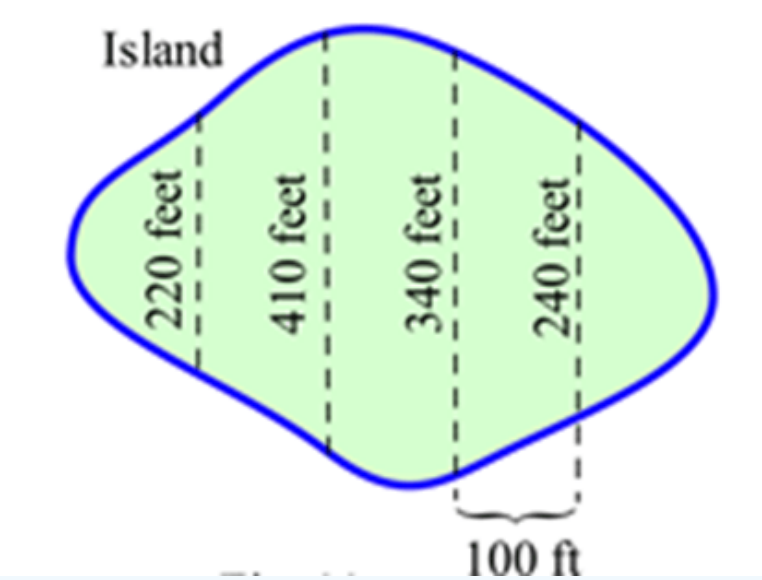
2. Estimate the area between g and h, between $x = 0$ and $x = 6$.

3. Estimate the area between f and h, between $x = 0$ and $x = 4$.

4. Estimate the area between f and g, between $x = 0$ and $x = 6$.

Exercise $5.E.1$

Estimate the area of the island shown



Exercise $5.E.6 - 5.E.15$

In problems 6 – 15, find the **area** between the graphs of f and g for x in the given interval. Remember to draw the graph!

6. $f(x) = x^2 + 3$, $g(x) = 1$ and $-1 \leq x \leq 2$.
7. $f(x) = x^2 + 3$, $g(x) = 1 + x$ and $0 \leq x \leq 3$.
8. $f(x) = x^2$, $g(x) = x$ and $0 \leq x \leq 2$.

9. $f(x) = (x–1)^2$, $g(x) = x + 1$ and $0 \le x \le 3$.
10. $f(x) = \frac{1}{x}$, $g(x) = x$ and $1 \le x \le e$.
11. $f(x) = \sqrt{x}$, $g(x) = x$ and $0 \le x \le 4$.
12. $f(x) = 4–x^2$, $g(x) = x + 2$ and $0 \le x \le 2$.
13. $f(x) = e^x$, $g(x) = x$ and $0 \le x \le 2$.
14. $f(x) = 3$, $g(x) = \sqrt{1 - x^2}$ and $0 \le x \le 1$.
15. $f(x) = 2$, $g(x) = \sqrt{4 - x^2}$ and $–2 \le x \le 2$.

Exercise $5.E.16 – 5.E.18$

For problems 16-18, find the volume of the solid obtained by rotating the specified region about the x axis.

16. Region under $f(x) = x^2 + 3$ for $–1 \le x \le 2$.

17. Region under $f(x) = 4–x^2$ for $0 \le x \le 2$.

18. Region under $f(x) = \frac{1}{x}$ for $1 \le x \le 2$.

Exercise $5.E.19 – 5.E.20$

In problems 19 and 20 use the values in the table to estimate the average values.

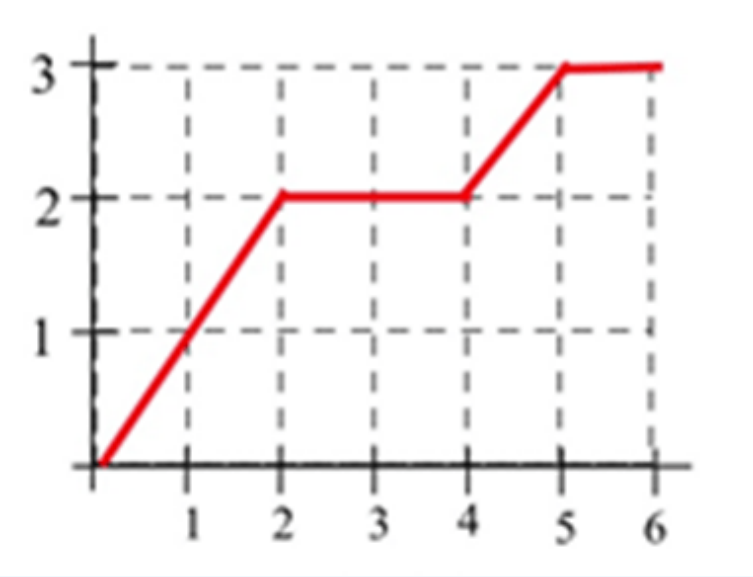
x	$f(x)$	$g(x)$
0	5	2
1	6	1
2	6	2
3	4	2
4	3	3
5	2	4
6	2	0

19. Estimate the average value of f on the interval [0, 6].

20. Estimate the average value of g on the interval [0, 6].

Exercise $5.E.21 - 5.E.26$

In problems 21 – 26, find the **average value** of f on the given interval.



21. $f(x)$ from the graph for $0 \leq x \leq 2$.

22. $f(x)$ from the graph for $0 \leq x \leq 4$.

23. $f(x)$ from the graph for $1 \leq x \leq 6$.

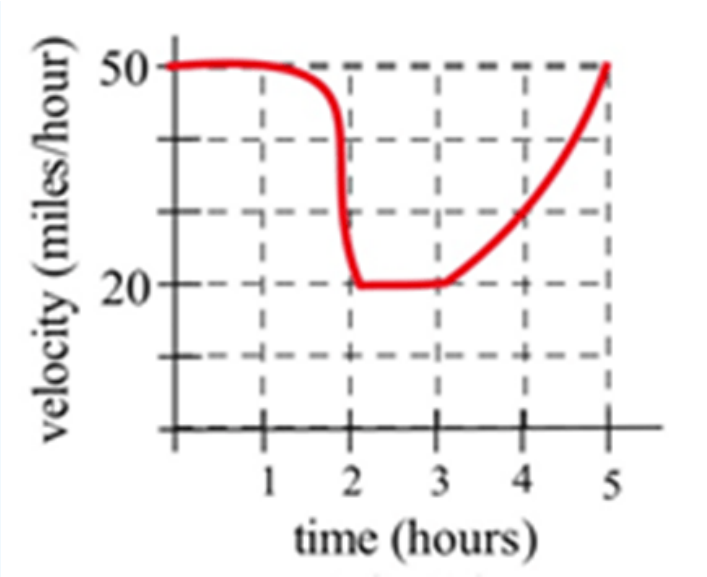
24. $f(x)$ from the graph for $4 \leq x \leq 6$.

25. $f(x) = 2x + 1$ for $0 \leq x \leq 4$.

26. $f(x) = x^2$ for $0 \leq x \leq 2$.

Exercise $5.E.27$

The graph shows the velocity of a car during a 5 hour trip.

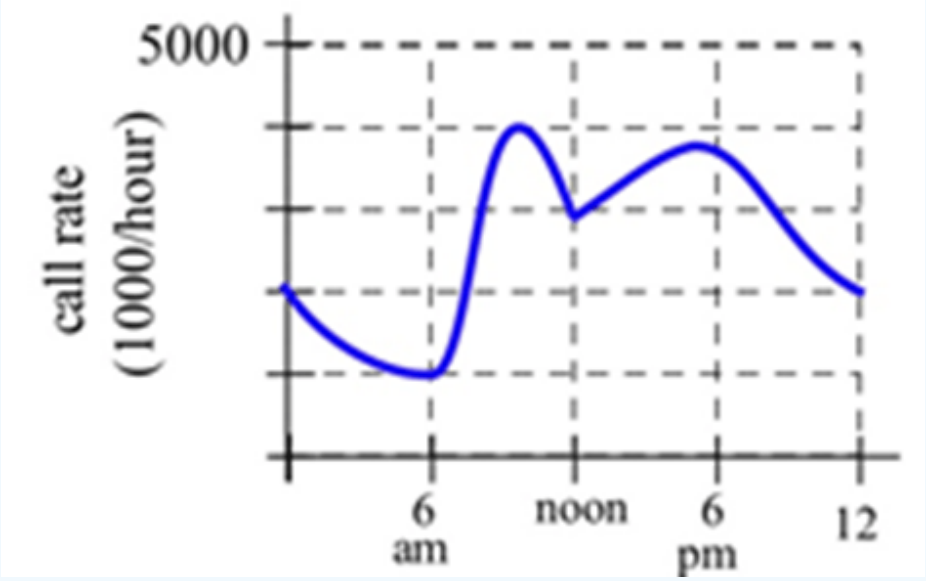


(a) Estimate how far the car traveled during the 5 hours.

(b) At what **constant** velocity should you drive in order to travel the same distance in 5 hours?

Exercise $5.E.28$

The graph shows the number of telephone calls per minute at a large company.



Estimate the average number of calls per minute

(a) From 8 am to 5 pm.

(b) From 9 am to 1 pm.

3.8 Exercises

Exercise $5.E.1$

The demand and supply functions for a certain product are given by $p = 150 - .5q$ and $p = .002q^2 + 1.5$, where p is in dollars and q is the number of items.

(a) Which is the demand function?

(b) Find the equilibrium price and quantity

(c) Find the total gains from trade at the equilibrium price.

Exercise $5.E.2$

Still thinking about the product from Exercise 1, with its demand and supply functions, suppose the price is set artificially at $70 (which is above the equilibrium price).

(a) Find the quantity supplied and the quantity demanded at this price.

(b) Compute the consumer surplus at this price, using the quantity demanded.

(c) Compute the producer surplus at this price, using the quantity demanded (why?).

(d) Find the total gains from trade at this price.

(e) What do you observe?

Exercise $5.E.3$

When the price of a certain product is $40, 25 items can be sold. When the price of the same product costs $20, 185 items can be sold. On the other hand, when the price of this product is $40, 200 items will be produced. But when the price of this product is $20, only 100 items will be produced. Use this information to find supply and demand functions (assume for simplicity that the functions are linear), and compute the consumer and producer surplus at the equilibrium price.

Exercise $5.E.4$

Find the present and future values of a continuous income stream of $5000 per year for 12 years if money can earn 1.3% annual interest compounded continuously.

Exercise $5.E.5$

Find the present value of a continuous income stream of $40,000 per year for 35 years if money can earn

(a) 0.8% annual interest, compounded continuously,

(b) 2.5% annual interest, compounded continuously,

(c) 4.5% annual interest, compounded continuously.

Exercise $5.E.6$

Find the present value of a continuous income stream $F(t) = 20 + t$, where t is in years and F is in tens of thousands of dollars per year, for 10 years, if money can earn 2% annual interest, compounded continuously.

Exercise $5.E.7$

Find the present value of a continuous income stream $F(t) = 12 + 0.3t^t$, where t is in years and F is in thousands of dollars per year, for 8 years, if money can earn 3.7% annual interest, compounded continuously.

Exercise $5.E.8$

Find the future value of a continuous income stream $F(t) = 8500 + \sqrt{640t + 100}$, where t is in years and F is in dollars per year, for 15 years, if money can earn 6% annual interest, compounded continuously.

Exercise $5.E.9$

A business is expected to generate income at a continuous rate of \$25,000 per year for the next eight years. Money can earn 3.4% annual interest, compounded continuously. The business is for sale for \$153,000. Is this a good deal?

3.9 Exercises

Exercise $5.E.1 - 5.E.4$

In problems 1 – 4, check that the function y is a solution of the given differential equation.

1. $y' + 3y = 6$. $y = e^{-3x} + 2$.	2. $y' - 2y = 8$. $y = e^{2x} - 4$.
3. $y' = -x/y$. $y = \sqrt{7 - x^2}$.	4. $y' = x - y$. $y = x - 1 + 2e^{-x}$.

Exercise $5.E.5 - 5.E.8$

In problems 5 – 8 check that the function y is a solution of the given initial value problem.

5. $y' = 6x^2 - 3$ and $y(1) = 2$. $y = 2x^3 - 3x + 3$.

6. $y' = 6x + 4$ and $y(2) = 3$. $y = 3x^2 + 4x - 17$.

7. $y' = 5y$ and $y(0) = 7$. $y = 7e^{5x}$.

8. $y' = -2y$ and $y(0) = 3$. $y = 3e^{-2x}$.

Exercise $5.E.9 - 5.E.12$

In problems 9 – 12, a family of solutions of a differential equation is given. Find the value of the constant C so the solution satisfies the initial value condition.

9. $y' = 2x$ and $y(3) = 7$. $y = x^2 + C$.	10. $y' = 3x^2 - 5$ and $y(1) = 2$. $y = x^3 - 5x + C$.

11. $y' = 3y$ and $y(0) = 5$. $y = Ce^{3x}$.	12. $y' = -2y$ and $y(0) = 3$. $y = Ce^{-2x}$.

Exercise $5.E.13 - 5.E.18$

In problems 13 – 18, solve the differential equation. (Assume that x and y are restricted so that division by zero does not occur.)

13. $y' = 2xy$	14. $y' = x/y$	15. $xy' = y + 3$
16. $y' = x^2y + 3y$	17. $y' = 4y$	18. $y' = 5(2-y)$

Exercise $5.E.19 - 5.E.22$

In problems 19 – 22, solve the initial value separable differential equations.

19. $y' = 2xy$ for $y(0) = 3$, $y(0) = 5$, and $y(1) = 2$.

20. $y' = x/y$ for $y(0) = 3$, $y(0) = 5$, and $y(1) = 2$.

21. $y' = 3y$ for $y(0) = 4$, $y(0) = 7$, and $y(1) = 3$.

22. $y' = -2y$ for $y(0) = 4$, $y(0) = 7$, and $y(1) = 3$.

Exercise $5.E.23$

The rate of growth of a population $P(t)$ which starts with 3,000 people and increases by 4% per year is $P'(t) = 0.0392 \cdot P(t)$. Solve the differential equation and use the solution to estimate the population in 20 years.

Exercise $5.E.24$

The rate of growth of a population $P(t)$ which starts with 5,000 people and increases by 3% per year is $P'(t) = 0.0296 \cdot P(t)$. Solve the differential equation and use the solution to estimate the population in 20 years.

Exercise $5.E.25$

A manufacturer estimates that she can sell a maximum of 130 thousand cell phones in a city. By advertising heavily, her total sales grow at a rate proportional to the distance below this upper limit. If she enters a new market, and after 6 months her total sales are 59 thousand phones, find a formula for the total sales (in thousands) t months after entering the market, and use this to estimate the total sales at the end of the first year.

Exercise $5.E.26$

The temperature of a turkey in the oven will grow like limited growth. The turkey starts out at 40 degrees Fahrenheit, and is placed into a 350 degree oven. After 30 minutes, the turkey's temperature has risen to 55 degrees. How long will it take until the turkey's temperature reaches 165 degrees?

Exercise $5.E.27$

A new cell phone is introduced into the market. It is predicted that sales will grow logistically. The manufacturer estimates that they can sell a maximum of 100 thousand cell phones. After 44 thousand cell phones have been sold, sales are increasing by 4 thousand phones per month. Use this to estimate the total sales at the end of the first year.

Exercise $5.E.28$

Biologists stocked a lake with 400 fish and estimated the carrying capacity of the lake to be 8000 fish. The number of fish tripled in the first year. How long will it take the population to increase to 4000?

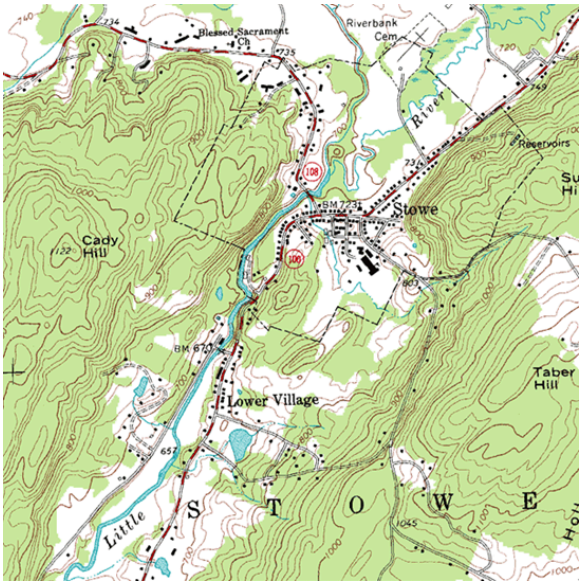
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6: FUNCTIONS OF TWO VARIABLES

Pre-Calculus Idea – Topological Maps

If you've ever hiked, you have probably seen a topographical map. Here is part of a topographic map of Stowe, Vermont.



(Figure courtesy of United States Geological Survey and http://en.Wikipedia.org/wiki/File:Topographic_map_example.png.)

Points with the same elevation are connected with curves, so you can read not only your east-west and your north-south location, but also your elevation. You may have also seen weather maps that use the same principle – points with the same temperature are connected with curves (isotherms), or points with the same atmospheric pressure are connected with curves (isobars). These maps let you read not only a places location but also its temperature or atmospheric pressure.

In this chapter, we will use that same idea to make graphs of functions of two variables.

6.1: Functions of Two Variables

6.2: Calculus of Functions of Two Variables

6.3: Optimization

6.E: Functions of Two Variables (Exercises)

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6.1: Functions of Two Variables

Introduction

Real life is rarely as simple as one input / one output. Many relationships depend on lots of variables. Examples:

- If I put a deposit into an interest-bearing account and let it sit, the amount I have at the end of 3 years depends on P (how much my initial deposit is), r (the annual interest rate), and n (the number of compoundings per year).
- The air resistance on a wing in a wind tunnel depends on the shape of the wing, the speed of the wind, the wing's orientation (pitch, yaw, and roll), plus a myriad of other things that I can't begin to describe.
- The amount of your television cable bill depends on which basic rate structure you have chosen and how many pay-per-view movies you ordered.

Since the real world is so complicated, we want to extend our calculus ideas to functions of several variables.

Functions of Two Variables

If $x_1, x_2, x_3, \ldots, x_n$ are real numbers, then $(x_1, x_2, x_3, \ldots, x_n)$ is called an n-tuple. This is an extension of ordered pairs and triples. A function of n variables is a function whose domain is some set of n-tuples and whose range is some set of real numbers.

For much of what we do here, everything will work the same whether we were working with 2, 3, or 47 variables. Because we're trying to keep things a little bit simpler, we'll concentrate on functions of two variables.

A Function of Two Variables

A function of two variables is a function, that is, to each input is associated exactly one output.

The *inputs* are ordered pairs, (x, y). The outputs are real numbers (each output is a single real number). The domain of a function is the set of all possible inputs (ordered pairs); the range is the set of all possible outputs (real numbers).

The function can be written $z = f(x, y)$.

Functions of two variables can be described numerically (a table), graphically, algebraically (a formula), or in English.

We will often now call the familiar $y = f(x)$ a function of one variable.

Example 6.1.1

The cost of renting a car depends on how many days you keep it and how far you drive. Represent this using a function.

Solution

Let d be the number of days you rent the car, and m be the number of miles you drive. Then the cost of the car rental $C(d, m)$ is a function of two variables.

Example 6.1.2

The demand for hot dog buns depends on the price for the hot dog buns and also on the price for hot dogs. Represent this as a function.

Solution

The demand $q_B = f(p_B, p_D)$ is a function of two variables. (The demand for hot dogs also depends on the price of both dogs and buns).

Formulas and Tables

Just as in the case of functions of one variable, we can display a function of two variables in a table. The two inputs are shown in the margin (top row, left column), and the outputs are shown in the interior cells.

Example 6.1.3

Here is a table that shows the cost $C(d, m)$ in dollars for renting a car for d days and driving it m miles:

d (labels in left column), m (labels in top row)	100	200	300	400
1	55	70	85	100
2	95	110	125	140
3	135	*150*	165	180

1. What is the cost of renting a car for 3 days and driving it 200 miles?
2. What is $C(100, 4)$? What is $C(4, 100)$?
3. Suppose we rent the car for three days. Is C an increasing function of miles?

Solution

1. According to the table, renting the car for three days (row with $d = 3$) and driving it 200 miles (column with $m = 200$) will cost $150 (italicized in the table).
2. Careful now – the input is an *ordered* pair, so in $C(100, 4)$, the 100 has to be a value of d and the 4 has to be a value of m. $C(100, 4)$ would be the cost of renting a car for 100 days and driving it 4 miles. That cost is not in the table. (And that would be a pretty silly way to rent a car.) On the other hand, $C(4, 100)$ is the cost of renting for 4 days and driving 100 miles – the table says that would cost $175.
3. If we know that d is fixed at 3, we're looking at $C(3, m)$. This is now a function of one variable: just m. We can see the table that displays values of this function by focusing our attention on just the row where $d = 3$:

d (label in left column), m (labels in top row)	100	200	300	400
3	135	*150*	165	180

Now we can see that if we rent for 3 days, the cost appears to be an increasing function of the number of miles we drive, which shouldn't be surprising.

The idea of fixing one variable and watching what happens to the function as the other varies will come up again and again.

It's hard to display a function of more than two variables in a table. But it's convenient to work with formulas for functions of two variables, or as many variables as you like.

Example 6.1.4

The cost $C(d, m)$ in dollars for renting a car for d days and driving it m miles is given by the formula

$$C(d, m) = 40d + 0.15m.$$

1. What is the cost of renting a car for 3 days and driving it 200 miles?

2. What is $C(100, 4)$? What is $C(4, 100)$?
3. Suppose we rent the car for 3 days. Is C an increasing function of miles?

Solution

1. $C(3, 200) = 40(3) + 0.15(200) = \$150$. This is the same value we got from the table. The formula will give us the same answers for any of the table values.
2. $C(100, 4)$ makes perfect sense to the formula (even if it doesn't make sense for actually renting a car). So now we can get an answer. To rent the car for 100 days and drive it for 4 miles should cost \$4000.60. $C(4, 100) = \$175$, as before.
3. If we fix $d = 3$, then $C(d, m)$ becomes $C(3, m) = 40(3) + 0.15m = 120 + 0.15m$. Yes, this is an increasing function of m – we can tell because it's linear and its slope is $0.15 > 0$.

Reality check – the formula that gives the cost for the rental car makes sense for all values of d and m. But that's not how the real cost works – you can't rent the car for a negative number of days or drive a negative number of miles. (That is, there are domain restrictions.) In addition, most car rental agreements don't compute a charge for fractions of days; they round up to the next whole number of days.

Example 6.1.5

Let $f(x, y, z, w) = 35x^2w - \frac{1}{z} + yz^2$. Evaluate $f(0, 1, 2, 3)$.

Solution

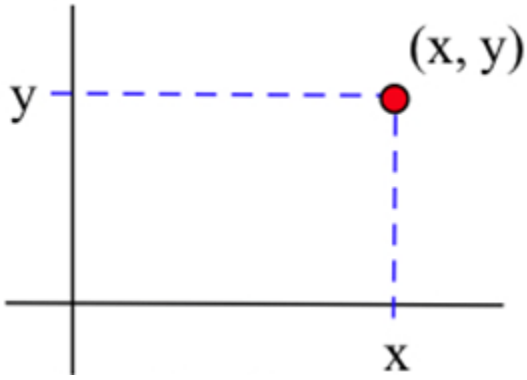
Remember that this is an ordered 4-tuple; make sure the numbers get substituted into the correct places:

$$f(0, 1, 2, 3) = 35(0)^2(3) - \frac{1}{2} + (1)(2)^2 = 3.5$$

Graphs

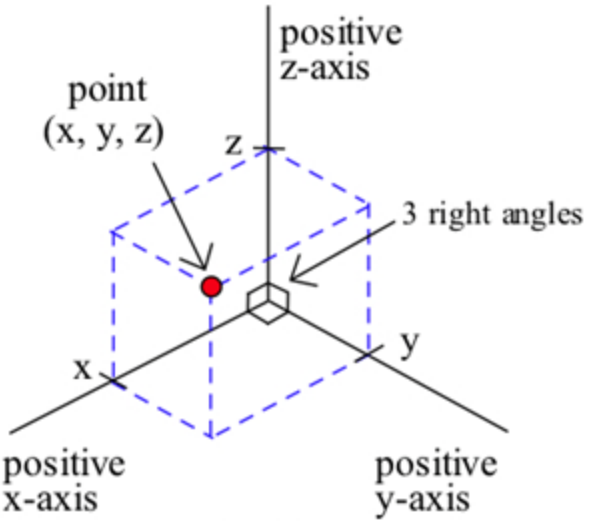
The graph of a function of two variables is a surface in three-dimensional space. Let's start by looking at the 3-dimensional rectangular coordinate system, how to locate points in three dimensions, and distance between points in three dimensions.

In the 2-dimensional rectangular coordinate system we have two coordinate axes that meet at right angles at the origin, and it takes two numbers, an ordered pair (x, y), to specify the rectangular coordinate location of a point in the plane (two dimensions).

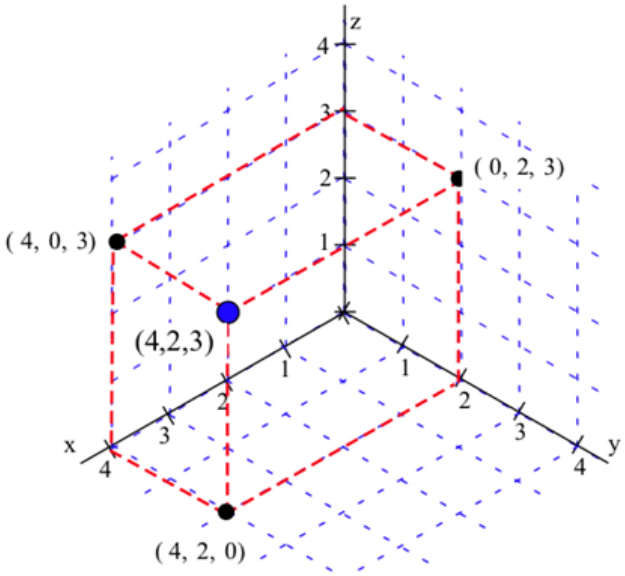


Each ordered pair (x, y) specifies the location of exactly one point, and the location of each point is given by exactly one ordered pair (x, y). The x and y values are the coordinates of the point (x, y).

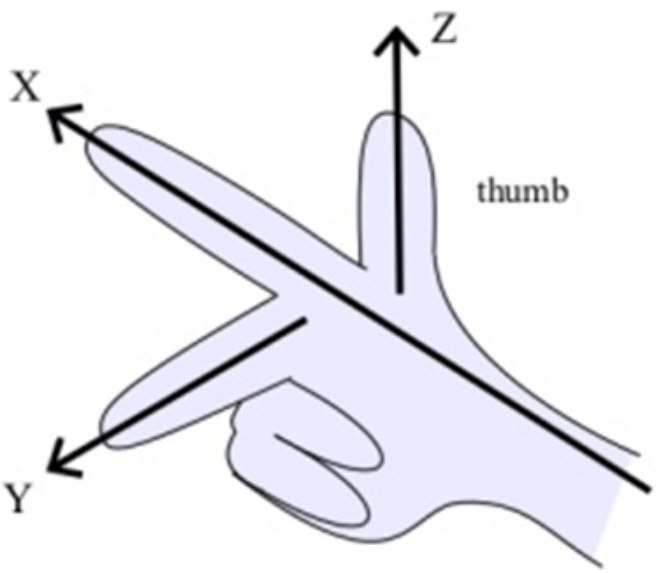
The situation in three dimensions is very similar. In the 3-dimensional rectangular coordinate system we have three coordinate axes that meet at right angles, and three numbers, an ordered triple (x, y, z), are needed to specify the location of a point.



Each ordered triple (x, y, z) specifies the location of exactly one point, and the location of each point is given by exactly one ordered triple (x, y, z). The x, y, and z values are the coordinates of the point (x, y, z). The figure below shows the location of the point (4, 2, 3).

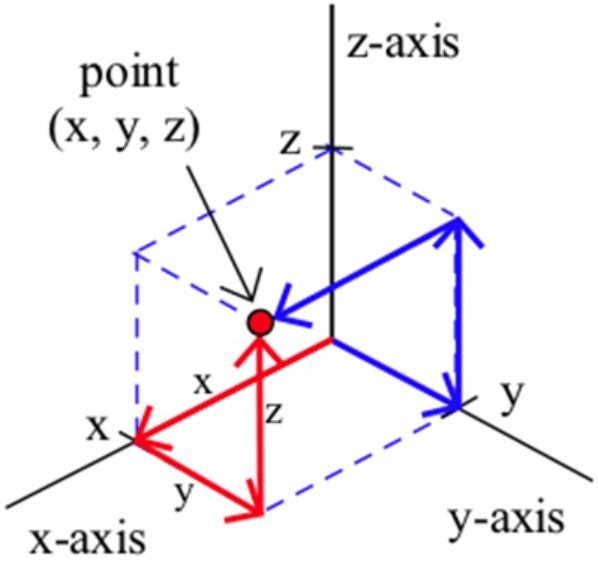


Typically we use a right-hand orientation. To see what this means, imagine your right hand in front hand in front of you with the palm toward your face, your thumb pointing up, you index finger straight out, and your next finger toward your face (and the two bottom fingers bent into the palm). Then, in the right hand coordinate system, your thumb points along the positive z-axis, your index finger along the positive x-axis, and the other finger along the positive y-axis.



Other orientations of the axes are possible and valid (with appropriate labeling), but the right-hand system is the most common orientation and is the one we will generally use. If another orientation is used, then the axes will be explicitly labeled.

Each ordered triple (x, y, z) specifies the location of a single point, and this location point can be plotted by locating the point $(x, y, 0)$ on the xy-plane and then going up z units (the red path in the figure below).



We could also get to the same (x, y, z) point in other ways. For instance, we could start by finding the point $(x, 0, z)$ on the xz-plane and then going y units parallel to the y-axis, or by finding $(0, y, z)$ on the yz-plane and then going x units parallel to the x-axis (the blue path in the figure above).

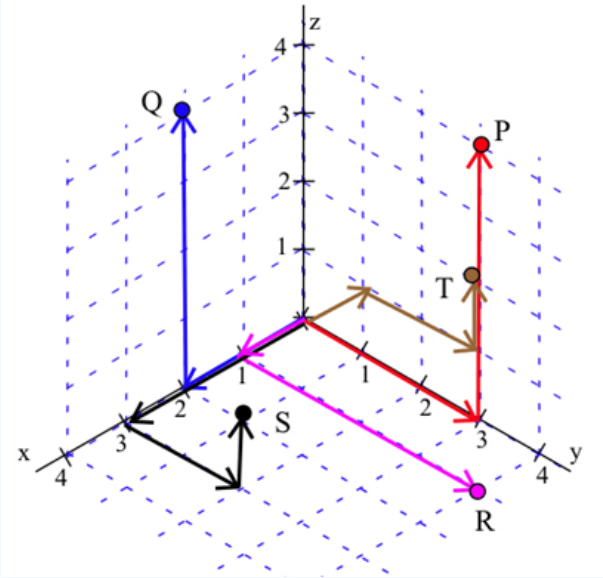
Example 6.1.6

Plot the locations of the points

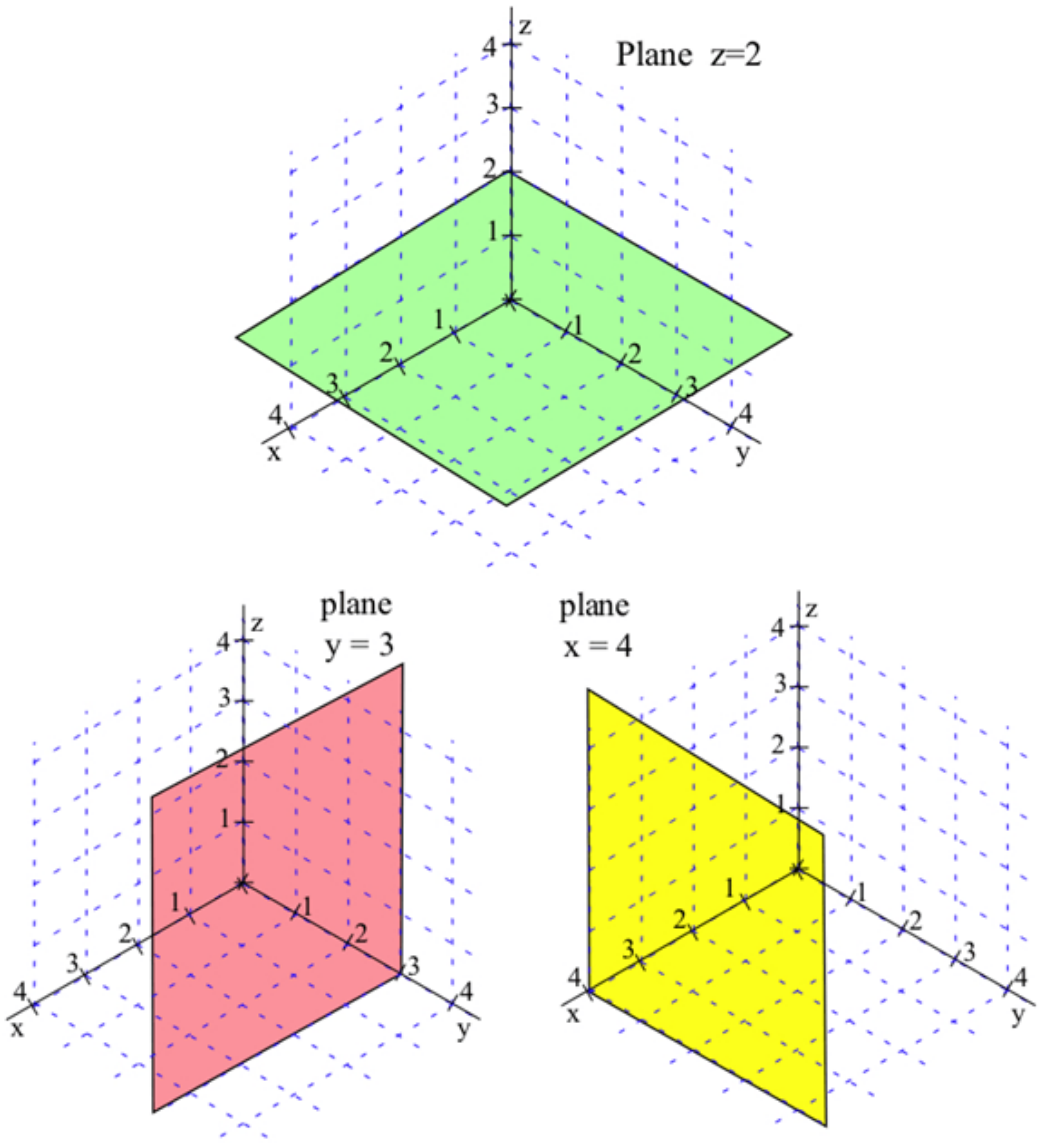
- $P = (0, 3, 4)$,
- $Q = (2, 0, 4)$,
- $R = (1, 4, 0)$,

- $S = (3, 2, 1)$, and
- $T = (-1, 3, 1)$.

The points are shown below.



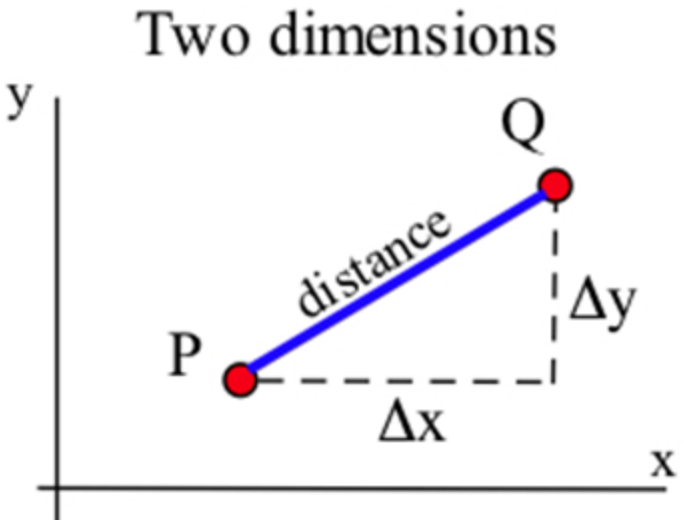
Once we can locate points, we can begin to consider the graphs of various collections of points. By the graph of "$z = 2$" we mean the collection of all points (x, y, z) which have the form "$(x, y, 2)$". Since no condition is imposed on the x and y variables, they take all possible values. The graph of $z = 2$ is a plane parallel to the xy-plane and 2 units above the xy-plane. Similarly, the graph of $y = 3$ is a plane parallel to the xz-plane, and $x = 4$ is a plane parallel to the yz-plane. (Note: The planes have been drawn as rectangles, but they actually extend infinitely far.)



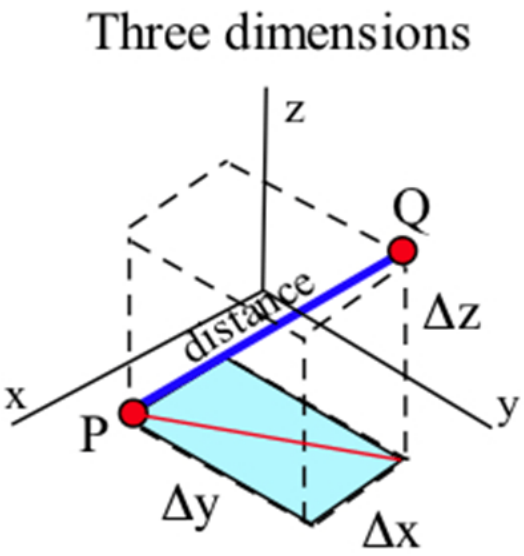
Distance Between Points

In two dimensions we can think of the distance between points as the length of the hypotenuse of a right triangle, and that leads to the Pythagorean formula:

$$\text{distance} = \sqrt{\Delta x^2 + \Delta y^2}.$$



In three dimensions we can also think of the distance between points as the length of the hypotenuse of a right triangle.



In this situation the calculations may appear more complicated, but they are straightforward and the final formula is what we hope it would be given the 2-dimensional formula:

$$\begin{aligned}\text{distance}^2 &= \text{base}^2 + \text{height}^2 \\ &= \left(\sqrt{\Delta x^2 + \Delta y^2}\right)^2 + \Delta z^2 \\ &= \Delta x^2 + \Delta y^2 + \Delta z^2\end{aligned}$$

so

$$\text{distance} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}.$$

Distance in 3-Dimensions

If $P = (x_1, y_1, z_1)$ and $Q = (x_2, y_2, z_2)$ are points in space, then the distance between P and Q is

$$\begin{aligned}\text{distance} &= \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \\ &= \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}\end{aligned}$$

The 3-dimensional pattern is very similar to the 2-dimensional pattern with the additional piece Δz^2.

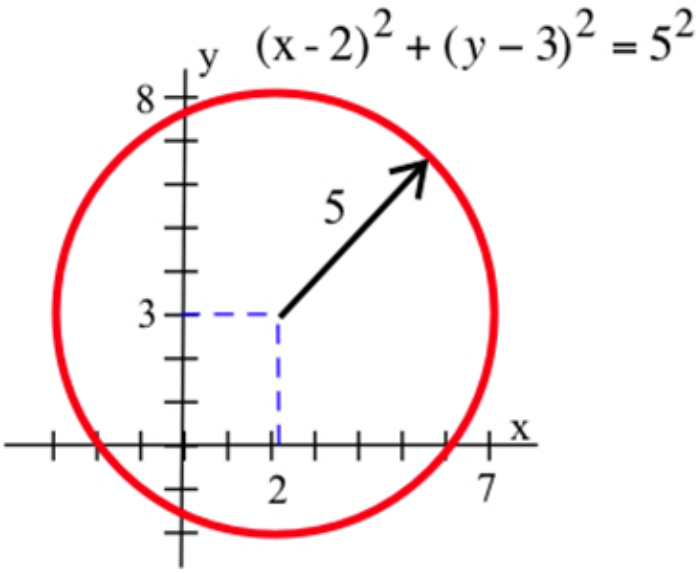
Example 6.1.7

Find the distances between points $A = (1, 2, 3)$ and $B = (7, 5, -3)$.

Solution

$$\text{Dist}(A, B) = \sqrt{6^2 + 3^2 + (-6)^2} = \sqrt{36 + 9 + 36} = \sqrt{81} = 9.$$

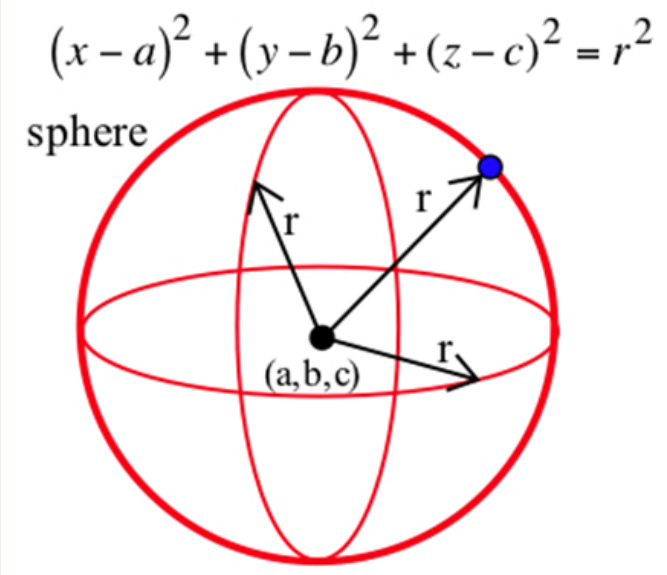
In two dimensions, the set of points at a fixed distance from a given point is a circle, and we used the distance formula to determine equations describing circles: the circle with center (2, 3) and radius 5 is given by $(x-2)^2 + (y-3)^2 = 5^2$ or $x^2 + y^2 - 4x - 6y = 12$.



The same ideas work for spheres in three dimensions.

Spheres

The set of points (x, y, z) at a fixed distance r from a point (a, b, c) is a sphere with center (a, b, c) and radius r.



The sphere is given by the equation

$$(x-a)^2+(y-b)^2+(z-c)^2=r^2.$$

Example 6.1.8

Write the equations of a sphere with center (2, -3, 4) and radius 3.

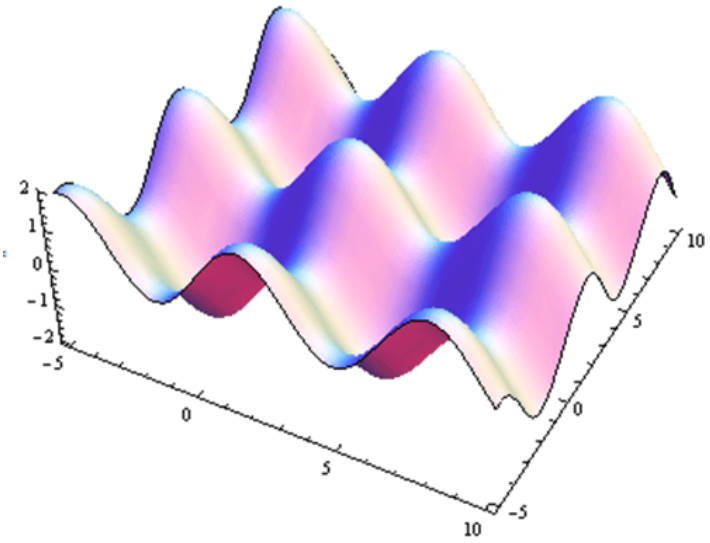
Solution

The equation is

$$(x-2)^2+(y+3)^2+(z-4)^2=3^2.$$

Now suppose that we want to graph a surface. We can think of each input (x,y) as a location on the plane, and plot the point $f(x,y)$ units above that point. Graphing that can be challenging. We have a few options:

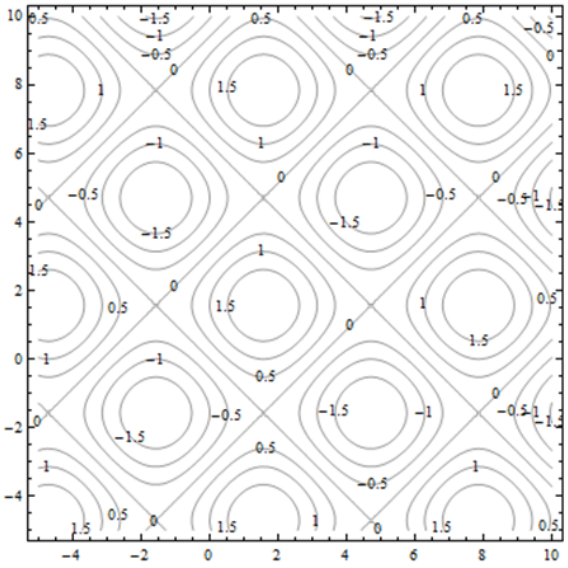
1. Use a computer program (such as GeoGebra or Mathematica) to draw beautiful perspective drawings.



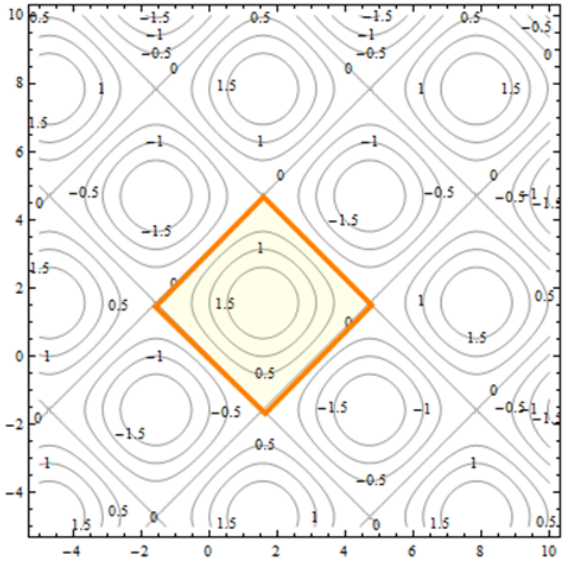
If such a program is available, then this is usually the most accurate option.

2. Try to draw a perspective drawing by hand. This is very challenging, and usually not worth the effort.
3. Use level curves to draw **contour diagrams** (or **contour maps**), which is the approach we'll focus on here. A contour diagram is like a topographical map – points with the same elevation (outputs) are connected with curves. Each particular output is called a *level*, and these curves are called *level curves* or *contours*. The closer the curves are to each other, the steeper that section of the surface. Topographical maps give hikers information about elevation, steep and shallow grades, peaks and valleys. Contour diagrams give us the same kind of information about a function.

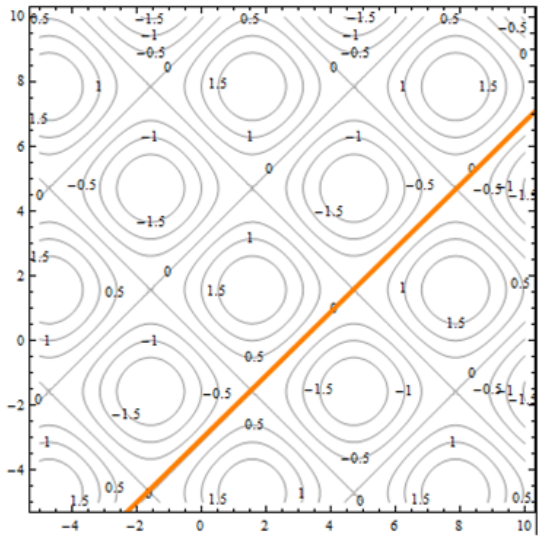
Below is a contour diagram of the same surface shown in above. The level curves are graphs in the xy-plane of curves $f(x, y) = c$ for various constants c.



Each of the squares corresponds to one of the bumps on the surface. If the contours are positive, as highlighted below, the bump is above the xy-plane. If the contours are negative, the bump extends below the xy-plane.



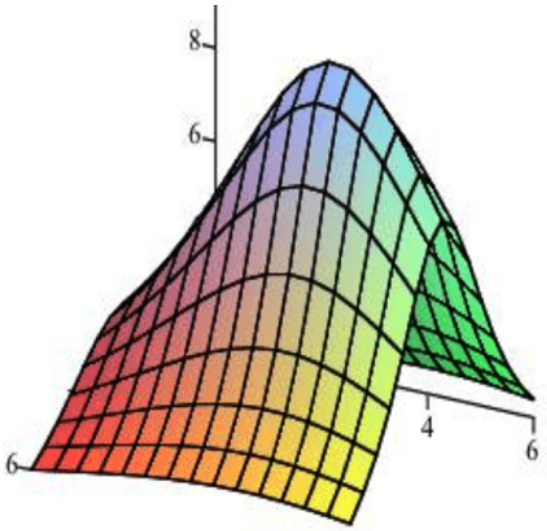
Everywhere on the crisscrossed pattern of diagonal lines, the height of the surface is 0, so the surface is on the xy-plane. This is a feature that we wouldn't necessarily have seen when we looked at the perspective drawing. Contour maps can help us see features of the surface that the 3-dimensional graph doesn't show.



To better understand contour diagrams, suppose we had a table of elevation data. We could graph this by plotting the height at each point and connecting the dots with smooth curves, which would result in the something like the graph shown.

Table: Elevations arranged in a table

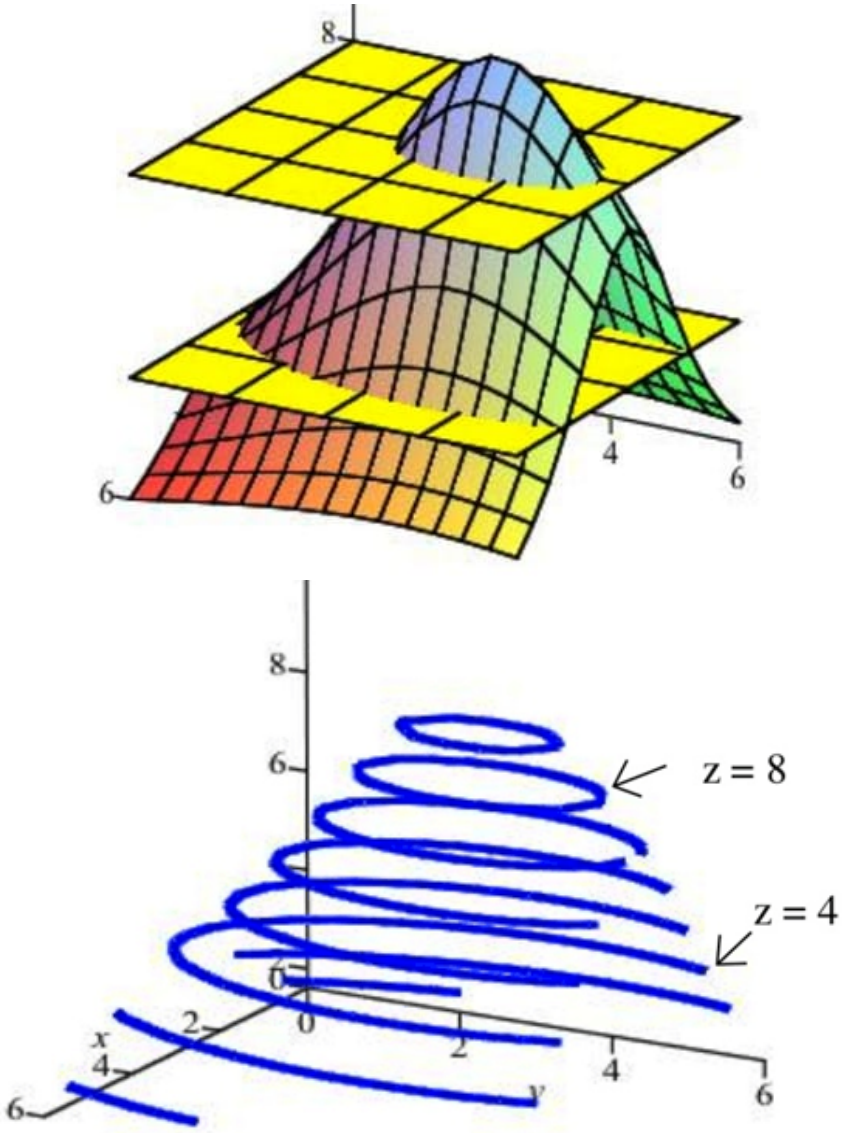
x (labels in left column), y (labels in top row)	0	1	2	3	4	5	6
0	1.6	1.8	2.0	2.1	2.2	2.1	2.0
1	2.4	2.9	3.3	3.7	5.9	3.7	3.3
2	3.3	4.3	5.6	6.7	7.1	6.7	5.6
3	3.8	5.3	7.1	9.1	9.9	9.1	7.1
4	3.3	4.3	5.6	6.7	7.1	6.7	5.6
5	2.4	2.9	3.3	3.7	5.9	3.7	3.3
6	1.6	1.8	2.0	2.1	2.2	2.1	2.0



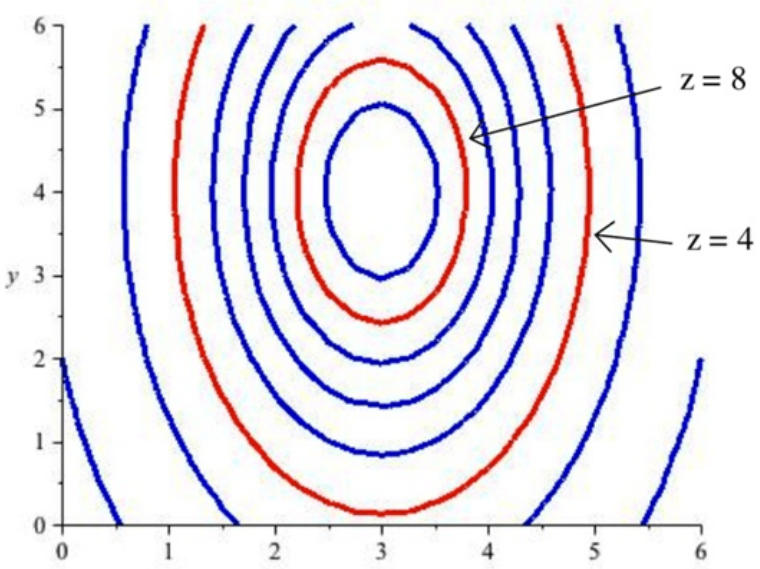
A surface from the data

If we “slice” the surface above with the plane $z = 8$, the points where the plane cuts the surface are those points where the

elevation of the surface is 8 units above the xy-plane. The figure below shows the surface being sliced by the planes $z = 8$ and $z = 4$. Slicing the surface at different elevations and sketching the curves where the plane intersects the surface results in the second graph below.



If we move all of those curves to the xy–plane (or, equivalently, view them from directly overhead), the result is a 2-dimensional graph of the level curves of the original surface. This is the contour diagram.



Example 6.1.9

Create a contour diagram for our car rental example with cost function $C(d, m) = 40d + 0.15m$. Draw curves for when the cost is $0, $100, $200, $300, and $400.

Solution

We'll set $C(d, m) = 40d + 0.15m = c$ for $c = \$0, \$100, \$200, \$300$, and $\$400$ and draw the curves in the dm-plane.

The first coordinate of the ordered pair is d, so the d-axis will be horizontal; the m-axis will be vertical. Remember that the domain for this function is really just where $d \geq 0$ and $m \geq 0$, so we will only draw the curves in the first quadrant.

When $c = 0$:

$$\begin{aligned} C(d, m) &= 40d + 0.15m = 0 \\ 0.15m &= -40d \\ m &= -\frac{40}{0.15}d \approx -267d \end{aligned}$$

This is the equation of a line, with slope about -267, passing through the origin. Because of the domain restrictions, the "curve" we will draw for this level is simply the origin. Putting this back into the car rental context, the only point where we pay $0 for renting the car is when we rent the car for 0 days and drive it 0 miles – that is, if we don't rent it at all.

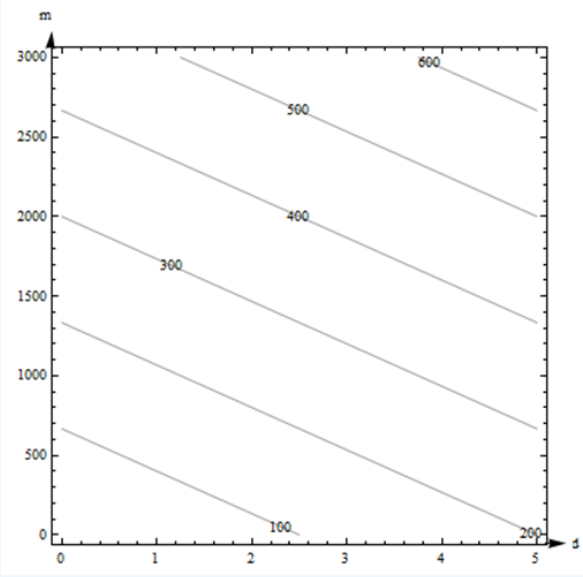
When $c = 100$:

$$\begin{aligned} C(d, m) &= 40d + 0.15m = 100 \\ 0.15m &= -40d + 100 \\ m &= -\frac{40}{0.15}d + \frac{100}{0.15} \approx -267d + 667 \end{aligned}$$

This is the equation of a line, with slope about -267, and d-intercept of about 667. This section of this line that lies in the first quadrant is shown with 100 labeling it.

Putting this into context, any point on that line represents a (d, m) combination of days and miles that will make the cost exactly $100. So, for example – if we rent the car for 0 days and drive it 667 miles, it will cost us $100. If we rent the car for 2.5 days and don't drive any miles, it will cost us $100.

We continue for $c = \$200, \$300$, and $\$400$ and sketch the curves in the plane, resulting in the contour diagram shown to the right.



Example 6.1.10

The contour diagram for the cost $C(d, m)$ in dollars for renting a car for d days and driving it m miles is shown in the previous example. Use the diagram to answer the following questions.

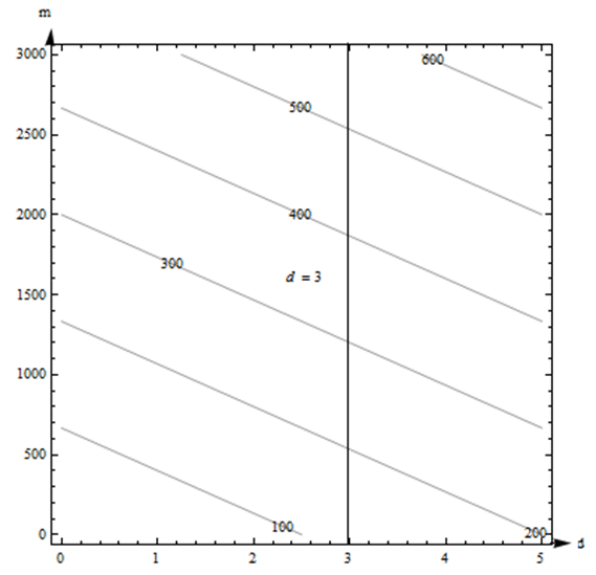
1. What is the cost of renting a car for 3 days and driving it 200 miles?
2. What is $C(100, 4)$? What is $C(4, 100)$?
3. Suppose we rent the car for 3 days. Is C an increasing function of miles?

Solution

1. The point (3, 200) is between contours on this graph, so we can't get an exact answer for $C(3, 200)$. (But it's typical for a graph that we would have to estimate). It looks to me as if (3, 200) is halfway between the 100 and the 200 contours, so let's estimate that $C(3, 200)$ is about \$150.

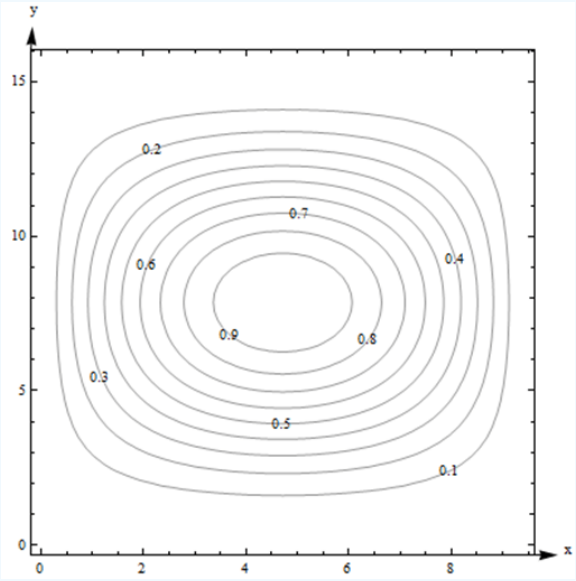
   Estimates from the graph are necessarily very rough. The graph only shows a little information (in this way, a contour diagram is like a table), so we have to extrapolate in between. But for most graphs, we don't actually know what happens between the contours. All we know for sure is that the output at (3, 200) is between the two levels we see. For this car rental example, we also know a formula, and my table showed this particular input, so we have other ways to get a better answer.

2. We can't find (100, 4) on this diagram, so we can't make an estimate of $C(100, 4)$ from this graph. (4, 100) lies between the contours for 100 and 200. It looks closer to 200, so let's estimate that $C(4, 100)$ is about \$180.
3. If we fix $d = 3$, we get a vertical line. What happens as m increases on this vertical line? As m increases, the function values shown on the contours increase, so C appears to be an increasing function of miles.



Example 6.1.11

Here is a contour diagram for a function $g(x, y)$.

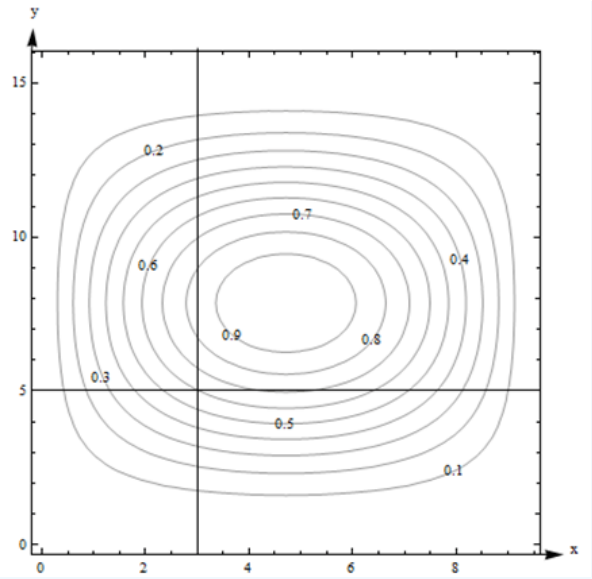


Use the diagram to answer the following questions:

1. What is $g(3, 5)$?
2. What is the highest point shown on the diagram? What is the lowest point shown?
3. If you start at (3, 5) and head in the positive x direction, do you go uphill or downhill first?

Solution

1. $g(3, 5)$ is 0.6. We can tell because the point is right on one of the contours, as illustrated in the image below.

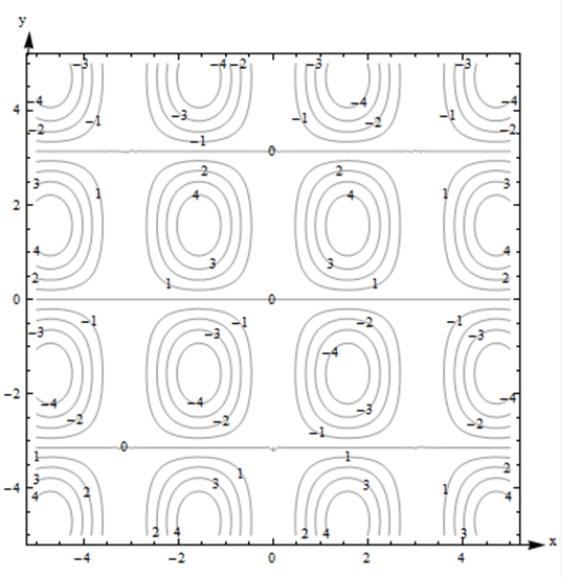


2. The highest contour shown is 0.9, and there would be a contour for 1.0 if the surface had ever got that high. However, the height seems to be increasing as we move in toward the center, so it appears that g gets to nearly 1 in the center. The lowest contour is 0.1. But again, we will guess that the height continues to decrease, so it appears that g is nearly 0 around the outside.
3. Starting at the point (3, 5, 0.6) on the surface and traveling to the right along the horizontal line shown in the previous part, we would cross the contour for 0.7 next. So the function increases first (we go uphill), and then decreases again.

Again, remember that we don't really know what happens between the contours. All we can do is estimate from the information in the graph.

Example 6.1.12

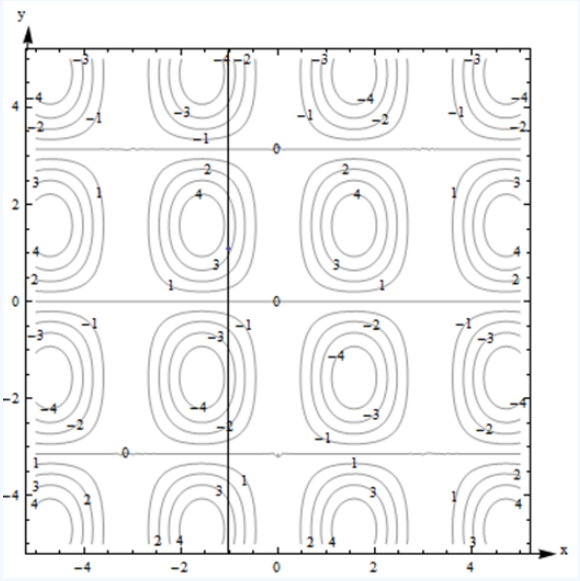
Here is a contour diagram for a function $F(x, y)$.



1. Describe the shape of the surface.
2. Suppose you travel along the surface in the positive y-direction, starting on the surface at the point above (or below) the point $(x, y) = (-1, 1)$. Describe your journey.

Solution

1. The surface is bumpy, with regularly spaced oval bumps. Notice that some of the bumps go up (positive contours), but others go down. Between the bumps, there are horizontal lines that are completely level, with an elevation of 0.
2. It looks as if $F(-1,1)$ is about 3. As we head in the positive y-direction along the line shown below, we first go uphill, nearly to 4, then we start going downhill. As we keep going north, we keep descending, going into the dip, until nearly -4. We're starting to go uphill again just as we leave the graph.



What happens if you have a function of more than two variables? Its graph will be a *hyper-surface*. For example, the graph of a function of four variables will be a hyper-surface in 5-dimensional space. This is very difficult (impossible for most of us) to visualize. Even the contours are hard to visualize – instead of curves in the plane, they're hyper-surfaces in 4-dimensional space. So if you have more than two variables, the graph isn't usually very useful.

Functions of Two Real-Life Variables

Complementary Goods and Substitute Goods

The demand for some pairs of goods have a relationship, where the quantity demanded for one product depends somehow on the prices for both

Complementary Goods

Two goods are **complementary** if an increase in the price of either decreases the demand for both.

Examples:

- The demand for cars depends on both the price for cars and the price of gasoline.
- The demand for hot dog buns depends on both the price for the buns and the price for the hot dogs.

Substitute Goods

Two goods are **substitutes** if an increase in the price of one increases the demand for the other.

Example:

- The demand for Brand A depends on its price and also on the price of its main competitor Brand B. If the Brand B raises its price, consumers will switch brands (substitute) and demand for Brand A will increase.

Think brands of soft drinks, detergent, or paper towels. A traditional example is coffee and tea: the idea is that consumers are simply looking for a hot drink and they'll buy whatever is cheaper. But this has always seemed fishy to me – I've never met any coffee- or tea-drinkers who would happily switch.

These demand functions are functions of two variables.

Example 6.1.13

The demand functions for two products are given below. p_1, p_2, q_1, and q_2 are the prices (in dollars) and quantities for Products 1 and 2:

$$q_1 = 200 - 3p_1 - p_2$$
$$q_2 = 150 - p_1 - 2p_2$$

Solution

Are these two products complementary goods or substitute goods? What is the quantity demanded for each when the price for Product 1 is $20 per item and the price for Product 2 is $30 per item?

These products are complementary: an increase in either price decreases both demands. You can see that because the coefficients are both negative in each demand function.

When $p_1 = 20$ and $p_2 = 30$, we have

$$q_1 = 200 - 3(20) - (30) = 110$$
$$q_2 = 150 - (20) - 2(30) = 70$$

So 110 units are demanded for Product 1 and 70 units are demanded for Product 2 when the price for Product 1 is $20 per item and the price for Product 2 is $30 per item.

Cobb-Douglas Production Function

Production functions are used to model the total output of a firm for a variety of inputs (doesn't this sound like a function of several variables?). One example is a Cobb-Douglas Production function:

$$P = AL^{\alpha}K^{\beta}$$

In this function P is the total production, A is a constant, α and β are constants between 0 and 1, L is the labor force, and K is the capital expenditure. (The units must be massaged well.)

You can read more about Cobb-Douglas Production functions at http://en.Wikipedia.org/wiki/Cobb-Douglas. You can read about other kinds of production functions at http://en.Wikipedia.org/wiki/Production_function.

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6.2: Calculus of Functions of Two Variables

Now that you have some familiarity with functions of two variables, it's time to start applying calculus to help us solve problems with them. In Chapter 2, we learned about the derivative for functions of two variables. Derivatives told us about the shape of the function, and let us find local max and min – we want to be able to do the same thing with a function of two variables.

First let's think. Imagine a surface, the graph of a function of two variables. Imagine that the surface is smooth and has some hills and some valleys. Concentrate on one point on your surface. What do we want the derivative to tell us? It ought to tell us how quickly the height of the surface changes as we move... Wait, which direction do we want to move? This is the reason that derivatives are more complicated for functions of several variables – there are so many (in fact, infinitely many) directions we could move from any point.

It turns out that our idea of fixing one variable and watching what happens to the function as the other changes is the key to extending the idea of derivatives to more than one variable.

Partial Derivatives

Partial Derivatives

Suppose that $z = f(x, y)$ is a function of two variables.

The **partial derivative of f with respect to x** is the derivative of the function $f(x, y)$ where we think of x as the only variable and act as if y is a constant.

The **partial derivative of f with respect to y** is the derivative of the function $f(x, y)$ where we think of y as the only variable and act as if x is a constant.

The "with respect to x" or "with respect to y" part is really important – you have to know and tell which variable you are thinking of as *THE* variable.

Geometrically

Geometrically the partial derivative with respect to x gives the slope of the curve as you travel along a cross-section, a curve on the surface parallel to the x-axis. The partial derivative with respect to y gives the slope of the cross-section parallel to the y-axis.

Notation for the Partial Derivative

The **partial derivative of $z = f(x, y)$ with respect to x** is written as

$$f_x(x, y)$$

or simply

$$f_x \quad \text{or} \quad z_x.$$

The Leibniz notation is

$$\frac{\partial f}{\partial x}$$

or

$$\frac{\partial z}{\partial x}.$$

We use an adaptation of the $\frac{\partial z}{\partial x}$ notation to mean "find the partial derivative of $f(x, y)$ with respect to x":

$$\frac{\partial}{\partial x}\left(f(x,y)\right) = \frac{\partial f}{\partial x}$$

To estimate a partial derivative from a table or contour diagram

The partial derivative with respect to x can be approximated by looking at an average rate of change, or the slope of a secant line, over a very tiny interval in the x-direction (holding y constant). The tinier the interval, the closer this is to the true partial derivative.

To compute a partial derivative from a formula

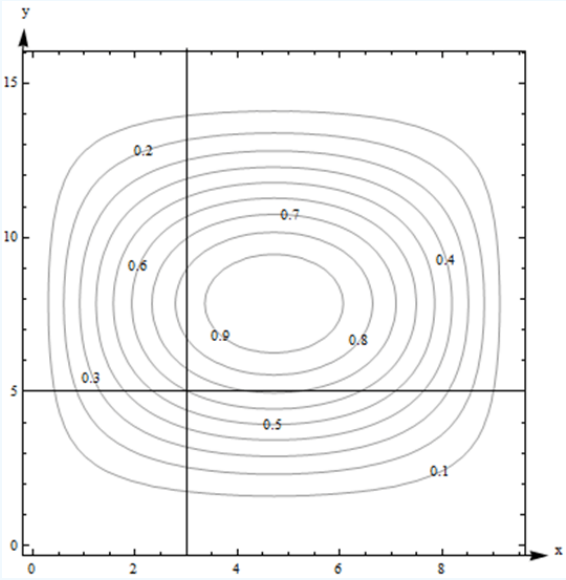
If $f(x,y)$ is given as a formula, you can find the partial derivative with respect to x algebraically by taking the ordinary derivative thinking of x as the only variable (holding y fixed).

Of course, **everything here works the same way if we're trying to find the partial derivative with respect to** y – just think of y as your only variable and act as if x is constant.

The idea of a partial derivative works perfectly well for a function of several variables: you focus on one variable to be *THE* variable and act as if all the other variables are constants.

Example 6.2.1

Here is a contour diagram for a function $g(x,y)$.



Use the diagram to answer the following questions:

1. Estimate $g_x(3,5)$ and $g_y(3,5)$.
2. Where on this diagram is g_x greatest? Where is g_y greatest?

Solution

1. $g_x(3,5)$ means we're thinking of x as the only variable, so we'll hold y fixed at $y = 5$. That means we'll be looking along the horizontal line $y = 5$. To estimate g_x, we need two function values. (3, 5) lies on the contour line, so we know that $g(3,5) = 0.6$. The next point as we move to the right is $g(4.2,5) = 0.7$.

   Now we can find the average rate of change:

$$\begin{aligned}\text{Average rate of change} &= \frac{(\text{change in output})}{(\text{change in input})}\\ &= \frac{\Delta g}{\Delta x}\\ &= \frac{0.7-0.6}{4.2-3}\\ &= \frac{1}{12} \approx 0.083\end{aligned}$$

We can do the same thing by going to the next point we can read to the left, which is $g(2.4, 5) = 0.5$. Then the average rate of change is

$$\frac{\Delta g}{\Delta x} = \frac{0.5-0.6}{2.4-3} = \frac{1}{6} \approx 0.167.$$

Either of these would be a fine estimate of $g_x(3, 5)$ given the information we have, or we could take their average. We can estimate that $g_x(3, 5) \approx 0.125$.

Estimate $g_y(3, 5)$ the same way, but moving on the vertical line. Using the next point up, we get the average rate of change is

$$\frac{\Delta g}{\Delta y} = \frac{0.7-0.6}{5.8-5} = \frac{1}{8} = 0.125.$$

Using the next point down, we get

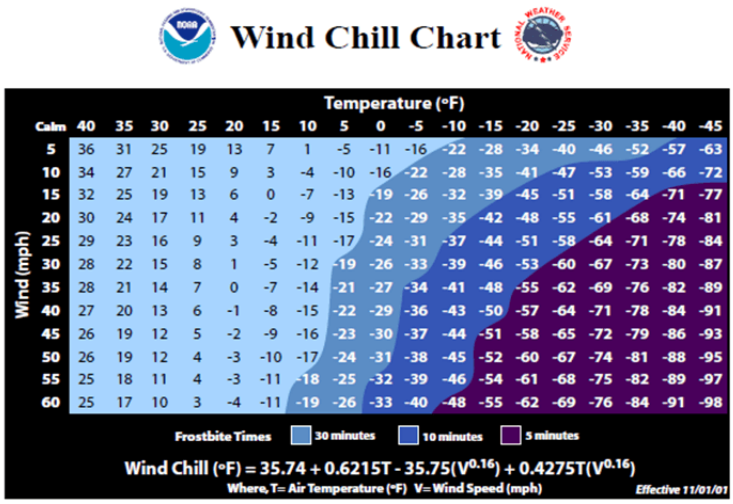
$$\frac{\Delta g}{\Delta y} = \frac{0.5-0.6}{4.5-5} = \frac{1}{5} = 0.2.$$

Taking their average, we estimate $g_y(3, 5) \approx 0.1625$.

2. g_x means x is our only variable, and we're thinking of y as a constant. So we're thinking about moving across the diagram on horizontal lines. g_x will be greatest when the contour lines are closest together, i.e., when the surface is steepest – then the denominator in $\frac{\Delta g}{\Delta x}$ will be small, so $\frac{\Delta g}{\Delta x}$ will be big. Scanning the graph, we can see that the contour lines are closest together when we head to the left or to the right from about (0.5, 8) and (9, 8). So g_x is greatest at about (0.5, 8) and (9, 8). For g_y, we want to look at vertical lines. g_y is greatest at about (5, 3.8) and (5, 12).

Example 6.2.2

Cold temperatures feel colder when the wind is blowing. Windchill is the perceived temperature, and it depends on both the actual temperature and the wind speed – a function of two variables! You can read more about windchill at www.nws.noaa.gov/om/windchill/. Below is a table that shows the perceived temperature for various temperatures and windspeeds.



(Table courtesy of the National Weather Service, www.nws.noaa.gov/om/windchill/images/windchill.gif.)

Note that they also include the formula, but for this example we'll use the information in the table.

1. What is the perceived temperature when the actual temperature is 25°F and the wind is blowing at 15 miles per hour?
2. Suppose the actual temperature is 25°F. Use information from the table to describe how the perceived temperature would change if the wind speed increased from 15 miles per hour?

Solution

1. Reading the table, we see that the perceived temperature is 13°F
2. This is a question about a partial derivative. We're holding the temperature (T) fixed at 25°F, and asking what happens as wind speed (V) increases from 15 miles per hour. We're thinking of V as the only variable, so we want $\text{WindChill}_V = W_V$ when $T = 25$ and $V = 15$. We'll find the average rate of change by looking in the column where $T = 25$ and letting V increase, and use that to approximate the partial derivative.

$$W_V \approx \frac{\Delta W}{\Delta V} = \frac{11 - 13}{20 - 15} = -0.4$$

What are the units? W is measured in °F and V is measured in mph, so the units here are °F/mph. And that lets us describe what happens: The perceived temperature would decrease by about 0.4°F for each mph increase in wind speed.

Example 6.2.3

Find f_x and f_y at the points (0, 0) and (1, 1) if $f(x, y) = x^2 - 4xy + 4y^2$.

Solution

To find f_x, take the ordinary derivative of f with respect to x, acting as if y is constant:

$$f_x(x, y) = 2x - 4y.$$

Note that the derivative of the $4y^2$ term with respect to x is zero because it's a constant (as far as x is concerned).

Similarly,

$$f_y(x, y) = -4x + 8y.$$

Now we can evaluate these at the points:

$f_x(0,0) = 0$ and $f_y(0,0) = 0$; this tells us that the cross sections parallel to the x- and y- axes are both flat at (0,0).

$f_x(1,1) = -2$ and $f_y(1,1) = 4$; this tells us that above the point (1, 1), the surface decreases if we move to more positive x values and increases if we move to more positive y values.

Example 6.2.4

Find $\frac{\partial f}{\partial x}$ and $\frac{\partial f}{\partial y}$ if $f(x,y) = \frac{e^{x+y}}{y^3+y} + y\ln(y)$.

Solution

$\frac{\partial f}{\partial x}$ means x is our only variable, we're thinking of y as a constant. Then we'll just find the ordinary derivative. From x's point of view, this is an exponential function, divided by a constant, with a constant added. The constant pulls out in front, the derivative of the exponential function is the same thing, and we need to use the chain rule, so we multiply by the derivative of that exponent (which is just 1):

$$\frac{\partial f}{\partial x} = \frac{1}{y^3+y}e^{x+y}.$$

$\frac{\partial f}{\partial y}$ means that we're thinking of y as the variable, acting as if x is constant. From y's point of view, f is a quotient plus a product, so we'll need the quotient rule and the product rule:

$$\begin{aligned}\frac{\partial f}{\partial y} &= \frac{(\,)(\,) - (\,)(\,)}{(\,)^2} + (\,)(\,) + (\,)(\,) \\ &= \frac{\left(e^{x+y}(1)\right)\left(y^3+y\right) - \left(e^{x+y}\right)\left(3y^2+1\right)}{\left(y^3+y\right)^2} + (1)\left(\ln(y)\right) + (y)\left(\frac{1}{y}\right)\end{aligned}$$

Example 6.2.5

Find f_z if $f(x,y,z,w) = 35x^2w - \frac{1}{z} + yz^2$.

Solution

f_z means we act as if z is our only variable, so we'll act as if all the other variables (x, y, and w) are constants and take the ordinary derivative:

$$f_z(x,y,z,w) = \frac{1}{z^2} + 2yz.$$

Using Partial Derivatives to Estimate Function Values

We can use the partial derivatives to estimate values of a function. The geometry is similar to the tangent line approximation in one variable. Recall the one-variable case: if x is close enough to a known point a, then

$$f(x) \approx f(a) + f'(a)(x-a).$$

In two variables, we do the same thing in both directions at once:

Approximating Function Values with Partial Derivatives

To approximate the value of $f(x,y)$, find some point (a,b) where

1. (x,y) and (a,b) are close, that is, x and a are close and y and b are close.
2. You know the exact values of $f(a,b)$ and both partial derivatives there.

Then

$$f(x,y) \approx f(a,b) + f_x(a,b)(x-a) + f_y(a,b)(y-b).$$

Notice that the total change in f is being approximated by adding the approximate changes coming from the x and y directions. Another way to look at the same formula:

$$\Delta f \approx f_x \Delta x + f_y \Delta y.$$

How close is close? It depends on the shape of the graph of f. In general, the closer the better.

Example 6.2.6

Use partial derivatives to estimate the value of $f(x,y) = x^2 - 4xy + 4y^2$ at (0.9, 1.1).

Solution

Note that the point (0.9, 1.1) is close to an "easy" point, (1, 1). In fact, we already worked out the partial derivatives at (1, 1): $f_x(x,y) = 2x - 4y$ so $f_x(1,1) = -2$, and $f_y(x,y) = -4x + 8y$ so $f_y(1,1) = 4$. We also know that $f(1,1) = 1$.

So,

$$f(0.9, 1.1) \approx 1 - 2(-0.1) + 4(0.1) = 1.6.$$

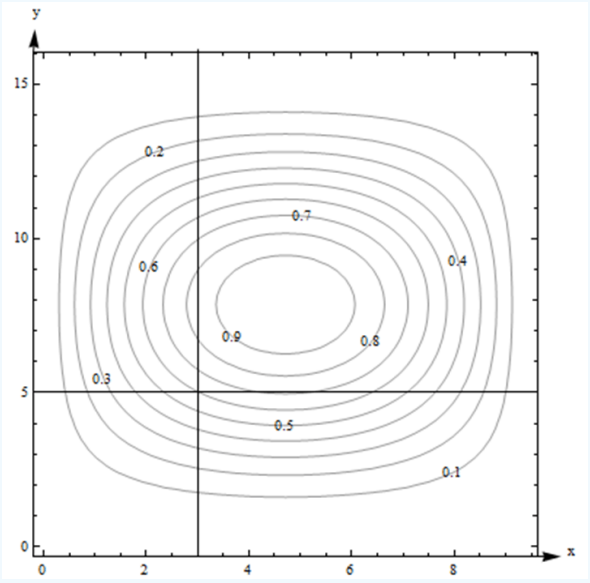
Note that in this example it would have been possible to simply compute the exact answer:

$$f(0.9, 1.1) = (0.9)^2 - 4(0.9)(1.1) + 4(1.1)^2 = 1.69.$$

Our estimate is not perfect, but it's pretty close.

Example 6.2.7

Here is a contour diagram for a function $g(x,y)$. Use partial derivatives to estimate the value of $g(3.2, 4.7)$.



Solution

This is the same diagram from before, so we already estimated the value of the function and the partial derivatives at the nearby point (3,5). $g(3,5)$ is 0.6, our estimate of $g_x(3,5) \approx 0.125$, and our estimate of $g_y(3,5) \approx 0.1625$. So

$$g(3.2, 4.7) \approx 0.6 + (0.125)(0.2) + (0.1625)(-0.3) = 0.57625.$$

Note that in this example we have no way to know how close our estimate is to the actual value.

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6.3: Optimization

The partial derivatives tell us something about where a surface has local maxima and minima. Remember that even in the one-variable cases, there were critical points which were neither maxima nor minima – this is also true for functions of many variables. In fact, as you might expect, the situation is even more complicated.

Second Derivatives

When you find a partial derivative of a function of two variables, you get another function of two variables – you can take its partial derivatives, too. We've done this before, in the one-variable setting. In the one-variable setting, the second derivative gave information about how the graph was curved. In the two-variable setting, the second partial derivatives give some information about how the surface is curved, as you travel on cross-sections – but that's not very complete information about the entire surface.

Imagine that you have a surface that's ruffled around a point, like what happens near a button on an overstuffed sofa, or a pinched piece of fabric, or the wrinkly skin near your thumb when you make a fist. Right at that point, every direction you move, something different will happen – it might increase, decrease, curve up, curve down... A simple phrase like “concave up” or “concave down” can't describe all the things that can happen on a surface.

Surprisingly enough, though, there is still a second derivative test that can help you decide if a point is a local max or min or neither, so we still do want to find second derivatives.

Second Partial Derivatives

Suppose $f(x,y)$ is a function of two variables. Then it has four **second partial derivatives**:

$$f_{xx} = \frac{\partial}{\partial x}(f_x) = (f_x)_x \qquad f_{xy} = \frac{\partial}{\partial y}(f_x) = (f_x)_y$$
$$f_{yx} = \frac{\partial}{\partial x}(f_y) = (f_y)_x \qquad f_{yy} = \frac{\partial}{\partial y}(f_y) = (f_y)_y$$

f_{xy} and f_{yx} are called the **mixed (second) partial derivatives of** f.

Leibniz notation for the second partial derivatives is a bit confusing, and we won't use it as often:

$$f_{xx} = \frac{\partial}{\partial x}\left(\frac{\partial f}{\partial x}\right) = \frac{\partial^2 f}{\partial x^2} \qquad f_{xy} = \frac{\partial}{\partial y}\left(\frac{\partial f}{\partial x}\right) = \frac{\partial^2 f}{\partial y \partial x}$$
$$f_{yx} = \frac{\partial}{\partial x}\left(\frac{\partial f}{\partial y}\right) = \frac{\partial^2 f}{\partial x \partial y} \qquad f_{yy} = \frac{\partial}{\partial y}\left(\frac{\partial f}{\partial y}\right) = \frac{\partial^2 f}{\partial y^2}$$

Notice that the order of the variables for the mixed partials goes from right to left in the Leibniz notation instead of left to right.

Example 6.3.1

Find all four partial derivatives of $f(x,y) = x^2 - 4xy + 4y^2$.

Solution

We have to start by finding the (first) partial derivatives:

$$f_x(x,y) = 2x - 4y$$
$$f_y(x,y) = -4x + 8y$$

Now we're ready to take the second partial derivatives:

$$f_{xx}(x,y) = \frac{\partial}{\partial x}(2x-4y) = 2$$
$$f_{xy}(x,y) = \frac{\partial}{\partial y}(2x-4y) = -4$$
$$f_{yx}(x,y) = \frac{\partial}{\partial x}(-4x+8y) = -4$$
$$f_{yy}(x,y) = \frac{\partial}{\partial y}(-4x+8y) = 8$$

You might have noticed that the two mixed partial derivatives were equal in this last example. It turns out that it's not a coincidence – it's a theorem!

Mixed Partial Derivative Theorem

If f, f_x, f_y, f_{xy}, and f_{yx} are all continuous (no breaks in their graphs), then

$$f_{xy} = f_{yx}.$$

In fact, as long as f and all its appropriate partial derivatives are continuous, the mixed partials are equal even if they are of higher order, and even if the function has more than two variables.

This theorem means that the confusing Leibniz notation for second derivatives is not a big problem – in almost every situation the mixed partials are equal, so the order in which we compute them doesn't matter.

Example 6.3.2

Find $\frac{\partial^2 f}{\partial x \partial y}$ for $f(x,y) = \frac{e^{x+y}}{y^3+y} + y\ln(y)$.

Solution

We already found the first partial derivatives in an earlier example:

$$\frac{\partial f}{\partial x} = \frac{1}{y^3+y}e^{x+y}$$
$$\frac{\partial f}{\partial y} = \frac{\left(e^{x+y}(1)\right)\left(y^3+y\right) - \left(e^{x+y}\right)\left(3y^2+1\right)}{\left(y^3+y\right)^2} + (1)\left(\ln(y)\right) + (y)\left(\frac{1}{y}\right)$$

Now we need to find the mixed partial derivative. The theorem says that $\frac{\partial f^2}{\partial x \partial y} = \frac{\partial f^2}{\partial y \partial x}$, so it doesn't matter whether we find the partial derivative of $\frac{\partial f}{\partial x}$ with respect to y or the partial derivative of $\frac{\partial f}{\partial y}$ with respect to x. Which would you rather do?

It looks like it will be easier to compute the mixed partial by finding the partial derivative of $\frac{\partial f}{\partial x} = \frac{1}{y^3+y}e^{x+y}$ with respect to y – it still looks messy, but it looks less messy:

$$\frac{\partial f^2}{\partial y \partial x} = \frac{\partial}{\partial y}\left(\frac{1}{y^3+y}e^{x+y}\right) = \frac{\left(e^{x+y}\right)\left(y^3+y\right) - \left(e^{x+y}\right)\left(3y^2+1\right)}{\left(y^3+y\right)^2}$$

If we had decided to do this the other way, we'd end up in the same place. Eventually...

Local Maxima, Local Minima, and Saddle Points

Let's briefly review max-min problems in one variable.

A local max is a point on a curve that is higher than all the nearby points. A local min is lower than all the nearby points. We know that local max or min can only occur at critical points, where the derivative is zero or undefined. But we also know that not all

critical points are max or min, so we also need to test them, with the First Derivative or Second Derivative Test.

The situation with a function of two variables is much the same. Just as in the one-variable case, the first step is to find critical points, places where both the partial derivatives are either zero or undefined.

Definition: Local Maximum and Minimum

- f has a **local maximum** at (a, b) if $f(a, b) \geq f(x, y)$ for all points (x, y) near (a, b).
- f has a **local minimum** at (a, b) if $f(a, b) \leq f(x, y)$ for all points (x, y) near (a, b).

A **critical point** for a function $f(x, y)$ is a point (x, y) (or $(x, y, f(x, y))$) where both the following are true:

1. $f_x = 0$ or is undefined, **and**
2. $f_y = 0$ or is undefined.

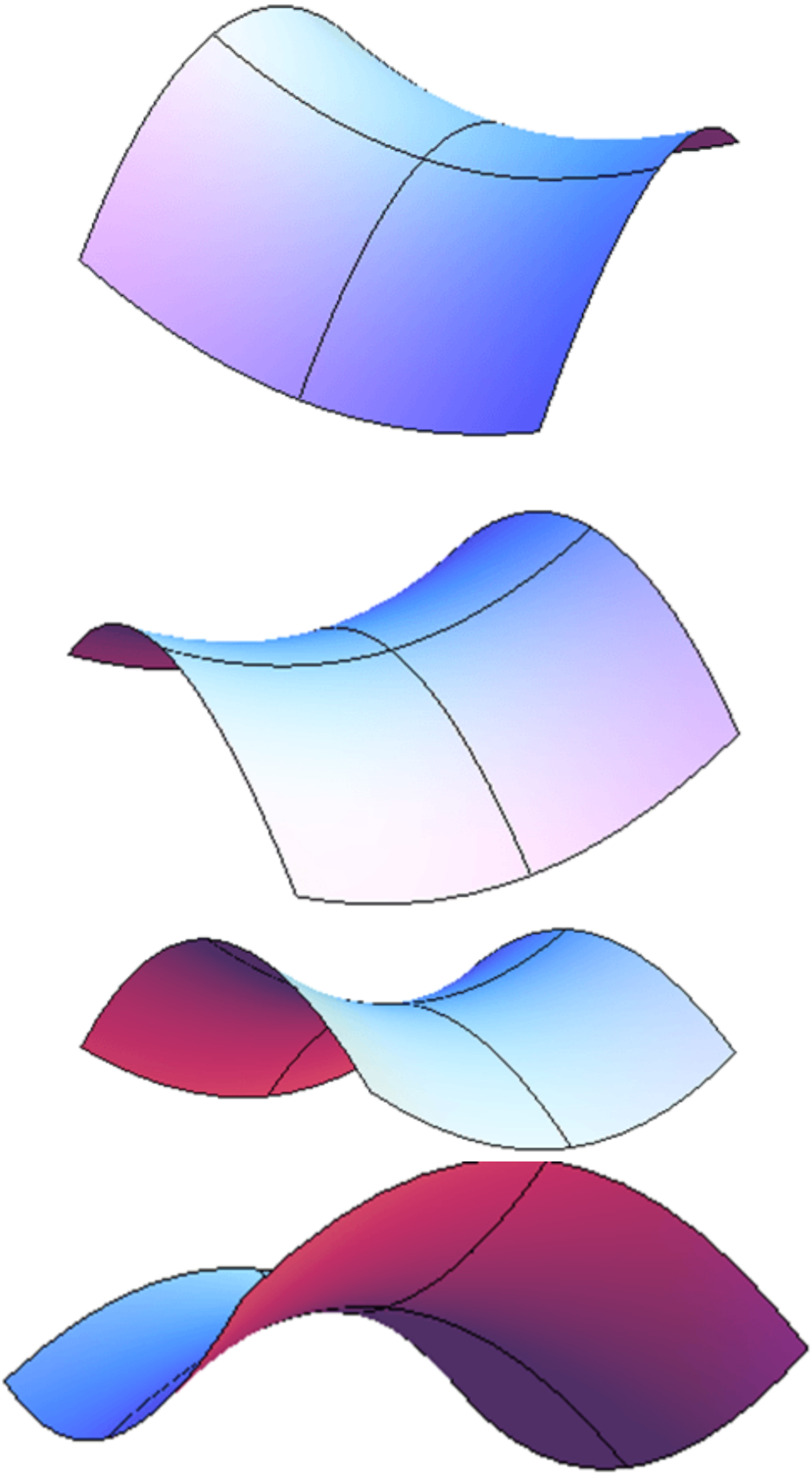
Just as in the one-variable case, a local max or min of f can only occur at a critical point.

Just as in the one-variable setting, not all critical points are local max or min. For a function of two variables, the critical point could be a local max, local min, or a saddle point.

A point on a surface is a local maximum if it's higher than all the points nearby; a point is a local minimum if it's lower than all the points nearby.

A saddle point is a point on a surface that is a minimum along some paths and a maximum along some others. It's called this because it's shaped a bit like a saddle you might use to ride a horse. You can see a saddle point by making a fist – between the knuckles of your index and middle fingers, you can see a place that is a minimum as you go across your knuckles, but a maximum as you go along your hand toward your fingers.

Here is a picture of a saddle point from a few different angles. This is the surface $f(x, y) = 5x^2 - 3y^2 + 10$, and there is a saddle point above the origin. The lines show what the surface looks like above the x- and y- axes. Notice how the point above the origin, where the lines cross, is a local minimum in one direction, but a local maximum in the other direction.



Second Derivative Test

Just as in the one-variable case, we'll need a way to test critical points to see whether they are local max or min. There is a second derivative test for functions of two variables that can help, but, just as in the one-variable case, it won't always give an answer.

The Second Derivative Test for Functions of Two Variables

1. Find all critical points of $f(x, y)$.
2. Compute
$$D(x, y) = (f_{xx})(f_{yy}) - (f_{xy})(f_{yx}),$$
and evaluate it at each critical point.
    1. If $D > 0$, then f has a local max or min at the critical point. To see which, look at the sign of f_{xx}:
        - If $f_{xx} > 0$, then f has a local minimum at the critical point.
        - If $f_{xx} < 0$, then f has a local maximum at the critical point.
    2. If $D < 0$ then f has a saddle point at the critical point.
    3. If $D = 0$, there could be a local max, local min, or neither (i.e., the test in inconclusive).

Example 6.3.3

Find all local maxima, minima, and saddle points for the function
$$f(x, y) = x^3 + y^3 + 3x^2 - 3y^2 - 8.$$

Solution

First we need the partial derivatives: $f_x = 3x^2 + 6x$ and $f_y = 3y^2 - 6y$.

Critical points are the places where both of these are zero (neither is ever undefined): $f_x = 3x^2 + 6x = 3x(x + 2) = 0$ when $x = 0$ or when $x = -2$. $f_y = 3y^2 - 6y = 3y(y - 2) = 0$ when $y = 0$ or when $y = 2$.

Putting these together, we get four critical points: (0, 0), (-2, 0), (0, 2), and (-2, 2).

Now to classify them, we'll use the Second Derivative Test. We'll need all the second partial derivatives:
$$f_{xx} = 6x + 6, \ f_{yy} = 6y - 6, \ f_{xy} = f_{yx} = 0.$$

Then
$$D(x, y) = (6x + 6)(6y - 6) - (0)(0) = (6x + 6)(6y - 6).$$

Now look at each critical point in turn:

- At (0, 0): $D(0, 0) = (6(0) + 6)(6(0) - 6) = (6)(-6) = -36 < 0$, so there is a saddle point at (0, 0).
- At (-2, 0): $D(-2, 0) = (6(-2) + 6)(6(0) - 6) = (-6)(-6) = 36 > 0$ and $f_{xx}(-2, 0) = 6(-2) + 6 = -6 < 0$, so there is a local maximum at (-2, 0).
- At (0, 2): $D(0, 2) = (6(0) + 6)(6(2) - 6) = (6)(6) = 36 > 0$ and $f_{xx}(0, 2) = 6(0) + 6 = 6 > 0$, so there is a local minimum at (0, 2).
- At (-2, 2): $D(-2, 2) = (6(-2) + 6)(6(2) - 6) = (-6)(6) = -36 < 0$, so there is another saddle point at (-2, 2).

Example 6.3.4

Find all local maxima, minima, and saddle points for the function
$$z = 9x^3 + \frac{y^3}{3} - 4xy.$$

Solution

We'll need all the partial derivatives and second partial derivatives, so let's compute them all first:

$$z_x = 27x^2 - 4y, \quad z_y = y^2 - 4x,$$
$$z_{xx} = 54x, \quad z_{xy} = z_{yx} = -4, \quad z_y = 2y.$$

Now to find the critical points: We need both z_x and z_y to be zero (neither is ever undefined), so we need to solve this set of equations simultaneously:

$$z_x = 27x^2 - 4y = 0$$
$$z_y = y^2 - 4x = 0$$

Perhaps it's been a while since you solved systems of equations. One solution method is the substitution method – solve one equation for one variable and substitute into the other equation:

$$27x^2 - 4y = 0$$
$$y^2 - 4x = 0$$

Solve $y^2 - 4x = 0$ for $x = \frac{y^2}{4}$ then substitute into the other equation:

$$27\left(\frac{y^2}{4}\right)^2 - 4y = 0$$
$$\frac{27}{16}y^4 - y = 0$$

Now we have just one equation in one variable to solve. Factoring out a y gives

$$y\left(\frac{27}{16}y^3 - 1\right) = 0,$$

so $y = 0$ or $\frac{27}{16}y^3 - 1 = 0$, giving $y = \sqrt[3]{\frac{1}{27/16}} = \frac{\sqrt[3]{4}}{3}$.

Plugging back in to the equation $x = \frac{y^2}{4}$ to find x gives us the two critical points: (0,0) and $\left(\frac{4}{9}, \frac{4}{3}\right)$.

Now to test them. First compute

$$\begin{aligned} D(x,y) &= (f_{xx})(f_{yy}) - (f_{xy})(f_{yx}) \\ &= (54x)(2y) - (-4)(-4) \\ &= 108xy - 16 \end{aligned}$$

Then evaluate D at the two critical points:

- At (0,0): $D(0,0) = -16 < 0$, so there is a saddle point at (0, 0).
- At $\left(\frac{4}{9}, \frac{\sqrt[3]{4}}{3}\right)$: $D\left(\frac{4}{9}, \frac{\sqrt[3]{4}}{3}\right) = 16(\sqrt[3]{4} - 1) > 0$, and $f_{xx}\left(\frac{4}{9}, \frac{\sqrt[3]{4}}{3}\right) > 0$, so there is a local minimum at $\left(\frac{4}{9}, \frac{\sqrt[3]{4}}{3}\right)$.

Applied Optimization

Example 6.3.5

A company makes two products. The demand equations for the two products are given below. p_1, p_2, q_1,and q_2 are the prices and quantities for Products 1 and 2.

$$q_1 = 200 - 3p_1 - p_2$$
$$q_2 = 150 - p_1 - 2p_2$$

Solution

Find the price the company should charge for each product in order to maximize total revenue. What is that maximum revenue?

Revenue is still price·quantity. If we're selling two products, the total revenue will be the sum of the revenues from the two products:

$$\begin{aligned} R(p_1, p_2) &= p_1 q_1 + p_2 q_2 \\ &= p_1(200 - 3p_1 - p_2) + p_2(150 - p_1 - 2p_2) \\ &= 200p_1 - 3p_1^2 - 2p_1 p_2 + 150p_2 - 2p_2^2 \end{aligned}$$

This is a function of two variables, the two prices, and we need to optimize it (just as in the previous examples). First we find critical points. The notation here gets a bit hard to look at, but hang in there – this is the same stuff we've done before.

$$R_{p_1} = 200 - 6p_1 - 2p_2 \quad \text{and} \quad R_{p_2} = 150 - 2p_1 - 4p_2.$$

Solving these simultaneously gives the one critical point $(p_1, p_2) = (25, 25)$

To confirm that this gives maximum revenue, we need to use the Second Derivative Test. Find all the second derivatives:

$$R_{p_1 p_2} = -6, \; R_{p_2 p_2} = -4, \quad \text{and} \quad R_{p_1 p_2} = R_{p_2 p_1} = -2.$$

So $D(25, 25) = (-6)(-4) - (-2)(-2) > 0$ and $R_{p_1 p_2}(25, 25) < 0$, so this really is a local maximum.

Thus, to maximize revenue the company should charge $25 per unit for both products. This will yield a maximum revenue of $4375.

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6.E: Functions of Two Variables (Exercises)

4.1 Exercises

Exercise $6.E.1$

$F(x,y) = x^2 - y^2$. Find

a) $F(0,4)$

b) $F(4,0)$

c) $F(x,4)$

d) $F(4,y)$

e) $F(800,800)$

f) $F(x,x)$

g) $F(x,-x)$

Exercise $6.E.2$

$g(s,t) = \sqrt{st^2}$. Find

a) $g(1,9)$

b) $g(9,1)$

c) $g(1,t)$

d) $g(s,9)$

e) $g(w,z+1)$

Exercise $6.E.3$

Let $f(x,y,z,w) = x^2 - \frac{1}{zw} + xyz^2$. Evaluate $f(1,2,3,4)$.

Exercise $6.E.4$

Let $f(x,y,z,w) = \sqrt{xy} - w^2 + 102yz$. Evaluate $f(1,2,3,4)$.

Exercise $6.E.5$

Here is a table showing the function $A(t,r)$

$\overset{t}{\downarrow}\ r\rightarrow$	.03	.04	.05	.06	.07
1	30.45	40.81	51.27	61.84	72.51
2	61.84	83.29	105.17	127.50	150.27
3	94.17	127.50	161.83	197.22	233.68

a) Find $A(2,.05)$

b) Find $A(.05,.2)$

c) Is $A(t,.06)$ an increasing or decreasing function of t?

d) Is $A(3,r)$ an increasing or decreasing function of r?

Exercise $6.E.6$

Here is a table showing values for the function $H(t,h)$.

$\overset{t}{\downarrow}\ h\rightarrow$	100	150	200
0	100	150	200
1	110.1	160.1	210.1
2	110.4	160.4	210.4
3	100.9	150.9	200.9
4	81.6	131.6	181.6
5	52.5	102.5	152.5

a) Is $H(t,150)$ an increasing or decreasing function of t?

b) Is $H(4,h)$ an increasing or decreasing function of h?

c) Fill in the blanks: The maximum value shown on this table is H(___,___) =___.

d) Fill in the blanks: The minimum value shown on this table is H(___,___) =____.

Exercise $6.E.7 - 6.E.10$

In problems 7 – 10, plot the given points.

7. $A = (0, 3, 4), B = (1, 4, 0), C = (1, 3, 4), D = (1, 4, 2)$

8. $E = (4, 3, 0), F = (3, 0, 1), G = (0, 4, 1), H = (3, 3, 1)$

9. $P = (2, 3, -4), Q = (1, -2, 3), R = (4, -1, -2), S = (-2, 1, 3)$

10. $T = (-2, 3, -4), U = (2, 0, -3), V = (-2, 0, 0), W = (-3, -1, -2)$

Exercise $6.E.11 - 6.E.14$

In problems 11 – 14, calculate the distances between the given points

11. $A = (5, 3, 4), B = (3, 4, 4)$

12. $A = (6, 2, 1), B = (3, 2, 1)$

13. $A = (3, 4, 2), B = (-1, 6, -2)$

14. $A = (-1, 5, 0), B = (1, 3, 2)$

Exercise $6.E.15 - 6.E.18$

In problems 15 – 18, graph the given planes.

15. $y = 1$ and $z = 2$	16. $x = 4$ and $y = 2$
17. $x = 1$ and $y = 0$	18. $x = 2$ and $z = 0$

Exercise $6.E.19 - 6.E.22$

In problems 19 – 22, the center and radius of a sphere are given. Find an equation for the sphere.

19. Center = (4, 3, 5), radius = 3	20. Center = (0, 3, 6), radius = 2
21. Center = (5, 1, 0), radius = 5	22. Center = (1, 2, 3), radius = 4

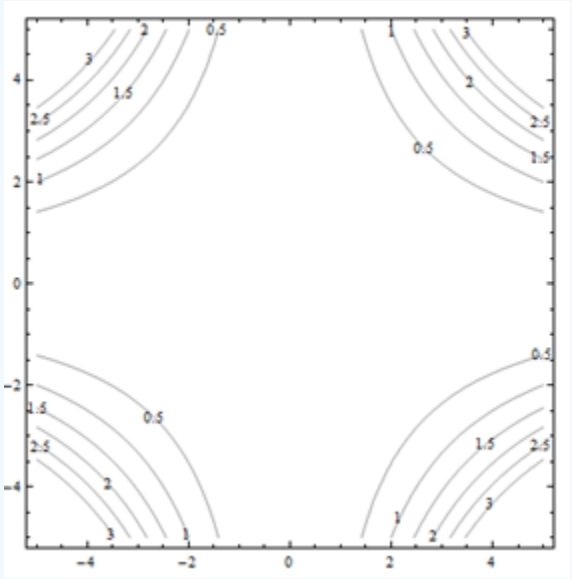
Exercise $6.E.23 - 6.E.24$

In problems 23 – 24, the equation of a sphere is given. Find the center and radius of the sphere.

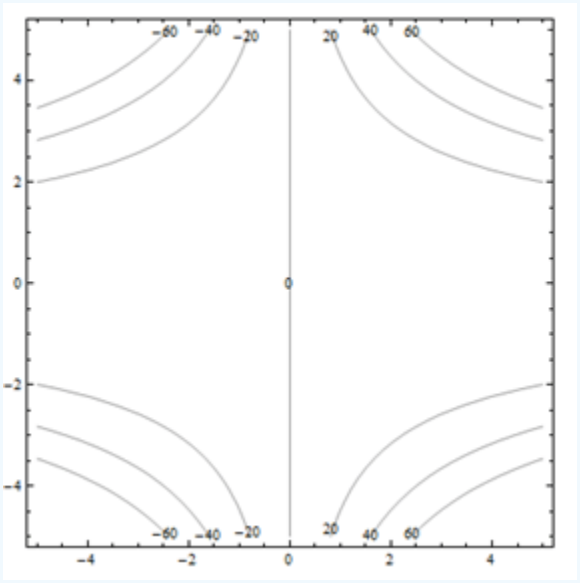
23. $(x-3)^2 + (y+4)^2 + (z-1)^2 = 16$	24. $(x+2)^2 + y^2 + (z-4)^2 = 25$

Exercise $6.E.25 - 6.E.30$

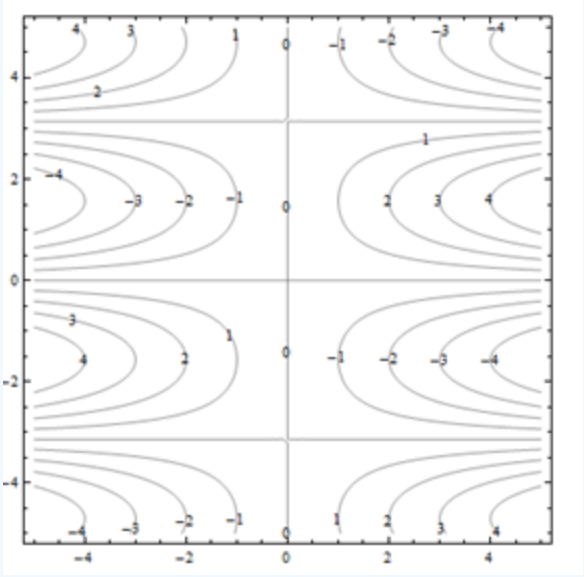
For problems 25 through 30. Match the contour diagram to the computer-generated, perspective drawing (a through f) it matches. Briefly explain your answer.



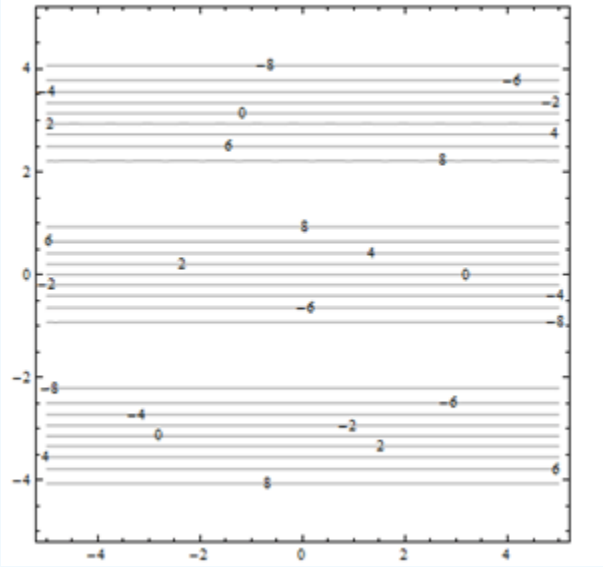
25.



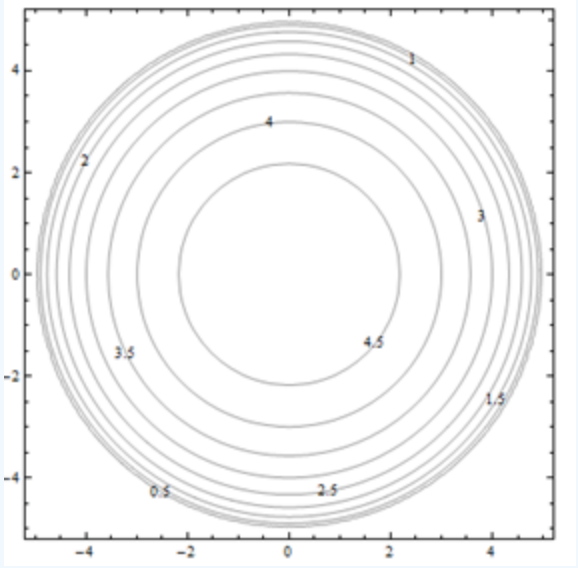
26.



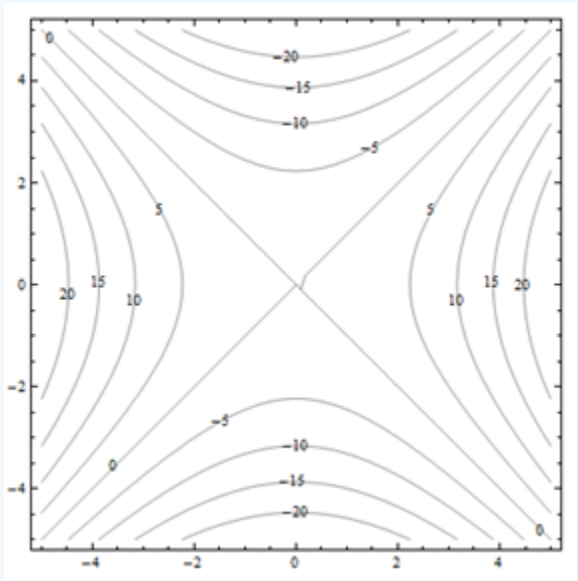
27.



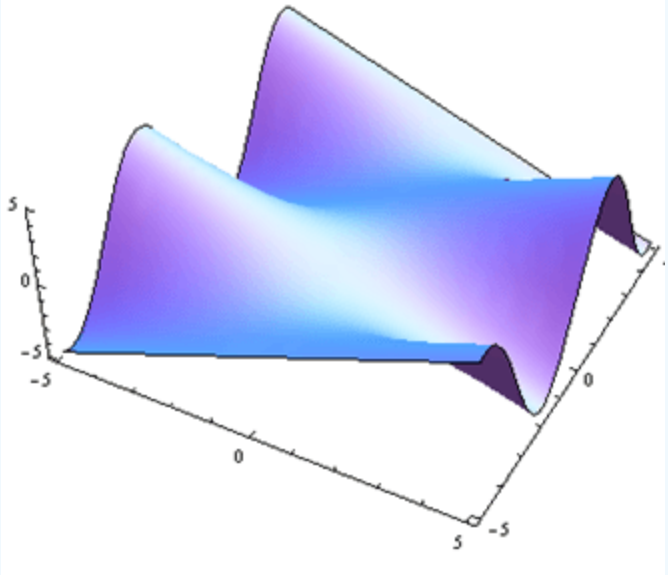
28.



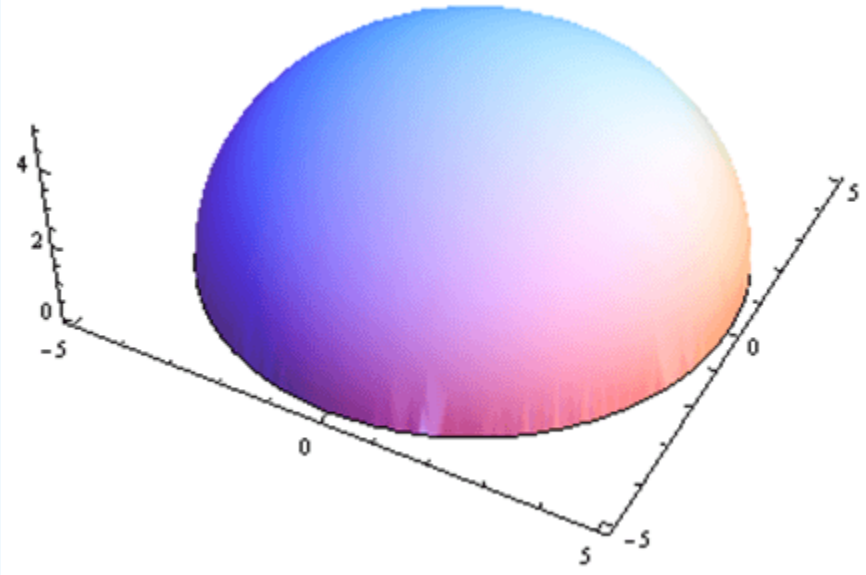
29.



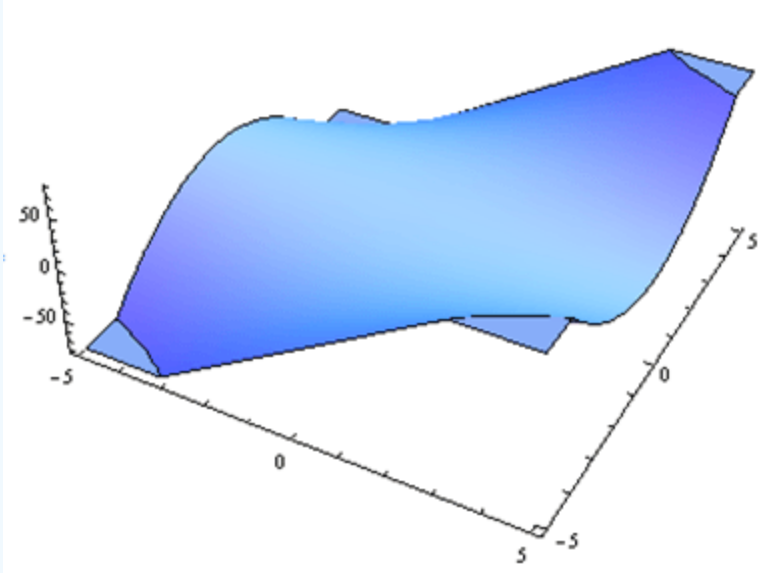
30.



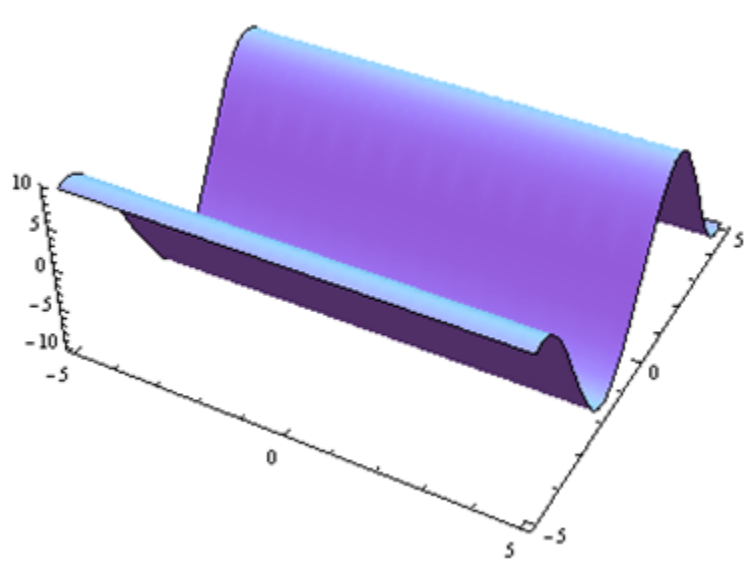
a.



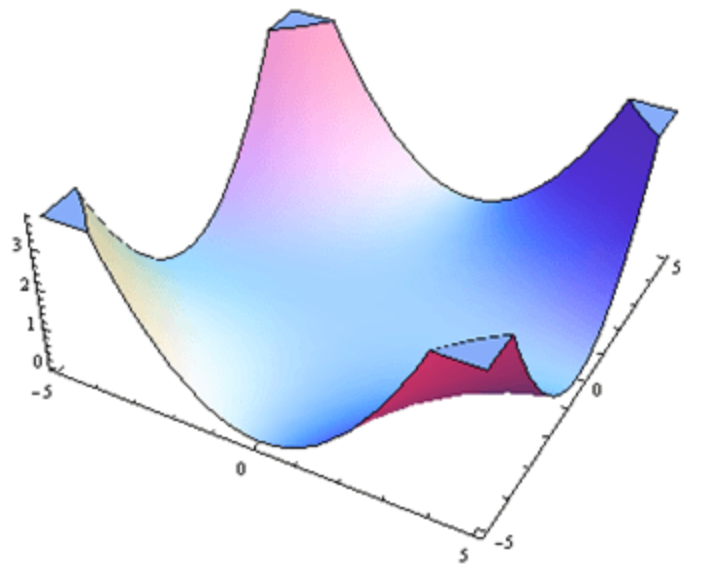
b.



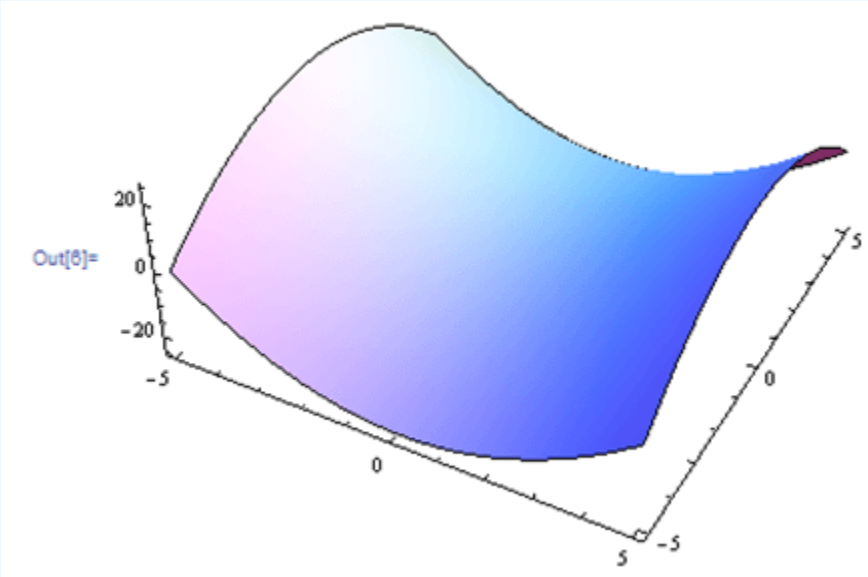
c.



d.



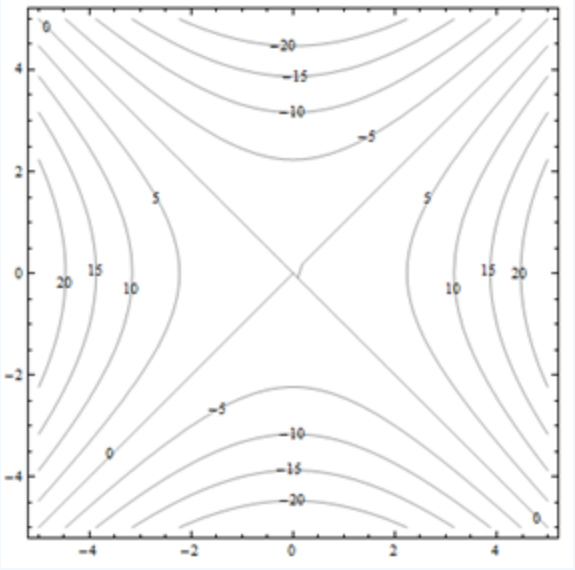
e.



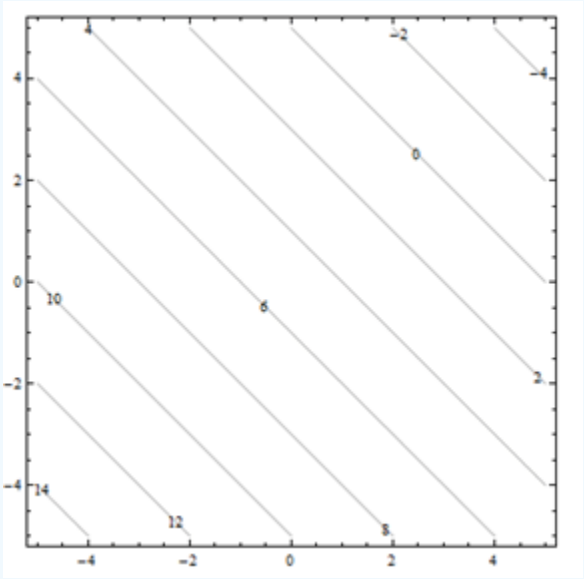
f.

Exercise $6.E.31 - 6.E.36$

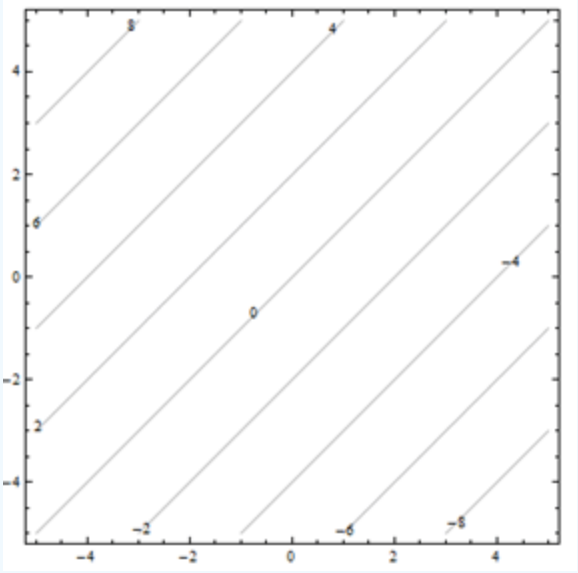
For problems 31 through 36. Match the contour diagram to the equation (a through f) it matches. Briefly explain your answer.


0
−20
−15
−10
−5
5
5
20
15
10
10
15
20
−5
0
−10
−15
−20
0
4
2
0
−2
−4
−4
−2
0
2
4

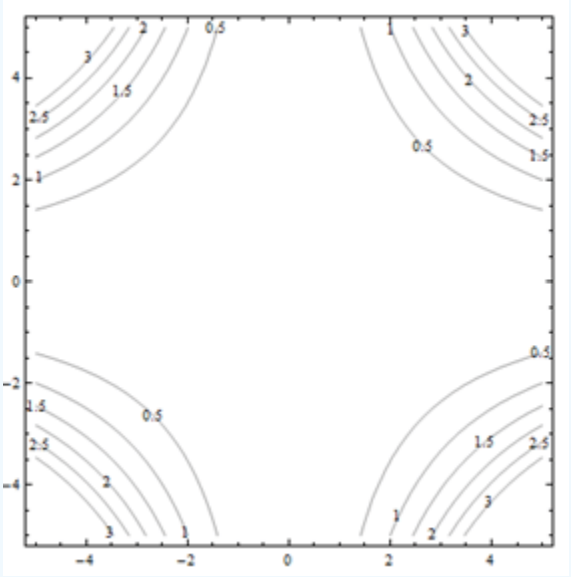
31.


4
−2
−4
0
10
6
2
14
12
8
4
2
0
−2
−4
−4
−2
0
2
4

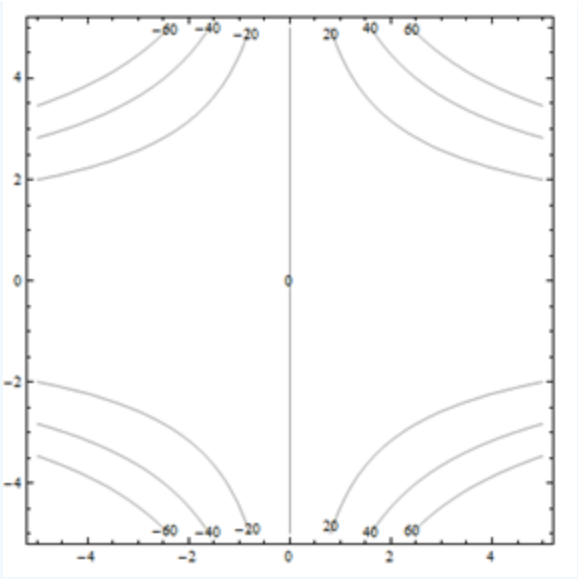
32.


8
4
6
0
2
−4
−2
−6
−8
4
2
0
−2
−4
−4
−2
0
2
4

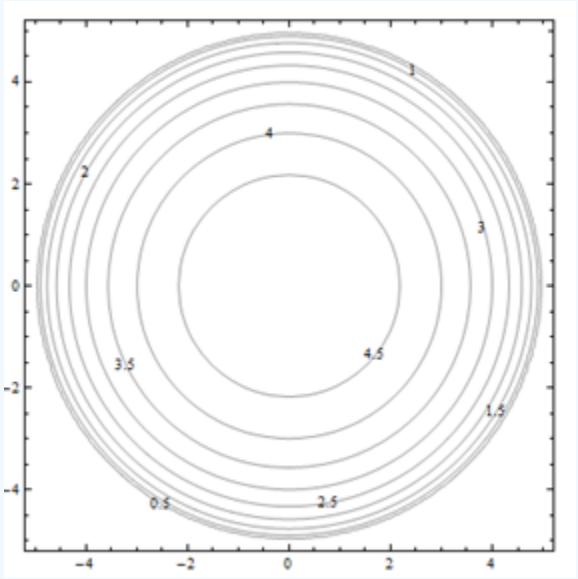
33.


0.5
1
3
2
1.5
2.5
3
2.5
1.5
0.5
1
4
2
0
−2
−4
0.5
1.5
2.5
2
3
1
1
2
3
1.5
2.5
0.5
−4
−2
0
2
4

34.



35.

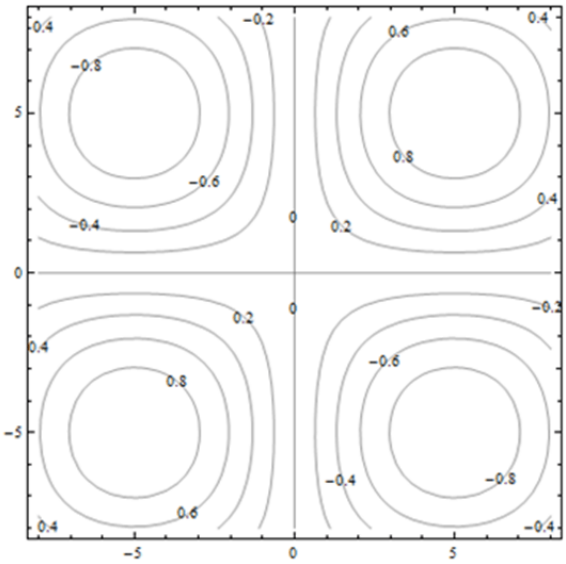


36.

a. $f(x,y) = y - x$	b. $f(x,y) = xy^2$
c. $f(x,y) = \sqrt{25 - x^2 - y^2}$	d. $f(x,y) = 5 - x - y$
e. $f(x,y) = 0.01x^2y^2$	f. $f(x,y) = x^2 - y^2$

Exercise $6.E.37$

The contour diagram shown is for a function $M(x,y)$.



Use the diagram to answer the following:

a) Estimate $M(1,3)$

b) Estimate $M(3,1)$

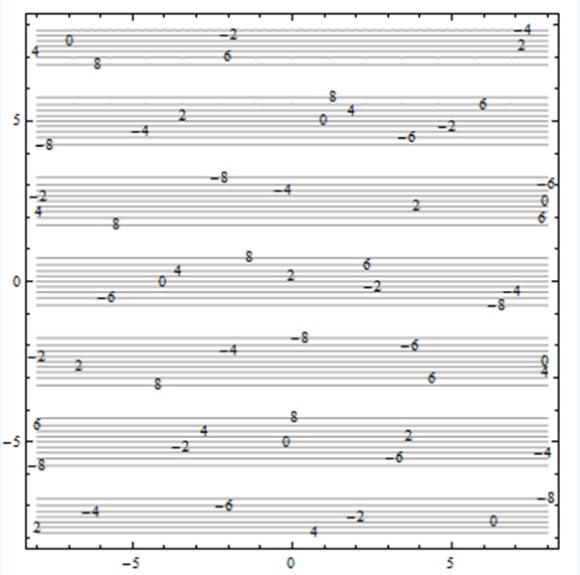
c) Is $M(x,3)$ an increasing or decreasing function of x?

d) Is $M(3,y)$ an increasing or decreasing function of y?

e) Find a value of c so that $M(c,y)$ is a constant function of y.

Exercise $6.E.38$

The contour diagram shown is for a function $G(x,y)$.



Use the diagram to answer the following:

a) Estimate $G(2,3)$

b) Suppose you travel north (in the direction of increasing y) along the surface, starting above (2, 3). Describe your journey.

c) Suppose you travel east (in the direction of increasing x) along the surface, starting above (2, 3). Describe your journey.

Exercise $6.E.39$

The demand functions for two products are given below. p_1, p_2, q_1, and q_2 are the prices (in dollars) and quantities for products 1 and 2. Are these two products complementary goods or substitute goods

$$q_1 = 200 - 3p_1 + p_2$$

$$q_2 = 150 + p_1 - 2p_2$$

Exercise $6.E.40$

The demand functions for two products are given below. p_1, p_2, q_1, and q_2 are the prices (in dollars) and quantities for products 1 and 2. Are these two products complementary goods or substitute goods

$$q_1 = 350 + p_1 + 2p_2$$

$$q_2 = 225 + p_1 + p_2$$

Exercise $6.E.41$

Consider the Cobb-Douglas Production function: $P(L,K) = 11L^{0.3}K^{0.7}$. Find the total units of production when 19 units of labor and 12 units of capital are invested.

Exercise $6.E.42$

Consider the Cobb-Douglas Production function: $P(L,K) = 6L^{0.6}K^{0.4}$. Find the total units of production when 24 units of labor and 8 units of capital are invested.

4.2 Exercises

Exercise $6.E.1 - 6.E.16$

For problems 1 through 16, find f_x and f_y for the function given

1. $f(x,y) = x^2 - 5y^2$
2. $f(x,y) = \frac{x^2-5y^2}{x+4}$
3. $f(x,y) = e^{x+6y}$
4. $f(x,y) = (x^2 - 5y^2)e^x$
5. $f(x,y) = (x^2 - 5y^2)\left(\frac{1}{3y} + 4\right)$
6. $f(x,y) = x$
7. $f(x,y) = 6$

8. $f(x,y) = \ln(xy + 2x - 6y)$
9. $f(x,y) = \frac{x^2-5y^2}{y^4-5x^4}$
10. $f(x,y) = e^{\sqrt{x-4y}}(x-4y)$
11. $f(x,y) = y^5 e^x$
12. $f(x,y) = \frac{1}{16xy}$
13. $f(x,y) = (x+e^y)^7$
14. $f(x,y) = x^4 + 4x^3y - 6x^2y^2 - 4xy^3 + y^4$
15. $f(x,y) = \sqrt{x+\sqrt{y}}$
16. $f(x,y) = x^2y^3 - 4x^3$

Exercise 6.E.17

Here is a table showing the function $A(t,r)$

$\overset{t}{\downarrow}\ r \rightarrow$	.03	.04	.05	.06	.07
1	30.45	40.81	51.27	61.84	72.51
2	61.84	83.29	105.17	127.50	150.27
3	94.17	127.50	161.83	197.22	233.68

a. Estimate $A_t(2,.05)$.

b. Estimate $A_r(2,.05)$

c. Use your answers to parts a and b to estimate the value of $A(2.5,.054)$

d. The values in the table came from $A(t,r) = 1000(e^{rt}-1)$, which shows the interest earned if 1000 dollars is deposited in an account earning r annual interest, compounded continuously, and left there for t years. How close are your estimates from parts a, b, and c?

Exercise 6.E.18

18. Here is a table showing values for the function $H(t,h)$.

$\overset{t}{\downarrow}\ h \rightarrow$	100	150	200
0	100	150	200

1	110.1	160.1	210.1
2	110.4	160.4	210.4
3	100.9	150.9	200.9
4	81.6	131.6	181.6
5	52.5	102.5	152.5

a. Estimate the value of $\frac{\partial H}{dt}$ at (3, 150).

b. Estimate the value of $\frac{\partial H}{dh}$ at (3, 150).

c. Use your answers to parts a and b to estimate the value of $H(2.6, 156)$.

d. The values in the table came from $H(t, h) = h + 15t - 4.9t^2$, which gives the height in meters above the ground after t seconds of an object that is thrown upward from an initial height of h meters with an initial velocity of 15 meters per second. How close are your estimates from parts a, b, and c?

Exercise $6.E.19$

Given the function $f(x, y) = x^2\sqrt{y}$

a. Calculate $f(2, 4)$, $f_x(2, 4)$, and $f_y(2, 4)$

b. Use your answers from part a to estimate $f(1.9, 4.1)$

Exercise $6.E.20$

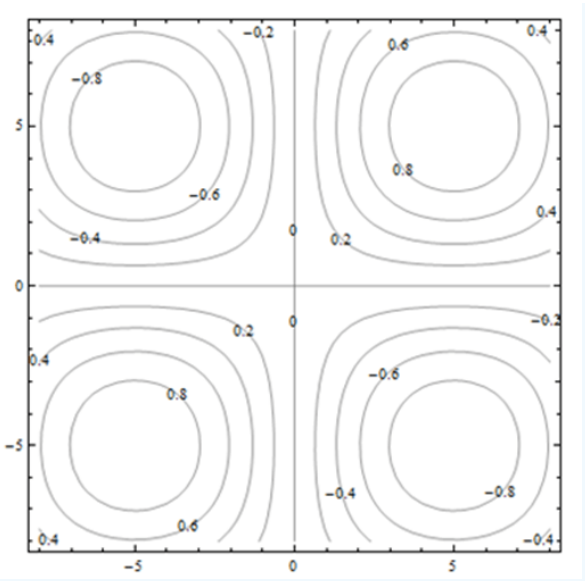
Given the function $f(x, y) = \ln(10 - x^2 - y)$

a. Calculate $f(2, 5)$, $f_x(2, 5)$, and $f_y(2, 5)$

b. Use your answers from part a to estimate $f(1.8, 4.8)$

Exercise $6.E.21 - 6.E.26$

In problems 21 - 26, use the contour plot shown to estimate the desired value.



21. $f_x(1,-5)$
22. $f_x(-5,2)$
23. $f_x(5,5)$
24. $f_x(0,0)$
25. $f_y(1,-5)$
26. $f_y(-5,2)$

4.3 Exercises

Exercise $6.E.1 - 6.E.6$

For problems 1 through 6, find f_{xx}, f_{yy}, f_{xy} and f_{yx} for the function given. Confirm that $f_{xy} = f_{yx}$.

1. $f(x,y) = x^2 - 5y^2$
2. $f(x,y) = x^4 + 4x^3y - 6x^2y^y - 4xy^3 + y^4$
3. $f(x,y) = 5x^2y^2$
4. $f(x,y) = e^{x+6y}$
5. $f(x,y) = \ln(xy + 2x - 6y)$
6. $f(x,y) = \frac{x^2}{y^4-5}$

Exercise $6.E.7$

Find the critical points of $f(x,y) = y^3 - x^3 + 15x^2 - 12y + 12$ and use the Second Derivative Test to classify them. If the test fails, say "the test fails."

Exercise $6.E.8$

Find the critical points of $f(x,y) = 2xy - x^2 - 2y^2 + 6x + 4$ and use the Second Derivative Test to classify them. If the test fails, say "the test fails."

Exercise $6.E.9$

Find the critical points of $f(x,y) = y^2 - 4\ln(x) + 4x$ and use the Second Derivative Test to classify them. If the test fails, say "the test fails."

Exercise $6.E.10$

Find the critical points of $f(x,y) = xy - 6x^2 + 3x - y + 2$ and use the Second Derivative Test to classify them. If the test fails, say "the test fails."

Exercise $6.E.11$

The origin is a critical point for the function $f(x,y) = x^3 + y^3$, and $D = 0$ there. That is, the Second Derivative Test fails. Use what you know about shapes of functions to decide if there is a local minimum, local maximum, or saddle point for this function at (0, 0).

Exercise $6.E.12$

The origin is a critical point for the function $f(x,y) = 15 - x^2y^2$, and $D = 0$ there. That is, the Second Derivative Test fails. Use what you know about shapes of functions to decide if there is a local minimum, local maximum, or saddle point for this function at (0, 0).

Exercise $6.E.13 - 6.E.18$

For problems 13 through 18, find all local maxima, minima, and saddle points for the function.

13. $f(x,y) = xy - 5x^2 - 5y^2 + 33y$
14. $f(x,y) = 10xy - x^2 - y^2 + 3x$
15. $f(x,y) = x^3 + y^3 - 3xy$
16. $f(x,y) = 5x^2 - 4xy + 2y^2 + 4x - 4y + 10$
17. $f(x,y) = y^2e^x + x^2$
18. $f(x,y) = xy + 2x - \ln(x^2y)$, for $x > 0$ and $y > 0$.

Exercise $6.E.19$

The demand functions for two products are given below. p_1, p_2, q_1, and q_2 are the prices (in dollars) and quantities for products 1 and 2.

$$q_1 = 200 + 3p_1 + p_2$$

$$q_2 = 150 + p_1 + 2p_2$$

a. Are these two products complementary goods or substitute goods?

b. What is the quantity demanded for each when the price for product 1 is $20 per item and the price for product 2 is $30 per item?

c. Write a function $R(p_1, p_2)$ that expresses the total revenue from these two products.

d. Find the price and quantity for each product that maximizes the total revenue.

Exercise $6.E.20$

The demand functions for two products are given below. p_1, p_2, q_1, and q_2 are the prices (in dollars) and quantities for products 1 and 2.

$$q_1 = 350 + p_1 + 2p_2$$

$$q_2 = 225 + p_1 + p_2$$

a. Are these two products complementary goods or substitute goods?

b. What is the quantity demanded for each when the price for product 1 is $20 per item and the price for product 2 is $30 per item?

c. Write a function $R(p_1, p_2)$ that expresses the total revenue from these two products.

d. Find the price and quantity for each product that maximizes the total revenue.

Exercise $6.E.21$

Suppose the demand functions for two products are $q_1 = f(p_1, p_2)$ and $q_2 = g(p_1, p_2)$, where p_1, p_2, q_1, and q_2 are the prices (in dollars) and quantities for products 1 and 2. Consider the four partial derivatives $\frac{\partial q_1}{\partial p_1}$, $\frac{\partial q_1}{\partial p_2}$, $\frac{\partial q_2}{\partial p_1}$, and $\frac{\partial q_2}{\partial p_2}$. Tell the sign of each of these partial derivatives if

a. the products are complementary goods.

b. the products are substitute goods.

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Table of Integrals

1. $\int \frac{1}{x(ax+b)}dx = \frac{1}{b}\ln\left|\frac{x}{ax+b}\right| + C$
2. $\int \frac{x}{ax+b}dx = \frac{x}{a} - \frac{b}{a^2}\ln|ax+b| + C$
3. $\int \frac{1}{(x+a)(x+b)}dx = \frac{1}{b-a}(\ln|x+a| - \ln|x+b|) + C = \frac{1}{b-a}\ln\left|\frac{x+a}{x+b}\right| + C, \quad a \neq b$
4. $\int \frac{1}{a^2-x^2}dx = \frac{1}{2a}\ln\left|\frac{x+a}{x-a}\right| + C$
5. $\int \frac{1}{\sqrt{x^2 \pm a^2}}dx = \ln\left|x + \sqrt{x^2 \pm a^2}\right| + C$
6. $\int \sqrt{x^2 \pm a^2}dx = \frac{x}{2}\sqrt{x^2 \pm a^2} + \frac{a^2}{2}\ln\left|x + \sqrt{x^2 \pm a^2}\right| + C$
7. $\int x(ax+b)^n dx = \frac{(ax+b)^{n+1}}{a}\left(\frac{ax+b}{n+2} - \frac{b}{n+1}\right) + C, \quad n \neq -1, -2$
8. $\int x^n e^{ax}dx = \frac{1}{a}x^n e^{ax} - \frac{n}{a}\int x^{n-1}e^{ax}dx + C$

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