2 Instantaneous Rate of Change: The Derivative

2.1 The Slope of a Function

Suppose that \( y \) is a function of \( x \), say \( y = f(x) \). It is often necessary to know how sensitive the value of \( y \) is to small changes in \( x \).

**EXAMPLE 2.1.1** Take, for example, \( y = \sqrt{625 - x^2} \) (the upper semicircle of radius 25 centered at the origin). When \( x = 7 \), we find that \( y = \sqrt{625 - 49} = 24 \). Suppose we want to know how much \( y \) changes when \( x \) increases a little, say to 7.1 or 7.01.

In the case of a straight line \( y = mx + A \), the slope \( m = \Delta y/\Delta x \) measures the change in \( y \) per unit change in \( x \). This can be interpreted as a measure of "sensitivity"; for example, if \( y = 100x + 5 \), a small change in \( x \) corresponds to a change one hundred times as large in \( y \), so \( y \) is quite sensitive to changes in \( x \).

Let us look at the same ratio \( \Delta y/\Delta x \) for our function \( y = \sqrt{625 - x^2} \) when \( x \) changes from 7 to 7.1. Here \( \Delta x = 7.1 - 7 = 0.1 \) is the change in \( x \), and

\[
\Delta y = f(7 + \Delta x) - f(7) = \sqrt{625 - (7 + \Delta x)^2} - 24 = -0.0294.
\]

Thus, \( \Delta y/\Delta x \approx -0.0294/0.1 = -0.294 \). This means that \( y \) changes by less than one third the change in \( x \), so apparently \( y \) is not very sensitive to changes in \( x \) at \( x = 7 \). We say "apparently" here because we don’t really know what happens between 7 and 7.1. Perhaps \( y \) changes dramatically as \( x \) runs through the values from 7 to 7.1, but at 7.1 \( y \) just happens to be close to its value at 7. This is not in fact the case for this particular function, but we don’t yet know why.

### 2.1 The slope of a function

Instead of looking at more particular values of \( \Delta x \), let’s see what happens if we do some algebra with the difference quotient using just \( \Delta x \). The slope of a chord from (7, 24) to a nearby point is given by

\[
\frac{\sqrt{625 - (7 + \Delta x)^2} - 24}{\Delta x} = \frac{\sqrt{625 - (7 + \Delta x)^2} - 24}{\Delta x} \approx \frac{\sqrt{625 - (7 + \Delta x)^2} - 24}{\Delta x}.
\]

Now, can we tell by looking at this last formula what happens when \( \Delta x \) gets very close to zero? The numerator clearly gets very close to -14 while the denominator gets very close to \( \sqrt{625 - 7^2} + 48 \). Is the fraction therefore very close to \( -14/48 = -7/24 \approx -0.295677 \)? It certainly seems reasonable, and in fact it is true: as \( \Delta x \) gets closer and closer to zero, the difference quotient does in fact get closer and closer to \(-7/24\), and so the slope of the tangent line is exactly \(-7/24\).

What about the slope of the tangent line at \( x = 12^2 \)? Well, 12 can’t be all that different from 7, we just have to redo the calculation with 12 instead of 7. This won’t be hard, but it will be a bit tedious. What if we try to do all the algebra without using a specific value for \( x \)? Let’s copy from above, replacing 7 by \( x \). We’ll have to do a bit more than that—for example, the “24” in the calculation came from \( \sqrt{625 - x^2} \), so we’ll need to fix that too.

\[
\frac{\sqrt{625 - (x + \Delta x)^2} - 24}{\Delta x} = \frac{\sqrt{625 - (x + \Delta x)^2} - 24}{\Delta x} \approx \frac{\sqrt{625 - (x + \Delta x)^2} - 24}{\Delta x}.
\]

Now what happens when \( \Delta x \) is very close to zero? Again it seems apparent that the quotient will be very close to

\[
\frac{\sqrt{625 - x^2} - x}{-2x} \approx \frac{\sqrt{625 - x^2} - x}{-2x}.
\]

Replacing \( x \) by 7 gives \(-7/24\), as before, and now we can easily do the computation for 12 or any other value of \( x \) between -25 and 25.

So now we have a simple, simple formula, \(-x/\sqrt{625 - x^2}\), that tells us the slope of the tangent line for any value of \( x \). This slope, in turn, tells us how sensitive the value of \( y \) is to changes in the value of \( x \).

What do we call such a formula? That is, a formula with one variable, so that substituting an "input" value for the variable produces a new "output" value? This is a function. Starting with one function, \( \sqrt{625 - x^2} \), we have derived, by means of some slightly nasty algebra, a new function, \(-x/\sqrt{625 - x^2}\), that gives us important information about the original function. This new function in fact is called the derivative of the original function. If the original is referred to as \( f \) or \( y \) then the derivative is often written \( f' \) or \( y' \) and pronounced "f prime" or "y prime", so in this case we might write \( f'(x) = -x/\sqrt{625 - x^2} \).

At a particular point, say \( x = 7 \), we say that \( f'(7) = -7/24 \) or "f prime of 7 is \(-7/24\) or "the derivative of \( f \) at \( x = 7 \) is \(-7/24\).

To summarize, we compute the derivative of \( f(x) \) by forming the difference quotient

\[
\frac{f(x + \Delta x) - f(x)}{\Delta x} \quad (2.1.1)
\]

which is the slope of a line, then we figure out what happens when \( \Delta x \) gets very close to zero.
We should note that in the particular case of a circle, there’s a simple way to find the derivative. Since the tangent to a circle at a point is perpendicular to the radius drawn to the point of contact, its slope is the negative reciprocal of the slope of the radius. The radius joining (0, 0) to (7, 24) has slope $-2$. Hence, the tangent line has slope $\frac{1}{2}$. In general, a radius to the point $(x, y)$ has slope $\frac{y}{x}$, so the slope of the tangent line is $-\frac{x}{y}$, before it. It is NOT always true that a tangent line is perpendicular to a line from the origin—don’t use this shortcut in any other circumstance.

As above, and as you might expect, for different values of $x$ we generally get different values of the derivative $f'(x)$. Could it be that the derivative always has the same value? This would mean that the slope of $f$, or the slope of the tangent line, is the same everywhere.

One curve that always has the same slope is a line; it seems odd to talk about the tangent line to a line, but if it makes sense at all the tangent line must be the line itself. It is not hard to see that the derivative of $f(x) = mx + b$ is $f'(x) = m$; see exercise 6.

Exercises 2.1.
1. Draw the graph of the function $y = f(x) = \frac{1}{\sqrt{x - 2}}$ between $x = 0$ and $x = 13$. Find the slope $\Delta y/\Delta x$ of the chord between the points of the curve lying over $(a) x = 12$ and $x = 13$, $(b) x = 12$ and $x = 13.1$, $(c) x = 12.1$ and $x = 12.001$, $(d) x = 12$ and $x = 12.001$. Now use the geometry of tangent lines on a circle to find $\frac{\sin(x)}{\cos(x)}$ the exact value of the derivative $f'(12)$.
2. Use geometry to find the derivative $f'(x)$ of the function $f(x) = \sqrt{x^2 - x^2}$ in the text for each of the following $x$: $(a) 20$, $(b) 24$, $(c) -7$, $(d) -15$. Draw a graph of the upper semicircle, and draw the tangent line at each of these four points.
3. Draw the graph of the function $f(x) = f(x) = \frac{f(x)}{x^2}$ between $x = 12$ and $x = 4$. Find the slope of the chord between $(a) x = 3$ and $x = 3.1$, $(b) x = 3$ and $x = 3.01$, $(c) x = 3$ and $x = 3.001$. Now use algebra to find a simple formula for the slope of the chord between $(3, f(3))$ and $(3 + \Delta x, f(3 + \Delta x))$. Determine what happens when $\Delta x$ approaches 0. In your graph of $y = \frac{f(x)}{x^2}$, draw the straight line through the point $(3, 1/3)$ whose slope is this limiting value of the difference quotient as $\Delta x$ approaches 0. That value is $f'(3)$.
4. Find an algebraic expression for the difference quotient $\frac{f(x + 2\Delta x) - f(x)}{2\Delta x}$ between $x = 2$ and $x = 1$. Simplify the expression as much as possible. Then determine what happens as $\Delta x$ approaches 0. That value is $f'(2)$.
5. Draw the graph of $y = f(x) = x^2$ between $x = 0$ and $x = 15$. Find the slope of the chord between $(a) x = 1$ and $x = 1.1$, $(b) x = 1$ and $x = 1.001$, $(c) x = 1$ and $x = 1.0001$. Then use algebra to find a simple formula for the slope of the chord between 1 and 1 + $\Delta x$. (Use the expansion $(4 + 8\Delta x) = 4^2 + 2(4)(8\Delta x) + (8\Delta x)^2$.) Determine what happens as $\Delta x$ approaches 0, and in your graph of $y = x^2$, draw the straight line through the point $(1, 1/3)$ whose slope is equal to the value you just found.
6. Find an algebraic expression for the difference quotient $\frac{f(x + 2\Delta x) - f(x)}{2\Delta x}$ between $x = 2$ and $x = 1$. Simplify the expression as much as possible. Then determine what happens as $\Delta x$ approaches 0. That value is $f'(x)$.

Chapter 2 Instantaneous Rate of Change: The Derivative

Exercises 2.2.
1. An object is traveling in a straight line so that its position (that is, distance from some fixed point) is given by this table:

<table>
<thead>
<tr>
<th>time (seconds)</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance (meters)</td>
<td>0</td>
<td>10</td>
<td>25</td>
<td>60</td>
</tr>
</tbody>
</table>

Find the average speed of the object during the following time intervals: $(0, 1)$, $(0, 2)$, $(0, 3)$, $(1, 3)$, $(2, 3)$. If you had to guess the speed at $t = 2$ just on the basis of these, what would you guess?
2. Let $y = f(t) = t^2$, where $t$ is the time in seconds and $y$ is the distance in meters that an object falls on a certain airless planet. Draw a graph of this function between $t = 0$ and $t = 3$. Make a table of the average speed of the falling object between $(a) 2$ sec and 3 sec, $(b) 2$ sec and 2.1 sec, $(c) 2$ sec and 2.001 sec, and $(d) 2$ sec and 2.0001 sec. Then use algebra to find a simple formula for the average speed between time 2 and time 2 + $\Delta t$. (If you subtract $\Delta t = 1, 0.1, 0.01, 0.001$ in this formula you should again get the answers to parts (a)-(d).) Next, in your formula for average speed (which should be in simplified form) determine what happens as $\Delta t$ approaches zero. This is the instantaneous speed. Finally, in your graph of $y = t^2$, draw the straight line through the point (2.4) whose slope is the instantaneous velocity you just computed; it should of course be the tangent line.
3. Can an object be dropped from an 80-meter high window, its height above the ground at time $t$ seconds is given by the formula $h(t) = 80 - 9.8t^2$. (Here we are neglecting air resistance; the graph of this function was shown in figure 10.1.) Find the average velocity of the falling object between $(a) 1$ sec and 1.1 sec, $(b) 1$ sec and 1.01 sec, $(c) 1$ sec and 1.001 sec. Now use algebra to find a simple formula for the average velocity of the falling object between 1 sec and 1 + $\Delta t$ sec. Determine what happens to this average velocity as $\Delta t$ approaches 0. That is the instantaneous velocity at time $t = 1$ sec (it will be negative, because the object is falling).

2.3 Limits

In the previous two sections we computed some quantities of interest (slope, velocity) by seeing that some expression “goes to” or “approaches” or “gets really close to” a particular value. In the examples we saw, this idea may have been clear enough, but it is too fuzzy to rely on in more difficult circumstances. In this section we will see how to make the idea more precise.

There is an important feature of the examples we have seen. Consider again the formula

$$-19.6x^2 - 4.9x^2$$

We wanted to know what happens to this fraction as $\Delta x$ goes to zero.” Because we were able to simplify the fraction, it was easy to see the answer, but it was not quite as simple
which is meaningless. The quantity we are really interested in does not make sense “at zero,” and this is why the answer to the original problem (finding a velocity or a slope) was not immediately obvious. In other words, we are generally going to want to figure out what a quantity “approaches” in situations where we can’t merely plug in a value. If you would like to think about a hard example (which we will analyze later) consider what happens to \( \sin(x)/x \) as \( x \) approaches zero.

**EXAMPLE 2.3.1** Does \( \sqrt{2} \) approach 1.41 as \( x \) approaches 2? In this case it is possible to compute the actual value \( \sqrt{2} \) to a high precision to answer the question. But since in general we won’t be able to do that, let’s not. We might start by computing \( \sqrt{2} + \Delta x \) for values of \( x \) close to 2 as we did in the previous sections. Here are some values: \( \sqrt{2} + 0.000001 = 1.414213566 \), \( \sqrt{2} + 0.0001 = 1.4142135663 \), \( \sqrt{2} + 0.01 = 1.41421356636 \), \( \sqrt{2} + 0.1 = 1.41421356638 \), \( \sqrt{2} + 1 = 1.41421356647 \). (That’s the “sane” I will never pick a value for \( \epsilon \).)

As is often the case in mathematical proofs, it helps to work backwards. We want to end up showing that under certain circumstances \( x \rightarrow 4 \) is close to 6; precisely, we want to show that \( |x - 4| < \epsilon \) whenever \( 0 < |x - 2| < \delta \). So the question becomes: can we choose a value for \( \delta \) that

\[
|\sqrt{2} + \Delta x - \sqrt{2}| = |\Delta x| < \epsilon
\]

Here is the actual, official definition of “limit”.

**DEFINITION 2.3.2 Limit** Suppose \( f \) is a function. We say that \( \lim_{x \to a} f(x) = L \) if for every \( \epsilon > 0 \) there is a \( \delta > 0 \) so that whenever \( 0 < |x - a| < \delta \), \( |f(x) - L| < \epsilon \).

The \( \epsilon \) and \( \delta \) here play exactly the role they did in the preceding discussion. The definition says, in a very precise way, that \( f(x) \) can be made as close as desired to \( L \) (that’s the \( |f(x) - L| < \epsilon \) part) by making \( x \) close enough to \( a \) (the \( 0 < |x - a| < \delta \) part). Note that we specifically make no mention of what must happen if \( x = a \), that is, if \( |x - a| = 0 \). This is because in the cases we are most interested in, substituting \( a \) for \( x \) doesn’t even make sense.

Make sure you are not confused by the names of important quantities. The generic definition talks about \( f(x) \), but the function and the variable might have other names. In the discussion above, the function we analyzed was

\[
\lim_{\Delta x \to 0} (\sqrt{2} + \Delta x - \sqrt{2}) = \frac{19.6 \Delta x - 1.95 \Delta x^2}{\Delta x} = -19.6 - 4.9 \Delta x.
\]

and the variable of the limit was not \( x \) but \( \Delta x \). The \( x \) was the variable of the original function, when we were trying to compute a slope or a velocity; \( x \) was essentially a fixed quantity, telling us at what point we wanted the slope. (In the velocity problem, this is literally a fixed quantity, as we focused on the time \( t \).) The quantity \( \Delta x \) of the definition in all the examples was zero: we were always interested in what happened as \( \Delta x \) became very close to zero.

Armed with a precise definition, we can now prove that certain quantities behave in a particular way. The bad news is that even proofs for simple quantities can be quite tedious and complicated; the good news is that we rarely need to do such proofs, because most expressions act the way you would expect, and this can be proved once and for all.

**EXAMPLE 2.3.3** Let’s show carefully that \( \lim_{x \to 4} x + 4 = 6 \). This is not something we “need” to prove, since it is “obviously” true. But if we couldn’t prove it using our official definition there would be something very wrong with the definition.

As is often the case in mathematical proofs, it helps to work backwards. We want to end up showing that under certain circumstances \( x \to 4 \) is close to 6; precisely, we want to show that \( |x - 4| < \epsilon \) whenever \( 0 < |x - 2| < \delta \). So the question becomes: can we choose a value for \( \delta \) that

\[
|\sqrt{2} + \Delta x - \sqrt{2}| = |\Delta x| < \epsilon
\]

Here is the actual, official definition of “limit”.

Thus, we can say with certainty that if \( \Delta x \) is positive and less than 0.000002, then \( \Delta x < 0.00000240204816327 \) and so \( -19.6 - 4.9 \Delta x > -19.600001 \). We could do a similar calculation if \( \Delta x \) is negative.

Now we have seen that we must make \( -19.6 - 4.9 \Delta x \) within one millionth of \( -19.6 \). But can we make it “as close as we want”? In this case, it is quite simple to see that the answer is yes, by modifying the calculation we’ve just done. It may be helpful to think of this as a game. I claim that we can make \( -19.6 - 4.9 \Delta x \) as close as you desire to \( -19.6 \) by making \( \Delta x \) “close enough” to \( -19.6 \). So the game is: you give me a number, like \( 10^{-5} \), and I have to come up with a number representing how close \( \Delta x \) must be to zero to guarantee that \( -19.6 - 4.9 \Delta x \) is at least as close to \( -19.6 \) as you have requested.

Now if we actually play this game, I could redo the calculation above for each new number you provide. What I’d like to do is somehow see that I will always succeed, and even more, I’d like to have a simple strategy so that I don’t have to do all that algebra every time. A strategy in this case would be a formula that gives me a correct answer no matter what you specify. So suppose the number you give me is \( \epsilon \). How close does \( \Delta x \) have to be to zero to guarantee that \(-19.6 - 4.9 \Delta x \) is in \((-19.6 - \epsilon, -19.6 + \epsilon)\)? If \( \Delta x \) is positive, we need:

\[
-19.6 - 4.9 \Delta x > -19.6 - \epsilon
\]

\[
-4.9 \Delta x > -\epsilon
\]

\[
\Delta x < -\epsilon/4.9
\]

So if I pick any number \( \delta \) that is less than \( 4/9 \), the algebra tells me that whenever \( \Delta x < \delta \) then \( -4.9 \Delta x < -\epsilon \) and so \( -19.6 - 4.9 \Delta x \) is in \((-19.6 - \epsilon, -19.6 + \epsilon)\). This is exactly what I did in the example: I picked \( \delta = 0.0000002 < 0.00000240204816327 \) . A similar calculation again works for negative \( \Delta x \). The important fact is that this is now a completely general result—it shows that I can always win, no matter what “move” you make.

Now we can condense this by giving a precise definition to replace the funny, “gets closer and closer” language we have used so far. Henceforward, we will say something like “the limit of \(-19.6 - 4.9 \Delta x\) as \( \Delta x \) goes to zero is -19.6” and abbreviate this mouthful

\[
\lim_{\Delta x \to 0} (-19.6 - 4.9 \Delta x) = -19.6
\]

as \( \lim_{x \to 0} f(x) = L \).

\[
|\sqrt{2} + \Delta x - \sqrt{2}| = |\Delta x| < \epsilon
\]

\[
19.6 \Delta x - 1.95 \Delta x^2 < 0.00000204204816327
\]

\[
-19.6 = -19.600001 \frac{1}{\sqrt{2}}
\]

\[
|\sqrt{2} + \Delta x - \sqrt{2}| = |\Delta x| < \epsilon
\]

\[
19.6 \Delta x - 1.95 \Delta x^2 < 0.00000204204816327
\]

\[
-19.6 = -19.600001 \frac{1}{\sqrt{2}}
\]
we don’t have to worry about it ever again. When we say that \( x \) might be “complicated” we really mean that in practice it might be a function. Here is then what we want to know:

**Theorem 2.3.5** Suppose \( \lim_{x \to a} f(x) = L \) and \( \lim_{x \to a} g(x) = M \). Then \( \lim_{x \to a} f(g(x)) = LM \).

**Proof.** We have to use the official definition of limit to make sense of this. So given any \( \epsilon > 0 \), we need to find a \( \delta > 0 \) so that \( 0 < |x - a| < \delta \) implies \( |f(g(x)) - LM| < \epsilon \). What do we have to work with? We know that we can make \( f(x) \) close to \( L \) and \( g(x) \) close to \( M \), and we have to somehow connect these facts to make \( f(g(x)) \) close to \( LM \).

We use, as is so often the case, a little algebraic trick:

\[
|f(g(x)) - LM| = |f((g(x) - M) + f(x)M - LM| \\
= |f(g(x) - M) + (f(x) - L)M| \\
\leq |f(g(x) - M) + |f(x)| - L|M| \\
= |f((g(x) - M) + |f(x)| - L)|M|.
\]

This is all straightforward except perhaps for the "\( \leq \)". That is an example of the triangle inequality, which says that if \( a \) and \( b \) are any real numbers then \( |a + b| \leq |a| + |b| \). If you look at a few examples, using positive and negative numbers in various combinations for \( a \) and \( b \), you should quickly understand why this is true; we will not prove it formally.

Since \( \lim_{x \to a} f(x) = L \), there is a \( \delta_1 \) so that \( 0 < |x - a| < \delta_1 \) implies \( |f(x) - L| < \epsilon/|M| \). This means that \( 0 < |x - a| < \delta_1 \) implies \( |f((g(x) - M)) < \epsilon/|M| \). You can see where this is going; if we can make \( |f(g(x)) - LM| < \epsilon/|M| \) we’ll be done.

We can make \( |g(x) - M| \) smaller than any fixed number by making \( x \) close enough to \( a \), unfortunately, \( \epsilon/(2|M|) \) is not a fixed number, since \( x \) is a variable. Here we need another little trick, just like the one we used in analyzing \( x^2 \). We can find a \( \delta_2 \) so that \( |x - a| < \delta_2 \) implies \( |f((g(x) - M) - L| < 1 \), meaning that \( L - 1 < f((g(x) - M) < L + 1 \). This means that \( f((g(x)) < N \), where \( N \) is either \( L - 1 \) or \( L + 1 \), depending on whether \( L \) is negative or positive. The important point is that \( N \) doesn’t depend on \( x \). Finally, we know that there is a \( \delta_3 \) so that \( 0 < |x - a| < \delta_3 \) implies \( |g(x) - M| < \epsilon/(2|N|) \). Now we’re ready to put everything together. Let \( \delta \) be the smallest of \( \delta_1, \delta_2, \) and \( \delta_3 \). Then \( |x - a| < \delta \) implies that \( |f(x) - L| < \epsilon/|M| \), \( |f(g(x)) - LM| < \epsilon/|M| \), and \( |g(x) - M| < \epsilon/(2|N|) \). Then

\[
|f(g(x)) - LM| = |f((g(x) - M) + |f(x)| - L)|M| \\
\leq |g(x) - M| + |f(x)| - L|M| < \frac{\epsilon}{|M|} + \frac{\epsilon}{|N|} = \epsilon.
\]

This is just what we needed, so by the official definition, \( \lim_{x \to a} f(g(x)) = LM \).

### 2.3 Limits

number. But 5 can, and should, be interpreted here as the function that has value 5 everywhere, \( f(x) = 5 \), with graph a horizontal line. From this point of view it makes sense to ask what happens to the limit function as \( x \) approaches 1. Of course, as we’ve already seen, we’re primarily interested in limits that aren’t so easy, namely, limits in which a denominator approaches zero. There are a handful of algebraic tricks that work on many of these limits.

**Theorem 2.3.6** Suppose \( \lim_{x \to a} f(x) = L \) and \( \lim_{x \to a} g(x) = M \) and \( k \) is some constant. Then

\[
\lim_{x \to a} k(f(x) + g(x)) = kL + M,
\]

\[
\lim_{x \to a} k(f(x) - g(x)) = kL - M,
\]

\[
\lim_{x \to a} k(f(x)) = k \lim_{x \to a} f(x) = kL.
\]

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A handful of these theorems give us the tools to compute many limits without explicitly working with the definition of limit.

**Theorem 2.3.7** Compute \( \lim_{x \to a} \frac{x^2 - 3x + 5}{x - 2} \). If we apply the theorem in all its gory detail, we get

\[
\lim_{x \to a} \frac{x^2 - 3x + 5}{x - 2} = \frac{\lim_{x \to a} (x^2 - 3x + 5) - \lim_{x \to a} (x - 2)}{\lim_{x \to a} (x - 2)} = \frac{\lim_{x \to a} x^2 - \lim_{x \to a} 3x + \lim_{x \to a} 5}{\lim_{x \to a} x - \lim_{x \to a} 2} = \frac{1 - 3 + 5}{1 - 2} = \frac{3}{-1} = -3.
\]

It is worth commenting on the trivial limit \( \lim_{x \to a} f(x) \) from one point of view this might seem meaningless, as the number 5 can’t “approach” any value, since it is simply a fixed number.

### 2.3.11 Compute \( \lim_{x \to a} \sqrt{x^2 - 2} \). For \( x \to 1 \) we get

\[
\lim_{x \to a} \sqrt{x^2 - 2} = \lim_{x \to 1} \sqrt{x^2 - 2} = \sqrt{1^2 - 2} = \sqrt{-1} = -1.
\]

At the very last step we have used theorems 2.3.9 and 2.3.10.

Occasionally we will need a slightly modified version of the limit definition. Consider the function \( f(x) = \sqrt{x^2 - 2} \), the upper half of the unit circle. What can we say about \( \lim_{x \to 1} f(x) \)? It is apparent from the graph of this familiar function that as \( x \) gets close to 1 from the left, the value of \( f(x) \) gets close to zero. It does not even make sense to ask what happens as \( x \) approaches 1 from the right, since \( f(x) \) is not defined there. The definition of the limit, however, demands that \( f(x) \) be close to \( f(1) \) whether \( \Delta x \) is positive or negative. Sometimes the limit of a function exists from one side or the other (or both) even though the limit does not exist. Since it is useful to be able to talk about this situation, we introduce the concept of one sided limit.

**Definition 2.3.12 One-sided limit** Suppose that \( f(x) \) is a function. We say that \( \lim_{x \to a} f(x) = L \) if for every \( \epsilon > 0 \) there is a \( \delta > 0 \) so that whenever \( 0 < x - a < \delta \), \( |f(x) - L| < \epsilon \). We say that \( \lim_{x \to a} f(x) = L \) if for every \( \epsilon > 0 \) there is a \( \delta > 0 \) so that whenever \( 0 < x - a < \delta \), \( |f(x) - L| < \epsilon \). Usually \( \lim_{x \to a} f(x) \) is read “the limit of \( f(x) \) from the left” and \( \lim_{x \to a} f(x) \) is read “the limit of \( f(x) \) from the right”.

**Example 2.3.13** Discuss \( \lim_{x \to a} \frac{1}{x} + \lim_{x \to b} \frac{1}{x} \). The function \( f(x) = x/2 \) is undefined at 0, when \( x > 0 \), \( |x| = x \) and \( f(x) = 1 \), when \( x < 0 \), \( |x| = -x \): and \( f(x) = -1 \). Thus \( \lim_{x \to a} \frac{1}{x} = \lim_{x \to -b} \frac{1}{x} = -1 \) while \( \lim_{x \to a} \frac{1}{x} \to -1 \) since \( \frac{1}{x} \to -\infty \) when \( x \to a \).
\[ \lim_{x \to 0} 1 = 1. \] The limit of \( f(x) \) must be equal to both the left and right limits; since they are different, the limit \( \lim_{x \to 0} f(x) \) does not exist.

### Exercises 2.3.

Compute the limits. If a limit does not exist, explain why:

1. \( \lim_{x \to 1} \frac{x^2 + x - 12}{x - 3} \)
2. \( \lim_{x \to 1} \frac{x^2 + x - 12}{x - 2} \)
3. \( \lim_{x \to 2} \frac{x^2 + x - 12}{x - 3} \)
4. \( \lim_{x \to 3} \frac{x^2 + x - 12}{x - 2} \)
5. \( \lim_{x \to 1} \frac{\sqrt{\frac{x}{2}} - 3}{x - 1} \)
6. \( \lim_{x \to 2} \frac{\sqrt{\frac{x}{2}} + 2 - \sqrt{\frac{3}{2}}}{x - 2} \)
7. \( \lim_{x \to 3} \frac{x^2 - 5x}{x - 1} \)
8. \( \lim_{x \to 4} \frac{x^2 - 5x}{x - 1} \)
9. \( \lim_{x \to 1} \frac{x^2 - 5}{x - 1} \)
10. \( \lim_{x \to 2} \frac{x^2 - 1}{x - 1} \)
11. \( \lim_{x \to 1} \frac{x^2 - x}{x - 1} \)
12. \( \lim_{x \to 2} \frac{x^2 - x}{x - 1} \)
13. \( \lim_{x \to 1} \frac{x - 5}{x - 1} \)
14. \( \lim_{x \to 2} \frac{x^2 + 4x}{x - 1} \)
15. \( \lim_{x \to 1} \frac{x - 5}{x - 1} \)
16. \( \lim_{x \to 2} \frac{x - 5}{x - 1} \)

(Hint: Use the fact that \( |\sin a| < 1 \) for any real number \( a \). You should probably use the definition of a limit here.)

17. Give an \( \varepsilon - \delta \) proof, similar to example 2.3.3, of the fact that \( \lim_{x \to a} (2x - 5) = 3 \).

### 2.4 The Derivative Function

We know that \( f' \) carries important information about the original function \( f \). In one example we saw that \( f'(x) \) tells us how steep the graph of \( f(x) \) is; in another we saw that \( f'(x) \) tells us the velocity of an object if \( f(x) \) tells us the position of the object at time \( x \).

As we said earlier, this same mathematical idea is useful whenever \( f(x) \) represents some changing quantity and we want to know something about how it changes, or roughly, the "rate" at which it changes. Most functions encountered in practice are built up from a small collection of "primitive" functions in a few simple ways, such as by adding or multiplying functions together to get new, more complicated functions. To make good use of the information provided by \( f'(x) \) we need to be able to compute it for a variety of such functions.

We will begin to use different notations for the derivative of a function. While initially confusing, each is often useful so it is worth maintaining multiple versions of the same thing.

Consider again the function \( f(x) = \sqrt{2x - x^2} \). We have computed the derivative \( f'(x) = -x/\sqrt{2x - x^2} \), and have already noted that if we use the alternate notation \( y = \sqrt{2x - x^2} \), then we might write \( y' = -x/\sqrt{2x - x^2} \). Another notation is quite different, and in time it will become clear why it is often a useful one. Recall that to compute the derivative of \( f \) we computed

\[
\lim_{\Delta x \to 0} \frac{\sqrt{2x - (x + \Delta x)^2} - 2x}{\Delta x}
\]

The denominator here measures a distance in the \( x \) direction, sometimes called the "run," and the numerator measures a distance in the \( y \) direction, sometimes called the "rise," and "rise over run" is the slope of a line. Recall that sometimes such a numerator is abbreviated \( \Delta y \), exchanging brevity for a more detailed expression. So in general, a derivative is given by

\[
y' = \lim_{\Delta x \to 0} \frac{\Delta y}{\Delta x}
\]

To recall the form of the limit, we sometimes say instead that

\[
\frac{dy}{dx} = \lim_{\Delta x \to 0} \frac{\Delta y}{\Delta x}
\]

In other words, \( dy/dx \) is another notation for the derivative, and it reminds us that it is related to an actual slope between two points. This notation is called Leibniz notation, after Gottfried Leibniz, who developed the fundamentals of calculus independently, at about the same time that Isaac Newton did. Again, since we often use \( f \) and \( f(x) \) to mean the original function, we sometimes use \( df/dx \) and \( df(x)/dx \) to refer to the derivative. If the function \( f(x) \) is written out in full we often write the last of these something like this

\[
f'(x) = \frac{d}{dx} \sqrt{2x - x^2}
\]

with the function written to the side, instead of trying to fit it into the numerator.

#### Example 2.4.2

Find the derivative of \( y = f(t) = t^2 \).

We compute

\[
y' = \lim_{\Delta t \to 0} \frac{\Delta y}{\Delta t} = \lim_{\Delta t \to 0} \frac{(t + \Delta t)^2 - t^2}{\Delta t}
\]

\[
= \lim_{\Delta t \to 0} \frac{t^2 + 2t\Delta t + \Delta t^2 - t^2}{\Delta t}
\]

\[
= \lim_{\Delta t \to 0} \frac{2t\Delta t + \Delta t^2}{\Delta t}
\]

\[
= \lim_{\Delta t \to 0} 2t + \Delta t = 2t
\]

Remember that \( \Delta t \) is a single quantity, not a "\( \Delta t \) times a "\( t \)", and so \( \Delta t^2 \) is \( (\Delta t)^2 \) not \( \Delta(t^2) \).

#### Example 2.4.3

Find the derivative of \( y = f(x) = 1/x \).

The computation:

\[
y' = \lim_{\Delta x \to 0} \frac{\Delta y}{\Delta x} = \lim_{\Delta x \to 0} \frac{1/(x + \Delta x) - 1/x}{\Delta x}
\]

\[
= \lim_{\Delta x \to 0} \frac{-\Delta x}{x(x + \Delta x)\Delta x}
\]

\[
= \lim_{\Delta x \to 0} \frac{-1}{x(x + \Delta x)} = -\frac{1}{x^2}
\]

Note. If you happen to know some "derivative formulas" from an earlier course, for the time being you should pretend that you do not know them. In examples like the ones above and the exercises below, you are required to know how to find the derivative.
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formulas from basic principles. We will later develop some formulas so that we do not always need to do such computations, but we will continue to need to know how to do the more involved computations.

Sometimes one encounters a point in the domain of a function where there is no derivative, because there is no tangent line. In order for the notion of the tangent line at a point to make sense, the curve must be “smooth” at that point. This means that if you imagine a particle traveling at some steady speed along the curve, then the particle does not experience an abrupt change of direction. There are two types of situations you should be aware of—corners and cusps—where there’s a sudden change of direction and hence no derivative.

EXAMPLE 2.4.4  Discuss the derivative of the absolute value function \( y = |x| \).

If \( x \) is positive, then this is the function \( y = x \), whose derivative is the constant 1. (Recall that when \( y = f(x) = mx + b \), the derivative is the slope \( m \).) If \( x \) is negative, then we’re dealing with the function \( y = -x \), whose derivative is the constant –1. If \( x = 0 \), then the function has a corner, i.e., there is no tangent line. A tangent line would have to point in the direction of the curve—but there are two directions of the curve that come together at the origin. We can summarize this as

\[
y' = \begin{cases} 
1 & \text{if } x > 0; \\
-1 & \text{if } x < 0; \\
\text{undefined} & \text{if } x = 0.
\end{cases}
\]

EXAMPLE 2.4.5  Discuss the derivative of the function \( y = x^{2/3} \), shown in figure 2.4.1. We will later see how to compute this derivative; for now we use the fact that \( y' = (2/3)x^{-1/3} \). Visually this looks much like the absolute value function, but it technically has a cusp, not a corner. The absolute value function has no tangent line at 0 because there are (at least) two obvious contenders—the tangent line of the left side of the curve and the tangent line of the right side. The function \( y = x^{2/3} \) does not have a tangent line at 0, but unlike the absolute value function it can be said to have a single direction: as we approach 0 from either side the tangent line becomes closer and closer to a vertical line; the curve is vertical at 0. But as before, if you imagine traveling along the curve, an abrupt change in direction is required at 0; a full 180 degree turn.

In practice we won’t worry much about the distinction between these examples; in both cases the function has a “sharp point” where there is no tangent line and no derivative.

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Make sure you indicate any places where the derivative does not exist.

8. Find the derivative of \( y = f(x) = 2\sqrt{x^2 + 1} \).

9. Find the derivative of \( y = g(t) = (2t - 1)/(t + 2) \).

10. Find an equation for the tangent line to the graph of \( f(x) = 5 - x - 3x^2 \) at the point \( x = 2 \).

11. Find a value for \( a \) so that the graph of \( f(x) = x^3 + ax - 3 \) has a horizontal tangent line at \( x = 4 \).

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Exercises 2.4.

1. Find the derivative of \( y = f(x) = \sqrt{36 - x^2} \).

2. Find the derivative of \( y = f(x) = 80 - 4x^2 \).

3. Find the derivative of \( y = f(x) = x^2 - (1/x) \).

4. Find the derivative of \( y = f(x) = ax^2 + bx + c \) (where \( a, b, \) and \( c \) are constants).

5. Find the derivative of \( y = f(x) = x^{3/2} \).

6. Show the graph of a function \( f(x) \) by estimating the derivative at a number of points in the interval; estimate the derivative at regular intervals from one end of the interval to the other, and also at “special” points, where the derivative is zero. Make sure you indicate any places where the derivative does not exist.

7. Show the graph of a function \( f(x) \). Sketch the graph of \( f'(x) \) by estimating the derivative at a number of points in the interval; estimate the derivative at regular intervals from one end of the interval to the other, and also at “special” points, where the derivative is zero.

Figure 2.5.1 Function Types: (a) a discontinuous function, (b) a continuous function, (c) a bounded, differentiable function, (d) an unbounded, differentiable function

DEFINITION 2.5.1 Bounded  A function \( f \) is bounded if there is a number \( M \) such that \( |f(x)| < M \) for every \( x \) in the domain of \( f \).

For the function in (c), one such choice for \( M \) would be 10. However, the smallest (optimal) choice would be \( M = 1 \). In either case, simply finding an \( M \) is enough to establish boundedness. No such \( M \) exists for the hyperbola in (d) and hence we can say that it is unbounded.

Continuity. The graphs shown in (b) and (c) both represent continuous functions. Geometrically, this is because there are no jumps in the graphs. That is, if you pick a point on the graph and approach it from the left and right, the values of the function
DEFINITION 2.5.2 Continuous at a Point  
A function \( f \) is continuous at a point \( a \) if \( \lim_{x \to a} f(x) = f(a) \).

DEFINITION 2.5.3 Continuous  
A function \( f \) is continuous if it is continuous at every point in its domain.  

Strangely, we can also say that (d) is continuous even though there is a vertical asymptote. A careful reading of the definition of continuous reveals the phrase “at every point in its domain.” Because the location of the asymptote, \( x = 0 \), is not in the domain of the function, and because the rest of the function is well-behaved, we can say that (d) is continuous.

Differentiability. Now that we have introduced the derivative of a function at a point, we can begin to use the adjective differentiable. We can see that the tangent line is well-defined at every point on the graph in (c). Therefore, we can say that (c) is a differentiable function.

DEFINITION 2.5.4 Differentiable at a Point  
A function \( f \) is differentiable at a point \( a \) if \( f'(a) \) exists.

DEFINITION 2.5.5 Differentiable  
A function \( f \) is differentiable if it is differentiable at every point (excluding endpoints and isolated points in the domain of \( f \)) in the domain of \( f \).

Take note that, for technical reasons not discussed here, both of these definitions exclude endpoints and isolated points in the domain from consideration.

We now have a collection of adjectives to describe the very rich and complex set of objects known as functions.

We close with a useful theorem about continuous functions:

THEOREM 2.5.6 Intermediate Value Theorem  
If \( f \) is continuous on the interval \([a, b]\) and \( d \) is between \( f(a) \) and \( f(b) \), then there is a number \( c \) in \([a, b]\) such that \( f(c) = d \).

This is most frequently used when \( d = 0 \).

EXAMPLE 2.5.7  
Explain why the function \( f = x^3 + 3x^2 + x - 2 \) has a root between \( 0 \) and \( 1 \).

By theorem 2.3.6, \( f \) is continuous. Since \( f(0) = -2 \) and \( f(1) = 3 \), and 0 is between \(-2 \) and \( 3 \), there is a \( c \in [0, 1] \) such that \( f(c) = 0 \).

This example also points the way to a simple method for approximating roots.

EXAMPLE 2.5.8  
Approximate the root of the previous example to one decimal place.

If we compute \( f(0.1), f(0.2), \) and so on, we find that \( f(0.6) < 0 \) and \( f(0.7) > 0 \), so by the Intermediate Value Theorem, \( f \) has a root between 0.6 and 0.7. Repeating the process with \( f(0.61), f(0.62) \), and so on, we find that \( f(0.61) < 0 \) and \( f(0.62) > 0 \), so \( f \) has a root between 0.61 and 0.62, and the root is 0.6 rounded to one decimal place.

Exercises 2.5.

1. Along the lines of Figure 2.5.1, for each part below sketch the graph of a function that is:
   a. differentiable everywhere except at \( d \).
   b. differentiable and unbounded.
   c. continuous at \( x = 0 \), not continuous at \( x = 1 \), and bounded.
   d. differentiable everywhere except at \( x = -1 \), continuous, and unbounded.

2. Is \( f(x) = \sin(x) \) a bounded function? If so, find the smallest \( M \).
3. Is \( g(x) = 1/(1 + x^2) \) a bounded function? If so, find the smallest \( M \).
4. Is \( v(t) = 2\ln(t) \) a bounded function? If so, find the smallest \( M \).
5. Consider the function
   \[ h(x) = \begin{cases} 
   2x - 3, & \text{if } x < 1 \\
   0, & \text{if } x \geq 1.
   \end{cases} \]
   Show that it is continuous at the point \( x = 0 \). Is \( h \) a continuous function?

6. Approximate a root of \( f = x^3 - 4x^2 + 2x + 2 \) to one decimal place.
7. Approximate a root of \( f = x^3 + x^2 - 5x + 1 \) to one decimal place.