4 Transcendental Functions

So far we have used only algebraic functions as examples when finding derivatives, that is, functions that can be built up by the usual algebraic operations of addition, subtraction, multiplication, division, and raising to constant powers. Both in theory and practice there are other functions, called transcendental, that are very useful. Most important among these are the trigonometric functions, the inverse trigonometric functions, exponential functions, and logarithms.

4.1 Trigonometric Functions

When you first encountered the trigonometric functions it was probably in the context of “triangle trigonometry,” defining, for example, the sine of an angle as the “side opposite over the hypotenuse.” While this will still be useful in an informal way, we need to use a more expansive definition of the trigonometric functions. First an important note: while degree measure of angles is sometimes convenient because it is so familiar, it turns out to be ill-suited to mathematical calculation, so (almost) everything we do will be in terms of radian measure of angles.

An angle, \( x \), at the center of the circle is associated with an arc of the circle which is said to subtend the angle. In the figure, this arc is the portion of the circle from point \((1, 0)\) to point \( A \). The length of this arc is the radian measure of the angle \( x \); the fact that the radian measure is an actual geometric length is largely responsible for the usefulness of radian measure. The circumference of the unit circle is \(2\pi\), so the radian measure of the full circular angle (that is, of the 360 degree angle) is \(2\pi\).

The simple triangle definitions work only for angles that can “fit” in a right triangle, namely, angles between \(0\) and \(\pi/2\). The coordinate definitions, on the other hand, apply to any angles, as indicated in this figure:

![Diagram of the unit circle with angles and coordinates labeled]

The angle \( x \) is subtended by the heavy arc in the figure, that is, \( x \approx 7\pi/6 \). Both coordinates of point \( A \) in this figure are negative, so the sine and cosine of \(7\pi/6\) are both negative.

The remaining trigonometric functions can be most easily defined in terms of the sine and cosine, as usual:

\[
\tan x = \frac{\sin x}{\cos x}, \quad \cot x = \frac{\cos x}{\sin x},
\]

\[
\sec x = \frac{1}{\cos x}, \quad \csc x = \frac{1}{\sin x},
\]

and they can also be defined as the corresponding ratios of coordinates.

Although the trigonometric functions are defined in terms of the unit circle, the unit circle diagram is not what we normally consider the graph of a trigonometric function. (The unit circle is the graph of, well, the circle.) We can easily get a qualitatively correct idea of the graph of the trigonometric functions from the unit circle diagram. Consider the sine function, \( y = \sin x \). As \( x \) increases from 0 in the unit circle diagram, the second coordinate of the point \( A \) goes from 0 to a maximum of 1, then back to 0, then to a minimum of \(-1\), then back to 0, and then it obviously repeats itself. So the graph of \( y = \sin x \) must look something like this:

![Graph of the sine function]

Similarly, as angle \( z \) increases from 0 in the unit circle diagram, the first coordinate of the point \( A \) goes from 1 to 0 to \(-1\), back to 0, and back to 1, so the graph of \( y = \cos z \) must look something like this:

![Graph of the cosine function]

Exercises 4.1.

Some useful trigonometric identities are in Appendix B.

1. Find all values of \( \theta \) such that \( \sin(\theta) = 1 \). Give your answer in radians. \( \Rightarrow \)

2. Find all values of \( \theta \) such that \( \cos(\theta) = 1/2 \). Give your answer in radians. \( \Rightarrow \)

3. Use an angle sum identity to compute \( \cos(\pi/12) \). \( \Rightarrow \)

4. Use an angle sum identity to compute \( \tan(5\pi/12) \). \( \Rightarrow \)

5. Verify the identity \( \cos^2(\theta) + \sin^2(\theta) = 1 \). \( \Rightarrow \)

6. Verify the identity \( 2 \cos(\theta) = \cos(2\theta) \). \( \Rightarrow \)

7. Verify the identity \( \sin(\theta) - \sin(\pi/2 - \theta) = \cos(\theta) \). \( \Rightarrow \)

8. Sketch \( y = 2 \sin(x) \). \( \Rightarrow \)

9. Sketch \( y = \sin(3x) \). \( \Rightarrow \)

10. Sketch \( y = \sin(x) - x \). \( \Rightarrow \)

11. Find all of the solutions of \( 2 \sin(x) - 1 = \sin^2(x) = 0 \) in the interval \([0, 2\pi]\). \( \Rightarrow \)

4.2 The Derivative of \( \sin x \)

What about the derivative of the sine function? The rules for derivatives that we have are no help, since \( \sin x \) is not an algebraic function. We need to return to the definition of the derivative, set up a limit, and try to compute it. Here’s the definition:

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

Using some trigonometric identities, we can make a little progress on the quotient:

\[
\frac{\sin(x + \Delta x) - \sin x}{\Delta x} = \frac{\sin x \cos \Delta x + \sin \Delta x \cos x - \sin x}{\Delta x}
\]

\[
= \sin x \frac{\cos \Delta x - 1}{\Delta x} + \sin \Delta x \frac{\cos x}{\Delta x}.
\]
This isolates the difficult bits in the two limits
\[ \lim_{\Delta x \to 0} \cos \Delta x - 1 \quad \text{and} \quad \lim_{\Delta x \to 0} \sin \Delta x. \]

Here we get a little lucky: it turns out that once we know the second limit the first is quite easy. The second is quite tricky, however. Indeed, it is the hardest limit we will actually compute, and we devote a section to it.

### 4.3 A Hard Limit

We want to compute this limit:
\[ \lim_{x \to 0} \frac{\sin x}{x}. \]

Equivalently, to make the notation a bit simpler, we can compute
\[ \lim_{\Delta x \to 0} \frac{\sin \Delta x}{\Delta x}. \]

In the original context we need to keep \( x \) and \( \Delta x \) separate, but here it doesn’t hurt to rename \( \Delta x \) to something more convenient.

To do this we need to be quite clever, and to employ some indirect reasoning. The indirect reasoning is embodied in a theorem, frequently called the squeeze theorem.

**Theorem 4.3.1: Squeeze Theorem.** Suppose that \( g(x) \leq f(x) \leq h(x) \) for all \( x \) close to \( a \) but not equal to \( a \). If \( \lim_{x \to a} g(x) = \lim_{x \to a} h(x) = L \), then \( \lim_{x \to a} f(x) = L \).

This theorem can be proved using the official definition of limit. We won’t prove it here, but point out that it is easy to understand and believe graphically. The condition says that \( f(x) \) is trapped between \( g(x) \) below and \( h(x) \) above, and that at \( x = a \), both \( g \) and \( h \) approach the same value. This means the situation looks something like figure 4.3.1.

The wiggly curve is \( x^2 \sin(1/x) \), the upper and lower curves are \( x^2 \) and \( -x^2 \). Since the sine function is always between \(-1\) and \(1\), \( x^2 \leq x^2 \sin(1/x) \leq x^2 \), and it is easy to see that \( \lim_{x \to 0} x^2 = 0 = \lim_{x \to 0} -x^2 \). It is not so easy to see directly, that is algebraically, that \( \lim_{x \to 0} x^2 \sin(1/x) = 0 \), because the \( 1/x \) prevents us from simply plugging in \( x = 0 \). The squeeze theorem makes this “hard limit” as easy as the trivial limits involving \( x^2 \).

To do the hard limit that we want, \( \lim_{x \to 0} \frac{\sin x}{x} \), we will find two simpler functions \( g \) and \( h \) so that \( g(x) \leq \frac{\sin x}{x} \leq h(x) \), and so that \( \lim_{x \to 0} g(x) = \lim_{x \to 0} h(x) = 1 \). Not too surprisingly, this will require some trigonometry and geometry. Referring to figure 4.3.2, \( x \) is the measure of the angle in radians. Since the circle has radius 1, the coordinates of point \( A \) are \((\cos x, \sin x)\), and the area of the small triangle is \((\cos x \sin x)/2\). This triangle is completely contained within the circular wedge-shaped region bounded by two lines and the circle from \((1,0)\) to point \( A \). Comparing the areas of the triangle and the wedge we see \((\cos x \sin x)/2 \leq x/2 \), since the area of a circular region with angle \( \theta \) and radius \( r \) is \( \theta r^2/2 \). With a little algebra this becomes \( \sin x \leq (\sin x)/x \).

So now we have
\[ \cos x \leq \frac{\sin x}{x} \leq \frac{1}{\cos x}. \]

### 4.4 Derivative of \( \sin x \), continued

Now we can complete the calculation of the derivative of the sine:

\[ \frac{d}{dx} \sin x = \lim_{\Delta x \to 0} \frac{\sin(x + \Delta x) - \sin x}{\Delta x} = \cos x. \]

The derivative of a function measures the slope or steepness of the function; if we examine the graphs of the sine and cosine side by side, it should be that the latter appears to accurately describe the slope of the former, and indeed this is true:

\[ \cos x = \frac{d}{dx} \sin x = \sin(\pi x/2). \]

Notice that where the cosine is zero the sine does appear to have a horizontal tangent line, and that the sine appears to be steepest where the cosine takes on its extreme values of \( 1 \) and \(-1 \).

Of course, now that we know the derivative of the sine, we can compute derivatives of more complicated functions involving the sine.

**Example 4.4.1** Compute the derivative of \( \sin(x^2) \).

\[ \frac{d}{dx} \sin(x^2) = \cos(x^2) \cdot 2x = 2x \cos(x^2). \]

**Example 4.4.2** Compute the derivative of \( \sin^2(x^2 - 5x) \).

\[ \frac{d}{dx} \sin^2(x^2 - 5x) = \frac{d}{dx} (\sin(x^2 - 5x))^2 = 2 (\sin(x^2 - 5x))^1 \cdot (\cos(x^2 - 5x))(\sin(x^2 - 5x)). \]
4.5 Derivatives of the Trigonometric Functions

All of the other trigonometric functions can be expressed in terms of the sine, and so their derivatives can easily be calculated using the rules we already have. For the cosine we need to use two identities,
\[
\cos x = \sin (x + 1) \quad \text{and} \quad \sin x = \cos (x + 2).
\]
Now,
\[
\begin{align*}
\frac{d}{dx} \cos x &= -\sin x \\
\frac{d}{dx} \sin x &= \cos (x + 1) \\
\frac{d}{dx} \tan x &= \frac{1}{\cos^2 x} = \sec^2 x \\
\frac{d}{dx} \sec x &= (\cos x)^2 = \sec x \\
\frac{d}{dx} \cot x &= -\csc^2 x \\
\frac{d}{dx} \csc x &= -\cot x \csc x
\end{align*}
\]

The derivatives of the cotangent and cosecant are similar and left as exercises.

4.6 Exponential and Logarithmic Functions

An exponential function has the form \(a^x\), where \(a\) is a constant; examples are \(2^x\), \(10^x\), \(e^x\). The logarithmic function are the inverses of the exponential functions, that is, functions that "undo" the exponential functions. For example, the cube root function "undoes" the cube function. \(\sqrt[3]{x} = x = x^{1/3} = x^{0.33} = x^{0.3333} = x^{0.33333} = \ldots\)

Exponential Functions

From the formula: 
\[
\log_a(a^x) = x \quad \text{and} \quad a^{\log_a x} = x
\]

Logarithmic Functions

We can use log rules to solve various problems. For example, if \(\log_{10} 100 = 2\), then \(10^2 = 100\).

Exercises 4.6.1

1. \(\log_{10}(10000)\) \(\Rightarrow\) \(\log_{10}(1000) = 3\)
2. \(\log_{10}(100000) = 5\) (because \(10^5 = 100000\))
3. \(\log_{10}(0.001) = -3\) (because \(10^{-3} = 0.001\))

EXAMPLE 4.6.1

The value of \(\log_{10}(1000)\) The "10" tells us the appropriate number to use for the base of the exponential function. The logarithm is the exponent, so the question is, what exponent makes \(10\) equal to \(1000\)? If we can find such an \(E\), then \(\log_{10}(1000) = E\); finding the appropriate exponent is the same as finding the logarithm. In this case, of course, it easy: \(E = 3\) so \(\log_{10}(1000) = 3\).

Exercises 4.6.2

1. \(\log_{10}(100)\) \(\Rightarrow\) \(2\)
2. \(\log_{10}(10000)\) \(\Rightarrow\) \(4\)
3. \(\log_{10}(0.001)\) \(\Rightarrow\) \(-3\)

4. Simplify \(\log_{10}(1000)\) \(\Rightarrow\) \(3\)
5. Simplify \(\log_{10}(0.001)\) \(\Rightarrow\) \(-3\)
6. Simplify \(\log_{10}(10000)\) \(\Rightarrow\) \(4\)
7. Simplify \(\log_{10}(0.0001)\) \(\Rightarrow\) \(-4\)
8. Simplify \(\log_{10}(100000)\) \(\Rightarrow\) \(5\)
9. Simplify \(\log_{10}(0.00001)\) \(\Rightarrow\) \(-5\)

4.7 Derivatives of the Exponential and Logarithmic Functions

With the sine, we don't know anything about derivatives that allows us to compute the derivatives of the exponential and logarithmic functions without going back to basics. Let's do a little work with the definition again:

\[
\frac{d}{dx} e^x = \lim_{\Delta x \to 0} \frac{e^{x + \Delta x} - e^x}{\Delta x}
\]

4.8 Chapter 4 Transcendental Functions

1. Find all points on the graph of \(f(x) = 2\sin x\) at which the tangent line is horizontal.
2. Find an equation for the tangent line to \(f(x) = \sin x\) at \(x = \pi/3\).
3. Find an equation for the tangent line to \(f(x) = \sin x\) at \(x = \pi/6\).
4. Find the points on the curve \(y = x + 2\cos x\) that have a horizontal tangent line.
5. Let \(C\) be a circle of radius \(r\). Let \(A\) be an arc on \(C\) subtending a central angle \(\theta\). Let \(B\) be the chord of \(C\) whose endpoints are the endpoints of \(A\). (Hence, \(B\) also subtends \(\theta\).) Let \(x\) be the length of \(A\) and let \(d\) be the length of \(B\). Sketch a diagram of the situation and compute \(\lim_{x \to \theta/d}\).

4.9 Chapter 4 Transcendental Functions

80. Find all points on the graph of \(f(x) = 2\sin x\) at which the tangent line is horizontal.
81. Find an equation for the tangent line to \(f(x) = \sin x\) at \(x = \pi/3\).
82. Find an equation for the tangent line to \(f(x) = \sin x\) at \(x = \pi/6\).
83. Find the points on the curve \(y = x + 2\cos x\) that have a horizontal tangent line.
There are two interesting things to note here. As in the case of the sine function we are left with a limit that involves $\Delta x$ but not $x$, which means that \( \lim_{\Delta x \to 0} (e^{\Delta x} - 1)/\Delta x \) is, we know that it is a number, that is, a constant. This means that $a^x$ has a remarkable property: its derivative is a constant times itself.

We earlier remarked that the hardest limit we would compute is $\lim_{x \to 0} \sin x/x = 1$; we now have a limit that is just a bit too hard to include here. In fact the hard part is to see that $\lim_{\Delta x \to 0} (e^{\Delta x} - 1)/\Delta x$ even exists—does this function really get closer and closer to some fixed value? Yes it does, but we will not prove this fact.

We can look at some examples. Consider \((2^x - 1)/x\) for some small values of $x$: 1, 0.828427124, 0.756828469, 0.724061894, 0.708398501, 0.706827877 when $x$ is 1, 1/2, 1/4, 1/8, 1/16, 1/32, respectively. It looks like this is settling in around 0.693147180559945. Consider next \((e^{0.01} - 1)/0.01\): 1.005006643, 1.004987269, 1.004987237, 1.004987236, at the same values of $x$. It turns out to be true that in the limit this is about 0.693147180559945. Two examples don’t establish a pattern, but if you do more examples you will find that the limit varies directly with the value of $a$: bigger $a$, bigger limit; smaller $a$, smaller limit. As we can already see, some of these limits will be less than 1 and some larger than 1. Somewhere between $a = 2$ and $a = 3$ the limit will be exactly 1; the value at which this happens is called $e$, so that

$$
\lim_{\Delta x \to 0} \frac{e^{\Delta x} - 1}{\Delta x} = 1.
$$

As you might guess from our two examples, $e$ is closer to 3 than to 2, and in fact $e \approx 2.718$. Now we see that the function $e^x$ has a truly remarkable property:

$$
\frac{d}{dx} e^x = \lim_{\Delta x \to 0} \frac{e^{x+\Delta x} - e^x}{\Delta x}
= \lim_{\Delta x \to 0} \frac{e^x e^{\Delta x} - e^x}{\Delta x}
= \lim_{\Delta x \to 0} \frac{e^x (e^{\Delta x} - 1)}{\Delta x}
= e^x \lim_{\Delta x \to 0} \frac{e^{\Delta x} - 1}{\Delta x}
= e^x.
$$

That is, $e^x$ is its own derivative, or in other words the slope of $e^x$ is the same as its height, or the same as its second coordinate. The function $f(z) = e^z$ goes through the point $(z, e^z)$ and has slope $e^z$ there, no matter what $z$ is. It is sometimes convenient to express the function $e^z$ without an exponent, since complicated exponents can be hard to read. In such cases we use $\exp(z)$, e.g., $\exp(1 + 2z)$ instead of $e^{1+2z}$.

### 4.7 Derivatives of the exponential and logarithmic functions

We have discussed this from the point of view of the graphs, which is easy to understand but is not normally considered a rigorous proof—it is too easy to be led astray by pictures that seem reasonable but that miss some hard point. It is possible to do this derivation without resorting to pictures, and indeed we will see an alternate approach soon. We can replace $\log_a e$ to get

$$
\frac{d}{dx} \log_a x = \frac{1}{\ln a}.
$$

You may if you wish memorize the formulas

$$
\frac{d}{dx} e^x = (\ln e) e^x = e^x
$$
and

$$
\frac{d}{dx} \log_a x = \frac{1}{\ln a} \log_a e.
$$

Because the “trick” $a = e^{\ln a}$ is often useful, and sometimes essential, it may be better to remember the trick, not the formula.

**EXAMPLE 4.7.1** Compute the derivative of $f(x) = 2^x$.

$$
\frac{d}{dx} f(x) = \frac{d}{dx} 2^x = \frac{d}{dx} e^{\ln 2^x} = \frac{d}{dx} e^{x \ln 2} = (\ln 2) e^{x \ln 2} = 2^{x \ln 2}.
$$

**EXAMPLE 4.7.2** Compute the derivative of $f(x) = x^2 = 2^{x \ln 2}$.

$$
\frac{d}{dx} f(x) = \frac{d}{dx} x^2 = \frac{d}{dx} e^{x \ln 2} = \frac{d}{dx} e^{x \ln 2} = (\ln 2) e^{x \ln 2} = 2^{x \ln 2}.
$$

**EXAMPLE 4.7.3** Compute the derivative of $f(x) = x^2$. At first this appears to be a simple function; it is not a constant power of $x$, and it does not seem to be an exponential function, since the base is not constant. But in fact it is no harder than the previous example.

$$
\frac{d}{dx} f(x) = \frac{d}{dx} x^2 = \frac{d}{dx} x^{2 \ln x} = \frac{d}{dx} x^{(2 \ln x) \ln x} = (2 \ln x + x) x^2.
$$
EXAMPLE 4.7.4 Recall that we have not justified the power rule except when the exponent is a positive or negative integer. We can use the exponential function to take care of other exponents.

\[
\frac{d}{dx} \ln x = \frac{d}{dx} e^{\ln x} = \left( \frac{1}{e^{\ln x}} \right) e^{\ln x} = x^{-1}
\]

4.8 Implicit Differentiation

In 1–19, find the derivatives of the functions.

1. \( x^3 \Rightarrow \)
2. \( \frac{\sin x}{x} \Rightarrow \)
3. \( e^x \Rightarrow \)
4. \( \cos(x^2) \Rightarrow \)
5. \( x^x \Rightarrow \)
6. \( x + 2x \Rightarrow \)
7. \( (1/x)^x \Rightarrow \)
8. \( e^{x^2} \Rightarrow \)
9. \( \ln(x + 3x) \Rightarrow \)
10. \( \ln(\cos x) \Rightarrow \)
11. \( \sqrt{\ln(x^2 + x^3)} \Rightarrow \)
12. \( \ln(\cos x + x) \Rightarrow \)
13. \( e^{x^2/3} \Rightarrow \)
14. \( \sin(x + \tan(x)) \Rightarrow \)
15. \( x^{x+x} \Rightarrow \)
16. \( x \ln x \Rightarrow \)
17. \( \ln(\ln(x)) \Rightarrow \)
18. \( \ln(x^2) \Rightarrow \)
19. \( \ln(x - 2)^{1/2} \Rightarrow \)
20. \( 2x^2 / (4x - 6)^2 \Rightarrow \)

4.8 Implicit Differentiation

As we have seen, there is a close relationship between the derivatives of \( e^x \) and \( \ln x \) because these functions are inverses. Rather than relying on pictures for our understanding, we would like to be able to exploit this relationship computationally. In fact this technique can help us find derivatives in many situations, not just when we seek the derivative of an inverse function.

4.8 Implicit Differentiation

The chain rule where \( y \) appears.

\[
\frac{dy}{dx} \cdot \frac{dx}{dx} = \frac{d}{dx} (x^2 + y^2) = 0
\]

Now we have an expression for \( y' \), but it contains \( y \) as well as \( x \). This means that if we want to compute \( y' \) for some particular value of \( x \) we'll have to know or compute \( y \) at that value of \( x \) as well. It is at this point that we will need to know whether \( y = U(x) \) or \( L(x) \). Occasionally it will turn out that we can avoid explicit use of \( U(x) \) or \( L(x) \) by the nature of the problem.

EXAMPLE 4.8.1 Find the slope of the circle \( x^2 + y^2 = 1 \) at the point \((1, -\sqrt{3})\). Since we know both the \( x \) and \( y \) coordinates of the point of interest, we do not need to explicitly recognize that this point is on \( L(x) \), and we do not need to use \( L(x) \) to compute \( y \) but we could. Using the calculation of \( y' \) from above,

\[
y' = -\frac{x}{y} = -\frac{1}{\sqrt{3}} = -\frac{1}{\sqrt{3}}
\]

It is instructive to compare this approach to others.

We might have recognized at the start that \((1, -\sqrt{3})\) is on the function \( y = L(x) = -\sqrt{1 - x^2} \). We could then take the derivative of \( L(x) \), using the power rule and the chain rule, to get

\[
L'(x) = -\frac{1}{2} (1 - x^2)^{-1/2} (-2x) = \frac{x}{\sqrt{1 - x^2}}
\]

Then we compute \( L'(1) = 1/\sqrt{3} \) by substituting \( x = 1 \).

Alternatively, we could realize that the point is on \( L(x) \), but use the fact that \( y' = -x/y \). Since the point is on \( L(x) \) we can replace \( y \) by \( L(x) \) to get

\[
y' = -\frac{x}{L(x)} = -\frac{x}{\sqrt{1 - x^2}}
\]

without computing the derivative of \( L(x) \) explicitly. Then we substitute \( x = 1 \) and get the same answer as before.

In the case of the circle it is possible to find the functions \( U(x) \) and \( L(x) \) explicitly, but there are potential advantages to using implicit differentiation anyway. In some cases it is more difficult or impossible to find an explicit formula for \( y \) and implicit differentiation is the only way to find the derivative.

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We will begin by illustrating the technique to find what we already know, the derivative of \( \ln x \). Let's write \( y = \ln x \) and then \( x = e^y \), that is, \( x = e^y \). We say that this equation defines the function \( y = \ln x \) implicitly because while it is not an explicit expression \( y = \ldots \), it is true that if \( x = e^y \) then \( y \) is in fact the natural logarithm function.

Now, for the time being, pretend that all we know of \( y \) is that \( x = e^y \), what can we say about derivatives? We can take the derivative of both sides of the equation:

\[
\frac{d}{dx} x = \frac{d}{dx} e^y.
\]

Then using the chain rule on the right hand side:

\[
1 = \left( \frac{dy}{dx} \right) e^y.
\]

Then we can solve for \( y' \):

\[
y' = \frac{1}{e^y} = \frac{1}{y}.
\]

There is one little difficulty here. To use the chain rule to compute \( d/dx(\ln x) = y' e^y \) we need to know that the function \( y = \ln x \) has a derivative. All we have shown is that if \( y \) has a derivative then that derivative must be \( 1/y \). When using this method we will always have to assume that the desired derivative exists, but fortunately this is a safe assumption for most such problems.

The example \( \ln x \) involved an inverse function defined implicitly, but other functions can be defined implicitly, and sometimes a single equation can be used to implicitly define more than one function. Here's a familiar example. The equation \( r = x^2 + y^2 \) describes a circle of radius \( r \). The circle is not a function \( y = f(x) \) because for some values of \( x \) there are two corresponding values of \( y \). If we want to work with a function, we can break the circle into two pieces, the upper and lower semicircles, each of which is a function.

Let's call these \( y = U(x) \) and \( y = L(x) \); in fact this is a fairly simple example, and it's possible to give explicit expressions for these: \( U(x) = \sqrt{r^2 - x^2} \) and \( L(x) = -\sqrt{r^2 - x^2} \). But it's somewhat easier, and quite useful, to view both functions as given implicitly by \( x^2 + y^2 = r^2 \); both \( x^2 + U(x)^2 \) and \( x^2 + L(x)^2 \) are true, and we can think of \( x^2 + y^2 \) as defining both \( U(x) \) and \( L(x) \).

Now we can take the derivative of both sides as before, remembering that \( y \) is not simply a variable but a function—in this case, \( y \) is either \( U(x) \) or \( L(x) \) but we're not yet specifying which one. When we take the derivative we just have to remember to apply the chain rule:
Now taking the derivative of both sides, we get

$\cos y \frac{dy}{dx} = 1$

$y' = \frac{1}{\cos y}$

As we expect when using implicit differentiation, $y$ appears on the right hand side here. We would certainly prefer to have $y'$ written in terms of $x$, and as in the case of $\ln x$ we can actually do that here. Since $\sin^2 y + \cos^2 y = 1$, we have $\cos^2 y = 1 - \sin^2 y = 1 - x^2$. So $y' = \frac{1}{\sqrt{1 - x^2}}$, but which is it—plus or minus? It could in general be either, but this isn’t “in general”: since $y = \arcsin(x)$ we know that $-\pi/2 \leq y \leq \pi/2$, and the cosine of an angle in this interval is always positive. Thus $y' = \sqrt{1 - x^2}$ and

$$\frac{d}{dx} \arcsin(x) = \frac{1}{\sqrt{1 - x^2}}$$

Note that this agrees with figure 4.9.1: the graph of the arcsine has positive slope everywhere.

We can do something similar for the cosine. As with the sine, we must first truncate the cosine so that it can be inverted, as shown in figure 4.9.2. Then we use implicit differentiation to find that

$$\frac{d}{dx} \arccos(x) = \frac{-1}{\sqrt{1 - x^2}}$$

Note that the truncated cosine uses a different interval than the truncated sine, so that if $y = \arccos(x)$ we know that $0 \leq y \leq \pi$. The computation of the derivative of the arccosine is left as an exercise.

Finally we look at the tangent; the other trigonometric functions also have “partial inverses” but the sine, cosine and tangent are enough for most purposes. The tangent, truncated tangent and inverse tangent are shown in figure 4.9.3; the derivative of the arctangent is left as an exercise.

Exercises 4.9.

1. Show that the derivative of $\arccos x$ is $\frac{1}{\sqrt{1 - x^2}}$
2. Show that the derivative of $\arctan x$ is $\frac{1}{1 + x^2}$
EXAMPLE 4.10.1 What happens to $1/x$ as $x$ goes to $0$? From the right, $1/x$ gets bigger and bigger, or goes to infinity. From the left it goes to negative infinity.

EXAMPLE 4.10.2 What happens to the function $\cot(1/x)$ as $x$ goes to infinity? It seems clear that as $x$ gets larger and larger, $1/x$ gets closer and closer to zero, so $\cot(1/x)$ should be getting closer and closer to $\cot(0) = 1$.

4.10 Limits revisited

First we use L'Hôpital's Rule: Since the numerator and denominator both approach zero,

\[
\lim_{x \to 0} \frac{x^2 - x^3}{\sin x} = \lim_{x \to 0} \frac{2x - 3x^2}{\cos x}
\]

provided the latter exists. But in fact this is an easy limit, since the denominator now approaches $-1$, so

\[
\lim_{x \to 0} \frac{x^2 - x^3}{\sin x} = \frac{2 \cdot 0 - 3 \cdot 0^2}{\cos 0} = -2.
\]

We don't really need L'Hôpital's Rule to do this limit. Rewrite it as

\[
\lim_{x \to 0} \frac{x + \pi - x - \pi}{\sin x}
\]

and note that

\[
\lim_{x \to 0} \frac{x + \pi - x - \pi}{\sin x} = \lim_{x \to 0} \frac{-2 \pi}{\sin x}
\]

since $x - \pi$ approaches zero as $x$ approaches $\pi$. Now

\[
\lim_{x \to \pi} \frac{x + \pi}{\sin x} = \lim_{x \to \pi} \frac{x + \pi}{\sin x} \cdot \frac{-2 \pi}{\sin x} = 2 \pi \lim_{x \to \pi} \frac{-2 \pi}{\sin x} = -2 \pi
\]

as before.

EXAMPLE 4.10.7 Compute $\lim_{x \to \infty} \frac{2x^2 - 3x + 7}{x^2 + 4x + 1}$ in two ways.

As $x$ goes to infinity both the numerator and denominator go to infinity, so we may apply L'Hôpital's Rule:

\[
\lim_{x \to \infty} \frac{2x^2 - 3x + 7}{x^2 + 4x + 1} = \lim_{x \to \infty} \frac{4x - 3}{2x + 4}.
\]

In the second quotient, it is still the case that the numerator and denominator both go to infinity, so we are allowed to use L'Hôpital's Rule again:

\[
\lim_{x \to \infty} \frac{4x - 3}{2x + 4} = \lim_{x \to \infty} \frac{4}{2} = 2.
\]

So the original limit is $2$ as well.

Again, we don't really need L'Hôpital's Rule, and in fact a more elementary approach is easier—we divide the numerator and denominator by $x^2$:

\[
\lim_{x \to \infty} \frac{2x^2 - 3x + 7}{x^2 + 4x + 1} = \lim_{x \to \infty} \frac{2 - \frac{3}{x} + \frac{7}{x^2}}{1 + \frac{4}{x} + \frac{1}{x^2}} = 2.
\]

Now as $x$ approaches infinity, all the quotients with some power of $x$ in the denominator approach zero, leaving $2$ in the numerator and $1$ in the denominator, so the limit again is $2$.

4.10 Limits revisited

As with ordinary limits, these concepts can be made precise. Roughly, we want $\lim_{x \to a} f(x) = \infty$ to mean that we can make $f(x)$ arbitrarily large by making $x$ close enough to $a$, and $\lim_{x \to a} f(x) = L$ should mean we can make $f(x)$ as close as we want to $L$ by making $x$ large enough. Compare this definition to the definition of limit in section 2.3, definition 2.3.2.

DEFINITION 4.10.3 If $f$ is a function, we say that $\lim_{x \to a} f(x) = \infty$ if for every $N > 0$ there is a $\delta > 0$ such that whenever $|x - a| < \delta$, $f(x) > N$. We can extend this in the obvious ways to define $\lim_{x \to a} f(x) = -\infty$, $\lim_{x \to a} f(x) = \pm \infty$, and $\lim_{x \to a} f(x) = \pm \infty$.

DEFINITION 4.10.4 Limit at infinity If $f$ is a function, we say that $\lim_{x \to \infty} f(x) = L$ if for every $\epsilon > 0$ there is an $N > 0$ so that whenever $x > N$, $|f(x) - L| < \epsilon$. We may similarly define $\lim_{x \to -\infty} f(x) = L$, and using the idea of the previous definition, we may define $\lim_{x \to \infty} f(x) = \pm \infty$.

We include these definitions for completeness, but we will not explore them in detail. Suffice it to say that such limits behave in the much the same way that ordinary limits do; in particular there are some analogs of theorem 2.3.6.

Now consider this limit:

\[
\lim_{x \to \infty} x^2 - x.
\]

As $x$ approaches $\infty$, both the numerator and denominator approach zero, so it is not obvious what, if anything, the quotient approaches. We can often compute such limits by application of the following theorem.

THEOREM 4.10.5 L'Hôpital's Rule

For "sufficiently nice" functions $f(x)$ and $g(x)$, if $\lim_{x \to a} f(x) = 0$ or $\lim_{x \to a} g(x) = 0$ both $\lim_{x \to a} f(x)/g(x) = \infty$ and $\lim_{x \to a} g(x)/f(x) = 0$, and if $g'(x)$ exists, then $\lim_{x \to a} f(x)/g(x) = \lim_{x \to a} g'/f'(x)$.

This remains true if "$x \to \infty$" is replaced by "$x \to -\infty$" or "$x \to \infty$".

This theorem is somewhat difficult to prove, in part because it incorporates so many different possibilities, so we will not prove it here. We also will not need to worry about the precise definition of "sufficiently nice", as the functions we encounter will be suitable.

EXAMPLE 4.10.6 Compute $\lim_{x \to \infty} \frac{x^2 - \sqrt{x}}{\sin x}$ in two ways.

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EXAMPLE 4.10.8 Compute $\lim_{x \to 0} \frac{\sec x - 1}{\sin x}$

Both the numerator and denominator approach zero, so applying L'Hôpital's Rule:

\[
\lim_{x \to 0} \frac{\sec x - 1}{\sin x} = \lim_{x \to 0} \frac{\tan x}{\cos x} = 1 \cdot 0 = 0.
\]

EXAMPLE 4.10.9 Compute $\lim_{x \to 0} \frac{\ln x}{x}$

This doesn't appear to be suitable for L'Hôpital's Rule, but it also is not "obvious". As $x$ approaches zero, $x$ goes to $-\infty$, so the product looks like (something very small) (something very large and negative). But this could be anything: it depends on how small and how large. For example, consider $(x^2)(\ln x), (x)(\ln x)$, and $(\sin x)(x^2)$. As $x$ approaches zero, each of these is (something very small) (something very large), yet the limits are respectively zero, 1, and $\infty$.

We can in fact turn this into a L'Hôpital's Rule problem:

\[
x \ln x = \lim_{x \to 0} \frac{x}{1/x} = \lim_{x \to 0} \frac{x}{x} = 0.
\]

Now as $x$ approaches zero, both the numerator and denominator approach infinity (one $-\infty$ and one $+\infty$, but only the size is important). Using L'Hôpital's Rule:

\[
\lim_{x \to 0} \frac{\ln x}{x} = \lim_{x \to 0} \frac{1/x}{1} = \lim_{x \to 0} \frac{1}{x} = -\infty.
\]

One way to interpret this is that since $\lim_{x \to 0} \ln x = 0$, the $x$ approaches zero much faster than the $\ln x$ approaches $-\infty$.

Exercises 4.10.

Compute the limits.

1. $\lim_{x \to 0} \frac{\cos x - 1}{x}$

2. $\lim_{x \to 0} \frac{x^2}{x}$

3. $\lim_{x \to 0} \frac{\sqrt{x^2 + x} - \sqrt{x^2 - x}}{x}$

4. $\lim_{x \to 0} \frac{\tan x}{x}$

5. $\lim_{x \to 0} \frac{\sin x}{x}$

6. $\lim_{x \to 0} \frac{x + 1}{x - 1}$

7. $\lim_{x \to 0} \frac{x^{3/2} - 1}{x}$

8. $\lim_{x \to 1^+} \frac{(1/x) - 1}{x - 1}$

9. $\lim_{x \to \infty} \frac{\sqrt{x^2 + x}}{\sqrt{x^2}}$

10. $\lim_{x \to \infty} \frac{x^2 + 2x + 1}{x^2}$

11. $\lim_{x \to \infty} \frac{\sqrt{x^2 + x}}{\sqrt{x^2} + 1}$

12. $\lim_{x \to \infty} \frac{\sqrt{x^2 - 1}}{x}$
4.11 Hyperbolic Functions

DEFINITION 4.11.3 The other hyperbolic functions are

\[
\begin{align*}
\tanh x &= \frac{\sinh x}{\cosh x} \\
\coth x &= \frac{\cosh x}{\sinh x} \\
\sech x &= \frac{1}{\cosh x} \\
\csch x &= \frac{1}{\sinh x}
\end{align*}
\]

The domain of coth and csch is \(x \neq 0\) while the domain of the other hyperbolic functions is all real numbers. Graphs are shown in figure 4.11.1.

Certainly the hyperbolic functions do not closely resemble the trigonometric functions graphically. But they do have analogous properties, beginning with the following identity.

THEOREM 4.11.4 For all \(x \in \mathbb{R}\), \(\cosh^2 x - \sinh^2 x = 1\).

Proof. The proof is a straightforward computation.

\[
\cosh^2 x - \sinh^2 x = \left(\frac{e^x + e^{-x}}{2}\right)^2 - \left(\frac{e^x - e^{-x}}{2}\right)^2 = \frac{e^{2x} + 2 + e^{-2x}}{4} - \frac{e^{2x} - 2e^x - 2e^{-x} + 1}{4} = \frac{4 - 4}{4} = 1.
\]

This immediately gives two additional identities:

\[
1 - \tanh^2 x = \text{sech}^2 x \quad \text{and} \quad \coth^2 x - 1 = \text{csch}^2 x.
\]

The identity of the theorem also helps to provide a geometric motivation. Recall that the graph of \(x^2 - y^2 = 1\) is a hyperbola with asymptotes \(y = \pm x\) whose axes-intcepts are \(\pm 1\). If \((x, y)\) is a point on the right half of the hyperbola, and if we let \(x = \cosh t\), then \(y = \sqrt{x^2 - 1} = \pm \sinh t\). So for some suitable \(t\), \(\cosh t\) and \(\sinh t\) are the coordinates of a typical point on the hyperbola. In fact, it turns out that \(t\) is twice the area shown in the first graph of figure 4.11.2. Even this is analogous to trigonometry; \(\cos t\) and \(\sin t\) are the coordinates of a typical point on the unit circle, and \(t\) is twice the area shown in the second graph of figure 4.11.2.

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50. The function \(f(x) = \frac{1}{x}\) has two horizontal asymptotes. Find them and give a rough sketch of \(f\) with its horizontal asymptotes.

4.11 Hyperbolic Functions

The hyperbolic functions appear with some frequency in applications, and are quite similar in many respects to the trigonometric functions. This is a bit surprising given our initial definitions.

DEFINITION 4.11.1 The hyperbolic cosine is the function

\[
\cosh x = \frac{e^x + e^{-x}}{2}
\]

and the hyperbolic sine is the function

\[
\sinh x = \frac{e^x - e^{-x}}{2}
\]

Notice that \(\sinh x\) is even (that is, \(\cosh(-x) = \cosh(x)\)); while \(\sinh x\) is odd (\(\sinh(-x) = -\sinh(x)\)), and \(\cosh x + \sinh x = e^x\). Also, for all \(x\), \(\cosh x > 0\), while \(\sinh x = 0\) if and only if \(e^x - e^{-x} = 0\), which is true precisely when \(x = 0\).

LEMMA 4.11.2 The range of \(\cosh x\) is \([1, \infty)\).

Proof. Let \(y = \cosh x\). We solve for \(x\):

\[
y = \frac{e^x + e^{-x}}{2}
\]

\[
2y = e^x + e^{-x}
\]

\[
2y = e^x + e^{-x} = e^x + 1
\]

\[
0 = e^x - 2ye^x + 1
\]

\[
e^x - 2ye^x + 1
\]

\[
e^x = y \pm \sqrt{y^2 - 1}
\]

From the last equation, we see \(y^2 \geq 1\), and since \(y \geq 0\), it follows that \(y \geq 1\).

Now suppose \(y \geq 1\), so \(y \pm \sqrt{y^2 - 1} > 0\). Then \(x = \ln(y \pm \sqrt{y^2 - 1})\) is a real number, and \(y = \cosh x\), so \(y\) is in the range of \(\cosh(x)\).
4.11 Hyperbolic Functions

The other derivatives are left to the exercises.

Exercises 4.11.

1. Show that the range of sinh $x$ is all real numbers. (Hint: show that if $y = \sinh x$ then $x = \ln(y + \sqrt{y^2 + 1})$.)

2. Compute the following limits:
   a. $\lim_{x \to \infty} \cosh x$
   b. $\lim_{x \to \infty} \sinh x$
   c. $\lim_{x \to \infty} \tanh x$
   d. $\lim_{x \to \infty} (\cosh x - \sinh x)$

3. Show that the range of tanh $x$ is $(-1, 1)$. What are the ranges of coth, sech, and csch? (Use the fact that they are reciprocal functions.)

4. Prove that for every $x, y \in \mathbb{R}$, $\sinh(x + y) = \sinh x \cosh y + \cosh x \sinh y$. Obtain a similar identity for $\sinh(x - y)$.

5. Prove that for every $x, y \in \mathbb{R}$, $\cosh(x + y) = \cosh x \cosh y + \sinh x \sinh y$. Obtain a similar identity for $\cosh(x - y)$.

6. Use exercises 4 and 5 to show that $\sinh(2x) = 2\sinh x \cosh x$ and $\cosh(2x) = \cosh^2 x + \sinh^2 x$ for every $x$. Conclude also that $((\cosh(2x) - 1)/2 = \sinh^2 x$.

7. Show that $\frac{d}{dx}(\tanh x) = \text{sech}^2 x$. Compute the derivatives of the remaining hyperbolic functions as well.

8. What are the domains of the six inverse hyperbolic functions?

9. Sketch the graphs of all six inverse hyperbolic functions.