

4

Transcendental Functions

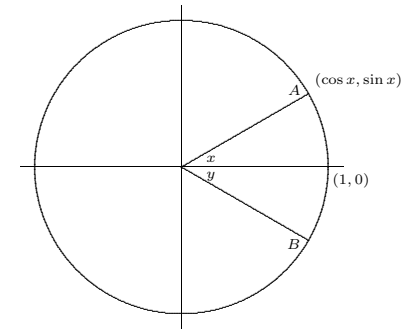
So far we have used only algebraic functions as examples when finding derivatives, that is, functions that can be built up by the usual algebraic operations of addition, subtraction, multiplication, division, and raising to constant powers. Both in theory and practice there are other functions, called 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.

72 Chapter 4 Transcendental Functions

To define the radian measurement system, we consider the unit circle in the xy -plane:



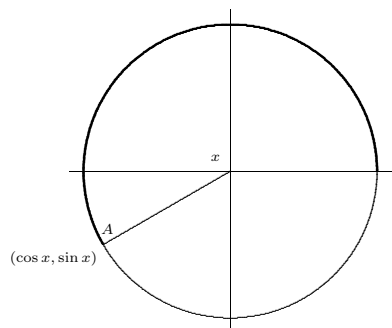
An angle, x , at the center of the circle is associated with an arc of the circle which is said to **subtend** the angle. In the figure, this arc is the portion of the circle from point $(1, 0)$ to point A . The length of this arc is the radian measure of the angle x ; the fact that the radian measure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

While an angle with a particular measure can appear anywhere around the circle, we need a fixed, conventional location so that we can use the coordinate system to define properties of the angle. The standard convention is to place the starting radius for the angle on the positive x -axis, and to measure positive angles counterclockwise around the circle. In the figure, x is the standard location of the angle $\pi/6$, that is, the length of the arc from $(1, 0)$ to A is $\pi/6$. The angle y in the picture is $-\pi/6$, because the distance from $(1, 0)$ to B along the circle is also $\pi/6$, but in a clockwise direction.

Now the fundamental trigonometric definitions are: the cosine of x and the sine of x are the first and second coordinates of the point A , as indicated in the figure. The angle x shown can be viewed as an angle of a right triangle, meaning the usual triangle definitions of the sine and cosine also make sense. Since the hypotenuse of the triangle is 1, the “side opposite over hypotenuse” definition of the sine is the second coordinate of point A over 1, which is just the second coordinate; in other words, both methods give the same value for the sine.

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:



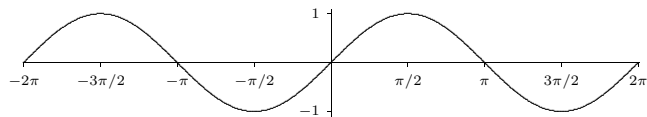
The angle x is subtended by the heavy arc in the figure, that is, $x = 7\pi/6$. Both coordinates of point A in this figure are negative, so the sine and cosine of $7\pi/6$ are both negative.

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

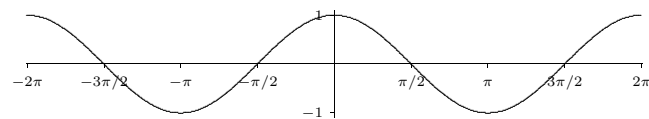
$$\begin{aligned}\tan x &= \frac{\sin x}{\cos x} \\ \cot x &= \frac{\cos x}{\sin x} \\ \sec x &= \frac{1}{\cos x} \\ \csc x &= \frac{1}{\sin x}\end{aligned}$$

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 graphs 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:



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



Exercises 4.1.

Some useful trigonometric identities are in appendix B.

1. Find all values of θ such that $\sin(\theta) = -1$; give your answer in radians. \Rightarrow
2. Find all values of θ such that $\cos(2\theta) = 1/2$; 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 $\cos^2(t)/(1 - \sin(t)) = 1 + \sin(t)$.
6. Verify the identity $2 \csc(2\theta) = \sec(\theta) \csc(\theta)$.
7. Verify the identity $\sin(3\theta) - \sin(\theta) = 2 \cos(2\theta) \sin(\theta)$.
8. Sketch $y = 2 \sin(x)$.
9. Sketch $y = \sin(3x)$.
10. Sketch $y = \sin(-x)$.
11. Find all of the solutions of $2 \sin(t) - 1 - \sin^2(t) = 0$ 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:

$$\frac{d}{dx} \sin x = \lim_{\Delta x \rightarrow 0} \frac{\sin(x + \Delta x) - \sin x}{\Delta x}.$$

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

$$\begin{aligned}\frac{\sin(x + \Delta x) - \sin x}{\Delta x} &= \frac{\sin x \cos \Delta x + \sin \Delta x \cos x - \sin x}{\Delta x} \\ &= \sin x \frac{\cos \Delta x - 1}{\Delta x} + \cos x \frac{\sin \Delta x}{\Delta x}.\end{aligned}$$

This isolates the difficult bits in the two limits

$$\lim_{\Delta x \rightarrow 0} \frac{\cos \Delta x - 1}{\Delta x} \quad \text{and} \quad \lim_{\Delta x \rightarrow 0} \frac{\sin \Delta x}{\Delta x}.$$

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:

$$\lim_{\Delta x \rightarrow 0} \frac{\sin \Delta x}{\Delta x}.$$

Equivalently, to make the notation a bit simpler, we can compute

$$\lim_{x \rightarrow 0} \frac{\sin x}{x}.$$

In the original context we need to keep x and Δx separate, but here it doesn't hurt to rename Δx 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 $\lim_{x \rightarrow a} g(x) = L = \lim_{x \rightarrow a} h(x)$, then $\lim_{x \rightarrow a} f(x) = L$. ■

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 $x^2 \sin(\pi/x)$, the upper and lower curves are x^2 and $-x^2$. Since the sine function is always between -1 and 1 , $-x^2 \leq x^2 \sin(\pi/x) \leq x^2$, and it is easy to see that $\lim_{x \rightarrow 0} -x^2 = 0 = \lim_{x \rightarrow 0} x^2$. It is not so easy to see directly, that is algebraically, that $\lim_{x \rightarrow 0} x^2 \sin(\pi/x) = 0$, because the π/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, $\lim_{x \rightarrow 0} (\sin x)/x$, we will find two simpler functions g and h so that $g(x) \leq (\sin x)/x \leq h(x)$, and so that $\lim_{x \rightarrow 0} g(x) = \lim_{x \rightarrow 0} h(x)$. 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

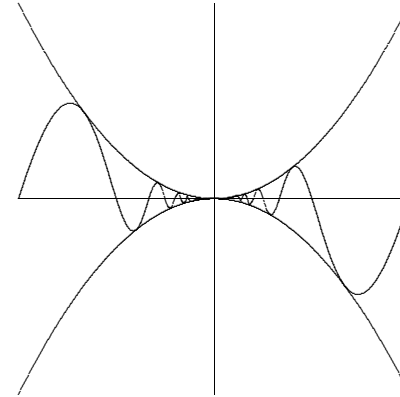


Figure 4.3.1 The squeeze theorem.

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 bordered 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 θ and radius r is $\theta r^2/2$. With a little algebra this turns into $(\sin x)/x \leq 1/\cos x$, giving us the h we seek.

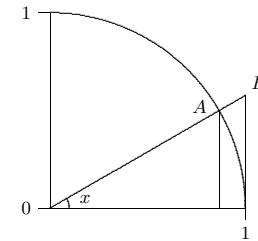


Figure 4.3.2 Visualizing $\sin x/x$.

To find g , we note that the circular wedge is completely contained inside the larger triangle. The height of the triangle, from $(1, 0)$ to point B , is $\tan x$, so comparing areas we get $x/2 \leq (\tan x)/2 = \sin x/(2 \cos x)$. With a little algebra this becomes $\cos x \leq (\sin x)/x$. So now we have

$$\cos x \leq \frac{\sin x}{x} \leq \frac{1}{\cos x}.$$

Finally, the two limits $\lim_{x \rightarrow 0} \cos x$ and $\lim_{x \rightarrow 0} 1/\cos x$ are easy, because $\cos(0) = 1$. By the squeeze theorem, $\lim_{x \rightarrow 0} (\sin x)/x = 1$ as well.

Before we can complete the calculation of the derivative of the sine, we need one other limit:

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

This limit is just as hard as $\sin x/x$, but closely related to it, so that we don't have to do a similar calculation; instead we can do a bit of tricky algebra.

$$\frac{\cos x - 1}{x} = \frac{\cos x - 1}{x} \frac{\cos x + 1}{\cos x + 1} = \frac{\cos^2 x - 1}{x(\cos x + 1)} = \frac{-\sin^2 x}{x(\cos x + 1)} = -\frac{\sin x}{x} \frac{\sin x}{\cos x + 1}.$$

To compute the desired limit it is sufficient to compute the limits of the two final fractions, as x goes to 0. The first of these is the hard limit we've just done, namely 1. The second turns out to be simple, because the denominator presents no problem:

$$\lim_{x \rightarrow 0} \frac{\sin x}{\cos x + 1} = \frac{\sin 0}{\cos 0 + 1} = \frac{0}{2} = 0.$$

Thus,

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

Exercises 4.3.

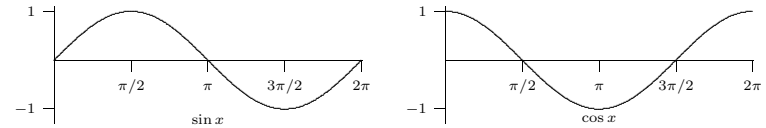
1. Compute $\lim_{x \rightarrow 0} \frac{\sin(5x)}{x} \Rightarrow$
2. Compute $\lim_{x \rightarrow 0} \frac{\sin(7x)}{\sin(2x)} \Rightarrow$
3. Compute $\lim_{x \rightarrow 0} \frac{\cot(4x)}{\csc(3x)} \Rightarrow$
4. Compute $\lim_{x \rightarrow 0} \frac{\tan x}{x} \Rightarrow$
5. Compute $\lim_{x \rightarrow \pi/4} \frac{\sin x - \cos x}{\cos(2x)} \Rightarrow$
6. For all $x \geq 0$, $4x - 9 \leq f(x) \leq x^2 - 4x + 7$. Find $\lim_{x \rightarrow 4} f(x)$. \Rightarrow
7. For all x , $2x \leq g(x) \leq x^4 - x^2 + 2$. Find $\lim_{x \rightarrow 1} g(x)$. \Rightarrow
8. Use the Squeeze Theorem to show that $\lim_{x \rightarrow 0} x^4 \cos(2/x) = 0$.

4.4 THE DERIVATIVE OF $\sin x$, CONTINUED

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

$$\begin{aligned} \frac{d}{dx} \sin x &= \lim_{\Delta x \rightarrow 0} \frac{\sin(x + \Delta x) - \sin x}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} \sin x \frac{\cos \Delta x - 1}{\Delta x} + \cos x \frac{\sin \Delta x}{\Delta x} \\ &= \sin x \cdot 0 + \cos x \cdot 1 = \cos x. \end{aligned}$$

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:



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 $\sin^2(x^3 - 5x)$.

$$\begin{aligned} \frac{d}{dx} \sin^2(x^3 - 5x) &= \frac{d}{dx} (\sin(x^3 - 5x))^2 \\ &= 2(\sin(x^3 - 5x))^1 \cos(x^3 - 5x)(3x^2 - 5) \\ &= 2(3x^2 - 5) \cos(x^3 - 5x) \sin(x^3 - 5x). \end{aligned}$$

□

Exercises 4.4.

Find the derivatives of the following functions.

1. $\sin^2(\sqrt{x}) \Rightarrow$
2. $\sqrt{x} \sin x \Rightarrow$
3. $\frac{1}{\sin x} \Rightarrow$
4. $\frac{x^2 + x}{\sin x} \Rightarrow$
5. $\sqrt{1 - \sin^2 x} \Rightarrow$

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,

$$\begin{aligned}\cos x &= \sin\left(x + \frac{\pi}{2}\right), \\ \sin x &= -\cos\left(x + \frac{\pi}{2}\right).\end{aligned}$$

Now:

$$\begin{aligned}\frac{d}{dx} \cos x &= \frac{d}{dx} \sin\left(x + \frac{\pi}{2}\right) = \cos\left(x + \frac{\pi}{2}\right) \cdot 1 = -\sin x \\ \frac{d}{dx} \tan x &= \frac{d}{dx} \frac{\sin x}{\cos x} = \frac{\cos^2 x + \sin^2 x}{\cos^2 x} = \frac{1}{\cos^2 x} = \sec^2 x \\ \frac{d}{dx} \sec x &= \frac{d}{dx} (\cos x)^{-1} = -1(\cos x)^{-2}(-\sin x) = \frac{\sin x}{\cos^2 x} = \sec x \tan x\end{aligned}$$

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

Exercises 4.5.

Find the derivatives of the following functions.

1. $\sin x \cos x \Rightarrow$
2. $\sin(\cos x) \Rightarrow$
3. $\sqrt{x} \tan x \Rightarrow$
4. $\tan x / (1 + \sin x) \Rightarrow$
5. $\cot x \Rightarrow$
6. $\csc x \Rightarrow$
7. $x^3 \sin(23x^2) \Rightarrow$
8. $\sin^2 x + \cos^2 x \Rightarrow$
9. $\sin(\cos(6x)) \Rightarrow$
10. Compute $\frac{d}{d\theta} \frac{\sec \theta}{1 + \sec \theta} \Rightarrow$
11. Compute $\frac{d}{dt} t^5 \cos(6t) \Rightarrow$
12. Compute $\frac{d}{dt} \frac{t^3 \sin(3t)}{\cos(2t)} \Rightarrow$
13. Find all points on the graph of $f(x) = \sin^2(x)$ at which the tangent line is horizontal. \Rightarrow

80 Chapter 4 Transcendental Functions

14. Find all points on the graph of $f(x) = 2 \sin(x) - \sin^2(x)$ at which the tangent line is horizontal. \Rightarrow
15. Find an equation for the tangent line to $\sin^2(x)$ at $x = \pi/3$. \Rightarrow
16. Find an equation for the tangent line to $\sec^2 x$ at $x = \pi/3$. \Rightarrow
17. Find an equation for the tangent line to $\cos^2 x - \sin^2(4x)$ at $x = \pi/6$. \Rightarrow
18. Find the points on the curve $y = x + 2 \cos x$ that have a horizontal tangent line. \Rightarrow
19. Let C be a circle of radius r . Let A be an arc on C subtending a central angle θ . Let B be the chord of C whose endpoints are the endpoints of A . (Hence, B also subtends θ .) Let s be the length of A and let d be the length of B . Sketch a diagram of the situation and compute $\lim_{\theta \rightarrow 0^+} s/d$.

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 functions are the **inverses** of the exponential functions, that is, functions that “undo” the exponential functions, just as, for example, the cube root function “undoes” the cube function: $\sqrt[3]{2^3} = 2$. Note that the original function also undoes the inverse function: $(\sqrt[3]{8})^3 = 8$.

Let $f(x) = 2^x$. The inverse of this function is called the logarithm base 2, denoted $\log_2(x)$ or (especially in computer science circles) $\lg(x)$. What does this really mean? The logarithm must undo the action of the exponential function, so for example it must be that $\lg(2^3) = 3$ —starting with 3, the exponential function produces $2^3 = 8$, and the logarithm of 8 must get us back to 3. A little thought shows that it is not a coincidence that $\lg(2^3)$ simply gives the exponent—the exponent *is* the original value that we must get back to. In other words, *the logarithm is the exponent*. Remember this catchphrase, and what it means, and you won’t go wrong. (You *do* have to remember what it means. Like any good mnemonic, “the logarithm is the exponent” leaves out a lot of detail, like “Which exponent?” and “Exponent of what?”)

EXAMPLE 4.6.1 What is 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 E makes $10^E = 1000$? If we can find such an E , then $\log_{10}(1000) = \log_{10}(10^E) = E$; finding the appropriate exponent is the same as finding the logarithm. In this case, of course, it is easy: $E = 3$ so $\log_{10}(1000) = 3$. \square

Let’s review some laws of exponents and logarithms; let a be a positive number. Since $a^5 = a \cdot a \cdot a \cdot a \cdot a$ and $a^3 = a \cdot a \cdot a$, it’s clear that $a^5 \cdot a^3 = a \cdot a \cdot a \cdot a \cdot a \cdot a \cdot a \cdot a = a^8 = a^{5+3}$, and in general that $a^m a^n = a^{m+n}$. Since “the logarithm is the exponent,” it’s no surprise that this translates directly into a fact about the logarithm function. Here are three facts

from the example: $\log_a(a^5) = 5$, $\log_a(a^3) = 3$, $\log_a(a^8) = 8$. So $\log_a(a^5 a^3) = \log_a(a^8) = 8 = 5 + 3 = \log_a(a^5) + \log_a(a^3)$. Now let's make this a bit more general. Suppose A and B are two numbers, $A = a^x$, and $B = a^y$. Then $\log_a(AB) = \log_a(a^x a^y) = \log_a(a^{x+y}) = x + y = \log_a(A) + \log_a(B)$.

Now consider $(a^5)^3 = a^5 \cdot a^5 \cdot a^5 = a^{5+5+5} = a^{5 \cdot 3} = a^{15}$. Again it's clear that more generally $(a^m)^n = a^{mn}$, and again this gives us a fact about logarithms. If $A = a^x$ then $A^y = (a^x)^y = a^{xy}$, so $\log_a(A^y) = xy = y \log_a(A)$ —the exponent can be “pulled out in front.”

We have cheated a bit in the previous two paragraphs. It is obvious that $a^5 = a \cdot a \cdot a \cdot a \cdot a$ and $a^3 = a \cdot a \cdot a$ and that the rest of the example follows; likewise for the second example. But when we consider an exponential function a^x we can't be limited to substituting integers for x . What does $a^{2.5}$ or $a^{-1.3}$ or a^π mean? And is it really true that $a^{2.5} a^{-1.3} = a^{2.5-1.3}$? The answer to the first question is actually quite difficult, so we will evade it; the answer to the second question is “yes.”

We'll evade the full answer to the hard question, but we have to know something about exponential functions. You need first to understand that since it's not “obvious” what 2^x should mean, we are really free to make it mean whatever we want, so long as we keep the behavior that *is* obvious, namely, when x is a positive integer. What else do we want to be true about 2^x ? We want the properties of the previous two paragraphs to be true for all exponents: $2^x 2^y = 2^{x+y}$ and $(2^x)^y = 2^{xy}$.

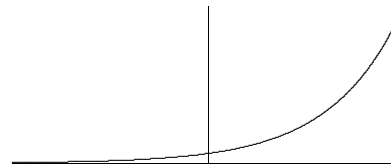
After the positive integers, the next easiest number to understand is 0: $2^0 = 1$. You have presumably learned this fact in the past; why is it true? It is true precisely because we want $2^a 2^b = 2^{a+b}$ to be true about the function 2^x . We need it to be true that $2^0 2^x = 2^{0+x} = 2^x$, and this only works if $2^0 = 1$. The same argument implies that $a^0 = 1$ for any a .

The next easiest set of numbers to understand is the negative integers: for example, $2^{-3} = 1/2^3$. We know that whatever 2^{-3} means it must be that $2^{-3} 2^3 = 2^{-3+3} = 2^0 = 1$, which means that 2^{-3} must be $1/2^3$. In fact, by the same argument, once we know what 2^x means for some value of x , 2^{-x} must be $1/2^x$ and more generally $a^{-x} = 1/a^x$.

Next, consider an exponent $1/q$, where q is a positive integer. We want it to be true that $(2^x)^y = 2^{xy}$, so $(2^{1/q})^q = 2$. This means that $2^{1/q}$ is a q -th root of 2, $2^{1/q} = \sqrt[q]{2}$. This is all we need to understand that $2^{p/q} = (2^{1/q})^p = (\sqrt[q]{2})^p$ and $a^{p/q} = (a^{1/q})^p = (\sqrt[q]{a})^p$.

What's left is the hard part: what does 2^x mean when x cannot be written as a fraction, like $x = \sqrt{2}$ or $x = \pi$? What we know so far is how to assign meaning to 2^x

whenever $x = p/q$; if we were to graph this we'd see something like this:



But this is a poor picture, because you can't see that the “curve” is really a whole lot of individual points, above the rational numbers on the x -axis. There are really a lot of “holes” in the curve, above $x = \pi$, for example. But (this is the hard part) it is possible to prove that the holes can be “filled in”, and that the resulting function, called 2^x , really does have the properties we want, namely that $2^x 2^y = 2^{x+y}$ and $(2^x)^y = 2^{xy}$.

Exercises 4.6.

1. Expand $\log_{10}((x + 45)^7(x - 2))$.
2. Expand $\log_2 \frac{x^3}{3x - 5 + (7/x)}$.
3. Write $\log_2 3x + 17 \log_2(x - 2) - 2 \log_2(x^2 + 4x + 1)$ as a single logarithm.
4. Solve $\log_2(1 + \sqrt{x}) = 6$ for x .
5. Solve $2^{x^2} = 8$ for x .
6. Solve $\log_2(\log_3(x)) = 1$ for x .

4.7 DERIVATIVES OF THE EXPONENTIAL AND LOGARITHMIC FUNCTIONS

As 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:

$$\begin{aligned} \frac{d}{dx} a^x &= \lim_{\Delta x \rightarrow 0} \frac{a^{x+\Delta x} - a^x}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} \frac{a^x a^{\Delta x} - a^x}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} a^x \frac{a^{\Delta x} - 1}{\Delta x} \\ &= a^x \lim_{\Delta x \rightarrow 0} \frac{a^{\Delta x} - 1}{\Delta x} \end{aligned}$$

There are two interesting things to note here: As in the case of the sine function we are left with a limit that involves Δx but not x , which means that whatever $\lim_{\Delta x \rightarrow 0} (a^{\Delta x} - 1)/\Delta x$ 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 $\lim_{x \rightarrow 0} \sin x/x = 1$; we now have a limit that is just a bit too hard to include here. In fact the hard part is to see that $\lim_{\Delta x \rightarrow 0} (a^{\Delta x} - 1)/\Delta x$ even exists—does this fraction 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, 0.756828460, 0.724061864, 0.70838051, 0.70070877 when x is 1, 1/2, 1/4, 1/8, 1/16, 1/32, respectively. It looks like this is settling in around 0.7, which turns out to be true (but the limit is not exactly 0.7). Consider next $(3^x - 1)/x$: 2, 1.464101616, 1.264296052, 1.177621520, 1.13720773, 1.11768854, at the same values of x . It turns out to be true that in the limit this is about 1.1. 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

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

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:

$$\begin{aligned} \frac{d}{dx} e^x &= \lim_{\Delta x \rightarrow 0} \frac{e^{x+\Delta x} - e^x}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} \frac{e^x e^{\Delta x} - e^x}{\Delta x} \\ &= \lim_{\Delta x \rightarrow 0} e^x \frac{e^{\Delta x} - 1}{\Delta x} \\ &= e^x \lim_{\Delta x \rightarrow 0} \frac{e^{\Delta x} - 1}{\Delta x} \\ &= e^x \end{aligned}$$

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 $f(x) = e^x$ 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^x without an exponent, since complicated exponents can be hard to read. In such cases we use $\exp(x)$, e.g., $\exp(1 + x^2)$ instead of e^{1+x^2} .

What about the logarithm function? This too is hard, but as the cosine function was easier to do once the sine was done, so the logarithm is easier to do now that we know the derivative of the exponential function. Let's start with $\log_e x$, which as you probably know is often abbreviated $\ln x$ and called the "natural logarithm" function.

Consider the relationship between the two functions, namely, that they are inverses, that one "undoes" the other. Graphically this means that they have the same graph except that one is "flipped" or "reflected" through the line $y = x$, as shown in figure 4.7.1.

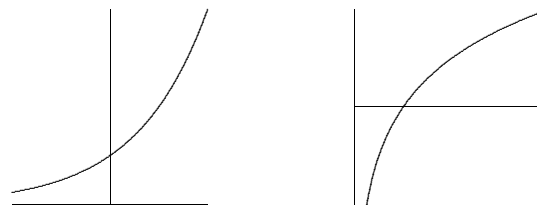


Figure 4.7.1 The exponential and logarithm functions.

This means that the slopes of these two functions are closely related as well: For example, the slope of e^x is e at $x = 1$; at the corresponding point on the $\ln(x)$ curve, the slope must be $1/e$, because the "rise" and the "run" have been interchanged. Since the slope of e^x is e at the point $(1, e)$, the slope of $\ln(x)$ is $1/e$ at the point $(e, 1)$.



Figure 4.7.2 Slope of the exponential and logarithm functions.

More generally, we know that the slope of e^x is e^z at the point (z, e^z) , so the slope of $\ln(x)$ is $1/e^z$ at (e^z, z) , as indicated in figure 4.7.2. In other words, the slope of $\ln x$ is the reciprocal of the first coordinate at any point; this means that the slope of $\ln x$ at $(x, \ln x)$ is $1/x$. The upshot is:

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

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.

Note that $\ln x$ is defined only for $x > 0$. It is sometimes useful to consider the function $\ln|x|$, a function defined for $x \neq 0$. When $x < 0$, $\ln|x| = \ln(-x)$ and

$$\frac{d}{dx} \ln|x| = \frac{d}{dx} \ln(-x) = \frac{1}{-x}(-1) = \frac{1}{x}.$$

Thus whether x is positive or negative, the derivative is the same.

What about the functions a^x and $\log_a x$? We know that the derivative of a^x is some constant times a^x itself, but what constant? Remember that “the logarithm is the exponent” and you will see that $a = e^{\ln a}$. Then

$$a^x = (e^{\ln a})^x = e^{x \ln a},$$

and we can compute the derivative using the chain rule:

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

The constant is simply $\ln a$. Likewise we can compute the derivative of the logarithm function $\log_a x$. Since

$$x = e^{\ln x}$$

we can take the logarithm base a of both sides to get

$$\log_a(x) = \log_a(e^{\ln x}) = \ln x \log_a e.$$

Then

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

This is a perfectly good answer, but we can improve it slightly. Since

$$\begin{aligned} a &= e^{\ln a} \\ \log_a(a) &= \log_a(e^{\ln a}) = \ln a \log_a e \\ 1 &= \ln a \log_a e \\ \frac{1}{\ln a} &= \log_a e, \end{aligned}$$

we can replace $\log_a e$ to get

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

You may if you wish memorize the formulas

$$\frac{d}{dx} a^x = (\ln a) a^x \quad \text{and} \quad \frac{d}{dx} \log_a x = \frac{1}{x \ln a}.$$

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 $f(x) = 2^x$.

$$\begin{aligned} \frac{d}{dx} 2^x &= \frac{d}{dx} (e^{\ln 2})^x \\ &= \frac{d}{dx} e^{x \ln 2} \\ &= \left(\frac{d}{dx} x \ln 2 \right) e^{x \ln 2} \\ &= (\ln 2) e^{x \ln 2} = 2^x \ln 2 \end{aligned} \quad \square$$

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

$$\begin{aligned} \frac{d}{dx} 2^{x^2} &= \frac{d}{dx} e^{x^2 \ln 2} \\ &= \left(\frac{d}{dx} x^2 \ln 2 \right) e^{x^2 \ln 2} \\ &= (2 \ln 2) x e^{x^2 \ln 2} \\ &= (2 \ln 2) x 2^{x^2} \end{aligned} \quad \square$$

EXAMPLE 4.7.3 Compute the derivative of $f(x) = x^x$. At first this appears to be a new kind of 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.

$$\begin{aligned} \frac{d}{dx} x^x &= \frac{d}{dx} e^{x \ln x} \\ &= \left(\frac{d}{dx} x \ln x \right) e^{x \ln x} \\ &= \left(x \frac{1}{x} + \ln x \right) x^x \\ &= (1 + \ln x) x^x \end{aligned} \quad \square$$

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.

$$\begin{aligned}\frac{d}{dx}x^r &= \frac{d}{dx}e^{r \ln x} \\ &= \left(\frac{d}{dx}r \ln x\right)e^{r \ln x} \\ &= \left(r \frac{1}{x}\right)x^r \\ &= rx^{r-1}\end{aligned}$$

□

Exercises 4.7.

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

- | | |
|---|--|
| 1. $3^{x^2} \Rightarrow$ | 2. $\frac{\sin x}{e^x} \Rightarrow$ |
| 3. $(e^x)^2 \Rightarrow$ | 4. $\sin(e^x) \Rightarrow$ |
| 5. $e^{\sin x} \Rightarrow$ | 6. $x^{\sin x} \Rightarrow$ |
| 7. $x^3 e^x \Rightarrow$ | 8. $x + 2^x \Rightarrow$ |
| 9. $(1/3)^{x^2} \Rightarrow$ | 10. $e^{4x}/x \Rightarrow$ |
| 11. $\ln(x^3 + 3x) \Rightarrow$ | 12. $\ln(\cos(x)) \Rightarrow$ |
| 13. $\sqrt{\ln(x^2)/x} \Rightarrow$ | 14. $\ln(\sec(x) + \tan(x)) \Rightarrow$ |
| 15. $x^{\cos(x)} \Rightarrow$ | 16. $x \ln x$ |
| 17. $\ln(\ln(3x))$ | 18. $\frac{1 + \ln(3x^2)}{1 + \ln(4x)}$ |
| 19. $\frac{x^8(x-23)^{1/2}}{27x^6(4x-6)^8}$ | |

20. Find the value of a so that the tangent line to $y = \ln(x)$ at $x = a$ is a line through the origin. Sketch the resulting situation. \Rightarrow
21. If $f(x) = \ln(x^3 + 2)$ compute $f'(e^{1/3})$.

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.

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 $x = e^{\ln x} = e^y$, 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 $y = \dots$, 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:

$$1 = \left(\frac{d}{dx}y\right)e^y = y'e^y.$$

Then we can solve for y' :

$$y' = \frac{1}{e^y} = \frac{1}{x}.$$

There is one little difficulty here. To use the chain rule to compute $d/dx(e^y) = y'e^y$ we need to know that the function y has a derivative. All we have shown is that *if* it has a derivative then that derivative must be $1/x$. 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 $y = \ln x$ 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 $r^2 = x^2 + y^2$ 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 $r^2 = x^2 + y^2$: both $r^2 = x^2 + U(x)^2$ and $r^2 = x^2 + L(x)^2$ are true, and we can think of $r^2 = x^2 + y^2$ 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 where y appears.

$$\begin{aligned}\frac{d}{dx}r^2 &= \frac{d}{dx}(x^2 + y^2) \\ 0 &= 2x + 2yy' \\ y' &= \frac{-2x}{2y} = -\frac{x}{y}\end{aligned}$$

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 is $U(x)$ 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 $4 = x^2 + y^2$ 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 $y = L(x) = -\sqrt{4 - x^2}$. We could then take the derivative of $L(x)$, using the power rule and the chain rule, to get

$$L'(x) = -\frac{1}{2}(4 - x^2)^{-1/2}(-2x) = \frac{x}{\sqrt{4 - x^2}}.$$

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

Alternately, 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

$$y' = -\frac{x}{L(x)} = \frac{x}{\sqrt{4 - x^2}},$$

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

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.

EXAMPLE 4.8.2 Find the derivative of any function defined implicitly by $yx^2 + e^y = x$. We treat y as an unspecified function and use the chain rule:

$$\begin{aligned}\frac{d}{dx}(yx^2 + e^y) &= \frac{d}{dx}x \\ (y \cdot 2x + y' \cdot x^2) + y'e^y &= 1 \\ y'x^2 + y'e^y &= 1 - 2xy \\ y'(x^2 + e^y) &= 1 - 2xy \\ y' &= \frac{1 - 2xy}{x^2 + e^y}\end{aligned}\quad \square$$

You might think that the step in which we solve for y' could sometimes be difficult—after all, we're using implicit differentiation here because we can't solve the equation $yx^2 + e^y = x$ for y , so maybe after taking the derivative we get something that is hard to solve for y' . In fact, *this never happens*. All occurrences y' come from applying the chain rule, and whenever the chain rule is used it deposits a single y' multiplied by some other expression. So it will always be possible to group the terms containing y' together and factor out the y' , just as in the previous example. If you ever get anything more difficult you have made a mistake and should fix it before trying to continue.

It is sometimes the case that a situation leads naturally to an equation that defines a function implicitly.

EXAMPLE 4.8.3 Consider all the points (x, y) that have the property that the distance from (x, y) to (x_1, y_1) plus the distance from (x, y) to (x_2, y_2) is $2a$ (a is some constant). These points form an ellipse, which like a circle is not a function but can be viewed as two functions pasted together. Because we know how to write down the distance between two points, we can write down an implicit equation for the ellipse:

$$\sqrt{(x - x_1)^2 + (y - y_1)^2} + \sqrt{(x - x_2)^2 + (y - y_2)^2} = 2a.$$

Then we can use implicit differentiation to find the slope of the ellipse at any point, though the computation is rather messy. \square

EXAMPLE 4.8.4 We have already justified the power rule by using the exponential function, but we could also do it for rational exponents by using implicit differentiation. Suppose that $y = x^{m/n}$, where m and n are positive integers. We can write this implicitly as $y^n = x^m$, then because we justified the power rule for integers, we can take the derivative

of each side:

$$\begin{aligned} ny^{n-1}y' &= mx^{m-1} \\ y' &= \frac{m}{n} \frac{x^{m-1}}{y^{n-1}} \\ y' &= \frac{m}{n} \frac{x^{m-1}}{(x^{m/n})^{n-1}} \\ y' &= \frac{m}{n} x^{m-1-(m/n)(n-1)} \\ y' &= \frac{m}{n} x^{m-1-m+(m/n)} \\ y' &= \frac{m}{n} x^{(m/n)-1} \end{aligned}$$

□

Exercises 4.8.

In exercises 1–8, find a formula for the derivative y' at the point (x, y) :

- $y^2 = 1 + x^2 \Rightarrow$
- $x^2 + xy + y^2 = 7 \Rightarrow$
- $x^3 + xy^2 = y^3 + yx^2 \Rightarrow$
- $4 \cos x \sin y = 1 \Rightarrow$
- $\sqrt{x} + \sqrt{y} = 9 \Rightarrow$
- $\tan(x/y) = x + y \Rightarrow$
- $\sin(x + y) = xy \Rightarrow$
- $\frac{1}{x} + \frac{1}{y} = 7 \Rightarrow$
- A hyperbola passing through $(8, 6)$ consists of all points whose distance from the origin is a constant more than its distance from the point $(5, 2)$. Find the slope of the tangent line to the hyperbola at $(8, 6)$. \Rightarrow
- Compute y' for the ellipse of example 4.8.3.
- If $y = \log_a x$ then $a^y = x$. Use implicit differentiation to find y' .
- The graph of the equation $x^2 - xy + y^2 = 9$ is an ellipse. Find the lines tangent to this curve at the two points where it intersects the x -axis. Show that these lines are parallel. \Rightarrow
- Repeat the previous problem for the points at which the ellipse intersects the y -axis. \Rightarrow
- Find the points on the ellipse from the previous two problems where the slope is horizontal and where it is vertical. \Rightarrow
- Find an equation for the tangent line to $x^4 = y^2 + x^2$ at $(2, \sqrt{12})$. (This curve is the **kampyle of Eudoxus**.) \Rightarrow
- Find an equation for the tangent line to $x^{2/3} + y^{2/3} = a^{2/3}$ at a point (x_1, y_1) on the curve, with $x_1 \neq 0$ and $y_1 \neq 0$. (This curve is an **astroid**.) \Rightarrow
- Find an equation for the tangent line to $(x^2 + y^2)^2 = x^2 - y^2$ at a point (x_1, y_1) on the curve, when $y_1 \neq 0$. (This curve is a **lemniscate**.) \Rightarrow

Definition. Two curves are **orthogonal** if at each point of intersection, the angle between their tangent lines is $\pi/2$. Two families of curves, \mathcal{A} and \mathcal{B} , are **orthogonal trajectories** of each other if given any curve C in \mathcal{A} and any curve D in \mathcal{B} the curves C and D are orthogonal. For example, the family of horizontal lines in the plane is orthogonal to the family of vertical lines in the plane.

- Show that $x^2 - y^2 = 5$ is orthogonal to $4x^2 + 9y^2 = 72$. (Hint: You need to find the intersection points of the two curves and then show that the product of the derivatives at each intersection point is -1 .)
- Show that $x^2 + y^2 = r^2$ is orthogonal to $y = mx$. Conclude that the family of circles centered at the origin is an orthogonal trajectory of the family of lines that pass through the origin.
Note that there is a technical issue when $m = 0$. The circles fail to be differentiable when they cross the x -axis. However, the circles are orthogonal to the x -axis. Explain why. Likewise, the vertical line through the origin requires a separate argument.
- For $k \neq 0$ and $c \neq 0$ show that $y^2 - x^2 = k$ is orthogonal to $yx = c$. In the case where k and c are both zero, the curves intersect at the origin. Are the curves $y^2 - x^2 = 0$ and $yx = 0$ orthogonal to each other?
- Suppose that $m \neq 0$. Show that the family of curves $\{y = mx + b \mid b \in \mathbb{R}\}$ is orthogonal to the family of curves $\{y = -(x/m) + c \mid c \in \mathbb{R}\}$.

4.9 INVERSE TRIGONOMETRIC FUNCTIONS

The trigonometric functions frequently arise in problems, and often it is necessary to invert the functions, for example, to find an angle with a specified sine. Of course, there are many angles with the same sine, so the sine function doesn't actually have an inverse that reliably "undoes" the sine function. If you know that $\sin x = 0.5$, you can't reverse this to discover x , that is, you can't solve for x , as there are infinitely many angles with sine 0.5. Nevertheless, it is useful to have something like an inverse to the sine, however imperfect. The usual approach is to pick out some collection of angles that produce all possible values of the sine exactly once. If we "discard" all other angles, the resulting function does have a proper inverse.

The sine takes on all values between -1 and 1 exactly once on the interval $[-\pi/2, \pi/2]$. If we truncate the sine, keeping only the interval $[-\pi/2, \pi/2]$, as shown in figure 4.9.1, then this truncated sine has an inverse function. We call this the inverse sine or the arcsine, and write $y = \arcsin(x)$.

Recall that a function and its inverse undo each other in either order, for example, $(\sqrt[3]{x})^3 = x$ and $\sqrt[3]{x^3} = x$. This does not work with the sine and the "inverse sine" because the inverse sine is the inverse of the truncated sine function, not the real sine function. It is true that $\sin(\arcsin(x)) = x$, that is, the sine undoes the arcsine. It is not true that the arcsine undoes the sine, for example, $\sin(5\pi/6) = 1/2$ and $\arcsin(1/2) = \pi/6$, so doing first the sine then the arcsine does not get us back where we started. This is because $5\pi/6$

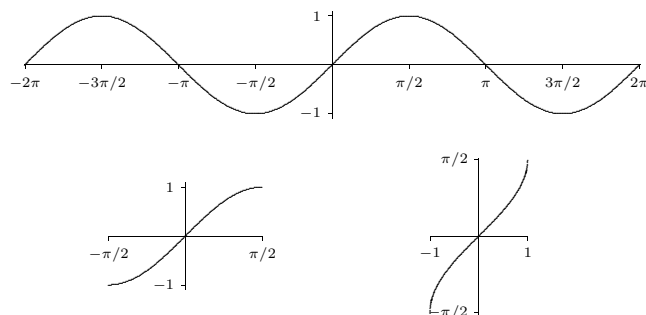


Figure 4.9.1 The sine, the truncated sine, the inverse sine.

is not in the domain of the truncated sine. If we start with an angle between $-\pi/2$ and $\pi/2$ then the arcsine does reverse the sine: $\sin(\pi/6) = 1/2$ and $\arcsin(1/2) = \pi/6$.

What is the derivative of the arcsine? Since this is an inverse function, we can discover the derivative by using implicit differentiation. Suppose $y = \arcsin(x)$. Then

$$\sin(y) = \sin(\arcsin(x)) = x.$$

Now taking the derivative of both sides, we get

$$\begin{aligned} y' \cos y &= 1 \\ y' &= \frac{1}{\cos y} \end{aligned}$$

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 $\sin^2 y + \cos^2 y = 1$, $\cos^2 y = 1 - \sin^2 y = 1 - x^2$. So $\cos y = \pm\sqrt{1-x^2}$, 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 $\cos y = \sqrt{1-x^2}$ 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

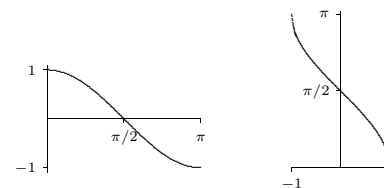


Figure 4.9.2 The truncated cosine, the inverse cosine.

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.

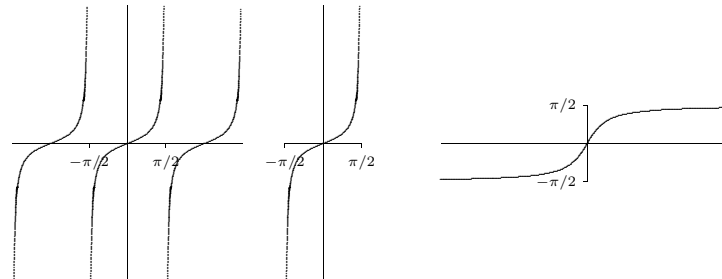


Figure 4.9.3 The tangent, the truncated tangent, the inverse tangent.

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 $\frac{1}{1+x^2}$.

3. The inverse of cot is usually defined so that the range of arccot is $(0, \pi)$. Sketch the graph of $y = \operatorname{arccot} x$. In the process you will make it clear what the domain of arccot is. Find the derivative of the arccotangent. \Rightarrow
4. Show that $\operatorname{arccot} x + \arctan x = \pi/2$.
5. Find the derivative of $\arcsin(x^2)$. \Rightarrow
6. Find the derivative of $\arctan(e^x)$. \Rightarrow
7. Find the derivative of $\arccos(\sin x^3)$. \Rightarrow
8. Find the derivative of $\ln((\arcsin x)^2)$. \Rightarrow
9. Find the derivative of $\arccos e^x$. \Rightarrow
10. Find the derivative of $\arcsin x + \arccos x$. \Rightarrow
11. Find the derivative of $\log_5(\arctan(x^x))$. \Rightarrow

4.10 LIMITS REVISITED

We have defined and used the concept of limit, primarily in our development of the derivative. Recall that $\lim_{x \rightarrow a} f(x) = L$ is true if, in a precise sense, $f(x)$ gets closer and closer to L as x gets closer and closer to a . While some limits are easy to see, others take some ingenuity; in particular, the limits that define derivatives are always difficult on their face, since in

$$\lim_{\Delta x \rightarrow 0} \frac{f(x + \Delta x) - f(x)}{\Delta x}$$

both the numerator and denominator approach zero. Typically this difficulty can be resolved when f is a “nice” function and we are trying to compute a derivative. Occasionally such limits are interesting for other reasons, and the limit of a fraction in which both numerator and denominator approach zero can be difficult to analyze. Now that we have the derivative available, there is another technique that can sometimes be helpful in such circumstances.

Before we introduce the technique, we will also expand our concept of limit, in two ways. When the limit of $f(x)$ as x approaches a does not exist, it may be useful to note in what way it does not exist. We have already talked about one such case: one-sided limits. Another case is when “ f goes to infinity”. We also will occasionally want to know what happens to f when x “goes to infinity”.

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. \square

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

As with ordinary limits, these concepts can be made precise. Roughly, we want $\lim_{x \rightarrow a} f(x) = \infty$ to mean that we can make $f(x)$ arbitrarily large by making x close enough to a , and $\lim_{x \rightarrow \infty} f(x) = L$ 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 $\lim_{x \rightarrow a} f(x) = \infty$ 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 $\lim_{x \rightarrow a} f(x) = -\infty$, $\lim_{x \rightarrow a^-} f(x) = \pm\infty$, and $\lim_{x \rightarrow a^+} f(x) = \pm\infty$. \square

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

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

Now consider this limit:

$$\lim_{x \rightarrow \pi} \frac{x^2 - \pi^2}{\sin x}.$$

As x approaches π , 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 $\lim_{x \rightarrow a} f(x) = 0 = \lim_{x \rightarrow a} g(x)$ or both $\lim_{x \rightarrow a} f(x) = \pm\infty$ and $\lim_{x \rightarrow a} g(x) = \pm\infty$, and if $\lim_{x \rightarrow a} \frac{f'(x)}{g'(x)}$ exists, then $\lim_{x \rightarrow a} \frac{f(x)}{g(x)} = \lim_{x \rightarrow a} \frac{f'(x)}{g'(x)}$. This remains true if “ $x \rightarrow a$ ” is replaced by “ $x \rightarrow \infty$ ” or “ $x \rightarrow -\infty$ ”. \blacksquare

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 $\lim_{x \rightarrow \pi} \frac{x^2 - \pi^2}{\sin x}$ in two ways.

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

$$\lim_{x \rightarrow \pi} \frac{x^2 - \pi^2}{\sin x} = \lim_{x \rightarrow \pi} \frac{2x}{\cos x},$$

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

$$\lim_{x \rightarrow \pi} \frac{x^2 - \pi^2}{\sin x} = \frac{2\pi}{-1} = -2\pi.$$

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

$$\lim_{x \rightarrow \pi} (x + \pi) \frac{x - \pi}{\sin x}$$

and note that

$$\lim_{x \rightarrow \pi} \frac{x - \pi}{\sin x} = \lim_{x \rightarrow \pi} \frac{x - \pi}{-\sin(x - \pi)} = \lim_{x \rightarrow 0} -\frac{x}{\sin x}$$

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

$$\lim_{x \rightarrow \pi} (x + \pi) \frac{x - \pi}{\sin x} = \lim_{x \rightarrow \pi} (x + \pi) \lim_{x \rightarrow 0} -\frac{x}{\sin x} = 2\pi(-1) = -2\pi$$

as before. \square

EXAMPLE 4.10.7 Compute $\lim_{x \rightarrow \infty} \frac{2x^2 - 3x + 7}{x^2 + 47x + 1}$ in two ways.

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

$$\lim_{x \rightarrow \infty} \frac{2x^2 - 3x + 7}{x^2 + 47x + 1} = \lim_{x \rightarrow \infty} \frac{4x - 3}{2x + 47}.$$

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:

$$\lim_{x \rightarrow \infty} \frac{4x - 3}{2x + 47} = \lim_{x \rightarrow \infty} \frac{4}{2} = 2.$$

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 :

$$\lim_{x \rightarrow \infty} \frac{2x^2 - 3x + 7}{x^2 + 47x + 1} = \lim_{x \rightarrow \infty} \frac{2x^2 - 3x + 7 \frac{1}{x^2}}{x^2 + 47x + 1 \frac{1}{x^2}} = \lim_{x \rightarrow \infty} \frac{2 - \frac{3}{x} + \frac{7}{x^2}}{1 + \frac{47}{x} + \frac{1}{x^2}}.$$

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. \square

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

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

$$\lim_{x \rightarrow 0} \frac{\sec x - 1}{\sin x} = \lim_{x \rightarrow 0} \frac{\sec x \tan x}{\cos x} = \frac{1 \cdot 0}{1} = 0. \quad \square$$

EXAMPLE 4.10.9 Compute $\lim_{x \rightarrow 0^+} x \ln x$.

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

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

$$x \ln x = \frac{\ln x}{1/x} = \frac{\ln x}{x^{-1}}.$$

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:

$$\lim_{x \rightarrow 0^+} \frac{\ln x}{x^{-1}} = \lim_{x \rightarrow 0^+} \frac{1/x}{-x^{-2}} = \lim_{x \rightarrow 0^+} \frac{1}{x}(-x^2) = \lim_{x \rightarrow 0^+} -x = 0.$$

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

Exercises 4.10.

Compute the limits.

- | | |
|---|---|
| 1. $\lim_{x \rightarrow 0} \frac{\cos x - 1}{\sin x} \Rightarrow$ | 2. $\lim_{x \rightarrow \infty} \frac{e^x}{x^3} \Rightarrow$ |
| 3. $\lim_{x \rightarrow \infty} \sqrt{x^2 + x} - \sqrt{x^2 - x} \Rightarrow$ | 4. $\lim_{x \rightarrow \infty} \frac{\ln x}{x} \Rightarrow$ |
| 5. $\lim_{x \rightarrow \infty} \frac{\ln x}{\sqrt{x}} \Rightarrow$ | 6. $\lim_{x \rightarrow \infty} \frac{e^x + e^{-x}}{e^x - e^{-x}} \Rightarrow$ |
| 7. $\lim_{x \rightarrow 0} \frac{\sqrt{9+x} - 3}{x} \Rightarrow$ | 8. $\lim_{t \rightarrow 1^+} \frac{(1/t) - 1}{t^2 - 2t + 1} \Rightarrow$ |
| 9. $\lim_{x \rightarrow 2} \frac{2 - \sqrt{x+2}}{4 - x^2} \Rightarrow$ | 10. $\lim_{t \rightarrow \infty} \frac{t + 5 - 2/t - 1/t^3}{3t + 12 - 1/t^2} \Rightarrow$ |
| 11. $\lim_{y \rightarrow \infty} \frac{\sqrt{y+1} + \sqrt{y-1}}{y} \Rightarrow$ | 12. $\lim_{x \rightarrow 1} \frac{\sqrt{x} - 1}{\sqrt[3]{x} - 1} \Rightarrow$ |

13. $\lim_{x \rightarrow 0} \frac{(1-x)^{1/4} - 1}{x} \Rightarrow$
14. $\lim_{t \rightarrow 0} \left(t + \frac{1}{t} \right) ((4-t)^{3/2} - 8) \Rightarrow$
15. $\lim_{t \rightarrow 0^+} \left(\frac{1}{t} + \frac{1}{\sqrt{t}} \right) (\sqrt{t+1} - 1) \Rightarrow$
16. $\lim_{x \rightarrow 0} \frac{x^2}{\sqrt{2x+1} - 1} \Rightarrow$
17. $\lim_{u \rightarrow 1} \frac{(u-1)^3}{(1/u) - u^2 + 3u - 3} \Rightarrow$
18. $\lim_{x \rightarrow 0} \frac{2 + (1/x)}{3 - (2/x)} \Rightarrow$
19. $\lim_{x \rightarrow 0^+} \frac{1 + 5/\sqrt{x}}{2 + 1/\sqrt{x}} \Rightarrow$
20. $\lim_{x \rightarrow 0^+} \frac{3 + x^{-1/2} + x^{-1}}{2 + 4x^{-1/2}} \Rightarrow$
21. $\lim_{x \rightarrow \infty} \frac{x + x^{1/2} + x^{1/3}}{x^{2/3} + x^{1/4}} \Rightarrow$
22. $\lim_{t \rightarrow \infty} \frac{1 - \sqrt{\frac{t}{t+1}}}{2 - \sqrt{\frac{4t+1}{t+2}}} \Rightarrow$
23. $\lim_{t \rightarrow \infty} \frac{1 - \frac{t}{t-1}}{1 - \sqrt{\frac{t}{t-1}}} \Rightarrow$
24. $\lim_{x \rightarrow -\infty} \frac{x + x^{-1}}{1 + \sqrt{1-x}} \Rightarrow$
25. $\lim_{x \rightarrow \pi/2} \frac{\cos x}{(\pi/2) - x} \Rightarrow$
26. $\lim_{x \rightarrow 0} \frac{e^x - 1}{x} \Rightarrow$
27. $\lim_{x \rightarrow 0} \frac{x^2}{e^x - x - 1} \Rightarrow$
28. $\lim_{x \rightarrow 1} \frac{\ln x}{x-1} \Rightarrow$
29. $\lim_{x \rightarrow 0} \frac{\ln(x^2 + 1)}{x} \Rightarrow$
30. $\lim_{x \rightarrow 1} \frac{x \ln x}{x^2 - 1} \Rightarrow$
31. $\lim_{x \rightarrow 0} \frac{\sin(2x)}{\ln(x+1)} \Rightarrow$
32. $\lim_{x \rightarrow 1} \frac{x^{1/4} - 1}{x} \Rightarrow$
33. $\lim_{x \rightarrow 1^+} \frac{\sqrt{x}}{x-1} \Rightarrow$
34. $\lim_{x \rightarrow 1} \frac{\sqrt{x} - 1}{x-1} \Rightarrow$
35. $\lim_{x \rightarrow \infty} \frac{x^{-1} + x^{-1/2}}{x + x^{-1/2}} \Rightarrow$
36. $\lim_{x \rightarrow \infty} \frac{x + x^{-2}}{2x + x^{-2}} \Rightarrow$
37. $\lim_{x \rightarrow \infty} \frac{5 + x^{-1}}{1 + 2x^{-1}} \Rightarrow$
38. $\lim_{x \rightarrow \infty} \frac{4x}{\sqrt{2x^2 + 1}} \Rightarrow$
39. $\lim_{x \rightarrow 0} \frac{3x^2 + x + 2}{x - 4} \Rightarrow$
40. $\lim_{x \rightarrow 0} \frac{\sqrt{x+1} - 1}{\sqrt{x+4} - 2} \Rightarrow$
41. $\lim_{x \rightarrow 0} \frac{\sqrt{x+1} - 1}{\sqrt{x+2} - 2} \Rightarrow$
42. $\lim_{x \rightarrow 0^+} \frac{\sqrt{x+1} + 1}{\sqrt{x+1} - 1} \Rightarrow$
43. $\lim_{x \rightarrow 0} \frac{\sqrt{x^2 + 1} - 1}{\sqrt{x+1} - 1} \Rightarrow$
44. $\lim_{x \rightarrow \infty} (x+5) \left(\frac{1}{2x} + \frac{1}{x+2} \right) \Rightarrow$
45. $\lim_{x \rightarrow 0^+} (x+5) \left(\frac{1}{2x} + \frac{1}{x+2} \right) \Rightarrow$
46. $\lim_{x \rightarrow 1} (x+5) \left(\frac{1}{2x} + \frac{1}{x+2} \right) \Rightarrow$
47. $\lim_{x \rightarrow 2} \frac{x^3 - 6x - 2}{x^3 + 4} \Rightarrow$
48. $\lim_{x \rightarrow 2} \frac{x^3 - 6x - 2}{x^3 - 4x} \Rightarrow$
49. $\lim_{x \rightarrow 1^+} \frac{x^3 + 4x + 8}{2x^3 - 2} \Rightarrow$

50. The function $f(x) = \frac{x}{\sqrt{x^2 + 1}}$ has two horizontal asymptotes. Find them and give a rough sketch of f with its horizontal asymptotes. \Rightarrow

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 \cosh is even (that is, $\cosh(-x) = \cosh(x)$) while \sinh 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 :

$$\begin{aligned} y &= \frac{e^x + e^{-x}}{2} \\ 2y &= e^x + e^{-x} \\ 2ye^x &= e^{2x} + 1 \\ 0 &= e^{2x} - 2ye^x + 1 \\ e^x &= \frac{2y \pm \sqrt{4y^2 - 4}}{2} \\ e^x &= y \pm \sqrt{y^2 - 1} \end{aligned}$$

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 $\cosh(x)$. ■

DEFINITION 4.11.3 The other hyperbolic functions are

$$\begin{aligned} \tanh x &= \frac{\sinh x}{\cosh x} \\ \coth x &= \frac{\cosh x}{\sinh x} \\ \operatorname{sech} x &= \frac{1}{\cosh x} \\ \operatorname{csch} x &= \frac{1}{\sinh x} \end{aligned}$$

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 □

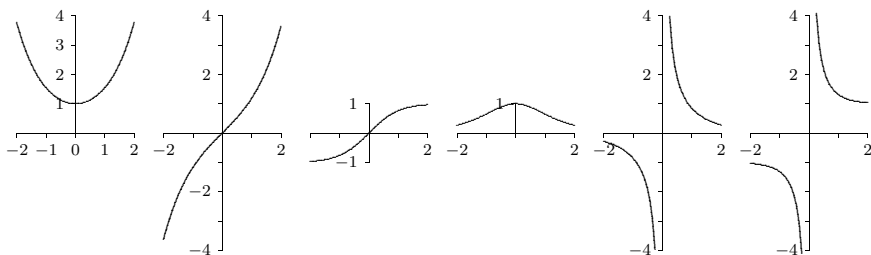


Figure 4.11.1 The hyperbolic functions: \cosh , \sinh , \tanh , sech , csch , \coth .

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:

$$\cosh^2 x - \sinh^2 x = \frac{(e^x + e^{-x})^2}{4} - \frac{(e^x - e^{-x})^2}{4} = \frac{e^{2x} + 2 + e^{-2x} - e^{2x} + 2 - e^{-2x}}{4} = \frac{4}{4} = 1. \quad \blacksquare$$

This immediately gives two additional identities:

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

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 $x = \pm y$ whose x -intercepts are

± 1 . If (x, y) is a point on the right half of the hyperbola, and if we let $x = \cosh t$, then $y = \pm\sqrt{x^2 - 1} = \pm\sqrt{\cosh^2 t - 1} = \pm\sinh t$. 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.

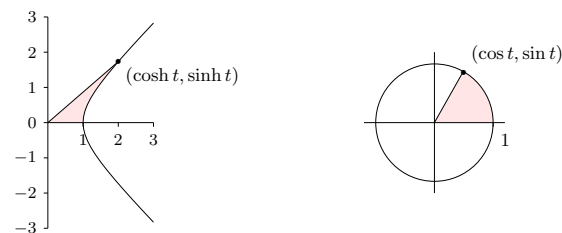


Figure 4.11.2 Geometric definitions of \sin , \cos , \sinh , \cosh : t is twice the shaded area in each figure.

Given the definitions of the hyperbolic functions, finding their derivatives is straightforward. Here again we see similarities to the trigonometric functions.

THEOREM 4.11.5 $\frac{d}{dx} \cosh x = \sinh x$ and $\frac{d}{dx} \sinh x = \cosh x$.

Proof. $\frac{d}{dx} \cosh x = \frac{d}{dx} \frac{e^x + e^{-x}}{2} = \frac{e^x - e^{-x}}{2} = \sinh x$, and $\frac{d}{dx} \sinh x = \frac{d}{dx} \frac{e^x - e^{-x}}{2} = \frac{e^x + e^{-x}}{2} = \cosh x. \quad \blacksquare$

Since $\cosh x > 0$, $\sinh x$ is increasing and hence injective, so $\sinh x$ has an inverse, $\operatorname{arcsinh} x$. Also, $\sinh x > 0$ when $x > 0$, so $\cosh x$ is injective on $[0, \infty)$ and has a (partial) inverse, $\operatorname{arcosh} x$. The other hyperbolic functions have inverses as well, though $\operatorname{arcsech} x$ is only a partial inverse. We may compute the derivatives of these functions as we have other inverse functions.

THEOREM 4.11.6 $\frac{d}{dx} \operatorname{arcsinh} x = \frac{1}{\sqrt{1+x^2}}$.

Proof. Let $y = \operatorname{arcsinh} x$, so $\sinh y = x$. Then $\frac{d}{dx} \sinh y = \cosh(y) \cdot y' = 1$, and so $y' = \frac{1}{\cosh y} = \frac{1}{\sqrt{1 + \sinh^2 y}} = \frac{1}{\sqrt{1 + x^2}}. \quad \blacksquare$

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. $\lim_{x \rightarrow \infty} \cosh x$
 - b. $\lim_{x \rightarrow \infty} \sinh x$
 - c. $\lim_{x \rightarrow \infty} \tanh x$
 - d. $\lim_{x \rightarrow \infty} (\cosh x - \sinh x)$
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 $\frac{d}{dx}(\tanh x) = \operatorname{sech}^2 x$. 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.