9 Transcendental Functions

9.1 Inverse functions

Informally, two functions $f$ and $g$ are inverses if each reverses, or undoes, the other. More precisely:

**DEFINITION 9.1.1** Two functions $f$ and $g$ are inverses if for all $x$ in the domain of $g$, $g(f(x)) = x$, and for all $x$ in the domain of $f$, $f(g(x)) = x$.

**EXAMPLE 9.1.2** $f = x^3$ and $g = x^{1/3}$ are inverses, since $(x^3)^{1/3} = x$ and $(x^{1/3})^3 = x$.

**EXAMPLE 9.1.3** $f = x^2$ and $g = x^{1/2}$ are not inverses. While $(x^2)^{1/2} = x$, it is not true that $(x^{1/2})^2 = x$. For example, with $x = -2$, $((-2)^{1/2})^2 = 4$.

The problem in the previous example can be traced to the fact that there are two different numbers with square equal to 4. This turns out to be precisely descriptive of functions without inverses.

**DEFINITION 9.1.4** Let $A$ and $B$ be sets and let $f : A \to B$ be a function. We say that $f$ is injective or one-to-one if $f(a) = f(b)$ implies that $a = b$.

We say that $f$ is surjective or onto if for every $b \in B$ there is an $a \in A$ such that $f(a) = b$.

If $f$ is both injective and surjective, then $f$ is bijective or one-to-one and onto.

**THEOREM 9.1.12** If $f$ is continuous and has a local maximum or minimum then $f$ is not injective.

**Proof.** Suppose that $f$ has a local maximum at $x = c$. Then in some interval $(c-h, c+h)$, $f(x) \leq f(c)$. Let $a \in (c-h, c)$. If $f(a) = f(c)$ then $f$ is not injective; otherwise, $f(a) < f(c)$. Let $b \in (c, c+h)$. If $f(b) = f(c)$ or $f(b) > f(a)$ then $f$ is not injective. Otherwise, either $f(b) < f(a) < f(c)$ or $f(b) < b < f(c)$. If $f(b) < f(a)$ then by the intermediate value theorem, there is a number $d \in (c, b)$ such that $f(d) = f(a)$ and so $f$ is not injective. Likewise, if $f(a) < f(b)$ then there is a number $d \in (a, c)$ such that $f(d) = f(b)$ and so $f$ is not injective.

In every case, we see that $f$ is not injective.

To return to our principal interest, inverse functions, we now connect bijections and inverses.

**THEOREM 9.1.13** Suppose $f : A \to B$ is a bijection. Then $f$ has an inverse function $g : B \to A$.

**Proof.** Suppose $b \in B$. Since $f$ is onto, there is an $a \in A$ such that $f(a) = b$. Since $f$ is 1-1, $a$ is the only element of $A$ with this property. We let $g(b) = a$. Now it is easy to see that for all $a \in A$, $g(f(a)) = a$ and for all $b \in B$, $g(g(b)) = b$.

We really don’t have any choice about how to define $g$ in this proof; if $f$ is a bijection, its inverse is completely determined. Thus, instead of using a new symbol $g$, we normally refer to the inverse of $f$ as $f^{-1}$.

Unfortunately, it is often difficult to find an explicit formula for the inverse of a given function, $f$, even if it is known that $f$ is bijective. Generally, we attempt to find an inverse in this way:

1. Write $y = f(x)$.
2. Interchange $x$ and $y$.
3. Solve for $y$.
4. Replace $y$ with $f^{-1}(x)$.

We are interested only in the case that $A$ and $B$ are sets of real numbers, and in this case there is a nice geometric interpretation of injectivity. It is often easy to use this interpretation to decide whether a function is or is not 1-1.

**THEOREM 9.1.15** Horizontal line test

If $f$ is a function defined on some subset of the real numbers, then $f$ is injective if and only if every horizontal line intersects the graph of $f$ at most once.

**EXAMPLE 9.1.16** The function $f = x^2$ fails this test: horizontal lines $y = k$ for $k > 0$ intersect the graph of $f$ twice. (The horizontal line $y = 0$ does intersect it only once, and lines $y = k$, $k < 0$, do not intersect the graph at all.)

**EXAMPLE 9.1.17** In each of these cases, we assume that $f : A \to R$, where $A$ is the set of all real numbers for which $f$ makes sense.

The function $f(x) = x$ is bijective.

The function $f(x) = x^3$ is neither injective nor surjective. If we think of $f$ as a function from $B$ to the non-negative real numbers, then $f$ is surjective; in other words, if a function is not surjective this is not a major stumbling block.

The function $f(x) = 1/x$ is injective but not surjective since there is no value of $x$ such that $f(x) = 0$.

The function $f(x) = x(x-1)(x+1)$ is surjective but not injective: $f(x) = 0$ for three different values of $x$. On the other hand lim $f(x) = \infty$ and lim $f(x) = -\infty$. Since $f$ is continuous on $\mathbb{R}$, the intermediate value theorem (2.5.6) guarantees that $f$ takes all values between $-\infty$ and $\infty$.

The derivative furnishes us with a convenient criterion for injectivity without explicitly looking for points where injectivity may fail.

**THEOREM 9.1.18** If $f$ is differentiable and $f'(x) > 0$ then $f$ is injective.

**Proof.** Suppose that $f(a) = f(b)$ for some $a, b$. By Rolle’s theorem (6.5.1) there exists $c \in (a, b)$ such that $f’(c) = (f(b) - f(a))/(b - a) = 0$, which contradicts the hypothesis that $f’(x) > 0$. Hence, if $f(a) = f(b)$ then $a = b$.

In the same way, we can see that if $f’(x) < 0$ then $f$ is injective.

**EXAMPLE 9.1.19** Let $f(x) = e^x + x$. Since $f’(x) = e^x + 1 > 0$, $f$ is injective.

**EXAMPLE 9.1.20** Let $f(x) = 2x + \sin x$. Then $f’(x) = 2 + \cos x \geq 1$ for every $x$. Hence, $f$ is injective.

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Step 3 is the hard part; indeed it is sometimes impossible to perform using algebraic operations.

**EXAMPLE 9.1.21** Find the inverse of $f(x) = (2x - 6)/(3x + 7)$. First we write $x = (2y - 6)/(3y + 7)$. Now we solve for $y$:

$$
\frac{2y}{3y+7} = \frac{2}{3} - \frac{2}{3y+7}
$$

$$
3y + 7 = 2y - 6
$$

$$
7 = 6
$$

Finally, we say $f^{-1}(x) = (2x - 6)/(3x + 7)$.

**EXAMPLE 9.1.15** Find the inverse function of $f(x) = x^2 - 4x + 8$ where $x \geq 2$. What are the domain and range of the inverse function?

First, $y = x^2 - 4x + 8$ becomes $y = x^2 - 4x + 8$. Now we complete the square: $x = (y - 2)^2 + 4$ and rearrange to get $x = y - (y - 2)^2$. Since in the original function $x \geq 2$, and we have switched $x$ and $y$, we know that $y > 2$. Thus taking the square root, we know $y - 2 = \sqrt{y - 2} - 2$, not $y - 2 = -\sqrt{y - 2} - 2$. Finally we write $y = f^{-1}(x) = 2 + \sqrt{x - 2}$. The domain of $f$ is $x \geq 4$ and the range is $y \geq 2$.

While simple in principle, this method is sometimes difficult or impossible to apply. For example, consider $f(x) = x^3 + x$. Since $f’(x) = 3x^2 + 1 > 0$ for every $x$, $f$ is injective. (In fact it is bijective.) To find the inverse as above, we would need to solve $x = y^3 + y$ for $y$, while possible, this is considerably more difficult than solving the quadratic of the previous example. Some simple looking equations are impossible to solve using algebraic manipulation.

For example, consider $f(x) = x^3 + x^2 + x + 1$ a “quintic” polynomial (i.e., a fifth degree polynomial). Since $f’(x) = 3x^2 + 2x + 1 > 0$, $f$ is injective (and indeed is bijective). If there were a quintic formula, analogous to the quadratic formula, we could use that to compute $f^{-1}$. Unfortunately, no such formula exists—fifth degree equations cannot in general be solved. (There are exceptions: $x^5 = 1$ can be solved, for example.)

Fortunately, it is often more important to know that a function has an inverse then to be able to come up with an explicit formula. Once an inverse is known to exist, numerical
9.1 Inverse functions

Techniques can often be employed to obtain approximations of the inverse function. Thus, theorem 9.1.8 and proposition 9.1.12 provide useful criteria for deciding whether a function is invertible.

We now turn to the calculus of inverse functions.

**THEOREM 9.1.16** Let $A$ be an open interval and let $f : A \to R$ be injective and continuous. Then $f^{-1}$ is continuous on $(A)$.

**Proof.** Since $A$ is an open interval and $f$ is injective and continuous it follows by proposition 9.1.12 that $f$ has no local maxima or minima. Hence, $f$ is either strictly increasing or strictly decreasing. Without loss of generality, $f$ is strictly increasing.

Fix $b \in f(A)$. Then there exists a unique $a \in A$ such that $f(a) = b$. Let $x > 0$ and we may assume that $(a - x, a + x) \subseteq A$. Let $L = \min \{f(a - x), f(a + x) - b\}$ and note that $\delta > 0$ since $f$ is increasing. Then the interval $(b - \delta, b + \delta)$ is mapped by $f^{-1}$ into $(a - \delta, a + \delta)$. Since $\epsilon$ was arbitrary, it follows that $f^{-1}$ is continuous at $b$.

Our principal interest in inverses is the simple relationship between the derivative of a function and its inverse.

**THEOREM 9.1.17** Inverse function theorem Let $A$ be an open interval and let $f : A \to R$ be injective and differentiable. If $f'(x) \neq 0$ for every $x \in A$ then $f^{-1}$ is differentiable on $f(A)$ and $(f^{-1})'(y) = 1/f'(f^{-1}(y))$.

**Proof.** Fix $b \in A$. Then there exists a unique $a \in A$ such that $f(a) = b$. For $y \neq b$, let $x = f^{-1}(y)$. Since $f$ is differentiable, it follows that $f$ and hence $f^{-1}$ are continuous. Then

$$
\lim_{y \to b} (f^{-1}(y) - f^{-1}(a)) = \lim_{x \to a} a - x = 1/f'(a).
$$

In Leibniz notation, this can be written $\frac{dy}{dx} = \frac{1}{f'(a)}$, which is easy to remember since it looks like ordinary fractional algebra.

**EXAMPLE 9.1.18** Let $f(x) = 3x^2 + 5x - 7$. Since $f(0) = -7$, $f^{-1}(-7) = 0$. Since $f'(x) = 6x + 5$, $f'(0) = 5$ and so $(f^{-1})'(-7) = 1/f'(0) = 1/5$.

**Exercises 9.1.**

1. Which of the following functions are injective? Which are surjective? Which are bijective? Sketch the graph of each function to illustrate your answers.

   a. $f : R \to R$, $f(x) = x^2$.

   b. $f : (0, \infty) \to R$, $f(x) = x^3$.

   c. $f : R \to (0, \infty)$, $f(x) = x^2$.

   d. $f : (-\infty, 0) \to [0, \infty)$, $f(x) = x^2$.

2. Which of the following functions are injective? Which are surjective? Which are bijective? Sketch the graph of each function to illustrate your answers.

   a. $f : R \to R$, $f(x) = x^3$.

   b. $f : (0, \infty) \to R$, $f(x) = x^2$.

   c. $f : R \to [-1, 1]$, $f(x) = \sin x$.

   d. $f : [0, \pi] \to [-1, 1]$, $f(x) = \cos x$.

3. Define $f(x) = \begin{cases} 1 & x \neq 0 \\ 0 & x = 0 \end{cases}$

   Show that $f$ is not injective on $R$. Show that $f'(x) > 0$ for $x \neq 0$. Why does this not contradict theorem 9.1.8?

4. Define $f(x) = \begin{cases} 1 - x & -2 \leq x < 0 \\ 0 & x = 0 \\ 10 + x & 0 < x \leq 2 \end{cases}$

   Show that $f$ is injective and has a local minimum. Why does this not contradict theorem 9.1.12?

5. If $A = R$ sketch the graph of the identity function on $A$.

6. Find the inverse function of $f(x) = (4x - 6)/(7x + 5)$. What are the domain and range of $f^{-1}$?

7. Find the inverse function of $f(x) = \ln(13x - 6)$. What are the domain and range of $f^{-1}$?

8. Find the inverse function of $f(x) = 2x + b$ when $a \neq 0$. What are the domain and range of $f^{-1}$?

9. Find the inverse function of $f(x) = 1/(cx + d)$ when $c \neq 0$. What are the domain and range of $f^{-1}$?

10. Suppose that $ad - bc \neq 0$. Find the inverse function of $f(x) = (ax + b)/(cx + d)$. What are the domain and range of $f^{-1}$? (The domain and range will depend on which if any of $a, b, c,$ and $d$ are zero.)

   Note: The condition $ad - bc \neq 0$ is a technical condition which ensures that both the domain of $f$ will be all real numbers with perhaps one exception and that the range of $f^{-1}$ will be all real numbers with perhaps one exception.

11. Find the inverse function of $f(x) = [x - 4]$ for $x \leq 4$. What are the domain and range of $f^{-1}$?

12. Find the inverse function of $f(x) = \sqrt{x - 3}$. What are the domain and range of $f^{-1}$?

13. Find the inverse function of $f(x) = x^2 - 5$. What are the domain and range of $f^{-1}$?

14. Find the inverse function of $f(x) = x^2 - 2$. What are the domain and range of $f^{-1}$?

15. Find the inverse function of $f(x) = 2x^2 + 8x - 4$ for $x \geq -2$. What are the domain and range of $f^{-1}$?

9.2 The natural logarithm

The function $f(t) = 1/t$ is continuous on $(0, \infty)$. By the fundamental theorem of calculus, $f$ has an antiderivative on the interval with end points $x$ and $y$ whenever $x > 0$. This observation allows us to make the following definition.

**DEFINITION 9.2.1** The natural logarithm $\ln(x)$ is an antiderivative of $1/x$, given by

$$
\ln x = \int_{1}^{x} \frac{1}{t} dt.
$$

Figure 9.2.1 gives a geometric interpretation of $\ln$. Note that when $x < 1$, $\ln x$ is negative.

![Figure 9.2.1](image-url)
In the remaining integral, use the substitution \( u = 1/x \) to get
\[
\int_{1}^{a} \frac{1}{x} \, dx = \int_{1}^{a} \frac{1}{u} \, du = \ln(u).
\]

Parts (d) and (c) are left as exercises.

Part (c) is in fact true for any real number \( q \) (not just rationals) but one of the points of our approach here is to give a rigorous definition of real powers which so far we have not done.

We now turn to the task of sketching the graph of \( \ln x \).

**THEOREM 9.2.3** \( \ln x \) is increasing and its graph is concave down everywhere.

**Proof.** Since \( \frac{d}{dx} \ln x = 1/x \) is positive for \( x > 0 \), the Mean Value Theorem (6.5.2) implies that \( \ln x \) is increasing. The second derivative of \( \ln x \) is then \(-1/x^2\) which is negative, so the graph is concave down.

Notice that this theorem implies that \( \ln x \) is injective.

**THEOREM 9.2.4** \( \lim_{x \to \infty} \ln x = \infty \).

**Proof.** Note that \( \ln 2 > 0 \) and for \( n \in \mathbb{N} \), \( \ln 2^n = n \ln 2 \). Since \( \ln x \) is increasing, when \( x > 2^n \), \( \ln(x) > n \ln 2 \). Since \( \lim_{n \to \infty} n \ln 2 = \infty \), also \( \lim_{x \to \infty} \ln x = \infty \).

**COROLLARY 9.2.5** \( \lim_{x \to 0^+} \ln x = -\infty \).

**Proof.** If \( 0 < x < 1 \), then \((1/x) > 1\) and \( \lim_{x \to 0^+} (1/x) = \infty \). Let \( y = 1/x \), then \( \lim_{y \to \infty} \ln y = \lim_{y \to \infty} \ln(1/y) = -\lim_{y \to \infty} \ln y = -\infty \).

Thus, the domain of \( \ln \) is \((0, \infty)\) and the range is \( \mathbb{R} \). \( \ln(x) \) is shown in figure 9.2.2.

![Figure 9.2.2 The graph of \( \ln(x) \).](image)

### Exercises 9.2.

1. Prove parts (d) and (e) of theorem 9.2.2.

2. Expand \( \ln(\pi^2) \) and \( \ln(e^2) \).

3. Expand \( \ln(\ln(x + 1)) \).

4. Sketch the graph of \( y = e^x - 1\).

5. Sketch the graph of \( y = \ln(\ln(x)) \).

6. Write \( \ln \) as \( \ln(\ln(\ln(x)^2 + 1)) \) as a single logarithm.

7. Differentiate \( f(x) = \ln(x) \).

8. Differentiate \( f(x) = \ln(x^2 + 1) \).

9. Sketch the graph of \( \ln(x^2 - 2x) \).

10. Differentiate \( f(x) = \ln(x^3 + 1) \).

11. Differentiate \( f(x) = \ln(\ln(x + 1)) \).

12. Find the second derivative of \( f(x) = \sqrt{\ln(x)^2 - 2} \).

13. Find the equation of the tangent line to \( f(x) = \ln(x) \) at \( x = a \).

14. Differentiate \( f(x) = \sqrt{x^2 + 1} \).

15. If \( f(x) = \ln(x^2 + 1) \) compute \( f'(x) \).

16. Compute \( \int_{1}^{e} \frac{1}{x} \, dx \).

17. Compute the derivative with respect to \( x \) of \( \int_{1}^{x} \ln(t) \, dt \). (Assume that \( x > 1 \).)

18. Compute \( \int_{0}^{\pi/2} \sin(2x) \, dx \).

19. Compute \( \int_{0}^{\pi/2} \tan(2x) \, dx \).

20. Compute \( \int_{0}^{\pi} \cos(2x) \, dx \).

21. Find the volume of the solid obtained by rotating the region under \( y = \sqrt{x} \) from 1 to \( e \) about the \( x \)-axis.

## 9.3 The exponential function

In this section, we define what is arguably the single most important function in all of mathematics. We have already noted that the function \( \ln x \) is injective, and therefore it has an inverse.

### 9.3.4 The general antiderivative of \( \exp(x) = e^x + C \).

By the intermediate value theorem (2.5.6) there is a number \( e \) such that \( \ln e = 1 \). The number \( e \) is also known as Napier’s constant.

It turns out that \( e \) is not rational. In fact, \( e \) is not the root of a polynomial with rational coefficients which means that \( e \) is a transcendental number. We will not prove these assertions here. The value of \( e \) is approximately 2.718.

**EXAMPLE 9.2.6** Let \( f(x) = \ln(x^2 + 7x + 12) \). Compute \( f'(x) \).

Using the chain rule: \( f'(x) = \frac{2x + 7}{x^2 + 7x + 12} \).

**EXAMPLE 9.2.7** Let \( f(x) = \ln(-x) \) for \( x < 0 \). Compute \( f'(x) \).

\( f'(x) = \frac{-1}{-x} \).

So the derivatives of \( \ln(x) \) and \( \ln(-x) \) are the same. Thus, you will often use \( \int \frac{1}{x} \, dx = \ln|x| + C \) as the general antiderivative of \( 1/x \).

**EXAMPLE 9.2.8** Compute \( \int \tan(x) \, dx \).

Let \( u = \cos(x) \).

\( \int \tan(x) \, dx = \int \frac{\sin(x)}{\cos(x)} \, dx = \left| \frac{\ln(\cos(x))}{\cos(x)} \right| = \ln(\sec(x)) + C \).

Using one of the properties of the logarithm, we could go further:

\( \ln(\cos(x)) + C = \ln(\cos(x)^{-1}) = -\ln(\sec(x)) + C \).

**EXAMPLE 9.2.9** Let \( f(x) = \frac{x^6(x + 2)^{1/3} + 1}{(x^3 + 4x^2 + 1)} \). Compute \( f'(x) \).

Computing the derivative directly is straightforward but irritating. We therefore take an indirect approach. Note that \( f(x) > 0 \) for every \( x \). Let \( g(x) = \ln(f(x)) \). Then \( g'(x) = f'(x)/f(x) \) and so \( f'(x) = f(x)g'(x) \).

\( g(x) = \ln \left( \frac{x^6(x + 2)^{1/3} + 1}{(x^3 + 4x^2 + 1)} \right) = \ln(x^6) + \ln((x + 2)^{1/3}) = 6\ln(x) + \ln((x + 2)^{1/3}) \).

Hence, \( g'(x) = \frac{6}{x} + \frac{1}{3(x + 2)} = \frac{18}{x} + \frac{6}{3(x + 2)} = \frac{6(10x^2 + 8x)}{x^3 + 4x^2 + 1} \).

Therefore, \( f'(x) = \frac{x^6(x + 2)^{1/3} + 1}{(x^3 + 4x^2 + 1)} (\frac{18}{x} + \frac{6}{3(x + 2)}) = \frac{6(10x^2 + 8x)}{x^3 + 4x^2 + 1} \).

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**DEFINITION 9.3.1** The inverse function of \( \ln(x) \) is \( y = \exp(x) \), called the natural exponential function.

The domain of \( \exp(x) \) is all real numbers and the range is \((0, \infty)\). Note that because \( \exp(x) \) is the inverse of \( \ln(x) \), \( \exp(\ln(x)) = x \) for \( x > 0 \), and \( \exp(\ln(x)) = x \) for all \( x \). Also, our knowledge of \( \ln(x) \) tells us immediately that \( \exp(1) = e \), \( \exp(0) = 1 \), \( \lim_{x \to \infty} \exp(x) = \infty \), and \( \lim_{x \to -\infty} \exp(x) = 0 \).

**THEOREM 9.3.2** \( \frac{d}{dx} \exp(x) = \exp(x) \).

**Proof.** By the Inverse Function Theorem (9.1.17), \( \exp(x) \) has a derivative everywhere. The theorem also tells us what the derivative is. Alternately, we may compute the derivative using implicit differentiation. Let \( y = \exp(x) \) so \( \ln y = x \). Differentiating with respect to \( x \) we get \( \frac{dy}{dx} = \exp(x) \). Hence, \( \frac{dy}{dx} = y \).

**COROLLARY 9.3.3** Since \( \exp x > 0 \), \( \exp x \) is an increasing function whose graph is concave up.

The graph of the natural exponential function is indicated in figure 9.3.1. Compare this to the graph of \( \ln x \), figure 9.2.2.

![Figure 9.3.1 The graph of \( \exp(x) \).](image)
LEMMA 9.3.5 For any rational number \( q \), \( \exp(q) = e^q \).

**Proof.** Let \( y = e^q \). Then \( \ln y = \ln(e^q) = q \ln e = q \), and so \( y = \exp(q) \).

In view of this lemma, we usually write \( \exp(x) \) as \( e^x \) for any real number \( x \). Conveniently, it turns out that the usual laws of exponents apply to \( e^x \).

**THEOREM 9.3.6** For every \( x, y \in \mathbb{R} \) and \( q \in \mathbb{Q} \):

(a) \( e^{x+y} = e^x e^y \)
(b) \( e^{x-y} = e^x / e^y \)
(c) \( (e^y)^x = e^{xy} \)

**Proof.** Parts (b) and (c) are left as exercises. For part (a), \( \ln(e^x e^y) = \ln e^x + \ln e^y = x + y \), so \( e^{x+y} = e^x e^y \).

**EXAMPLE 9.3.7** Solve \( e^{x+3} = 3 - 30 \) for \( x \).
If \( e^{x+3} = 3 - 30 \) then \( 4x + 5 = \ln 3 - \frac{30}{e} \) and so \( x = \frac{\ln 3 - 30}{4} \).

**EXAMPLE 9.3.8** Find the derivative of \( f(x) = e^x \sin(4x) \).
By the product and chain rules, \( f'(x) = 3x^2 e^x \sin(4x) + 4e^x \cos(4x) \).

**EXAMPLE 9.3.9** Evaluate \( \int e^x \sin x \, dx \).
Let \( u = x^2 \), so \( du = 2x \, dx \). Then
\[
\int e^x \sin x \, dx = \frac{1}{2} \int e^x \sin x \, dx + \frac{1}{2} e^x + C.
\]

**Exercises 9.3.**
1. Prove parts (b) and (c) of theorem 9.3.6.
2. Solve \( \ln(1 + \sqrt{2}) = 6 \) for \( x \).
3. Solve \( e^x = 8 \) for \( x \).
4. Solve \( \ln(\sin x) = x \) for \( x \).
5. Sketch the graph of \( f(x) = e^{x-4} + 4 \).
6. Sketch the graph of \( f(x) = 4e^{x-4} - 4 \).
7. Find the equation of the tangent line to \( f(x) = e^x \) at \( x = a \).
8. Compute the derivative of \( f(x) = 1 e^x e^x - e^x \).

### 9.4 Other bases 193

(a) We compute: \( a^{x+y} = e^{(x+y) \ln a} = e^{x \ln a + y \ln a} = e^{x \ln a} e^{y \ln a} = a^x a^y \).

The proof of (b) is similar and left as an exercise.

(c) We compute: \( (a^x)^y = e^{(x \ln a)^y} = e^{y(x \ln a)} = e^{xy \ln a} = (e^x)^{y \ln a} \).

(d) We compute: \( (a^x)^y = e^{(x \ln a)^y} = e^{y(x \ln a)} = e^{xy \ln a} = (e^x)^{y \ln a} \).

**THEOREM 9.4.3** If \( f(x) = a^x \) (with \( a > 0 \)) then \( f'(x) = a^x \ln a \).

**Proof.**
\[
f'(x) = \frac{d}{dx} e^{x \ln a} = (e^{x \ln a})' = a^x \ln a.
\]

**COROLLARY 9.4.4** For \( a > 0 \) and \( a \neq 1 \), \( \int e^x \, dx = \frac{e^x}{\ln a} + C \).

We are now in a position to prove the general power rule.

**THEOREM 9.4.5** Power Rule
If \( f(x) = x^a \), \( x > 0 \), and \( n \) is any real number, then \( f'(x) = ax^{a-1} \).

**Proof.**
\[
f'(x) = \frac{d}{dx} x^a = \frac{d}{dx} e^{a \ln x} = e^{a \ln x} \frac{d}{dx} (a \ln x) = ax^{a-1}.
\]

The restriction that \( x > 0 \) is necessary since we have not defined exponential expressions with negative bases and arbitrary real powers.

We now turn to logarithms base \( a \). Note that if \( a > 0 \) and \( a \neq 1 \) then \( a^x \ln a \neq 0 \) for every \( x \). Hence, the function \( f(x) = a^x \) is injective.

**DEFINITION 9.4.6** If \( a > 0 \) and \( a \neq 1 \), the inverse of \( a^x \) is called the logarithmic function base \( a \). In symbols, we write this function as \( \log_a x \).

We exclude \( a = 1 \) because \( 1^x = 1 \) is not injective on any domain containing more than one point.

**Remark.** If \( a = 10 \) we usually write \( \log \) instead of \( \log_{10} \), and of course \( \log_e = \ln \). In more advanced texts, "log" refers to the natural logarithm.

**THEOREM 9.4.7** The following hold for \( a, x, y > 0 \), \( a \neq 1 \), and \( \in \mathbb{R} \):

a. \( \log_a(xy) = \log_a x + \log_a y \)

b. \( \log_a \frac{x}{y} = \log_a x - \log_a y \)

c. \( \log_a x^y = y \log_a x \)

**Proof.**
(a) Let \( u = \log_a x \) and \( v = \log_a y \). Then \( a^u = x \) and \( a^v = y \), and \( xy = a^{u+v} = a^u a^v \), so \( \log_a(xy) = u + v = \log_a x + \log_a y \).

(c) \( \log_a x^y = \log_a (a^{uy}) = y \log_a (a^u) = y \log_a x \).

9. Chapter 9 Transcendental Functions

9. Compute the derivative of \( f(x) = x^e \left( 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots \right) \).

10. Prove: if \( x > 0 \) then \( a^x > 1 \) for \( x > 0 \).

11. Use the previous two exercises to prove: (a) If \( a^x > 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \cdots \), then \( a^x > 1 + x \) for \( x > 0 \).

12. Use the preceding exercise to show that \( e > 2.7 \).

13. Differentiate \( e^{x^4} \) with respect to \( x \).

14. Compute: \( \lim_{x \to 0} e^{x^2} \).

15. Integrate \( 5x e^{x^2} \) with respect to \( x \).

16. Compute \( \int_0^1 \cos(2x) e^{x^2} \, dx \).

17. Compute \( f(x) = \int_{\ln 2}^x e^t \, dt \).

18. Let \( F(x) = \int_0^x e^t \, dt \). Compute \( F'(0) \).

19. If \( f(x) = e^x \), what is \( f^{(n)}(x) \) if \( f^{(n)}(x) \)?

### 9.4 Other bases

Notice that if \( q \in \mathbb{Q} \) and \( a > 0 \) then \( a^q = e^{q \ln a} = e^{\ln a^q} \). This equation motivates the following definition.

**DEFINITION 9.4.1** For \( a > 0 \) and \( x \in \mathbb{R} \), we define \( a^x \). The function \( f(x) = a^x \) is the exponential function with base \( a \). Typically, we define \( a^x \) for \( x \geq 0 \).

Notice also that for \( x \in \mathbb{R} \) and \( a > 0 \), \( \ln a^x = \ln(e^{x \ln a}) = x \ln a \). Hence, the power rule for the natural logarithm works even when the power is irrational.

We now show that the familiar rules for exponents are valid.

**THEOREM 9.4.2** For \( x, y \in \mathbb{R} \) and \( a, b > 0 \):

a. \( a^{x+y} = a^x a^y \)

b. \( a^{x-y} = a^x / a^y \)

c. \( (a^x)^y = a^{xy} \)

d. \( (ab)^x = a^x b^x \)

**Proof.**
Start with \( f(x) = x^2 - e^{3x}. \) Then
\[
f'(x) = e^{3x} \left( \frac{2}{3} + \ln x \right) = x^2(1 + \ln x).
\]
For the limit, we again notice that
\[
\lim_{x \to 0} x^2 = \lim_{x \to 0} e^{3x} = e^{3(\ln x)} = e^{\ln x^3} = x^3.
\]
Thus \( \lim_{x \to 0} x^2 = e^0 = 1. \)

**EXAMPLE 9.4.12** Compute \( \int \frac{x/2}{2^x - \sin x} \, dx. \)

Let \( u = \cos x, \) so \( du = -\sin x \, dx. \) Changing the limits, when \( x = \pi/6, u = \sqrt{3}/2, \) and when \( x = \pi/3, u = 1/2. \) Then
\[
\int_{\pi/6}^{\pi/3} 2^u \sin x \, dx = -\int_{\sqrt{3}/2}^{1/2} 2^u \, du = \frac{2^{1/2} - 2^{3/2}}{\ln 2}.
\]

### Exercises 9.4.

1. Prove part (b) of theorem 9.4.2.
2. Sketch the graph of \( y = x^2 \) in the three cases \( a > 1, a = 1, \) and \( 0 < a < 1. \) What happens to the graph as \( a \to 0^+? \) What happens to the graph as \( a \to \infty? \)
3. Sketch the graph of \( y = \log_a x \) in the two cases \( a > 1 \) and \( 0 < a < 1. \) What happens to the graph as \( a \to 0^+? \) What happens to the graph as \( a \to \infty? \)
4. Prove parts (b) and (c) of theorem 9.4.7.
5. Sketch the graph of \( y = x^{3-x} + 5. \)
6. Sketch the graph of \( y = -(-1/2)^{-x}. \)
7. Sketch the graph of \( y = 4\log_2(12x + 6) - 2. \)
8. Compute the second derivative of \( f(x) = x^2. \)
9. Compute \( j'(e^4) \) when \( j(x) = \tan^{-1} x + \log_e x. \)
10. Compute the derivative of \( f(x) = \pi^3 - 4x^2 + \sin(3a) - y^2. \)

### 9.5 Inverse Trigonometric Functions

Recall that a function and its inverse undo each other in either order, for example, \((\sqrt{7})^2 = x \) and \(\sqrt{x^2} = x. \) 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, \( \sin(\pi/6) = \pi/2 \) and \( \arcsin(1/2) = \pi/6, \) so doing the sine first then the arcsine does not get us back where we started. This is because \( \pi/6 \) 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: \( \sin(\pi/6) = \pi/2 \) and \( \arcsin(\pi/2) = \pi/6. \)

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
\[
y' \cos y = 1
\]
\[
y' = \frac{1}{\cos y}
\]
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 \( \sin^2 y + \cos^2 y = 1, \) \( \cos y = 1 - \sin^2 y = 1 - x^2. \) So \( \cos y = \sqrt{1 - x^2}, \) 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
\[
dy = \frac{1}{\sqrt{1 - x^2}}.
\]

Note that this agrees with figure 9.5.1: 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 9.5.2. Then we use implicit differentiation to find that
\[
dy = \frac{-1}{\sqrt{1 - x^2}}.
\]

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.
10. Find the derivative of arcsin ′x + arccos ′x ⇒
11. Find the derivative of \( \log(\arctan(x')) \) ⇒

12. Compute \( \frac{d}{dx} \arccos x \)
13. Compute \( \int \frac{\ln(\arcsin x)}{\sqrt{1 - x^2}} \) \( dx \)
14. Compute \( \int \frac{e^x + x^2}{1 + x^2} \) \( dx \)
15. Compute \( \int \frac{dx}{x + \sqrt{9 - x^2}} \)
16. Find the equation of the tangent line to \( f(x) = \arccos x \) at \( x = \pi/6 \).
17. Let \( A = \{(x,y) | 1 \leq x \leq e^t, 0 \leq y \leq \sqrt{e^t - 1} \} \).

Sketch the region \( A \). Let \( S \) be the solid obtained from rotating \( A \) about the \( x \)-axis. Compute the volume of \( S \).

9.6 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 9.6.1**
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 \( \cosh x \) is even (that is, \( \cosh(-x) = \cosh(x) \)) while \( \sinh x \) is odd (\( \sinh(-x) = -\sinh(x) \)).

**LEMMA 9.6.2** The range of \( \cosh x \) is \([1, \infty)\).

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

**THEOREM 9.6.4** For all \( x \in \mathbb{R} \), \( \cosh^2 x - \sinh^2 x = 1 \).

**Proof.** The proof is a straightforward computation:
\[
\cosh^2 x - \sinh^2 x = \frac{(e^x + e^{-x})^2}{4} - \frac{(e^x - e^{-x})^2}{4} = \frac{e^{2x} + 2 + e^{-2x} - e^{2x} + 2 - e^{-2x}}{4} = \frac{4}{4} = 1.
\]

This immediately gives two additional identities:

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

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 \( \pm 1 \). If \((x, y)\) is a point on the right half of the hyperbola, and if we let \( x = \cosh t \), then \( y = \pm \sqrt{\cosh^2 t - 1} = \pm \sinh t \). 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 9.6.2. Even this is analogous to trigonometry; \( \cot \) and \( \sin \) are the coordinates of a typical point on the unit circle, and \( t \) is twice the area shown in the second graph of figure 9.6.2.

![Figure 9.6.2 Geometric definitions of \( \sin, \cos, \sinh, \cosh, t \) is twice the shaded area in each figure.](image)

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

**THEOREM 9.6.5** \( \frac{d}{dx} \cosh x = \sinh x \) and \( \frac{d}{dx} \sinh x = \cosh x \).

**Exercise 9.6.1**

1. Show that the range of \( \sinh x \) is all real numbers. (Hint: show that if \( y = \sinh x \) then \( x = \ln(y \pm \sqrt{y^2 - 1}) \).)
2. Compute the following limits:
   a. \( \lim_{x \to 0} \cosh x \)
   b. \( \lim_{x \to 0} \sinh x \)
   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 \( \coth, \text{sech}, \text{ and } \cosh \)? (Use the fact that they are reciprocals of \( \sinh \).
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 \( x \).
7. Show that \( \frac{d}{dx} (\tanh x) = \cosh^{-2} x \). 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.

The following four exercises expand on the geometric interpretation of the hyperbolic functions. Refer to figure 9.6.2.

10. 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 that \( \cosh(2x) - 1)/2 = \sinh^2 x \).

11. Compute \( \int \sqrt{x^2 - 1} \, dx \). (Hint: make the substitution \( u = \cosh x \) and then use the preceding exercise.)

12. Fix \( t > 0 \). Sketch the region \( R \) in the right half plane bounded by the curves \( y = \tanh t \), \( y = -\tanh t \), and \( y^2 - x^2 = 1 \). Note well: \( t \) is fixed, the plane is the \( x-y \) plane.

13. Prove that the area of \( R \) is \( t \).