3.5 Inverse Functions

Inverse functions are a special class of functions that undo each other. The input and output values for two inverse functions, \( f(x) = 2x + 1 \) and \( g(x) = \frac{x - 1}{2} \), are shown.

Notice that the output of the first function, \( f(x) \), becomes the input for the second function, \( g(x) \). The function \( g(x) \) undoes what \( f(x) \) does. The ordered pairs of \( g(x) \) can be found by switching the coordinates in each ordered pair of \( f(x) \).

<table>
<thead>
<tr>
<th>Input, ( x )</th>
<th>Output, ( f(x) )</th>
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<tbody>
<tr>
<td>0</td>
<td>1</td>
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<td>1</td>
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<thead>
<tr>
<th>Input, ( x )</th>
<th>Output, ( g(x) )</th>
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<td>1</td>
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The Paralympic Games are the world’s second-largest sporting event, after the Olympic Games. At the Paralympics held in Sydney, Australia, over 4000 competitors represented more than 100 countries. Canada finished fifth in the medal standings with 38 gold, 33 silver, and 25 bronze medals. Among the Canadians who won gold medals were wheelchair racers Chantal Petitclerc and Jeff Adams.

1. Wheelchair races are held over various distances, from 100 m to the marathon. The table includes data for some of the events that are held on a 400-m track. Copy and complete the table.

<table>
<thead>
<tr>
<th>Distance, ( d ) (km)</th>
<th>Number of Laps, ( n )</th>
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<tbody>
<tr>
<td>5</td>
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</table>
2. a) Write a function in the form \( d(n) = \_\_n \), where \( d \) is the distance of the race, in kilometres, and \( n \) is the number of laps.
   b) What operation does the function \( d(n) \) perform on each input value?
   c) List the ordered pairs of the function \( d(n) \).

3. a) Write a function in the form \( n(d) = \_\_d \), where \( n \) is the number of laps and \( d \) is the distance of the race, in kilometres.
   b) What operation does the function \( n(d) \) perform on each input value?
   c) List all the ordered pairs of the function \( n(d) \).

4. How can the ordered pairs of \( n(d) \) be obtained from the ordered pairs of \( d(n) \)?

5. Are \( d(n) \) and \( n(d) \) inverse functions? Explain.

6. How does the domain of each function compare with the range of the other?

7. Find the inverse, \( g(x) \), of each of the following functions.
   a) \( f(x) = 2x \)
   b) \( f(x) = \frac{3x}{4} \)
   c) \( f(x) = x + 2 \)
   d) \( f(x) = x - 4 \)

Recall that a relation is a set of ordered pairs. The inverse of a relation can be found by interchanging the domain and the range of the relation.

<table>
<thead>
<tr>
<th>Relation</th>
<th>Inverse Relation</th>
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<tbody>
<tr>
<td>((-3, 4), (0, 7), (2, 9))</td>
<td>((4, -3), (7, 0), (9, 2))</td>
</tr>
</tbody>
</table>

![Graph showing relation and inverse relation](image)

Also recall that a function is a special relation. For each element in the domain of a function, there is exactly one element in the range. If the inverse of a function \( f(x) \) is also a function, it is called the inverse function of \( f(x) \). This inverse function is denoted by \( f^{-1}(x) \).

The notation \( f^{-1} \) is read as “the inverse of \( f \)” or “\( f \) inverse.”

Note that the \(-1\) in \( f^{-1} \) is not an exponent, so \( f^{-1} \neq \frac{1}{f} \).
**Example 1  Interchanging Coordinates**

a) Find the inverse \( f^{-1} \) of the function \( f \) whose ordered pairs are \( \{(-2, -8), (0, -2), (3, 4), (4, 7)\} \).

b) Graph both functions.

**Solution**

a) Switch the first and second coordinates of each ordered pair.

\[ f^{-1} = \{(-8, -2), (-2, 0), (4, 3), (7, 4)\} \]

b) The graph of \( f \) is shown in red and the graph of \( f^{-1} \) is shown in blue.

Note that, in Example 1, switching the \( x \)- and \( y \)-coordinates reflects the function \( f \) in the line \( y = x \). So, the graph of \( f^{-1} \) is the reflection of the graph of \( f \) in the line \( y = x \). Notice the symmetry of the graphs in the line \( y = x \). If the diagram were folded along the line \( y = x \), the graph of \( f \) and the graph of \( f^{-1} \) would exactly match.

One way to find the inverse of a function is to reverse the operations that the function specifies.

The function \( f(x) = 2x + 3 \) means: Multiply \( x \) by 2, and then add 3.

Reversing the operations means: Subtract 3 from \( x \), and then divide the result by 2.

So, the inverse function of \( f(x) \) is \( f^{-1}(x) = \frac{x - 3}{2} \).

Let \( x = 6 \) and check that the inverse function undoes the other function.

The functions \( f(x) = 2x + 3 \) and \( f^{-1}(x) = \frac{x - 3}{2} \) are inverses, because one function undoes the other.

One way to reverse the operations that a function specifies is to interchange the variables.
**Example 2** Inverse of a Linear Function

a) Find the inverse of the function \( f(x) = 4x + 3 \).

b) Is the inverse of \( f(x) = 4x + 3 \) a function?

**Solution**

a) \( f(x) = 4x + 3 \)

Replace \( f(x) \) with \( y \):

\[ y = 4x + 3 \]

Interchange \( x \) and \( y \):

\[ x = 4y + 3 \]

Solve for \( y \):

\[ x - 3 = 4y \]

\[ \frac{x - 3}{4} = y \]

The inverse of \( f(x) = 4x + 3 \) is \( f^{-1}(x) = \frac{x - 3}{4} \).

b) The inverse of \( f(x) = 4x + 3 \) is a function, since only one \( y \)-value can be found for each \( x \)-value.

In Example 2, the inverse function can be written in the slope and \( y \)-intercept form, \( y = mx + b \), as \( y = \frac{x}{4} - \frac{3}{4} \).

The inverse function is linear, with a slope of \( \frac{1}{4} \) and a \( y \)-intercept of \( -\frac{3}{4} \).

If we graph the functions \( f(x) = 4x + 3 \) and \( f^{-1}(x) = \frac{x}{4} - \frac{3}{4} \) on the same axes, or in the same viewing window of a graphing calculator, we see two straight lines that are reflections of each other in the line \( y = x \).

In general, for the point \((x, y)\) on the graph of \( y = f(x) \), there is a corresponding point \((y, x)\) on the graph of its inverse, \( x = f(y) \). The graph of \( x = f(y) \) is a reflection of the graph of \( y = f(x) \) in the line \( y = x \). Points that lie on the line \( y = x \) are invariant, because their \( x \)- and \( y \)-coordinates are equal. In Example 2, the point \((-1, -1)\) is invariant.
Example 3 Inverse of a Quadratic Function

a) Find the inverse of \( f(x) = x^2 - 1 \)
b) Graph \( f(x) \) and its inverse.
c) Is the inverse of \( f(x) \) a function?
d) Determine the domain and the range of \( f(x) \) and its inverse.

Solution

a) \( f(x) = x^2 - 1 \)
Replace \( f(x) \) with \( y \):
Interchange \( x \) and \( y \):
Isolate \( y \):
Take the square root of both sides:
The inverse is \( f^{-1}(x) = \pm \sqrt{x + 1} \).
b) The graphs of \( f(x) \) and \( f^{-1} \) are shown.
To graph \( f^{-1}(x) = \pm \sqrt{x + 1} \) manually, graph the two branches \( y = \sqrt{x + 1} \) and \( y = -\sqrt{x + 1} \).
To graph \( f \) and \( f^{-1} \) on a graphing calculator, use the DrawInv instruction. You can use DrawInv without finding an equation for \( f^{-1} \).

c) For the inverse \( f^{-1} \), there are two values of \( y \) for each value of \( x \), except \( x = -1 \). In other words, \( f^{-1} \) does not pass the vertical line test. So, the inverse \( f^{-1} \) is not a function.

The notation \( f^{-1} \) can be used whether or not the inverse is a function.

Recall that, if you can draw a vertical line that intersects a graph in more than one point, the graph does not represent a function.
d) For \( f(x) = x^2 - 1 \), the domain is the set of real numbers. The range is the set of real numbers, \( y \geq -1 \).

For \( f^{-1}(x) = \pm \sqrt{x + 1} \), the domain is the set of real numbers, \( x \geq -1 \). The range is the set of real numbers.

**Example 4  Restricting the Domain of \( f(x) \)**

a) Find the inverse of \( f(x) = x^2 + 2 \).

b) Graph \( f(x) \) and its inverse.

c) Is the inverse of \( f(x) \) a function? If not, restrict the domain of \( f(x) \) so that its inverse is a function.

**Solution**

a) \( f(x) = x^2 + 2 \)

Replace \( f(x) \) with \( y \):

\[ y = x^2 + 2 \]

Interchange \( x \) and \( y \):

\[ x = y^2 + 2 \]

Isolate \( y \):

\[ x - 2 = y^2 \]

Take the square root of both sides:

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

So, \( f^{-1}(x) = \pm \sqrt{x - 2} \).

b) The graphs of \( f \) and \( f^{-1} \) are shown.

c) The inverse does not pass the vertical line test. So, the inverse \( f^{-1} \) is not a function.

The inverse has two branches, \( y = \sqrt{x - 2} \) and \( y = -\sqrt{x - 2} \).

The graph of one branch would pass the vertical line test. So, if the domain of \( f \) is restricted so that \( f^{-1} \) has only one branch, then \( f^{-1} \) will be a function.

For example, restricting the domain of \( f(x) \) to real values of \( x \geq 0 \) and reflecting \( f(x) = x^2 + 2 \), \( x \geq 0 \), in the line \( y = x \) would result in an inverse function \( f^{-1}(x) = \sqrt{x - 2} \). The graphs are as shown.
**Example 5  Car Rental**

The cost of renting a car for a day is a flat rate of $40, plus a charge of $0.10 per kilometre driven.

**a)** Let $r$ dollars be the total rental cost and $d$ kilometres be the distance driven. Write the function $r(d)$ to represent the total cost of a one-day rental.

**b)** Find the inverse of the function.

**c)** What does the inverse represent?

**d)** Give an example of how the inverse could be used.

**Solution**

**a)** $r(d) = 0.1d + 40$

**b)** Substitute $y$ for $r$ and $x$ for $d$:  
\[ y = 0.1x + 40 \]
Interchange $x$ and $y$:  
\[ x = 0.1y + 40 \]

Solve for $y$:  
\[ x - 40 = 0.1y \]
\[ \frac{x - 40}{0.1} = y \]
\[ 10(x - 40) = y \]
\[ 10x - 400 = y \]

Because $x$ and $y$ were interchanged, $x$ represents $r$ and $y$ represents $d$ in the inverse.
So, the inverse is $d(r) = 10r - 400$.  
*Note that solving $r = 0.1d + 40$ for $d$ gives the inverse.*

**c)** The inverse shows the distance that can be driven for a given rental cost.

**d)** The distance that can be driven for a total rental cost of $48 for a day is given by
\[ d = 10(48) - 400 \]
\[ = 480 - 400 \]
\[ = 80 \]

So, a distance of 80 km can be driven for a total rental cost of $48.

Note that the use of the inverse cannot include values of $r < 40$, since $40$ is the minimum daily rate and the distance driven cannot be negative.
**Key Concepts**

- A function, \( f(x) \), and its inverse function, \( f^{-1}(x) \), undo each other.
- The inverse of a function can be found by interchanging the domain and range of the function.
- The inverse of a function can be found by interchanging \( x \) and \( y \) in the equation of the function.
- The graph of \( x = f(y) \) is the graph of \( y = f(x) \) reflected in the line \( y = x \).
- A function and its inverse are congruent and are symmetric about the line \( y = x \).

**Communicate Your Understanding**

1. Describe how you would find the inverse of \( f = \{(-2, 4), (1, 3), (4, 7), (8, 11)\} \).
2. Describe how you would find the inverse of \( f(x) = 4x + 7 \).
3. Describe how you would find the inverse of \( f(x) = x^2 - 5 \).

**Practise**

**A**

1. Given the ordered pairs of each function, find the inverse, and graph the function and its inverse.
   
   a) \( f = \{(0, 2), (1, 3), (2, 4), (3, 5)\} \)
   
   b) \( g = \{(-1, 3), (1, -2), (3, 4), (5, 0), (6, 1)\} \)

2. Given the ordered pairs of each function, find the inverse, and state whether the inverse is a function.
   
   a) \( f = \{(-2, 3), (-1, 2), (0, 0), (4, -2)\} \)
   
   b) \( g = \{(4, -2), (2, 1), (1, 3), (0, -2), (-3, -3)\} \)

3. Sketch the inverse of each function.
   
   a) 
   
   b)
4. Solve each equation for \( x \).
   a) \( f(x) = 3x + 2 \)  
   b) \( f(x) = \frac{12 - 2x}{3} \)
   c) \( f(x) = 3 - 4x \)  
   d) \( f(x) = \frac{x + 3}{4} \)
   e) \( f(x) = \frac{x}{2} - 5 \)  
   f) \( f(x) = x^2 + 3 \)

5. Find the inverse of each function.
   a) \( f(x) = x - 1 \)  
   b) \( f(x) = \frac{x}{2} \)
   c) \( f(x) = x + 3 \)  
   d) \( f(x) = \frac{4}{3} x \)
   e) \( f(x) = 2x + 1 \)  
   f) \( f(x) = \frac{x + 2}{3} \)
   g) \( g(x) = \frac{5}{2} x - 4 \)  
   h) \( h(x) = 0.2x + 1 \)

6. Find the inverse of each function. Graph the function and its inverse.
   a) \( f(x) = x + 2 \)  
   b) \( f(x) = 4x \)
   c) \( f(x) = 3x - 2 \)  
   d) \( f(x) = x \)
   e) \( f(x) = 3 - x \)  
   f) \( f(x) = \frac{x - 2}{3} \)

7. Find the inverse of each function and determine whether the inverse is a function.
   a) \( f(x) = 2x - 5 \)  
   b) \( f(x) = \frac{x + 3}{4} \)
   c) \( f(x) = \frac{x}{4} + 3 \)  
   d) \( f(x) = 5 - x \)

8. Determine if the functions in each pair are inverses of each other.
   a) \( f(x) = x + 5 \)  
   b) \( f(x) = 7x \)  
   c) \( f(x) = 2x - 1 \)  
   d) \( f(x) = x - 3 \)  
   e) \( f(x) = \frac{x}{3} - 4 \)  
   f) \( g(x) = \frac{x}{3} - 5 \)  
   g) \( h(x) = \frac{x - 8}{4} \)  
   h) \( k(x) = 4(x + 2) \)

9. Verify algebraically and graphically that the functions in each pair are inverses of each other.
   a) \( y = 3x + 4 \)  
   b) \( y = 3 - 2x \)  
   c) \( y = \frac{1}{3} (x - 4) \)  
   d) \( y = -\frac{1}{2} (x - 3) \)

10. For each of the following functions,
    a) find the inverse of \( f(x) \)
    b) graph \( f(x) \) and its inverse
    c) determine the domain and range of \( f(x) \)
        and its inverse
   i) \( f(x) = x^2 - 3 \)  
   ii) \( f(x) = x^2 + 1 \)  
   iii) \( f(x) = -x^2 \)  
   iv) \( f(x) = -x^2 - 1 \)  
   v) \( f(x) = (x - 2)^2 \)  
   vi) \( f(x) = (x + 1)^2 \)
11. The blue graph is a reflection of the red graph in the line \( y = x \). The equation of the red graph is given. Write the equation of the blue graph.

a) \( y = 2x + 3 \)

b) \( f(x) = x^2 + 4 \)

12. Determine if the functions in each pair are inverses of each other.

a) \( y = x^2 - 3 \) and \( y = -x + 3 \)

b) \( y = x^2 + 1 \) and \( y = \sqrt{x + 1} \)

13. Find the inverse of each function. If the inverse is a function, determine the domain and range of the inverse.

a) \( y = 2x - 3 \)

b) \( y = 2 - 4x \)

c) \( y = 3(x - 2) \)

d) \( y = \frac{1}{2}(x - 6) \)

e) \( y = x^2 \)

f) \( y = x^2 + 2 \)

g) \( y = x^2 - 4 \)

h) \( y = 2x^2 - 1 \)

i) \( y = (x - 3)^2 \)

j) \( y = (x + 2)^2 \)

14. For each of the following functions,

a) find the inverse of \( f(x) \)

b) graph \( f(x) \) and its inverse

c) determine the domain and range of \( f(x) \) and its inverse

i) \( f(x) = x^2, x \geq 0 \)

ii) \( f(x) = x^2 - 2, x \geq 0 \)

iii) \( f(x) = x^2 + 4, x \leq 0 \)

iv) \( f(x) = 3 - x^2, x \geq 0 \)

v) \( f(x) = (x - 4)^2, x \geq 4 \)

vi) \( f(x) = (x + 3)^2, x \leq -3 \)

15. Find the inverse of each of the following functions.

a) \( y = \sqrt{x - 2} \)

b) \( y = \sqrt{3 - x} \)

c) \( y = \sqrt{x^2 + 9} \)

16. For each of the following functions,

a) find the inverse \( f^{-1} \)

b) graph \( f(x) \) and its inverse

c) restrict the domain of \( f \) so that \( f^{-1} \) is also a function

d) with the domain of \( f \) restricted, sketch a graph of \( f \) and \( f^{-1} \)

i) \( f(x) = x^2 + 3 \)

ii) \( f(x) = 2x^2 \)

iii) \( f(x) = x^2 - 1 \)

iv) \( f(x) = -x^2 \)

v) \( f(x) = 1 - x^2 \)

vi) \( f(x) = (x - 2)^2 \)

vii) \( f(x) = (4 - x)^2 \)

viii) \( f(x) = -(x + 5)^2 \)

17. a) Find the inverse of \( f(x) = \frac{1}{x} \).

b) Is the inverse a function? Explain.

18. **Communication**

a) Find the inverse of \( f(x) = \sqrt{x} \).

b) Is the inverse a function? Explain.
Apply, Solve, Communicate

19. **Van Rental**  The cost of renting a van for one day is a flat rate of $50, plus a variable rate of $0.15/km.
   a) Write a function to express the total cost of a one-day rental, \( c(d) \) dollars, in terms of the distance driven, \( d \) kilometres.
   b) Determine the inverse of the function.
   c) What does the inverse represent?
   d) What is the domain of the inverse?

20. **Measurement**
   a) Let \( x \) represent the radius of a circle. Write a function \( f(x) \) to express the circumference in terms of the radius.
   b) Find the inverse of this function.
   c) Is the inverse a function?
   d) What does the inverse represent?

21. **Application**
   a) Let \( x \) represent the radius of a sphere. Write a function \( f(x) \) to express the surface area in terms of the radius.
   b) Find the inverse of this function.
   c) Determine the domain and range of the inverse.
   d) Is the inverse a function?
   e) What does the inverse represent?

22. **Retail Sales**
   A sale at an appliance store advertised that all appliances were being sold at 30% off the original selling price.
   a) Write a function that gives the sale price as a function of the original selling price.
   b) Find the inverse of this function.
   c) What does the inverse represent?

23. **Foreign currency exchange**
   One day, the Canadian dollar was worth US$0.70.
   a) Write a function that expresses the value of the US dollar, \( u \), in terms of the Canadian dollar, \( c \).
   b) Find the inverse. Round the coefficient to the nearest hundredth.
   c) Use the inverse to convert US$150 to Canadian dollars.
24. **Geology** The approximate temperature, in degrees Celsius, of rocks beneath the surface of the Earth can be found by multiplying their depth, in kilometres, by 35 and adding 20 to the product.

a) Let \( d \) kilometres represent the depth of some rocks. Write a function \( T(d) \) that expresses the Celsius temperature of the rocks in terms of their depth.

b) Write the inverse function.

c) At what depth do rocks have a temperature of 90°C?

25. **Weekly wages** Jana works at a clothing store. She earns $400 a week, plus a commission of 5% of her sales.

a) Write a function that describes Jana's total weekly earnings as a function of her sales.

b) Find the inverse of this function.

c) What does the inverse represent?

d) One week, Jana earned $575. Calculate her sales that week.

26. **Measurement** The measure of an interior angle, \( i \), of a regular polygon is related to the number of sides \( n \) by the function \( i(n) = 180 - \frac{360}{n} \).

a) Determine the measure of an interior angle of a regular heptagon.

b) Find the inverse of the function.

c) Use the inverse to identify the regular polygon with interior angles of 144°.

27. **Falling objects** If an object is dropped from a height of 80 m, its approximate height, \( h(t) \) metres, above the ground \( t \) seconds after being dropped is given by the function \( h(t) = -5t^2 + 80 \).

a) Graph the function.

b) Find and graph the inverse.

c) Is the inverse a function? Explain.

d) What does the inverse represent?

e) After what length of time is the object 35 m above the ground?

f) How long does the object take to reach the ground?

28. a) Given \( f(x) = 2x - 4 \), write equations for \( -f(x) \), \( f(-x) \), and \( f^{-1}(x) \).

b) Sketch the four graphs on the same set of axes.

c) Determine any points that are invariant for each reflection.

29. a) Given \( f(x) = -3x + 2 \), write equations for \( -f(x) \), \( f(-x) \), and \( f^{-1}(x) \).

b) Sketch the four graphs on the same set of axes.

c) Determine any points that are invariant for each reflection.

30. a) Given \( f(x) = \sqrt{x + 3} \), write equations for \( -f(x) \), \( f(-x) \), and \( f^{-1}(x) \).

b) Sketch the four graphs on the same set of axes.
31. Write an equation for the line obtained by reflecting the line \( x = 2 \) in the line \( y = x \).

32. **Sequencing reflections** Copy the graph of \( y = f(x) \) as shown. Sketch the graph of each relation obtained after a reflection in the \( y \)-axis, followed by a reflection in the \( x \)-axis, followed by a reflection in the line \( y = x \).

33. **Inquiry/Problem Solving** Write four functions that are their own inverses.

34. The function \( f \) includes the ordered pair \((2, 3)\). Can \( f^{-1} \) include each of the following ordered pairs? Explain.
   a) \((3, 4)\)  
   b) \((4, 2)\)

35. **Analytic geometry** Find the area of the figure formed by the intersection of \( f'(x) = 4 - x \), \( g(x) = 12 - 3x \), and \( g^{-1} \).

36. a) Is the relation \( y = k \), where \( k \) is a constant, a function? Explain.
   b) Is the inverse of \( y = k \) a function? Explain.

37. What is the inverse of the inverse of a function? Explain.

38. **Slope** If a line is not horizontal or vertical, how is the slope of the line related to the slope of its inverse?

39. a) In how many different ways could you restrict the domain of \( f(x) = x^2 + 3 \), so that the inverse is a function? Give examples and use graphs to justify your answer.
   b) In how many different ways could you restrict the domain of \( f(x) = x^2 + 3 \), so that the inverse is not a function? Give examples and use graphs to justify your answer.

**Achievement Check**

<table>
<thead>
<tr>
<th>Knowledge/Understanding</th>
<th>Thinking/Inquiry/Problem Solving</th>
<th>Communication</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Sketch the graph of the function ( f(x) = \sqrt{x} ).</td>
<td></td>
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<tr>
<td>b) On the same set of axes, graph ( y = f^{-1}(x) ), ( y = f^{-1}(-x) ), and ( y = -f^{-1}(-x) ).</td>
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<td>c) Compare the graphs of ( y = f(x) ) and ( y = -f^{-1}(-x) ). If the graph of ( y = -f^{-1}(-x) ) is drawn from the graph of ( y = f(x) ) by a single reflection, what is the equation of the reflection line?</td>
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