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A7 WHERE APPROPRIATE, INTERPRET SIMPLE EXPRESSIONS AS FUNCTIONS WITH INPUTS AND OUTPUTS; **INTERPRET THE REVERSE PROCESS AS THE 'INVERSE FUNCTION'; INTERPRET THE SUCCESSION OF TWO FUNCTIONS AS A 'COMPOSITE FUNCTION' (THE USE OF FORMAL FUNCTION NOTATION IS EXPECTED) (higher tier)**

In GCSE Mathematics equations are written as shown below:

$y = 3x + 4$ $\qquad\qquad$ $y = x^2 + 5$

Sometimes a different notation is used which is called **function notation**.

We often use the letters f and g and we write the above equations as

$f(x) = 3x + 4$ $\qquad\qquad$ $g(x) = x^2 + 5$

EXAMPLE 1

Using the equation $y = 3x + 4$, find the value of y if

(a) $x = 4$ $\qquad\qquad$ (b) $x = -6$

(a) $y = 3(4) + 4 = 12 + 4 = 16$ ← Substitute for $x = 4$ in the equation

(b) $y = 3(-6) + 4 = -18 + 4 = -14$ ← Substitute for $x = -6$ in the equation

EXAMPLE 2

f is a function such that $f(x) = 3x + 4$

Find the values of

(a) f(4) $\qquad\qquad$ (b) f(–6)

(a) $f(4) = 3(4) + 4 = 12 + 4 = 16$ ← Substitute for $x = 4$ in the equation

(b) $f(-6) = 3(-6) + 4 = -18 + 4 = -14$ ← Substitute for $x = -6$ in the equation

EXAMPLE 3

g is a function such that $g(x) = 2x^2 - 5$

Find the values of (a) g(3) (b) g(–4)

(a) $g(3) = 2(3)^2 - 5 = 18 - 5 = 13$ ← Substitute for $x = 3$ in the equation

(b) $g(-4) = 2(-4)^2 - 5 = 32 - 5 = 17$ ← Substitute for $x = -4$ in the equation

EXAMPLE 4

The functions f and g are defined for all real values of x and are such that

$f(x) = x^2 - 4$ and $g(x) = 4x + 1$

Find (a) f(–3) (b) g(0.3)

(c) Find the two values of x for which $f(x) = g(x)$.

(a) $f(-3) = (-3)^2 - 4 = 9 - 4 = 5$ ← Substitute for $x = -3$ in the equation $f(x)$

(b) $g(0.3) = 4(0.3) + 1 = 1.2 + 1 = 2.2$ ← Substitute for $x = 0.3$ in the equation $g(x)$

(c) $x^2 - 4 = 4x + 1$ ← Put $f(x) = g(x)$

$x^2 - 4 - 4x - 1 = 0$ ← Rearrange the equation as a quadratic = 0

$x^2 - 4x - 5 = 0$ ← Simplify

$(x - 5)(x + 1) = 0$ ← Solve the quadratic by factorising

$x - 5 = 0$ or $x + 1 = 0$

$x = 5$ or $x = -1$

EXERCISE 1:

1. The function f is such that $f(x) = 5x + 2$

   Find (a) f(3) (b) f(7) (c) f(−4)

   (d) f(−2) (e) f(−0.5) (f) f(0.3)

2. The function f is such that $f(x) = x^2 - 4$

   Find (a) f(4) (b) f(6) (c) f(−2)

   (d) f(−6) (e) f(−0.2) (f) f(0.9)

3. The function g is such that $g(x) = x^3 - 3x^2 - 2x + 1$

   Find (a) g(0) (b) g(1) (c) g(2)

   (d) g(−1) (e) g(−0.4) (f) g(1.5)

4. The function f is such that $f(x) = \sqrt{2x + 5}$

   Find (a) f(0) (b) f(1) (c) f(2)

   (d) f(−1) (e) f(−0.7) (f) f(1.5)

5. $f(x) = 3x^2 - 2x - 8$

   Express $f(x + 2)$ in the form $ax^2 + bx$

6. The functions f and g are such that

   $f(x) = 3x - 5$ and $g(x) = 4x + 1$

   (a) Find (i) f(−1) (ii) g(2)

   (b) Find the two values of x for which $f(x) = g(x)$.

7. The functions f and g are such that

   $f(x) = 2x^2 - 1$ and $g(x) = 5x + 2$

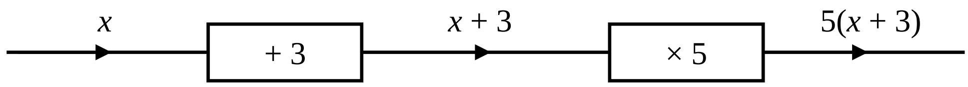
   (a) Find f(−3) and g(−5)

   (b) Find the two values of x for which $f(x) = g(x)$.

COMPOSITE FUNCTIONS

A **composite function** is a function consisting of 2 or more functions.

The term composition is used when one operation is performed after another operation.
For instance:



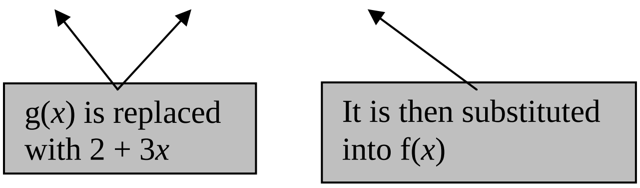
This function can be written as f(x) = 5(x + 3)

Suppose f(x) = x^2 and g(x) = 2 + 3x

What is fg(x)? Now fg(x) = f[g(x)]

This means apply g first and then apply f.

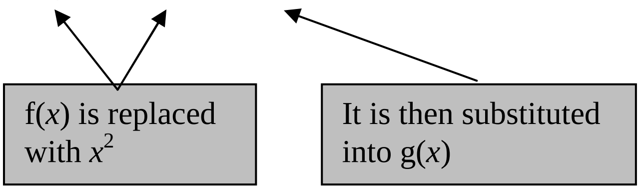
fg(x) = f(2 + 3x) = (2 + 3x)^2



What is gf(x)?

This means apply f first and then apply g.

gf(x) = f(x^2) = 2 + 3x^2



NOTE: The composite function **gf(x)** means apply f first followed by g.

NOTE: The composite function **fg(x)** means apply g first followed by f.

NOTE: fg(x) can be written as fg and gf(x) can be written as gf; fg is not the same as gf.

EXAMPLE 5

f and g are functions such that $f(x) = \frac{1}{x}$ and $g(x) = 3 - 2x$

Find the composite functions (a) fg (b) gf

(a) $fg = fg(x) = f(3 - 2x)$ ← Do g first: Put $(3 - 2x)$ instead of $g(x)$

$= \frac{1}{3-2x}$ ← Substitute $(3 - 2x)$ for x in $\frac{1}{x}$

(b) $gf = gf(x) = g\left(\frac{1}{x}\right)$ ← Do f first: Put $\frac{1}{x}$ instead of $f(x)$

$= 3 - 2\frac{1}{x} = 3 - \frac{2}{x}$ ← Substitute $\frac{1}{x}$ for x in $(3 - 2x)$

EXAMPLE 6

$f(x) = 7 - 2x$ $g(x) = 4x - 1$ $h(x) = 3(x - 1)$

Find the following composite functions: (a) gf (b) gg (c) fgh

(a) $gf = gf(x) = g(7 - 2x)$ ← Do f first: Put $(7 - 2x)$ instead of $f(x)$

$= 4(7 - 2x) - 1$ ← Substitute $(7 - 2x)$ for x in $4x - 1$

$= 27 - 8x$ ← Simplify $28 - 8x - 1$

(b) $gg = gg(x) = g(4x - 1)$ ← Put $(4x - 1)$ instead of $g(x)$

$= 4(4x - 1) - 1$ ← Substitute $(4x - 1)$ for x in $4x - 1$

$= 16x - 5$ ← Simplify $16x - 4 - 1$

(c) $fgh = fgh(x) = fg[3(x - 1)]$ ← Put $3(x - 1)$ instead of $h(x)$

$= fg(3x - 3)$ ← Expand $3(x - 1)$

$= f[4(3x - 3) - 1]$ ← Substitute $(3x - 3)$ for x in $4x - 1$

$= f(12x - 13)$ ← Simplify $12x - 12 - 1$

$= 7 - 2(12x - 13)$ ← Substitute $(12x - 13)$ for x in $7 - 2x$

$= 33 - 24x$ ← Simplify $7 - 24x + 26$

EXAMPLE 7

$f(x) = 7 - 2x$ $g(x) = 4x - 1$ $h(x) = 3(x - 1)$

Evaluate (a) fg (5) (b) ff (–2) (c) ghf (3)

(a) $fg(5) = f(20 - 1) = f(19)$ ← Substitute for $x = 5$ in $4x - 1$

$= 7 - 2(19) = -31$ ← Substitute for $x = 19$ in $7 - 2x$

(b) $ff(-2) = f[7 - 2(-2)] = f(11)$ ← Substitute for $x = -2$ in $7 - 2x$ and simplify

$= 7 - 2(11) = -15$ ← Substitute for $x = 11$ in $7 - 2x$ and simplify

(c) $ghf(3) = gh(7 - 6) = gh(1)$ ← Substitute for $x = 3$ in $7 - 2x$ and simplify

$= g[3(1 - 1)] = g(0)$ ← Substitute for $x = 1$ in $3(x - 1)$ and simplify

$= 4(0) - 1 = -1$ ← Substitute for $x = 0$ in $4x - 1$ and simplify

EXAMPLE 8

$f(x) = 3x + 2$ and $g(x) = 7 - x$

Solve the equation $gf(x) = 2x$

$gf(x) = g(3x + 2)$ ← Put $(3x + 2)$ instead of $f(x)$

$= 7 - (3x + 2)$ ← g's rule is subtract from 7

$= 5 - 3x$ ← Simplify $7 - 3x - 2$

$5 - 3x = 2x$ ← Put $gf(x) = 2x$ and solve

$5 = 5x$ ← Add $3x$ to both sides

$x = 1$

EXAMPLE 9

(more challenging question)

Functions f, g and h are such that

f: $x \to 4x - 1$ g: $x \to \frac{1}{x+2}, x \neq -2$ h: $x \to (2 - x)^2$

Find (a)(i) fg(x)   (ii) hh(x)   (b) Show that fgh(x) = $\frac{8x+1}{4x+1}$

(a) $fg(x) = f\left(\frac{1}{x+2}\right)$ ← Substitute for g(x)

$= 4\left(\frac{1}{x+2}\right) - 1$ ← f's operation is × 4 − 1

$= \frac{4 - 1(x+2)}{x+2}$ ← Simplify using a common denominator of $x + 2$

$= \frac{2-x}{x+2}$

(b) $hh(x) = h(2 - x)^2$ ← Substitute for h(x)

$= [2 - (2 - x)^2]^2$ ← h's operation is subtract from 2 and then square

$= [2 - (4 - 2x + x^2)]^2$ ← $(2 - x)^2 = (2 - x)(2 - x) = 4 - 2x + x^2$

$= (-2 + 4x - 2x^2)^2$

(c) $hgf(x) = hg(4x - 1)$ ← Put $(4x - 1)$ for f(x)

$= h\left(\frac{1}{4x-1+2}\right)$ ← Substitute $(4x - 1)$ for x in g(x)

$= \left(2 - \frac{1}{4x+1}\right)^2$ ← $4x - 1 + 2 = 4x + 1$, so put $4x + 1$ for x in h(x)

$= \left[2\left(\frac{4x+1}{4x+1}\right) - \frac{1}{4x+1}\right]^2$ ← Simplify using a common denominator of $4x + 1$

$= \left(\frac{8x+2-1}{4x+1}\right)^2$

$= \frac{8x+1}{4x+1}$

EXERCISE 2:

1. Find an expression for $fg(x)$ for each of these functions:

   (a) $f(x) = x - 1$ and $g(x) = 5 - 2x$

   (b) $f(x) = 2x + 1$ and $g(x) = 4x + 3$

   (c) $f(x) = \frac{3}{x}$ and $g(x) = 2x - 1$

   (d) $f(x) = 2x^2$ and $g(x) = x + 3$

2. Find an expression for $gf(x)$ for each of these functions:

   (a) $f(x) = x - 1$ and $g(x) = 5 - 2x$

   (b) $f(x) = 2x + 1$ and $g(x) = 4x + 3$

   (c) $f(x) = \frac{3}{x}$ and $g(x) = 2x - 1$

   (d) $f(x) = 2x^2$ and $g(x) = x + 3$

3. The function f is such that $f(x) = 2x - 3$

   Find (i) $ff(2)$ (ii) Solve the equation $ff(a) = a$

4. Functions f and g are such that

   $f(x) = x^2$ and $g(x) = 5 + x$

   Find (a)(i) $fg(x)$ (ii) $gf(x)$

   (b) Show that there is a single value of x for which $fg(x) = gf(x)$ and find this value of x.

5. Given that $f(x) = 3x - 1$, $g(x) = x^2 + 4$ and $fg(x) = gf(x)$, show that $x^2 - x - 1 = 0$

6. The function f is defined by $f(x) = \frac{x-1}{x}$, $x \neq 0$

   Solve $ff(x) = -2$

7. The function g is such that $g(x) = \frac{1}{1-x}$ for $x \neq 1$

   (a) Prove that $gg(x) = \frac{x-1}{x}$

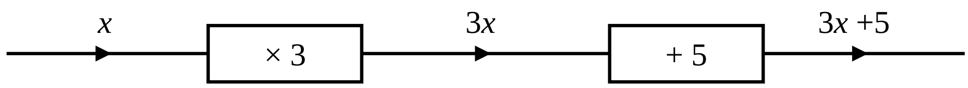
   (b) Find $ggg(3)$

8. Functions f, g and h are such that $f(x) = 3 - x$, $g(x) = x^2 - 14$ and $h(x) = x - 2$

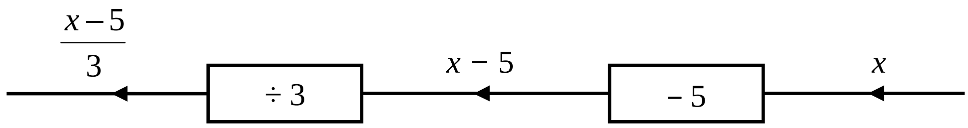
   Given that $f(x) = gfh(x)$, find the values of x.

INVERSE FUNCTIONS

The function f(x) = 3x +5 can be thought of as a sequence of operations as shown below



Now reversing the operations



The new function, $\frac{x-5}{3}$, is known as the **inverse** function.

> Inverse functions are denoted as $f^{-1}(x)$.

EXAMPLE 10

Find the inverse function of $f(x) = 3x - 4$

$y = 3x - 4$ ← **Step 1:** Write out the function as y = ...

$x = 3y - 4$ ← **Step 2:** Swap the x and y

$x + 4 = 3y$

$\frac{x+4}{3} = y$ ← **Step 3:** Make y the subject

$f^{-1}(x) = \frac{x+4}{3}$ ← **Step 4:** Instead of $y =$ write $f^{-1}(x) =$

EXAMPLE 11

Find the inverse function of $f(x) = \frac{x-2}{7}$

$$y = \frac{x-2}{7}$$ ← **Step 1:** Write out the function as $y = ...$

$$x = \frac{y-2}{7}$$ ← **Step 2:** Swap the x and y

$$7x = y - 2$$
$$7x + 2 = y$$ ← **Step 3:** Make y the subject

$$f^{-1}(x) = 7x + 2$$ ← **Step 4:** Instead of $y =$ write $f^{-1}(x) =$

EXAMPLE 12

Find the inverse function of $f(x) = \sqrt{x+4}$

$$y = \sqrt{x+4}$$ ← **Step 1:** Write out the function as $y = ...$

$$x = \sqrt{y+4}$$ ← **Step 2:** Swap the x and y

$$x^2 = y + 4$$
$$x^2 - 4 = y$$ ← **Step 3:** Make y the subject

$$f^{-1}(x) = x^2 - 4$$ ← **Step 4:** Instead of $y=$ write $f^{-1}(x) =$

RULES FOR FINDING THE INVERSE $f^{-1}(x)$:

Step 1: Write out the function as $y = ...$

Step 2: Swap the x and y

Step 3: Make y the subject

Step 4: Instead of $y=$ write $f^{-1}(x) =$

EXERCISE 3:

1. Find the inverse function, $f^{-1}(x)$, of the following functions:

(a) $f(x) = 3x - 1$

(b) $f(x) = 2x + 3$

(c) $f(x) = 1 - 2x$

(d) $f(x) = x^2 + 5$

(e) $f(x) = 6(4x - 1)$

(f) $f(x) = 4 - x$

(g) $f(x) = 3x^2 - 2$

(h) $f(x) = 2(1 - x)$

(i) $f(x) = \dfrac{2}{x+1}$

(j) $f(x) = \dfrac{x+1}{x-2}$

2. The function f is such that $f(x) = 7x - 3$

(a) Find $f^{-1}(x)$.

(b) Solve the equation $f^{-1}(x) = f(x)$.

3. The function f is such that $f(x) = \dfrac{8}{x+2}$

(a) Find $f^{-1}(x)$.

(b) Solve the equation $f^{-1}(x) = f(x)$.

4. The function f is such that $f(x) = \dfrac{1}{x+4}$, $x \neq -4$.

Evaluate $f^{-1}(x)$. [Hint: First find $f^{-1}(x)$ and then substitute for $x = -3$]

5. $f(x) = \dfrac{x}{x+3}$, $x \in R$, $x \neq -3$

(a) If $f^{-1}(x) = -5$, find the value of x.

(b) Show that $ff^{-1}(x) = x$

6. Functions f and g are such that

$f(x) = 3x + 2$ $\qquad$ $g(x) = x^2 + 1$

Find an expression for $(fg)^{-1}(x)$ [Hint: First find $fg(x)$]

MIXED EXERCISE:

1. Here is a number machine.

(a) Work out the **output** when the input is 4

(b) Work out the **input** when the output is 11

(c) Show that there is a value of the input for which the input and the output have the same value.

2. Functions f and g is such that $f(x) = 2x - 1$ and $g(x) = \dfrac{3}{x}$

(a) Find the value of

(i) f(3)

(ii) fg(6)

(b) Express the inverse function in the form $f^{-1}(x)) =$ .....

(c) Express the composite function gf in the form $gf(x) =$ .....

3. The function f is such that $f(x) = 4x - 1$

(a) Find $f^{-1}(x)$

The function g is such that $g(x) = kx^2$ where k is a constant.

(b) Given that $fg(2) = 12$, work out the value of k

4. Functions f and g are such that $f(x) = 3(x - 4)$ and $g(x) = \dfrac{x}{5} + 1$

(a) Find the value of f(10)

(b) Find $g^{-1}(x)$

(c) Show that $ff(x) = 9x - 48$

5. Given that $f(x) = x^2$ and $g(x) = x - 6$, solve the equation $fg(x) = g^{-1}(x)$

6. f and g are functions such that $f(x) = 2x - 3$ and $g(x) = 1 + \sqrt{x}$

(a) Calculate $f(-4)$

(b) Given that $f(a) = 5$, find the value of a.

(c) Calculate gf(6).

(d) Find the inverse function $g^{-1}(x)$.

7. Functions f and g are such that

$f(x) = \frac{1}{x+2}$ and $g(x) = \sqrt{x-1}$

(a) Calculate fg(10)

(b) Find the inverse function $g^{-1}(x)$.

8. Functions f and g are such that

$f(x) = 2x + 2$ and $g(x) = 2x - 5$

(a) Find the composite function fg.
Give your answer as simply as possible.

(b) Find the inverse function $f^{-1}(x)$.

(c) Hence, or otherwise, solve $f^{-1}(x)$.= $g^{-1}(x)$.

9. The function f is such that $f(x) = \frac{1}{x+3}$

(a) Find the value of f(2)

(b) Given that $f(a) = \frac{1}{10}$, find the value of a.

The function g is such that $g(x) = x + 2$

(c) Find the function gf.

Give your answer as a single algebraic fraction in its simplest form.

10. Functions f and g are such that $f(x) = x^2$ and $g(x) = x - 3$

(a) Find gf(x).

(b) Find the inverse function $g^{-1}(x)$.

(c) Solve the equation $gf(x) = g^{-1}(x)$.

11. The function f is such that $f(x) = (x - 1)^2$

(a) Find f(8)

The function g is such that $g(x) = \frac{x}{x-1}$

(b) Solve the equation $g(x) = 1.2$

(c) (i) Express the inverse function g^{-1} in the form $g^{-1}(x) =$ ....

(ii) Hence write down gg(x) in terms of x.

12. f is a function such that $f(x) = \frac{1}{x^2+1}$

(a) Find $f(\frac{1}{2})$

g is a function such that g(x) = $\sqrt{x-1}$, $x \geq 1$

(b) Find fg(x)
Give your answer as simply as possible.

13. The function f is such that $f(x) = \frac{x-6}{2}$

(a) Find f(8)

(b) Express the inverse function f^{-1} in the form $f^{-1}(x) = \dots$

The function g is such that $g(x) = \sqrt{x-4}$

(c) Express the function gf in the form gf(x) = …
Give your answer as simply as possible.

14. Functions f and g are such that f(x) = 3x – 2 and g(x) = $\frac{10}{x+2}$

(a) Express the inverse function f^{-1} in the form $f^{-1}(x) = ...$

(b) Find gf(x)
Simplify your answer.

15. Functions f and g are such that f(x) = $\frac{2}{x}$ and g(x) = $\frac{x+1}{x}$

(a) Solve gf(a) = 3

(b) Express the inverse function g^{-1} in the form $g^{-1}(x) = ...$

16. Functions g and h are such that g(x) = $\frac{x}{2x-5}$ and h(x) = x + 4

(a) Find the value of g(1)

(b) Find gh(x)
Simplify your answer.

(c) Express the inverse function g^{-1} in the form $g^{-1}(x) = \dots$

ANSWERS

Exercise 1

1. (a) 17 (b) 37 (c) −18
   (d) –8 (e) −0.5 (f) 3.5

2. (a) 12 (b) 32 (c) 0
   (d) 32 (e) −3.96 (f) −3.19

3. (a) 1 (b) −3 (c) −7
   (d) –1 (e) 1.256 (f) −5.375

4. (a) $\sqrt{5}$ (b) $\sqrt{3}$ (c) 3
   (d) $\sqrt{3}$ (e) $\frac{3\sqrt{10}}{5}$ (f) $2\sqrt{2}$

5. $3x^2 + 10x$

6. (a) f(− 1) = 8 and g(2) = 9 (b) $x = -6$

7. (a) f(− 3) = 17 and g(− 5) = − 23 (b) $x = -\frac{1}{2}$ and $x = 3$

Exercise 2

1. (a) $4 - 2x$ (b) $8x + 17$ (c) $\frac{3}{2x-1}$ (d) $2(x + 3)^2$

2. (a) $7 - 2x$ (b) $8x + 7$ (c) $\frac{6}{x} - 1$ (d) $2x^2 + 3$

3. (a) – 1 (b) $a = 3$

4. (a)(i) $(5 + x)^2$ (ii) $5 + x^2$ (b) $x = -2$

5. $3(x^2 + 4) - 1 = (3x - 1)^2 + 4$
   $3x^2 + 12 - 1 = 9x^2 - 6x + 1 + 4$
   $3x^2 + 11 = 9x^2 - 6x + 5$
   $6x^2 - 6x - 6 = 0$
   $x^2 - x - 1 = 0$

6. $x = \frac{3}{2}$

7. (a) $g\left(\frac{1}{1-x}\right) = \frac{1}{1-\frac{1}{1-x}} = \frac{1}{\frac{1-x-1}{1-x}} = \frac{1-x}{-x} = \frac{x-1}{x}$ (b) $-\frac{1}{4}$

8. $x = 1$ and $x = 8$

Exercise 3

1. (a) $\frac{x+1}{3}$ (b) $\frac{x-3}{2}$ (c) $\frac{1-x}{2}$ (d) $\pm\sqrt{x-5}$

   (e) $\frac{x+6}{24}$ (f) $4 - x$ (g) $\pm\sqrt{\frac{x+2}{3}}$ (h) $\frac{2-x}{2}$

   (i) $\frac{2-x}{x}$ (j) $\frac{2x+1}{x-1}$

2. (a) $\frac{x+3}{7}$ (b) $x = 0.5$

3. (a) $\frac{8}{x}-2$ (b) $x = -4$ and $x = 2$

4. $-\frac{13}{3}$

5. (a) $\frac{5}{2}$ (b) $f\left(\frac{3x}{1-x}\right)=\frac{\frac{3x}{1-x}}{\frac{3x}{1-x}+3}=\frac{\frac{3x}{1-x}}{\frac{3x+3(1-x)}{1-x}}=\frac{\frac{3x}{1-x}}{\frac{3x+3-3x}{1-x}}=\frac{3x}{3}=x$

6. $\pm\sqrt{\frac{x-5}{3}}$

Mixed Exercise

1. (a) 8 (b) 29 (c) 2

2. (a) (i) 5 (ii) 0 (b) $\frac{x+1}{2}$ (c) $\frac{3}{x}$

3. (a) $\frac{x+1}{4}$ (b) $k = \frac{13}{16}$

4. (a) 18 (b) $5(x - 1)$
   (c) $\text{ff}(x) = 3(3(x - 4) - 4) = 3(3x - 12 - 4) = 3(3x - 16) = 9x - 48$

5. $x = 6$ and $x = 7$

6. (a) -11 (b) $a = 4$ (c) 4 (d) $(x - 1)^2$

7.	(a) $\frac{1}{5}$	(b) $x^2 + 2$		
8.	(a) $6x - 13$	(b) $\frac{x-2}{3}$	(c) $x = -19$	
9.	(a) $\frac{1}{5}$	(b) $a = 7$	(c) $\frac{2x+7}{x+3}$	
10.	(a) $x^2 - 3$	(b) $x + 3$	(c) $x = -2$ and $x = 3$	
11.	(a) 49	(b) $x = 6$	(c) (i) $\frac{x}{x-1}$	(ii) x
12.	(a) 0.8	(b) $\frac{1}{x}$		
13.	(a) 1	(b) $2x + 6$	(c) $\sqrt{\frac{x-14}{2}}$	
14.	(a) $\frac{x+2}{3}$	(b) $\frac{10}{3x}$		
15.	(a) $x = 4$	(b) $\frac{1}{x-1}$		
16.	(a) $-\frac{1}{3}$	(b) $\frac{x+4}{2x+3}$	(c) $\frac{5x}{2x-1}$	