1 Newton's laws of motion

KEY KNOWLEDGE

In this topic, you will:

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions
- investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance
- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane: $\left(F_{\text{net}} = \frac{mv^2}{r}\right)$, including:
  - a vehicle moving around a circular road
  - a vehicle moving around a banked track
  - an object on the end of a string
- model natural and artificial satellite motion as uniform circular motion
- investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only).

PRACTICAL WORK AND INVESTIGATIONS

Practical work is a central component of VCE Physics. Experiments and investigations, supported by a **practical investigation eLogbook** and **teacher-led video**, are included in this topic to provide opportunities to undertake investigations and communicate findings.

EXAM PREPARATION

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1.1 Overview

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1.1.1 Introduction

Backwards and forwards. Faster and slower. Why do objects in motion behave the way they do, and how can such behaviour be consistently described?

Before Sir Isaac Newton published *Principia Mathematica* in 1687, there was no plausible theory that could clearly describe objects, also called bodies, the forces acting upon them, and their movements in response to those forces. Newton's laws of motion changed humanity's understanding of the entire universe by providing a mathematical description of the universe. They describe everything from a ball rolling down a hill to the positions of the planets.

FIGURE 1.1 Whether you are driving a car, riding a bike or riding a roller-coaster, your motion is controlled by the forces acting on the vehicle.

To this day, more than 300 years later, Newton's laws of motion and gravity remain the foundations on which mechanics and engineering are based. They gave humanity the knowledge needed to send astronauts to the Moon and put satellites into orbit. Everyday motion, from driving a car and riding a bike, to enjoying a ride on a roller-coaster, are all governed by forces that can be described by Newton's laws.

LEARNING SEQUENCE

on Resources

Solutions	Solutions — Topic 1 (sol-0815)
Practical investigation eLogbook	Practical investigation eLogbook — Topic 1 (elog-1632)
Digital documents	Key science skills — VCE Physics Units 1–4 (doc-36950) Key terms glossary — Topic 1 (doc-37165) Key ideas summary — Topic 1 (doc-37166)
Exam question booklet	Exam question booklet — Topic 1 (eqb-0098)

1.2 BACKGROUND KNOWLEDGE Motion review

BACKGROUND KNOWLEDGE

- identify parameters of motion as vectors or scalars
- analyse graphically, numerically and algebraically, straight-line motion under constant acceleration:

$$\boldsymbol{v} = \boldsymbol{u} + \boldsymbol{a}t \qquad \boldsymbol{v}^2 = \boldsymbol{u}^2 + 2\boldsymbol{as} \qquad \boldsymbol{s} = \frac{1}{2}(\boldsymbol{u} + \boldsymbol{v})t \qquad \boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2 \qquad \boldsymbol{s} = \boldsymbol{v}t - \frac{1}{2}\boldsymbol{a}t^2$$

- graphically analyse non-uniform motion in a straight line
- apply concepts of momentum to linear motion: $\boldsymbol{p} = m\boldsymbol{v}$

1.2.1 Describing motion

To explain the motion of objects, it is important to be able to measure and describe the motion clearly. The language used to describe motion must therefore be precise and unambiguous.

The language of motion

The physical quantities used to describe and explain motion fall into two distinct groups: scalar quantities and vector quantities.

Scalar quantities are fully described by magnitude (size) only. Mass, energy, time, power and temperature are all examples of scalar quantities.

Vector quantities are fully described by specifying both a direction and a magnitude. Force, displacement, velocity and acceleration are all examples of vector quantities.

Note: Vector quantities are bolded in this resource but other notations are common, such as an arrow above or below the variable.

Distance is a measure of the length of the path taken during the change in position of an object. Distance is a scalar quantity. It does not specify a direction.

Displacement is a measure of the length of the change in position of an object. To fully describe a displacement, a direction must be specified as well as a magnitude. Displacement is therefore a vector quantity.

Speed is a measure of the rate at which an object moves over a distance. Because distance is a scalar quantity, speed is also a scalar quantity. The average speed of an object can be calculated by dividing the distance travelled by the time taken:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

Velocity is a measure of the rate of displacement of an object. Because displacement (change in position) is a vector quantity, velocity is also a vector quantity. The velocity has the same direction as the displacement. The symbol $\boldsymbol{v}$ is used to denote velocity. (The symbol $\boldsymbol{v}$ is often used to represent speed as well.)

The average velocity of an object, $\boldsymbol{v}_{\text{av}}$, during a time interval can be expressed as:

$$\boldsymbol{v}_{\text{av}} = \frac{\Delta \boldsymbol{s}}{\Delta t}$$

where: $\boldsymbol{s}$ represents the displacement
Δt represents the time interval

scalar quantity quantity with only a magnitude (size)

vector quantity quantity requiring both a direction and a magnitude

distance measure of the full length of the path taken when an object changes position, a scalar quantity

displacement measure of the change in position of an object, a vector quantity

speed the rate at which distance is covered per unit time; a scalar quantity

velocity the rate of change of position of an object; a vector quantity

Neither the average speed nor the average velocity provide information about movement at any particular instant of time. The speed at any particular instant of time is called the **instantaneous speed**. The velocity at any particular instant of time is called the **instantaneous velocity**. It is only if an object moves with a constant velocity during a time interval that its instantaneous velocity throughout the interval is the same as its average velocity.

The rate at which an object changes its velocity is called its **acceleration**. Because velocity is a vector quantity, it follows that acceleration is also a vector quantity. The average acceleration of an object, $\boldsymbol{a}_{\text{av}}$, can be expressed as:

$$\boldsymbol{a}_{\text{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{\boldsymbol{v} - \boldsymbol{u}}{t_f - t_i}$$

where: $\Delta \boldsymbol{v}$ represents the change in velocity $(\boldsymbol{v} - \boldsymbol{u})$, $\boldsymbol{v}$ is the final velocity and $\boldsymbol{u}$ the initial velocity

Δt represents the time interval, where t_i is the initial time and t_f is the final time, where

$\Delta t = t_f - t_i$

The direction of the average acceleration is the same as the direction of the change in velocity. The instantaneous acceleration of an object is its acceleration at a particular instant of time.

A non-zero acceleration is not always caused by a change in speed. The vector nature of acceleration means that the object can be accelerating if it has a constant speed but is changing direction. Hence, acceleration is the rate of change of velocity.

Reviewing vectors

A vector quantity is one that has both direction and magnitude. These are represented diagrammatically using arrows, in which the length of the arrow reflects the magnitude of the quantity and the arrowhead allows the direction to be shown. Vectors are used constantly in physics, particularly in the study of motion, in which many variables are vector quantities.

Adding vectors

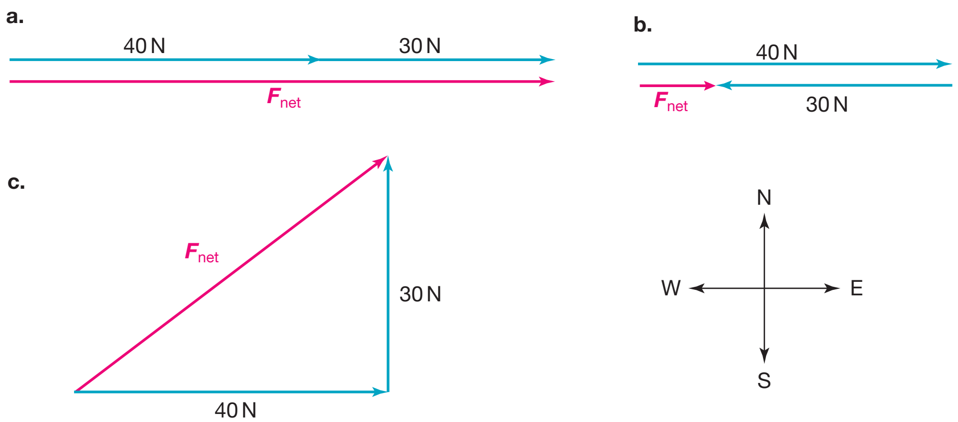
When vector quantities are added together, both direction and magnitude need to be taken into account. The example of forces in figure 1.2 illustrates this. The labelled arrows that represent vectors can be used to perform the addition by placing them 'head to tail'. When adding pairs of vectors, the labelled arrows are redrawn so that the 'tail' of the second arrow abuts the 'head' of the first arrow. The sum of the vectors is represented by the arrow drawn between the tail of the first vector and the head of the second. Figure 1.2 illustrates how this method has been used to determine the net force in the three examples shown. The sum of the vectors ($\boldsymbol{F}_{\text{net}}$) is represented in each case.

instantaneous speed speed at a particular instant of time

instantaneous velocity velocity at a particular instant of time

acceleration rate of change of velocity; a vector quantity

FIGURE 1.2 When adding vectors, both magnitude and direction need to be considered.



Determining the magnitude of a vector sum (resultant vector)

The vectors in figure 1.2 have been drawn to scale. This means that the length of the arrow representing the vector sum (resultant vector) can be measured. The magnitude of the vector sum can then be calculated. The direction of the vector sum is given by the direction in which the third arrow points. If the vectors have been drawn to scale, the direction can be determined by measuring the appropriate angle with a protractor.

The vector addition shown in figure 1.3 results in a right-angled triangle. The magnitude of the vector sum can be determined by using Pythagoras's theorem. The hypothenuse arrow of the triangle is the vector sum and its length represents the magnitude.

$$
\begin{aligned}
c^2 &= a^2 + b^2 \\
&= (40)^2 + (30)^2 \\
&= 2500 \text{ (calculating the sum of the squares of both sides)} \\
\Rightarrow c &= 50\text{ N (taking the positive square root of the sum of the squares)}
\end{aligned}
$$

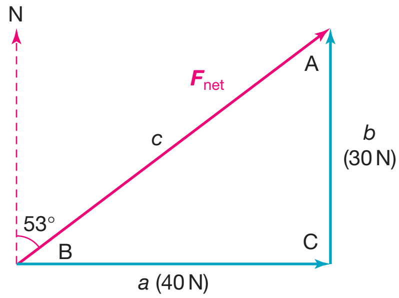
The direction of the net force can be found using trigonometric ratios. In this case, we can use $\tan \mathrm{B} = \frac{\mathrm{O}}{\mathrm{A}}$.

$$
\begin{aligned}
\tan \mathrm{B} &= \frac{30}{40} \\
&= 0.75 \\
\mathrm{B} &= \tan^{-1}(0.75) \\
&= 37°
\end{aligned}
$$

The vector sum, and net force, is 50 N at an angle of N53°E (53° clockwise from north as A + B = 90°).

Knowing the various trigonometric ratios is important when finding unknown angles (when at least 2 side lengths are known) or unknown sides (when at least one angle and one side length is known) for right-angled triangles. Alternatively, the sine or cosine rule could be used.

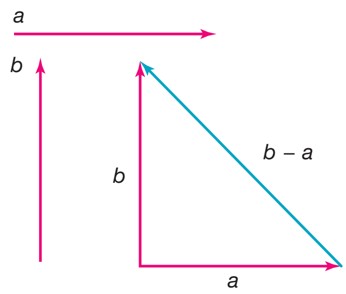
FIGURE 1.3 The magnitude and direction of vector addition can be determined using Pythagoras's theorem. $\boldsymbol{F}_{\text{net}}$ is the resultant vector, or vector sum.



Subtracting vectors

One vector can be subtracted from another simply by adding its negative. It works because subtracting a vector is the same as adding the negative vector (just as subtracting a positive number is the same as adding the negative of that number). Another way to *subtract* vectors is to place them tail to tail, as shown in figure 1.4. The difference between the vectors $\boldsymbol{a}$ and $\boldsymbol{b}$ ($\boldsymbol{b} - \boldsymbol{a}$) is given by the vector that begins at the head of vector $\boldsymbol{a}$ and ends at the head of vector $\boldsymbol{b}$.

FIGURE 1.4 Subtracting vectors can be done either by placing them tail to tail, or through adding the negative vector.



Finding vector components

The magnitude of vector components can be determined using trigonometric ratios. The vector $\boldsymbol{P}$ in figure 1.5 can be resolved into vertical and horizontal components.

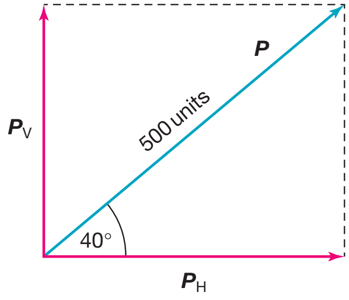
The magnitude of the horizontal component, labelled $\boldsymbol{P}_{\mathrm{H}}$, is given by:

$$\boldsymbol{P}_{\mathrm{H}} = \boldsymbol{P}\cos 40° \left(\text{since } \cos 40° = \frac{\boldsymbol{P}_{\mathrm{H}}}{\boldsymbol{P}}\right)$$
$$\Rightarrow P_{\mathrm{H}} = 500\,\text{units} \times \cos 40°$$
$$\Rightarrow P_{\mathrm{H}} = 500\,\text{units} \times 0.7660$$
$$= 383\,\text{units}.$$

The magnitude of the vertical component, labelled as $\boldsymbol{P}_{\mathrm{V}}$, is given by:

$$\boldsymbol{P}_{\mathrm{V}} = \boldsymbol{P}\sin 40° \left(\text{since } \sin 40° = \frac{\boldsymbol{P}_{\mathrm{V}}}{\boldsymbol{P}}\right)$$
$$\Rightarrow P_{\mathrm{V}} = 500\,\text{units} \times \sin 40°$$
$$\Rightarrow P_{\mathrm{V}} = 500\,\text{units} \times 0.6428$$
$$= 321\,\text{units}.$$

FIGURE 1.5 A vector can be split into vertical and horizontal components.



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SAMPLE PROBLEM 1 Determining the average acceleration

Determine the average acceleration of each of the following objects.

a. A car starting from rest reaches a velocity of 60 km h^{-1} due north in 5.0 s.

b. A car travelling due west at a speed of 15 m s^{-1} turns due north at a speed of 20 m s^{-1}. The change occurs in a time interval of 2.5 s.

c. A cyclist riding due north at 8.0 m s^{-1} turns right to ride due east without changing speed in a time interval of 4.0 s.

THINK

a. 1. The change in velocity of the car is 60 km h^{-1} north. To determine the acceleration in SI units, the velocity should be expressed in m s^{-1} (divide by 3.6 to convert from km h^{-1} to m s^{-1}).

2. Use the formula $\boldsymbol{a}_{\mathrm{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t}$ to calculate the average acceleration.

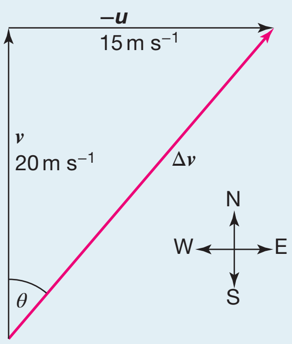
b. 1. The change in velocity must first be found by subtracting vectors because $\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u}$. The final velocity ($\boldsymbol{v}$) is 20 m s^{-1} north and the initial velocity ($\boldsymbol{u}$) is 15 m s^{-1} west. That is $-\boldsymbol{u} = 15$ m s^{-1} east.
Use Pythagoras's theorem or trigonometry to determine the magnitude of the change of velocity. Subtracting $\boldsymbol{u}$ is the same as adding the negative vector for $\boldsymbol{u}$ (as shown in the diagram — in this case 15 m s^{-1} east, not west).

WRITE

a. $60\,\text{km h}^{-1} = \frac{60}{3.6}\,\text{m s}^{-1} = 16.7\,\text{m s}^{-1}$

$$\boldsymbol{a}_{\mathrm{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{16.7}{5.0}$$
$$= 3.3\,\text{m s}^{-2}\text{ north}$$

b.



$$\Delta v = \sqrt{20^2 + 15^2}$$
$$= 25\,\text{m s}^{-1}$$

2. The direction of a vector is usually given as an angle of rotation of the vector about its *tail*. Then look at where the *head* of the vector sum (resultant vector) is pointing. The direction can be found by calculating the value of the angle θ.

$$\tan\theta = \frac{15}{20} = 0.75$$
$$\Rightarrow \theta = 37°$$

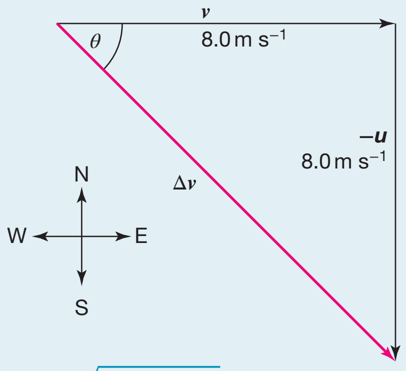
The direction of the change in velocity is therefore N37°E.

3. Use the formula $\boldsymbol{a}_{\text{av}} = \dfrac{\Delta \boldsymbol{v}}{\Delta t}$ to calculate the average acceleration, where $\Delta \boldsymbol{v}$ = 25 m s^{-1} N37°E and t = 2.5 s.

$$\boldsymbol{a}_{\text{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{25}{2.5} = 10\ \text{m s}^{-2}\ \text{N}\,37°\text{E}$$

c. 1. The change in velocity must first be found by subtracting vectors because $\Delta \boldsymbol{v} = \boldsymbol{v} - \boldsymbol{u}$. The final velocity ($\boldsymbol{v}$) is 8.0 m s^{-1} east and the initial velocity ($\boldsymbol{u}$) is 8.0 m s^{-1} north. That is $-\boldsymbol{u} = 8.0\ \text{m s}^{-1}$ south. Use Pythagoras's theorem or trigonometry to determine the magnitude of the change of velocity. Subtracting $\boldsymbol{u}$ is the same as adding the negative vector for $\boldsymbol{u}$ (as shown in the diagram as going 8.0 m s^{-1} south, not north).

c.



$$\Delta \boldsymbol{v} = \sqrt{8.0^2 + 8.0^2} = 11.3\ \text{m s}^{-1}$$

2. The direction can be found by calculating the value of the angle θ.

The triangle formed by the vector diagram shown is a right-angled isosceles triangle. The angle θ is therefore 45° and the direction of the change in velocity is south-east.

3. Use the formula $\boldsymbol{a}_{\text{av}} = \dfrac{\Delta \boldsymbol{v}}{\Delta t}$ to calculate the average acceleration, where $\Delta \boldsymbol{v}$ = 11.3 m s^{-1} S45°E and Δt = 4.0 s.

$$\boldsymbol{a}_{\text{av}} = \frac{\Delta \boldsymbol{v}}{\Delta t} = \frac{11.3}{4.0} = 2.8\ \text{m s}^{-2}\ \text{south-east (or S45°E)}$$

PRACTICE PROBLEM 1

Determine the average acceleration (in m s^{-2}) of:

a. a rocket launched from rest that reaches a velocity of 15 m s^{-1} during the first 5.0 s after lift-off

b. a roller-coaster cart travelling due north at 20 m s^{-1} that turns 90 degrees to the left during an interval of 4.0 s without changing speed

c. a rally car travelling west at 100 km h^{-1} that turns 90 degrees to the left and slows to a speed of 80 km h^{-1} south. The turn takes 5.0 s to complete.

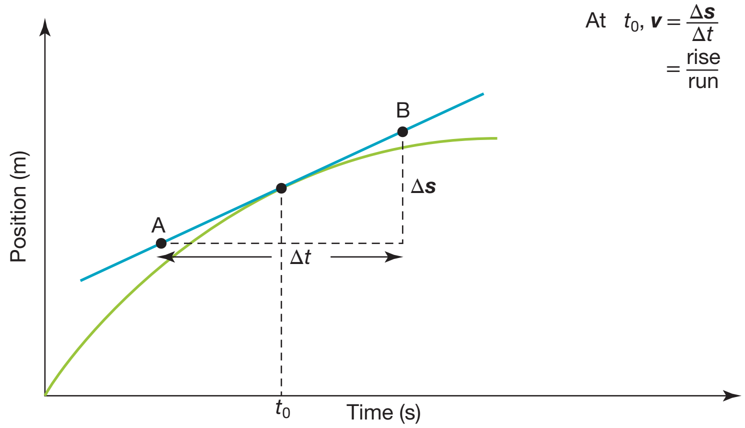
1.2.2 Graphical analysis of motion

A description of motion in terms of displacement, average velocity and average acceleration is not complete. These quantities provide a 'summary' of motion but do not provide detailed information. By describing the motion of an object in graphical form, it is possible to estimate its displacement, velocity or acceleration at any instant during a chosen time interval.

Position–time graphs

A graph of position versus time provides information about the displacement and velocity at any instant of time during the interval described by the graph. If the graph is a straight line or smooth curve, it is also possible to estimate the displacement and velocity outside the time interval described by the data displayed in the graph using extrapolation.

FIGURE 1.6 The instantaneous velocity $\boldsymbol{v}$ of an object is equal to the gradient of the position–time graph. If the graph is a smooth curve, the gradient of the tangent must be determined.



The velocity of an object at an instant of time can be obtained from a position–time graph by determining the gradient of the line or curve at the point representing that instant. This method is a direct consequence of the fact that velocity is a measure of the rate of change in position. If the graph is a smooth curve, the gradient at an instant of time is the same as the gradient of the tangent to the curve at that instant.

Similarly, the speed of an object at an instant of time can be obtained by determining the gradient of a graph of the object's distance from a reference point versus time.

Velocity–time graphs

A graph of velocity versus time provides information about the velocity and acceleration at any instant of time during the interval described by the graph. It also provides information about the displacement between any two instants.

The instantaneous acceleration of an object can be obtained from a velocity–time graph by determining the gradient of the line or tangent to a curve at the point representing that instant in time. This method is a direct consequence of the fact that acceleration is defined as the rate of change of velocity.

The displacement of an object during a time interval can be obtained by determining the area under the velocity–time graph representing that time interval. The actual position of an object at any instant during the time interval can be found only if the starting position is known.

Similarly, the distance travelled by an object during a time interval can be obtained by determining the corresponding area under the speed versus time graph for the object.

Acceleration–time graphs

A graph of acceleration versus time provides information about the acceleration at any instant of time during the time interval described by the graph. It also provides information about the change in velocity between any two instants.

The change in velocity of an object during a time interval can be obtained by determining the area under the acceleration–time graph representing that time interval. The actual velocity of the object can be found at any instant during the time interval only if the initial velocity is known.

The relationship between position, velocity and acceleration–time graphs

Position–time, velocity–time and acceleration–time graphs are all related. As velocity is the change of position over time, it is equivalent to the gradient of the position–time graph. Acceleration is the change of velocity over time, and is the gradient of the velocity–time graph, as seen in figure 1.7.

FIGURE 1.7 The position–time, velocity–time and acceleration–time graphs for an object thrown vertically into the air (assume negligible air resistance). As long as one graph is given, the other two can be deduced. Some extra information may be needed.

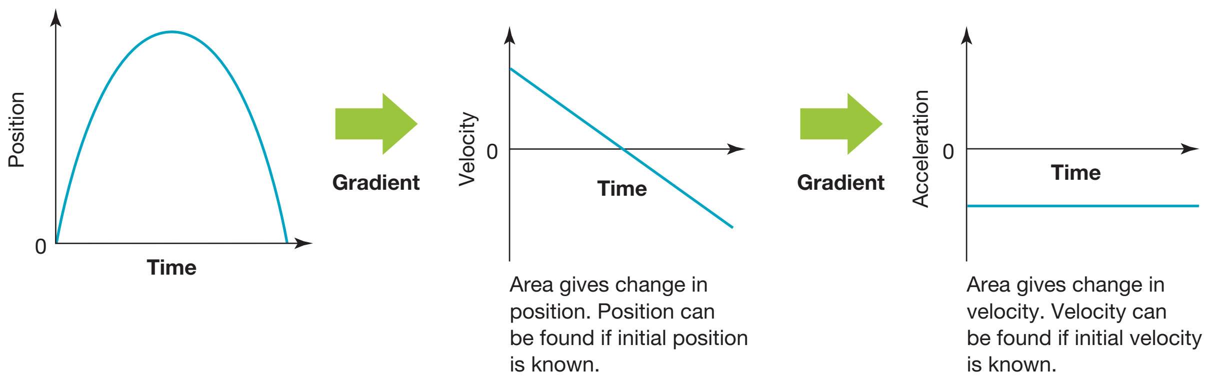


TABLE 1.1 Summary of motion graphs

		Position versus time graphs	Velocity versus time graphs	Acceleration versus time graphs
Quantities that can be read directly from the graph	Horizontal axis	Time	Time	Time
	Vertical axis	Position	Velocity	Acceleration
Quantities that can be calculated from the graph	Gradient of tangent	Instantaneous velocity	Instantaneous acceleration	
	Area under the graph		Change in position (displacement)	Change in velocity

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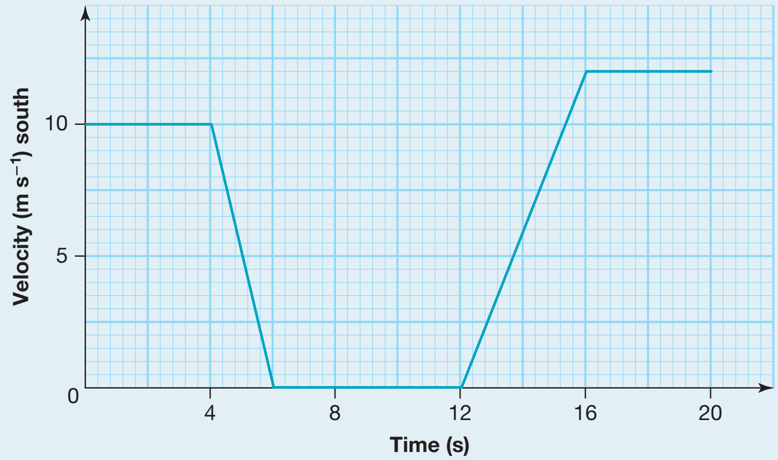
SAMPLE PROBLEM 2 Using a velocity-time graph

The following velocity–time graph describes the motion of a car travelling south through an intersection. The car was stationary for 6.0 s while the traffic lights were red.

a. What was the displacement of the car during the interval in which it was slowing down?

b. What was the acceleration of the car during the first 4.0 s after the lights turned green?

c. Determine the average velocity of the car during the interval described by the graph.



THINK

WRITE

a. The displacement of the car slowing down is the area under the graph between the times 4.0 s and 6.0 s.
To fully describe displacement, units and direction need to be considered.

a. $\text{area} = \frac{1}{2} \times 2.0\,\text{s} \times 10\,\text{m s}^{-1}$ south
$= 10$ m south

b. The acceleration is given by the gradient of the graph for the first 4.0 s after the lights turned green; the time interval is between 12 and 16 s. During this time, the velocity increases from 0 m s^{-1} south to 12 m s^{-1}. Therefore the 'rise' is 12 m s^{-1} south and the 'run' is 4.0 s.

b. $\boldsymbol{a} = \frac{\text{rise}}{\text{run}}$
$= \frac{12}{4.0}$
$= 3.0\,\text{m s}^{-2}$ south

c. 1. The displacement during the whole time interval described by the graph is given by the total area under the graph. In this case, the area is split into four shapes (two rectangles and two triangles).

c. $\text{area} = (4.0 \times 10) + \left(\frac{1}{2} \times 2.0 \times 10\right) + \left(\frac{1}{2} \times 4.0 \times 12\right) + (4.0 \times 12)$
$= 40 + 10 + 24 + 48$
$= 122$ m south

2. The average velocity is determined by the formula: $\boldsymbol{v}_{\text{av}} = \frac{\Delta \boldsymbol{s}}{\Delta t}$, where $\Delta \boldsymbol{s} = 122$ m south and $\Delta t = 20$ s

$\boldsymbol{v}_{\text{av}} = \frac{\Delta \boldsymbol{s}}{\Delta t}$
$= \frac{122}{20}$
$= 6.1\,\text{m s}^{-1}$ south

PRACTICE PROBLEM 2

Use the velocity–time graph in sample problem 2 to answer the following questions.

a. **Determine the acceleration of the car while it had a positive southerly acceleration.**
b. **Determine the acceleration of the car during the 2.0 s before it came to a stop at the traffic lights.**
c. **Determine the average velocity of the car during the 6.0 s before it stopped at the traffic lights.**

on Resources

Video eLesson Motion with constant acceleration (eles-0030)

1.2.3 Algebraic analysis of motion

The motion of an object moving in a straight line with a constant acceleration can be described by a number of formulas. The formulas can be used to determine unknown quantities of straight-line motion with constant acceleration.

$$v = u + at \qquad s = \frac{1}{2}(u + v)t \qquad s = ut + \frac{1}{2}at^2 \qquad v^2 = u^2 + 2as \qquad s = vt - \frac{1}{2}at^2$$

where: u is the initial velocity
v is the final velocity
s is the displacement
a is the acceleration
t is the time interval

Because the formulas describe motion along a straight line, vector notation is not necessary. The displacement, velocity and acceleration can be expressed as positive or negative quantities.

It is possible to rearrange each of the equations to make different variables the subject. Table 1.2 summarises all possible versions of the equations and may be useful when solving problems. Note that each formula uses 4 out of the 5 possible variables (s u v a t).

TABLE 1.2 Equations for solving problems

		Variables that are involved in the problem				
		u v a t	u v a s	u v t s	u a t s	v a t s
Variable that is to be calculated	u	$u = v - at$	$u^2 = v^2 - 2as$	$u = \frac{2s}{t} - v$	$u = \frac{s}{t} - \frac{at}{2}$	—
	v	$v = u + at$	$v^2 = u^2 + 2as$	$v = \frac{2s}{t} - u$	—	$v = \frac{s}{t} + \frac{at}{2}$
	a	$a = \frac{v - u}{t}$	$a = \frac{v^2 - u^2}{2s}$	—	$a = \frac{2(s - ut)}{t^2}$	$a = \frac{2(vt - s)}{t^2}$
	t	$t = \frac{v - u}{a}$	—	$t = \frac{2s}{(u + v)}$	Determine v then solve	Determine u then solve
	s	—	$s = \frac{v^2 - u^2}{2a}$	$s = \frac{1}{2}(u + v)t$	$s = ut + \frac{1}{2}at^2$	$s = vt - \frac{1}{2}at^2$

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SAMPLE PROBLEM 3 Algebraic analysis of straight line motion with constant acceleration

Amy rides a toboggan down a steep snow-covered slope. Starting from rest, she reaches a speed of 12 m s^{-1} as she passes her brother, who is standing 19 m further down the slope from her starting position. Assume that Amy's acceleration is constant.

a. Determine Amy's acceleration.

b. How long did she take to reach her brother?

c. How far had Amy travelled when she reached an instantaneous velocity equal to her average velocity?

d. At what instant was Amy travelling at an instantaneous velocity equal to her average velocity?

THINK	WRITE
a. 1. List the given information. Let's consider down the slope as the positive direction.	**a.** $\boldsymbol{u} = 0$, $\boldsymbol{v} = 12$ m s^{-1}, $\boldsymbol{s} = 19$ m, $\boldsymbol{a} = ?$
2. The appropriate formula is: $\boldsymbol{v}^2 = \boldsymbol{u}^2 + 2\boldsymbol{a}\boldsymbol{s}$, because it includes the three known quantities and the unknown quantity $\boldsymbol{a}$.	$\boldsymbol{v}^2 = \boldsymbol{u}^2 + 2\boldsymbol{a}\boldsymbol{s}$ $\Rightarrow 12^2 = 0 + 2\boldsymbol{a} \times 19$ $144 = 38 \times \boldsymbol{a}$ $\Rightarrow \boldsymbol{a} = 3.8\ \text{m s}^{-2}$ down the slope
b. 1. List the information. (Note that it is better to use the data given rather than data calculated in the previous part of the question. That way, rounding or errors in an earlier part of the question will not affect the answer.)	**b.** $\boldsymbol{u} = 0$, $\boldsymbol{v} = 12$ m s^{-1}, $\boldsymbol{s} = 19$ m, $t = ?$
2. The appropriate formula is: $\boldsymbol{s} = \frac{1}{2}(\boldsymbol{u} + \boldsymbol{v})t$.	$\boldsymbol{s} = \frac{1}{2}(\boldsymbol{u} + \boldsymbol{v})t$ $\Rightarrow 19 = \frac{1}{2}(0 + 12)t$ $19 = 6.0 \times t$ $\Rightarrow t = \frac{19}{6.0}$ $= 3.2$ s
c. 1. The magnitude of the average velocity during a period of constant acceleration is given by: $\boldsymbol{v}_{\text{av}} = \frac{\boldsymbol{u} + \boldsymbol{v}}{2}$	**c.** $\boldsymbol{v}_{\text{av}} = \frac{\boldsymbol{u} + \boldsymbol{v}}{2}$ $= \frac{0 + 12}{2}$ $= 6.0\ \text{m s}^{-1}$
2. The distance travelled when Amy reaches an instantaneous velocity of this magnitude can now be calculated. List the information.	$\boldsymbol{u} = 0$, $\boldsymbol{v} = 6.0\ \text{m s}^{-1}$, $\boldsymbol{a} = 3.8\ \text{m s}^{-2}$, $\boldsymbol{s} = ?$

3. The appropriate formula is $v^2 = u^2 + 2as$.

$$v^2 = u^2 + 2as$$
$$\Rightarrow (6.0)^2 = 0 + 2 \times 3.8 \times s$$
$$36 = 7.6 \times s$$
$$\Rightarrow s = \frac{36}{7.6}$$
$$= 4.7 \text{ m}$$

d. 1. List the information.

d. $u = 0$, $v = 6.0$ m s^{-1}, $a = 3.8$ m s^{-2} , $t = ?$

2. The appropriate formula is $v = u + at$.

$$v = u + at$$
$$\Rightarrow 6.0 = 0 + 3.8 \times t$$
$$6.0 = 3.8 \times t$$
$$\Rightarrow t = \frac{6.0}{3.8}$$
$$= 1.6 \text{ s}$$

This is the midpoint of the entire time interval. In fact, during any motion in which the acceleration is constant, the instantaneous velocity halfway (in time) through the interval is equal to the average velocity during the interval.

PRACTICE PROBLEM 3

A car initially travelling at a speed of 20 m s^{-1} on a straight road accelerates at a constant rate for 16 s over a distance of 400 m.

a. **Calculate the final speed of the car.**
b. **Determine the car's acceleration without using your answer to part (a).**
c. **What is the average speed of the car?**
d. **What is the instantaneous speed of the car after:**
   i. **2.0 s**
   ii. **8.0 s?**

1.2.4 Momentum

When explaining changes in motion, it is necessary to consider another property of the object: its mass. Consider how much more difficult it is to stop a truck moving at 20 m s^{-1} than it is to stop a tennis ball moving at the same speed. The physical quantity **momentum** is useful in explaining changes in motion, because it takes into account the mass as well as the velocity of a moving object.

momentum the product of the mass of an object and its velocity; a vector quantity

Newton described momentum as 'quantity of motion' and understood the special nature of mass in motion.

The momentum $\boldsymbol{p}$ of an object is defined as the product of its mass m and its velocity $\boldsymbol{v}$.

$$p = mv$$

where: p is the momentum, in kg m s^{-1}, or N s
m is the mass, in kg
v is the velocity, in m s^{-1}

Momentum is a vector quantity that has the same direction as that of the velocity. The SI unit of momentum is kg m s^{-1}. Momentum is also sometimes expressed in N s.

1.2 Activities

learnon

Students, these questions are even better in jacPLUS

- Receive immediate feedback and access sample responses
- Access additional questions
- Track your results and progress

Find all this and MORE in jacPLUS

1.2 Quick quiz on | 1.2 Exercise

1.2 Exercise

1. Two Physics students are trying to determine the instantaneous speed of a bicycle 5.0 m from the start of a 1000-m sprint. They use a stopwatch to measure the time taken for the bicycle to cover the first 10 m. If the acceleration was constant, and the measured time was 4.0 s, what was the instantaneous speed of the bicycle at the 5.0 m mark?
2. A car travelling north at a speed of 40 km h^{-1} turns right to head east at a speed of 30 km h^{-1}. This change in direction and speed takes 2.0 s. Calculate the average acceleration of the car in:
   a. km h^{-1} s^{-1}
   b. m s^{-2}.
3. An aeroplane approaches Melbourne Airport and touches down on the runway while travelling at 70 m s^{-1}. This speed is maintained for 8.0 s. Following this, the brakes are engaged, and the aeroplane comes to a stop with a uniform deceleration of 4.0 m s^{-2}.
   a. Calculate how long it takes the aeroplane to stop after landing.
   b. Draw a velocity–time graph to describe the motion of the aeroplane from landing to the moment it comes to a stop. Ensure your graph is fully labelled.
   c. Use your graph to determine the length of runway used in the landing process.
4. A 65.0-kg student runs at a velocity of 35.0 km h^{-1}. Determine the student's momentum.

1.3 Newton's laws of motion and their application

KEY KNOWLEDGE

- Investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions.

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1.3.1 Newton's three laws of motion

Sir Isaac Newton's three laws of motion, first published in 1687, explain changes in the motion of objects in terms of the forces acting on them. However, Einstein and others have since shown that Newton's laws have limitations. Newton's laws fail, for example, to explain successfully the motion of objects travelling at speeds close to the speed of light. They do not explain the bending of light by the gravitational forces exerted by stars, planets and other large bodies in the universe. However, they do successfully explain the motion of most objects at Earth's surface, the motion of satellites and the orbits of the planets that make up the solar system. In fact, it was Newton's laws that enabled NASA to plan the trajectories of artificial satellites.

Newton's First Law of Motion

Every object continues in its state of rest or uniform motion unless made to change by a non-zero net force.

net force the vector sum of all the forces acting on an object

Newton's First Law of Motion explains why things move. For example, you need to strike a golf ball with the club before it will soar through the air. Without a **net force** acting on the golf ball, it will remain in its state of rest on the tee or grass. (Recall that the vector sum of the forces acting on an object is called the net force.) The law explains why seatbelts should be worn in a moving car and why you should never leave loose objects (like books, luggage or pets) in the back of a moving car. When a car stops suddenly, it does so because there is a large net force acting on it — as a result of braking or a collision. However, the large force does not act on you or the loose objects in the car. The loose objects continue their motion until they are stopped by a non-zero net force. Without a properly fitted seatbelt, you would move forward until stopped by the airbag in the steering wheel, the windscreen or even the road. The loose objects in the car will also continue moving forward, posing a danger to anyone in the car. This is why Newton's First Law is sometimes referred to as the Law of Inertia. Inertia is a property of mass and describes the tendency of a body to remain at rest or to move with a constant velocity in a straight line unless acted upon by a net force.

Newton's First Law of Motion can also be expressed in terms of momentum by stating that the momentum of an object does not change unless the object is acted upon by a non-zero net force.

Newton's Second Law of Motion

The rate of change in momentum is directly proportional to the magnitude of the net force and is in the direction of the net force.

$$\boldsymbol{F}_{net} = \frac{\Delta \boldsymbol{p}}{\Delta t} = \frac{m\Delta \boldsymbol{v}}{\Delta t} = m\boldsymbol{a}$$

(provided the mass is constant)

where: $\Delta \boldsymbol{p}$ is the change in momentum, in kg m s^{-1} (or N s)

$\Delta \boldsymbol{v}$ is the change in velocity, in m s^{-1}

Δt is the time interval, in s

m is the mass, in kg

$\boldsymbol{a}$ is the acceleration, in m s^{-2}

This expression of Newton's Second Law of Motion is especially useful because it relates the net force to a description of the motion of objects. An acceleration of 1 m s^{-2} results when a net force of 1 N acts on an object of mass 1 kg. Newton's Second Law gives the relationship between the net force acting upon a body, its mass and the resulting acceleration of that body. Acceleration is directly proportional to the net force applied to a body but inversely proportional to its mass. The derived equation above, $\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$ is commonly associated with the second law.

Newton's Third Law of Motion

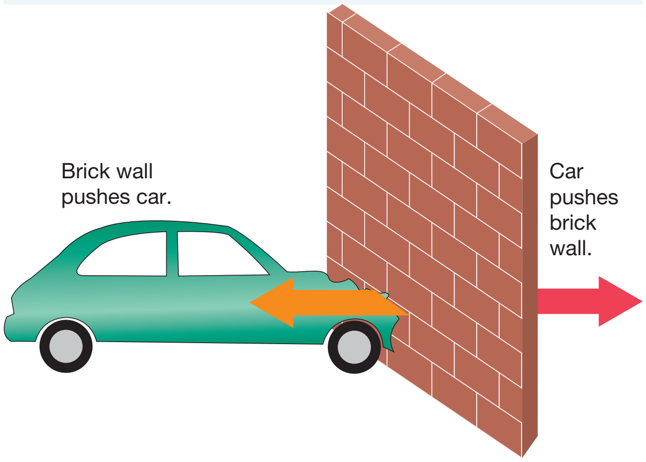
Newton's Third Law of Motion

If object B applies a force on object A, then object A applies an equal and opposite force on object B:

$$\boldsymbol{F}_{\text{on A by B}} = -\boldsymbol{F}_{\text{on B by A}}$$

It is important to remember that the forces that make up the force pair act on different objects. The subsequent motion of each object is determined by the net force acting on it. For example, in figure 1.8, the net force on the brick wall at the left is the sum of the force applied to it by the car (shown by the red arrow) and all the other forces acting on it. The force shown by the orange arrow is applied to the car and does not affect the state of motion of the brick wall. The net force on the car is the sum of the force applied by the brick wall (shown by the orange arrow) and all the other forces acting on it. The 'Newton pairs' of forces are of the same type but act on different bodies. They are equal and opposite in nature.

FIGURE 1.8 Newton's Third Law of Motion in action



Applying Newton's laws of motion

Newton's laws of motion can be used to explain the motion of objects. It is important to determine the specific laws that should be applied to a particular problem:

- Newton's First Law refers only to objects at rest or in uniform motion and can be applied in instances when an object is *not* accelerating
- Newton's Second Law applies to a *single* object (or a system of more than one body where the bodies are connected to each other) being acted upon by one or more forces
- Newton's Third Law applies when *two* objects interact with one another and exert equal but opposite forces on each other

Often, more than one of Newton's laws will be required to solve a problem.

on Resources

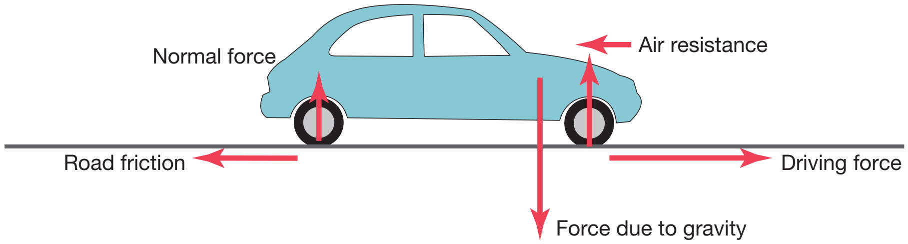
Video eLesson Newton's Second Law (eles-0033)

1.3.2 On level ground

Whether you are walking on level ground, driving a car, riding in a roller-coaster or flying in an aeroplane, your motion is determined by the net force acting on you.

Figure 1.9 shows the forces acting on a car moving at a constant velocity on a level surface. The net force on the car is zero as the forces are balanced (in equilibrium).

FIGURE 1.9 Forces acting on a car moving on a level surface. The car's engine is making the front wheels turn.



The forces acting on the car are described as follows.

- *The force due to gravity*. The force due to gravity of an object is given by:

$$\boldsymbol{F}_g = m\boldsymbol{g}$$

  where m is mass and $\boldsymbol{g}$ is the gravitational field strength.
  Throughout this text, the magnitude of $\boldsymbol{g}$ at the Earth's surface will be taken as 9.8 N kg^{-1}. The force due to gravity of a medium-sized sedan carrying a driver and passenger is about 15 000 N.
- *Normal force*. The normal force is the upward push of the supporting surface on the car. A normal force acts on all four wheels of the car. It is described as a normal force because it acts at right angles to the surface. Considering that the road surface is not accelerating up or down, the force applied to the surface by the object is the same as the force due to gravity acting on the object. The total normal force is therefore equal and opposite in direction to the force due to gravity.
- *Driving force*. The force that pushes the car forward is provided at the driving wheels — the wheels that are turned by the motor. In most cars, either the front wheels or the rear wheels are the driving wheels. The motor of a four-wheel drive pushes all four wheels. As the tyres push back on the road, the road pushes forward on the tyres, propelling the car forward. The forward push of the road on the tyres is a frictional force, as it is the resistance to movement of one surface across another. In this case, it is the force that prevents the tyres from sliding across the road. If the tyres or the road is too smooth, the driving force is reduced, the tyres slide backwards and the wheels spin. Note that if a car is braking, the wheels are not being driven by the engine and the driving force is not present.
- *Resistance forces*. As the car moves, it applies a force to the air in front of it. The air applies an equal force opposite to its direction of motion. This force is called **air resistance**. The air resistance on an object increases as its speed increases. The other resistance force acting on the car is **road friction**. It opposes the forward motion of the non-driving wheels, rotating them in the same direction as the driving wheels. In the car in figure 1.9, the front wheels are the driving wheels. Road friction opposes the motion of the rear wheels along the road and, therefore, the forward motion of the car. This road friction is an example of static friction, which is considerably smaller than the kinetic or sliding friction that acts if a wheel slips on the surface and spins.

The centre of mass

The forces on a moving car do not all act at the same point on the car. When analysing the translational motion of an object (its movement across space without considering rotational motion), all of the forces applied to an object can be considered to be acting at one particular point. That point is the **centre of mass**. The centre of mass of a symmetrical object with uniform mass distribution is at the centre of the object. For example, the centre of mass of a ruler, a solid ball or an ice cube is at the centre, unlike the centres of mass of asymmetrical objects, such as a person or a car. Note that the centre of mass can also lie outside of an object.

air resistance the force applied to an object opposite to its direction of motion, by the air through which it is moving

road friction the force applied by the road surface to the wheels of a vehicle in a direction opposite to the direction of motion of the vehicle

centre of mass the point at which all of the mass of an object can be considered to be positioned when modelling the external forces acting on the object

AS A MATTER OF FACT

If you hold an object such as a ruler at its centre of mass, it will perfectly balance. However, the centre of mass does not have to be within the object. For example, the centre of mass of a donut is in the middle of its hole. A high jumper can improve her performance by manoeuvring her body over the bar so that her centre of mass is below the bar. The centre of gravity of an object is a point through which the gravitational force can be considered to act. For most objects near the Earth's surface, it is reasonable to assume that the centre of mass is at the same point as the centre of gravity. This is because the gravitational field strength is approximately constant at the Earth's surface.

FIGURE 1.10 Where is the centre of mass of a boomerang? Try balancing a boomerang in a horizontal plane on one finger.

1.3.3 Applying Newton's Second Law of Motion

Sample problem 4 shows how Newton's Second Law of Motion can be applied to single objects or to a system of two objects, often referred to as connected bodies.

Remember that when the problem involves connected bodies, the whole system, as well as each individual part of the system, will have the same acceleration.

Tips for using Newton's Second Law of Motion

1. Draw a simplified diagram of the system.
2. Clearly label the diagrams to represent the forces acting on each object in the system. Draw all the forces as though they were acting through the centre of mass.
3. Apply Newton's Second Law to the system and/or each individual object as required.

tlvd-8943

SAMPLE PROBLEM 4 Applying Newton's Second Law of Motion

A car of mass 1600 kg starts from rest on a horizontal road with a forward driving force of 5400 N east. The sum of the forces resisting the motion of the car is 600 N.

a. **Determine the acceleration of the car.**
b. **The same car is used to tow a 400 kg trailer with the same driving force as before. The sum of the forces resisting the motion of the trailer is 200 N.**
   i. **Determine the acceleration of the system of the car and the trailer.**
   ii. **What is the magnitude of the force, F_{ct}, exerted on the car by the trailer?**

THINK

a. 1. Determine the net force acting on the car. The forward driving force is 5400 N and the sum of the forces acting in the negative direction is 600 N.

2. Apply Newton's Second Law to determine the acceleration of the car, where the net force is 4800 N and the mass is 1600 kg.

WRITE

a. $\boldsymbol{F}_{\text{net}} = \text{Driving forces } \boldsymbol{F}_{\text{D}} - \text{Resisting forces on car } \boldsymbol{F}_{\text{rc}}$

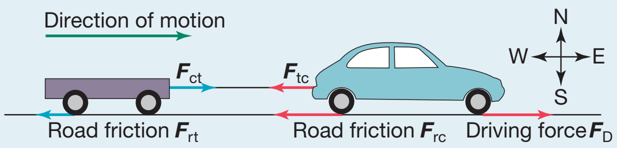
$\boldsymbol{F}_{\text{net}} = 5400 - 600$

$= 4.80 \times 10^3 \text{ N}$

$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$

$$\mathbf{a} = \frac{\boldsymbol{F}_{\text{net}}}{m} = \frac{4.80 \times 10^3}{1600} = 3.00 \text{ m s}^{-2} \text{ east}$$

b. i. • A diagram must be drawn to show the forces acting on the car and trailer. The vertical forces can be omitted because their sum is zero. (If not, there would be a vertical component of acceleration.) Assign east as positive.



• Determine the net force acting on the entire system.

b. i. $\boldsymbol{F}_{\text{net}} = \boldsymbol{F}_{\text{D}} - \boldsymbol{F}_{\text{rc}} - \boldsymbol{F}_{\text{rt}}$

$\boldsymbol{F}_{\text{net}} = 5400 - 600 - 200$

$= 4600 \text{ N}$

• Apply Newton's Second Law to determine the acceleration of the system, where the net force is 4600 N and the mass of the system is 2000 kg.

$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$

$$\boldsymbol{a} = \frac{\boldsymbol{F}_{\text{net}}}{m} = \frac{4600}{2000} = 2.30 \text{ m s}^{-2} \text{ east}$$

ii. Newton's Second Law can be applied to either the car or the trailer to answer this question.

ii. $\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$

$= 1600 \times 2.30$

$= 3.68 \times 10^3 \text{ N}$

• *Method 1: Applying Newton's Second Law to the car*

• Write an expression for the net force acting on the car, and use it to determine the magnitude of the force exerted on the car by the trailer.

$\boldsymbol{F}_{\text{net}} = 5400 - 600 - \boldsymbol{F}_{\text{ct}}$ where $\boldsymbol{F}_{\text{ct}}$ is the magnitude of the force exerted by the trailer on the car.

$3680 = 5400 - 600 - \boldsymbol{F}_{\text{ct}}$

$\Rightarrow \boldsymbol{F}_{\text{ct}} = 5400 - 600 - 3680$

$= 1.12 \times 10^3 \text{ N}$

or

• *Method 2: Applying Newton's Second Law to the trailer*

$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$

$= 400 \times 2.30$

$= 920 \text{ N}$

- Write an expression for the net force acting on the trailer, and use it to determine the magnitude of the force exerted on the trailer by the car.

Note: $F_{ct} = F_{tc}$

$\boldsymbol{F}_{net} = \boldsymbol{F}_{tc} - 200$
where $\boldsymbol{F}_{tc}$ is the magnitude of the force exerted on the trailer by the car.

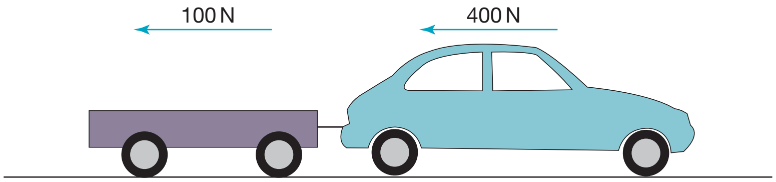
$920 = \boldsymbol{F}_{tc} - 200$

$\Rightarrow \boldsymbol{F}_{tc} = 920 + 200$

$= 1.12 \times 10^3$ N

PRACTICE PROBLEM 4

a. **A car of mass 1400 kg tows a trailer of mass 600 kg north along a level road at constant speed. The forces resisting the motion of the car and trailer are 400 N and 100 N respectively.**



i. **Determine the forward driving force applied to the car.**
ii. **What is the magnitude of the tension in the bar between the car and the trailer?**

b. **If the car and trailer in part (a), with the same resistance forces, have a northerly acceleration of 2.0 m s^{-2}, what is:**
i. **the net force applied to the trailer**
ii. **the magnitude of the tension in the bar between the car and the trailer**
iii. **the forward driving force applied to the car?**

1.3.4 Feeling lighter — feeling heavier

As you sit reading this, the force due to gravity on you by the Earth $(\boldsymbol{F}_g = m\boldsymbol{g})$ is pulling you down towards the centre of the Earth, but the chair is in the way. The material in the chair is being compressed and pushes up on you. This force is called the normal force ($\boldsymbol{F}_N$) because it is perpendicular or normal to the surface. If these two forces, the force due to gravity and the normal force, balance, then the net force on you is zero.

The normal force is responsible for the feeling of 'heaviness'.

The greater the normal force, the 'heavier' you will feel.

You 'feel' the Earth's pull on you because of Newton's Third Law. The upward compressive force on you by the chair is paired with the downward force on the chair by you. You sense this upward force through the compression in the bones in your pelvis.

$$\boldsymbol{F}_{\text{on you by chair}} = -\boldsymbol{F}_{\text{on chair by you}}$$

What happens to these forces when you are in a lift? A lift going up initially accelerates upwards, then travels at a constant speed (no acceleration) and finally slows down (the direction of acceleration is downwards). You experience each of these stages differently.

Accelerating upwards

When you are accelerating upwards, the net force on you is upwards. The only forces acting on you are the force due to gravity downwards and the normal force by the floor acting upwards. The force due to gravity is not going to change. So, if the net force on you is up, then the normal force on you must be greater than the force due to gravity: $\boldsymbol{F}_\text{N} > m\boldsymbol{g}$.

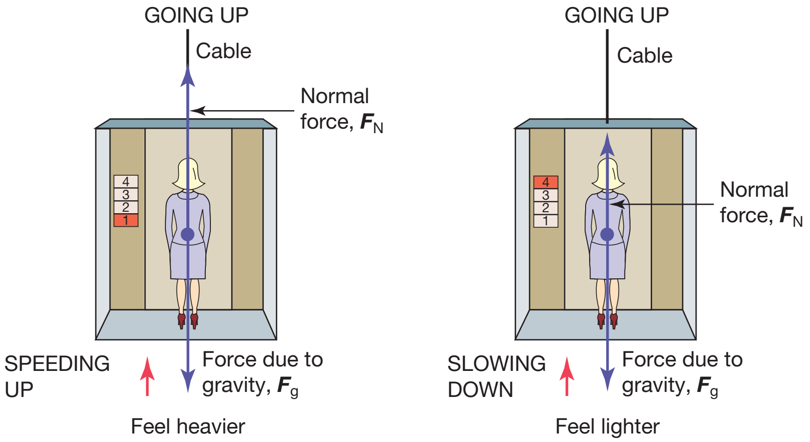
You 'feel heavier'.

Accelerating downwards

When you are accelerating downwards, the net force on you is downwards. So, the normal force on you must be less than the force on you due to gravity: $\boldsymbol{F}_\text{N} < m\boldsymbol{g}$. You 'feel lighter'. Note that if the lift were in free-fall, the person would not experience a normal force from the floor of the lift, and she would experience 'apparent weightlessness'. This concept of absence of normal force will be revisited in subtopic 3.4, to explain astronauts floating in space.

Note that 'apparent weightlessness' is no longer part of the study design.

FIGURE 1.11 The magnitude of the normal force determines how 'heavy' you feel.



on Resources

Interactivity Going up? (int-6606)

1.3.5 Motion on an incline

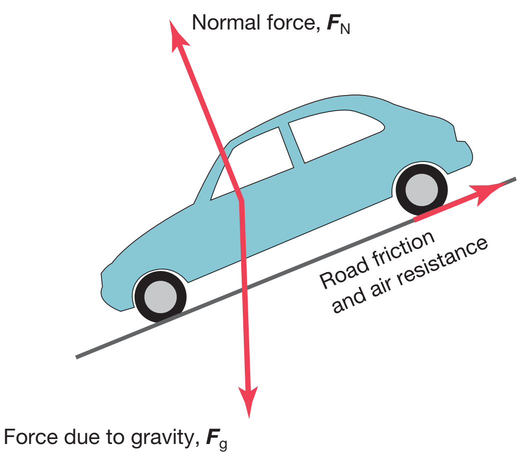
The forces acting on objects on an inclined plane are similar to those acting on the same objects on a level surface.

The forces acting on a car rolling down an inclined plane are shown in figure 1.12. The car is considered to behave like a single particle and the rotational motion of the wheels is ignored.

Resolving forces into components

The net force on a car can be found by finding the vector sum of the forces acting on it. Figure 1.13 shows how the force due to gravity can be resolved (divided) into two components — one parallel to the surface and one perpendicular to the surface.

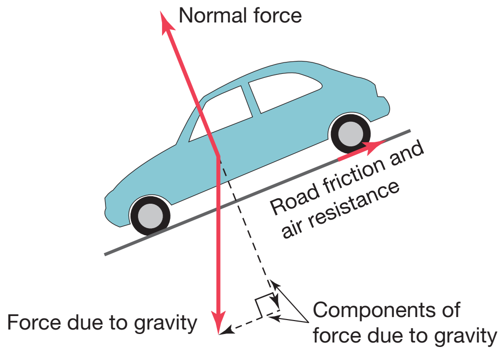
FIGURE 1.12 The forces acting on a car rolling down an inclined plane



By resolving the force due to gravity into these components, the motion of the car can be analysed. Consider the forces perpendicular to the inclined plane in figure 1.13. The magnitude of the normal force is equal to the component of the force due to gravity that is perpendicular to the surface. These forces balance each other out; therefore, the net force has no perpendicular component. (Imagine what would happen if this wasn't the case!)

Now consider the forces parallel to the inclined plane. It can be seen that the horizontal component of the force due to gravity is greater than the sum of road friction and air resistance. The net force is therefore parallel to the surface. The car will accelerate down the slope, as the downslope force exceeds the smaller upslope frictional force in the example.

FIGURE 1.13 Forces can be resolved into components. In this case, the force due to gravity has been resolved into two components.



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SAMPLE PROBLEM 5 Calculating the normal reaction force and sum of resistance forces

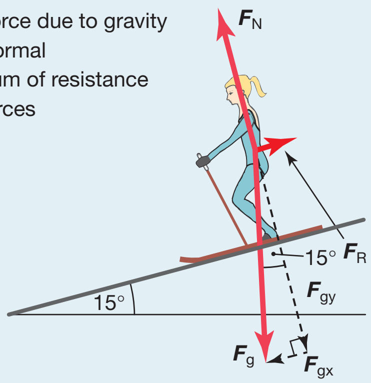
A snow skier of mass 70 kg is moving down a slope inclined at 15° to the horizontal with a constant velocity.
Determine the magnitude and direction of:
a. the normal force ($\boldsymbol{F}_N$)
b. the sum of the resistance forces ($\boldsymbol{F}_R$) acting on the skier.

THINK

a. 1. A diagram must be drawn to show the forces acting on the skier. Note that the forces have been drawn as though they were acting through the centre of mass of the skier but remember that the normal force and the friction forces act at the surface between the slope and the skis.

WRITE

a. $\boldsymbol{F}_g$ = Force due to gravity
$\boldsymbol{F}_N$ = Normal
$\boldsymbol{F}_R$ = Sum of resistance forces



2. The perpendicular net force is zero, so $\boldsymbol{F}_N = \boldsymbol{F}_{gy}$. Use $\boldsymbol{F}_g = m\boldsymbol{g}$, where m = 70 kg and $\boldsymbol{g}$ = 9.8 N kg^{-1}.

$$\begin{aligned}\boldsymbol{F}_N &= \boldsymbol{F}_{gy}\\ &= \boldsymbol{F}_g \cos 15° \left(\text{since } \cos 15° = \frac{\boldsymbol{F}_{gy}}{\boldsymbol{F}_g} \Rightarrow \boldsymbol{F}_{gy} = \boldsymbol{F}_g \cos 15°\right)\\ &= m\boldsymbol{g} \cos 15°\\ &= 70 \times 9.8 \times \cos 15°\\ &= 663 \text{ N, rounded to } 6.6 \times 10^2 \text{ N}\end{aligned}$$

The normal force is therefore 6.6×10^2 N in the direction perpendicular to the surface as shown (as we are specifying the direction, we do not need to use a negative sign).

b. The skier has a constant velocity, so the net force on the skier in the direction parallel to the surface is zero. Therefore, the magnitude of the sum of resistance forces must be equal to the component of the force due to gravity that is parallel to the surface, $\boldsymbol{F}_{\text{R}} = \boldsymbol{F}_{\text{gx}}$.

b.
$$\begin{aligned}
\boldsymbol{F}_{\text{R}} &= \boldsymbol{F}_{\text{gx}} \\
&= \boldsymbol{F}_{\text{g}} \sin 15° \left(\text{since } \sin 15° = \frac{\boldsymbol{F}_{\text{gx}}}{\boldsymbol{F}_{\text{g}}} \Rightarrow \boldsymbol{F}_{\text{gx}} = \boldsymbol{F}_{\text{g}} \sin 15° \right) \\
&= mg \sin 15° \\
&= 70 \times 9.8 \times \sin 15° \\
&= 178\text{ N, rounded to } 1.8 \times 10^2\text{ N}
\end{aligned}$$

The sum of the resistance forces (air resistance and friction) acting on the skier is 1.8×10^2 N opposite to the direction of motion.

PRACTICE PROBLEM 5

a. A cyclist rides at constant velocity up a hill that is inclined at 15° to the horizontal. The total mass of the cyclist and bicycle is 90 kg. The sum of the resistive forces on the cyclist and bicycle is 20 N. Determine:
   i. the forward driving force provided by the road on the bicycle
   ii. the normal force.

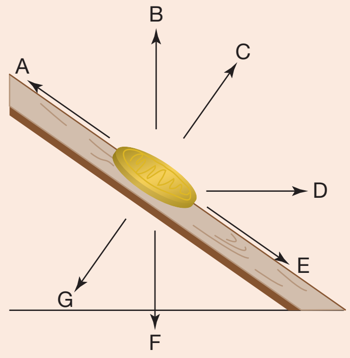
b. If the cyclist in part (a) coasts down the same hill with a constant total resistance of 50 N, what is the cyclist's acceleration?

1.3 Activities

1.3 Quick quiz | 1.3 Exercise | 1.3 Exam questions

1.3 Exercise

1. Draw a sketch (the length of the arrows should give a rough indication of relative size of the force) showing all the forces acting on a tennis ball while it is:
   a. falling to the ground
   b. in contact with the ground just before rebounding upwards
   c. on its upward path after bouncing on the ground.
2. A coin is allowed to slide with a constant velocity down an inclined plane as shown in the diagram. Which of the arrows A to G on the diagram represents the direction of each of the following? Write X if no direction is correct.
   a. The force due to gravity on the coin
   b. The normal force
   c. The net force



3. A child pulls a 4.0-kg toy cart along a horizontal path with a rope so that the rope makes an angle of 30° with the horizontal. The tension in the rope is 12 N.
   a. What is the force due to gravity acting on the toy cart?
   b. What is the component of tension in the direction of motion?
   c. What is the magnitude of the normal force?

4. A 200-kg dodgem car is driven due south into a rigid barrier at an initial speed of 5.0 m s^{-1}. The dodgem rebounds at a speed of 2.0 m s^{-1}. It is in contact with the barrier for 0.20 s. Calculate:
   a. the average acceleration of the car during its interaction with the barrier
   b. the average net force applied to the car during its interaction with the barrier.
5. A 1500-kg car is resting on a slope inclined at 20° to the horizontal. It has been left out of gear, so the only reason it doesn't roll down the hill is that the handbrake is on.
   a. Draw a labelled diagram showing the forces acting on the car.
   b. Calculate the magnitude of the normal force. Give your answer to 2 significant figures.
   c. What is the net force acting on the car?
   d. What is the magnitude of the frictional force acting on the car? Give your answer to 2 significant figures.
6. An experienced downhill skier with a mass of 60 kg (including skis) moves in a straight line down a slope inclined at 30° to the horizontal with a constant speed of 15 m s^{-1}.
   a. What is the direction of the net force acting on the skier?
   b. What is the magnitude of the resistive forces opposing the skier's motion? Give your answer to 2 significant figures.
7. A 70.0-kg waterskier is towed in a northerly direction by a 350-kg speedboat. The frictional forces opposing the forward motion of the waterskier total 240 N.
   a. If the waterskier has an acceleration of 2.0 m s^{-2} due north, what is the tension in the rope towing the waterskier?
   b. If the frictional forces opposing the forward motion of the speedboat are increased to total 600 N, what is the thrust force applied to the boat due to the action of the motor?
8. A 0.3-kg magpie flies towards a very tight plastic wire on a clothes line. The wire is perfectly horizontal and is stretched between poles 4.0 m apart. The magpie lands on the centre of the wire, depressing it by a vertical distance of 4.0 cm. What is the magnitude of the tension in the wire?
9. An old light globe hangs by a wire from the roof of a train. What angle does the globe make with the vertical when the train is accelerating at 1.5 m s^{-2}?

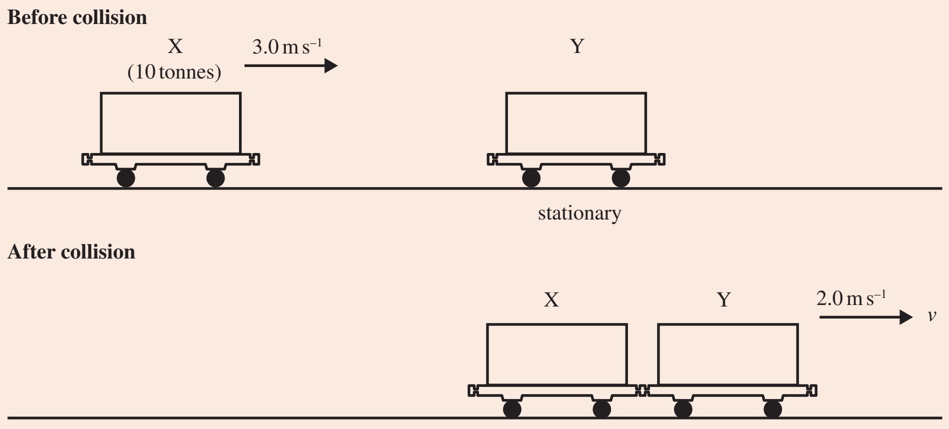
1.3 Exam questions

Question 1 (1 mark)

Source: *VCE 2022 Physics Exam, Section A, Q.7*; © VCAA

MC A railway truck (X) of mass 10 tonnes, moving at 3.0 m s^{-1}, collides with a stationary railway truck (Y), as shown in the diagram below.

After the collision, they are joined together and move off at speed v = 2.0 m s^{-1}.



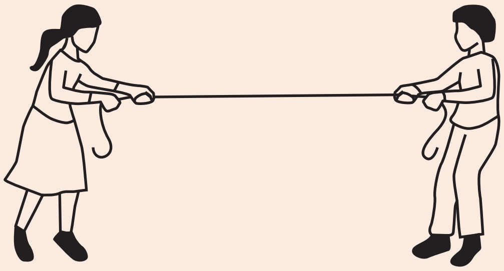
Which one of the following best describes the force exerted by the railway truck X on the railway truck Y ($F_{X \text{ on } Y}$) and the force exerted by the railway truck Y on the railway truck X (F_Y on X) at the instant of collision?

A. $F_{X \text{ on } Y} < F_{Y \text{ on } X}$
B. $F_{X \text{ on } Y} = F_{Y \text{ on } X}$
C. $F_{X \text{ on } Y} = -F_{Y \text{ on } X}$
D. $F_{X \text{ on } Y} > F_{Y \text{ on } X}$

Question 2 (1 mark)

Source: *VCE 2022 Physics Exam, Section A, Q.9*; © VCAA

MC Two students pull on opposite ends of a rope, as shown in the diagram below. Each student pulls with a force of 400 N.



Which one of the following is closest to the magnitude of the force of the rope on each student?

A. 0 N
B. 400 N
C. 600 N
D. 800 N

Question 3 (5 marks)

Source: *VCE 2021 Physics Exam, NHT, Section B, Q.8*; © VCAA

A car is driving up a uniform slope with a trailer attached, as shown in Figure 11. The slope is angled at 15° to the horizontal. The trailer has a mass of 200 kg and the car has a mass of 750 kg. Ignore all retarding friction forces down the slope.

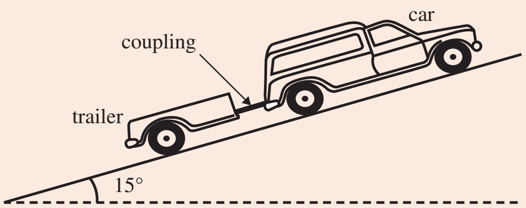


Figure 11

a. On Figure 12 below, draw labelled arrows to indicate the direction of the forces acting on the trailer. The labels should also indicate the kind of force that each arrow represents. **(3 marks)**

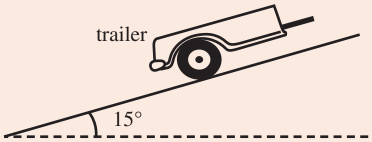


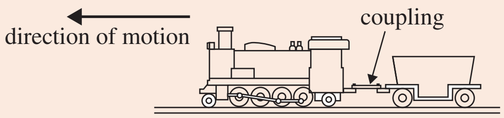
Figure 12

b. The car and trailer are travelling at a constant speed of 8 m s^{-1} up the slope.
Calculate the magnitude of the force that the car exerts on the trailer. Show your working. **(2 marks)**

Question 4 (2 marks)

Source: *VCE 2016, Physics Exam, Q.1.a; © VCAA*

A train consists of an engine of mass 20 tonnes (20 000 kg) towing one wagon of mass 10 tonnes (10 000 kg), as shown in the figure.



The train accelerates from rest with a constant acceleration of 0.10 m s^{-2}.

Calculate the speed of the train after it has moved 20 m. Show your working.

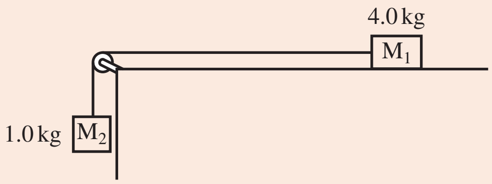
Question 5 (2 marks)

Source: *VCE 2015, Physics Exam, Q.2.a; © VCAA*

Students set up an experiment as shown in the figure.

M_1, of mass 4.0 kg, is connected by a light string (assume it has no mass) to a hanging mass, M_2, of 1.0 kg.

The system is initially at rest. Ignore mass of string and friction.



The masses are released from rest.

Calculate the acceleration of M_1.

More exam questions are available in your learnON title.

1.4 Projectile motion

KEY KNOWLEDGE

- Investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance.

Any object that is launched into the air is a projectile. A basketball thrown towards a goal, a trapeze artist soaring through the air, and a package dropped from a helicopter are all examples of projectiles.

Except for those projectiles whose motion is initially straight up or down, or those that have their own power source (such as a guided missile), projectiles generally follow a parabolic path. Deviations from this path can be caused either by air resistance, by the spinning of the object or by wind. These effects are often small and can be ignored in many cases. A major exception, however, is the use of spin in many ball sports, but this effect will not be dealt with in this title.

1.4.1 Falling down

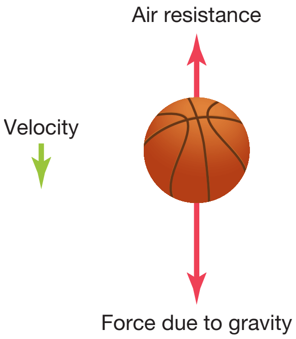
Imagine a ball that has been released some distance above the ground. Once the ball is set in motion, the only forces acting on it are the force due to gravity (straight down) and air resistance (straight up).

After the ball is released, the projection device (hand, gun, slingshot or whatever) stops exerting a force on the ball.

The net force on the ball in figure 1.14 is downwards. As a result, the ball accelerates downwards. If the size of the forces and the mass of the ball are known, the acceleration can be calculated using Newton's Second Law of Motion.

Often the force exerted on the ball by air resistance is very small in comparison to the force of gravity, and so can be ignored. This makes it possible to model projectile motion by assuming gravity is the only force on it so its acceleration is 9.8 m s^{-2} downwards.

FIGURE 1.14 The forces acting on a ball falling downwards



tlvd-8945

SAMPLE PROBLEM 6 Calculating the time and distance for an object to fall from a stationary object

A helicopter delivering supplies to a flood-stricken farm hovers 100 m above the ground. A package of supplies is dropped from rest, just outside the door of the helicopter. Air resistance can be ignored.

a. Calculate how long it takes the package to reach the ground.

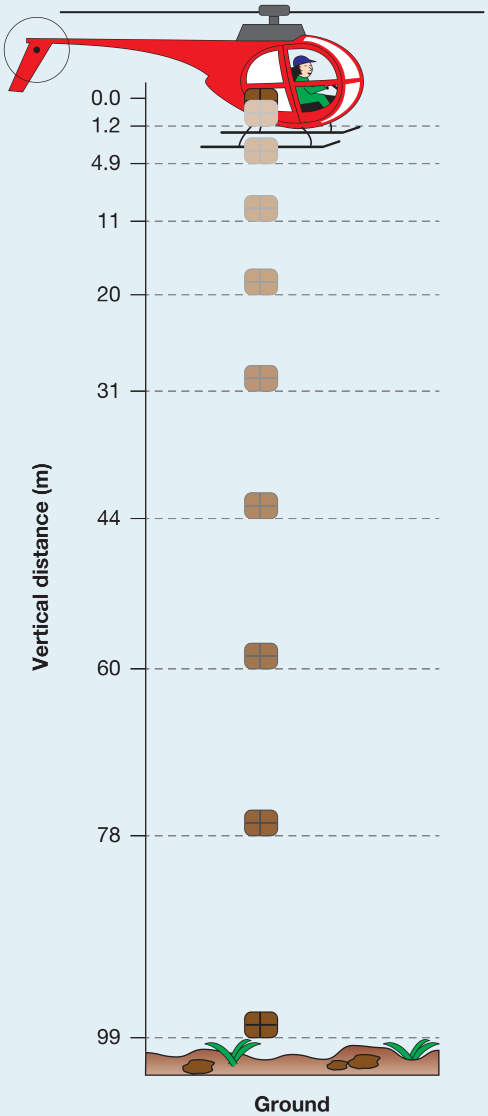
b. Calculate how far from its original position the package has fallen after 0.50 s, 1.0 s, 1.5 s, 2.0 s and so on until it hits the ground. (A spreadsheet could be used here.) Draw a scale diagram of the package's position at half-second intervals.

THINK	WRITE
a. 1. List the known information.	a. $\boldsymbol{u} = 0$ m s^{-1}, $\boldsymbol{s} = 100$ m, $\boldsymbol{a} = 9.8$ m s^{-2}
2. Use the rule $\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ to determine the time taken for the package to reach the ground. (*Note*: The negative square root can be ignored as time will be positive.)	$\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ $100 = 0 \times t + \frac{1}{2}(9.8)t^2$ $\frac{100}{4.9} = t^2$ $t = \sqrt{\frac{100}{4.9}}$ $t = 4.5$ s
b. 1. Look at the position of the package after 0.50 s. List the known information.	b. $t = 0.50$ s, $\boldsymbol{u} = 0$ m s^{-1}, $\boldsymbol{a} = 9.8$ m s^{-2}
2. Use the rule $\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ to determine the distance the package has travelled between $t = 0.00$ s and $t = 0.50$ s.	$\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ $= 0 \times 0.5 + \frac{1}{2}(9.8)(0.5)^2$ $= 1.2$ m

3. Repeat this for t = 1.0 s, 1.5 s, 2.0 s and so on until the package hits the ground, and list the results in a table.

Time (s)	0.50	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Vertical distance (m)	1.2	4.9	11	20	31	44	60	78	99

4. Draw a scale diagram of the package's position at half-second intervals.



PRACTICE PROBLEM 6

A camera is dropped by a tourist from a lookout and falls vertically to the ground. The thud of the camera hitting the hard ground below is heard by the tourist 3.0 seconds later. Air resistance and the time taken for the sound to reach the tourist can be ignored.

a. **How far did the camera fall?**

b. **What was the velocity of the camera when it hit the ground?**

Terminal velocity

The air resistance on a falling object increases as its velocity increases. An object falling from rest initially experiences no air resistance. Eventually, if the object doesn't hit a surface first, the air resistance will become as large as the force due to gravity acting on the object. The net force on it becomes zero and the object continues to fall with a constant velocity, referred to as its **terminal velocity**.

terminal velocity velocity reached by a falling object when the upward air resistance becomes equal to the downward force of gravity

on Resources

Video eLessons Ball toss (eles-0031)
Air resistance (eles-0035)

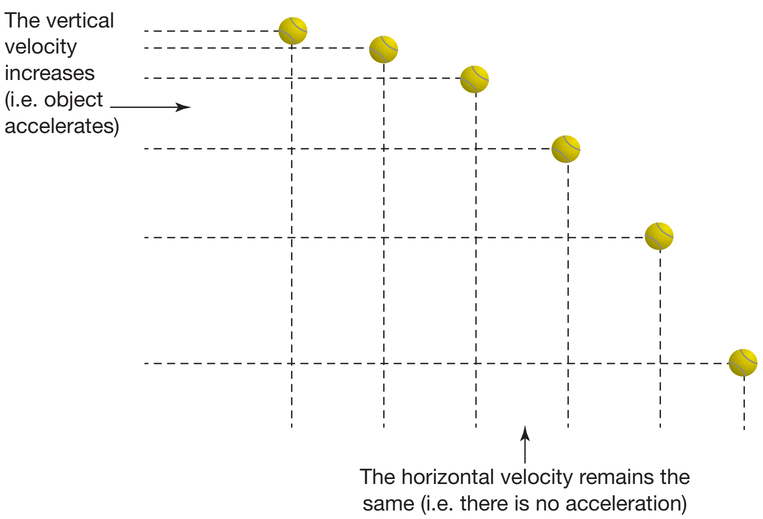
1.4.2 Moving and falling

Moving and falling

If a ball is thrown horizontally, as in figure 1.15, the only force acting on the ball once it has been released is the force due to gravity (ignoring air resistance). As the force of gravity is the same regardless of the motion of the ball, the ball will still accelerate downwards at the same rate as if it were dropped. There will not be any horizontal acceleration as there is no net force acting horizontally. This means that, while the ball's vertical velocity will change, its horizontal velocity remains the same throughout its motion.

It is the constant horizontal velocity and changing vertical velocity that give projectiles their characteristic parabolic motion.

FIGURE 1.15 Position of a ball at constant time intervals



Notice that the vertical distance travelled by the ball in each time period increases, but that the horizontal distance is constant.

In modelling projectile motion, the vertical and horizontal components of the motion are treated separately.

1. The total time taken for the projectile motion is determined by the vertical part of the motion as the projectile cannot continue to move horizontally once it has hit the ground, the target or whatever else it might collide with.
2. This total time can then be used to calculate the horizontal distance, or range, over which the projectile travels.

tlvd-8946

SAMPLE PROBLEM 7 Calculating the time and distance for an object to fall from a moving object

Imagine that the helicopter described in sample problem 6 is not stationary but is flying at a slow and steady speed of 20 m s^{-1} and is 100 m above the ground when the package is dropped.

a. Calculate how long it takes the package to hit the ground.

b. What is the range of the package?

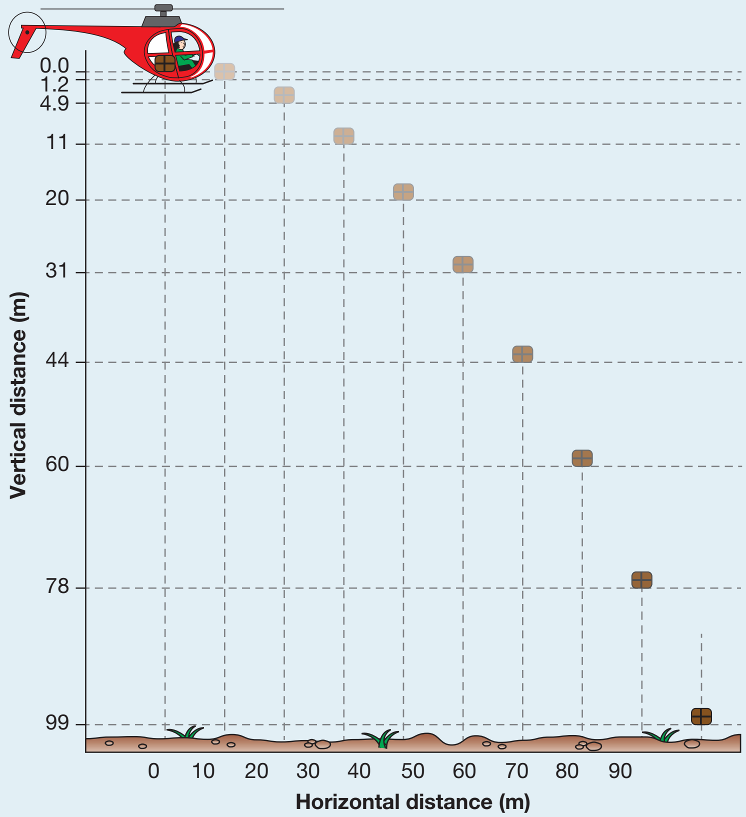
c. **Calculate the vertical distance the package has fallen after 0.50 s, 1.0 s, 1.5 s, 2.0 s and so on until the package has reached the ground. (You may like to use a spreadsheet here.) Then calculate the corresponding horizontal distance, and hence draw a scale diagram of the package's position at half-second intervals.**

THINK	WRITE
a. 1. Remember, the horizontal and vertical components of the package's motion must be considered separately. In this part of the question, the vertical component is important.	**a.** $\boldsymbol{u} = 0$ m s^{-1}, $\boldsymbol{s} = 100$ m, $\boldsymbol{a} = 9.8$ m s^{-2}
2. Use the rule $\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ to determine the time taken for the package to reach the ground.	$\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ $100 = 0 \times t + \frac{1}{2}(9.8)\,t^2$ $\frac{100}{4.9} = t^2$ $t = \sqrt{\frac{100}{4.9}}$ $t = 4.5\,\text{s}$ (*Note:* The positive square root is taken, as the concern is only with what happens after $t = 0$.)
b. 1. The range of the package is the horizontal distance over which it travels. It is the horizontal component of velocity that must be used here. List the known information in relation to the horizontal motion of the helicopter.	**b.** $\boldsymbol{u} = 20$ m s^{-1} (The initial velocity of the package is the same as the velocity of the helicopter it was travelling in.) $\boldsymbol{a} = 0$ m s^{-2} (No forces act horizontally so there is no horizontal acceleration.) $t = 4.5$ s (from part (a) of this example)
2. Use the rule $\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ to determine the horizontal distance over which the package travels.	$\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ $= 20 \times 4.5 + 0$ $= 90$ m
c. 1. For $t = 0.50$ s, list the known information regarding the vertical and horizontal motions separately. Use the rule $\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ to determine the vertical and horizontal distance over which the package travels.	**c.** **Vertical component** $\boldsymbol{u} = 0$ m s^{-1}, $t = 0.50$ s, $\boldsymbol{a} = 9.8$ m s^{-2} $\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ $= 0 \times 0.5 + \frac{1}{2}(9.8)(0.50)^2$ $= 1.2$ m **Horizontal component** $\boldsymbol{u} = 20$ m s^{-1}, $t = 0.50$ s, $\boldsymbol{a} = 0$ m s^{-2} $\boldsymbol{s} = \boldsymbol{u}t + \frac{1}{2}\boldsymbol{a}t^2$ $= 20 \times 0.50 + 0$ $= 10$ m

2. Repeat the calculations for t = 1.0 s, 1.5 s, 2.0 s and so on until the package reaches the ground.

Time (s)	Vertical distance (m)	Horizontal distance (m)
0.5	1.2	10
1.0	4.9	20
1.5	11.0	30
2.0	20.0	40
2.5	31.0	50
3.0	44.0	60
3.5	60.0	70
4.0	78.0	80
4.5	99.0	90

3. Draw a scale diagram of the package's position at half-second intervals.



PRACTICE PROBLEM 7

A ball is thrown horizontally at a speed of 40 m s^{-1} from the top of a cliff into the ocean below and takes 4.0 seconds to land in the water. Air resistance can be ignored.

a. **What is the height of the cliff above sea level if the thrower's hand releases the ball from a height of 2.0 metres above the ground?**
b. **What horizontal distance did the ball cover?**
c. **Calculate the vertical component of the velocity at which the ball hits the water.**
d. **At what angle to the horizontal does the ball strike the water?**

elog-1694

tlvd-10809

INVESTIGATION 1.1

online only

Modelling projectile motion

Aim

To model projectile motion by studying the motion of a ball bearing projected onto an inclined plane

elog-1695

tlvd-10810

INVESTIGATION 1.2

online only

The drop zone

Aim

To explore the relationship between the initial speed of a horizontally launched object and its range

on Resources

Digital document eModelling: Falling from a helicopter (doc-0005)

1.4.3 What goes up must come down

Most projectiles are set in motion with an initial velocity. The simplest case is that of a ball thrown vertically upwards. When the ball leaves the hand, the only force acting on the ball is the force due to gravity (ignoring air resistance). The ball accelerates downwards. Initially, this results in the ball slowing down. Eventually, it comes to a stop, then begins to move downwards, speeding up as it goes.

When air resistance is ignored, at the same height up or down, the speed will be the same. Therefore, if a ball is thrown upwards and its final height is the same as its initial height, the ball will return with the same speed with which it was projected. Throughout the motion illustrated in figure 1.16 (graphs are shown in figure 1.17), the acceleration of the ball is a constant 9.8 m s^{-2} downwards. A common error made by physics students is to suggest that the acceleration of the ball is zero at the top of its flight. If this were true, would the ball ever come down? The velocity is zero but not the acceleration. Remember, acceleration is the rate of change of velocity.

FIGURE 1.16 The motion of a ball projected vertically upwards

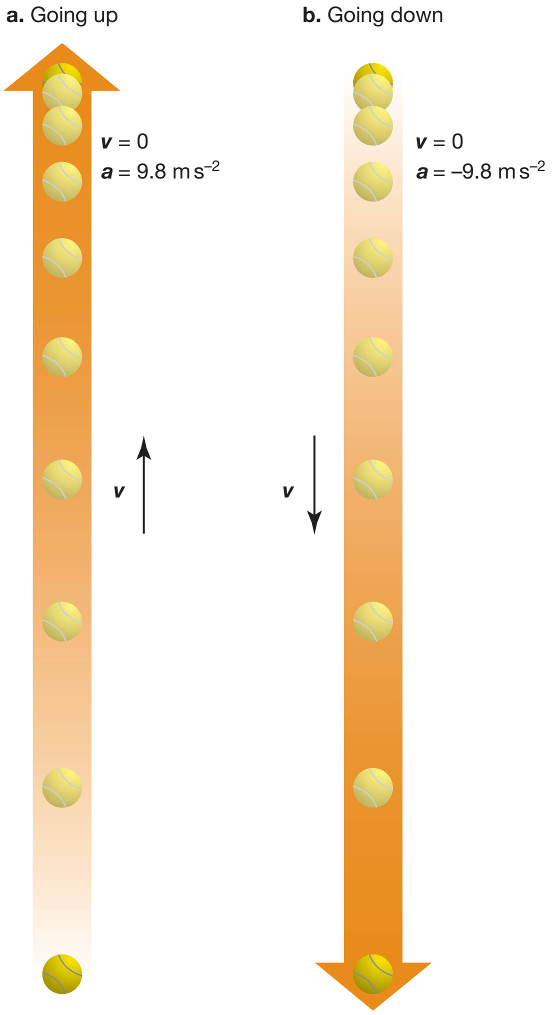
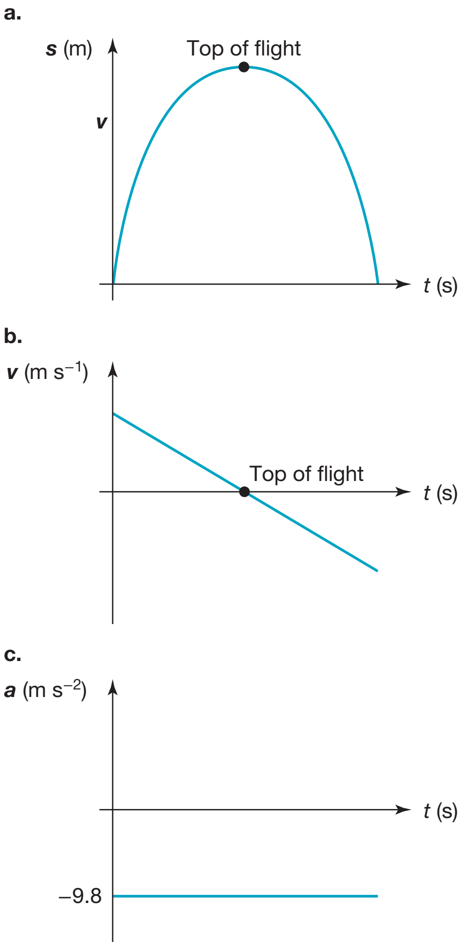


FIGURE 1.17 Graphs of motion for a ball thrown straight upwards



AS A MATTER OF FACT

The axiom 'what goes up must come down' applies equally so to bullets as it does to balls. Unfortunately, this means that people sometimes get killed when they shoot guns straight up into the air. If the bullet left the gun at a speed of 60 m s^{-1}, it will return to Earth at that speed. This speed is fast enough to kill a person who is hit by the returning bullet.

tlvd-8947

SAMPLE PROBLEM 8 Examining the displacement, velocity and acceleration of a dancer

A dancer jumps vertically upwards with an initial velocity of 4.0 m s^{-1}. Assume the dancer's centre of mass was initially 1.0 m above the ground, and ignore air resistance.

a. **How long did the dancer take to reach her maximum height?**

b. **What was the maximum displacement of the dancer's centre of mass?**

c. **What is the acceleration of the dancer at the top of her jump?**

d. **Calculate the velocity of the dancer's centre of mass when it returns to its original height above the ground.**

THINK	WRITE
a. 1. List the known information regarding the dancer's upward motion. Assign up as positive and down as negative.	**a.** $\boldsymbol{u} = 4.0 \text{ m s}^{-1}$, $\boldsymbol{a} = -9.8 \text{ m s}^{-2}$, $\boldsymbol{v} = 0 \text{ m s}^{-1}$ (as the dancer comes to a halt at the highest point of the jump)
2. Use the rule $\boldsymbol{v} = \boldsymbol{u} + \boldsymbol{a}t$ to determine the time taken for the dancer to reach her maximum height.	$\boldsymbol{v} = \boldsymbol{u} + \boldsymbol{a}t$ $0 = 4.0 + (-9.8) \times t$ $\Rightarrow t = \dfrac{4.0}{9.8}$ $= 0.41 \text{ s}$ The dancer takes 0.41 s to reach her highest point.
b. 1. List the known information regarding the dancer's upward motion.	**b.** $\boldsymbol{u} = 4.0 \text{ m s}^{-1}$, $\boldsymbol{a} = -9.8 \text{ m s}^{-2}$, $\boldsymbol{v} = 0 \text{ m s}^{-1}$ (as the dancer comes to a halt at the highest point of the jump)
2. Use the rule $\boldsymbol{v}^2 = \boldsymbol{u}^2 + 2\boldsymbol{as}$ to determine the displacement over the upward part of the dancer's motion.	$\boldsymbol{v}^2 = \boldsymbol{u}^2 + 2\boldsymbol{as}$ $(0)^2 = (4.0)^2 + 2(-9.8)s$ $16 = 19.6\boldsymbol{s}$ $\Rightarrow s = 0.82 \text{ m}$ The maximum displacement of the dancer's centre of mass is 0.82 m.
c. At the top of the jump, the only force acting on the dancer is the force of gravity (but gravity acts at all other points of the jump too). Therefore, the acceleration of the dancer is acceleration due to gravity.	**c.** 9.8 m s^{-2} downwards
d. 1. For this calculation, only the downward motion needs to be investigated. List the known information regarding the dancer's downward motion. (Alternatively, you could look at the whole motion rather than using previously calculated values.)	**d.** $\boldsymbol{u} = 0 \text{ m s}^{-1}$, $\boldsymbol{a} = -9.8 \text{ m s}^{-2}$, $\boldsymbol{s} = -0.82 \text{ m}$ (as the motion is downwards)
2. Use the rule $\boldsymbol{v}^2 = \boldsymbol{u}^2 + 2\boldsymbol{as}$ to determine the dancer's velocity when she returns to the ground. (*Note:* Here, the negative square root is used, as the dancer is moving downwards. Remember, the positive and negative signs show direction only.)	$\boldsymbol{v}^2 = \boldsymbol{u}^2 + 2\boldsymbol{as}$ $\boldsymbol{v}^2 = (0)^2 + 2(-9.8)(-0.82)$ $\boldsymbol{v}^2 = 16.072$ $\Rightarrow \boldsymbol{v} = -4.0 \text{ m s}^{-1}$ The velocity of the dancer's centre of mass when it returns to its original height is 4.0 m s^{-1} downwards.

PRACTICE PROBLEM 8

A basketball player jumps vertically upwards so that his centre of mass reaches a maximum displacement of 50 cm.

a. What is the velocity of the basketballer's centre of mass when it returns to its original height above the ground?

b. For how long was the basketballer's centre of mass above its original height?

HANGING IN MID AIR

Sometimes dancers, basketballers and high jumpers seem to hang in mid air. It is as though the force of gravity had temporarily stopped acting on them. Of course this is not so! It is only the person's centre of mass that moves in a parabolic path. The arrangement of the person's body can change the position of the centre of mass, causing the body to appear to be hanging in mid air even though the centre of mass is still following its original path.

High jumpers can use this effect to increase the height of their jumps. By bending her body as she passes over the bar, a high jumper can cause her centre of mass to be outside her body! This allows her body to pass over the bar, while her centre of mass passes under it. The amount of energy available to raise the high jumper's centre of mass is limited, so she can raise her centre of mass only by a certain amount. This technique allows her to clear a higher bar than other techniques for the same amount of energy.

FIGURE 1.18 Croatian high jumper Ana Simic's centre of mass passes under the bar, while her body passes over the bar!

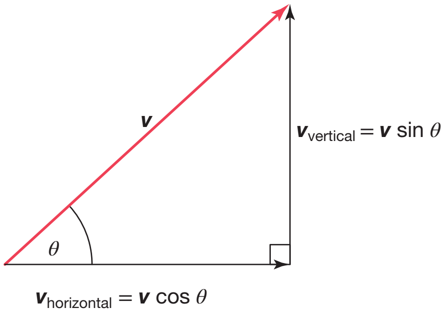
1.4.4 Shooting at an angle

Generally, projectiles are shot, thrown or driven at some angle to the horizontal. In these cases, the initial velocity may be resolved into its horizontal and vertical components to help simplify the analysis of the motion.

If the velocity and the angle to the horizontal are known, the size of the components can be calculated using trigonometry.

The motion of projectiles with an initial velocity at an angle to the horizontal can be dealt with in exactly the same manner as those with a velocity straight up or straight across. Once the initial velocity has been separated into its vertical and horizontal components, the vertical and horizontal motion can be analysed separately. The time of flight must be the same for both the vertical and horizontal motion and this is often used to link them when solving problems.

FIGURE 1.19 The velocity can be resolved into a vertical and a horizontal component.



Projectile motion calculations

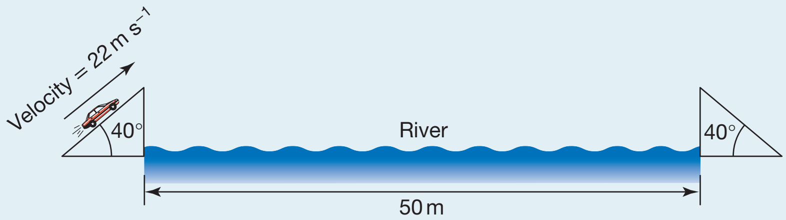
Tips for projectile motion calculations

- Draw a diagram and to write down all known information that you can identify.
- Always separate the motion into vertical and horizontal components.
- Remember to resolve the initial velocity into its components if necessary.
- The time in flight is the link between the separate vertical and horizontal components of the motion.
- At the end of any calculation, check to see if the quantities you have calculated are reasonable.

tlvd-8948

SAMPLE PROBLEM 9 Calculating a ramp jump

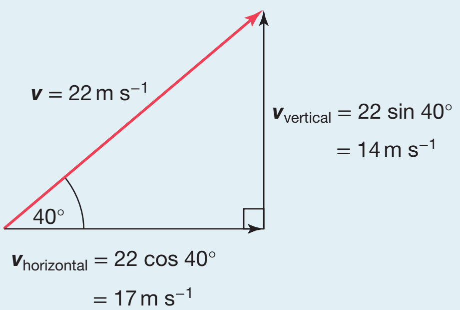
A stunt driver is trying to drive a car over a small river. The car will travel up a ramp (at an angle of 40°) and leave the ramp at 22 m s^{-1} before landing back at its initial height. The river is 50 m wide. Will the car make it?



THINK

1. Before either part of the motion can be examined, it is important to calculate the vertical and horizontal components of the initial velocity. Assign up as positive and down as negative.

WRITE



Therefore, the initial vertical velocity is 14 m s^{-1} and the initial horizontal velocity is 17 m s^{-1}.

2. The vertical motion is used to calculate the time in the air. Use the first half of the motion — from take-off until the car has reached its highest point.
(It is possible to double the time in this situation because air resistance has been ignored. The two parts of the motion are symmetrical.)

Vertical component

$\boldsymbol{u} = 14$ m s^{-1}, $\boldsymbol{a} = -9.8$ m s^{-2}, $\boldsymbol{v} = 0$ m s^{-1} (as the car comes to a vertical halt at its highest point):

$$\boldsymbol{v} = \boldsymbol{u} + \boldsymbol{a}t$$
$$0 = 14 + (-9.8) \times t$$
$$\Rightarrow t = \frac{14}{-9.8}$$
$$= 1.4\text{ s}$$

As this is only half the motion, the total time in the air is 2.8 s.

3. The horizontal component is used to calculate the range.

Horizontal component

$\boldsymbol{u} = 17$ m s^{-1}, $t = 2.8$ s, $\boldsymbol{a} = 0$ m s^{-2}:

$$\boldsymbol{s} = \boldsymbol{u}t$$
$$= 17 \times 2.8$$
$$= 48\text{ m}$$

Therefore, the unlucky stunt driver will fall short of the second ramp and will land in the river. Perhaps the study of physics should be a prerequisite for all stunt drivers!

PRACTICE PROBLEM 9

A hockey ball is hit towards the goal at an angle of 25° to the ground with an initial speed of 32 km h^{-1}.

a. **What are the horizontal and vertical components of the initial velocity of the ball?**
b. **How long does the ball spend in flight?**
c. **What is the range of the hockey ball?**

on Resources

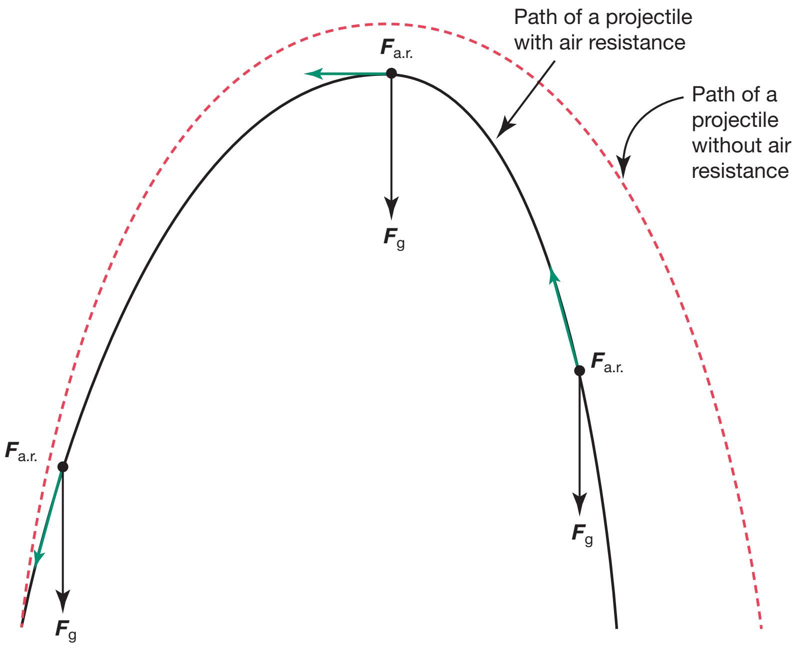
Digital documents eModelling: Free throw shooter (doc-0006)
eModelling: Modelling a stunt driver (doc-0007)

1.4.5 The real world — including air resistance

So far in this topic, the effects of air resistance have been ignored so that projectile motion can easily be modelled. The reason the force of air resistance complicates matters so much is that it is not constant throughout the motion. It depends on a number of factors. Consider what differences you might expect when you throw a crumpled-up piece of paper versus when you throw a cricket ball. Or, the difference between throwing a cricket ball in humid air conditions and dry air conditions.

The impact of air resistance can be influenced by the velocity ($\boldsymbol{v}$) of the object — the faster an object moves, the greater the air resistance. The size of the object in cross-section to the direction it is being thrown also has an impact — the greater the area, the greater the air resistance. Related to the size of the object is the shape of the object — objects that are more streamlined will experience less air resistance. Finally, the density of the air can impact air resistance — the more dense the air, the greater the air resistance.

FIGURE 1.20 While the magnitude of air resistance changes throughout the motion, it always opposes the direction of the motion. Note that the projectile has a steeper descent than its initial ascent when air resistance is taken into consideration.



on Resources

Weblink Projectile motion applet

1.4 Activities

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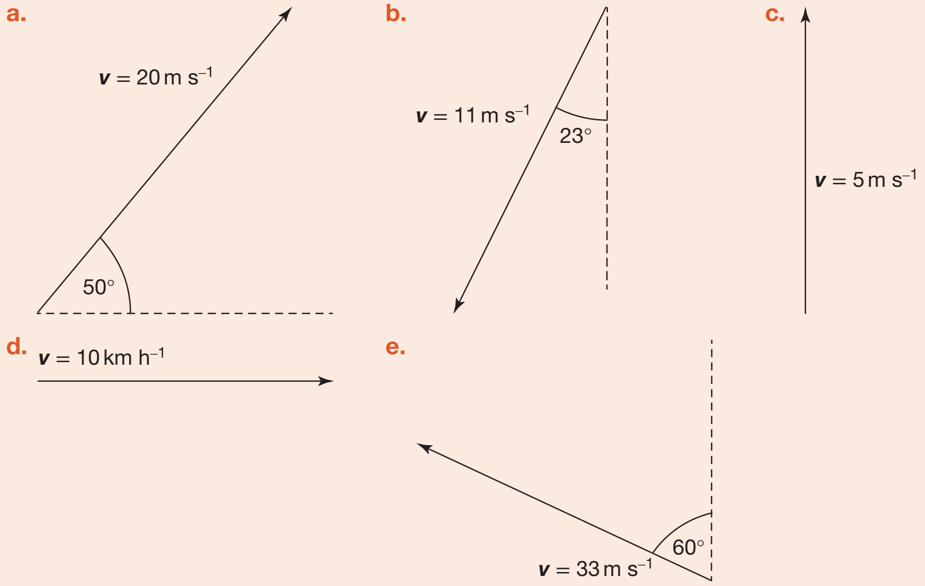
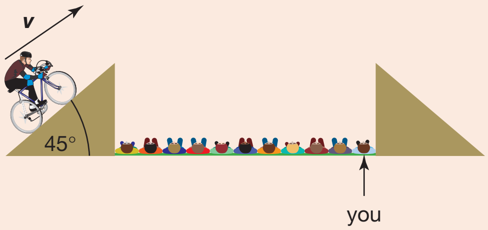
1.4 Quick quiz on	1.4 Exercise	1.4 Exam questions

1.4 Exercise

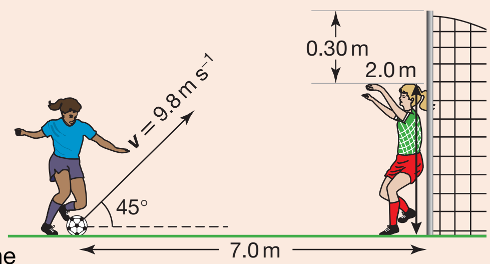
1. A ball has been thrown directly upwards. Draw the ball at three points during its flight (going up, at the top and going down) and mark on the diagram(s) all the forces acting on the ball at each stage.
2. Ignoring air resistance, the acceleration of a projectile in flight is always the same, whether it is going up or down. Use graphs of motion to show why this is true.
3. In each of the following cases, calculate the magnitude of the vertical and horizontal components of the velocity.



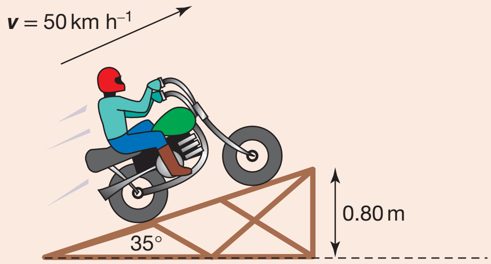
4. After taking a catch, a cricketer throws the cricket ball up into the air in jubilation.
   a. The vertical velocity of the ball as it leaves her hands is 18.0 m s^{-1}. How long will the ball take to return to its original position?
   b. What was the ball's maximum vertical displacement?
   c. Draw vectors to indicate the net force on the ball (ignoring air resistance),
      i. the instant it left her hands
      ii. at the top of its flight
      iii. as it returns to its original position.
5. A friend wants to get into the *Guinness Book of Records* by jumping over 11 people on his pushbike and landing on the other side at the same height he jumped from. He has set up two ramps as shown in the following figure, and has allowed a space of 0.5 m within which each person can lie down. In practice attempts, he has averaged a speed of 7.0 m s^{-1} at the top of the ramp. Will you lie down as the eleventh person between the ramps? Justify your answer using physics calculations.



6. A skateboarder jumps a horizontal distance of 2.0 m (starting from the ground), taking off at a speed of 5.0 m s^{-1}. The jump takes 0.42 s to complete.
   a. What was the skateboarder's initial horizontal velocity?
   b. What was the angle of take-off?
   c. What was the maximum height above the ground reached during the jump?
7. During practice, a soccer player shoots for goal. The goalkeeper is able to stop the ball only if it is more than 30 cm beneath the crossbar. The ball is kicked at an angle of 45° with a speed of 9.8 m s^{-1}. The arrangement of the players is shown in the following diagram.
   a. How long does it take the ball to reach the top of its flight?
   b. How far vertically and horizontally has the ball travelled at this time?
   c. How long does it take the ball to reach the soccer net from the top of its flight?
   d. Will the ball go into the soccer net, over it, or will the goalkeeper stop it?



8. A motocross rider rides over the jump shown in the following diagram at a speed of 50 km h^{-1}.



a. How long does it take the bike to reach the top of its flight?
b. How far vertically and horizontally has the bike travelled at this time?
c. How long does it take the bike to reach the ground from the top of its flight?
d. What is the total range of the jump?

9. A water skier at the Moomba Masters competition in Melbourne leaves a ramp at a speed of 50 km h^{-1} and at an angle of 30°. The edge of the ramp is 1.7 m above the water. Calculate:
a. the range of the jump
b. the velocity at which the jumper hits the water.
(*Hint*: Split the waterskier's motion into two sections, before the highest point and after the highest point, to avoid solving a quadratic equation.)

10. A gymnast wants to jump a horizontal distance of 2.5 m, leaving the ground at an angle of 28°. With what speed must the gymnast take off?

11. A horse rider wants to jump a stream that is 3.0 metres wide. The horse can approach the stream with a speed of 7.0 m s^{-1}. At what angle must the horse take off? (This question is a challenge. *Hint:* You will need to use trigonometric ratios from mathematics, or model the situation using a spreadsheet to solve this problem.)

1.4 Exam questions

Question 1 (6 marks)

Source: *VCE 2022 Physics Exam, NHT, Section B, Q.10*; © VCAA

A basketball player throws a ball with an initial velocity of 7.0 m s^{-1} at an angle of 50° to the horizontal, as shown in Figure 7. The ball is 2.2 m above the ground when it is released. By the time the ball passes through the ring at the top of the basket, it has travelled a horizontal distance of 3.2 m. Ignore air resistance.

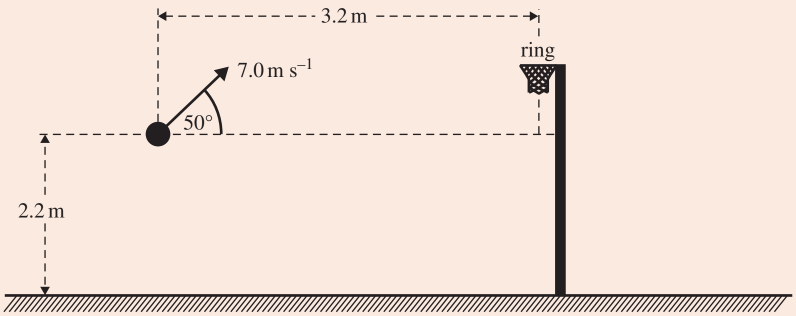


Figure 7

a. Show that the time taken for the ball's flight from launch to passing through the ring is 0.71 s. Show your working. **(2 marks)**
b. How far above the ground is the ring at the top of the basket? Show your working. **(4 marks)**

Question 2 (6 marks)

***Source:** VCE 2018 Physics Exam, Section B, Q.7*; © VCAA

A small ball of mass 0.20 kg rolls on a horizontal table at 3.0 m s^{-1}, as shown in Figure 9.

The ball hits the floor 0.40 s after rolling off the edge of the table. The radius of the ball may be ignored. In this question, take the value of g to be 10 m s^{-2}.

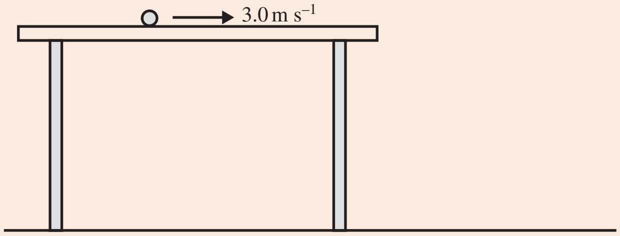


Figure 9

a. Calculate the horizontal distance from the right-hand edge of the table to the point where the ball hits the floor. **(1 mark)**

b. Calculate the height of the table. Show your working. **(2 marks)**

c. Calculate the speed at which the ball hits the floor. Show your working. **(3 marks)**

Question 3 (3 marks)

***Source:** VCE 2017 Physics Exam, Section B, Q.9a*; © VCAA

Students use a catapult to investigate projectile motion. In their first experiment, a ball of mass 0.10 kg is fired from the catapult at an angle of 30° to the horizontal. Ignore air resistance. In this first experiment, the ball leaves the catapult at ground level with a speed of 20 m s^{-1}.

However, instead of reaching the ground, the ball strikes a wall 26 m from the launching point, as shown in Figure 8a. Figure 8b shows an enlarged view of the catapult.

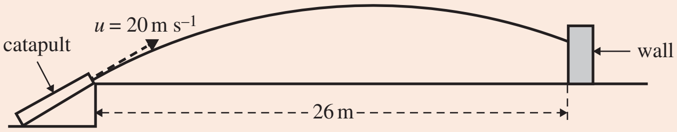


Figure 8a

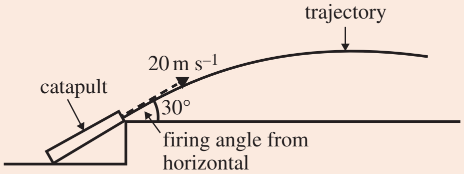


Figure 8b

Calculate the height of the ball above the ground when it strikes the wall. Show your working

Question 4 (7 marks)

***Source:** VCE 2018 Physics Exam, NHT, Section B, Q.6*; © VCAA

A rock of mass 2.0 kg is thrown horizontally from the top of a vertical cliff 20 m high with an initial speed of 25 m s^{-1}, as shown in Figure 3.

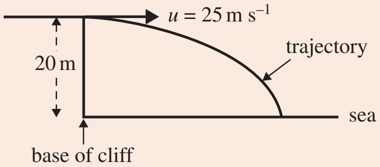


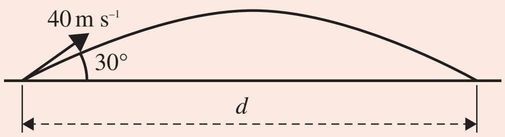
Figure 3

a. Calculate the time taken for the rock to reach the sea. Show your working. **(3 marks)**
b. Calculate the horizontal distance from the base of the cliff to the point where the rock reaches the sea. Show your working. **(2 marks)**
c. Calculate the kinetic energy of the rock as it reaches the surface of the sea. Show your working. **(2 marks)**

Question 5 (3 marks)

Source: *VCE 2016, Physics Exam, Q.5.a; © VCAA*

A ball is projected from the ground at an angle of 30° to the horizontal and at a speed of 40 m s^{-1}, as shown in the figure. Ignore any air resistance.



Calculate the distance, d, to the point where the ball hits the ground. Show your working.

More exam questions are available in your learnON title.

1.5 Uniform circular motion

KEY KNOWLEDGE

- Investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane $\left(F_{net} = \frac{mv^2}{r}\right)$ including:
  - a vehicle moving around a circular road
  - a vehicle moving around a banked track
  - an object on the end of a string.

Source: VCE Physics Study Design (2024–2027) extracts © VCAA; reproduced by permission.

Uniform circular motion is the motion of an object in a circle at constant speed, such as traffic at roundabouts, children on merry-go-rounds and cyclists in velodromes. If you stop to think about it, you are always going around in circles as a result of Earth's rotation.

The satellites orbiting Earth, including the Moon, travel in ellipses. However, their orbits can be modelled as circular motion. This motion is covered in subtopic 3.4, when gravitational forces are closely explored.

This section will investigate and analyse the uniform circular motion of objects moving in a horizontal plane. In doing so, the way that the variables of motion are calculated will need to account for the fact that the motion is circular, rather than in a straight line. Examples include a vehicle moving around a circular road, a vehicle moving around a banked track and an object at the end of a string.

FIGURE 1.21 The motion of satellites around Earth can be modelled as circular motion with a constant speed.

1.5.1 Period and frequency

The time taken for an object, moving in a circular path and at a constant speed, to complete one revolution is called the **period**, T. The number of revolutions the object completes each second is called the **frequency**, f.

period time taken for an object, moving in a circular path and at a constant speed, to complete one revolution

frequency number of revolutions that an object completes each second

$$f = \frac{1}{T} \text{ and } T = \frac{1}{f}$$

where: f is the frequency in Hertz (Hz)

T is the period in seconds (s)

1.5.2 Instantaneous velocity

FIGURE 1.22 A dog running in circles at a constant speed will have a constantly changing instantaneous velocity but an average velocity of zero, assuming the dog's starting and stopping positions are the same.

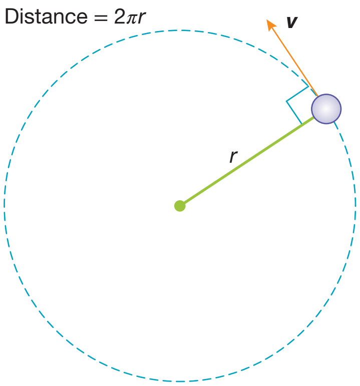
Imagine this scenario: Ralph the dog is chained to pole in the backyard while his owner does the gardening (don't worry — the chain is long enough so that he can still move around). A neighbourhood cat likes to tease him and makes Ralph run around in circles at a constant speed. Ralph's owner, Julie, is a physics teacher. She knows that no matter how great Ralph's average speed, if he always ends up in the same place his average velocity is always zero.

Although Ralph's average velocity for a single lap is zero, his instantaneous velocity is continually changing. Velocity is a vector and has a magnitude and direction. While the magnitude of Ralph's velocity may be constant, the direction is continually changing. At one point, Ralph is travelling east, so his instantaneous velocity is in an easterly direction. A short time later, he will be travelling south, so his instantaneous velocity is in a southerly direction.

If Ralph could maintain a constant speed, the magnitude of his velocity would not change, but the direction would be continually changing.

The speed is therefore constant and can be calculated using the formula speed $= \frac{d}{t}$, where d is the distance travelled, and t is the time interval. It is most convenient to use the period of the object travelling in a circle. Thus:

FIGURE 1.23 An object moving in circular motion



$$\text{speed} = \frac{d}{t}$$
$$= \frac{\text{circumference}}{\text{period}}$$
$$= \frac{2\pi r}{T}$$

where: r = radius of the circle
T = period

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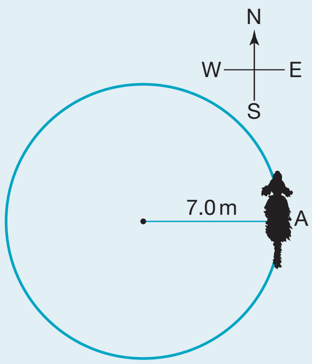
SAMPLE PROBLEM 10 Determining the average speed and instantaneous velocity in a uniform circular motion

Ralph's chain is 7.0-m long and attached to a small post in the middle of the garden. It takes an average of 9 s to complete one lap.

a. What is Ralph's average speed?

b. What is Ralph's average velocity after three laps?

c. What is Ralph's instantaneous velocity at point A? (Assume he travels at a constant speed around the circle.)



THINK	WRITE
a. 1. To calculate Ralph's speed, the distance he has travelled is required. Use the formula for the circumference of a circle: distance $= 2\pi r$.	**a.** distance $= 2\pi r$ $= 2\pi \times 7.0$ m $= 44$ m
2. Now the average speed can be calculated.	speed $= \frac{d}{t}$ $= \frac{44}{9}$ $= 5\ \text{m s}^{-1}$ The average speed is $5\ \text{m s}^{-1}$.
b. After three laps, Ralph is in exactly the same place as he started, so his displacement is zero. No matter how long he took to run these laps, his average velocity would still be zero, as $\boldsymbol{v}_{\text{av}} = \frac{\Delta \boldsymbol{x}}{\Delta t}$.	**b.** $\boldsymbol{v}_{\text{av}} = \frac{\Delta \boldsymbol{x}}{\Delta t}$ $= \frac{0}{3 \times 9}$ $= 0\ \text{m s}^{-1}$
c. Ralph's speed is a constant $5\ \text{m s}^{-1}$ as he travels around the circle. At point A, the magnitude of his instantaneous velocity is also $5\ \text{m s}^{-1}$.	**c.** At point A, Ralph's velocity is $5\ \text{m s}^{-1}$ north.

PRACTICE PROBLEM 10

A battery-operated toy car completes a single lap of a horizontal circular track in 15 s with an average speed of 1.3 m s^{-1}. Assume that the speed of the toy car is constant.

a. **What is the radius of the track?**
b. **What is the magnitude of the toy car's instantaneous velocity halfway through the lap?**
c. **What is the average velocity of the toy car after half of the lap has been completed?**
d. **What is the average velocity of the toy car over the entire lap?**

1.5.3 Changing velocities and accelerations

As all objects with changing velocities are experiencing an acceleration, this means all objects that are moving in a circle are accelerating.

An acceleration can be caused only by an unbalanced force, so non-zero net force is needed to move an object in a circle. For example, a hammer thrower must apply a force to the hammer to keep it moving in a circle. When the hammer is released, this force is no longer applied and the hammer moves off with the velocity it had when released. The hammer will then experience projectile motion.

FIGURE 1.24 The hammer is always accelerating while it moves in a circle.

In which direction is the force?

Figure 1.26 shows diagrammatically the head of the hammer moving in a circle at two different times. It takes t seconds to move from A to B. (This movement is also covered in subtopic 3.4, in which the motion of satellites is explored.)

FIGURE 1.25 The hammer moves in a circle while the thrower turns. When the hammer is released, it moves in a straight line.

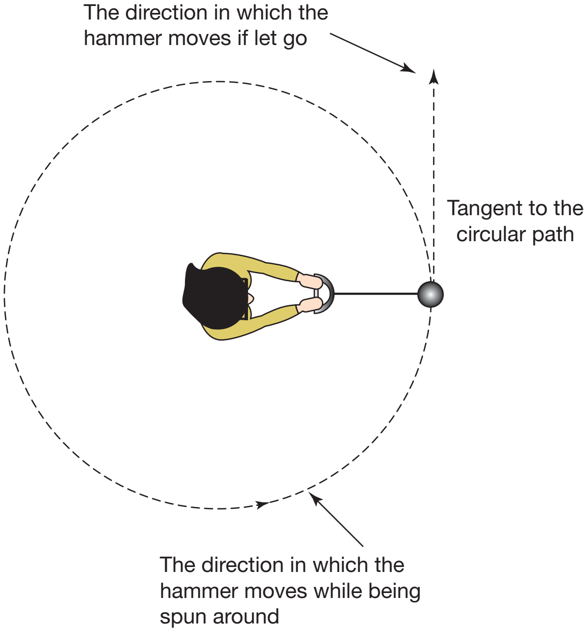
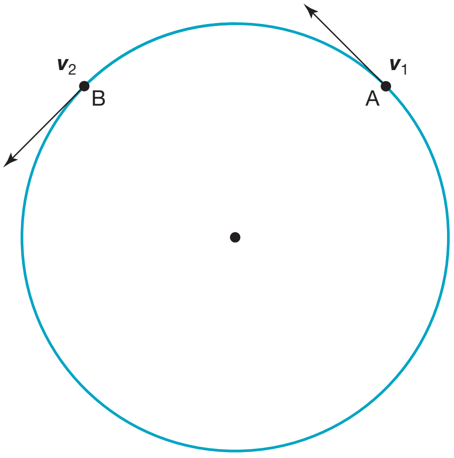


FIGURE 1.26 Velocity vectors for a hammer moving in an anticlockwise circle



To determine the acceleration, the change in velocity between these two points must be known. Vector addition needs to be used:

$$\Delta \boldsymbol{v} = \boldsymbol{v}_2 - \boldsymbol{v}_1$$

$$\Delta \boldsymbol{v} = \boldsymbol{v}_2 + (-\boldsymbol{v}_1)$$

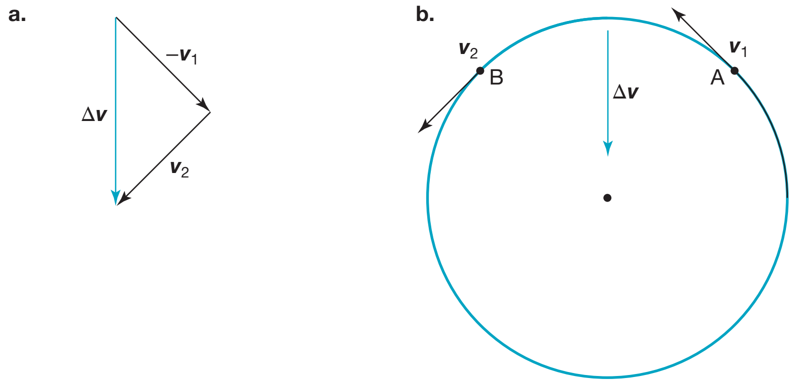
Notice that when the $\Delta \boldsymbol{v}$ vector is transferred back to the original circle halfway between the two points in time, it is pointing towards the centre of the circle. (See figure 1.27b. Such calculations become more accurate when very small time intervals are used; however, a large time interval has been used here to make the diagram clear.)

As $\boldsymbol{a} = \frac{\Delta \boldsymbol{v}}{t}$, the acceleration vector is in the same direction as $\Delta \boldsymbol{v}$, but has a different magnitude and different units.

No matter which time interval is chosen, the acceleration vector always points towards the centre of the circle. So, for an object to have uniform circular motion, the acceleration of the object *must be towards the centre* of the circle. Such an acceleration is called **centripetal acceleration**. The word *centripetal* literally means 'centre-seeking'. As stated in Newton's Second Law of Motion, the net force on an object is in the same direction as the acceleration ($\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$). Therefore, the net force on an object moving with uniform circular motion is towards the centre of the circle.

centripetal acceleration the acceleration towards the centre of a circle experienced by an object moving in a circular motion

FIGURE 1.27 a. Vector addition **b.** The change in velocity is towards the centre of the circle.



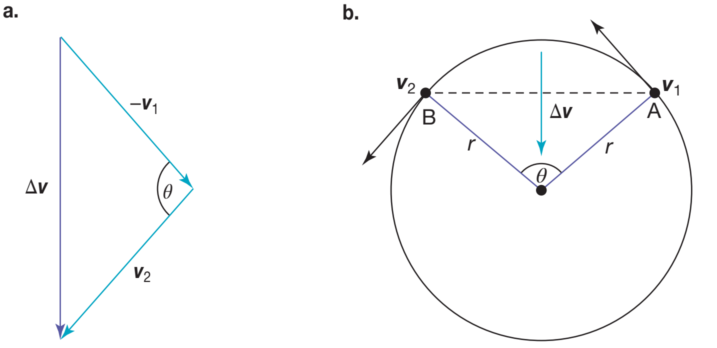
The acceleration of an object moving with uniform circular motion must be towards the centre of the circle. This is called centripetal acceleration. The net force on this object must also be towards the centre of the circle.

Remember that while the hammer thrower is exerting a force on the hammer head towards the centre of the circle, the hammer head must be exerting an equal and opposite force on the thrower away from the centre of the circle (according to Newton's Third Law of Motion).

1.5.4 Calculating accelerations and forces

Using vector diagrams and the formulas $\boldsymbol{a} = \frac{\Delta \boldsymbol{v}}{t}$ and $\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$, it is possible to calculate the accelerations and forces involved in circular motion. However, doing calculations this way is tedious, and results can be inaccurate if the vector diagrams are not drawn carefully. It is simpler to use a formula that will avoid these difficulties. The derivation of such a formula is a little challenging, but it is worth the effort!

FIGURE 1.28 The triangles shown in parts (a) and (b) are both isosceles triangles.



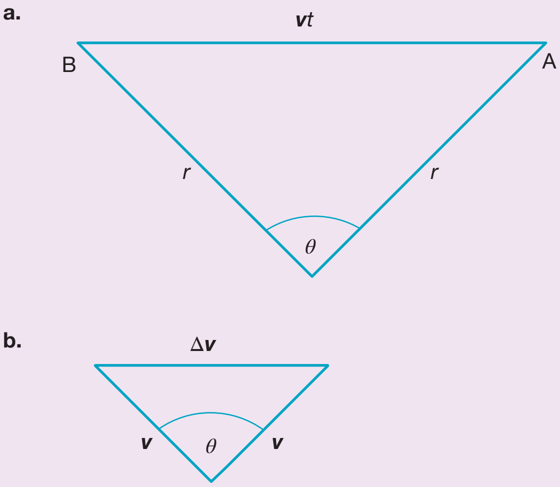
The circular motion formula explained

By re-examining the two previous figures, it is possible to see that they both 'contain' isosceles triangles. These are shown in figure 1.29.

In figure 1.29, diagram (a) shows distances. It has the radius of the circle marked in twice. These radii form two sides of an isosceles triangle. The third side is formed by a line, or chord, joining point A with point B. It is the distance between the two points. When the angle θ is very small, the length of the chord is virtually the same as the length of the arc that also joins these two points. As this is a distance, its length can be calculated using $\boldsymbol{s} = \boldsymbol{v}t$.

In figure 1.29, diagram (b) shows velocities. As the object was moving with *uniform* circular motion, the length of the vectors $\boldsymbol{v}_2$ and $-\boldsymbol{v}_1$ are identical and form two sides of an isosceles triangle. As both diagrams (a) and (b) are derived from figure 1.27, both of the angles marked as θ are the same size. Therefore, the triangles are both isosceles triangles, containing the same angle, θ. This means they are similar triangles — they can be thought of as the same triangle drawn on two different scales. Figure 1.29 shows these triangles redrawn to make this more obvious.

FIGURE 1.29 The two triangles are *similar* triangles.



As the triangles are similar, the ratio of their sides must be constant, so:

$$\frac{\Delta \boldsymbol{v}}{\boldsymbol{v}t} = \frac{\boldsymbol{v}}{r}$$

Multiplying both sides by $\boldsymbol{v}$:

$$\frac{\Delta \boldsymbol{v}}{t} = \frac{\boldsymbol{v}^2}{r}$$

As $\boldsymbol{a} = \frac{\Delta \boldsymbol{v}}{t}$:

$$\boldsymbol{a} = \frac{\boldsymbol{v}^2}{r}$$

Sometimes it is not easy to measure the velocity of the object undergoing circular motion. However, this can be calculated from the radius of the circle and the time taken to complete one circuit using the equation $\boldsymbol{v} = \frac{2\pi r}{T}$. It can also be found using the equation $\boldsymbol{a} = \frac{\boldsymbol{v}^2}{r}$. Combining these two equations yields the following relationship:

$$\boldsymbol{a} = \frac{\boldsymbol{v}^2}{r} = \frac{4\pi^2 r}{T^2}$$

where: $\boldsymbol{a}$ is the centripetal acceleration directed towards the centre of the circle

$\Delta \boldsymbol{v}$ is the speed

r is the radius of the circle

T is the period of motion

This formula provides a way of calculating the centripetal acceleration of a mass moving with uniform circular motion having speed $\boldsymbol{v}$ and radius r.

If the acceleration of a known mass moving in a circle with constant speed has been calculated, the net force can be determined by applying $\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$. Note that because in this scenario the net force is causing the centripetal acceleration, you may sometimes see it referred to as the centripetal force, $\boldsymbol{F}_{\text{c}}$.

The magnitude of the net force can also be calculated using:

$$\boldsymbol{F}_{\text{net}} = m\boldsymbol{a} = \frac{m\boldsymbol{v}^2}{r} = \frac{4\pi^2 rm}{T^2} = \boldsymbol{F}_{\text{c}}$$

where: $\boldsymbol{F}_{\text{net}}$ is the net force on the object

$\boldsymbol{a}$ is the centripetal acceleration directed towards the centre of the circle

$\boldsymbol{v}$ is the speed

r is the radius of the circle

T is the period of motion

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SAMPLE PROBLEM 11 Determining the magnitude and direction of the acceleration and the force of an object moving in a circular motion

A car is driven around a roundabout at a constant speed of 20 km h^{-1} (5.6 m s^{-1}). The roundabout has a radius of 3.5 m and the car has a mass of 1200 kg.

a. **What is the magnitude and direction of the acceleration of the car?**

b. **What is the magnitude and direction of the net force on the car?**

THINK	WRITE
a. **1.** List the known information.	**a.** $v = 5.6\ \text{m s}^{-1}$, $r = 3.5$ m
2. Calculate the acceleration.	$\boldsymbol{a} = \frac{v^2}{r} = \frac{(5.6)^2}{3.5} = 9.0\ \text{m s}^{-2}$ The car accelerates at $9.0\ \text{m s}^{-2}$ towards the centre of the roundabout.
b. **1.** There are two different formulas that can be used to calculate this answer. **i.** Use the answer to (a) and substitute into $\boldsymbol{F}_{\text{net}} = m\boldsymbol{a}$.	**b.** $\boldsymbol{a} = 9.0\ \text{m s}^{-2}$, $m = 1200$ kg $\boldsymbol{F}_{\text{net}} = m\boldsymbol{a} = 1200 \times 9.0 = 1.1 \times 10^4\ \text{N}$
ii. Use the formula $\boldsymbol{F}_{\text{net}} = \frac{mv^2}{r}$.	$v = 5.6\ \text{m s}^{-1}$, $r = 3.5$ m, $m = 1200$ kg $\boldsymbol{F}_{\text{net}} = \frac{mv^2}{r} = \frac{1200\,(5.6)^2}{3.5} = 1.1 \times 10^4\ \text{N}$ Both methods give the force on the car as 1.1×10^4 N towards the centre of the roundabout.

PRACTICE PROBLEM 11

Kwong (mass 60 kg) rides the Gravitron at the amusement park. This ride moves Kwong in a circle of radius 3.5 m, at a rate of one rotation every 2.5 s.

a. **What is Kwong's acceleration?**
b. **What is the net force acting on Kwong? (Include a magnitude and a direction.)**
c. **Draw a labelled diagram showing all the forces acting on Kwong.**

elog-1696

tlvd-0238

INVESTIGATION 1.3

online only

Exploring circular motion

Aim

To examine some of the factors affecting the motion of an object undergoing uniform circular motion, and then to determine the quantitative relationship between the variables of force, velocity and radius

1.5.5 Forces that produce centripetal acceleration

Whenever an object is in uniform circular motion, the net force on that object must be towards the centre of the circle. Some examples of situations involving forces producing centripetal acceleration follow.

Tension

The force applied by an object that is being pulled or stretched can be referred to as a tension force.

FIGURE 1.30 a. Tension contributes to the net force in many amusement park rides. **b.** The net force acting on a compartment in the ride

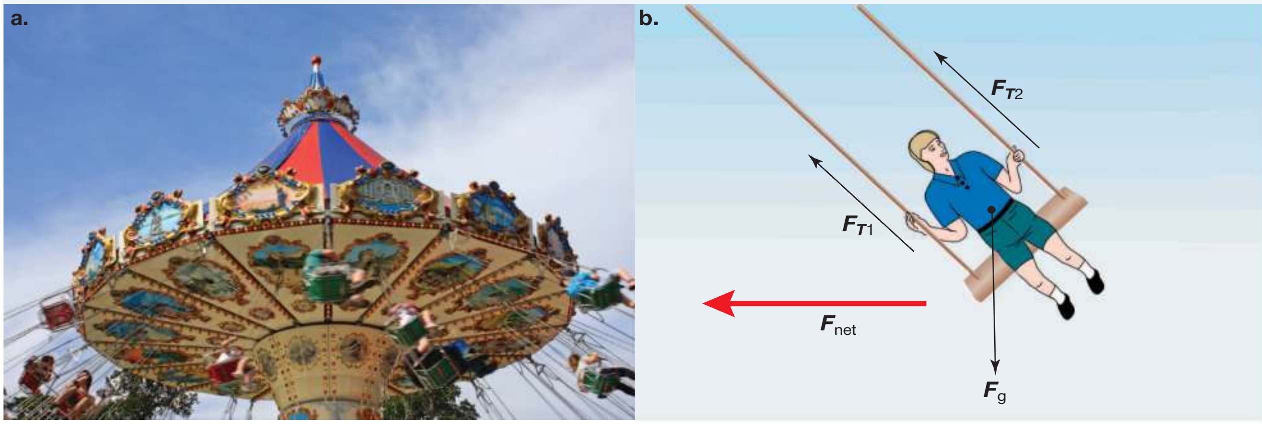
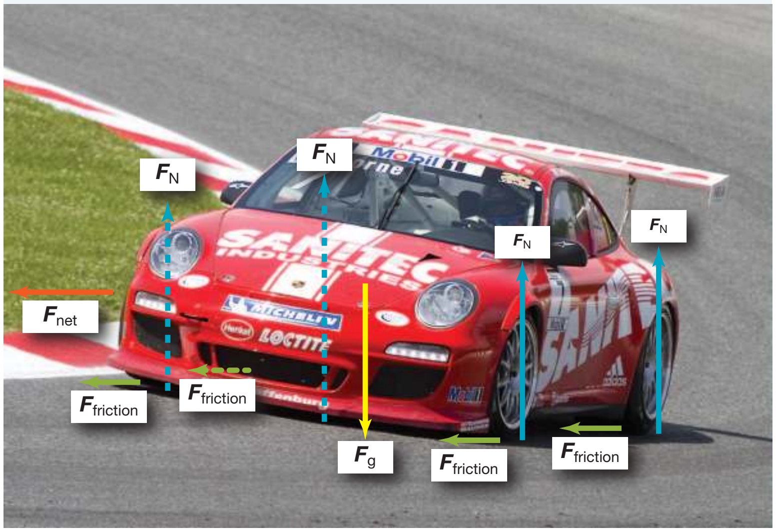


FIGURE 1.31 A component of the tension is the net force acting on the female skater when she is performing a 'death roll'.

Friction

When a car rounds a corner, the sideways frictional forces contribute to the net force. The forward frictional forces by the ground on the tyres keep the car moving, but if the sideways frictional forces are not sufficient, the net force on the car will not be towards the centre of the curve. Since the net force is less than the force required to keep the car moving in a circle at this radius, the car will not make it around the corner but move sideways!

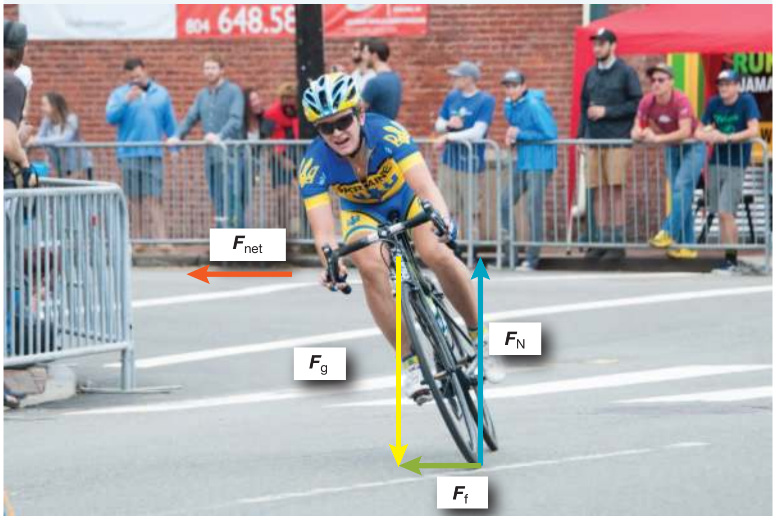
FIGURE 1.32 The sideways frictional forces of the ground on the tyres enable a car to move around a corner.



The formula $\boldsymbol{F}_{\text{net}} = \frac{m\boldsymbol{v}^2}{r}$ shows that as the velocity increases, the force needed to move in a circle greatly increases $\left(\boldsymbol{F}_{\text{net}} \propto \boldsymbol{v}^2\right)$. This is why it is vital that cars do not attempt to corner while travelling too fast.

Track athletes, cyclists and motorcyclists also rely on sideways frictional forces to enable them to manoeuvre around corners. They often lean into corners to increase the size of the sideways frictional forces, to turn more quickly. Leaning also means that they are pushing on the surface at an angle, so the reaction force is no longer normal to the ground (Newton's Third Law). It has an upward component, the normal force $\boldsymbol{F}_{\text{N}}$, which balances the force due to gravity, $\boldsymbol{F}_{\text{g}}$, and a horizontal component towards the centre of their circular motion due to the frictional force $\boldsymbol{F}_{\text{f}}$.

FIGURE 1.33 Leaning into a corner increases the size of the net force, allowing a higher speed while cornering. Leaning sideways induces a sideways frictional force, resulting in the horizontal net force experienced by the bicycle.



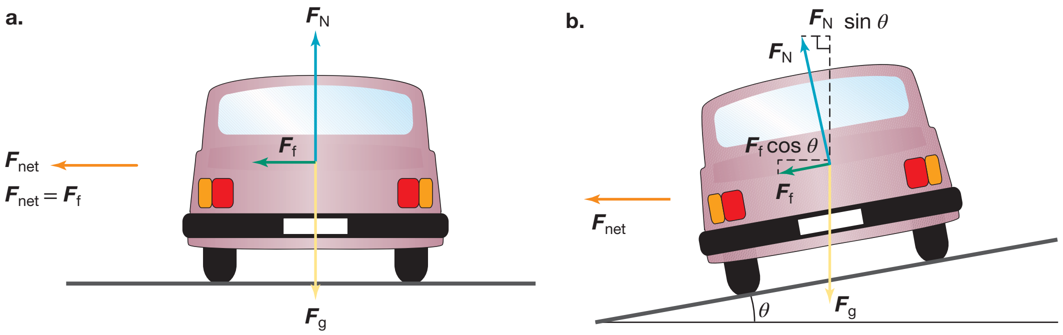
In velodromes, the track is banked so that a component of the normal force acts towards the centre of the velodrome, thus increasing the net force in this direction. As the centripetal force is larger, the cyclists can move around the corners faster than if they had to rely on friction alone.

Going around a bend

When a vehicle travels around a bend, or curve, at constant speed, its motion can be considered to be part of a circular motion. The curve makes up the arc of a circle. For a car to travel around a corner safely, the net force acting on it must be towards the centre of the circle.

Figure 1.34a shows the forces acting on a vehicle of mass m travelling around a curve with a radius r at a constant speed $\boldsymbol{v}$. The forces acting on the car are the force due to gravity, $\boldsymbol{F}_g$, friction, $\boldsymbol{F}_f$, and the normal force, $\boldsymbol{F}_N$.

FIGURE 1.34 a. For the vehicle to take the corner safely, the net force must be towards the centre of the circle. **b.** Banking the road allows a component of the normal force to contribute to the centripetal force. Note that the forces have been drawn as though they were acting through the centre of mass.



On a level road, the only force with a component towards the centre of the circle is the 'sideways' friction. This sideways friction makes up the whole of the magnitude of the net force on the vehicle. That is:

$$\begin{aligned}\boldsymbol{F}_{net} &= \text{sideways friction}\\ &= \frac{m\boldsymbol{v}^2}{r}\end{aligned}$$

If you drive the vehicle around the curve with a speed so that $\frac{m\boldsymbol{v}^2}{r}$ is greater than the sideways friction, the motion is no longer circular and the vehicle will skid off the road. If the road is wet, sideways friction is less and a lower speed is necessary to drive safely around the curve.

CASE STUDY: Calculating the net force on a banked road

If the road is banked at an angle θ towards the centre of the circle, a component of the normal force, $\boldsymbol{F}_N \sin\theta$, can also contribute to the net force, which acts in the horizontal direction. This is shown in figure 1.34b.

$$\boldsymbol{F}_{net} = \boldsymbol{F}_f \cos\theta + \boldsymbol{F}_N \sin\theta$$

The larger net force means that, for a given curve, banking the road makes a higher speed possible.

Loose gravel on bends in roads is dangerous because it reduces the sideways friction force. At low speeds this is not a problem, but a vehicle travelling at high speed is likely to lose control and run off the road in a straight line.

Cycling velodromes are steeply banked (often up to 40°), allowing cyclists to achieve very fast speeds. When engineers design velodromes (and other banked tracks, such as banked roadways) they need to consider the speed at which the force due to friction becomes zero. This is dependent on the angle at which the track is banked. The speed at which the force due to friction becomes zero is called the **design speed** and means that frictional force is not required to keep the vehicle on the track. As shown in figure 1.35, only the horizontal component of the normal force is contributing to the net force and there is no frictional force acting sideways.

design speed speed at which the force due to friction becomes zero, as seen on a banked track

The equation for net force can be simplified as follows:

$$\begin{aligned} \boldsymbol{F}_{\text{net}} &= \boldsymbol{F}_{\text{f}}\cos\theta + \boldsymbol{F}_{\text{N}}\sin\theta \\ &= 0 + \boldsymbol{F}_{\text{N}}\sin\theta \\ &= \boldsymbol{F}_{\text{N}}\sin\theta \end{aligned}$$

From figure 1.35, it can also be shown that:

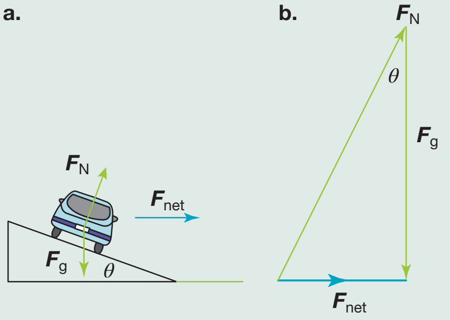
$$\begin{aligned} \boldsymbol{F}_{\text{g}} &= \boldsymbol{F}_{\text{N}}\cos\theta \\ \boldsymbol{F}_{\text{net}} &= \boldsymbol{F}_{\text{g}}\tan\theta \end{aligned}$$

These equations can be used to determine the angle a road needs to be banked at to achieve a certain design speed, or if the angle is known, the design speed can be determined.

Recall that $\boldsymbol{F}_{\text{net}} = \frac{m\boldsymbol{v}^2}{r}$ and $\boldsymbol{F}_{\text{g}} = m\boldsymbol{g}$. If the following is used in substitution, $\tan\theta = \frac{\frac{m\boldsymbol{v}^2}{r}}{m\boldsymbol{g}}$, then:

$$\begin{aligned} \tan\theta &= \frac{\boldsymbol{v}^2}{r\boldsymbol{g}} \\ \Rightarrow \theta &= \tan^{-1}\left(\frac{\boldsymbol{v}^2}{r\boldsymbol{g}}\right) \end{aligned}$$

FIGURE 1.35 a. When travelling in circular motion at the design speed, the force due to friction is zero, so the only forces acting on the object are the force due to gravity and the normal force. **b.** The vector addition of the force due to gravity and the normal force gives the net force as acting horizontally towards the centre of the circle.



When travelling at the design speed, where the frictional force will be zero, the angle of the bank can be found by using:

$$\tan\theta = \frac{\boldsymbol{F}_{\text{net}}}{\boldsymbol{F}_{\text{g}}} = \frac{\boldsymbol{v}^2}{r\boldsymbol{g}}$$

$$\theta = \tan^{-1}\left(\frac{\boldsymbol{v}^2}{r\boldsymbol{g}}\right)$$

where: θ is the angle of the bank

$\boldsymbol{F}_{\text{net}}$ is the net force

$\boldsymbol{F}_{\text{g}}$ is the force due to gravity

$\boldsymbol{v}$ is the speed

r is the radius of the track

$\boldsymbol{g}$ is the acceleration due to gravity

The equation can be arranged so that the design speed can be determined if the bank angle is known.

The design speed can be found by using:

$$\begin{aligned} \boldsymbol{v}^2 &= r\boldsymbol{g}\tan\theta \\ \boldsymbol{v} &= \sqrt{r\boldsymbol{g}\tan\theta} \end{aligned}$$

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SAMPLE PROBLEM 12 Calculating the maximum constant speed of a car with sideways wheel friction

A car of mass 1280 kg travels around a bend with a radius of 12.0 m. The total sideways friction on the wheels is 16 400 N. The road is not banked. Calculate the maximum constant speed at which the car can be driven around the bend without skidding off the road.

THINK	WRITE
The car will maintain the circular motion around the bend if: $\boldsymbol{F}_{\text{net}} = \dfrac{mv^2}{r}$ where $\boldsymbol{v}$ = maximum speed, $\boldsymbol{F}_{\text{net}}$ is the sideways friction (16 400 N), m = 1280 kg and r = 12.0 m. If $\boldsymbol{v}$ were to exceed this speed, $\boldsymbol{F}_{\text{net}} < \dfrac{mv^2}{r}$, the circular motion would not be maintained and the vehicle would skid.	$\boldsymbol{F}_{\text{net}} = 1280 \times \dfrac{v^2}{12.0}$ $v^2 = 16\,400 \times \dfrac{12.0}{1280}$ $= 153.75 \text{ m}^2 \text{ s}^{-2}$ $\Rightarrow v = 12.4 \text{ m s}^{-1}$ The maximum constant speed at which the vehicle can be driven around the bend is 12.4 m s^{-1}.

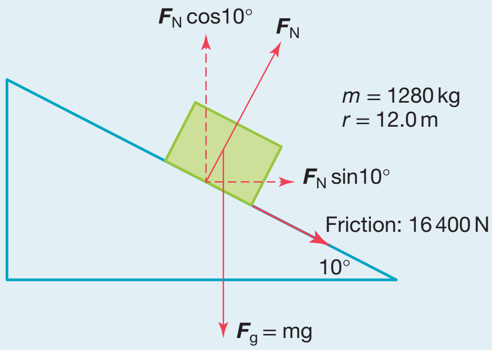
PRACTICE PROBLEM 12

A motorcyclist is travelling around a circular track at a constant speed of 30 m s^{-1}. The surface is flat and horizontal. The radius of the track is 100 m. The mass of the cyclist with her motorbike is 200 kg. What is the net force experienced by the rider and her bike?

tlvd-8952

SAMPLE PROBLEM 13 Calculating the maximum constant speed of a car on a banked road

Calculate the maximum speed of the car in sample problem 12 (without skidding off the road) if the road is banked at an angle of 10° to the horizontal.

THINK	WRITE
1. Draw a diagram to represent the known information.	

2. The vertical forces are balanced.

$$F_N \cos 10° = 16\,400 \sin 10° + 1280 \times 9.8$$
$$F_N = \frac{15\,392}{\cos 10°}$$
$$= 15\,629 \text{ N}$$

3. The net force is equal to the sum of the horizontal forces.

$$F_{net} = \frac{mv^2}{r}$$
$$F_N \sin 10° + 16\,400 \cos 10° = \frac{1280 \times v^2}{12}$$
$$15\,629 \sin 10° + 16\,400 \cos 10° = \frac{1280 \times v^2}{12}$$
$$\Rightarrow v = 13.3 \text{ m s}^{-1}$$

PRACTICE PROBLEM 13

A cyclist is training at her local velodrome. The velodrome has a radius of 25 m and she is travelling at 8.0 m s^{-1}. The total mass of the cyclist and her bike is 80 kg. The velodrome track is banked at an angle that results in there being no sideways frictional force on the bike's wheels by the track. Calculate the angle at which the track is banked for there to be no sideways frictional force.

1.5.6 Inside circular motion

What happens to people and objects inside larger objects that are travelling in circles? The answer to this question depends on several factors.

Consider passengers inside a bus. The sideways frictional forces by the road on the bus tyres act towards the centre of the circle, which increases the net force on the bus and keeps the bus moving around the circle. If the passengers are also to move in a circle with the bus (therefore keeping the same position in the bus) they must also have a net force towards the centre of the circle. Without such a force, they would continue to move in a straight line and probably hit the side of the bus! Usually the friction between the seat and a passenger's body is sufficient to prevent this happening.

However, if the bus is moving quickly, friction alone may not be adequate. In such cases, passengers may grab hold of the seat in front, thus adding a force through their arms. Hopefully, the sum of the frictional force of the seat on a passenger's legs and the horizontal component of force through the passenger's arms will provide a large enough force to keep that person moving in the same circle as the bus!

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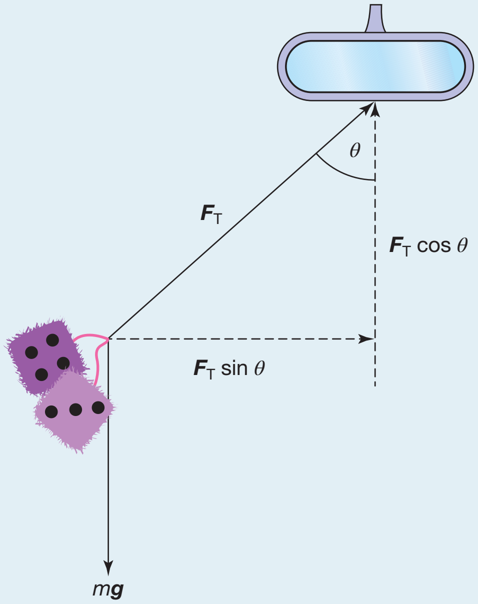
SAMPLE PROBLEM 14 Calculating the angle of an object inside circular motion

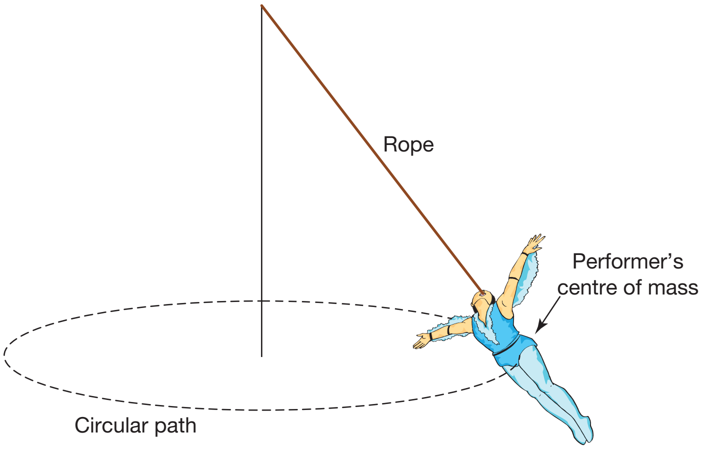
When travelling around a roundabout, John notices that the fluffy dice suspended from his rear-vision mirror swing out. If John is travelling at 8.0 m s^{-1} and the roundabout has a radius of 5.0 m, what angle will the string connected to the fluffy dice (mass 100 g) make with the vertical?

THINK	WRITE
1. When John enters the roundabout, the dice, which are hanging straight down, will begin to move outwards. As long as John maintains a constant speed, they will reach a point at which they become stationary at some angle to the vertical. At this point, the net force on the dice is the centripetal force. Because the dice appear stationary to John, they must be moving in the same circle, with the same speed, as John and his car.	$v = 8.0$ m s^{-1}, $r = 5.0$ m, $m = 0.100$ kg 
2. Consider the vertical components of the forces. The acceleration has no vertical component.	$m\boldsymbol{g} = \boldsymbol{F}_\text{T} \cos\theta$ $\Rightarrow \boldsymbol{F}_\text{T} = \dfrac{m\boldsymbol{g}}{\cos\theta} \ldots (1)$
3. Consider the horizontal components of the forces.	$\boldsymbol{F}_\text{net} = \dfrac{m\boldsymbol{v}^2}{r} = \boldsymbol{F}_\text{T} \sin\theta$ $\Rightarrow \dfrac{m\boldsymbol{v}^2}{r} = \boldsymbol{F}_\text{T} \sin\theta \ldots (2)$
4. To solve the simultaneous equations, substitute for T (from equation (1) into equation (2)).	$\dfrac{m\boldsymbol{v}^2}{r} = \dfrac{m\boldsymbol{g}}{\cos\theta} \times \sin\theta$ $= m\boldsymbol{g} \tan\theta$ $\Rightarrow \tan\theta = \dfrac{\boldsymbol{v}^2}{r\boldsymbol{g}}$ $= \dfrac{(8.0)^2}{5.0 \times 9.8}$ $\Rightarrow \theta = 53°$

PRACTICE PROBLEM 14

A 50 kg circus performer grips a vertical rope with her teeth and sets herself moving in a circle with a radius of 5.0 m at a constant horizontal speed of 3.0 m s^{-1}.

a. **What angle does the rope make with the vertical?**
b. **What is the magnitude of the tension in the rope?**



1.5 Activities

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1.5 Quick quiz on	1.5 Exercise	1.5 Exam questions

1.5 Exercise

1. A 65-kg jogger runs around a circular track of radius 120 m with an average speed of 6.0 km h^{-1}.
   a. What is the centripetal acceleration of the jogger?
   b. What is the net force acting on the jogger?
2. At a children's amusement park, the miniature train ride completes a circuit of radius 350 m, maintaining a constant speed of 15 km h^{-1}.
   a. What is the centripetal acceleration of the train?
   b. What is the net force acting on a 35-kg child riding on the train?
   c. What is the net force acting on the 1500-kg train?
   d. Explain why the net forces acting on the child and the train are different and yet the train and the child are moving along the same path.
3. Explain why motorcyclists lean into bends.
4. A rubber stopper of mass 50.0 g is whirled in a horizontal circle on the end of a 1.50-m length of string. The time taken for ten complete revolutions of the stopper is 8.00 s. The string makes an angle of 6.03 with the horizontal. Calculate the following:
   a. the speed of the stopper
   b. the centripetal acceleration of the stopper
   c. the net force acting on the stopper
   d. the magnitude of the tension in the string.

5. Carl is riding around a corner on his bike at a constant speed of 15 km h^{-1}. The corner approximates part of a circle of radius 4.5 m. The combined mass of Carl and his bike is 90 kg. Carl keeps the bike in a vertical plane.
   a. What is the net force acting on Carl and his bike?
   b. What is the sideways frictional force acting on the tyres of the bike?
   c. Carl rides onto a patch of oil on the road; the sideways frictional forces are now 90% of their original amount. If Carl maintains a constant speed, what will happen to the radius of the circular path he is taking?
6. A road is to be banked so that any vehicle can take the bend at a speed of 30 m s^{-1} without having to rely on sideways friction. The radius of curvature of the road is 12 m. At what angle should it be banked?

1.5 Exam questions

Question 1 (5 marks)

Source: *VCE 2022 Physics Exam, Section B, Q.8*; © VCAA

A Formula 1 racing car is travelling at a constant speed of 144 km h^{-1} (40 m s^{-1}) around a horizontal corner of radius 80.0 m. The combined mass of the driver and the car is 800 kg. Figure 8a shows a front view and Figure 8b shows a top view.

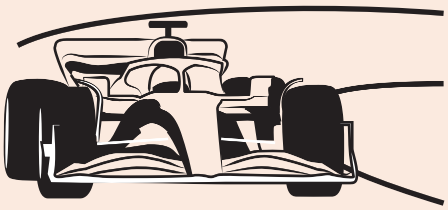


Figure 8a – Front view

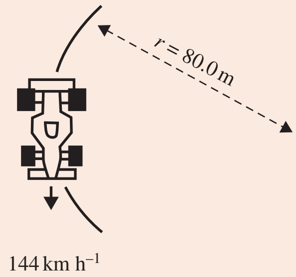


Figure 8b – Top view

a. Calculate the magnitude of the net force acting on the racing car and driver as they go around the corner. **(2 marks)**
b. On Figure 8b, draw the direction of the net force acting on the racing car using an arrow. **(1 mark)**
c. Explain why the racing car needs a net horizontal force to travel around the corner and state what exerts this horizontal force. **(2 marks)**

Question 2 (4 marks)

Source: *VCE 2018 Physics Exam, Section B, Q.10*; © VCAA

Members of the public can now pay to take zero gravity flights in specially modified jet aeroplanes that fly at an altitude of 8000 m above Earth's surface. A typical trajectory is shown in Figure 12. At the top of the flight, the trajectory can be modelled as an arc of a circle.

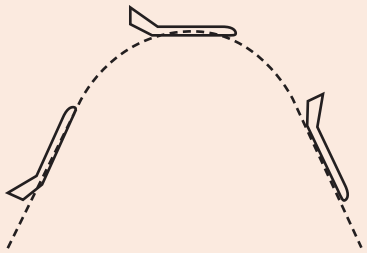


Figure 12

a. Calculate the radius of the arc that would give passengers zero gravity at the top of the flight if the jet is travelling at 180 m s^{-1}. Show your working. **(2 marks)**
b. Is the force of gravity on a passenger zero at the top of the flight? Explain what 'zero gravity experience' means. **(2 marks)**

Question 3 (7 marks)

Source: *VCE 2022 Physics Exam, NHT, Section B, Q.7*; © VCAA

A spherical mass of 2.0 kg is attached to a piece of string with a length of 2.0 m. The spherical mass is pulled back until it makes an angle of 60° with the vertical, as shown in Figure 4. The spherical mass is then released. Ignore the mass of the string.

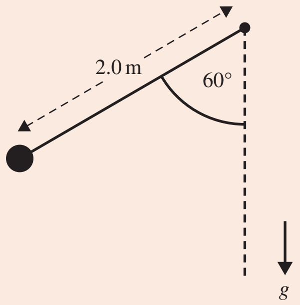


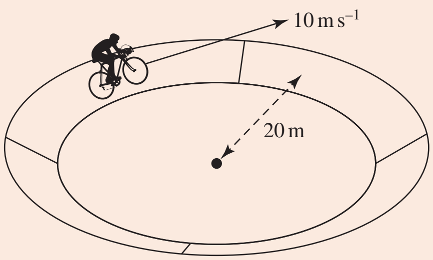
Figure 4

a. Show that the maximum speed of the spherical mass is 4.4 m s^{-1}. **(2 marks)**
b. At what part of its path is the spherical mass at its maximum speed? Explain your reasoning. **(2 marks)**
c. Calculate the maximum tension in the string. **(3 marks)**

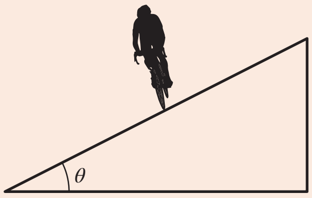
Question 4 (4 marks)

Source: *VCE 2017, Physics Exam, Section B, Q.7;* © VCAA

A bicycle and its rider have a total mass of 100 kg and travel around a circular banked track at a radius of 20 m and at a constant speed of 10 m s^{-1}, as shown in the figure. The track is banked so that there is no sideways friction force applied by the track on the wheels.



a. On the diagram below, draw all of the forces on the rider and the bicycle, considered as a single object, as arrows. Draw the net resultant force as a dashed arrow labelled F_{net}. **(2 marks)**

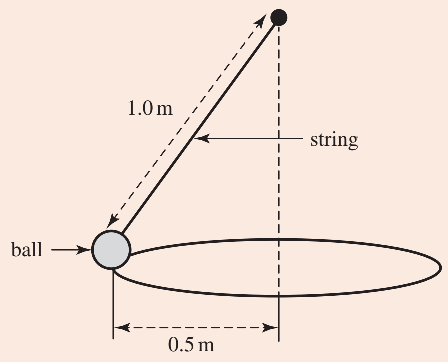


b. Calculate the correct angle of bank for there to be no sideways friction force applied by the track on the wheels. Show your working. **(2 marks)**

Question 5 (5 marks)

Source: *Adapted from VCE 2016, Physics Exam, Section A, Q.2*; © VCAA

A steel ball of mass 2.0 kg is swinging in a circle of radius 0.50 m at a constant speed of 1.7 m s^{-1} at the end of a string of length 1.0 m, as shown in the figure.



a. On the figure, draw all the forces **on the ball**. Label all forces. Draw the resultant force as a dotted line labelled $\boldsymbol{F}_{\mathrm{R}}$. **(2 marks)**

b. Calculate the tension in the string. Show your working. **(3 marks)**

More exam questions are available in your learnON title.

1.6 Non-uniform circular motion

KEY KNOWLEDGE

- Investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only).

So far, we have considered only what happens when circular motion is carried out at a constant speed. However, in many situations the speed is not constant. When the circle is vertical, the effects of gravity can cause the object to go slower at the top of the circle than at the bottom. Such situations can be examined either by analysing the energy transformations that take place or by applying Newton's laws of motion.

1.6.1 Energy review

Energy can be classified into different types, including kinetic energy and gravitational potential energy. These concepts will help in the investigation of non-circular motion and will be explored further in topic 2.

Kinetic energy is the energy associated with the movement of an object. Gravitational potential energy is the energy an object has based on its position within a gravitational field that can cause work to be done on it.

The Law of Conservation of Energy states that energy cannot be created or destroyed, only converted from one form to another. When motion is in a vertical circle you will need to consider that energy is converted from gravitational potential energy to kinetic energy.

$$E_g = mg\Delta h$$

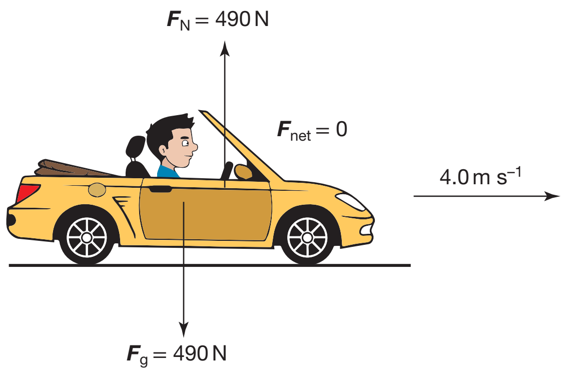
$$E_k = \frac{1}{2}mv^2$$

where: E_g is the gravitational potential energy
E_k is the kinetic energy
m is the mass
$\boldsymbol{g}$ is the acceleration due to gravity
Δh is the change in height, or the height above a reference point
$\boldsymbol{v}$ is the velocity

1.6.2 Uniform horizontal motion

If a person is sitting in a car moving in a straight line at a constant speed, the force due to gravity on them by the Earth balances the normal force from the seat.

FIGURE 1.37 The forces acting on an object in uniform horizontal motion

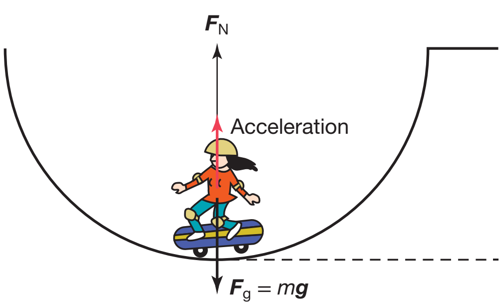


1.6.3 Travelling through dips

When a skateboarder enters a half-pipe from the top, that person has a certain amount of gravitational potential energy, but a velocity, and hence kinetic energy, close to zero. At the bottom of the half-pipe, most of the gravitational potential energy of the skateboarder has been transformed into kinetic energy. As long as the person's change in height is known, it is possible to calculate the speed at that point.

At the bottom of the half-pipe, the normal force acting on the skateboarder is greater than the force due to gravity, causing the skateboarder to feel 'heavier' than usual. The net force acting on the skateboarder is given by $\boldsymbol{F}_{net} = m\boldsymbol{a} = \boldsymbol{F}_N + \boldsymbol{F}_g = \boldsymbol{F}_N - m\boldsymbol{g}$ (taking the upward direction as positive). In this case, the normal force is greater than the force due to gravity. The net force, and hence the acceleration, is directed upwards towards the centre of the circle.

FIGURE 1.38 Forces acting on the skateboarder at the bottom of a dip. The normal force is greater than the force due to gravity; the skateboarder feels 'heavier'.



For circular motion, the acceleration is centripetal and is given by the expression $\frac{v^2}{r}$:

$$\frac{mv^2}{r} = F_N - mg$$

tlvd-8954

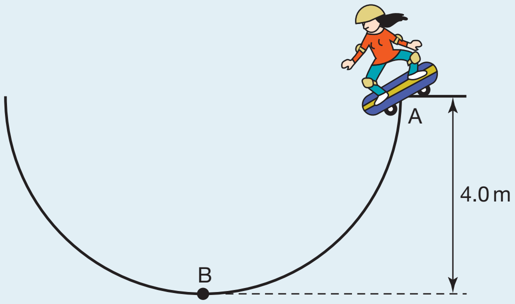
SAMPLE PROBLEM 15 Calculating the speed and forces acting on an object travelling through a dip

A skateboarder, with an initial velocity of 0 m s^{-1} and a mass of 60 kg, enters the half-pipe at point A, as shown in the figure. Assume the frictional forces are negligible.

a. **What is the skateboarder's speed at point B?**

b. **What is the net force on the skateboarder at B?**

c. **What is the normal force on the skateboarder at B? Explain whether the skateboarder feel lighter or heavier than usual.**



THINK

a. 1. At point A, the skateboarder has potential energy but no kinetic energy. At point B, all the potential energy has been converted to kinetic energy. Once the kinetic energy is known, it is easy to calculate the velocity of the skateboarder.

WRITE

a. $m = 60$ kg, $h_A = 4.0$ m, $h_B = 0.0$ m, $g = 9.8$ m s^{-2}

2. Find the change in energy. The decrease of potential energy from A to B is equal to the increase of kinetic energy from A to B.

$$\Delta GPE = \Delta KE$$

$$-mg\,(h_B - h_A) = \frac{1}{2}mv^2$$

Cancelling m from both sides:

$$-g\,(h_B - h_A) = \frac{1}{2}v^2$$

$$-9.8\,(0 - 4.0) = \frac{1}{2}v^2$$

$$\Rightarrow v^2 = 78.4$$

$$\Rightarrow v = 8.9 \text{ m s}^{-1}$$

The skateboarder's speed at B is 8.9 m s^{-1}.

b. The formula $F_{net} = \frac{mv^2}{r}$ can still be used for any point of the centripetal motion. It must be remembered, however, that the force will be different at each point as the velocity is constantly changing.

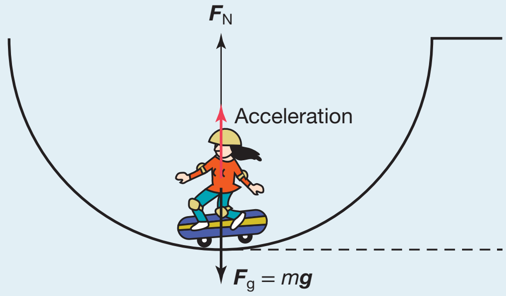
b. $m = 60$ kg, $r = 4.0$ m, $v = 8.9$ m s^{-1}

$$F_{net} = \frac{mv^2}{r} = \frac{60 \times (8.9)^2}{4.0} \approx 1.2 \times 10^3 \text{ N}$$

The net force acting on the skateboarder at point B is 1200 N upwards.

c. 1. As there is more than one force acting on the skateboarder, it helps to draw a diagram.

c.



2. The net force is determined by adding together all the forces acting on the skateboarder.

$\boldsymbol{F}_{net} = \boldsymbol{F}_N + \boldsymbol{F}_g$

3. Taking the upward direction as positive.

$F_{net} = F_N - mg$
$\Rightarrow F_N = F_{net} + mg$
$= 1.2 \times 10^3 + 60 \times 9.8$
$\approx 1.8 \times 10^3$ N

The normal force acting on the skateboarder at point B is 1.8×10^3 N upwards. This is larger than the normal force if the skateboarder was stationary. This causes the skateboarder to experience a sensation of heaviness.

PRACTICE PROBLEM 15

A roller-coaster car travels through the bottom of a dip of radius 9.0 m at a speed of 13 m s^{-1}.

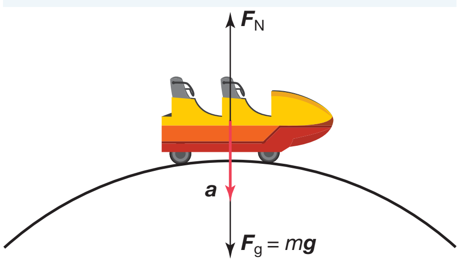
a. **What is the net force on a passenger of mass 60 kg?**
b. **What is the normal force on the passenger by the seat?**
c. **Compare the size of the normal force to the force due to gravity and comment on how the passenger would feel.**

1.6.4 Travelling over humps

The experience of 'heaviness' described in the previous section, when the normal force is greater than the force due to gravity, occurs on a roller-coaster when the roller-coaster car travels through a dip at the bottom of a vertical arc. When the car is at the top of a vertical arc, the passengers experience a feeling of being 'lighter'. How can this be explained?

When the roller-coaster car is on the top of the track, the normal force is upwards, and the force due to gravity and the net force are downwards. Taking the upward direction as positive, $\boldsymbol{F}_{net} = m\boldsymbol{a} = \frac{mv^2}{r} = \boldsymbol{F}_g - \boldsymbol{F}_N$. This clearly shows that $\boldsymbol{F}_g$ is larger than $\boldsymbol{F}_N$, and hence the passenger will feel 'lighter'.

FIGURE 1.39 The forces acting on a roller-coaster car at the top of a hump



For circular motion, the acceleration is centripetal and is given by the expression $\frac{v^2}{r}$.

$$ma = mg - F_N = \frac{mv^2}{r}$$

tlvd-8955

SAMPLE PROBLEM 16 Calculating the speed and forces acting on an object travelling over a hump

A passenger is in a roller-coaster car at the top of a circular arc of radius 9.0 m.

a. At what speed would the normal force on the passenger equal half the force due to gravity?

b. What happens to the normal force as the speed increases?

c. What would the passenger experience?

THINK	WRITE
a. 1. Write the known information.	a. $F_N = \frac{mg}{2}$, $r = 9.0$ m
2. Calculate the speed using $\frac{mv^2}{r} = mg - F_N$.	$\frac{mv^2}{r} = mg - \frac{mg}{2}$ $\frac{v^2}{r} = \frac{g}{2}$ $\Rightarrow v = \sqrt{\frac{gr}{2}}$ $= \sqrt{\frac{9.8 \times 9.0}{2}}$ $= 6.6 \text{ m s}^{-1}$
b. 1. Rearrange $\frac{mv^2}{r} = mg - F_N$ to make F_N the subject of the equation.	b. Rearranging $\frac{mv^2}{r} = mg - F_N$ gives $F_N = mg - \frac{mv^2}{r}$
2. Comment on the effect of increasing v on F_N.	The force due to gravity, mg, is constant, so as the speed, v, increases, the normal force, F_N, gets smaller.
c. The normal force determines whether the passenger feels 'heavier' or 'lighter'.	c. The normal force is less than the force due to gravity, so the passenger will feel lighter.

PRACTICE PROBLEM 16

a. A car of mass 800 kg slows down to a speed of 4.0 m s^{-1} to travel over a speed hump that forms the arc of a circle of radius 2.4 m. What normal force acts on the car at the top of the speed hump?

b. At what minimum speed would a car of mass 1000 kg have to travel to momentarily leave the road at the top of the speed hump described in part (a)? (To leave the road, the normal force would have to decrease to zero.)

The normal force is a push by the track on the wheels of the roller-coaster car. The track can only push up on the wheels; it cannot pull down on the wheels to provide a downward force. So as the speed increases, there is a limit on how small the normal force can be. The smallest value is zero. What would the passenger feel? And what is happening to the roller-coaster car?

When the normal force is zero, the passenger will feel as if they are floating just above the seat. They will feel no compression in the bones of their backside. At this point the car has lost contact with the track. Any attempt to put on the brakes will not slow down the car, as the frictional contact with the track depends on the size of the normal force. No normal force means no friction.

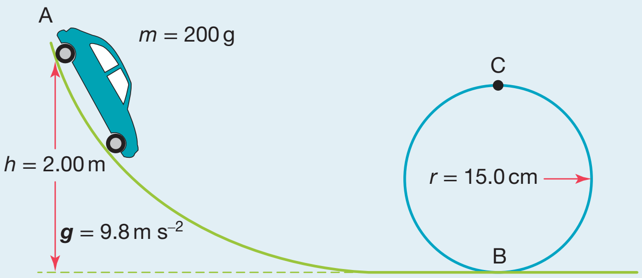
Modern roller-coaster cars have two sets of wheels, one set above the track and one set below the track, so that if the car is moving too fast, the track can supply a downward normal force on the lower set of wheels.

The safety features of roller-coasters cannot be applied to cars on the road. If a car goes too fast over a hump on the road, the situation is potentially very dangerous. Loss of contact with the road means that turning the steering wheel to avoid an obstacle or an oncoming car will have no effect whatsoever. The car will continue on in the same direction.

tlvd-8956

SAMPLE PROBLEM 17 Determining the speed and forces acting on a toy car inside a loop

A toy car travels through a vertical loop of radius 15.0 cm on a racetrack. The toy car, of mass 200 g, is released from rest at point A, which is 2.00 m above the lowest point on the track. The car rolls down the track and travels inside the loop. Friction can be ignored.



a. **Calculate the speed of the car at point B, the bottom of the loop.**
b. **What is the net force on the toy car at point B?**
c. **What is the normal force on the car at point B?**
d. **What is the speed of the car when it reaches point C?**
e. **What is the normal force on the car at point C?**

THINK	WRITE
a. 1. List all known information at points A and B.	**a.** At point A, $m = 0.200$ kg, $h = 2.00$ m, $\boldsymbol{v} = 0$ m s^{-1}, $\boldsymbol{g} = 9.8$ m s^{-2} At point B, $m = 0.2$ kg, $h = 0.00$ m, $\boldsymbol{g} = 9.8$ m s^{-2}
2. Calculate the total energy of the car at point A by adding the car's gravitational potential energy and kinetic energy.	$E_A = E_k + E_g$ $= \frac{1}{2}mv^2 + mg\Delta h$ $= 0 + (0.200 \times 9.8 \times 2.00)$ $= 3.92$ J

3. The total energy of the car at point B is equal to the total energy of the car at point A. This is the Law of Conservation of Energy.

$$\begin{aligned}
E_B &= E_k + E_g \\
&= \frac{1}{2}m\boldsymbol{v}^2 + m\boldsymbol{g}\Delta h \\
3.92 &= \left(\frac{1}{2} \times 0.200 \times \boldsymbol{v}^2\right) + 0 \\
3.92 &= 0.100\boldsymbol{v}^2 \\
\boldsymbol{v}^2 &= \frac{3.92}{0.100} \\
\Rightarrow \boldsymbol{v} &= \sqrt{39.2} \\
&= 6.26 \text{ m s}^{-1}
\end{aligned}$$

b. During circular motion, the net force is always directed towards the centre of the circle. So, at point B, the net force will be directed upwards.

b. $$\begin{aligned}
\boldsymbol{F}_{net} &= \frac{m\boldsymbol{v}^2}{r} \\
&= \frac{0.200 \times 6.26^2}{0.15} \\
&= 78.4 \text{ N up}
\end{aligned}$$

c. The net force is equal to the sum of the normal force and the force due to gravity. Take the upward direction to be positive.

c. $$\begin{aligned}
\boldsymbol{F}_{net} &= \boldsymbol{F}_N + \boldsymbol{F}_g \\
\boldsymbol{F}_{net} &= \boldsymbol{F}_N - m\boldsymbol{g} \\
78.4 &= \boldsymbol{F}_N - (0.200 \times 9.8) \\
78.4 &= \boldsymbol{F}_N - 1.96 \\
\boldsymbol{F}_N &= 78.4 + 1.96 \\
&= 80.4 \text{ N up}
\end{aligned}$$

d. 1. List all known information at point C.

d. $m = 0.200$ kg, $h = 0.300$ m, $\boldsymbol{g} = 9.8$ m s^{-2}

2. From part (a), it is known that the total energy of the car at all points is 3.92 J.

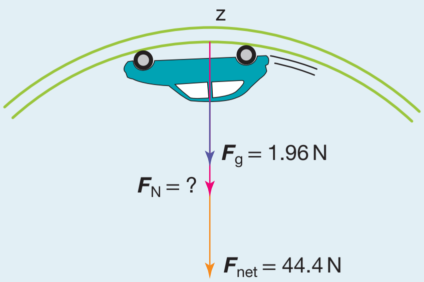
At point C,

$$\begin{aligned}
E_C &= E_k + E_g \\
&= \frac{1}{2}m\boldsymbol{v}^2 + m\boldsymbol{g}\Delta h \\
3.92 &= \left(\frac{1}{2} \times 0.200 \times \boldsymbol{v}^2\right) \\
&\quad + (0.200 \times 9.8 \times 0.300) \\
3.92 &= 0.100\boldsymbol{v}^2 + 0.588 \\
0.100\boldsymbol{v}^2 &= 3.332 \\
\boldsymbol{v}^2 &= \frac{3.332}{0.100} \\
\Rightarrow \boldsymbol{v} &= \sqrt{33.32} \\
&= 5.77 \text{ m s}^{-1}
\end{aligned}$$

e. 1. Determine the net force acting on the car at point C. The net force on the car at point C will be directed downwards towards the centre of the circle.

e. $$\boldsymbol{F}_{\text{net}} = \frac{m\boldsymbol{v}^2}{r} = \frac{0.200 \times 5.77^2}{0.15} = 44.4 \text{ N down}$$

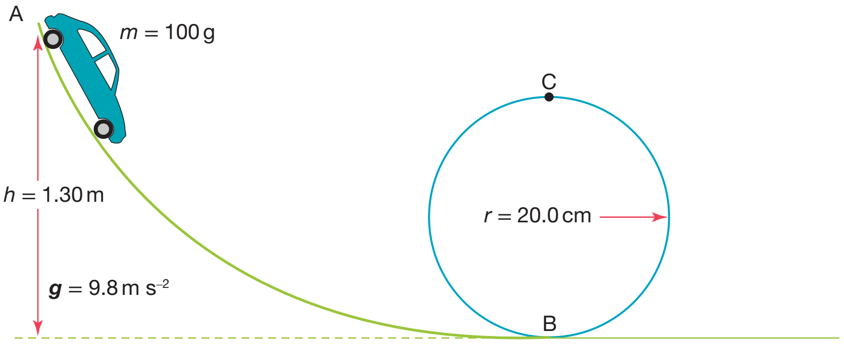
2. The net force is equal to the sum of the normal force and the force due to gravity. Take the downward direction to be positive. *Note:* In this case, both the normal force and the force due to gravity act in the downward direction.



$$\begin{aligned}
\boldsymbol{F}_{\text{net}} &= \boldsymbol{F}_{\text{N}} + \boldsymbol{F}_{\text{g}} \\
44.4 &= \boldsymbol{F}_{\text{N}} + (0.200 \times 9.8) \\
44.4 &= \boldsymbol{F}_{\text{N}} + 1.96 \\
\Rightarrow \boldsymbol{F}_{\text{N}} &= 44.4 - 1.96 \\
\boldsymbol{F} &= 42.7 \text{ N down}
\end{aligned}$$

PRACTICE PROBLEM 17

A toy car travels through a vertical loop of radius 20.0 cm on a racetrack. The toy car, of mass 100 g, is released from rest at point A, which is 1.30 m above the lowest point on the track. The car rolls down the track and travels inside the loop. Friction can be ignored.



a. **Calculate the speed of the car at point B, the bottom of the loop.**
b. **What is the net force on the toy car at point B?**
c. **What is the normal force on the car at point B?**
d. **What is the speed of the car when it reaches point C?**
e. **What is the normal force on the car at point C?**

1.6 Activities

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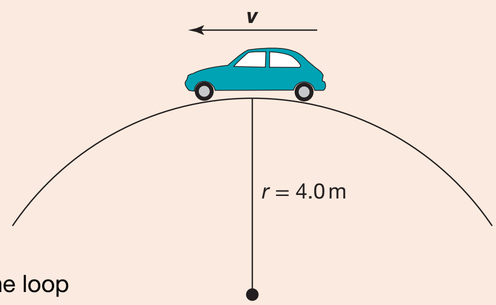
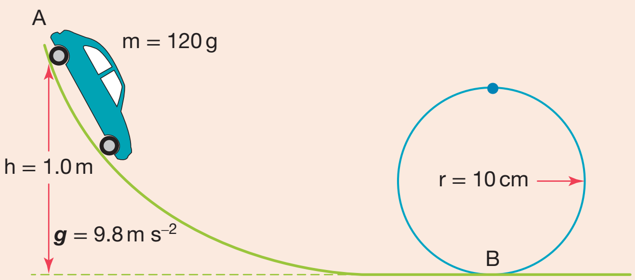
1.6 Quick quiz on	1.6 Exercise	1.6 Exam questions

1.6 Exercise

1. A ball is swung in a vertical circle with a constant speed. At which point is the tension force:
   a. at its maximum value
   b. at its minimum value?
2. An 800-kg car travels over the crest of a hill that forms the arc of a circle, as shown in the figure.



   a. Draw a labelled diagram showing all the forces acting on the car.
   b. The car travels just fast enough for it to leave the ground momentarily at the crest of the hill. This means the normal force is zero at this point.
      i. What is the net force acting on the car at this point?
      ii. What is the speed of the car at this point?
3. A 120-g toy car travels through a vertical loop on a racetrack. The loop has a radius of 10 cm.
   The car is released from the start of the track, which is at a height of 1.0 m (position A), and travels inside the loop. Assume $\boldsymbol{g}$ is 9.8 m s^{-2} downwards and ignore friction.



   a. Calculate the speed of the car at point B, the bottom of the loop.
   b. What is the net force on the toy car at point B?
   c. What is the normal force on the car at point B?
4. A 60-kg passenger is in a roller-coaster and travels down a small dip with a radius of 12 m. At the bottom of the dip, the passenger is travelling with a speed of 14 m s^{-1} and is feeling a larger than normal force. Use Newton's Second Law to calculate the normal force acting upon their body.
5. A 75-kg BMX rider is riding in a half-pipe with a radius of 2.5 m. At the lowest point of the half-pipe, the rider attains a speed of 7.0 m s^{-1}. Assume there is no air resistance or friction.
   a. What is the acceleration of the rider at the lowest point of the half-pipe?
   b. Determine the magnitude of the normal force acting on the rider at the lowest point of the half-pipe.

1.6 Exam questions

Question 1 (5 marks)

Source: *VCE 2022 Physics Exam, NHT, Section B, Q.9*; © VCAA

A small ball of mass 0.30 kg travels horizontally at a speed of 6 m s^{-1}. It enters a vertical circular loop of diameter 0.80 m, as shown in Figure 6. Assume that the radius of the ball and that the frictional forces are negligible.

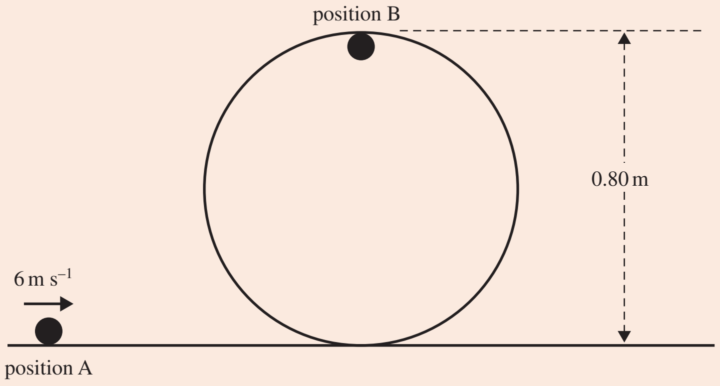


Figure 6

a. Show that the kinetic energy of the ball at position A in Figure 6 is 5.4 J. **(1 mark)**

b. Will the ball remain on the track at the top of the loop (position B in Figure 6)? Give your reasoning. **(4 marks)**

Question 2 (5 marks)

Source: *VCE 2018 Physics Exam, NHT, Section B, Q.8*; © VCAA

In an experiment, a ball of mass 2.5 kg is moving in a vertical circle at the end of a string, as shown in Figure 5. The string has a length of 1.5 m.

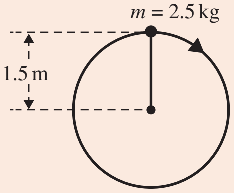


Figure 5

a. Calculate the minimum speed the ball must have at the top of its arc for the string to remain tight (under tension). **(2 marks)**

b. In another experiment, the ball is moving at 6.0 m s^{-1} at the top of its arc. Calculate the speed of the ball at the lowest point. **(3 marks)**

Question 3 (7 marks)

Source: *VCE 2017 Physics Exam, NHT, Section B, Q.3*; © VCAA

An amusement park has a car ride consisting of vertical partial circular tracks, as shown in Figure 4a. The track is arranged so that the car remains upright at both the top and bottom positions. The track has a radius of 12.0 m and its lowest point is point P.

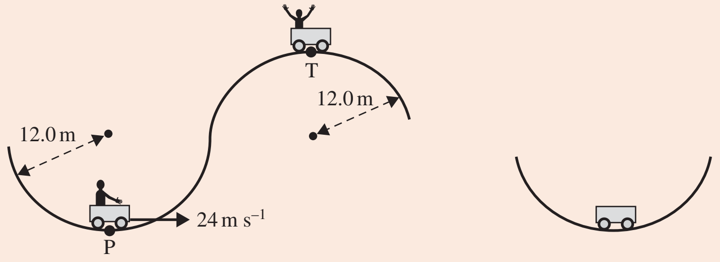


Figure 4a **Figure 4b**

a. On the diagram in Figure 4b, draw labelled arrows showing all of the forces on the car at point P and draw the resultant force with a dotted arrow labelled F_R. **(3 marks)**

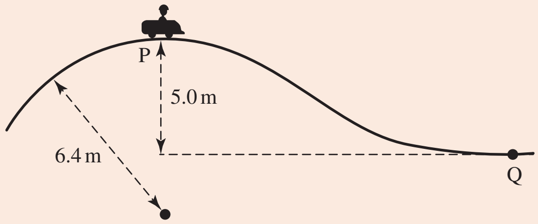
b. At point P, the car is moving at 24 m s^{-1}.
Calculate the force of the car seat on a passenger of mass 50 kg as the car passes point P. Show your working. **(2 marks)**

c. Emily says that if the car moves at the correct speed at the top, point T, a person can feel weightless at that point.
Roger says this is nonsense; a person can only feel weightless in deep space, where there is no gravity.
Who is correct? Justify your answer. **(2 marks)**

Question 4 (2 marks)

Source: *VCE 2017, Physics Exam, Q.8.a;* © VCAA

A roller-coaster is arranged so that the normal reaction force on a rider in a car at the top of the circular arc at point P, shown in the figure, is briefly zero. The section of track at point P has a radius of 6.4 m.



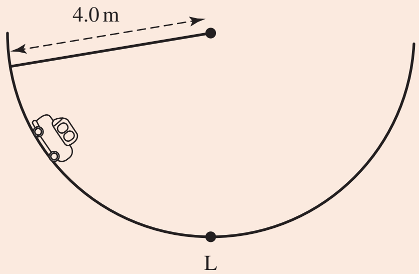
Calculate the speed that the car needs to have to achieve a zero normal reaction force on the rider at point P.

Question 5 (2 marks)

Source: *VCE 2015, Physics Exam, Q.3.b;* © VCAA

A model car of mass 2.0 kg is on a track that is part of a vertical circle of radius 4.0 m, as shown in the figure.

At the lowest point, L, the car is moving at 6.0 m s^{-1}. Ignore friction.



Calculate the magnitude of the force exerted by the track on the car at its lowest point (L). Show your working.

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1.7 Review

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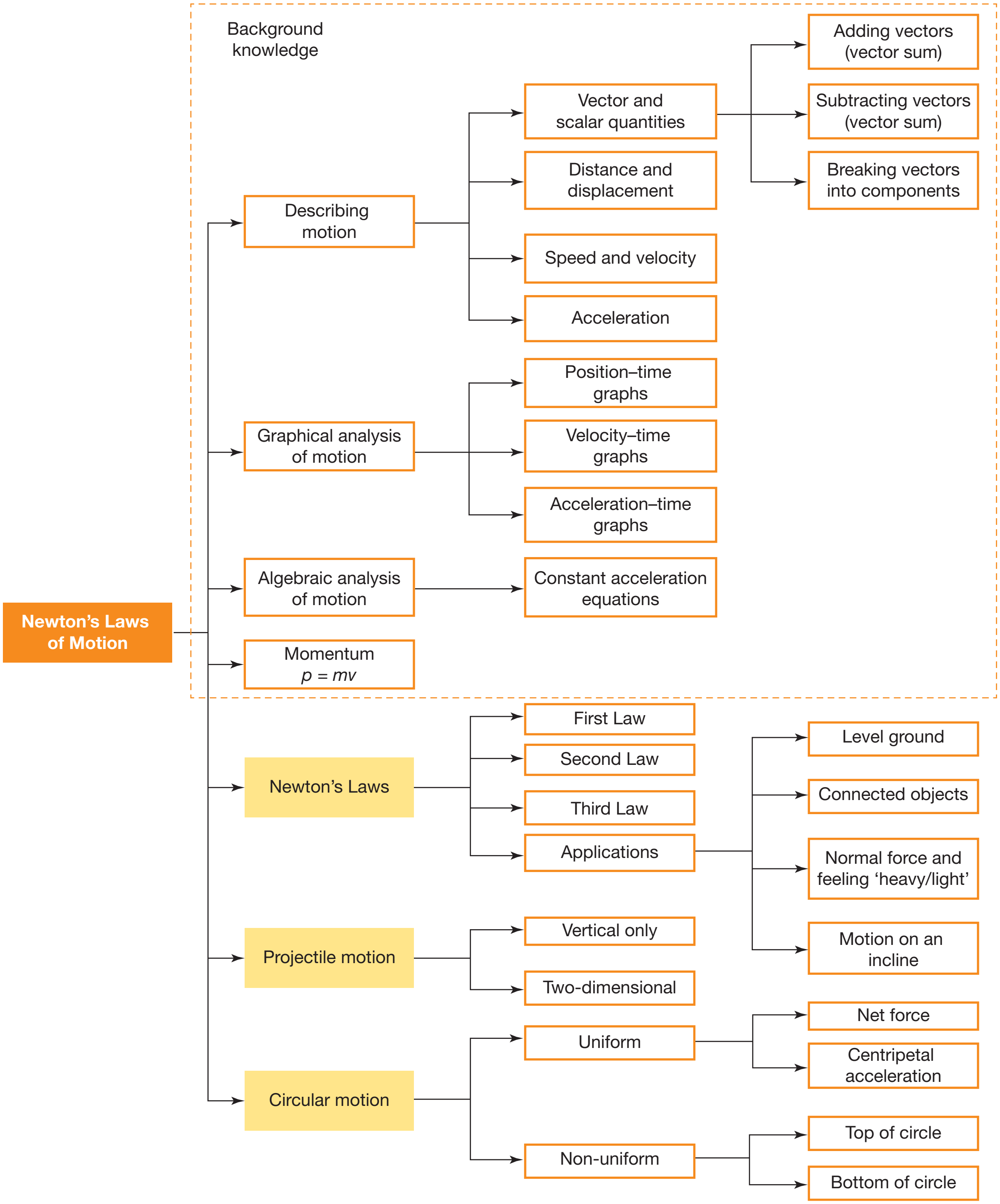

1.7.2 Key ideas summary

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1.7.3 Key terms glossary

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on Resources

Solutions	Solutions — Topic 1 (sol-0815)
Practical investigation eLogbook	Practical investigation eLogbook — Topic 1 (elog-1632)
Digital documents	Key science skills — VCE Physics Units 1–4 (doc-36950) Key terms glossary — Topic 1 (doc-37165) Key ideas summary — Topic 1 (doc-37166)
Exam question booklet	Exam question booklet — Topic 1 (eqb-0098)

1.7 Activities

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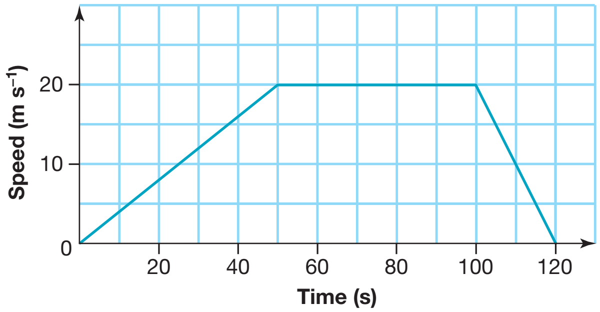
1.7 Review questions

1. When a stationary car is hit from behind by another vehicle at moderate speed, headrests behind the occupants reduce the likelihood of injury. Explain in terms of Newton's laws how they do this.
2. It is often said that seatbelts prevent a passenger from being thrown forward in a car collision. What is wrong with such a statement?
3. What is the matching 'reaction' to the gravitational pull of Earth on you?
4. Explain why the horizontal component of velocity remains the same when a projectile's motion is modelled.
5. While many pieces of information relating to the vertical and horizontal parts of a particular projectile's motion are different, the time is always the same. Explain why.
6. Describe the effects of air resistance on the motion of a basketball falling vertically from a height.
7. When a mass moves in a circle, it is subject to a net force. This force acts at right angles to the direction of motion of the mass at any point in time. Use Newton's laws to explain why the mass does not need a propelling force to act in the direction of its motion.
8. The following graph describes the motion of a 40 tonne (4.0×10^4 kg) train as it travels between two neighbouring railway stations. The total friction force resisting the motion of the train while the brakes are not applied is 8.0 kN. The brakes are not applied until the final 20 s of the journey.



a. What is the braking distance of the train?
b. A cyclist travels between the stations at a constant speed, leaving the first station and arriving at the second station at the same time as the train. What is the constant speed of the cyclist?
c. What forward force is applied to the train by the tracks while it is accelerating?
d. What additional frictional force is applied to the train while it is braking?

9. At a children's amusement park, the miniature train ride completes a circuit of radius 300 m, maintaining a constant speed of 12 km h^{-1}.

a. What is the centripetal acceleration of the train?
b. What is the net force acting on a 45-kg child riding on the train?
c. What is the net force acting on the 1250-kg train?
d. Explain why the net forces acting on the child and the train are different and yet the train and the child are moving along the same path.

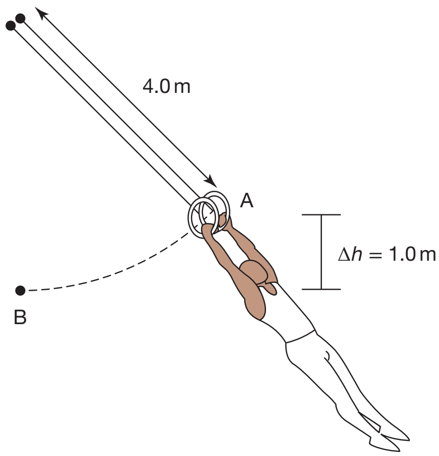
10. During a game of totem tennis, a 100-g ball is whirled in a horizontal circle on the end of a 1.30-m length of string. The time taken for ten complete revolutions of the ball is 12.0 s. The string makes an angle of 30.0° with the horizontal. Calculate:

a. the speed of the ball
b. the centripetal acceleration of the ball
c. the net force acting on the ball
d. the magnitude of the tension in the string

11. A road is to be banked so that any vehicle can take the bend at a speed of 40.0 m s^{-1} without having to rely on sideways friction. The radius of curvature of the road is 15.0 m. At what angle should it be banked?

12. A 65-kg gymnast, who is swinging on the rings, follows the path shown in the following figure.

a. What is the speed of the gymnast at point B, if he is at rest at point A?
b. What is the centripetal force acting on the gymnast at point B?
c. Draw a labelled diagram of the forces acting on the gymnast at point B. Include the magnitude of all forces.



1.7 Exam questions

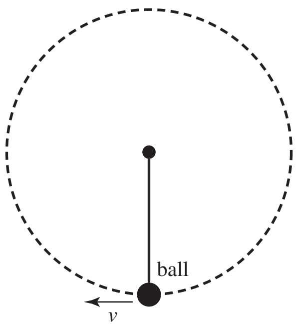
Section A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

Question 1

Source: *VCE 2020 Physics Exam, Section A, Q.8;* © VCAA

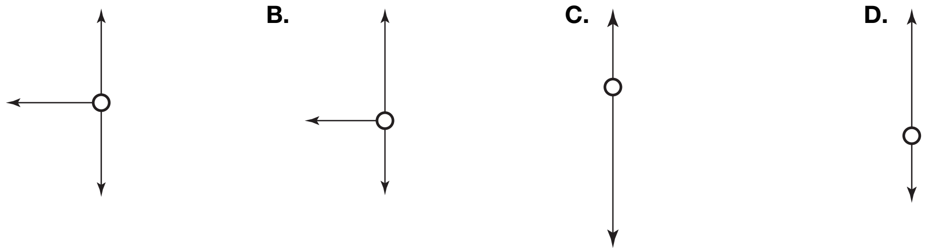
A ball is attached to the end of a string and rotated in a circle at a constant speed in a vertical plane, as shown in the diagram below.



The arrows in options A. to D. below indicate the direction and the size of the forces acting on the ball.

Ignoring air resistance, which one of the following best represents the forces acting on the ball when it is at the bottom of the circular path and moving to the left?

A. **B.** **C.** **D.**



Question 2

Source: *VCE 2019, Physics Exam, Section A, Q.11*; © VCAA

An ultralight aeroplane of mass 500 kg flies in a horizontal straight line at a constant speed of 100 m s^{-1}.

The horizontal resistance force acting on the aeroplane is 1500 N.

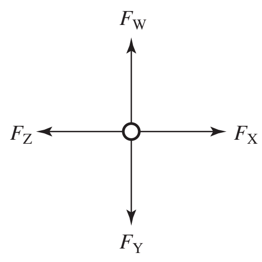
Which one of the following best describes the magnitude of the forward horizontal thrust on the aeroplane?

A. 1500 N
B. slightly less than 1500 N
C. slightly more than 1500 N
D. 5000 N

Question 3

Source: *VCE 2018, Physics Exam, Section A, Q.5;* © VCAA

Four students are pulling on ropes in a four-person tug of war. The relative sizes of the forces acting on the various ropes are $F_W = 200$ N, $F_X = 240$ N, $F_Y = 180$ N and $F_Z = 210$ N. The situation is shown in the diagram below.



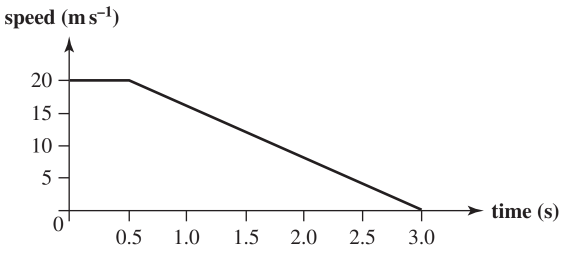
Which one of the following **best** gives the magnitude of the resultant force acting at the centre of the tug-of-war ropes?

A. 28.3 N
B. 30.0 N
C. 36.1 N
D. 50.0 N

Question 4

Source: *VCE 2018, Physics Exam, Section A, Q.6;* © VCAA

Lisa is driving a car of mass 1000 kg at 20 m s^{-1} when she sees a dog in the middle of the road ahead of her. She takes 0.50 s to react and then brakes to a stop with a constant braking force. Her speed is shown in the graph below. Lisa stops before she hits the dog.



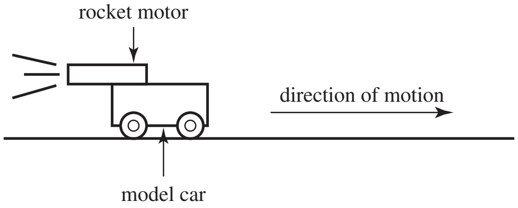
Which one of the following is closest to the magnitude of the braking force acting on Lisa's car during her braking time?

A. 6.7 N
B. 6.7 kN
C. 8.0 kN
D. 20.0 kN

Question 5

Source: *VCE 2017, Physics Exam, Section A, Q.7;* © VCAA

A model car of mass 2.0 kg is propelled from rest by a rocket motor that applies a constant horizontal force of 4.0 N, as shown below. Assume that friction is negligible.



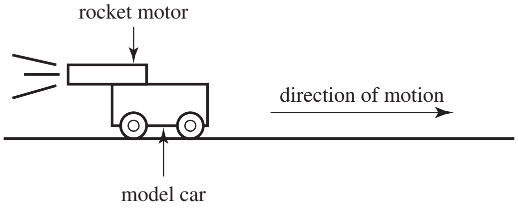
Which one of the following best gives the magnitude of the acceleration of the model car?

A. 0.50 m s^{-2}
B. 1.0 m s^{-2}
C. 2.0 m s^{-2}
D. 4.0 m s^{-2}

Question 6

Source: *VCE 2017, Physics Exam, Section A, Q.9*; © VCAA

A model car of mass 2.0 kg is propelled from rest by a rocket motor that applies a constant horizontal force of 4.0 N, as shown below. Assume that friction is negligible.



With the same rocket motor, the car accelerates from rest for 10 s.

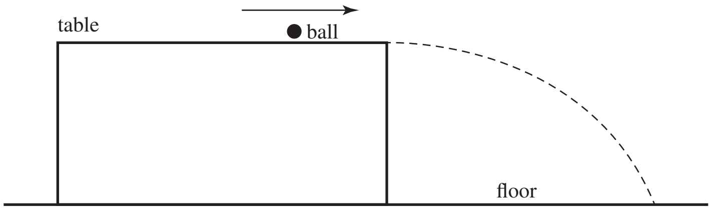
Which one of the following best gives the final speed?

A. 6.3 m s^{-1}
B. 10 m s^{-1}
C. 20 m s^{-1}
D. 40 m s^{-1}

Question 7

Source: *VCE 2019, Physics Exam, Section A, Q.12*; © VCAA

A small ball is rolling at constant speed along a horizontal table. It rolls off the edge of the table and follows the parabolic path shown in the diagram below. Ignore air resistance.



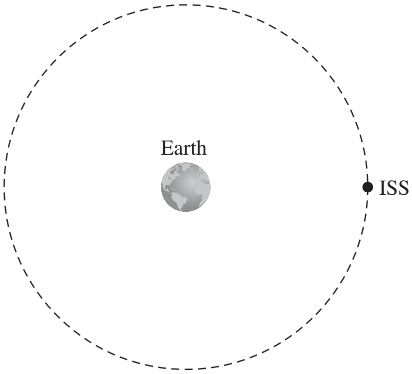
Which one of the following statements about the motion of the ball as it falls is correct?

A. The ball's speed increases at a constant rate.
B. The momentum of the ball is conserved.
C. The acceleration of the ball is constant.
D. The ball travels at constant speed.

Question 8

Source: *VCE 2020 Physics Exam, Section A, Q.11;* © VCAA

The International Space Station (ISS) is travelling around Earth in a stable circular orbit, as shown in the diagram below.



Which one of the following statements concerning the momentum and the kinetic energy of the ISS is correct?

A. Both the momentum and the kinetic energy vary along the orbital path.
B. Both the momentum and the kinetic energy are constant along the orbital path.
C. The momentum is constant, but the kinetic energy changes throughout the orbital path.
D. The momentum changes, but the kinetic energy remains constant throughout the orbital path.

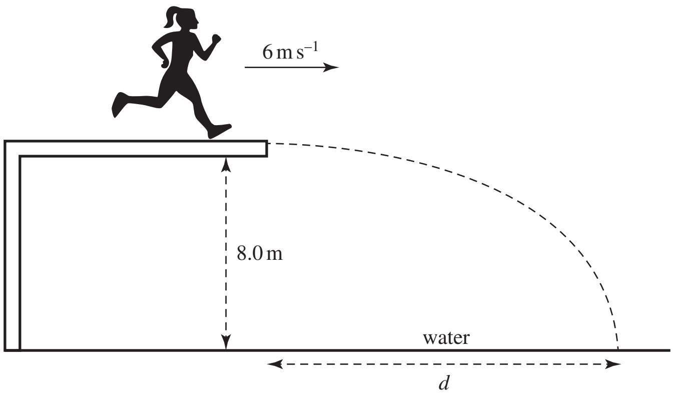
Question 9

Source: *VCE 2021 Physics Exam, Section A, Q.9;* © VCAA

Lucy is running horizontally at a speed of 6 m s^{-1}along a diving platform that is 8.0 m vertically above the water.

Lucy runs off the end of the diving platform and reaches the water below after time *t*.

She lands feet first at a horizontal distance *d* from the end of the diving platform.



Which one of the following expressions correctly gives the distance *d*?

A. 0.8*t*
B. 6*t*
C. $5t^2$
D. $6t + 5t^2$

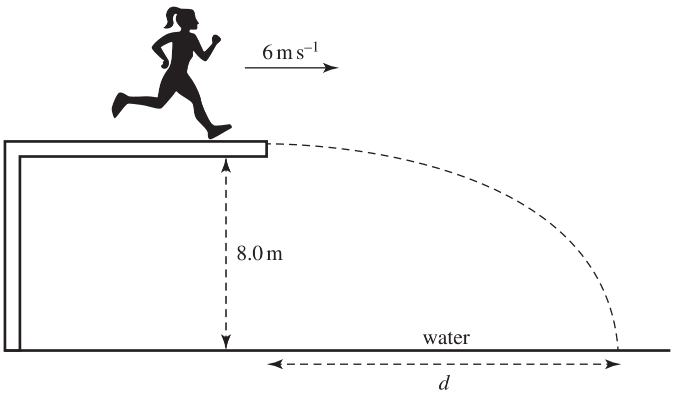
Question 10

Source: *VCE 2021, Physics Exam, Section A, Q.10;* © VCAA

Lucy is running horizontally at a speed of 6 m s^{-1}along a diving platform that is 8.0 m vertically above the water.

Lucy runs off the end of the diving platform and reaches the water below after time *t*.

She lands feet first at a horizontal distance *d* from the end of the diving platform.



Which one of the following is closest to the time taken, *t*, for Lucy to reach the water below?

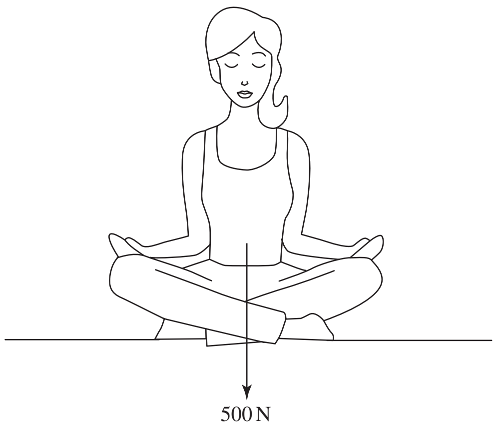
A. 0.8 *s*
B. 1.1 *s*
C. 1.3 *s*
D. 1.6 *s*

Section B – Short answer questions

Question 11 (2 marks)

Source: *VCE 2021, Physics Exam, Section B, Q.4;* © VCAA

Liesel, a student of yoga, sits on the floor in the lotus pose, as shown in the figure. The action force, F_g, on Liesel due to gravity is 500 N down.

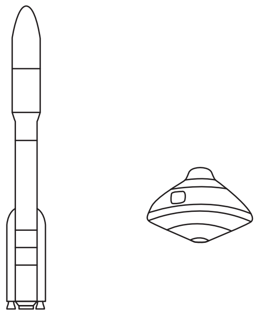


Identify and explain what the reaction force is to the action force, F_g, shown in the figure.

Question 12 (3 marks)

Source: *VCE 2021 Physics Exam, Section B, Q.8a;* © VCAA

On 30 July 2020, the National Aeronautics and Space Administration (NASA) launched an Atlas rocket containing the Perseverance rover space capsule on a scientific mission to explore the geology and climate of Mars, and search for signs of ancient microbial life.



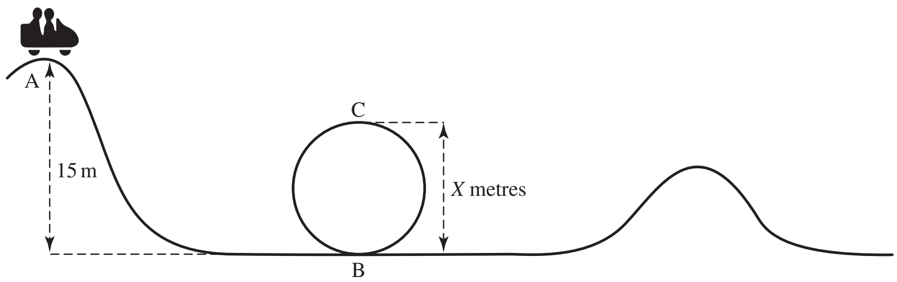
At lift-off from launch, the acceleration of the rocket was 7.20 m s^{-2}. The total mass of the rocket and capsule at launch was 531 tonnes.

Calculate the magnitude and the direction of the thrust force on the rocket at launch. Take the gravitational field strength at the launch site to be g = 9.80 N kg^{-1}. Give your answer in meganewtons. Show your working.

Question 13 (2 marks)

Source: *VCE 2021 Physics Exam, Section B, Q.9b;* © VCAA

Abbie and Brian are about to go on their first loop-the-loop roller-coaster ride. As competent Physics students, they are working out if they will have enough speed at the top of the loop to remain in contact with the track while they are upside down at point C, shown in the figure. The radius of the loop CB is *r*.



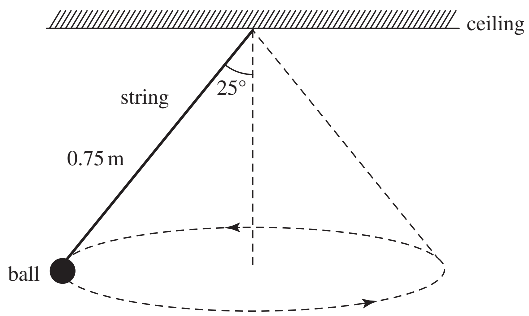
The highest point of the roller-coaster (point A) is 15 m above point B and the car starts at rest from point A. Assume that there is negligible friction between the car and the track.

By considering the forces acting on the car, show that the condition for the car to just remain in contact with the track at point C is given by $\frac{v^2}{r} = g$. Show your working.

Question 14 (6 marks)

Source: *VCE 2020 Physics Exam, Section B, Q.8;* © VCAA

The figure below shows a small ball of mass 1.8 kg travelling in a horizontal circular path at a constant speed while suspended from the ceiling by a 0.75-m long string.



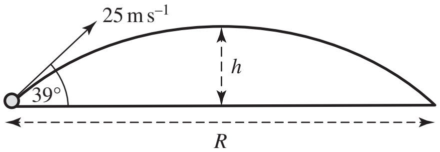
a. Use labelled arrows to indicate on the figure the two physical forces acting on the ball. **(2 marks)**

b. Calculate the speed of the ball. Show your working. **(4 marks)**

Question 15 (4 marks)

Source: *VCE 2019, Physics Exam, Section B, Q.10*; © VCAA

A projectile is launched from the ground at an angle of 39° and at a speed of 25 m s^{-1}, as shown in the figure. The maximum height that the projectile reaches above the ground is labelled *h*.



a. Ignoring air resistance, show that the projectile's time of flight from the launch to the highest point is equal to 1.6 s. Give your answer to two significant figures. Show your working and indicate your reasoning. **(2 marks)**

b. Calculate the range, *R*, of the projectile. Show your working. **(2 marks)**