

# NATIONAL 5 PHYSICS MECHANICS

# **VELOCITY & VECTORS**

## Vector and Scalar Quantities

Physical quantities can be divided into two groups:

- Scalar quantities are completely described by stating their magnitude.
- Vector quantities are completely described by stating their magnitude and direction.

For example — speed is a scalar (i.e. the man was walking at  $4 \text{ m s}^{-1}$ ), but force is a vector (i.e. the block was pushed with a force of 4 N to the right).

Vectors are represented in diagrams by drawing arrows. The length of the arrow gives the magnitude of the vector and the direction of the arrow gives the direction of the vector.

A force of 4 N to the right can be represented like this:

4N

A force of 8 N to the left can be represented like this:

8N

Quantities that are vectors can be represented by using a **bold** version of their usual symbol. For instance if the variable r is a vector it can be written as **r**. Using bold type is difficult to do when using handwriting however so it is common to add an arrow above the symbol like this —  $\vec{r}$ .

## Vector or Scalar?

The table below shows which quantities in National 5 physics are vectors and which are scalars.

Vectors	Scalars
Force	Speed
Velocity	Distance
Displacement	Mass
Acceleration	Time
	Energy

## **Distance and Displacement**

Distance is the total distance travelled. It is a scalar quantity.

Displacement is the length measured from the starting point of a journey to the finishing point in a straight line. Its direction must be stated because it is a vector quantity. The direction can be given as left or right, up or down, as one of the compass points, as an angle or as a three figure bearing.

Example: A man travels 4 km East to A, then 2 km South to B and then 4 km West as shown below.



The total distance travelled by the man is:

$$4 + 2 + 4 = 10 \text{ km}$$

The displacement of the man from the start is:

2 km South

#### Scale diagram

Displacement can be found by drawing a scale diagram of the problem. For instance If a ship sails 3 km north and then sails 4km east you could represent that motion like this...



Here a scale of 1 cm = 1 km was used.

The displacement is found by drawing on a new vector joining the start to the finish, like this:



To find the displacement you simply measure the length of the new vector using a ruler, and measure the angle using a protractor. In the diagram above you should find the length of the displacement vector to be 5 cm and the angle from North to be 53°. Therefore the displacement of the ship is 5 km on a bearing of 053°.

## Trigonometry

Another way to find displacement is to use the rules and laws you have learnt in maths; the pythagorean theorem and SOHCAHTOA. These do **not** appear on the formula sheet, so you must remember them by heart. If in doubt — use a **scale diagram**.

- 1. What is the difference between a vector and a scalar?
- 2. What is the difference between distance and displacement?
- 3. A car travels 40 km north, then turns back south for 10 km. The journey takes 1 hour. Calculate:
  - a) The displacement of the car
  - b) The distance the car has travelled
  - c) The average speed of the car (in km/h)
- 4. One complete lap of a running track is 400 m. An athlete completes one lap in 48 s in the 400 m race. Calculate the athlete's:
  - a) Total distance travelled
  - b) Displacement
  - c) Average speed
- 5. An aircraft flies 100 km due west. There is a crosswind blowing which has moved the plane 5 km due north. What is the displacement of the aircraft?

## Speed

When we measure the speed of something we are measuring the distance travelled each second (or hour).

Speed is found by measuring the distance travelled in a certain time interval. The speed is then calculated by dividing the distance by the time.

## Speed, Distance and Time Formula

Speed is equal to the distance travelled divided by the time taken to travel that distance. In the formula book the equation is written like this:

= vtTime measured in seconds (s) Distance measured in Speed measured in metres metres (m) per second  $(m s^{-1})$ 

## **Average Speed**

Sometimes an object's speed varies. For instance a car travelling along a road will speed up and slow down due to traffic. In these situations we calculate the average speed. Average speed is represented in formulae by adding a 'bar' above the symbol<sup>1</sup>.

Average speed = Total distance travelled  $\div$  Total time taken

$$\frac{-}{v} = \frac{d}{t}$$

#### Instantaneous speed

Instantaneous speed is the speed of an object at any given moment. In a car this is shown by the speedometer. The police can measure the instantaneous speed of a car using a RADAR gun or speed camera. In Physics experiments we use a piece of equipment called a light gate connected to an electronic timer.

#### Units of speed

In Britain we measure road speeds in miles per hour (mph).

In Europe they measure road speeds in kilometres per hour (km/h).

In Physics we usually measure speed in metres per second  $(m s^{-1})$ .

In towns the speed limit is 30 mph, this is 48 km/h or 13.4 m s<sup>-1</sup>.

On motorways the speed limit is 70 mph, this is 113 km/h or 31.3 m s<sup>-1</sup>.

<sup>&</sup>lt;sup>1</sup> This works for any quantity, adding a 'bar' means the average (mean) quantity.

- 1. A car travels 600 km in 5 hours. Calculate its average speed in km/h.
- 2. A train travels 150 miles in 3 hours, what is its average speed in miles per hour?
- 3. What is the average speed of a man who walks 50 metres in 25 seconds?
- 4. How long will it take a car travelling at an average speed of 25 m s<sup>-1</sup> to travel 2 km?
- 5. How far will an aeroplane travel in 6 hours if it travels at a constant speed of 2160 km/h? Give your answer in km.
- 6. A London to Glasgow flight takes 50 minutes to travel a distance of 850 km. What is its average speed in  $m s^{-1}$ ?

## More practice problems

- 1. A car has an average speed of 40 mph on the road from Laurencekirk to Aberdeen. Behind a tractor its speed is 20 mph but on a straight the car's speed is 55 mph. From this information, identify the average and instantaneous speeds (stating them) and explain the difference between average speed and instantaneous speed.
- 2. In the laboratory, a vehicle travels down a ramp. The vehicle is 10 cm long and takes 0.2 s to travel through a light gate. What is the instantaneous speed of the vehicle?
- 3. Given the following information from an experiment, calculate the instantaneous speed of a vehicle. Mass of vehicle, 0.5 kg; Length of card on vehicle, 2 cm; Time taken to pass through light gate, 0.05 s.
- 4. Two light gates are set up on a ramp. One light gate is 20 cm down the ramp. The other is 60 cm down the ramp. A vehicle with a 2 cm wide card on it rolls down the ramp. Times for the first and second gate are listed below:

First gate 0.018 s Second gate 0.012 s

#### Calculate:

- a) The first instantaneous speed.
- b) The second instantaneous speed.
- c) The change in speed.
- d) Describe the motion of the vehicle.

## Velocity

The main difference between speed and velocity is that:

- Speed is a *scalar* quantity and requires only a magnitude.
- Velocity is a *vector* quantity and requires a magnitude **and direction**.

## Velocity equation

Velocity is equal to the displacement divided by the time. In the formula book the equation is written like this:



However this should properly be written with vector notation as shown below:



NB: The velocity will be in the **same direction as the displacement**.

Example: A person on a train is travelling at 100 m s<sup>-1</sup>. They walk to the front of the train at 2 m s<sup>-1</sup>. The person's resultant velocity is 102 m s<sup>-1</sup> in the direction of the train. They then walk back to their seat at 3 m s<sup>-1</sup>. The person's new resultant velocity is 97 m s<sup>-1</sup>, still in the direction of the train.

Example: A woman walks 3 km due North and then 4 km due East. She takes two hours.



a) Find the distance she has walked and her displacement.

b) Calculate her average speed and velocity.

The easiest way to solve this type of problem is by drawing a scale diagram, in this case 1 cm = 1 km (the diagram above is already to scale).

a) The distance she has travelled is:

3 km + 4 km = 7 km

Her displacement is from A to C. This can be measured on the diagram as 5 cm. Using the scale this is converted to 5 km.

The angle BAC is measured using a protractor to find the direction of her final displacement. BAC is 53°. Therefore the woman's displacement is:

5 km at on a bearing of  $053^{\circ}$ 

b) Her average speed and velocity are:

speed = distance  $\div$  time = 7  $\div$  2 = 3.5 km/h

velocity = displacement  $\div$  time = 5  $\div$  2 = 2.5 km/h on a bearing of 053°

## ACCELERATION

The rate at which an object changes its velocity is called its acceleration. Acceleration is a vector quantity as it has a direction. Deceleration is simply acceleration in the opposite direction to the velocity of an object, i.e. it is slowing down. Deceleration is sometimes called a negative acceleration. An object travelling at a constant velocity has an acceleration of zero. Note that an object can have a constant speed but still be accelerating if it is changing direction.

## Acceleration formula

The acceleration of an object is given by the change in velocity divided by the time taken. The formula is on the formula sheet and is shown below:



However it can be useful to use the following form as well:



- 1. Calculate the acceleration of a car that changes its speed by 20 m s<sup>-1</sup> in 5 seconds.
- 2. What is the acceleration of an object that has a changes its speed by 50 m s<sup>-1</sup> in 10 seconds?
- 3. What is the acceleration of a vehicle as it brakes from 30 m s<sup>-1</sup> to rest in 1.5 s?
- 4. An object accelerates at 4 m s<sup>-2</sup>, how long will it take to change its speed by  $500 \text{ m s}^{-1}$ ?
- 5. A car accelerates from rest at 2 m s<sup>-2</sup> for 15 seconds. What is the car's final speed?
- 6. A car accelerates from 30 m s<sup>-1</sup> to 43 m s<sup>-1</sup> in 0.5 seconds. What is the car's acceleration?
- 7. The space shuttle takes 45 seconds from launch to reach a speed of  $1000 \text{ m s}^{-1}$ . Calculate its acceleration.
- 8. An intercity train increases its speed from 0 to  $55 \text{ m s}^{-1}$  in 10 minutes. Calculate its acceleration.
- 9. A lorry travelling at a constant speed begins to accelerate at 1.5 m s<sup>-2</sup> for 6 seconds to 20 m s<sup>-1</sup>. What was the original speed of the lorry?

# VELOCITY / TIME GRAPHS

One of the best ways to get a 'picture' of how something is moving is to draw a graph of velocity against time. The graph will display the instantaneous speed at any time on the journey. The graph will clearly show when an object is accelerating, decelerating or moving with constant speed.

Acceleration	the line slopes up
Deceleration	the line slopes down
Constant speed	the line is horizontal

The **gradient** of the line is equal to the acceleration.

The area underneath the line is equal to the displacement of the object.

## Example



This velocity time graph shows the motion of an object over one minute. Simply by looking at the graph we can describe the motion of the object.

- From 0 to 10 seconds the object is accelerating from  $0 \text{ m s}^{-1}$  to 15 m s<sup>-1</sup>.
- From 10 to 20 seconds the object is at a constant velocity of 15 m s<sup>-1</sup>. It is not accelerating.
- From 20 to 30 seconds the object is decelerating from 15 m s<sup>-1</sup> to 10 m s<sup>-1</sup>.
- From 30 to 40 seconds the object is at a constant velocity of 10 m s<sup>-1</sup>. It is not accelerating.
- From 40 to 50 seconds the object is decelerating from  $10 \text{ m s}^{-1}$  to  $0 \text{ m s}^{-1}$ .
- From 50 to 60 seconds the object is stationary. It is not accelerating.

You can now do some calculations to find:

- a) The acceleration from 0 to 10 seconds
- b) The deceleration from 20 to 30 seconds
- c) The deceleration from 40 to 50 seconds

Plot a speed/time graph using the following data:

Time (s)	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32
Speed (ms <sup>-1</sup> )	0	6	12	18	24	30	30	30	30	30	30	30	30	30	20	10	0

On your graph

- 1. Label the parts of the motion where the object is at a constant velocity.
- 2. Label the parts of the motion where the object is accelerating.
- 3. Label the parts of the motion where the object is decelerating.

Using information on your graph calculate the acceleration and the deceleration of the object. Then write a description of the motion of the object.

#### Area underneath a line

The area underneath a speed time graph shows the displacement of the object. At National 5 it will also show the distance travelled by the object (as the object will not change direction). However the shapes of the graphs you will see will not always be a rectangle or triangle. Often they will look similar to this...



To tackle this sort of problem you simply split the area into rectangles and triangles. In this case we have two triangles and a rectangle:



The area of the three shapes added together will give the distance travelled.

area of triangle  $1 = 0.5 \times (10 \times 20) = 100$ 

area of rectangle =  $10 \times 20 = 200$ 

area of triangle  $2 = 0.5 \times (10 \times 10) = 50$ 

distance travelled = total area = 100 + 200 + 50 = 350 m

1. The graph below shows how the velocity of a car changes as it accelerates from rest. What is the acceleration of the car?



2. A bus moves from a bus stop to a set of traffic lights. The velocity/time graph for the journey is shown below.



- a) Calculate the initial acceleration.
- b) Calculate the deceleration.
- c) Find the distance travelled in the first 20 seconds.
- d) Calculate the average speed for the journey.

## FORCES

Forces can do three things to an object:

- 1. Push them.
- 2. Pull them.
- 3. Change their shape.

## **Measuring forces**

Forces are a **vector**, they have both magnitude and direction. Forces can be measured using a Newton Balance. A Newton balance is simply a calibrated spring. A spring is used to measure forces because it increases its length when you apply a force to it (according to Hooke's Law). The change in length of the spring (or its *extension*) is proportional to the force applied to it. If you double the force on a spring its extension will double. When the force is removed the spring returns to its original length. If you apply too much force to a spring you can break this relationship and the spring will not return to its original length, so Newton meters have a maximum force that they can measure.

The unit used to measure force is the newton (N) — after Sir Isaac Newton.



Sir Isaac Newton PRS MP (25 December 1642 – 1727)



Robert Hooke FRS (28 July 1635 – 3 March 1703)

## **Combining Forces**

When two or more forces act together the effect will depend on the size and the direction of these forces. In Physics we combine multiple forces into a **resultant** force.

If forces are acting in the **same** direction you simply add the forces together.



The block above has two 5 N forces acting on it. Both are acting from the left to the right. The resultant force will be:

F = 5 + 5 = 10 N to the right

If forces are acting in **opposite** directions you subtract the forces.



The block above has a 10 N and a 5 N force acting on it. The 10 N is acting to the left and the 5 N is acting to the right. The resultant force will be:

F = 10 - 5 = 5 N to the left

## **Balanced Forces**

If the forces are equal in size but opposite in direction the forces are said to be **balanced**. The combined effect is the same as no force. The resultant force is zero.



The block above has two forces of equal size acting in opposite directions. The resultant force will be:

$$F = 7 - 7 = 0 N$$

The forces are **balanced**.

Calculate the resultant forces in the situations below:



# NEWTON'S FIRST LAW

Every body persists in its state of being at rest or of moving uniformly straight forward, except insofar as it is compelled to change its state by force impressed — Isaac Newton, *Philosophiæ Naturalis Principia Mathematica*, 1687.

Or, in today's language, an object will travel at the same speed, in a straight line, unless a force acts on the object. Newton's first law means that an object will never speed up, slow down or change direction unless there is an **unbalanced** force acting on it. This law is sometimes known as the *law of inertia*. It is a somewhat counter-intuitive law as we are used to friction acting on everything. So a car travelling along a road will slow to a stop if the engine was turned off. We tend to forget that there *is* an unbalanced force acting on the car, friction. In space, where there is no friction, Newton's first law is clearly evident — spacecraft need to use rockets or a planet to slow down. Newton's first law is also important when you consider going around a corner. To change direction, even if you have the same speed, need an unbalanced force.

## NEWTON'S SECOND LAW

The alteration of motion is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed — Isaac Newton *Philosophiæ Naturalis Principia Mathematica*, 1687.

In more modern language what Newton stated in his second law is that an object will accelerate in the same direction as the unbalanced force acting on it. He also stated that the magnitude of the acceleration was proportional to the magnitude of the unbalanced force.

## Newton's Second Law — formula

The unbalanced force acting on an object is equal to the mass times the acceleration of the object. This is the mathematical way of representing Newton's Second Law. It appears in the formula book and looks like this:

Mass measured in kilograms (kg) F = maResultant force measured Acceleration measured in in newtons (N) metres per second squared  $(m s^{-2})$ 

Note that both force and acceleration are vectors. Therefore Newton's second law can also be written like this  $\mathbf{F} = m\mathbf{a}$ .

- 1. A 7 kg bag of potatoes accelerates down a factory chute at 3 m s<sup>-2</sup>. Calculate the unbalanced force acting on potatoes.
- 2. A sprinter of mass 70 kg accelerates at 10 m s<sup>-2</sup>. Calculate the unbalanced force driving him forward.
- 3. There is an unbalanced force acting on a car of 500 N and this causes it to accelerate at  $2.5 \text{ m s}^{-2}$ . Calculate the mass of the car.
- 4. An oil tanker of mass 10,000,000 kg is travelling at a steady speed. The tankers engines are switched off causing it to decelerate at 0.01 m s<sup>-2</sup>. Calculate the size of the frictional forces causing the deceleration.
- 5. What was the size of the forward force exerted by the tanker's engines before they were switched off?

Force (N)	Mass	Acceleration ( $m s^{-2}$ )
10	2 kg	
5	500 g	
20		5
4		0.5
	6 kg	20
	0.2 kg	5

6. Fill in the missing values.

## Gravity

All objects with mass attract each other; this force is called the force of gravity.

The force of gravity depends on:

- The magnitude of the two masses
- Their distance apart

The force of gravity is not very noticeable unless one of the masses is huge like the Earth or the Sun. The strength of the gravitational force between two masses gets weaker as they move further apart. In National 5 we are only going to look at how gravity affects objects close to the surface of a planet, which makes things much easier.

## Gravitational Field Strength (g)

The gravitational field strength is a measure of how strong the gravity of an object is. The gravitational field strength on a planet or moon's surface depends on the mass of the planet or moon. On the surface of Earth the gravity pulls with a force of 9.8 Newtons on each kilogram of mass, usually written as 9.8 Nkg<sup>-1</sup>. On the Moon the gravitation field strength is 1.6 Nkg<sup>-1</sup>.

## Weight

The pull of gravity on an object is called its **weight**. Like all forces weight is measured in newtons (N).

## Weight formula

The weight of an object is given by the object's mass multiplied by the gravitational field strength. It appears in the formula book and looks like this:

Mass measured in kilograms (kg)  $' = \dot{m}g_{\sim}$ Weight measured in Gravitational field strength newtons (N) measured in newtons per kilogram (Nkg<sup>-1</sup>)

On Earth *g* is always equal to 9.8 N kg<sup>-1</sup> in National 5. Note that weight is a vector (as it is a force) and that *g* is also a vector. Therefore this formula could be written like this  $\mathbf{W} = m\mathbf{g}$ .

## Weight and Mass

Mass is a measure of the amount of matter (stuff) contained in an object and is measured in kilograms (kg). Weight is the pull of gravity on an object and is measured in newtons (N). Do not confuse the two! If someone states that their weight is 70 kg they are **incorrect**. They should have used the above formula to calculate their weight in newtons.

## Weight problems

- 1. A pupil says that his weight is 60 kg. Is he correct? What is his weight?
- 2. A lift is designed to hold 5 adults. The mass of the lift is 500 kg. The average mass of an adult is 80 kg.

a) Calculate the weight of the lift when it is fully loaded.

- b) Calculate the upward pull by the cable when the lift is stationary.
- 3. Complete the following table:

Mass	Weight
1 kg	
	10 N
5kg	
	7 N
500g	
	2.5 N

## Leaving Earth

Weight is caused because a mass is in a gravitational field — what happens to weight when you leave the gravitational field? Below is a table of measurements indicating the relationship between distance and g the further you get from Earth.

Distance $(\text{km} \times 10^3)$	0	1.0	2.5	5.0	10	25	50	75	100
g (Nkg <sup>-1</sup> )	10	7.3	5.1	3.1	1.5	0.41	0.13	0.06	0.04

Plot a graph of the above data. Looking at your graph what do you think the relationship between the distance from a body and the gravitational field strength at that distance is?

The international space station and shuttle missions all occur in Low Earth Orbit (approximately 330 km in altitude). Although all the objects and personnel appear weightless — are they truly weightless?

If you went to Mars, would you still have weight? Would you still have mass?

Mass is a measure of how much stuff (protons, neutrons, electrons etc.) there is in a object. Mass **does not change** unless a part of the object is removed or something added to it. Weight on the other hand is dependent on *g* and will be different on different planets and will also change as an object moves away from a planet. Below are the values of *g* at the 'surface' of some celestial bodies in the Solar System.

Body	g (N kg <sup>-1</sup> )	Body	g (N kg <sup>-1</sup> )	Body	g (N kg <sup>-1</sup> )
Mercury	3.7	Jupiter	23	The Sun	270
Venus	8.9	Saturn	9	Pluto	0.7
Earth	9.8	Uranus	8.7	Titan	1.4
Mars	3.7	Neptune	11	Eris	0.8

- 1. An astronaut is touring the solar system and visiting the Moon, Venus and Mercury. If the astronaut has a mass of 75 kg, what is the astronaut's weight on each planet?
- 2. The same astronaut goes to another planet. On this planet their weight is 277.5 N. Assuming they lost no mass, what planet are they on?
- 3. The Curiosity Mars Rover has a mass of 750 kg. Calculate its weight on Earth and Mars.
- 4. As Curiosity travels from Earth to Mars does its mass change?
- 5. As Curiosity travels from Earth to Mars does its weight change?
- 6. What is the mass of an astronaut who has a weight of 660 N on Neptune?

## Friction

Friction is a force which opposes movement. For instance, brake pads produce a large frictional force when pushed against the disc on the wheel. This force is used to change the speed of the car. Friction decreases the speed (it causes deceleration).

Whenever an object moves or tries to move and is in contact with something else friction is present. Friction is always in the **opposite** direction to the motion. Drag and air resistance are also caused by friction.

## **Reducing friction**

You can reduce friction by:

- Putting oil or other lubricants between the surfaces.
- Having air between the surfaces.
- Using rollers or ball bearings which reduce the area of contact and allow surfaces to slide past each other more easily.

## **Practice Problems**

List as many ways as possible to **decrease** the force of friction — not just between two surfaces but in any situation. Compare these with your neighbour.

List as many ways as possible to **increase** the force of friction. Compare these with your neighbour.

#### **Rocket problems**

Rockets are a common type of problem in National 5. When dealing with Newton's second law rocket problems are slightly more complex.

For example: A short time after take off, a rocket of mass 10,000 kg has a thrust of 350,000 N and experiences air resistance of 30,000 N. Find the acceleration.

How to solve —Draw a diagram and then find the resultant force acting on the object. Using the **resultant** force, find the acceleration of the rocket.



Resultant force (F) = 350000 - (30000 + mg)

 $F = 350000 - (30000 + (10000 \times 9.8))$ 

F = 350000 - (30000 + 98000)

F = 350000 - 128000

#### F = 222000N

F = ma

222000 = 10000a

a = 222000 ÷ 10000, a = 22.2 m s<sup>-2</sup>

- 1. A rocket of mass 1500 kg is initially accelerated upwards by the thrust of rocket engines.
  - a) What is the weight of the rocket?
  - b) If the engine thrust is 20,000 N, what is the unbalanced force on the rocket?
  - c) Find the acceleration of the rocket.
- 2. A rocket of mass 100 kg is accelerated upwards by a thrust of 3,000 N. What is the acceleration of the rocket?
- 3. If a rocket of thrust 20,000 N accelerates and has a weight is 4,000 N. What is the acceleration of the rocket?

# NEWTON'S THIRD LAW

To every action there is always an equal and opposite reaction — Isaac Newton *Philosophiæ Naturalis Principia Mathematica*, 1687.

Newton's third law simply means that if you push something, the something pushes back with the same force. This is why you do not fall through your chair. But it also explains how rockets and jet engines generate thrust. Imagine sitting on a chair with wheels that is on a surface with very low friction. You have a bucket of tennis balls. When you throw a tennis ball you exert a force on the ball (to throw it). However the ball exerts the same size of force on **you**. This force will actually move you backwards. Rockets use the same principle but use a stream of extremely hot gasses instead of tennis balls.

- 1. A rugby ball has a mass of 400 g. When kicked, the ball accelerates briefly at 500 m s<sup>-2</sup>.
  - a) What is the unbalanced force acting on the ball?
  - b) What is the magnitude of the force acting on the kickers boot?
  - c) What is the direction of the force on the kickers boot?
- 2. A girl steps out of a stationary rowing boat. She has a mass of 65 kg and the boat has a mass of 25 kg. She steps up and pushes herself away from the boat and onto the shore with a force of 375 N
  - a) What is the force acting on the boat?
  - b) What is the acceleration of the boat?
  - c) If the force acts for 0.16 s, what is the final speed of the boat?

## Freefall

Galileo Galilei once conducted a (now famous) experiment. He went to the top of the Leaning Tower of Pisa and dropped two objects with different masses from the top. The Physics of Aristotle and the ancient Greeks said that the more massive object would hit the ground first. Galileo found that they both hit the ground at the (almost) same time. When the Apollo astronauts tried this type of experiment on the Moon they found that a hammer and a feather both hit the ground at the same time. Why? Consider two objects with different masses:



Galileo Galilei (15 February 1564 — 8 January 1642)



What forces are acting on the two objects if we ignore air resistance?



The weight of object 1 is 10 times as large as the weight of object 2. This is why Aristotle thought that object 1 would hit the ground first. However what happens when we calculate the accelerations of the two objects using Newton's second law?

$\mathbf{a}_1 = \mathbf{F} \div \mathbf{m}_1$	$a_2 = F \div m_2$
$a_1 = 9.8 \div 1$	$a_2 = 0.98 \div 0.1$
$a_1 = 9.8 \text{ m s}^{-2}$	$a_2 = 9.8 \ m  s^{\!-\!2}$

The acceleration of the two objects is the **same** and equal to *g*. As both objects are dropped with the same initial speed ( $0 \text{ m s}^{-1}$ ) and from the same height they must hit the ground at the same time.

This happens to projectiles as well. If you fire a gun horizontally and at the same time drop a bullet, both bullets will hit the ground at the same time.

## **Terminal Velocity**

Under realistic conditions you know that a feather and a hammer do not hit the ground at the same time. This is because on Earth we have an atmosphere. This causes air resistance — which means that weight is **not** the only force acting on a falling object. Air resistance increases the faster you go. Eventually the force of air resistance will be the same as the weight of the object. Now the forces are **balanced** which means that the resultant force on the object is **zero**. This means it will stop accelerating and travel at a constant velocity.

We call this terminal velocity.



# PROJECTILE MOTION

A projectile is any object, which, once projected, continues its motion by its own inertia and is influenced only by the downward force of gravity. Projectiles have both *horizontal* and *vertical* components of motion. As there is only a single force, gravity, acting in a single direction, only one of the components is being acted upon by a force. The two components are not undergoing the same kind of motion and must be treated **separately**.

#### Projectiles fired horizontally

In National 5 you only have to worry about projectiles fired horizontally, which makes things much easier. Here is a classic horizontal projectile scenario, from the time of Newton. In projectile motion we **ignore air resistance**, or any force other than gravity. When we look at the horizontal and vertical components we find that...

Horizontally: There are no forces acting on the object and therefore the horizontal velocity is constant. You use the speed, distance, time formula in the horizontal direction.

Vertically: The force due to gravity is constant so the cannonball undergoes a constant acceleration equal to the gravitational field strength *g*. You use the acceleration formula in the vertical direction.

The combination of these two motions causes the curved path of a projectile.

#### Horizontal projectile formulae

You can solve projectile problems in National 5 using the speed, distance, time and acceleration formulae that you have already learnt in this unit. There is a 'shortcut' formula that you can use as well in the **vertical direction only**. Note that *a* will usually be the gravitational field strength on Earth –  $9.8 \text{ Nkg}^{-1}$ .

$$v_v = u_v + at$$

Example: A cannonball is fired horizontally from a cliff with a velocity of  $100 \text{ m s}^{-1}$ . The cliff is 20 m high and the cannonball takes 2 s to hit the water.

Determine:

- 1. The vertical speed of the cannonball, just before it hits the water.
- 2. If the cannonball will hit a ship that is 200 m from the base of the cliff.
- Solution 1: v = u + at  $v = 0 + (9.8 \times 2)$   $v = 19.6 \text{ ms}^{-1}$ Solution 2: s = vt  $s = 100 \times 2$ s = 200 m

The cannonball will hit the ship (just).

- 1. A stone thrown horizontally from a cliff lands 24 m out from the cliff after 3 s. Find:
  - a) The horizontal speed of the stone.
  - b) The vertical speed at impact
- 2. A ball is thrown horizontally from a high window at 6 ms<sup>-1</sup> and reaches the ground after 2 s. Calculate:
  - a) The horizontal distance travelled
  - b) The vertical speed at impact.
- 3. A ball is projected horizontally at  $15 \text{ m s}^{-1}$  from the top of a vertical cliff. It reaches the ground 5 s later. For the period between projection until it hits the ground, draw graphs, with numerical values on the scales, of the ball's:
  - a) Horizontal velocity against time
  - b) Vertical velocity against time
  - c) From the graphs, calculate the horizontal and vertical distances travelled.

## Satellites

Newton conducted a thought experiment that is now dubbed "Newton's Cannon". He imagined placing a cannon on top of a mountain and firing a cannonball horizontally. He knew that the cannonball would fall towards the ground at a constant acceleration due to its weight and also that Earth was a sphere. He reasoned that if the mountain were high enough, and the cannonball fired fast enough, the cannonball would 'miss' the earth and travel right around the planet.

This is what we call a satellite. Though scientists knew in Newton's time that the planets went around the sun in well defined orbits, Newton was the first to explain how the force of gravity could cause this type of motion.



# **MECHANICS**

## You need to know:

	√?X
The difference between a scalar and a vector	
Whether a quantity is a vector or a scalar	
How to work out a resultant vector	
The difference between distance and displacement	
How to calculate displacement	
How to calculate velocity	
How to draw a velocity time graph	
How to describe the motion of an object from its velocity time graph	
How to calculate displacement from a velocity time graph	
How to use the $a=(v-u)/t$ formula	
How to calculate acceleration from a velocity time graph	
Newton's First Law and its implications	
Newton's Second Law and how to use the F=ma formula	
The difference between mass and weight	
How to use the W=mg formula and how it relates to $F=ma$	
Newton's Third Law and its implications	
What free fall and terminal velocity are	
How to explain projectile motion	
How to do calculations involving horizontally launched projectiles	
How to explain orbital motion (in terms of projectiles)	