THE PHYSICS OF MOTION

Footballers, golfers, tennis players, runners, skiers – they all have something in common. They have the ability to make split-second decisions about how their actions will affect their performance: how the curve of a ball will affect whether they score that crucial penalty, whether a change of angle of the club will give them a hole-in-one. Whether or not they know it, they are making use of the physics of motion.

In the first section of 'Our Dynamic Universe' you will learn more about the motion of objects: from raindrops to roller coasters. You will be able to use the language of physics to describe and explain the motion of bouncing balls and sky divers. You will understand the principles of the physics of motion and explain it using words, diagrams, graphs and equations.

VECTORS AND SCALARS

Exploring the physics of motion, the terms acceleration, velocity and displacement have been used.

What do these terms mean? Is displacement the same as distance? Is velocity the same as speed?

Quantities can be defined as vectors or scalars. You will be familiar with working with scalar quantities but you probably did not realise it. You may also be familiar with some vector quantities and have performed simple vector additions.

SCALAR QUANTITIES

A scalar quantity is defined only by its magnitude (ie its size). Examples of scalar quantities include:

Quantity	Units
Distance	m
Speed	m s^{-1}
Energy	J
Time	S
Mass	kg

VECTOR QUANTITIES

A vector quantity is defined both by its magnitude (ie its size) and its direction. Examples of vector quantities include:

Quantity	Units
Displacement	m
Velocity	$m\ s^{-1}$
Acceleration	$m\ s^{-2}$
Force	N
Impulse	N s
Momentum	$kg\ m\ s^{-1}$
Weight	N

VECTORS AND SCALARS: WHY DO THEY MATTER?

In physics, we are studying the real, physical world and finding models which explain our observations of motion in this world. Vectors give us a method of describing motion in the real world.

So why does this matter? Consider a pilot coming in to land an aircraft in very windy conditions. As he tries to land the plane in the centre of the runway, he must take into account the speed of the wind and its direction, ie the velocity of the wind.

Consider the corrective action that will have to be taken by the pilot to land an aircraft in a cross wind – and realise the importance of understanding vectors!

THE SIGN CONVENTION

Direction matters and so a system of defining direction is needed. Normally, we use

| upwards	↑	positive
downwards	↓	negative
right	→	positive
left	←	negative

## GRAPHING MOTION AND INTERPRETING GRAPHS

Although the ability to plot a graph accurately is important, it is absolutely essential to be able to interpret graphs and to visualise the shape of a graph for a given motion.

For an object that is stationary, the displacement–time, velocity–time and acceleration–time graphs are shown below.
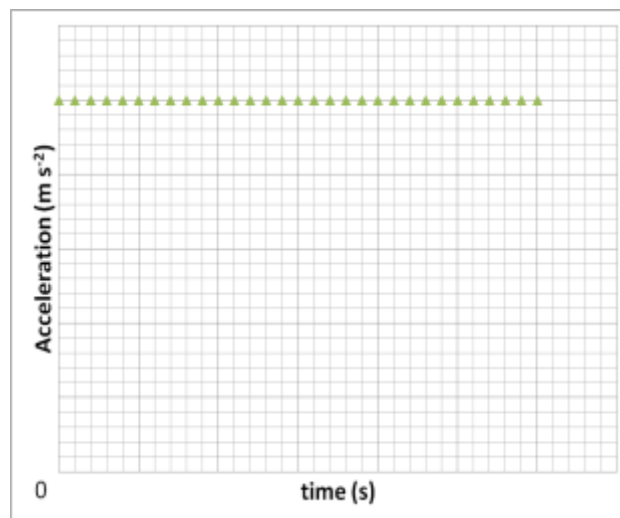
Displacement-Time Graph

Velocity-Time Graph

Acceleration-Time Graph
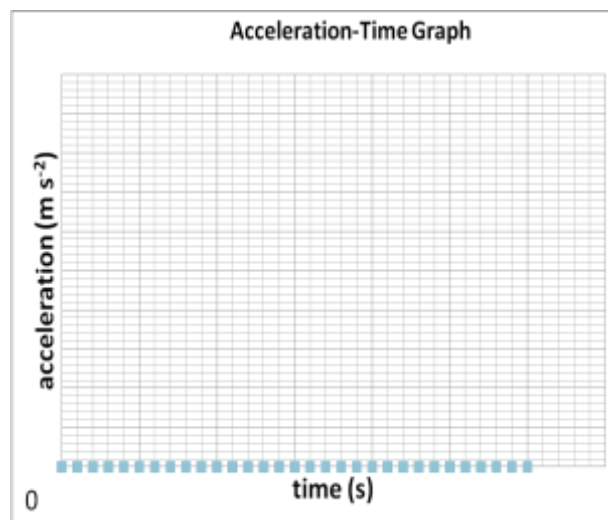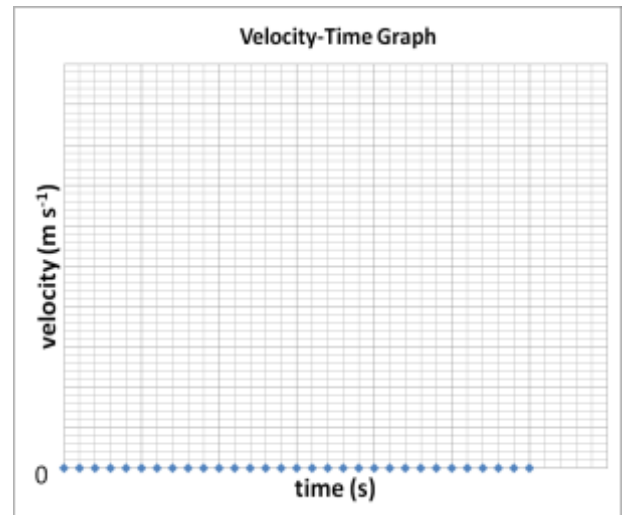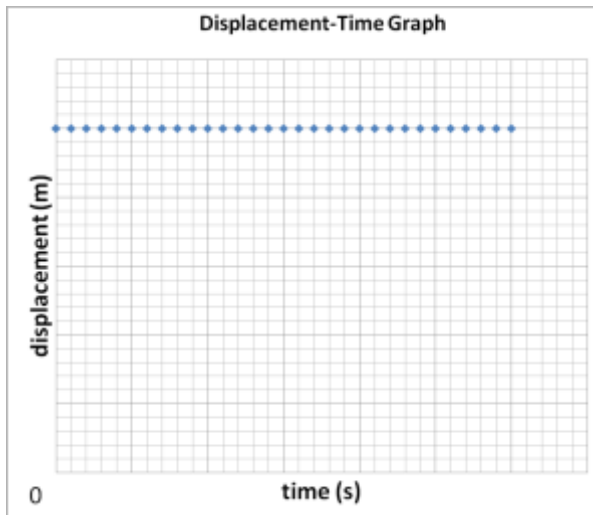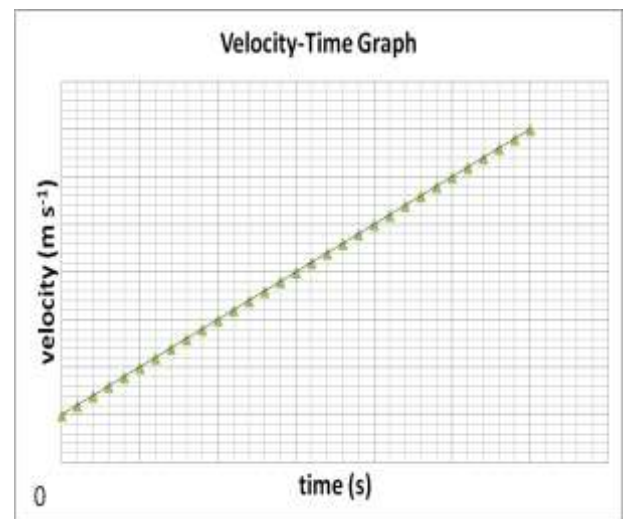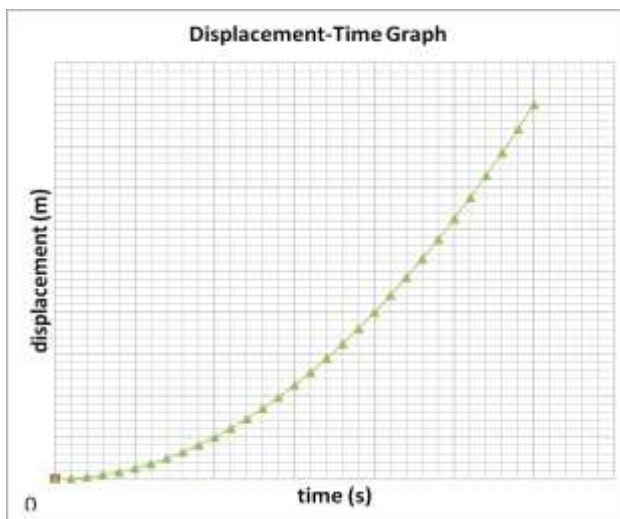
For an object that is moving with constant velocity, the displacement–time, velocity–time and acceleration–time graphs are shown below.

Displacement-Time Graph

Velocity-Time Graph
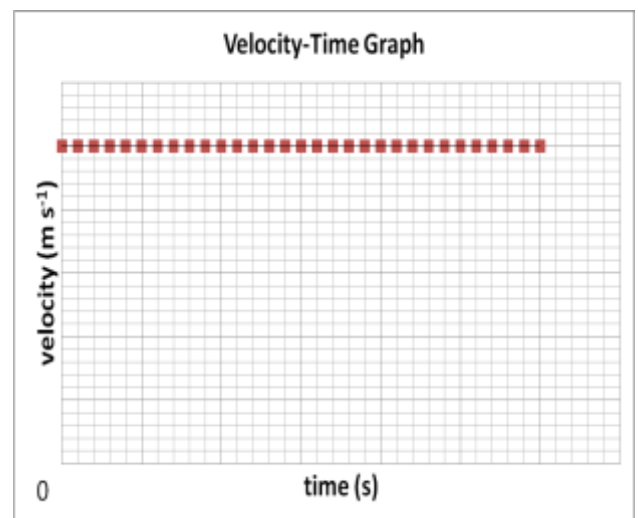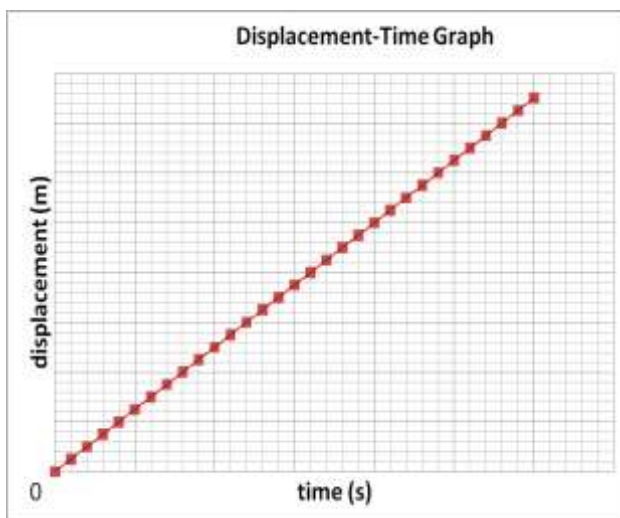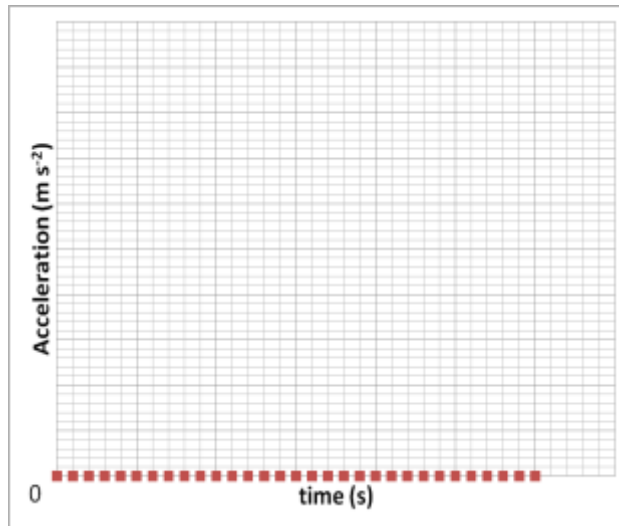
For an object that is accelerating uniformly, (ie moving with a constant acceleration) the displacement–time, velocity–time and acceleration–time graphs are shown below.

Each time you are presented with a graph, you should ask yourself two key questions:

Is there any significance to the gradient of the graph?

Is there any significance to the area under the graph?

INTERPRETING DISPLACEMENT–TIME GRAPHS

The gradient of the displacement–time graph is the velocity of the object. Mathematically this is the equivalent of dividing the *y*-axis quantity by the *x*-axis quantity: in this case displacement divided by time. Displacement divided by time is rate of change of displacement, which is velocity.

The area under the graph does not give us any meaningful information. Mathematically this is the equivalent of multiplying the two quantities, in this case displacement and time.

INTERPRETING VELOCITY–TIME GRAPHS

The gradient of the velocity–time graph is the acceleration of the object: the steeper the line the greater the rate of change of velocity (or acceleration) of the object.

The area under the graph is the displacement.

INVESTIGATING ACCELERATION

Acceleration is defined as the rate of change of velocity per unit time.

From this definition, an equation can be written:

$$a = \frac{v - u}{t}$$

a = acceleration in metres per second per second (m s^{-2})

v = final velocity in metres per second (m s^{-1})

u = initial velocity in metres per second (m s^{-1})

t = time in seconds (s)

The acceleration of an object can be investigated in a number of ways. You should give consideration to the different methods, and the advantages and disadvantages of each method for measurement of acceleration in different circumstances. Methods of measurement of acceleration include:

- using light gates connected to a timing unit, with single-mask and double-mask set-ups

- using a motion sensor, which measures displacement with time and from this calculates velocity and acceleration

- using an accelerometer, which measures acceleration directly.

You should predict, investigate and explain the displacement–time, velocity–time and acceleration–time graphs for a variety of motions, including trolleys on slopes. Consider the uncertainties in each piece of equipment and which is most appropriate for the measurements you are making. Evaluate your experimental set-up to be able to suggest problems and potential improvements.

Remember that displacement (*s*), velocity (*u*, *v*) and acceleration (*a*) are vector quantities. A positive and negative direction must be chosen and used consistently in your predictions and explanations.

THE EQUATIONS OF MOTION

The equation which links acceleration, initial and final velocity, and time is the first of the **equations of motion**.

These equations are used to describe motion in a straight line with uniform acceleration. You must to be able to:

- select the correct formula

- identify the symbols and units used

- carry out calculations to solve problems of real life motion

- carry out experiments to verify the equations of motion.

You should develop an understanding of how the graphs of motion can be used to derive the equations. This is an important part of demonstrating that you understand the principles of describing motion, and the link between describing it graphically and mathematically.

$$a = \frac{v - u}{t}$$

a = acceleration in metres per second per second (m s^{-2})

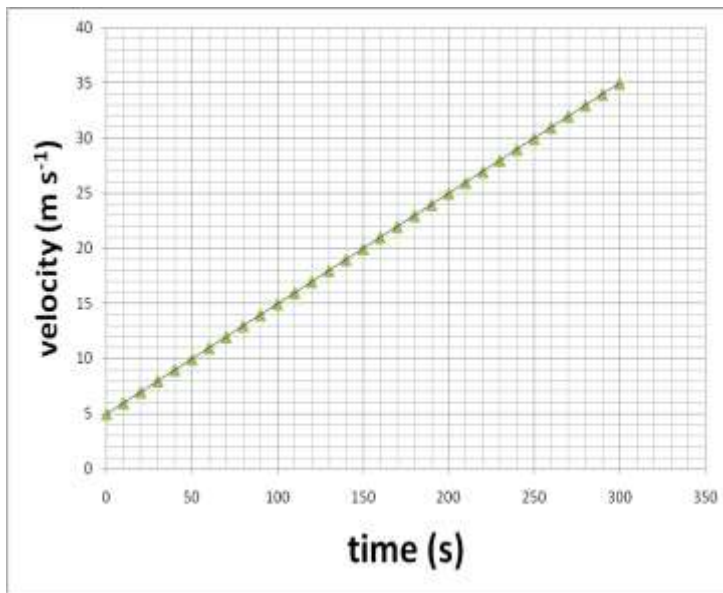v = final velocity in metres per second (m s^{-1})

u = initial velocity in metres per second (m s^{-1})

t = time in seconds (s)

$v = u + at$

Equation of motion 1

You should now be sufficiently familiar with graphing motion to be able to describe the motion represented by the graph below.


This graph represents an object moving with a positive velocity of 5 m s^{-1}, which is accelerating at a constant rate. After 300 s the object is moving with velocity of 35 m s^{-1}. A constant acceleration means the velocity is increasing at a constant rate.

The displacement of the object can be determined by calculating the area under the graph. You may already be familiar with the idea of using the area under a speed–time graph to determine the distance travelled by an object.


Area under the graph = 1500 + 4500 = 6000 m

Area 2 = ½ bh
= ½ x (35-5) x300
=4500 m

Area 1 = 5 x 300 = 1500 m
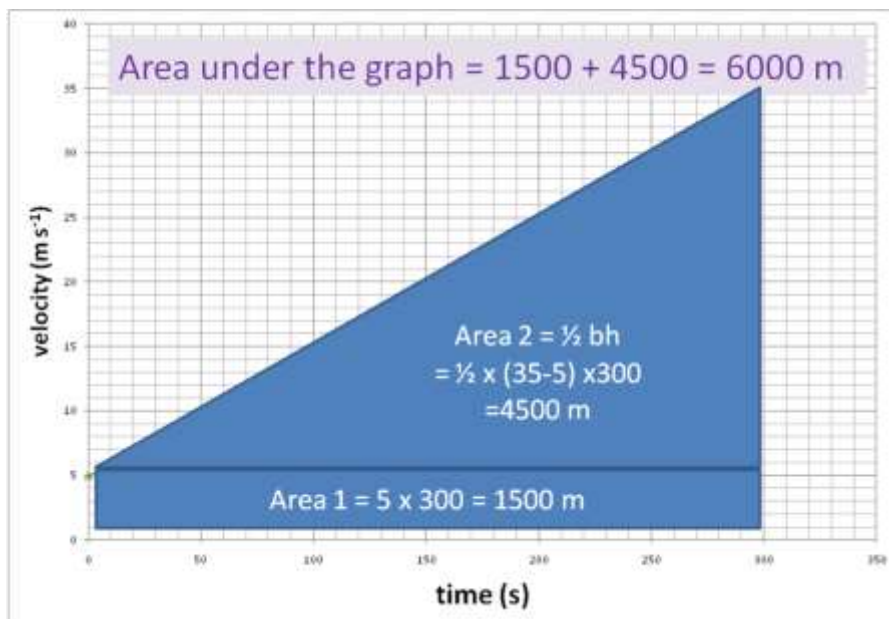
Removing the numbers from the axis, we can work instead with the symbols which represent the quantities, ie final velocity (v), initial velocity (u) and time (t).
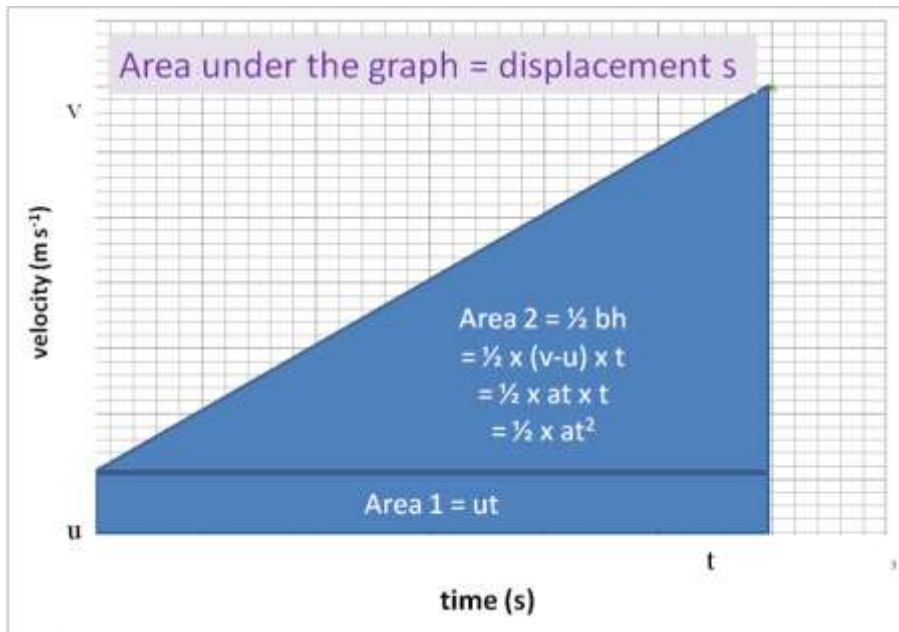
Notice that Equation 1 has been rearranged to give $v - u = at$ and substituted into the equation above.

Adding the two areas under the graph gives us:
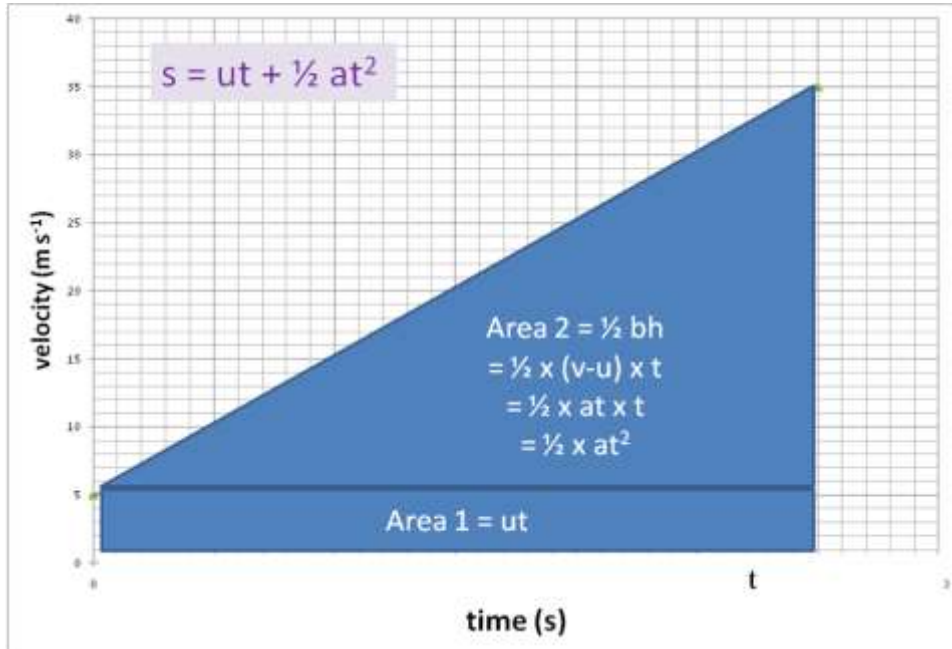
$s = ut + \frac{1}{2}at^2$

s = displacement in metres (m)

u = initial velocity in metres per second (m s^{-1})

t = time in seconds (s)

a = acceleration in metres per second per second (m s^{-2})

$s = ut + \frac{1}{2}at^2$ **Equation of motion 2**

The third equation of motion is derived from with Equation 1.

Equation 1	$v = u + at$
square each side to give	$v^2 = (u + at)^2$
	$v^2 = u^2 + 2uat + a^2t^2$
	$v^2 = u^2 + 2a(ut + \frac{1}{2}at^2)$
substitute in Equation 2	$v^2 = u^2 + 2as$

$v^2 = u^2 + 2as$ **Equation of motion 3**