National 4/5 Physics   Dynamics and Space

Summary Notes

The coloured boxes contain National 5 material.

Section 1 – Mechanics

Average Speed

Average speed is the distance travelled per unit time.

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

average speed (m/s)

distance (m)

time (s)

Note **to avoid confusion it is better to write this formula in words.**

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

SI unit of average speed is m/s (metres per second) since the SI unit for distance is metres (m) and SI unit for time is seconds (s).

Examples of alternative units for average speed are kilometres per hour (km/h) or miles per hour (mph).

Measurement of average speed

To measure an average speed, you must:

- measure the distance travelled with a measuring tape, metre stick or trundle wheel
- measure the time taken with a stop clock
- calculate the average speed by dividing the distance by the time

Calculations involving distance, time and average speed

Note: care must be taken to use the correct units for time and distance.

Example

Calculate the average speed in metres per second of a runner who runs 1500 m in 5 minutes.

Solution

distance = 1500 m t = 5 minutes = 5 $\times$ 60 seconds = 300 s v = ?

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

$$= \frac{1500}{300}$$

$$= 5\ \mathrm{m/s}$$

Instantaneous speed

The instantaneous speed of a vehicle at a given point can be measured by finding the average speed during a **very short time interval** as the vehicle passes that point.

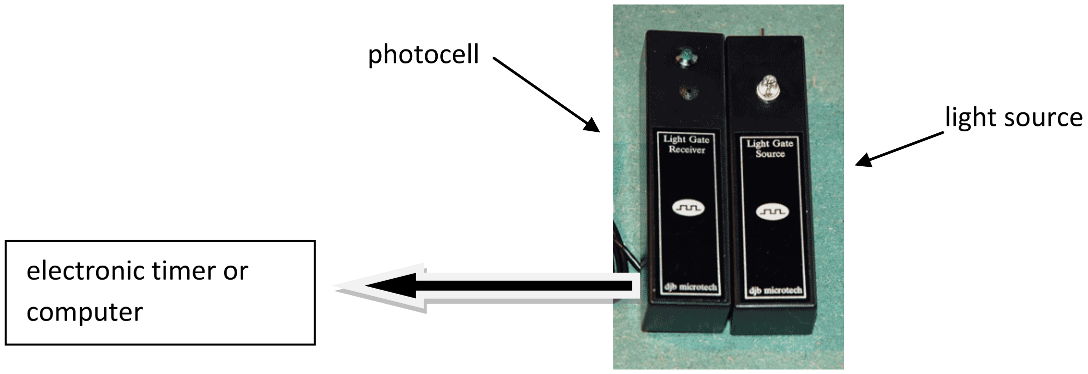
Average speed and instantaneous speed are often very different e.g. the average speed for a car over an entire journey from Glasgow to Edinburgh could be 40 mph, but at any point in the journey, the instantaneous speed of the car could be 30 mph, 70 mph, 60 mph or 0 mph if the car is stationary at traffic lights.

Measuring Instantaneous Speed

To measure instantaneous speeds, it is necessary to measure **very** short time intervals.

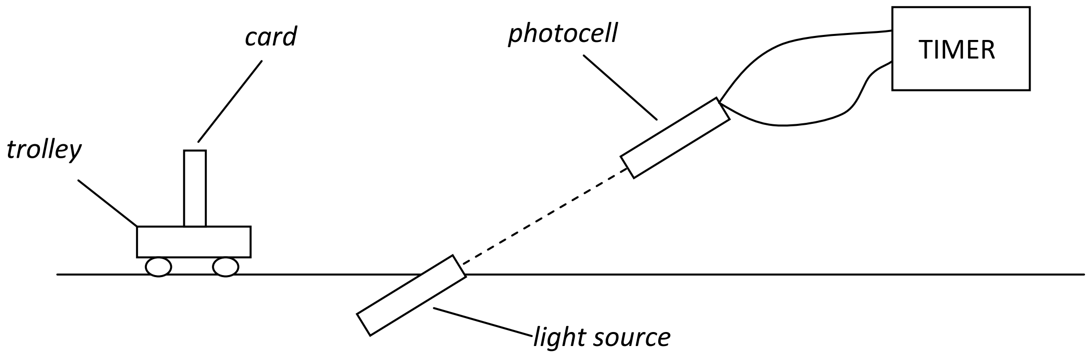
With an ordinary stop clock, human reaction time introduces large uncertainties. These can be avoided by using electronic timers. The most usual is a **light gate.**

A light gate consists of a light source aimed at a photocell. The photocell is connected to an electronic timer or computer.



The timer measures how long an object takes to pass through the light beam.
The distance travelled is the **length of the object** which passes through the beam.
Often a card is attached so that the card passes through the beam.

<u>Procedure to measure the instantaneous speed of a trolley</u>



- Set up apparatus as shown
- Measure length of card
- Push trolley through light beam
- Timer measures time taken for card to pass through light gate
- Calculate instantaneous speed by

$$instantaneous\ speed = \frac{length\ of\ card}{time\ to\ pass\ through\ light\ beam}$$

Example

In the above experiment, the following measurements are made:

Length of card: 10 cm
Time on timer: 0.25 s

Calculate the instantaneous speed of the vehicle

Solution

Length of card = 10 cm = 0.1 m
Time on timer = 0.25 s

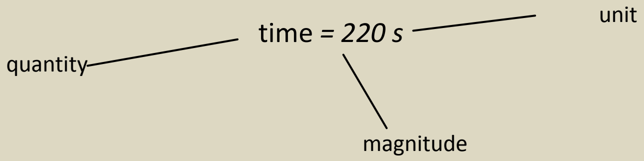
$$\text{instantaneous speed} = \frac{\text{length of card}}{\text{time to pass through light beam}}$$

$$= \frac{0.1}{0.25}$$

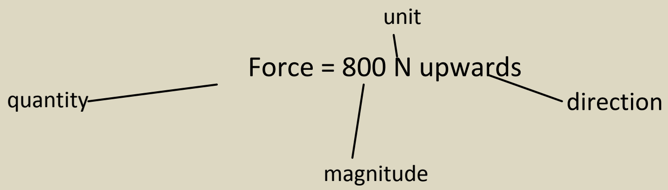
= 0.4 m/s

Vector and Scalar Quantities

A **scalar quantity** is fully described by its magnitude (size) and unit, e.g.



A **vector quantity** is fully described by its magnitude, unit, **and direction,** e.g.



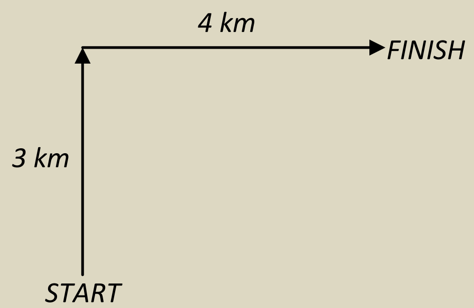
Distance and Displacement

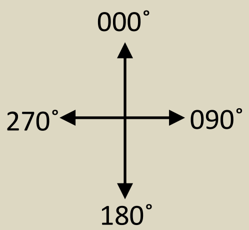
Distance is a **scalar** quantity. It measures the total distance travelled, no matter in which direction.

Displacement is a **vector** quantity. It is the length measured from the starting point to the finishing point in a straight line. Its **direction** must be stated.

Example

A girl walks 3 km due north then turns and walks 4 km due east as shown in the diagram.





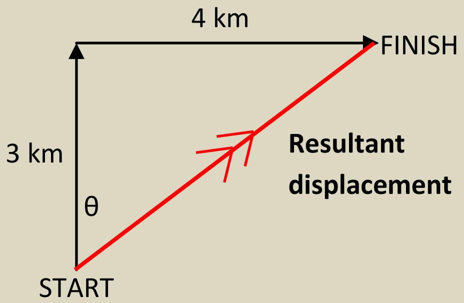
Calculate

(a) The total distance travelled
(b) The girl's final displacement relative to her starting position.

Solution

(a) Total distance = 3 km + 4 km
= 7 km

(b) ***(to calculate displacement, we need to draw a vector diagram)***
(this solution involves using a scale diagram).



- Choose an appropriate scale
- Remember to join the vectors tip-to-tail
- Measure the resultant displacement and the angle.

Resultant displacement = 5 km at 053˚

Speed and Velocity

Speed is a **scalar** quantity. As discussed above, speed is the **distance** travelled per unit time.

$$average\ speed = \frac{distance}{time}$$

Velocity is a **vector** quantity (the vector equivalent of speed). Velocity is defined as the **displacement** per unit time.

$$average\ velocity = \frac{displacement}{time}$$

Since velocity is a **vector,** you **must** state its direction.

The direction of velocity will be the same as the displacement.

Example

The girl's walk in the previous example took 2.5 hours.

Calculate

(a) The average speed
(b) The average velocity for the walk, both in km/h

Solution

(a) Distance = 7 km Time = 2.5 hours

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

$$= \frac{7}{2.5}$$

$$= \underline{\underline{2.8 \text{ km/h}}}$$

(b) Displacement = 5 km (053˚) Time = 2.5 hours

$$\text{average velocity} = \frac{\text{displacement}}{\text{time}}$$

$$\left(\bar{v} = \frac{s}{t} \right)$$

$$= \frac{5}{2.5}$$

$$= \underline{\underline{2 \text{ km/h at } 053^{\circ}}}$$

Acceleration

Acceleration is defined as the **change in velocity per unit time.**

$$a = \frac{\Delta v}{t}$$

The change in velocity can be given by the moving object's final velocity (v) – initial velocity (u)

$$\Delta v = v - u$$

Therefore we can write our equation for acceleration as

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

final velocity (m/s)

initial velocity (m/s)

acceleration (m/s^2)

metres per second per second

time (s)

Acceleration is a **vector** quantity. If the final speed is less than the initial speed, the acceleration is in the opposite direction to motion and will be **negative.** This indicates a **deceleration.**

The equation for acceleration can be rearranged in terms of the final velocity, v

$$v = u + at$$

Example

A car is travelling with an initial velocity of 15 m/s. The driver presses the accelerator pedal and the car accelerates at a rate of 2 m/s^2 for 4 s. Calculate the final velocity of the car.

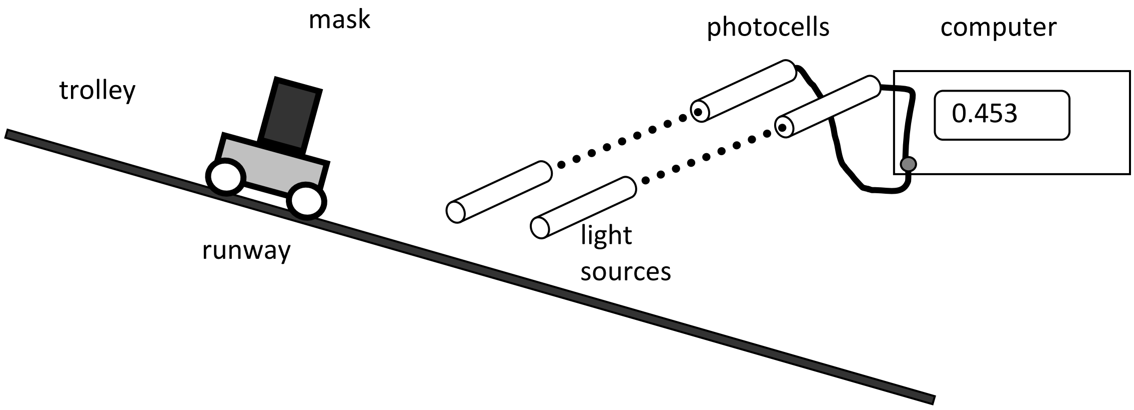
v = ? u = 15 m/s a = 2 m/s^2 t = 4 s

$v = u + at$

$= 15 + (2 \times 4)$

$= 23$ m/s

Measuring Acceleration



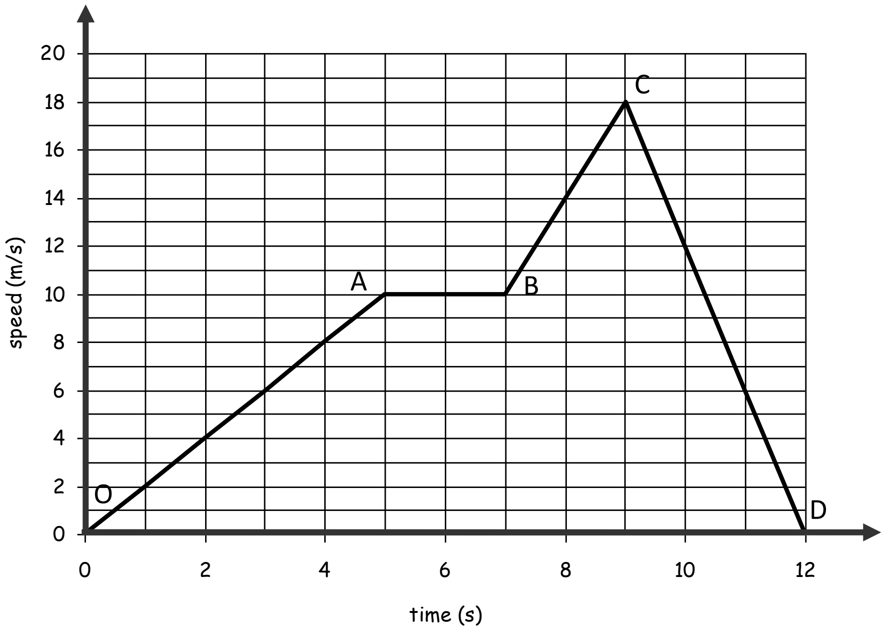
- Set up apparatus as shown
- Measure length of mask
- Let the trolley accelerate past the two photocells
- Computer measures time taken for card to pass through both light gates. Computer also measures the time between both light gates
- u is calculated using the formula for distance, instantaneous speed and time
- v is calculated using the formula for distance, instantaneous speed and time
- acceleration is then calculated using

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

Speed Time Graphs

Speed time graphs are useful to physicists because they can be used to:

a) describe the motion of the object
b) calculate the acceleration of the object
c) calculate the distance travelled by the object



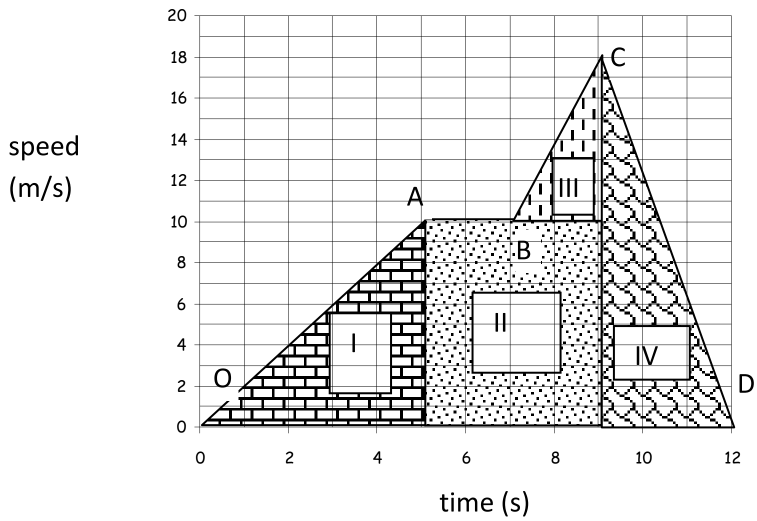
a) OA: Constant acceleration from 0 to 10 m/s in 5 seconds.

b) OA: acceleration = Δv/t

acceleration = (10 – 0)/5

acceleration = $\underline{\underline{2 m/s^2}}$

c) To calculate the distance the area under the graph must be used.



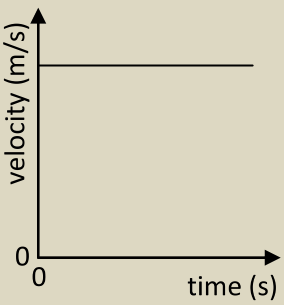
Area I :	Triangle area	= ½ x b x h	= ½ x 5 x 10	= 25m
Area II :	Rectangle area	= l x b	= 4 x 10	= 40m
Area III :	Triangle area	= ½ x b x h	= ½ x 2 x 8	= 8m
Area IV :	Triangle area	= ½ x b x h	= ½ x 3 x 18	= 27m
Total Area				= 100m
Distance travelled				**= 100m**

Velocity-time graphs

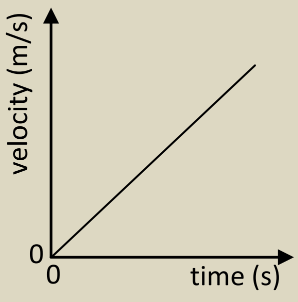
Velocity-time graphs provide a useful way of displaying the motion of an object.

They can be used to:

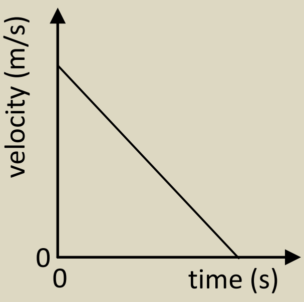
1) Describe the motion of the object in detail.
2) Calculate values for accelerations and decelerations using **gradients**.
3) Calculate distances travelled and resultant displacements **using area under graph**.
4) Calculate the average velocity for a journey.



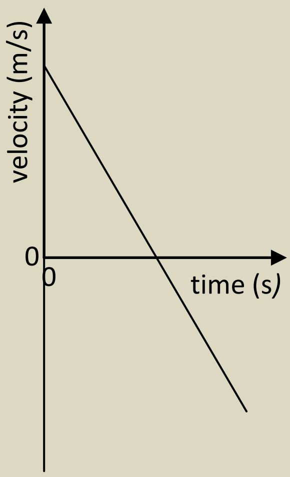
constant velocity



constant acceleration



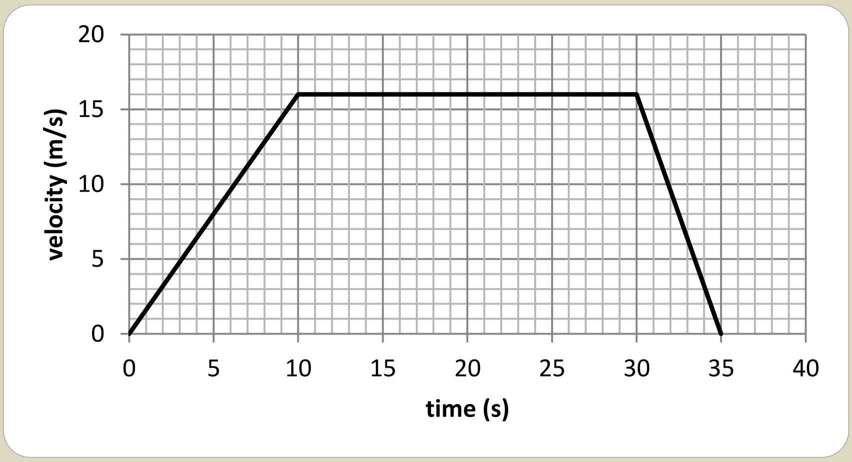
constant deceleration



constant deceleration to rest,then constant acceleration in the opposite direction

Example

The graph below shows the motion of a car over 35 seconds.



(a) Describe the motion of the car during the 35 seconds
(b) Calculate the acceleration between 0 and 10 seconds
(c) Calculate the acceleration between 30 and 35 seconds
(d) Calculate the final displacement of the car from the starting position
(e) Calculate the average velocity during the 35 seconds.

Solution

(a)

0→10 seconds:	constant acceleration from rest to 16 m/s
10→30 seconds:	constant velocity of 16 m/s
30→35 seconds	constant deceleration from 16 m/s to rest.

(b) a = ? v = 16 m/s u= 0 t = 10 s

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

$$a = \frac{16 - 0}{10}$$

$$a = \underline{\underline{1.6\ m/s^2}}$$

(c) a = ? v = 0 m/s u= 16 t = 5 s

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

$a = \frac{16 - 0}{5}$

$a = \underline{\underline{3.2\ m/s^2}}$

(d) displacement = area under v-t graph

= (½ x 10 x 16) + (20 x 16) + (½ x 5 x 16)

= 80 + 320 + 40

= $\underline{\underline{440\ m}}$

(e) average velocity = ? displacement = 440 m time = 35 s

$v = \frac{s}{t}$

$= \frac{440}{35}$

$= \underline{\underline{12.6\ m/s}}$

Newton's Laws

Effects of Forces

We can't see forces themselves, but we can observe the effects that they have.

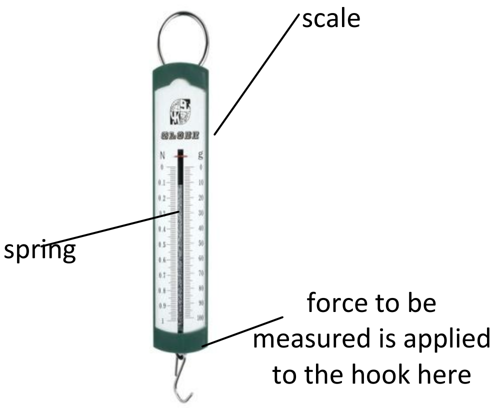
Forces can change:

- the shape of an object
- the speed of an object
- the direction of travel of an object

Measuring Force

The unit of force is the Newton.

The size of a force can be measured using a device called a **Newton Balance.**



A force is applied to the hook and the spring is stretched.

The greater the force applied, the greater the extension of the spring.

The size of the force is read from the scale.

Mass and Weight

Mass and Weight mean different things!

Mass is a measure of the amount of matter that an object is made of. The units of mass are kilograms (kg).

Weight is the size of the **force** that gravity exerts on an object. The units of weight are Newtons (N) since weight is a force.

Gravitational field strength

Gravitational field strength is the **weight per unit mass,** i.e. gravitational field strength is the amount of force that gravity exerts on every kilogram of an object.

$$g = \frac{W}{m}$$

Therefore the units of gravitational field strength are **Newtons per kilogram (N/kg).**

This can be rearranged to give:

$$W = m\,g$$

weight (N) — W; mass (kg) — m; gravitational field strength (N/kg) — g

Example

The gravitational field strength on the surface of Earth is 10 N/kg.
The gravitational field strength on the surface of the Moon is 1.6 N/kg.

Calculate the weight of an astronaut of mass 60 kg

(a) on the surface of the Earth
(b) on the surface of the Moon

Solution

(a) W=? m=60 kg g=10 N/kg

W = m g
= 60 x 10
= <u>600 N</u>

(b) W=? m=60 kg g=1.6 N/kg

W = m g
= 60 x 1.6
= <u>96 N</u>

Friction

Friction is a **resistive** force, which opposes the motion of an object. This means that it acts in the **opposite** direction to motion. Friction acts between any two surfaces in contact. When one surface moves over another, the force of friction acts between the surfaces and the size of the force depends on the surfaces, e.g. a rough surface will give a lot of friction.

Friction caused by collisions with particles of air is usually called **air resistance**. It depends mainly on two factors:

- the shape and size of the object
- the speed of the moving object.

Air resistance **increases** as the speed of movement increases.

Increasing and Decreasing Friction

Where friction is making movement difficult, friction should be reduced.

This can be achieved by:

- lubricating the surfaces with oil or grease
- separating the surfaces with air, e.g. a hovercraft
- making the surfaces roll instead of slide, e.g. use ball bearings
- streamlining to reduce air friction.

Where friction is used to slow an object down, it should be increased.

This can be achieved by:

- choosing surfaces which cause high friction e.g. sections of road before traffic lights have higher friction than normal roads
- increasing surface area and choosing shape to increase air friction, e.g. parachute.

Force is a vector

Force is a vector quantity. The direction that a force acts in will dictate the effect that it has.

Balanced Forces

Two forces acting in opposite directions are said to be **balanced**. The effect is equivalent to **no force** acting on the object at all.

Newton's First Law

"An object will remain at rest or move at a constant velocity in a straight line unless acted on by an unbalanced force".

This means that if the forces acting on an object are balanced, then the object will remain stationary if it was already stationary. For a moving object, if the forces acting on it are balanced, then it will continue to move in a straight line at a constant velocity.

balanced forces ↔ Object at rest OR object moving at a constant velocity in a straight line

Newton's Second Law

If an overall resultant (or unbalanced) force is applied to an object, then the object will accelerate in the direction of the unbalanced force.

- The greater the resultant force, the greater the acceleration.
- The smaller the mass, the greater the acceleration.

These two relationships are combined to give

(resultant or unbalanced) force (N)

$$F_u = m\,a$$

acceleration (m/s^2)

mass (kg)

This equation shows that a force of 1 N is the force needed to accelerate a mass of 1 kg at a rate of 1 m/s^2

Example

A trolley of mass 2 kg accelerates at a rate of 2.5 m/s^2.
Calculate the resultant force acting on the trolley.

Solution

F_u=? m=2kg a=2.5 m/s^2

F_u = m a

F_u = 2 x 2.5

F_u = 5 N

Free Body Diagrams and Newton's Second Law

"Free body diagrams" are used to analyse the forces acting on an object. The **names** of the forces are labelled on the diagram. (It is also useful to mark the **sizes** of the forces on the diagram).

This enables us to calculate the resultant force, and then apply F_{un}=ma.

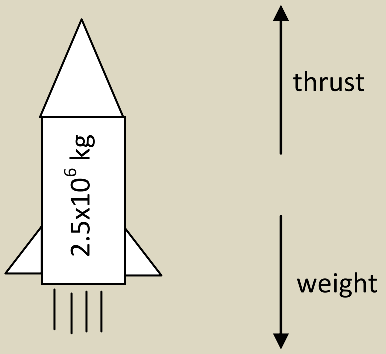
Example

A space rocket of mass 2.5x10^6 kg lifts off from the earth with a thrust of 3.5x10^7 N.

(a) Draw a free body diagram of the rocket at lift-off
(b) Calculate the resultant force acting on the rocket
(c) Calculate the initial acceleration of the rocket.

Solution

(a)



(Initially, no air resistance will act on the rocket at the instant it lifts off. Air resistance will only begin to act once the rocket starts moving).

(b) F_{un} = thrust – weight

= 3.5x10^7 – 2.5x10^7

= 1.0 x 10^7 N

W = mg

= 2.5x10^6 x 10

= 2.5x10^7 N

(c) $F_u = 1 \times 10^7$ N $m = 2.5 \times 10^6$ kg   a = ?

$$F_u = m\,a$$

$$1 \times 10^7 = 2.5 \times 10^6 \times a$$

$$F_u = \underline{\underline{4\ m/s^2}}$$

<u>Forces at Right Angles</u>

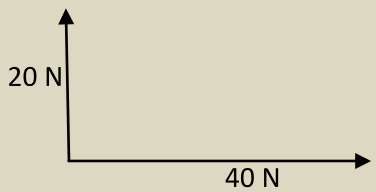
The resultant force arising from two forces acting at right angles can be found by

(a) Drawing the force vectors “nose-to-tail”

(b) Then find the magnitude using a ruler and your chosen scale, and the direction using a protractor.

Example

Two forces act on an object at right angles to each other as shown.

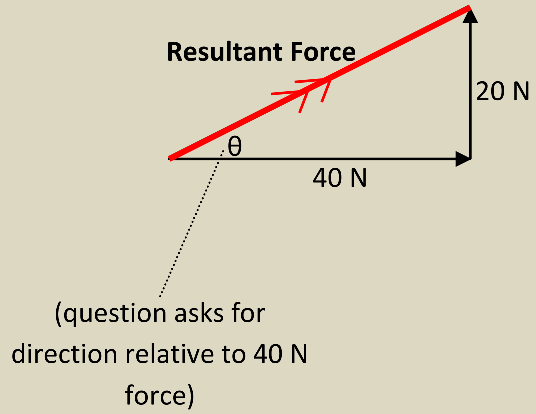


Calculate

(a) The magnitude of the resultant force
(b) The direction of the resultant force, relative to the 40 N force.

Solution

(arrange vectors "nose-to-tail" and draw resultant from tail of first to nose of last)



Using a scale diagram, work out the size of the resultant force and measure the angle.

Resultant force = <u>44.7 N at 26.6˚ to 40 N force</u>

<u>Acceleration Due to Gravity and Gravitational Field Strength</u>

Weight is the **force** which causes an object to accelerate downwards and has the value mg, where g is the gravitational field strength.

The value of the acceleration caused by weight can be calculated from Newton's second law, using $F_{un} = ma$ where F is now the weight W, and W = mg.

$$a = \frac{F_u}{m}$$

$$a = \frac{W}{m}$$

$$a = \frac{mg}{m}$$

$$a = g$$

This shows that the acceleration due to gravity and the gravitational field strength are **numerically equivalent.**

Therefore the acceleration due to gravity on Earth is 10 m/s^2 since the gravitational field strength is 10 N/kg.

The acceleration due to gravity on the moon is 1.6 m/s^2 since the gravitational field strength is 1.6 N/kg.

Example

An astronaut drops a hammer on the Moon where the gravitational field strength is 1.6 m/s^2. The hammer lands on the surface of the Moon 2.2 s after being dropped.

Calculate the velocity of the hammer at the instant it strikes the surface of the Moon.

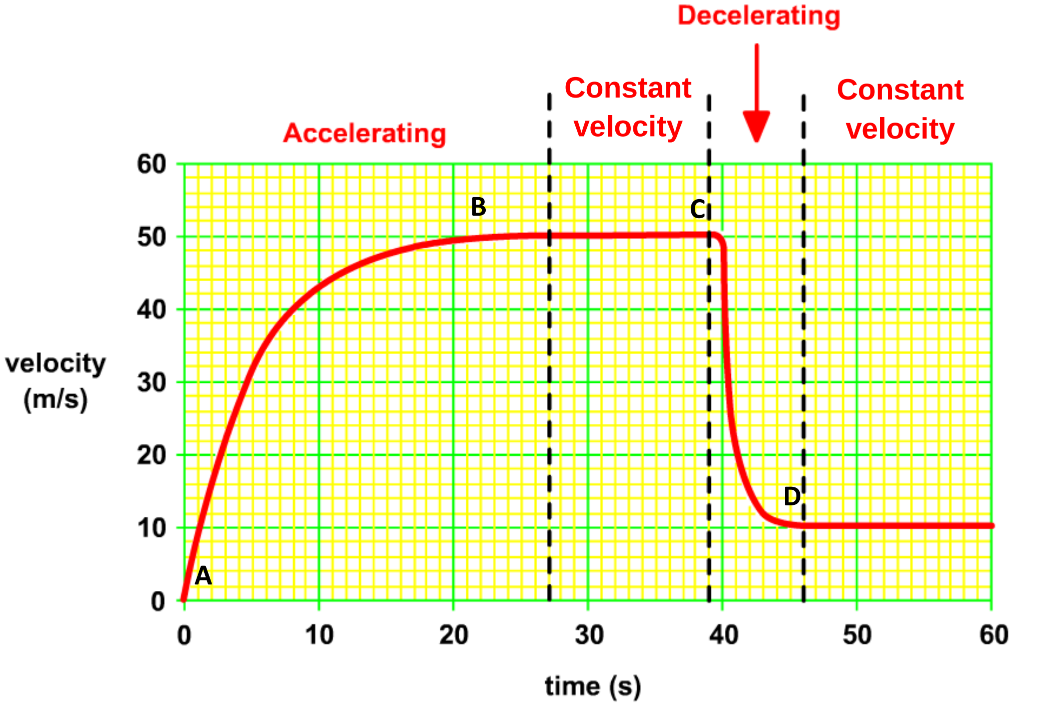
Solution

u=0 v= ? a=1.6 m/s^2 t=2.2 s

$v = u + at$
$v = 0 + (1.6 \times 2.2)$
$v = \underline{\underline{3.52\ m/s}}$

<u>Free-fall and Terminal Velocity</u>

An object falling from a height on Earth will **accelerate** due to its weight. This is called **free-fall.**
As the velocity increases, the air resistance acting on the object will increase.
This means that the unbalanced force on the object will decrease, producing a smaller acceleration.
Eventually, the air resistance will balance the object's weight, meaning that the object will fall with a **constant velocity.**
This final velocity is called **terminal velocity.**
The velocity-time graph shown below is for a parachutist undergoing free-fall before opening her parachute.



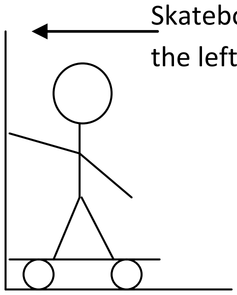
Point A –	parachutist jumps from plane and undergoes acceleration due to gravity **(free-fall)**
Point B –	air resistance has increased to balance weight – constant velocity: **terminal velocity 1**
Point C –	parachutist opens parachute – increased air resistance causes deceleration
Point D –	weight and air resistance balanced again so new slower constant velocity reached: **terminal velocity 2**

Newton's Third Law

"For every action, there is an equal and opposite reaction".
Newton noticed that forces occur in pairs. He called one force the **action** and the other the **reaction**. These two forces are always **equal in size, but opposite in direction**. They do not both act on the same object.
If an object A exerts a force (the action) on object B, then object B will exert an equal, but opposite force (the reaction) on object A.

Examples

Skateboarder pushes wall to the left (action force)



Wall pushes skateboarder to right (reaction force)

Water pushes swimmer to left (reaction force)

Swimmer pushes water to right (action force)

Fuel forces rocket upwards (reaction force)

Rocket forces fuel downwards (action force)

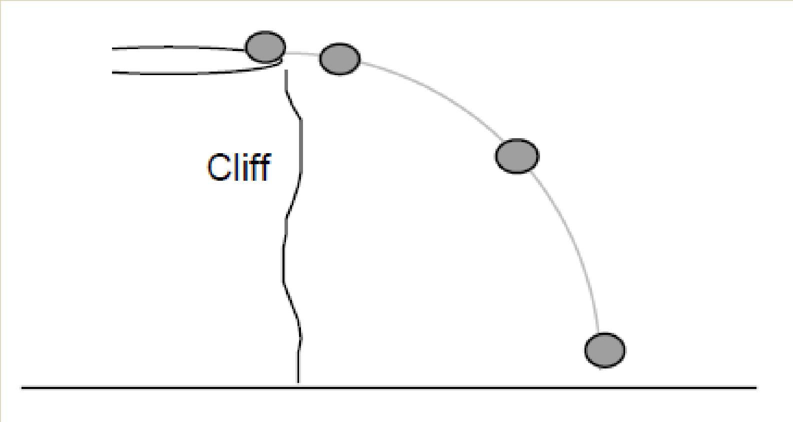
Cannon fires cannonball to the right (action force)

Cannonball forces cannon back to the left (reaction force)

These action and reaction forces are also known as **Newton Pairs.**

Projectile Motion

A projectile is an object which has been given a forward motion through the air, but which is also pulled downward by the force of gravity. This results in the path of the projectile being curved.



A projectile has two **separate** motions at right angles to each other.

Each motion is **independent** of the other.

The **horizontal** motion is at a **constant velocity** since there are no forces acting horizontally (air resistance can be ignored).

So

$$d_h = v_h t$$

horizontal distance (m)

horizontal velocity (m/s)

time (s)

The **vertical** motion is one of **constant acceleration**, equal to g (10 m/s^2 on earth).

For projectiles which are projected horizontally, the initial vertical velocity is zero.

For vertical calculations, use

$$v_v = u_v + at$$

where $u_v = 0$ and $a = g$

final vertical velocity (m/s)

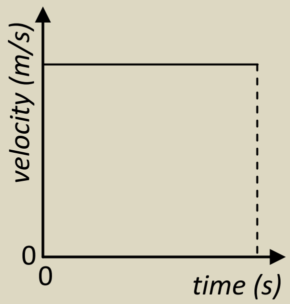
initial vertical velocity (m/s)

acceleration due to gravity (m/s^2)

time (s)

<u>Velocity time graphs for horizontal and vertical motion</u>

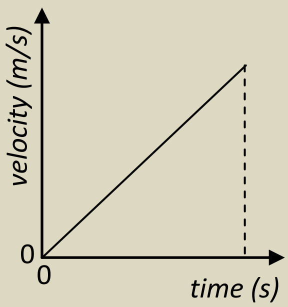
Horizontal motion



constant velocity

horizontal distance can be found using area under graph (equivalent to $d_h=v_ht$)

Vertical motion



constant acceleration from rest

vertical height can be found from area under graph (equivalent to $h=½\ v_{max}t$)

Example

An aircraft flying horizontally at 200 m/s drops a food parcel which lands on the ground 12 seconds later.

Calculate:

a) the horizontal distance travelled by the food parcel after being dropped

b) the vertical velocity of the food parcel just before it strikes the ground

c) the height that the food parcel was dropped from.

Solution

(a useful layout is to present the horizontal and vertical data in a table)

(then select the data you need for the question, and clearly indicate whether you are using horizontal or vertical data).

Horizontal	Vertical
d_h = ?	u_v = 0
v_h = 200 m/s	v_v = ?
t = 12 s	a = 10 m/s^2
	t = 12 s

initial vertical velocity always 0 for a projectile launched horizontally

acceleration due to gravity

time of flight the same for both

(a) Horizontal:

$d_h = ?$ $v_h = 200$ m/s $t = 12$ s

$d_h = v_h t$

$d_h = 200 \times 12$

$d_h = \underline{\underline{2400 \text{ m}}}$

(b) Vertical:

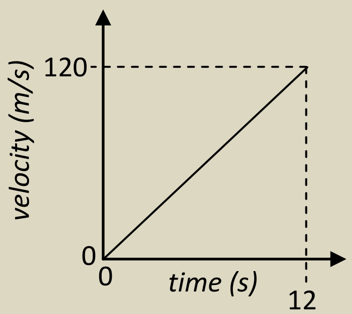
$u_v = 0$ $v_v = ?$ $a = 10 \text{ m/s}^2$ $t = 12$ s

$v_v = u_v + at$

$v_v = 0 + 10 \times 12$

$v_v = \underline{\underline{120 \text{ m/s}}}$

(c) (Draw a velocity time graph of **vertical** motion)



height = area under v-t graph

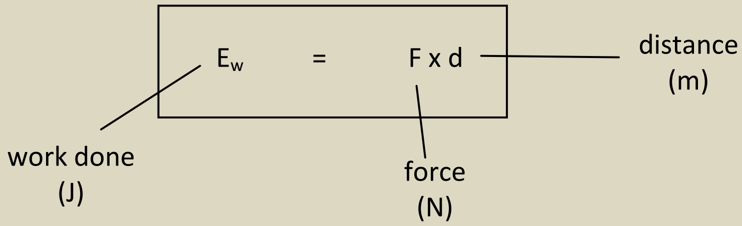
= ½ x 12 x 120

= $\underline{\underline{720 \text{ m}}}$

Work

Work is a measure of how much energy has been used or transferred.

work done = force x distance



Example

An engine exerts a pull of 5 000 N to pull a train a distance of 400 m.

How much work is done?

Solution

E_w = ? F = 5 000 N d = 400 m

E_w = F x d

E_w = 5 000 x 400

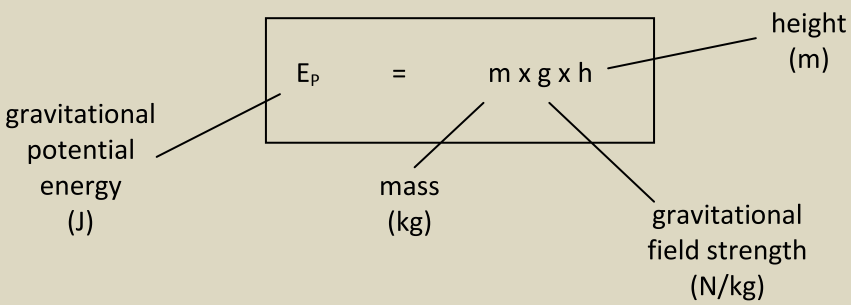
E_w = 200 000 J

Gravitational potential energy

When an object is lifted it will gain energy. This energy is known as gravitational potential energy.

gravitational potential energy = mass x gravitational field strength x height

E_P = m x g x h



Example

A lift raises a person of mass 55 kg to a height of 60 m.

How much potential energy does the person gain?

Solution

E_P = ? m = 55 kg g = 10 N/kg h = 60 m

$E_P = m \times g \times h$

$E_P = 55 \times 10 \times 60$

$E_P = \underline{\underline{33\,000\text{ J}}}$

<u>Power</u>

Power is a measure of how quickly energy is converted. The more powerful an appliance, machine or person the greater the quantity of energy converted each second.

Power = energy ÷ time

$$P = \frac{E}{t}$$

power (W)

energy (J)

time (s)

Example

A man pushes a wheelbarrow for 60 m using a 50 N force. If he takes 10 s, what is his average power?

Solution

This must be answered in two steps. Calculate the work done, then the power.

E_w = ? F = 50 N d = 60 m

$E_w = F \times d$

$E_w = 50 \times 60$

$E_w = \underline{\underline{3000\text{ J}}}$

$P = ?$ $E = 3000\ J$ $t = 10\ s$

$$P = \frac{E}{t}$$

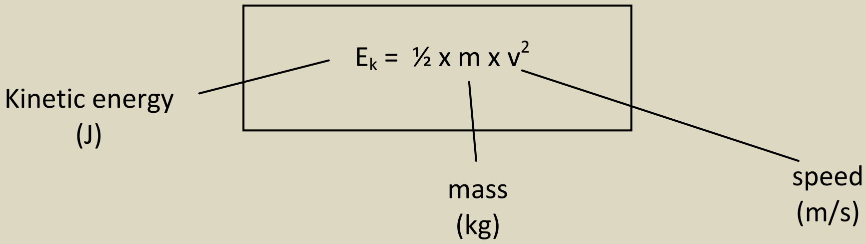
$$P = \frac{3000}{10}$$

$$P = \underline{\underline{300\ W}}$$

Kinetic energy

Kinetic energy is the energy of movement. The kinetic energy of an object increases with its speed.

Kinetic energy = ½ x mass x speed^2



Example

Calculate the kinetic energy of a 0.02 kg bullet moving at 100 m/s.

Solution

$E_k = ?$ $m = 0.02\ kg$ $v = 100\ m/s$

$E_k = ½ \times m \times v^2$

$E_k = ½ \times 0.02 \times 100^2$

$E_k = ½ \times 0.02 \times 10\,000$

$E_k = \underline{\underline{100\ J}}$

Conservation of Energy

Energy cannot be created or destroyed but it can change from one form to another.
Sometimes the energy produced is not useful; we say that this energy has been lost to the system.
Normally this energy is lost as heat due to friction.