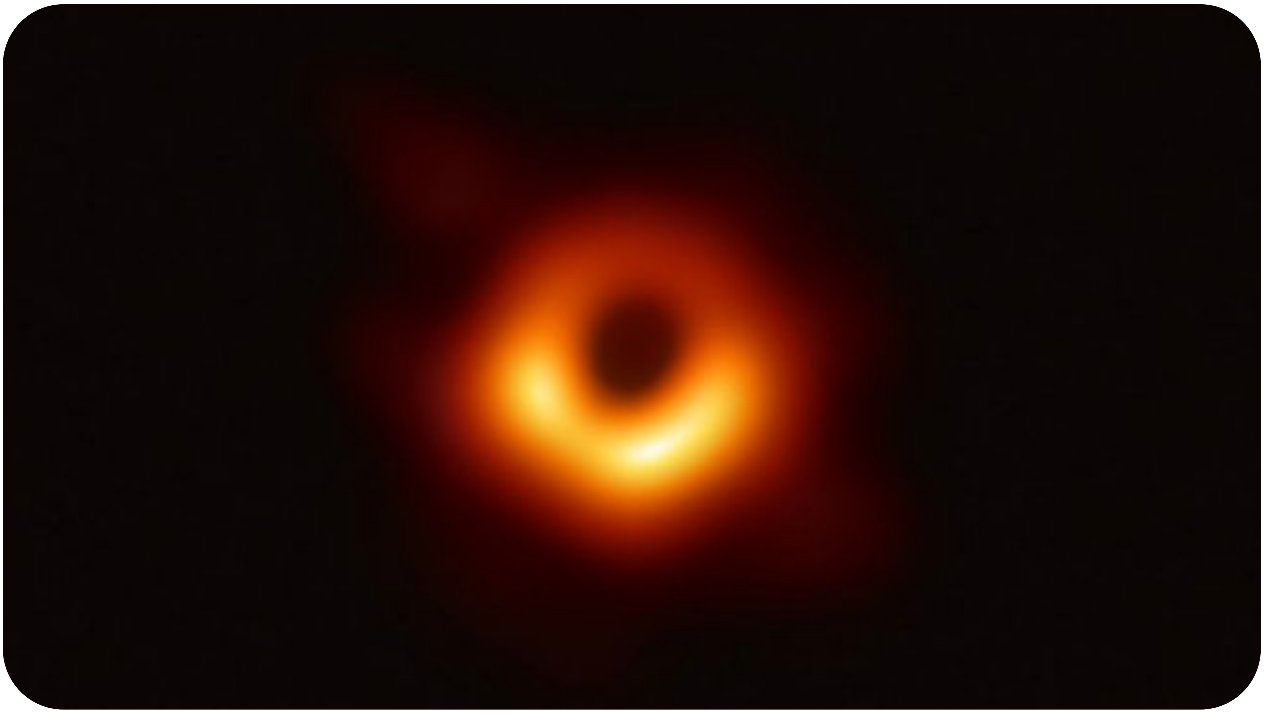
EDEXCEL International Advanced Level



Edexcel IAL Physics Unit 1

Summary©

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HS

SI Units

Base quantity	Base Unit	Symbol
Length	Metre	m
Mass	Kilogram	kg
Time	Second	s
Current	Ampere	A
Temperature interval	Kelvin	K
Amount of substance	Mole	mol
Luminous intensity	Candela	cd

Derived Units

Quantity	Definition	Derived Unit	Base units
Speed	$\frac{distance}{time}$		ms^{-1}
Acceleration	$\frac{\Delta velocity}{\Delta time}$		ms^{-2}
Force	$F = m \times a$	Newton (N)	$kg\ m\ s^{-2}$
Pressure	$p = \frac{F}{A}$	Pascal (Pa)	$kg\ m^{-1}\ s^{-2}$
Work (energy)	$W = F \times x$	Joule (J)	$kg\ m^{2}\ s^{-2}$
Power	$P = \frac{W}{t}$	Watt (W)	$kg\ m^{2}\ s^{-3}$
Charge	$Q = I \times t$	Coulomb (C)	A s
Potential difference	$V = \frac{W}{Q}$	Volt (V)	$kg\ m^{2}\ A^{-1}\ s^{-3}$
Resistance	$R = \frac{V}{I}$	Ohm (Ω)	$kg\ m^{2}\ A^{-2}\ s^{-3}$

Prefixes

Prefix	Symbol	Multiple
Pico	p	10^{-12}
Nano	n	10^{-9}
Micro	µ	10^{-6}
Milli	m	10^{-3}
Kilo	K	10^{3}
Mega	M	10^{6}
Giga	G	10^{9}
Tera	T	10^{12}

Motion

1 Speed and Distance

Average speed

An object's speed is calculated by dividing the distance moved by the time taken to move that distance.

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

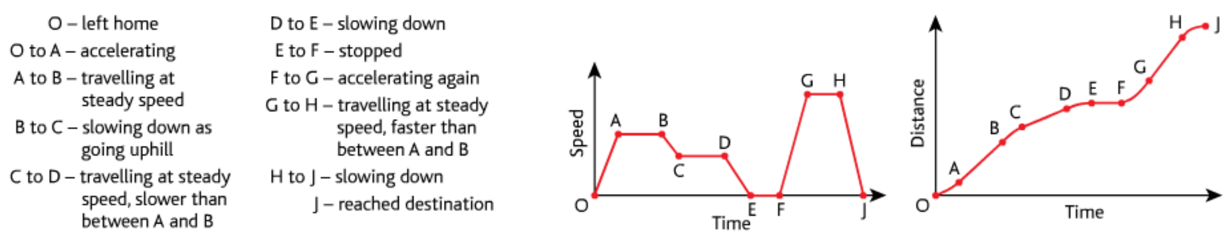
Instantaneous speed

The instantaneous speed is defined as the speed at an instant.

$$v = \frac{\delta x}{\delta t}$$

Graphs

It is often very useful to represent motion using a graph. This graph could plot distance against time or it could plot speed against time.



- Where the speed-time graph is horizontal between two points, the distance-time graph has a steady slope between the same points because the distance travelled per unit time is constant.
- Where the speed-time graph has a value of zero, the distance-time graph is horizontal because the person is stationary. In other words, the slope or gradient of a distance-time graph represents the speed at that particular point, the instantaneous speed.

Steady speed corresponds to a straight line on the distance-time graph. Where an object has a steady speed, the slope of the distance-time graph is constant, and the object's average speed and instantaneous speed are the same.

HSW-Recording motion

Measurements made with electronic sensors will be more precise and more accurate than measurements made by people using stopwatches and rulers, for example. The electronic measurements will not suffer from human errors such as:

- Reaction time
- Misreading of scales

Light gates could also be used. They allow greater precision than stopwatches. The data will have improved validity and reliability. With light gates, the length of card interrupting the beam, or the distance between the gates, must still be measured manually.

2 DISTANCE AND DISPLACEMENT

Clearly we need a way of distinguishing between these two meanings of distance. In physics we use the terms distance and displacement. To describe fully the distance travelled, we only need to say how far you have gone. To describe your displacement, we not only need to specify how far you are from where you started, but also in what direction you would need to travel to get there. Distance is a scalar quantity-it has only magnitude. Displacement is a vector quantity-as well as its magnitude, it has direction.

Displacement and velocity

We have seen that speed is defined as distance moved in unit time. In the same way, we can now use the definition of displacement to calculate a new quantity, velocity:

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

Velocity is a vector too just as displacement.

Acceleration

Acceleration is a measure of the rate at which the velocity changes. Velocity is the rate of change of displacement. Acceleration is the rate of change of velocity, so it is a vector too. If the direction of an object changes, yet its magnitude stays constant, its velocity changes, so does its acceleration.

Acceleration happens when there is:

- a change in speed
- a change in direction
- a change in speed and direction

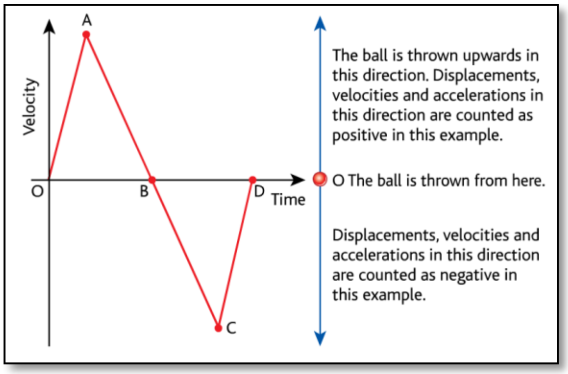
$$average\ acceleration = \frac{final\ velocity - initial\ velocity}{time\ taken\ for\ change}$$

3 MORE INFORMATION FROM GRAPHS OF MOTION

Velocity-time graphs are particularly useful in providing information about motion. The slope of a distance-time graph gives us information about an object’s speed, because speed is the rate of change of distance with time. In the same way, the slope of a velocity time graph gives us information about an object’s acceleration.

Where a velocity-time graph is a straight line, the acceleration is uniform. Acceleration may be represented as the rate of change of velocity with time.

The area between the graph and time axis on a velocity-time graph is equal to displacement.



Direction of acceleration

The graph shows the motion of a ball thrown upwards, and falling back to Earth again to be caught.
OA- Uniform upwards acceleration
AB- Acceleration in a downward direction (slows down)
B- At rest, highest point of its trajectory
BC- Acceleration in a downward direction (speeds up)
C- Ball is caught.
CD- Large upward acceleration to bring the ball back to rest

The slope of each part tells us about the acceleration of the ball, while the line itself shows how the velocity of the ball changes.

Area OAB = Area BCD

- Since the area under the line represents the ball's displacement, this shows that the ball's displacement upwards is equal to its displacement downwards. In other words, the ball falls back to the Earth the same distance as it rises- it finishes up where it began.

Non-linear graphs

The method for measuring the area under a graph to determine the distance travelled may be used for graphs which non-linear too. It could be measured in two different ways.

- Dividing the area into strips and calculating the area of each strip, then adding them up.
- By counting the number of squares and multiplying this value with the magnitude of one square

Note: If the area is under the x-axis, the area is negative because it represents a displacement in the opposite direction to the first displacement.

4 EQUATIONS OF MOTION

s= displacement	$v = u + at$
u= initial velocity	$s = ut + \frac{1}{2}at^2$
v= final velocity	
a= acceleration	$s = \frac{(u+v)t}{2}$
t= time taken	$v^2 = u^2 + 2as$

These equations only apply where the acceleration is uniform, which does include zero acceleration. Displacement, velocity and acceleration are all vector quantities, so you need to define one direction as positive and the opposite direction as negative.

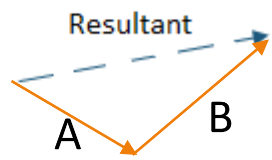
5 VECTORS

Vectors give us a fairly simple way of handling motion when it is not in a straight line. Vectors can represented by arrows drawn to scale. The length of the arrow represents the magnitude of the vector, while the direction of the arrow represents the direction of the vector.

Combining vectors

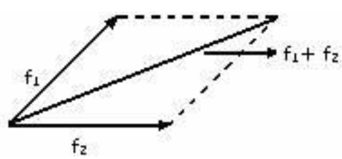
- ❖ The triangle rule

The sum of two or more quantities is called their resultant. In triangle rule, to determine the resultant of two vectors, the two vectors are drawn tip-to-tail and the resultant is the third side.



- ❖ The parallelogram rule

The parallelogram rule can be applied whenever vectors act at the same time or from the same point. Two vectors can be shown as two sides of a parallelogram. The diagonal of the parallelogram is the resultant.



6 FORCES

Causes of motion

Since ancient times, philosophers have tried to reason motion. Aristotle identified that motion was maintained by forces. After many years, Galileo understood that the idea of force is central to the understanding of motion, but realised that Aristotle's explanation was incomplete. Galileo carried out experiments with a pendulum and realised that the bob was rising to the height from which it was released. He extended his experiment by carrying out a 'thought experiment'. He reasoned that if a ball rolls down a slope onto an indefinitely long flat surface, by simple analogy with the pendulum experiment it will continue moving until something else causes it to stop.

7 NEWTON'S FIRST LAW OF MOTION

Newton's first law of motion states that an object will remain in a state of rest or continue to move with constant velocity unless acted upon by a resultant external force.

In other words, an object has constant velocity which may be zero until a force acts on it. So the first law of motion defines for what a force is, or rather what it does- a force is something which can cause acceleration.

The reason why we appear to need to push something to keep it moving steadily is because the motion of any object on Earth is opposed by friction forces. If there were no friction forces, then one push would cause an object to move indefinitely along a flat surface at steady speed.

Newton's first law in mathematical terms

Since Newton's first law expresses motion in terms of the total force acting on a body, it can be written down involving mathematical terms.

If a body has a number of forces F_1, F_2…F_N acting on it, it will remain in state of constant motion only if:

$$\Sigma F = 0$$

(that is, the sum of all the forces from F_1 to F_n is equal to zero).

Free body diagrams

Since a force can cause acceleration, it is a vector quantity, with both magnitude and direction. It therefore requires a way of representing both magnitude and direction on a diagram. A diagram which shows all the forces acting on a body in a certain situation is called a free-body force diagram.

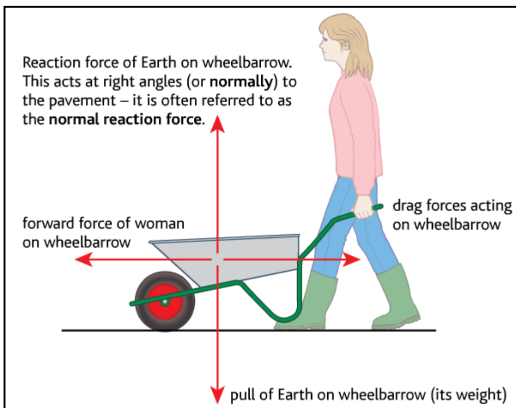


fig. 1.2.3 A simplified free-body diagram of a wheelbarrow being pushed at a steady speed along a flat surface. Notice how each force acting is cancelled out by a force exactly equal in size but opposite in direction to it. This is what Newton's first law tells us – the resultant force acting on something with constant velocity is zero.

Centre of gravity and centre of mass

In problems involving solid objects, we often draw the weight of an object as acting through a single point. This point is called the centre of gravity.

The centre of gravity of an object is the point at which the weight of the objects appears to act.

An object's centre of mass has a similar definition:

It is the point at which all the object's mass may be considered to be concentrated. In most common circumstances an object's centre of mass and centre of gravity are at the same place.

For uniform objects, the centre of mass will be at the intersection of all lines of symmetry, essentially in the middle of the object.

8 DRAG FORCES

Imagine an object with constant motion. Remove the forward force acting on it and the forces are no longer balanced. The resultant force now acts backwards, so the object accelerates backwards, that is, it slows down and eventually stops. It does not continue to move in backward direction because of the way that drag forces work. The frictional forces act simply to oppose any motions that take place. It cannot actually cause motion. When an object comes to rest, the frictional force stops acting. It will only become important again when the object begins to move again.

Air resistance

Aerodynamic drag is caused by the fact that an object has to push out air out of the way in order to move through it and this requires force. The force that is exerted by two surfaces rubbing together does not depend on the speed at which the two surfaces move over each other. However, the aerodynamic drag caused by an object moving through air does depend on speed- the faster the object moves, the greater the aerodynamic drag. Because aerodynamic drag increases as an object's velocity increases, objects with constant driving force tend to reach a maximum velocity when they accelerate.

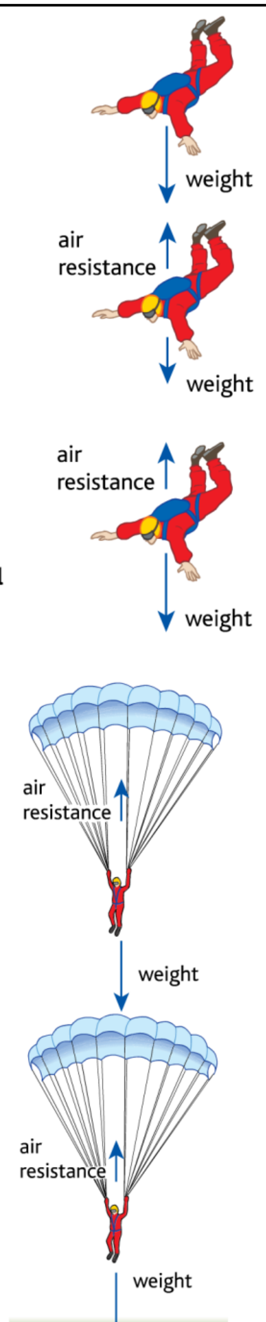
At the top of the jump, the man is instantaneously stationary, so his air resistance is zero. The resultant force acting on him is greatest at this point, so his acceleration at this point has its maximum value.

A little later the man is moving more rapidly and his air resistance is now significant. The magnitude of his weight is still greater than his air resistance, so he is still accelerating downwards, but not as quickly as at first.

Later still his velocity has reached a point where his air resistance is equal to his weight. Now the resultant force acting on him is zero – and he is no longer accelerating. The velocity at which this happens is called the **terminal velocity**. For a human being without a parachute, terminal velocity is about $56\,m\,s^{-1}$.

On opening the parachute, the air resistance increases dramatically due to the parachute's large surface area. Now the air resistance is greater than the weight – so the resultant force on the man is upwards. The man accelerates upwards and his velocity decreases.

Eventually the man's velocity decreases to a new terminal velocity. This terminal velocity is much lower than the previous terminal velocity – about $10\,m\,s^{-1}$. Hitting the ground at this speed still requires some care – it is like jumping off a wall 5 m high!



9 NEWTON'S SECOND LAW OF MOTION

Newton's second law of motion states that the acceleration of a body of constant mass is proportional to the resultant force applied to it and in the direction of the resultant force.

The unit of force is Newton. This equation defines the Newton as being the resultant force which produces acceleration of one metre per second per second when it acts on a mass of one kilogram. The mathematical statement of Newton's second law of motion is:

$$\Sigma F = ma$$

10 INERTIA, MASS AND WEIGHT

The tendency of an object to stay in its state of rest or uniform motion is called its inertia. An object's inertia depends only on its mass. An example of inertia is:

- Without the help of a seatbelt, it can be hard for someone sitting in a moving car to stop moving when the driver of the car applies the brakes sharply.

The term weight is often used in everyday life. An object's weight is a force acting on it. Newton argued that it was this attractive force that we call weight. Our modern interpretation of this theory says that all masses have a gravitational field around them which causes the mass to attract other mass which is close to it. The size of the field around a particular mass depends on the size of the mass and whereabouts in the field you are.

Gravitational field strength and weight

Gravitational field strength, g, at a point in a gravitational field is defined as the force per unit mass acting at that point. In mathematical terms:

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

The weight of an object may be calculated from this relationship.

$$W = mg$$

11 NEWTON'S THIRD LAW OF MOTION

Newton's third law of motion states that if body A exerts a force on body B, then body B exerts a force of the same size on body A, but in opposite direction.

Newton's third law pairs of forces must always:

- Act on two separate bodies
- Be of the same type
- Act along the same line
- Be equal in magnitude
- Act in opposite directions

12 Statics

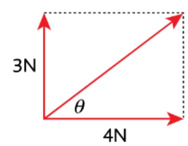
Some objects may be in equilibrium that is they are at a steady state. The forces on a body in equilibrium are balanced. Statics is the study of forces on objects that are not moving.

Adding forces

Since force is a vector quantity, when we add forces together we must be careful to take into account both their magnitude and their direction. To do this easily we draw vector diagrams.

Although it is not always as easy as this, the principle of adding two forces is always the same:

- Draw the forces acting at the same point
- Construct the parallelogram
- Draw in the diagonal from the point at which the forces act to the opposite corner of the parallelogram
- Measure or calculate the size and direction of the resultant

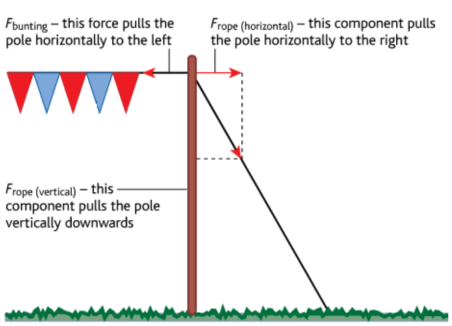


Scale drawing to find the resultant of two forces

Resolving forces

A single vector can be represented as the sum of two perpendicular vectors, known as its components. Vectors at right angles can then be treated independently, and can have magnitudes added to other parallel vectors if necessary.

The components of a vector are found by using that vector as the diagonal of a parallelogram of vectors or as the hypotenuse of a right-angled triangle of vectors.



By resolving the forces in this way it becomes clear that the tension in the bunting and the rope has two effects:

1. pulling the pole sideways
2. pulling the pole downwards.

The example of bunting provides us with a good opportunity to gain an understanding of the idea of static equilibrium. As the pole is at rest, Newton's first law of motion tells us that:

$$\Sigma F = 0$$

This means that:

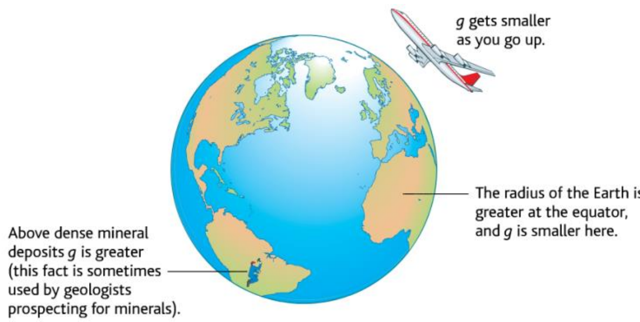
$$F_{bunting} = -F_{rope\ (horizontal)}$$

,and that $F_{rope\ (vertical)}$ must also be balanced by an equal and opposite force- supplied by the ground pushing upwards on the base of the pole.

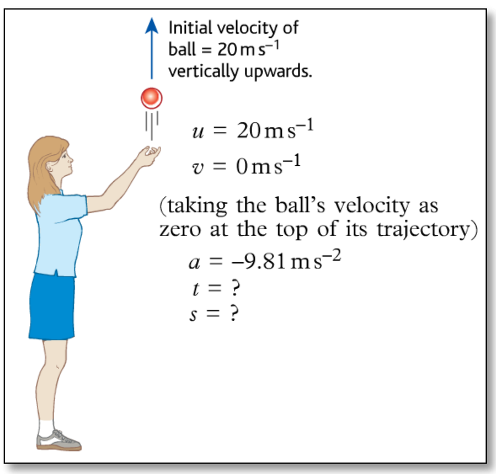
13 Projectiles

A projectile is an object which is projected that is to say a force acts on it to start it moving and it then subjected to a constant force while it moves. In most cases this will mean that the object is in free fall in the Earth's gravitational field.

An object which is dropped from rest a small distance above the surface of the Earth accelerates vertically downwards under the influence of its weight. Theoretically the acceleration of an object in free fall is independent of its mass, although this is strictly true only in vacuum- air resistance affects the motion of objects unequally, according to their cross-sectional area.



Vertical projection



Equations of motion should be used to determine the time and the maximum height.

Using equation of motion 4:

$$v^2 = u^2 + 2as$$

Substitute values:

$$(0)^2 = (20)^2 + 2 \times -9.81 \times s$$

$$s = \frac{400}{2 \times 9.81}$$

$$= 20.4\,\text{m}$$

$$v = u + at$$

Substitute values:

$$0 = 20 + -9.81 \times t$$

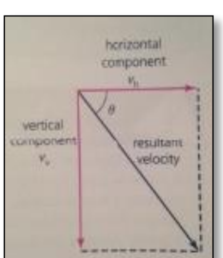
so:

$$t = \frac{20}{9.81}$$

$$= 2.04\,\text{s}$$

- The ball takes 2.04s to return to its initial height from the top of its trajectory.
- Its final velocity before being caught again is -20ms^{-1}.

Horizontal projection

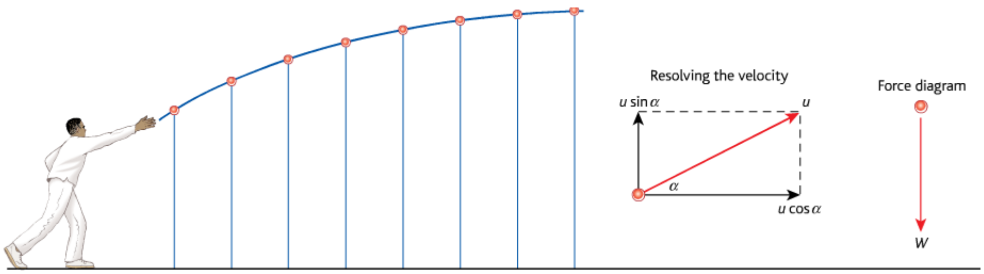


The diagram shows an object that has been projected horizontally and is now falling freely under gravity. The horizontal velocity is the same at each point, but the downward velocity is increasing. The path followed is determined by the resultant velocity at each instant and is parabolic.

Horizontal and vertical velocities at successive time intervals

The vertical motion and the horizontal motion can be considered quite separately. This leads to the surprising conclusion that the time of flight of an object is the same whether it is dropped or projected horizontally- in both cases the initial vertical component of velocity is zero.

Projection at an angle



The velocity of the ball can be resolved into a horizontal and vertical component. The force diagram shows the force acting on the ball. This acts only in vertical direction, so the ball will accelerate in a vertical direction only. As a result, horizontal motion of the ball is not subject to any acceleration, and so the horizontal component of the ball's velocity is constant.

The key variable that links the vertical and horizontal motion of the ball as it travels through the air is the time, which is normally measured from the instant of launching the object.

14 Energy and Power

The law of conservation of energy

We commonly think of energy as coming in a number of forms. Investigation of energy and its forms lead us to conclude that although energy may appear in different forms when a change occurs, the total amount of energy remains constant. This rule has a status of a law in physics, and is called the law of conservation of energy. This is often expressed as:

Energy cannot be created or destroyed.

HSW- Laws and theories

A law supplies us with information on how the physical world may be expected to behave based on past experience, but it does not tell us why the physical world behaves in this way. It is the job of theories in science to tell us about the behaviour of things rather in more depth. A law is of course built on a limited number of observations, so it is necessary for physicists to assume that it is possible to predict the behaviour of the Universe in the future based on observations made in the past.

15 Energy Transformations

Transferring energy – heating and working

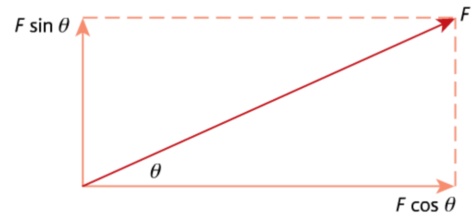
The difference between heating and working lies in the way that energy is transferred. If we heat an object, we transfer energy to it using temperature difference. If we wish to transfer energy without making use of temperature difference, we do it by doing work – for example, by lifting an object off the floor onto a table. The terms heat and work therefore describe energy which has been transferred in a particular way – by means of a temperature gradient or by means of using force.

Work and the units of energy

Energy is the ability to do work.

$$energy\ transferred = work\ done$$

$$energy\ transferred = Force \times distance$$



Although in calculating work done we are multiplying two vectors together, the result is a scalar. Energy has magnitude only.

Although work done is a scalar quantity, force and displacement are vectors, so their directions are important. If force and displacement are not in the same direction, use the component of force in direction of the displacement.

Note: The component of a force perpendicular to the displacement does no work, as it does not move in the direction in which it is acting.

16 ENERGY AND EFFICIENCY

Kinetic energy and potential energy

We are used to saying that an object has gravitational potential energy when it is raised through a distance Δh.

$$\Delta E_{grav} = m \times g \times \Delta h$$

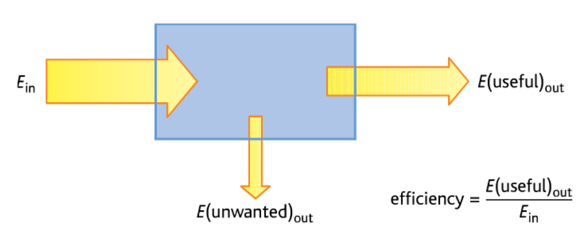
In the same way, we talk about a moving object possessing kinetic energy, and write the amount of energy as:

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

Mechanical energy is the sum of the kinetic and potential energy of an object.

Efficiency

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{energy input}} \times 100\%$$



The idea of efficiency is a useful one when we are considering energy transfers. With some thought it comes as little surprise to find that it is often impossible to take all the energy in an energy store and transfer it so that it does something useful. If we think of a machine or a process box which has energy going in and energy coming out of it, then we define efficiency as shown on the right:

17 POWER

The definition of power relates energy transferred to the time taken to do it. So:

$$power = \frac{energy\ transferred}{time\ taken}$$

Since we often refer to power developed when work is done, power may also be defined as:

$$power = \frac{work\ done}{time\ taken}$$

If a force is being moved at a steady rate, provided that we know the velocity at which the force is moving and the size of the force, we can calculate the power:

$$work\ done = force \times distance\ moved\ in\ direction\ of\ force$$

,and

$$power = \frac{work\ done}{time\ taken}$$

,so

$$power = force \times distance\ at\ which\ velocity\ is\ moving$$

,in symbols:

$$P = Fv$$

Relating power and efficiency

$$efficiency = \frac{useful\ energy\ output/time}{power\ input} \times 100\%$$

Materials

1 FLUID FLOW

A fluid is defined as any substance that can flow. Normally this means any gas or liquid, but solids made up of tiny particles can sometimes behave as fluids.

Density

One of the key properties of a fluid is its density. Density is a measure of the mass per unit volume of a substance. Its value depends on the mass of the particles from which the substance is made, and how closely those particles are packed.

$$density = \frac{mass}{volume}$$

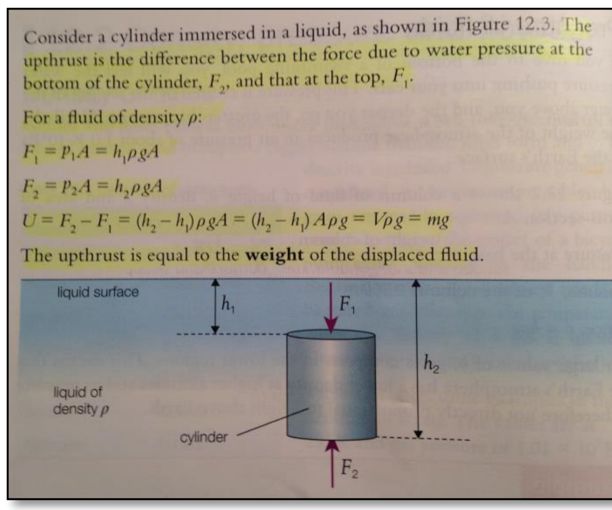
2 EUREKA!

When an object is submerged in a fluid, it experiences an upwards force caused by the fluid pressure – the upthrust. It turns out that the size of this force is equal to the weight of the fluid that has been displaced by the object. This is known as Archimedes' Principle. Thus, if an object is completely submerged, the mass of fluid displaced is equal to the volume of the object multiplied by the density of the liquid.

$$m = V\rho$$

The weight of the fluid displace, thus upthrust is then found using the relationship:

$$W = mg$$


Consider a cylinder immersed in a liquid, as shown in Figure 12.3. The upthrust is the difference between the force due to water pressure at the bottom of the cylinder, F_2, and that at the top, F_1.

For a fluid of density ρ:

$F_1 = P_1A = h_1\rho gA$

$F_2 = P_2A = h_2\rho gA$

$U = F_2 - F_1 = (h_2 - h_1)\rho gA = (h_2 - h_1)A\rho g = V\rho g = mg$

The upthrust is equal to the **weight** of the displaced fluid.

Sinking

When the weight of an object is greater than the upthrust acting on it, it sinks. It accelerates downwards within the water until it reaches the bottom of the container, which then exerts an extra upward force to balance the weight so the object rests on the bottom.

Floating

Imagine an object falling into a fluid. When the object is at the surface there is no upthrust, because no fluid has been displaced. As the object sinks deeper into the fluid, it displaces greater volume of the fluid, so increasing the upthrust acting upon it. When the upthrust and weight are balanced exactly, the object will float. So for an object to float, it will have to sink until it has displaced its own weight of fluid.

HSW- The Plimsoll Line

The Plimsoll Line on a ship indicates the safe loading level. As cargo is loaded, the ship will sink lower to displace a greater weight of water and thus balance the new, heavier overall weight of the ship.

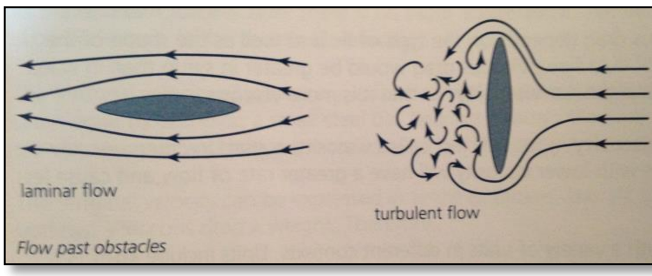
The hydrometer

The idea of floating at different depths is the principle behind the hydrometer, used to determine the density of a fluid. The device has a constant weight, so it will sink lower in fluids of lesser density. This is because a greater volume of a less dense fluid must be displaced to balance the weight of the hydrometer. Scale markings on the narrow stem of the hydrometer indicate the density of liquid.

3 FLUID MOVEMENT

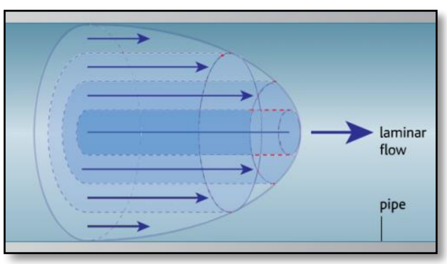
When a fluid moves, there are two ways this can happen:

- Laminar flow (streamline flow): Laminar flow occurs when adjacent layers of fluid do not cross into each other. It is smooth fluid flow in which layers have a constant velocity.
- Turbulent flow: Turbulent flow occurs when layers of fluid cross into each other, resulting in the formation of vortices or eddy currents. The fluid velocity is not constant over time.

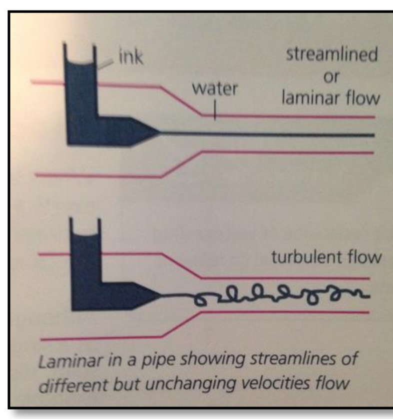


Flow past obstacles

In general, laminar flow occurs at lower speeds, and will change to turbulent flow as the fluid velocity increases past a certain value. The velocity at which this changeover occurs will vary depending upon the fluid in question and the shape of the area through which it is flowing.



If we take a simple example like water flowing slowly through a pipe, it will be laminar flow. The inner layers have a greater velocity than the outer layers. The difference in velocities of different layers is due to different frictions.



Laminar in a pipe showing streamlines of different but unchanging velocities flow

The laminar flow of water continues uniformly over time. Remember that velocity is a vector, so this means that the water at any given point in the pipe will always move in the same direction and the same speed. The direction and/or speed may be different in different places, but at any given place the direction and speed must stay constant. The lines of laminar flow are called streamlines. At any point on any one of these streamlines, the velocity of the flow will be constant over time.

In turbulent flow the fluid velocity in any given place changes over time. The flow becomes chaotic and eddies form, causing unpredictable higher and lower pressure areas. Turbulent flow, for example, increases the drag on a vehicle and so increases fuel consumption.

Streamline flow produces much lower air resistance than turbulent flow. Thus by altering the aerodynamics of their suits, skiers can raise the velocity at which the air movement past their body will change from laminar flow to turbulent flow. This is the principle behind all streamlined designs.

4 DRAG ACT

When you wade through a swimming pool, you find it much harder than walking through air. The friction acting against you is greater in water that it is in air. This frictional force in fluids is due to viscosity. If the frictional force caused by movement through the fluid is small, we say the viscosity is low.

Friction in fluids depends on several factors. As viscosity determines the friction force acting within a fluid, it has a direct effect on the rate of flow of the fluid. The rate of flow and viscosity are inversely proportional. The constituents of a fluid determine its viscosity. For instance, more sugar may mean greater viscosity of a chocolate, thus slower flow through the pipes.

An even greater variation in viscosity of a fluid is caused by changes in its temperature. Viscosity is directly related to fluid temperature. In general, liquids have a lower coefficient of viscosity at higher temperatures. For gases, viscosity increases with temperature.

5 TERMINAL VELOCITY

In order to calculate an object's actual acceleration when falling (it's not $9.81ms^{-2}$), we need to use Newton's second law. If we can take account of all the forces acting on an object, and combine these to find a resultant force, we can calculate the resulting acceleration.

For a falling object, we need to include the weight, the upthrust caused by the object being in the fluid air, and the viscous drag force caused by movement. The tricky part is that the viscous drag varies with speed through the fluid, and that is constantly changing as a result of acceleration. Usually, we consider equilibrium situation, in which the weight exactly balances the sum of upthrust and drag, meaning that the falling velocity remains constant. This constant velocity is terminal velocity.

HSW – Stokes' Law

Stokes' Law equation is for calculating the viscous drag on small sphere at low speeds.

$$F = 6\Pi r\eta v$$

Where, r is the radius of the sphere, v is the velocity of the sphere, and η is the coefficient of viscosity of the fluid.

If you consider the terminal velocity of the ball bearing in terms of the forces in detail, then:

weight = upthrust + Stokes force

$m_s g$ = weight of fluid displaced + $6\pi r\eta v_{term}$

where m_s is the mass of the sphere and v_{term} is its terminal velocity.

For the sphere, the mass m_s is given by:

m_s = volume × density of sphere = $\frac{4}{3}\pi r^3 \times \rho_s$

so the weight of the sphere W_s is given by:

$W_s = m_s g = \frac{4}{3}\pi r^3 \rho_s g$

For the sphere, the upthrust is equal to the weight of fluid displaced. The mass m_f of fluid displaced is given by:

m_f = volume × density of fluid = $\frac{4}{3}\pi r^3 \times \rho_f$

so the weight of fluid displaced W_f is given by:

$W_f = m_f g = \frac{4}{3}\pi r^3 \rho_f g$

Overall then:

$$\frac{4}{3}\pi r^3 \rho_s g = \frac{4}{3}\pi r^3 \rho_f g + 6\pi r\eta v_{term}$$

We can rearrange the equation to find the terminal velocity:

$$v_{term} = \frac{\frac{4}{3}\pi r^3 g\ (\rho_s - \rho_f)}{6\pi r\eta}$$

Cancelling the π and the radius term:

$$v_{term} = \frac{2r^2 g\ (\rho_s - \rho_f)}{9\eta}$$

Thus in such a simple situation, the drag force is directly proportional to the radius of the sphere, and directly proportional to the velocity.

So, terminal velocity is proportional to the square of radius. This means that a larger sphere falls faster.

6 STRENGTH OF MATERIALS – THE PHYSICAL PROPERTIES OF SOLIDS

Hooke's Law

There is a direct relationship between stretching a spring and the force it exerts. Hooke's Law states that the force F exerted by a spring is proportional to its extension Δx. This usually written as:

$$F = -k\Delta x$$

,where k is a constant for a particular spring called the spring constant. The negative sign shows that the force exerted by the spring is in the opposite direction to the extension. By using force exerted by the spring rather than force exerted on the spring, we ensure that we are always focusing on two properties concerned with spring itself.

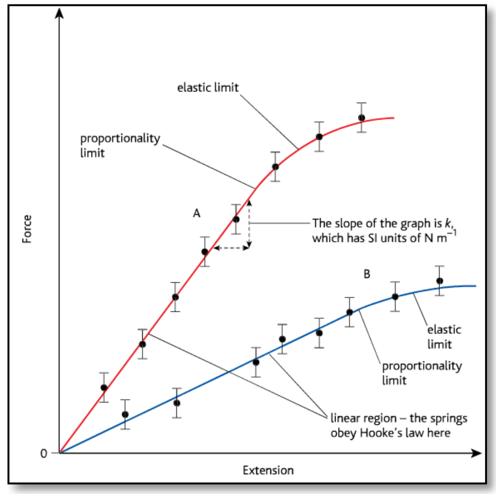
Investigations show that this law applies only for a load up to a certain limit. Up to this limit, the spring regains its original shape when the load is removed. The load at which this happens is called the elastic limit.

Beyond the elastic limit, materials no longer obey Hooke's Law and may be permanently deformed if stretched any further. This is known as plastic deformation.

HSW – Plotting graphs

- Axes

In plotting a graph we represent the way in which one variable changes with respect to another variable. This is done by changing the independent variable whilst keeping all other conditions constant, and making observations of the dependent variable. Independent variables are shown on the x-axis and dependent variables are shown on the y-axis.



- Errors

Any investigation will involve uncertainty in measurements. These uncertainties arise in different ways. When plotting variables on a graph it is good practice to estimate the likely uncertainty in the measurement of dependent variable, and to show this as a vertical error bar. This can then be used when drawing a line through the points.

- Lines

A line through the points may be straight or curved, and it may pass through the origin or through some point on y-axis. Using the error bars, a line through the points can then be drawn, from which gradients and intercepts can be calculated.

Elastic strain energy

The energy involved in stretching a spring can be calculated if Hooke's law is obeyed. The energy stored in the stretched spring is equal to work done on it as it is stretched which is a result of the average force used to stretch it to the extension Δx. Since the force increases from zero to F as the spring is stretch the average force is given by:

$$\frac{0+F}{2} = {}^{1}/_{2}\, F$$

So,

$$workdone = E_{el} = {}^{1}/_{2}\, k\Delta x^2$$

When we calculate the work done in stretching a spring, we are in effect calculating the area under the force-extension graph.

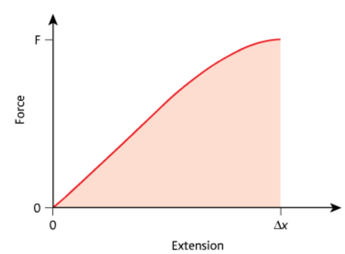


fig. 2.2.3 The shaded area in each graph represents the work done in stretching a spring from zero extension to an extension of Δx.

7 STRESS, STRAIN AND YOUNG MODULUS

In stretching a spring we are applying a tensile force to it. The properties of materials involved climbing ropes should be carefully chosen. Knowing the amount of extension for a given force would be a good start, and it could be helpful to know something about the force required to actually pull the material apart – its tensile stress. This will require us to know something about the size of the sample of material used, especially its area of cross-section, since this will have a great effect on its stretching behaviour and its strength. Length of the sample is also of great importance.

It can be easier to select the right materials if two new properties are defined.

- If we consider tensile force per unit area rather that tensile force alone, this takes into account the sample's area of cross-section.
- If we consider extension per unit length rather than extension alone, this takes into account the length of the sample.

Tensile force per unit area is called tensile stress,

$$tensile\ stress = \frac{tensile\ force}{area\ of\ cross - section}$$

Extension per unit length is called tensile strain,

$$tensile\ strain = \frac{extension}{original\ length}$$

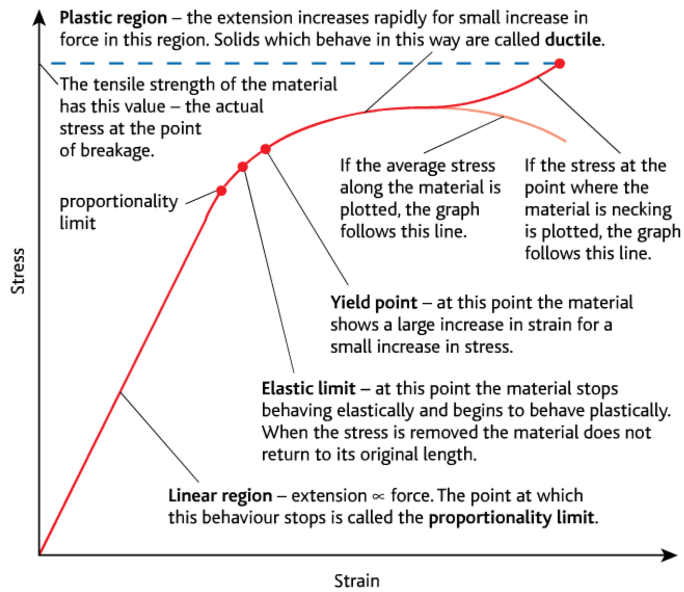
Samples of many materials, particularly metals, are found to obey Hooke's law for small tensile strains. Under these circumstances,

$$Young\ modulus = \frac{tensile\ stress}{tensile\ strain}$$

Note: The greater the Young modulus of a material, the stiffer it is. Young modulus has the unit of pascal.

8 CHARACTERISTICS OF SOLIDS

The behaviour of materials which are subject to stress is often represented by means of stress-strain curves.



Stress–strain curve for a metal.

Deforming solids

In many situations, the force on a material will be tending to reduce the volume. This is known as compressive force and puts the material under compression.

Compressive force per unit area is called compressive stress:

$$compressive stress = \frac{compressive\ force}{area\ of\ cross - section}$$

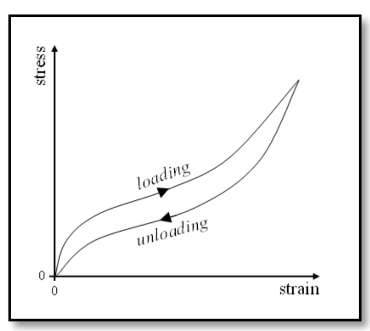
The compressive strength of a material is the compressive stress at which the material breaks.

Extension per unit length is called compressive strain:

$$compressive\ strain = \frac{extension}{original\ length}$$

Hysteresis in rubber

The elastic property of rubber is complex. When a rubber band is stretched and relaxed it does return to its original length, but the manner it does so is very different to that of a metal. The area of gap between loading and unloading is called hysteresis loop. This represents the energy per unit volume transferred to internal energy. If a rubber band is repeatedly stretched and relaxed in short time, it will become warm.



Characteristics

- Brittleness

A brittle object will shatter or crack with little or no plastic deformation.

- Ductility

Ductile materials are those which show plastic deformation under tension and can be drawn out into wires. Materials which break or crack easily are called brittle.

- Toughness

Tough materials are able to withstand impact forces without breaking and require a large force to produce a small plastic deformation. Tough materials are therefore not brittle. Tough materials absorb energy from impact forces so their internal energy increases.

- Stiffness

A stiff material is a material that exhibits very small deformations even when subjected to large forces. High young modulus, gradient of a force-extension graph

- Hardness

Hard materials are those which resist plastic deformation by denting. The harder the material, the more difficult it is to indent the surface.

- Malleability

Materials which show plastic deformation under compression and can be hammered into thin sheets are called malleable. These are not brittle, although they are not necessarily tough. It is a similar property to ductility, as a malleable material can be reshaped easily without fracturing.

Property	Definition	Example	Opposite	Definition	Example
strong	high breaking stress	steel	weak	low breaking stress	expanded polystyrene
stiff	gradient of a force–extension graph; high Young modulus	steel	flexible	low Young modulus	natural rubber
tough	high energy density up to fracture: metal that has a large plastic region	mild steel, copper, rubber tyres	brittle	little or no plastic deformation before fracture	glass, ceramics
elastic	regains original dimensions when the deforming force is removed	steel in Hooke's law region, rubber	plastic	extends extensively and irreversibly for a small increase in stress beyond the yield point	copper, modelling clay
hard	difficult to indent the surface	diamond	soft	surface easily indented/ scratched	foam rubber, balsa wood
ductile	can be readily drawn into wires	copper	hard, brittle		
malleable	can be hammered into thin sheets	gold	hard, brittle		