Module 3 Forces & Motion

Unit 2 Forces in Action

3.2 Forces in action

This section provides knowledge and understanding of the motion of an object when it experiences several forces and also the equilibrium of an object. Learners will also learn how pressure differences give rise to an *upthrust* on an object in a fluid.

There are opportunities to consider contemporary applications of terminal velocity, moments, couples, pressure, and Archimedes principle (HSW6, 7, 9, 11, 12).

Experimental work must play a pivotal role in the acquisition of key concepts and skills (HSW4).

Module 2 – Foundations of physics

2.1 Physical quantities and units
2.2 Making measurements and analysing data
2.3 Nature of quantities

Module 3 – Forces and motion

3.1 Motion
You are here! → 3.2 Forces in action
3.3 Work, energy and power
3.4 Materials
3.5 Newton's laws of motion and momentum

Module 4 – Electrons, waves and photons

4.1 Charge and current
4.2 Energy, power and resistance
4.3 Electrical circuits
4.4 Waves
4.5 Quantum physics

3.2 Forces in Action

- 3.2.1 Dynamics
- 3.2.2 Motion with Non-Uniform Acceleration
- 3.2.3 Equilibrium
- 3.2.4 Density & Pressure

3.2.1 Dynamics

3.2.1 Dynamics

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) net force = mass x acceleration; $F = ma$

(b) the newton as the unit of force

(c) weight of an object; $W = mg$

(d) the terms tension, normal contact force, upthrust and friction

(e) free-body diagrams

(f) one- and two-dimensional motion under constant force.

How do we define force, mass and weight?

Force & the Newton

- Force – a vector quantity (has direction & magnitude)
  - At KS3 forces were either pushes, pulls or twists.
  - At GCSE we introduced drag, thrust, weight, friction, tension and others applying to particular forces.
  - At A Level a force comes in just 3 types outside the nucleus of an atom:
    - Gravitational force
    - Magnetic force
    - Electrical force

The 3 forces

- Gravitational Force
  - An attraction between any two objects with mass.
  - AS Physics is concerned only with weight.
- Magnetic Force
  - A force between two magnetic objects, or at an atomic level a force between moving charges.
- Electrical Force
  - A force between charged objects.
  - This is responsible for all contact forces between objects.
    - The atoms in your hand exert an electrical force on the atoms of a ball, allowing it to be pushed.
- Nuclear Forces
  - Strong or weak forces acting over very short distances.

Force, Mass & Acceleration

- Isaac Newton saw the link between these three quantities.
  - He described a resultant force causing an object to accelerate.
  - If the resultant force on an object is zero, then there will be no acceleration.
    - This does not mean the object is stationary – just that it is not accelerating

F = ma

- Newton found that if mass is constant then acceleration is proportional to force.

  $a \ \alpha \ F$

- He also saw that if the force is constant then acceleration is inversely proportional to mass.

  $a \ \alpha \ 1/m$

- If these are combined we get:

  $F=kma$ (where k is a constant)

The Unit of Force – The Newton

- 1N is the force that causes a mass of 1kg to have an acceleration of $1ms^{-2}$.

  So $1N = k \times 1kg \times 1ms^{-2}$

- Therefore k equals 1 **IF** the units are Newtons, Kilograms and Metres per $Second^2$.

- Therefore, with these units, $F=ma$

Einstein’s spanner in the works

- Einstein later developed his Theory of Special Relativity.
  - In it he said that at speeds approaching the speed of light, the mass of an object increases.
  - So particle physicists use Einstein’s equations rather than Newton’s.
  - However, Newton’s equations are good enough to send satellites into orbit.

Mass

- A measure of the amount of matter in a substance.
- Measured in kilograms, kg.
- The international kilogram is stored in a vault in Paris.

Weight a minute!

- Weight is a force.
- Measured in newtons, N.

- Weight is the gravitational force acting on a mass in a downward direction.
  - Its magnitude is dependent on the acceleration of freefall.

$$W = mg$$

$$F = ma$$

Weight is a force,
g is the acceleration of freefall.

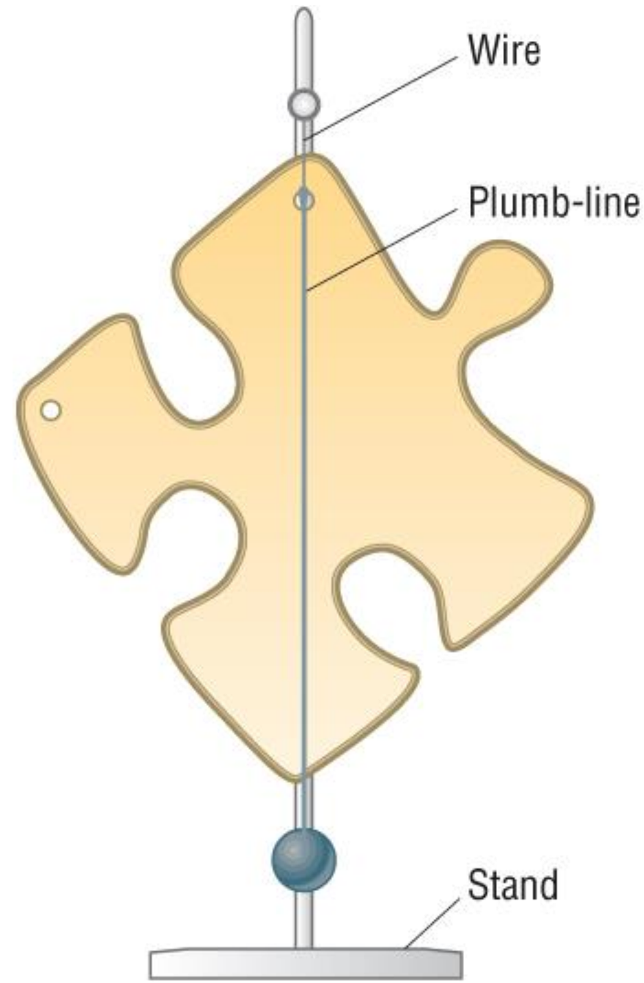
Where is the centre of gravity?

Centre of Gravity

- Calculations of forces on objects are much simpler if we just assume all forces act on a single point on the object.
  - ie. The object is considered to be a point mass.
- The position of this point mass on an object is called the Centre of Gravity.
  - At this point the whole weight of an object can be thought to act as a single force

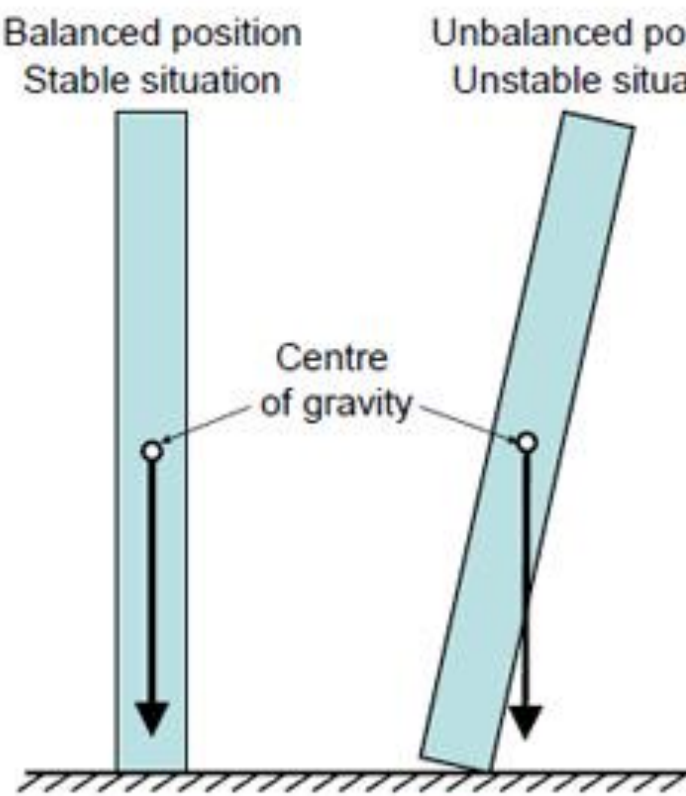
Finding the Centre of Gravity

- Suspend an object from its edge and mark the vertical plumb line.
- Repeat for a different part of the object.
- Where the two marked plumb lines cross will be the centre of gravity.
  - For some objects the CoG will not actually be on the object itself.



CoG Implications

- Designers need to know the Centres of Gravity of buses, cars, etc since it affects their stability on the road.



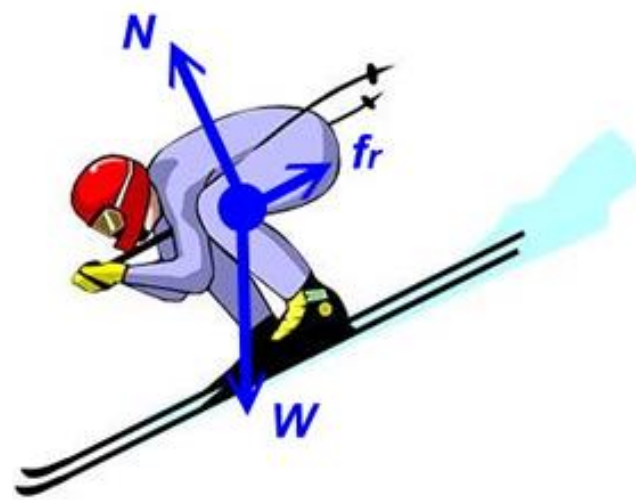
What’s the difference between centre of gravity and centre of mass?

- Centre of mass:
  - The point through which an external force produces straight-line motion but no rotation.
- Centre of Gravity:
  - The point through which an object’s weight appears to act.
- Here on Earth, CoM and CoG are at the same point.

How can we analyse the forces acting on an object?

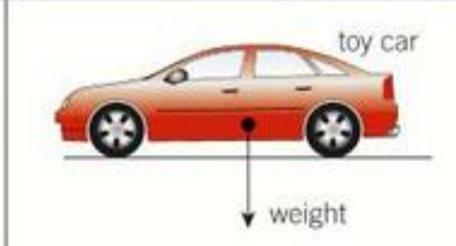
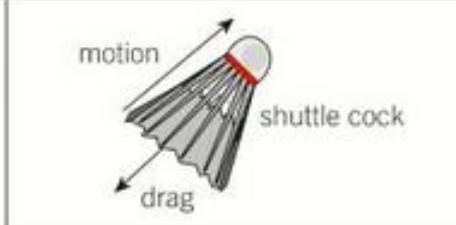
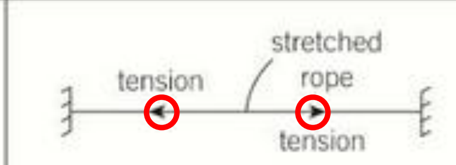
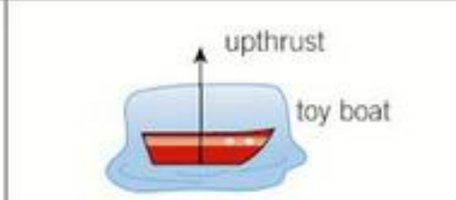
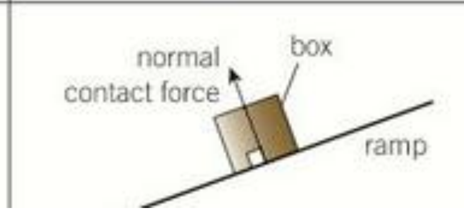
Free-body Diagrams

- Free-body diagrams are the easiest way to represent the forces acting on an object:
  - Force vectors are represented as labelled arrows.
  - Each arrow is drawn to scale to show the relative magnitudes.

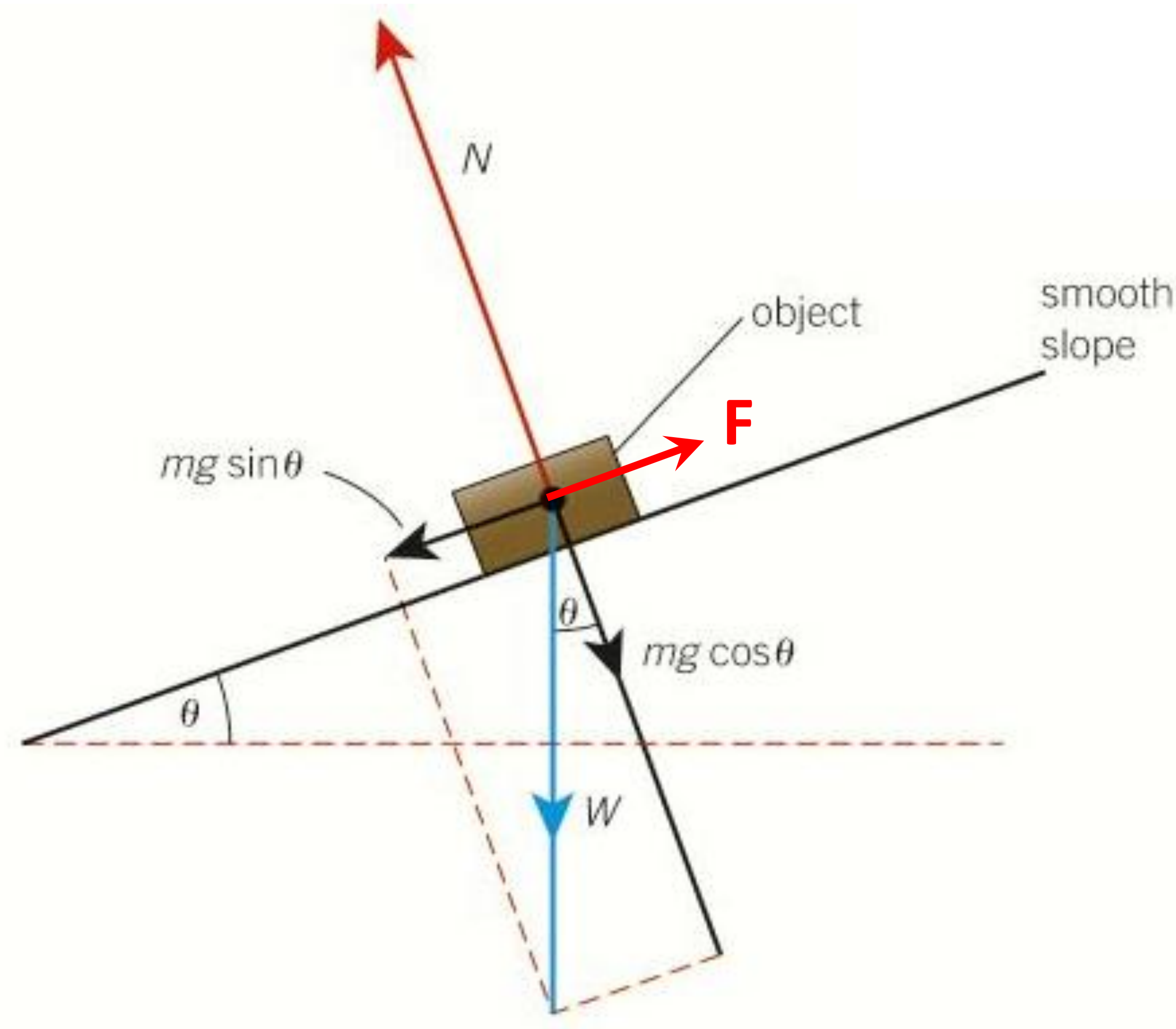


Some key forces

Spot the mistake!!!

Force	Comment	Force diagram
weight	the gravitational force acting on an object through its centre of mass	
friction	the force that arises when two surfaces rub against each other	
drag	the resistive force on an object travelling through a fluid (e.g., air and water); the same as friction	
tension	the force within a stretched cable or rope	
upthrust	an upward buoyancy force acting on an object when it is in a fluid	
normal contact force	a force arising when one object rests against another object	

Objects on a slope



- Weight acts vertically.
- W can be resolved to show forces acting down the slope and perpendicular to the slope.
- N is the normal contact force.
  - Normal means at right angle.
- Where would friction act if the object is stationary?

3.2.1 Dynamics (review)

3.2.1 Dynamics

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) net force = mass x acceleration; $F = ma$

(b) the newton as the unit of force

(c) weight of an object; $W = mg$

(d) the terms tension, normal contact force, upthrust and friction

(e) free-body diagrams

(f) one- and two-dimensional motion under constant force.

3.2.2 Motion with Non-Uniform Acceleration

3.2.2 Motion with non-uniform acceleration

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) drag as the frictional force experienced by an object travelling through a fluid

(b) factors affecting drag for an object travelling through air

(c) motion of objects falling in a uniform gravitational field in the presence of drag

(d) (i) terminal velocity

(ii) techniques and procedures used to determine terminal velocity in fluids.

How is drag related to terminal velocity?

Drag forces

- The physics of drag can be complicated.
- Drag force (F_D)can be described as:
  - A frictional force which opposes the motion of an object.

Factors affecting drag

$$F_D = \frac{C_D \rho V^2 A_{proj}}{2}$$

- Drag Coefficient.
  - Shape of the object.
  - Roughness of the object
- Density of the fluid through which the object travels.
- Velocity of the object (squared) through the fluid.
- Cross sectional area (projected area) of the object.

The last two factors are the most influential.

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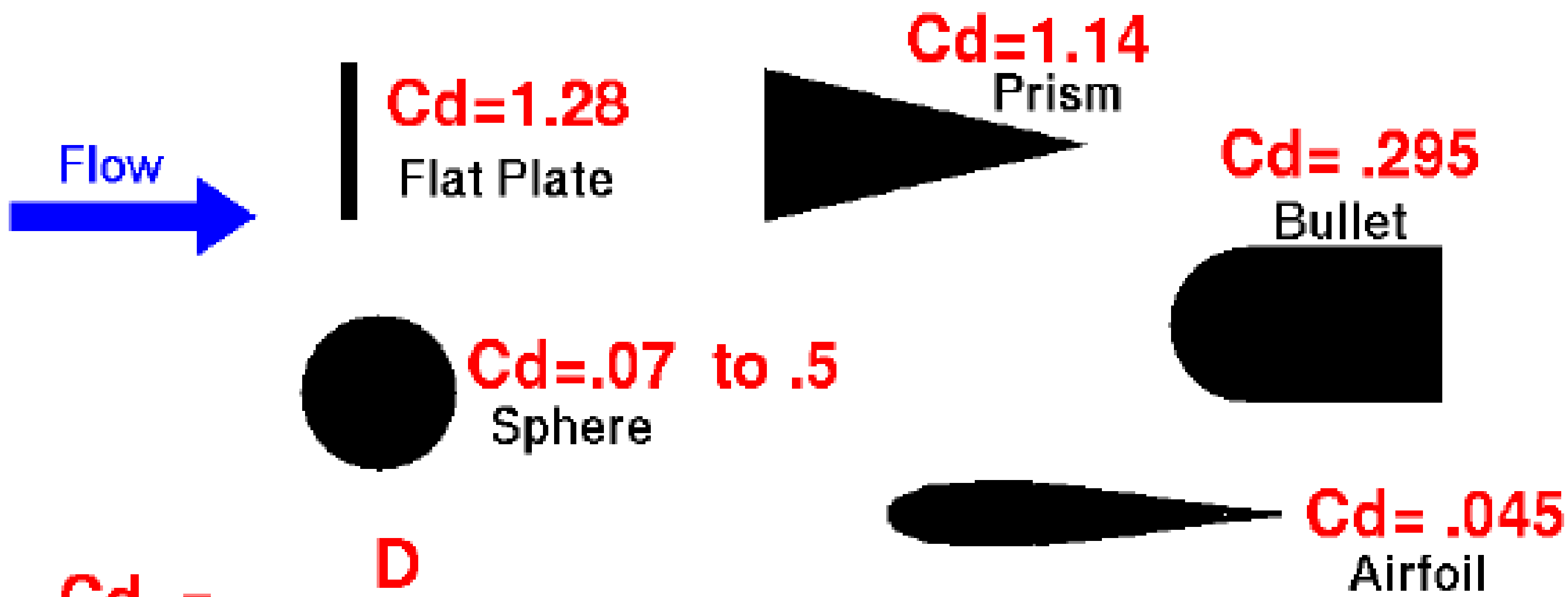
Shape Effects on Drag

The shape of an object has a very great effect on the amount of drag.



$$Cd = \frac{D}{r \; A \; V^2 / 2}$$

A = frontal area

All objects have the same frontal area.

Some terms

- Drag force when an object is moving in air is called:
  - Air resistance

- Drag force when an object is moving in water is called:
  - Water resistance

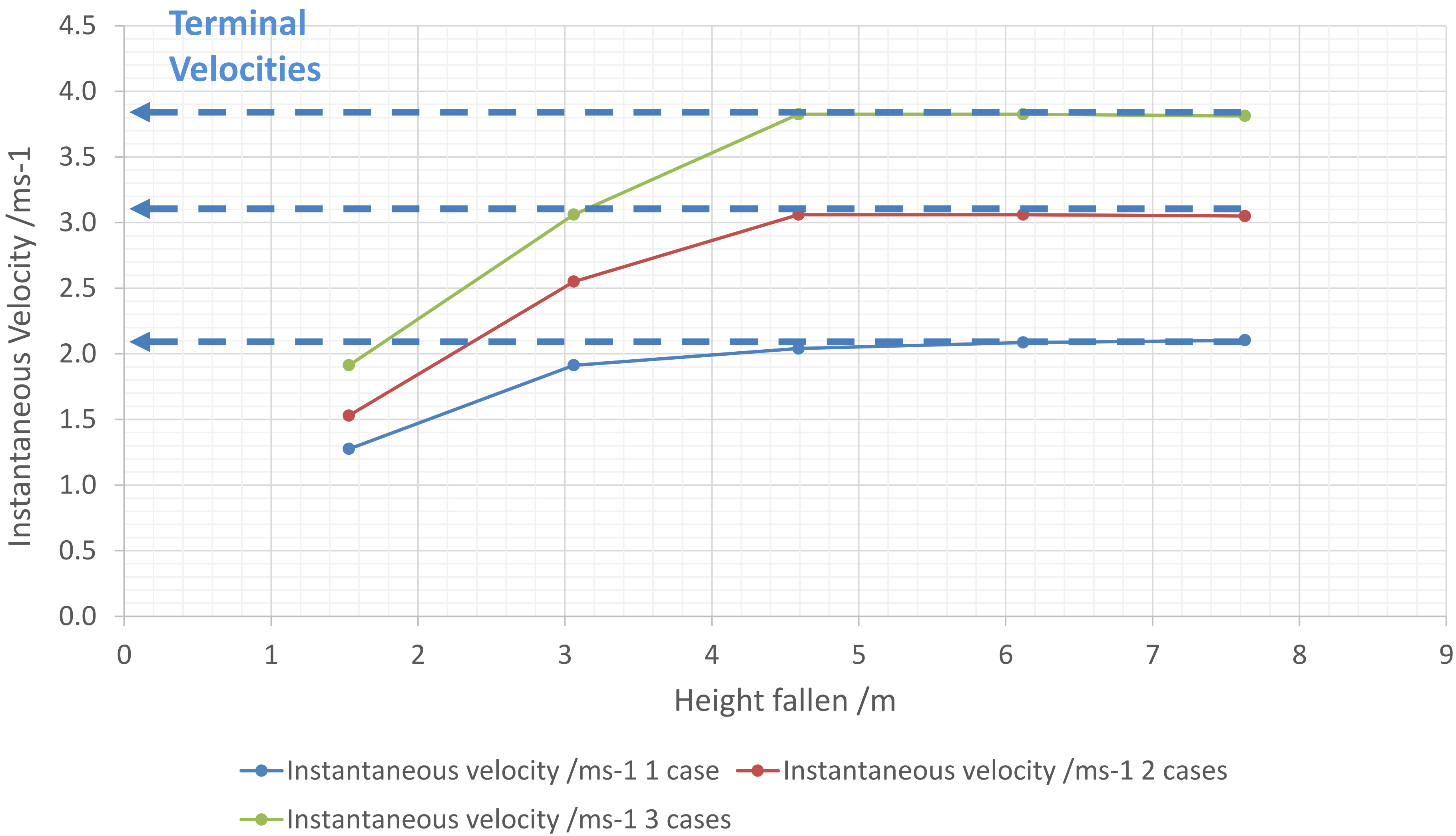
Terminal Velocity

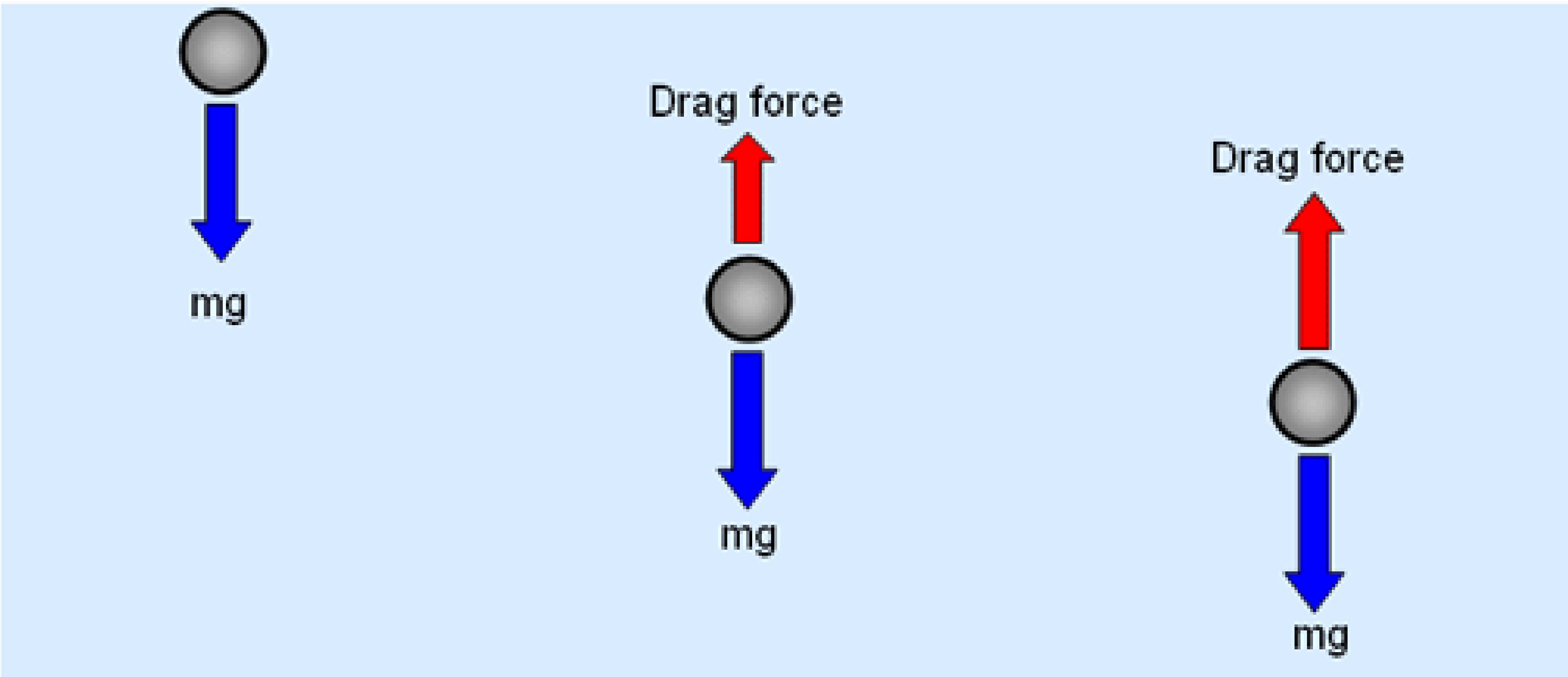
- As an object accelerates in freefall the drag increases with its increasing velocity, until the drag equals the weight.
  - At this point the resultant forces are equal and velocity is constant – called Terminal Velocity.

Drag & Terminal Velocity Practical

- Using cake cases:
  - Drop from the stairwell.
  - Measure time taken to fall each metre for at least 4m.
  - Repeat and calculate mean times.
  - Calculate a mean velocity for each metre (dist/time)
  - Plot on a v-t graph.
  - Repeat for multiple cake cases (increased mass but constant area).
  - Explain results.

How drop velocity of cake cases changes with mass





Body released from rest

Forces on body during acceleration

Forces on body at terminal velocity

Terminal Velocity

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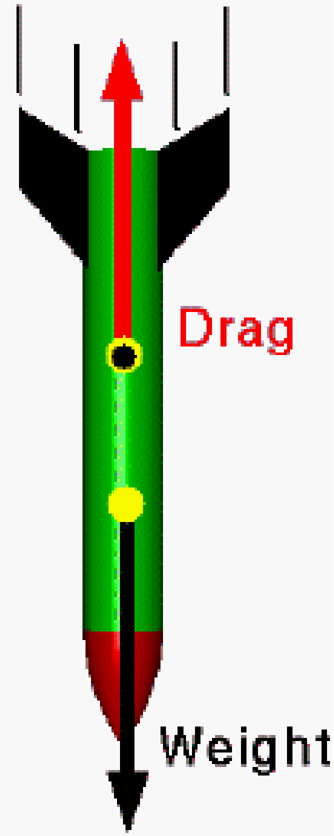
W = weight
D = drag
Cd = drag coefficient
V = velocity
r = air density
A = frontal area

Motion of a falling object with air resistance (drag).

$$F = m\,a$$

$$a = \frac{F}{m} = \frac{W - D}{m}$$



When Drag is equal to Weight, acceleration is zero, velocity is constant.

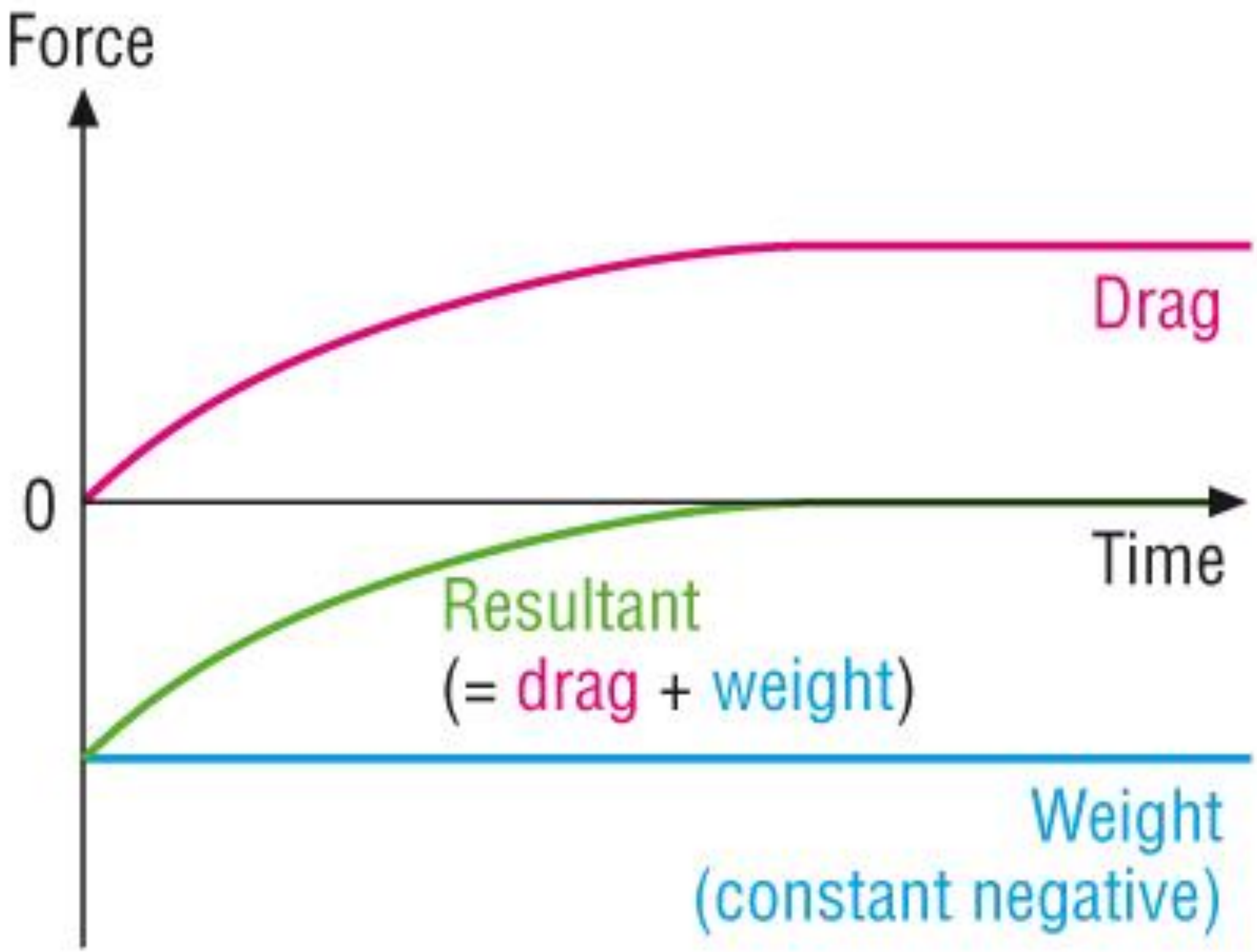
Then: $$W = D = Cd\ r\ \frac{V^2}{2}\ A$$

Terminal Velocity : $$V = \mathrm{sqrt}\left(\frac{2\,W}{Cd\ r\ A}\right)$$

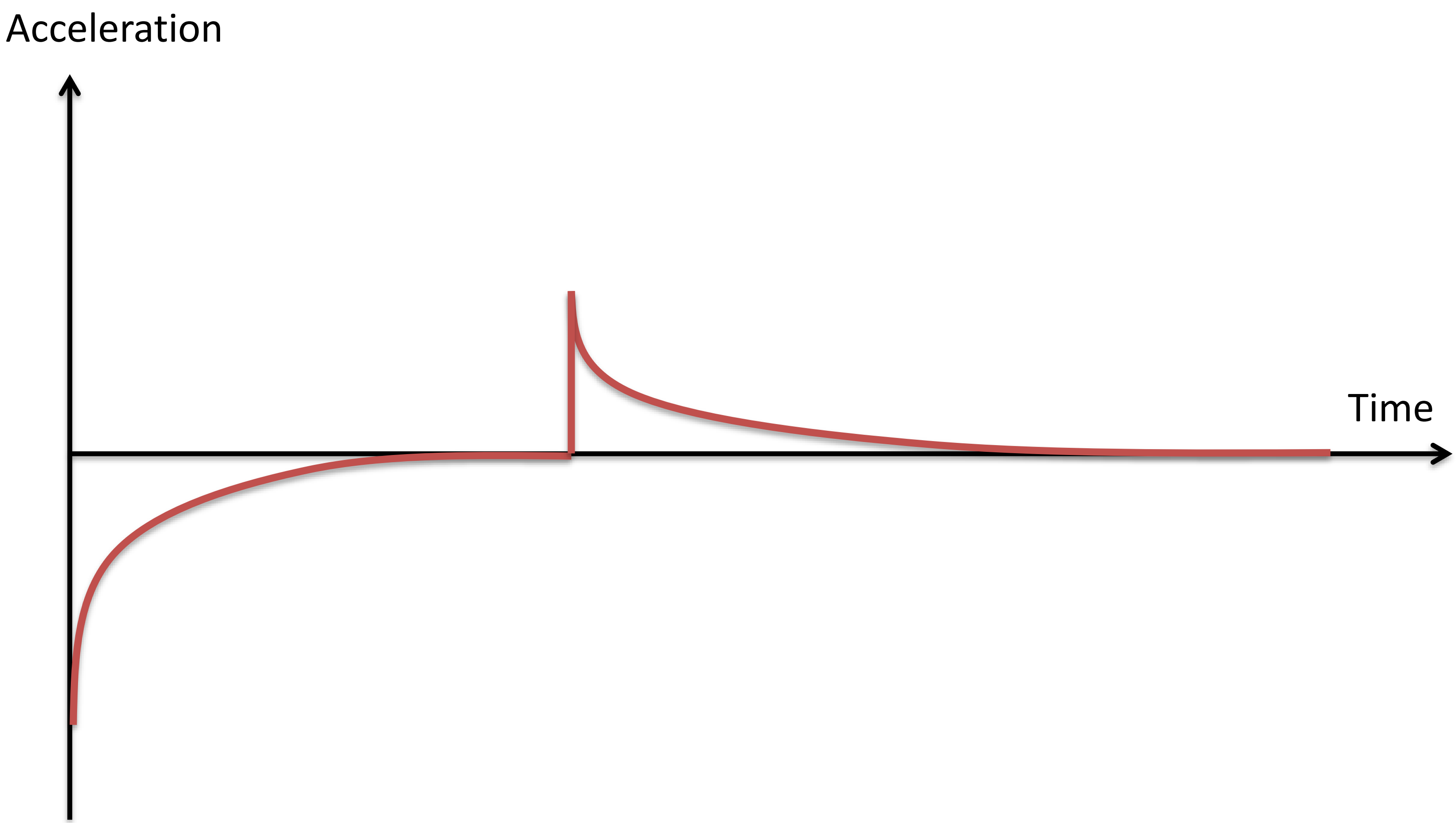
Lower terminal velocity with large area or high drag coefficient.

Or high medium density

Describe the graph



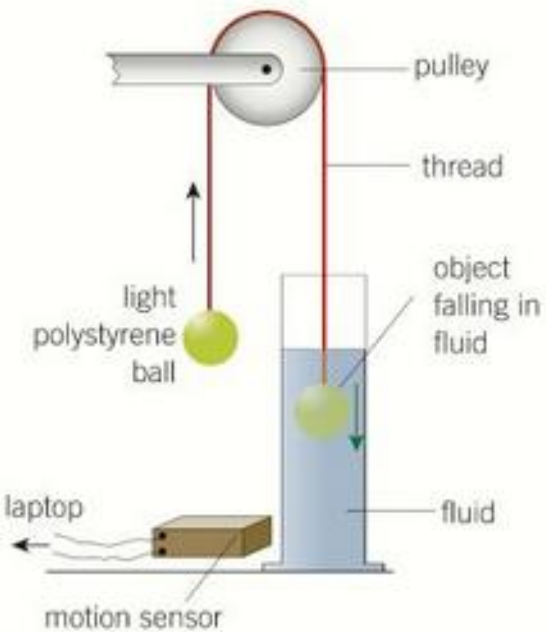
Complete the graph for a parachutist



Remember: Negative acceleration is in a downward direction

Investigating motion in a fluid

You can easily investigate the motion of an object falling affected by a drag force by using a motion sensor connected to a data-logger or a laptop. The falling object is attached to a light polystyrene ball by a thin thread passed over a pulley. The object is then dropped through a cylinder of liquid such as water or glycerol, pulling the polystyrene ball vertically upwards. The motion of this ball is identical to that of the object falling through the fluid. You can generate and analyse velocity–time and acceleration–time graphs with this arrangement.



▲ **Figure 5** *Investigating an object falling through a fluid*

1. A student suggests that the motion sensor can be pointed directly towards the object falling in the fluid. Explain why this will not produce any useful data.
2. Describe how you could *estimate* the terminal velocity of the falling object without using the motion sensor.

3.2.2 Motion with Non-Uniform Acceleration (review)

3.2.2 Motion with non-uniform acceleration

Learning outcomes

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3.2.3 Equilibrium

3.2.3 Equilibrium

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) moment of force

(b) couple; torque of a couple

(c) the principle of moments

(d) centre of mass; centre of gravity; experimental determination of centre of gravity

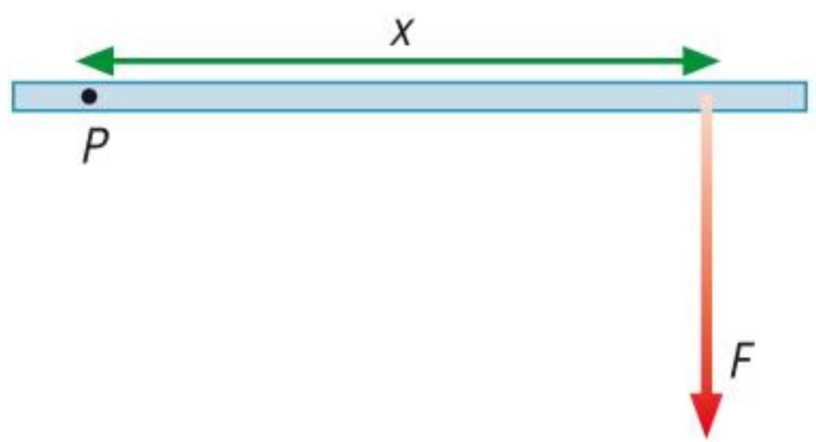
(e) equilibrium of an object under the action of forces and torques

(f) condition for equilibrium of three coplanar forces; triangle of forces.

Hang on a moment, what is a moment?

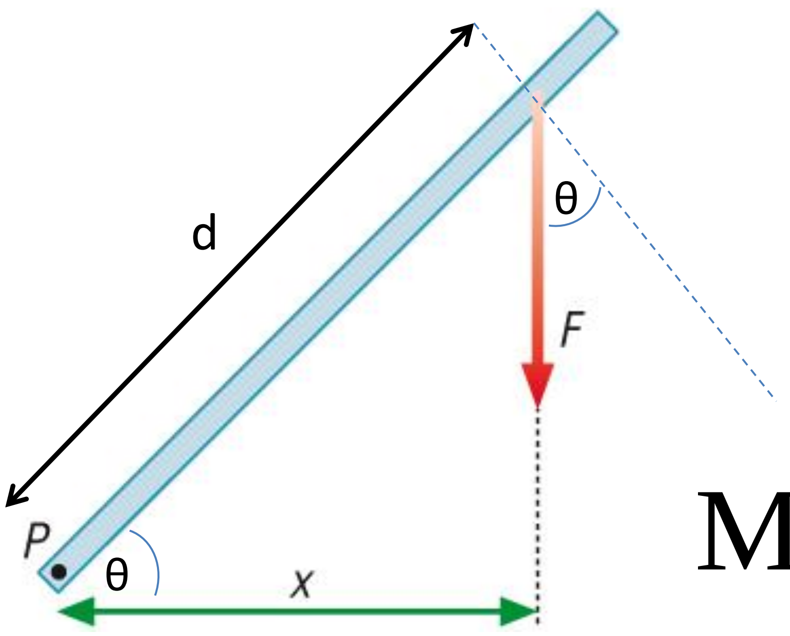
Turning Forces

- Moment
  - The moment of a force is the force multiplied by the perpendicular distance from a pivot point
    - Moment = Fx (measured in newton metres, Nm).
  - If an object is to be in rotational equilibrium, the sum of the clockwise moments must equal the sum of the anticlockwise moments.



Perpendicular Distance?

- It is crucial that we use perpendicular distance when calculating moments.
- Perpendicular distance can be calculated using trigonometry:

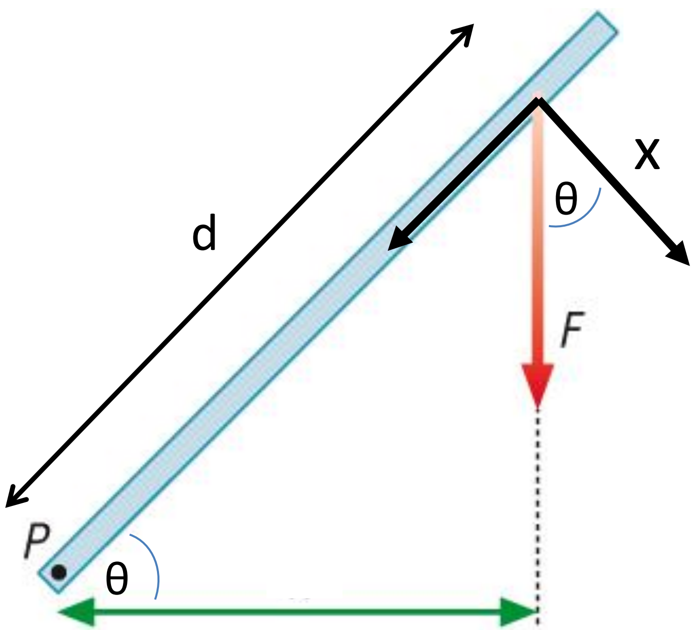


$$x = d\cos\theta$$

$$\text{Moment} = Fd\cos\theta$$

Perpendicular Distance?

- Or...
- A moment can be calculated by resolving the force vector:



$$x = F\cos\theta$$

$$\text{Moment} = Fd\cos\theta$$

Principle of Moments

- For a body in rotational equilibrium (ie. It is not rotating), the sum of all the clockwise moments will equal the sum of all the anticlockwise moments.

Worked Examples

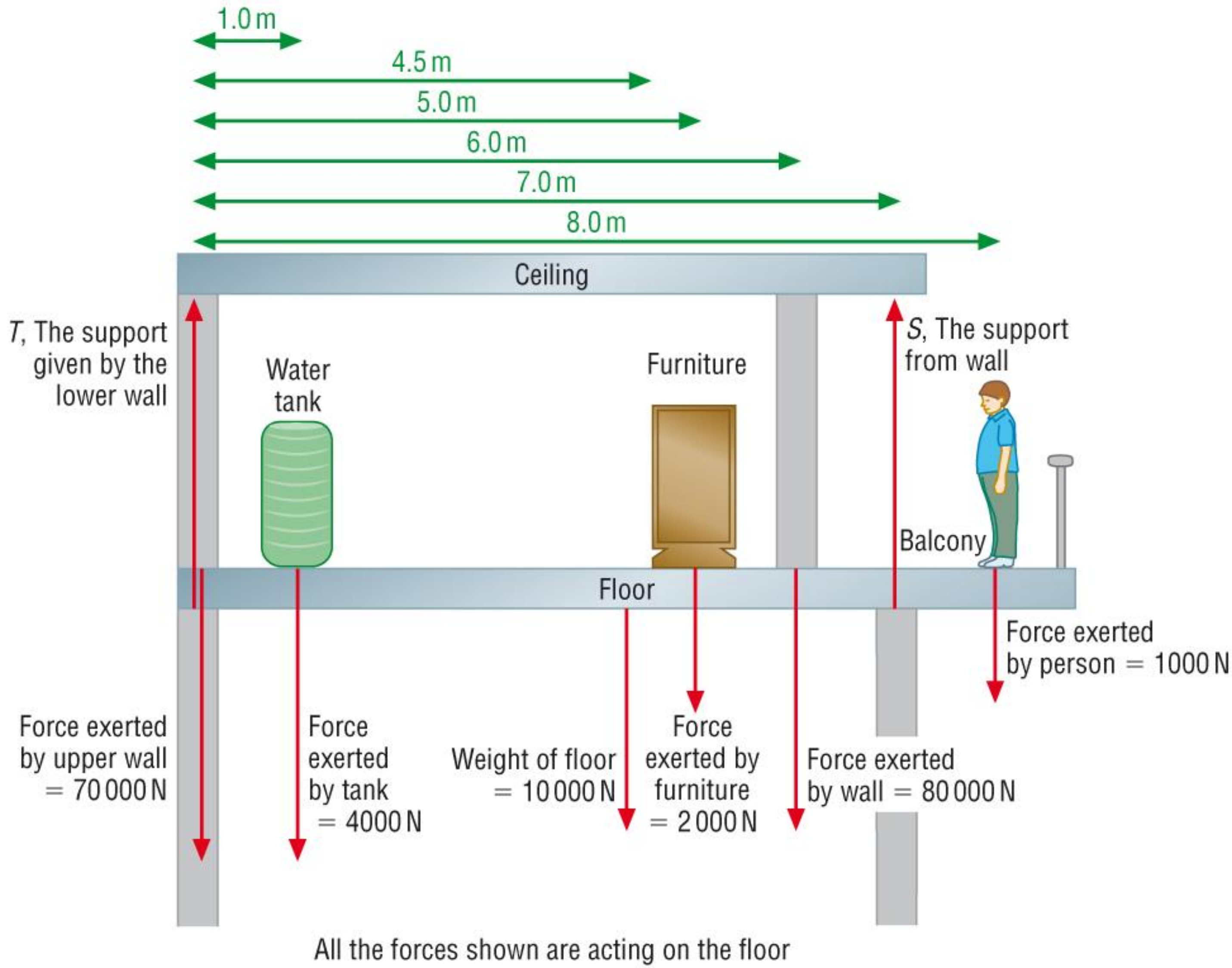
Calculate forces S and T

T = 70000N

CWM = (1x4000) + (4.5x10000) + (5x2000) + (6x80000) + (8x1000)

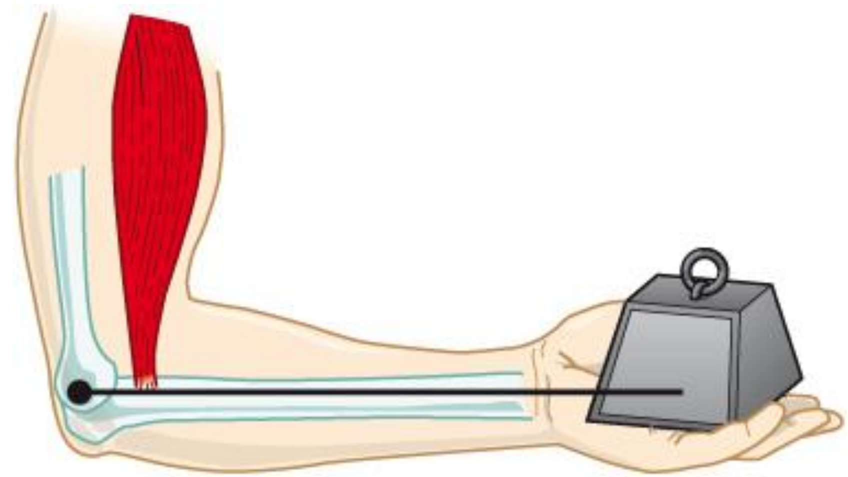
ACWM = 7S

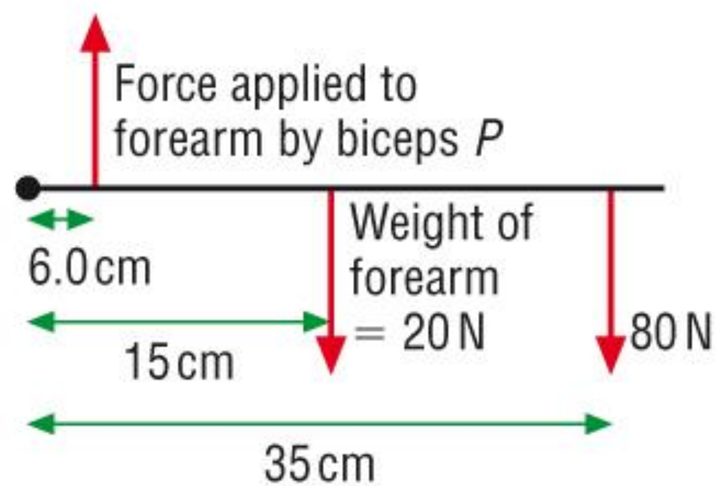
S = CWM/7
S = 78143 or 80000N



Worked Examples

Calculate P, the force applied to the forearm by the biceps muscle.





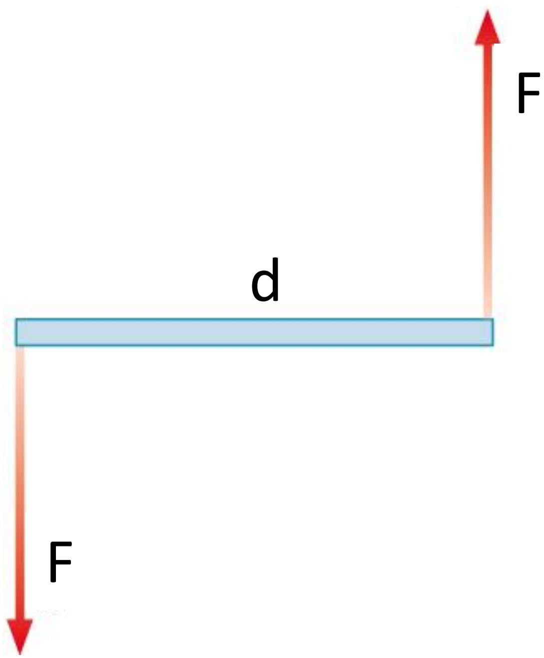
Using moments to measure the mass of a clamp stand.

- Practical.

Other Turning Forces

- Couple
  - A couple is a pair of equal & parallel but opposite forces which tend to produce rotation only.
  - The resultant of these is zero so no linear acceleration is produced.
- Torque
  - The turning effect of the couple.

    = one of the forces x the perpendicular distance between them (measured in newton metres).

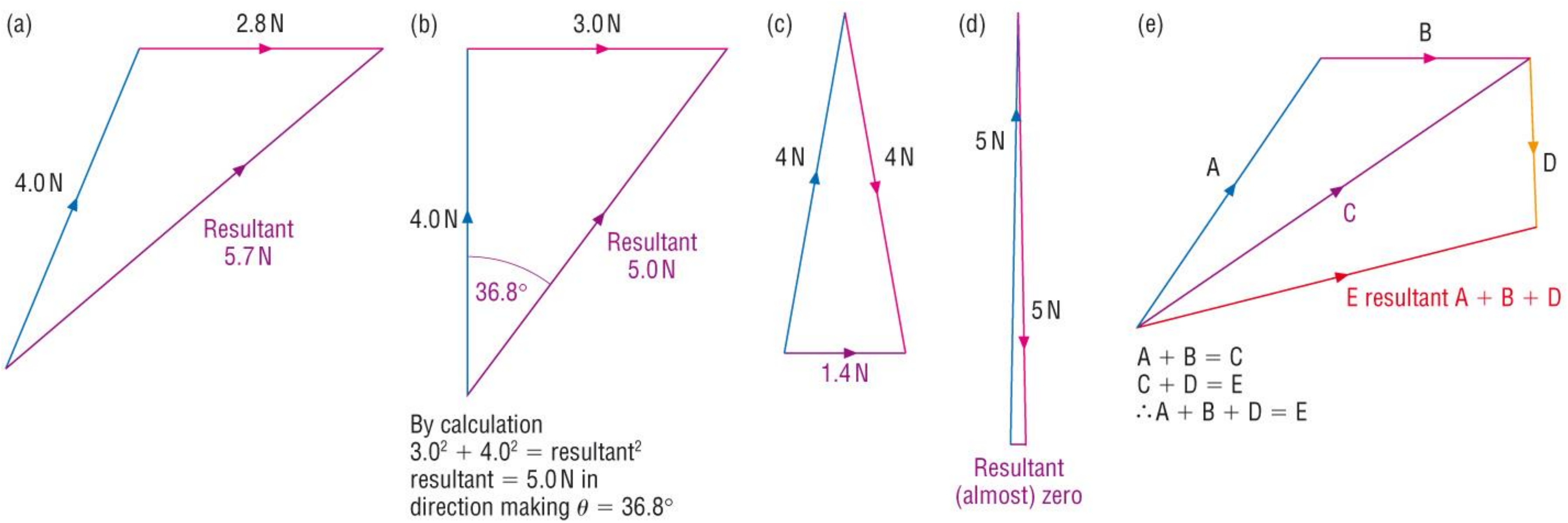


Taking moments: $$\text{Moment} = \left(F \times \frac{d}{2}\right) + \left(F \times \frac{d}{2}\right) = Fd$$

Why are coplanar forces which are in equilibrium often shown as triangles?

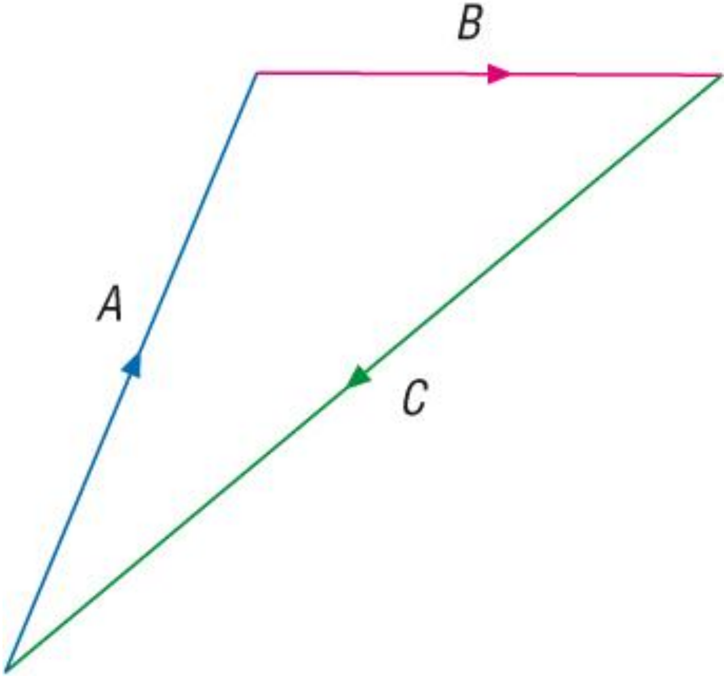
Force Diagrams

- Since forces are vector quantities they can be drawn as arrows.
- We can use these arrows to add and subtract forces to obtain the resultant force.



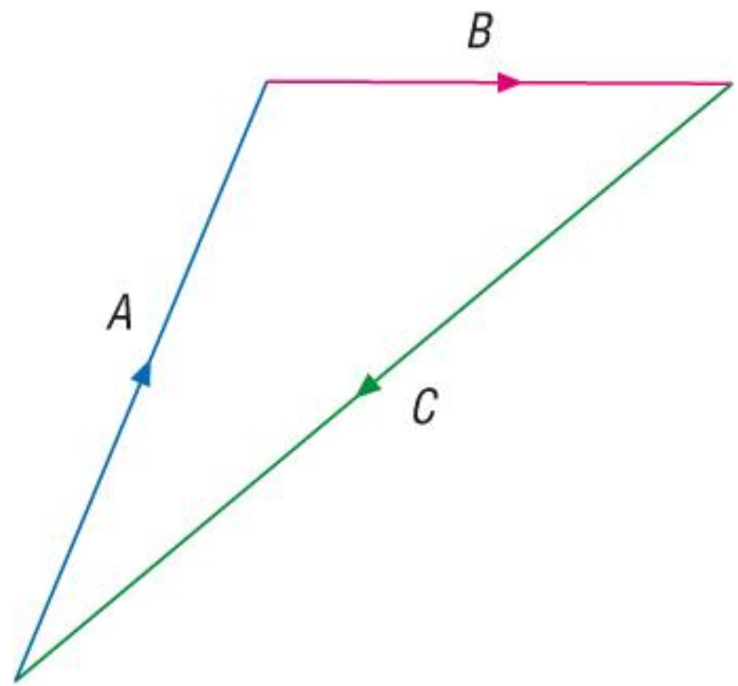
Triangles of forces

- A resultant force of zero produces an acceleration of zero – the object is said to be in equilibrium.
- Force diagrams of objects in equilibrium produce closed shapes (eg triangles).



Or consider it like this:

- The resultant force between two of the three forces must be equal and opposite to the third.
  - This applies to any two of three forces.
- The resultant vertical force must be zero as must the resultant horizontal force.
  - Resolve all forces into H & V.



3.2.3 Equilibrium (review)

3.2.3 Equilibrium

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) moment of force

(b) couple; torque of a couple

(c) the principle of moments

(d) centre of mass; centre of gravity; experimental determination of centre of gravity

(e) equilibrium of an object under the action of forces and torques

(f) condition for equilibrium of three coplanar forces; triangle of forces.

3.2.4 Density & Pressure

3.2.4 Density and pressure

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) density; $\rho = \dfrac{m}{V}$

(b) pressure; $p = \dfrac{F}{A}$ for solids, liquids and gases

(c) $p = h\rho g$; upthrust on an object in a fluid; Archimedes' principle.

You’re Dense!!

What does that actually mean?

Density

- Density = Mass/Volume

$$\rho = \frac{m}{V}$$

(ρ is the Greek letter Rho)

- The unit of density is therefore:

  kgm^{-3}

Some material densities:

Material	Density/kg m^{-3}	Material	Density/kg m^{-3}
hydrogen	0.0899	silicon	2300
helium	0.176	concrete	2400
oxygen	1.33	iron	7870
air	1.29	copper	8930
ethanol	789	silver	10 500
olive oil	920	gold	19 300
water	1000	platinum	21 500
mercury	13 600	osmium	22 500
aluminium	2710		

Densities for gases are given at 273 K and atmospheric pressure.

- Identify the **solids**, **liquids** & **gases** in the above table.
- The density of solids & liquids do not vary by much. The density of gases vary a lot depending on temperature or pressure.

How can we measure density?

- Practical

Why can I easily push a drawing pin into a cork board?

Pressure

- Pressure = Force/Area.

$$p = \frac{F}{A}$$

- The unit of pressure is:
  - Nm^{-2} or Pa
  - A force of 1N over an area of $1m^2$ is 1Pa.

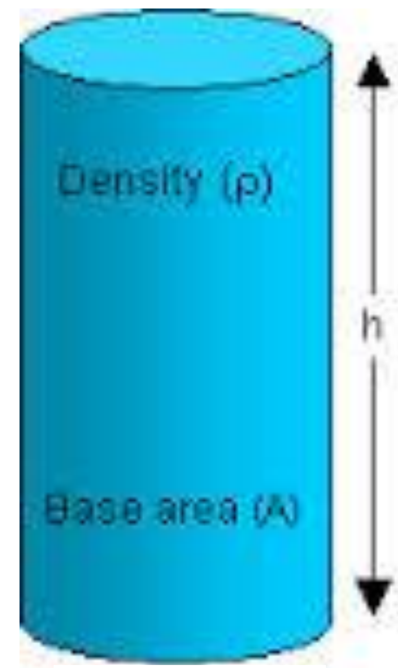
- Atmospheric pressure is approximately 100000Pa (or 100kPa, or 1bar)

Differences in Pressure

- In order to get a liquid to flow along a pipe we need a difference in pressure between one end of the pipe and the other.

Pressure in fluids

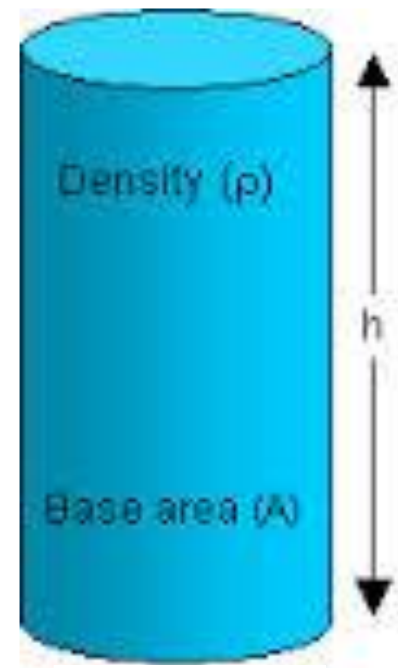
- Gases and liquids are fluids – they can flow.
- Fluids exert a pressure on objects due to the constant collisions from their molecules.
- We can calculate the pressure exerted by a vertical column of fluid from its weight and its cross sectional area.



p=hρg

(you also need to know how to derive this equation)

- Pressure = Force/Area $$p = \frac{W}{A}$$
- Weight =mg $$p = \frac{mg}{A}$$
- Mass = ρV $$p = \frac{\rho V g}{A}$$
- Volume = Ah $$p = \frac{\rho A h g}{A}$$
- Finally: $$\boxed{p = h\rho g}$$



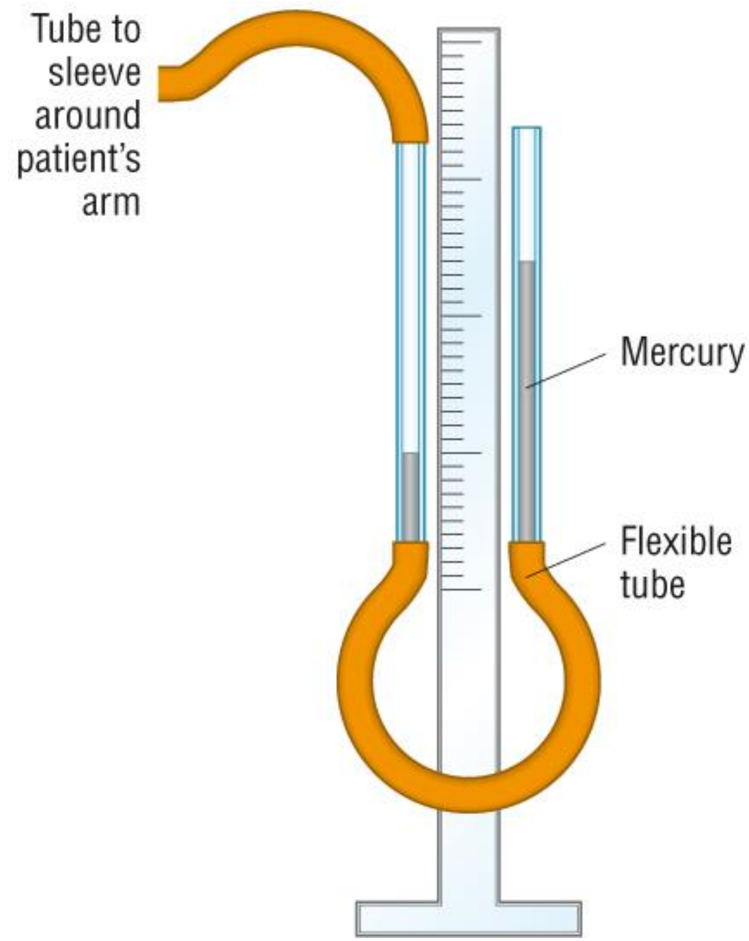
$$p = h\rho g$$

- Fluid pressure does not depend on area.
- Fluid pressure increases with:
  - Height (or depth if we’re talking about diving in water).
  - Density.

- The pressure in a fluid at any particular depth is the same in all directions.

Measuring Pressure

- A manometer is often used to measure blood pressure.
  - A sleeve is inflated around the arm until the blood flow stops and is slowly released until flow just starts again.
  - The pressure of air in the sleeve now equals the pressure of blood in the artery.
  - This pressure is measured as a difference between the two mercury levels (normal systolic pressure is 140mmHg).



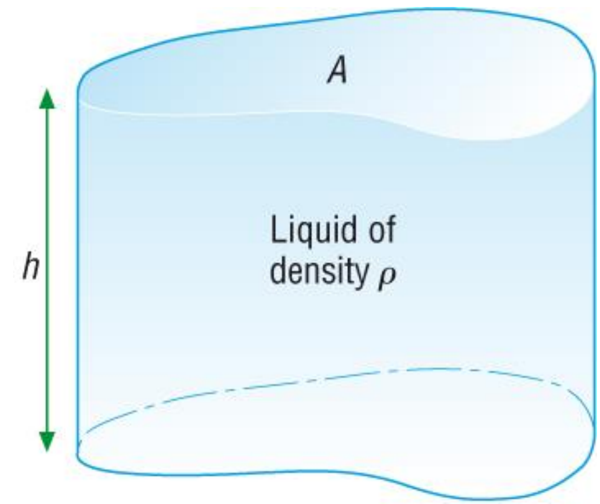
What does 140mmHg mean?

- Calculate the pressure in Pa of 140mmHg:

- The pressure on the base of the tube = hρg.
- The pressure of 140mmHg is therefore:

  $0.140m \times 13600kgm^{-3} \times 9.81ms^{-2}$

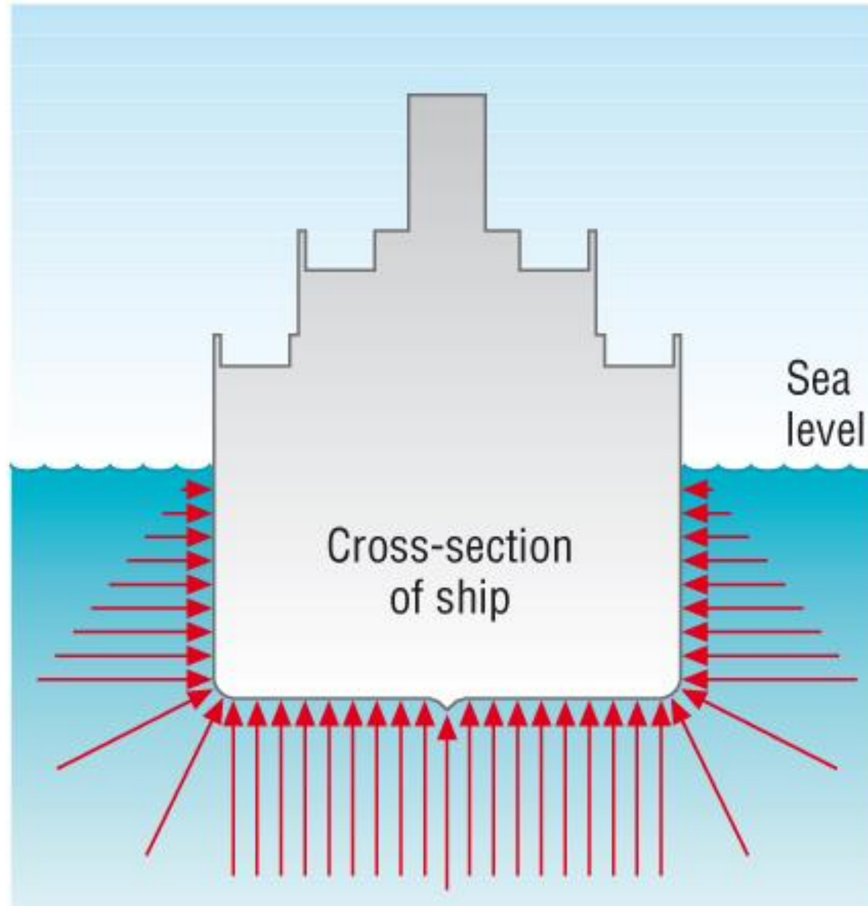
  18678Pa



ρ (Hg) = $13600kgm^{-3}$

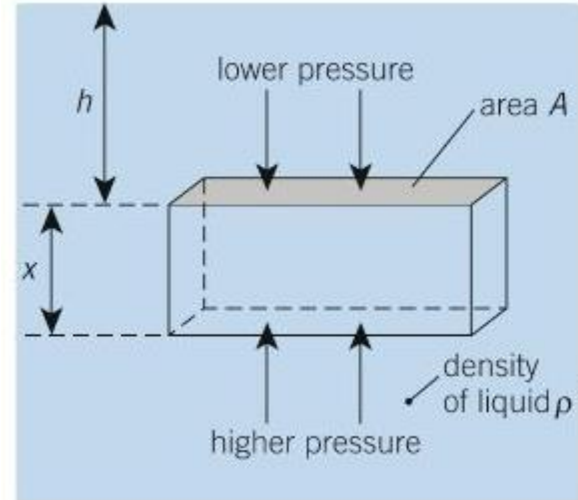
Floating/Upthrust

- Upthrust is the resultant upward force on the bottom of an object in a fluid.
- For equilibrium to be established, the upthrust must equal the weight.



Forces due to pressure always act at right angles to the surface

Calculating Upthrust



- Looking at this submerged block:
- The downward force at the top surface (F=pA):

$$F = h\rho g A$$

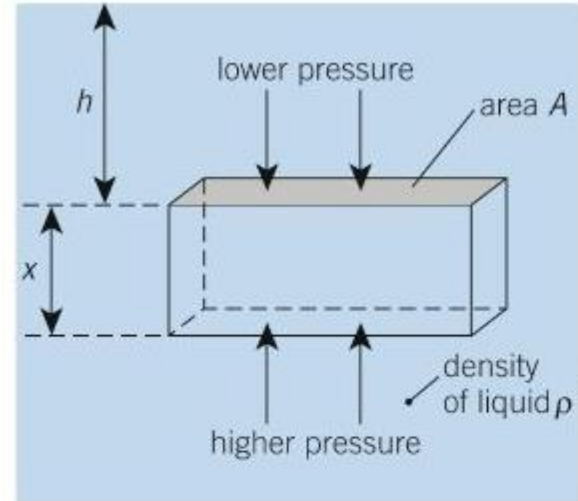
- The upward force at the bottom surface (F=pA):

$$F = (h + x)\rho g A$$

- The resultant upthrust:

$$F = (h + x)\rho g A - h\rho g A = x\rho g A$$

Upthrust = Weight of displaced fluid



Remember:

$$\text{Upthrust} = Ax\rho g$$

- Weight of fluid displaced: $W = mg$
- Mass = ρV $W = \rho V g$
- Volume = Ax $W = \rho A x g = \text{Upthrust}$

Archimedes’ Principle

- Archimedes (2000 yrs ago) knew the upthrust on a submerged (or partially submerged) object is equal to the weight of the fluid displaced by the object.

- An object will sink if its own weight exceeds the upthrust.
- It will float if its weight is equal to the upthrust.

3.2.4 Density & Pressure (review)

3.2.4 Density and pressure

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) density; $\rho = \dfrac{m}{V}$

(b) pressure; $p = \dfrac{F}{A}$ for solids, liquids and gases

(c) $p = h\rho g$; upthrust on an object in a fluid; Archimedes' principle.

Complete! →

Module 2 – Foundations of physics

2.1 Physical quantities and units
2.2 Making measurements and analysing data
2.3 Nature of quantities

Module 3 – Forces and motion

3.1 Motion
3.2 Forces in action
3.3 Work, energy and power
3.4 Materials
3.5 Newton's laws of motion and momentum

Module 4 – Electrons, waves and photons

4.1 Charge and current
4.2 Energy, power and resistance
4.3 Electrical circuits
4.4 Waves
4.5 Quantum physics