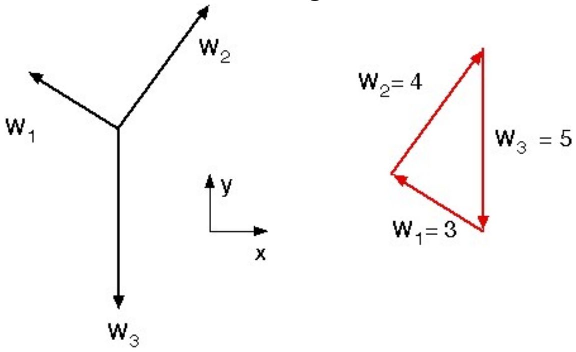
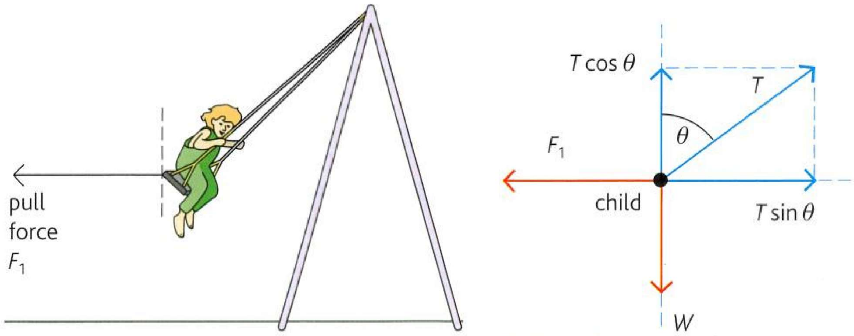
3.4.1 Force, energy and momentum

3.4.1.1 Scalars and vectors

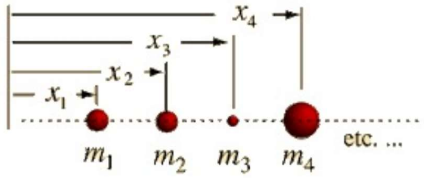
- Vector
  - Any physical quantity that has a direction as well as a magnitude
  - e.g. velocity, force / weight, acceleration, displacement
- Scalar
  - Any physical quantity that is not directional
  - e.g. speed, mass, distance, temperature
- Conditions for equilibrium
  - For an object to be in equilibrium, the sum of all the forces acting on an it must be 0
  - e.g. 3 forces form a closed triangle
    - 

- Explaining what forces balance each other
  - e.g. child on swing
    - Pull force balances with the **horizontal component** of tension
    - Weight balances with the **vertical component** of tension
    - 

a *On a swing* **b** *Force diagram*

3.4.1.2 Moments

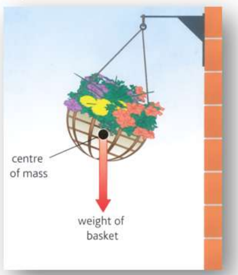
- Moment formula
  - Moment of a force about a point
    $= \text{force} \times \text{perpendicular distance from the pivot point to the line of action of the force}$
- Couple
  - A pair of equal and opposite parallel / coplanar forces acting on a body along different points
  - Exerts a turning force on a body
  - Moment of couple
    $= \text{force} \times \text{perpendicular distance between the lines of action of the forces}$
- Principle of moments
  - For an object in equilibrium, the sum of anticlockwise moments about a pivot is equal to the sum of clockwise moments
- Centre of mass
  - The point at which an object's mass acts
  - The point through which a single force on the body has no turning effect
- Finding centre of mass

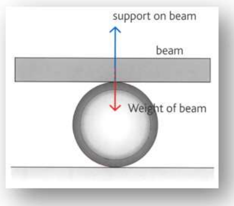
- Uniform regular solid
    - Centre of mass at the centre
- Non-regular card
    - Hang object (and plumb line) by first pivot
    - Draw first line vertically below pivot (by sketching a plumb line hang from the pivot)
    - Hang object (and the plumb line) by second pivot
    - Draw second line vertically below pivot
    - Intersection of lines is the centre of mass
- Multiple mass on a rod
    - $x_{cm} = \dfrac{\sum m_i x_i}{\sum m_i}$
    - 

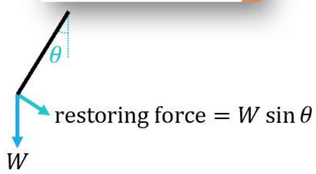
- Equilibrium stability
    - Stable
        - Object returns to its equilibrium position if displaced (a little)
        - Wide base, low centre of gravity
        - Tilted for a certain angle before centre of mass crosses the pivot point and topple
    - Unstable
        - Object does not return to its equilibrium position if displaced
        - Topple immediately after being tilted
    - Neutral
        - Stay in place when left alone
        - Stay in the new position when moved
        - The object's centre of mass is always exactly over the point which is its 'base'

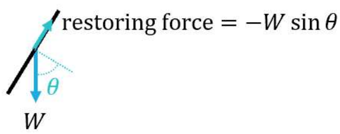
    Stable equilibrium

    Unstable equilibrium

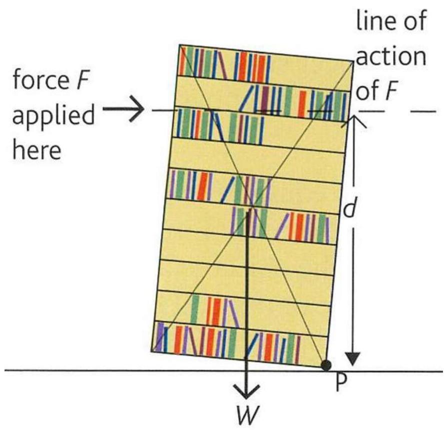
    - 

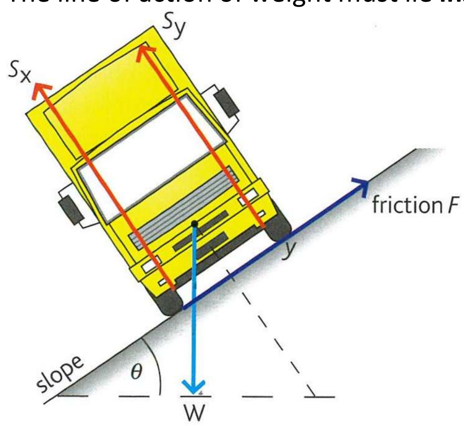






- Tilting / topping
    - Tilting
        - An object resting on a surface is acted on by a force that raises it up on 1 side
        - For an object to tilt: $Fd > \frac{Wb}{2}$ (b = width of base)

- 

  - Toppling
    - Tilted too far
    - Line of action of its weight passes beyond the pivot = topple over if allowed to
- Two support problems
  - When an object is in equilibrium and supported by 2 points then the 2 supports add up to the weight of the object
  - The support closer to the centre of mass provides more of the support force
- On a slope
  - The line of action of weight must lie **inside the base** of the object to prevent tilting
  - 

  - $S_x > S_y$ since x is lower than y (more moment is needed to be produced from x as it is closer to the centre of mass)
- Conditions for equilibrium
  - No resultant force
  - No resultant moment / torque (the principle of moments must apply)

3.4.1.3 Motion along a straight line

- Terms

Term	Definition
Speed	A scalar quantity describing how quickly an object is travelling
Displacement (s)	The overall distance travelled from the starting position (includes a direction, vector quantity)
Velocity (v)	Rate of change of displacement ($= \frac{\Delta s}{\Delta t}$)
Instantaneous velocity	The velocity of an object at a specific point in time
Average velocity	The velocity of an object over a specified time frame
Acceleration (a)	Rate of change of velocity ($= \frac{\Delta v}{\Delta t}$)
Uniform acceleration	The acceleration of an object is constant

- SUVAT equations

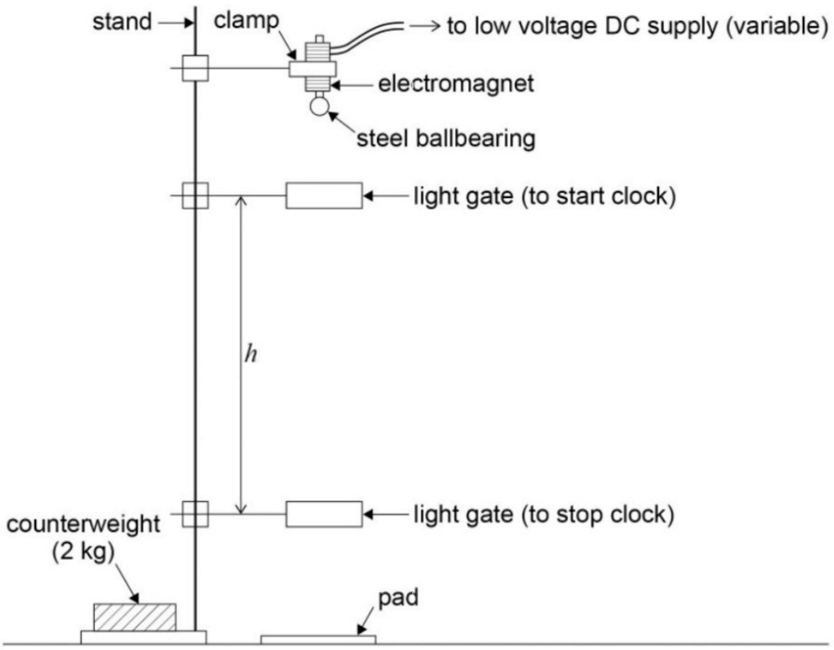
- For <u>uniform acceleration</u>
  - $v = u + at$
  - $s = \left(\frac{u+v}{2}\right)t$
  - $s = ut + \frac{1}{2}at^2$
  - $s = vt - \frac{1}{2}at^2$
  - $v^2 = u^2 + 2as$
- Motion graphs

	Displacement-time	Velocity-time	Acceleration-time
Gradient	Velocity	Acceleration	/
Area	/	(Change in) displacement	Change in velocity

- Free fall
  - $u = 0$
  - $a = g$
- Light gate
  - $\text{speed through the light gate} = \frac{\text{length of the object}}{\text{time for the light to be obscured}}$

Required practical 3 - determining g

- Equipment
  - Stand
  - Bosses and clamps
  - Electromagnet
  - Steel ball bearing
  - Light gate
  - Timer (connected to the light gate)
  - Soft cushion pad
- How to determine g by free fall
  - Set up the apparatus as shown

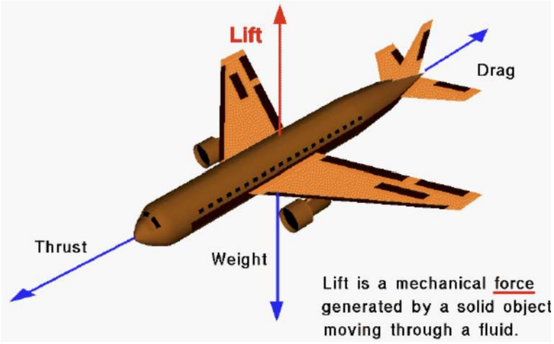


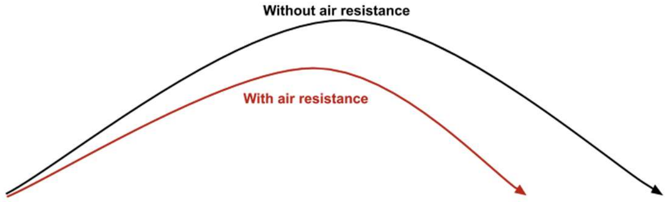
  - The position of the lower light gate should be adjusted such that the height h is 0.500m, measured using the metre rule
  - Turn on the electromagnet and attach the ball bearing
  - Reset the timer to zero and switch off the electromagnet
  - Read and record the time t on the timer for the ball to pass through the 2 light dates
  - Reduce h by 0.050m by moving the **lower light gate** upwards and repeat this, reducing h by

0.050m each time until h reaches 0.250m (at least 5-10 values of h)
    - Repeat the experiment twice more for each value of h and find and record the mean t for each h
    - Plot a graph of $\frac{2h}{t}$ against t and draw a line of best fit ($\frac{2h}{t} = 2u + gt$)
    - Gradient = g, y-intercept = $2u$
        - (You might want to draw lines of maximum and minimum gradient and find the mean gradient)
- Errors
    - Systematic
        - Residue magnetism after the electromagnet is switched off may cause t to be recorded as longer than it should be
        - Air resistance reduces the value of g determined
    - Random
        - Large uncertainty in h from using a metre rule with a precision of 1 mm
        - Parallax error from reading h
        - The ball may not fall accurately down the centre of each light gate (less time obscuring the light)
        - Random errors are reduced through repeating the experiment for each value of h at least 3-5 times and finding an average time, t
- Safety
    - The electromagnetic requires current
        - No water near it
        - Only switch on the current to the electromagnet once everything is set up to avoid electrocution
    - A cushion or a soft surface must be used to catch the ball-bearing so it doesn't roll off / damage the surface
    - The tall clamp stand needs to be attached to a surface with a G clamp so it stays rigid

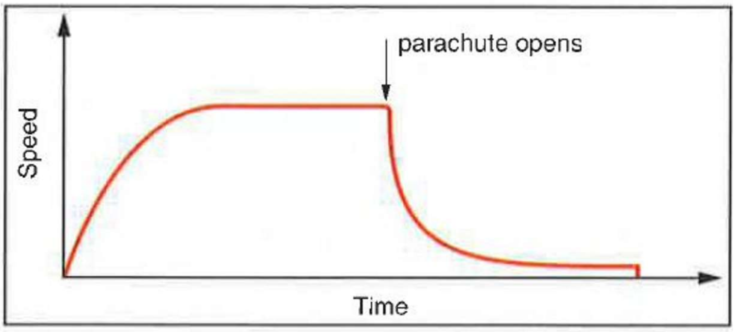
3.4.1.4 Projectile motion

- Motion equations ignoring air resistance
    - $v_x = u\cos\theta$
    - $x = ut\cos\theta$
    - $v_y = u\sin\theta - gt$
    - $y = ut\sin\theta - \frac{1}{2}gt^2$
- Range and maximum height
    - $\text{Maximum height} = \frac{u^2\sin^2\theta}{2g}$
    - $\text{Horizontal range} = \frac{u^2\sin 2\theta}{g}$
    - $\text{Time to maximum height} = \frac{u\sin\theta}{g}$
    - $\text{Time back to starting height} = \frac{2u\sin\theta}{g}$
- Friction
    - A force which opposes the motion of an object
    - AKA drag / air resistance
    - Convert KE into other forms of energy such as heat and sound (work done on the surface / fluid)
- Lift
    - An upward force which acts on objects travelling in a fluid
    - Caused by the object creating a change in the direction of the fluid flow
    - Happens if the shape of the projectile causes the air to flow faster over the top of the object than underneath it
        - Pressure of air on the top surface < pressure of the air on the bottom surface
        - Produces a net upward force

- Acts perpendicular to the direction of fluid flow
- 

- Effect of air resistance (friction)
  - Air resistance / drag force acts in the opposite direction of motion of the projectile
  - Increases as the projectile's speed increases
  - Reduces both the horizontal speed of the projectile and its range
  - Has both horizontal and vertical components
  - Reduces the maximum height of the projectile if its initial direction is above the horizontal and makes its descent steeper than its ascent
  - 

- Terminal velocity
  - Occurs where **the frictional forces acting on an object and the driving forces are equal**
  - No resultant force → no acceleration → travels at constant speed / velocity
- Terminal velocity for objects falling
  - Start initially with free fall (uniform acceleration) briefly
    - The only force acting on the object is weight
    - (Other forces are very small and negligible)
  - Speed still increases but acceleration decreases
    - Air resistance increase because speed increase
    - Resultant force gets smaller
  - Eventually the object falls in uniform velocity (reached terminal velocity)
    - Weight balanced exactly by resistive force upwards
    - Resultant force = 0 so there is no acceleration
    - Air resistance is not increasing anymore because speed is not increasing
    - Potential energy of the object is transferred to the internal energy of the fluid by drag forces
  - Effect of parachute
    - Increase air resistance due to larger area perpendicular to direction of travelling
    - Resultant force upwards so deceleration
    - Air resistance falls as speed falls
    - Decelerates until air resistance get as big as speed so the object falls at uniform speed again
  - Graph
    - Gradient should start with gradient **9.81 m s^{-2}** not bigger than **9.81 m s^{-2}**

- 

    - (Same to other situations moving through a fluid - resistance increase until the maximum speed is reached)
- Factors affecting terminal velocity
    - Higher mass → higher acceleration → higher terminal velocity
    - Higher volume / CSA → more air resistance → less acceleration →' lower terminal velocity

3.4.1.5 Newton's laws of motion

- Newton's 1st law of motion
    - If no resultant external force are acting on a body, it will
        - If at rest, remain at rest
        - If moving, keep moving at constant speed in a straight line
- Newton's 2nd law of motion
    - The acceleration of an object is proportional to the resultant force experienced by the object
    - Acceleration is in the same direction as the resultant force
    - $\text{resultant force} = \text{mass} \times \text{acceleration}$
    - $F = ma$
- Newton's 3rd law of motion
    - When two objects interact, they exert **equal and opposite** forces on each other

3.4.1.6 Momentum

- Momentum calculation
    - $\text{Momentum} = \text{mass} \times \text{velocity}$
    - $p = mv$
- The principle of conservation of momentum
    - Momentum is always conserved for a system of interacting objects provided that no external resultant force acts on the system
    - Total final momentum = total initial momentum
- Types of collisions
    - Elastic
        - There is no loss of kinetic energy during the collision
        - Both momentum and KE are conserved
        - $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$
    - Inelastic: only momentum is conserved, some KE is lost
        - Stick together: $m_1u_1 + m_2u_2 = (m_1 + m_2)v_{1+2}$
        - Colliding objects have less KE after the collision than before the collision
- Explosion
    - $m_1v_1 + m_2v_2 = 0$
    - KE of the objects has increased
- Newton's 2nd law of motion with momentum
    - The rate of change of momentum of an object is proportional to the resultant force on it
    - (The resultant force is proportional to the change of momentum per second)
    - $F = \dfrac{\Delta(mv)}{\Delta t}$
- Impulse
    - The change in momentum
    - $\text{Impulse} = F\Delta t = \Delta(mv)$
- Force-time graph

    - Area = $F\Delta t$ = change in momentum
- Stopping distances
    - $\text{Thinking distance } s_1 = \text{speed} \times \text{reaction time} = ut_0$
    - $\text{Braking distance } s_2 = \dfrac{u^2}{2a}$
    - $\text{Stopping distance} = s_1 + s_2 = ut_0 + \dfrac{u^2}{2a}$
- Contact and impact time
    - $\text{impact time} = \dfrac{2s}{u+v} = \dfrac{2 \times \text{distanced moved by cars}}{\text{initial velocity} + \text{final velocity}}$
    - $a = \dfrac{v-u}{t}$
    - $F = ma = \dfrac{mv - mu}{t}$
    - (These calculations only need to be applied onto one car)
- Why airbags / seatbelts / etc. work
    - With no seat belt / airbag / etc. the person would not start to change their momentum until they hit the dashboard or windscreen
    - The person comes to stop quickly (short impact time)
        - Large change of momentum in a short time = large resultant force = large injury ($F = \frac{\Delta(mv)}{t}$)
    - With the seatbelt / airbag / etc. they will have a longer impact time (comes to stop more slowly)
        - They will experience a smaller resultant force and so less injury

3.4.1.7 Work, energy and power

- Work
    - $\text{Work done} = \text{force} \times \text{distance moved in the direction of the force}$
    - Unit = joules (J)
    - $W = Fs\cos\theta = \text{force} \times \text{displacement} \times \text{angle between force and direction of motion}$
- Force-displacement graphs
    - Area under line = work done
- Power
    - Rate of doing work = rate of energy transfer
    - $P = \dfrac{\Delta E}{\Delta t} = \dfrac{\Delta \mathrm{W}}{\Delta t} = Fv\cos\theta = \text{driving force} \times \text{velocity} \times \cos\theta$
- Efficiency
    - $\text{Efficiency} = \dfrac{\text{Useful work done}}{\text{Total energy input}} = \dfrac{\text{Useful energy output}}{\text{Total energy input}} = \dfrac{\text{Useful power output}}{\text{Total power input}}$
    - Can be expressed as a percentage

3.4.1.8 Conservation of energy

- Principle of conservation of energy
    - Energy cannot be created or destroyed but transferred from one store to another
- Kinetic energy
    - $E_k = \dfrac{1}{2}mv^2$
- (Gravitational) potential energy
    - $E_p = mg\Delta h$