Gravity + Motion

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Gravitational Motion + Satellites

Gravitation is a force of attraction between any two masses. The F acts from the centre of each mass. 'For every action there's an = and opposite reaction' ∴ gravitation acts equally and oppositely on each mass.

Newton's Law of Universal Gravitation

$$F_g = \frac{G M_1 m_2}{r^2}$$

As $r \uparrow$ $F_g \downarrow$: $F_g \propto \frac{1}{r^2}$

As $m \uparrow$ $F_g \uparrow$: $F_g = mg$

F_g = Gravitational Force (N)

M_1 = larger mass

m_2 = smaller mass

r = Distance between the CENTRES of the masses.

G = Universal Gravitational Constant.

The Universal Gravitational Constant

$6.67 \times 10^{-11}\ N m^2 kg^{-2}$

Verg small ∴ only applies to VERY large masses and is not noticeable in everyday life. Gravitational force is extremely weak compared to other fundamental forces.

Gravitational Fields

GRAVITATIONAL FIELD:

A region around a mass in which other masses will experience a gravitational force.

GRAVITATIONAL FIELD STRENGTH (g)

$F_W = F_g = \frac{G M_E M_o}{r^2}$ M_E = Earth mass, M_o = object mass

$F_W = M_o g$ g = Gravitational Field Strength

$\therefore M_o g = \frac{G M_E M_o}{r^2}$ $(N\,kg^{-1})$ (ms^{-2})

$\therefore g = \frac{G M_E}{r^2}$

∴ Gravitational field strength (g) is independent of object mass.

∴ g depends on the planet's mass and the distance of something from the planet's centre.

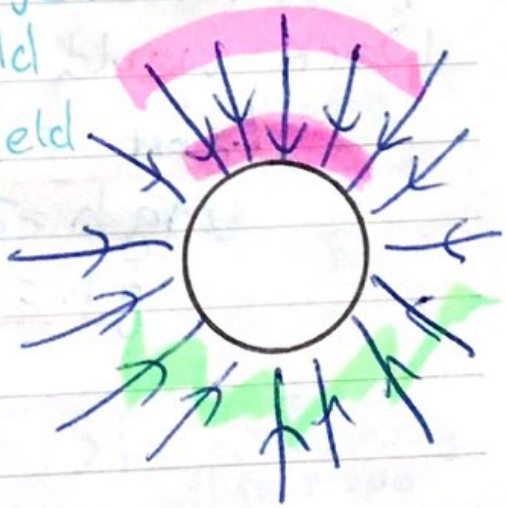
DIAGRAMMATIC REPRESENTATION

- Arrow direction is towards object
- More arrows = ↑ mass = ↑ field
- Arrow Density indicates field strength at any point.

: Dense ∴ ↑ g

: Sparse ∴ ↓ g

: Lots! ∴ ↑ m ∴ ↑ g



Work in a Gravitational Field

When a mass moves or is moved from 1 point to another in a gravitational field and its potential energy changes, WORK is done on the mass by the field.

$W = Fs$ ∴ One N of force supplied by the field moving something 1 m + does 1 Joule of Work (or as $W = \Delta E$, uses 1 Joule of E_p to move the object 1m)

$f = ma$ ∴ $W = mas$

$E_p = mgh$

An object h m above earth with mass m will have a particular amount of gravitational potential energy. If it were to move due to the g field Work would be done and $E_p \rightarrow E_k$.

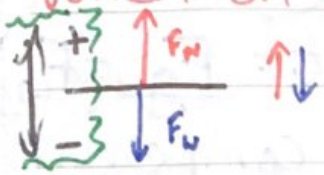
$E_{p\ lost} = E_{k\ gained}$

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

$gh = \frac{1}{2}v^2$

Apparent Weight (Lessness)

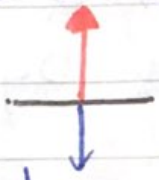
When on a surface at constant velocity



$\therefore F_{Net} = 0$ $(F_{Net} = F_W + F_N)$ $F_W = F_N$

$F_N + (-F_W) = 0$

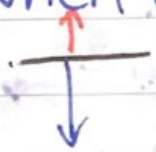
When on a surface accelerating upwards



$F_N > F_W \therefore F_N + (-F_W) =$ +ve F_{NET}

$F_{NET} = \overset{\text{apparent}}{\text{weight}} = F_{aw} = m(g+a)$

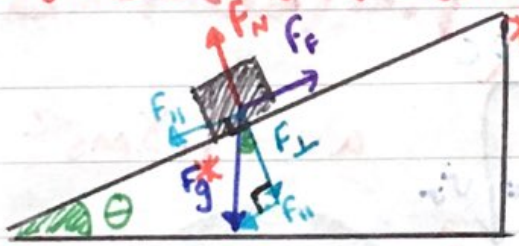
When on a surface accelerating downwards



$F_W > F_N \therefore F_N + (-F_W) =$ −ve F_{NET}

$F_{NET} = \overset{\text{apparent}}{\text{weight}} = F_{aw} = m(g-a)$

Inclined Planes



$F_g = F_W = mg$

F_g can be broken into 2 components to oppose F_F and F_N

$F_\perp$ opposes F_N

$F_\perp = mg\cos\theta$

$g\cos\theta$ = ⊥ to surface component of g

$F_{||}$ opposes F_F

$F_{||} = mg\sin\theta$

In the absence of F_F

$a = g\sin\theta$

$= \frac{F_{||}}{m} = \frac{ma = mg\sin\theta}{m}$

If $F_{||} = F_F \Rightarrow$ object has constant v

If $F_{||} > F_F$ object is accelerating ∥ to slope

Projectile Motion

Projectile – object projected into air with no power source.

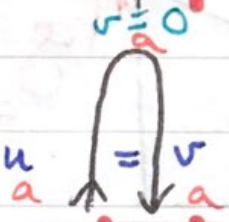
∴ only force in flight = F_g (F_w)

Horizontal and vertical components of flight are independent of one another but connected by flight time.

Horizontal	vs	Vertical
$a = 0$		$a = 9.80\ ms^{-2}$ ↓
$u_h = v_h$ (velocity constant)		velocity dynamic (a)

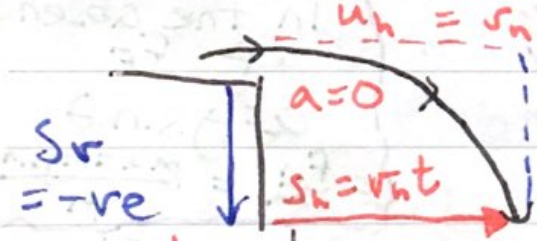
$t_h = t_v$

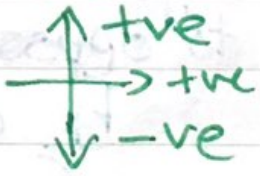
vertical projectiles



$a = -9.8\ ms^{-2}$

Horizontal projectiles





	h	v
s		-ve
u	const.	0
v		
a	0	-9.8
t	LINK	

Horizontal v = constant $u_h = v_h$

Initial vertical v = 0 $u_v = 0$

Horizontal a = 0

vertical $a = -9.8\ ms^{-2}$

$t_h = t_v$

Oblique projectiles

PROJECTED AT ANGLE, LANDS SAME HEIGHT

- Flight is symmetrical
- ∴ can $\frac{1}{2}$ where $v_v = 0$
- launch θ = land θ
- velocity launch = velocity land
  $v_i = v_f$
- vertical disp. = 0 $s_v = 0$
- $t_{rise} = t_{fall}$

	h	v
s		0
u	const.	a
v		-a
a	0	-9.8
t	link	

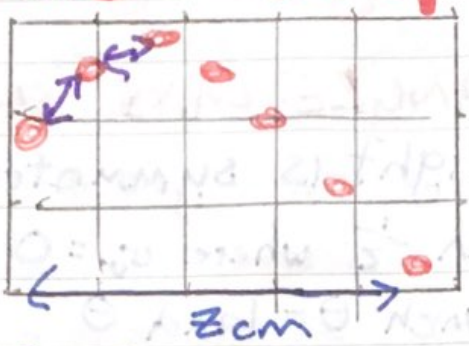
- $u_v = V_T \sin\theta$
  $u_h = V_T \cos\theta$
- $u_v = -v_v$

PROJECTED AT ANGLE, LANDS AT DIFFERENT HEIGHT

- NON symmetrical flight
- s_v = diff b/n levels +ve/-ve
  If land lower s_v = -ve
  If land higher s_v = +ve
- v_v at max = 0
- ∴ can divide flight into 2 NOT even parts
- $u_h = v_h$
  $|u_v| \neq |v_v|$
- $u_v = V_T \sin\theta$
- $u_h = V_T \cos\theta$

	h	v
s		
u	const.	
v		
a	0	-9.8
t	LINK	

Stroboscopic diagrams



Scale: xcm = ym

zcm : wm = xcm : ym

$\frac{z}{w} = \frac{x}{y}$

$\therefore zcm = \frac{x}{y} \times wm$

If $f = f$ Hz

$T = \frac{1}{f}$ s = time of gaps b/n balls

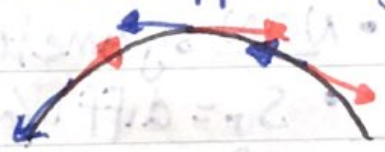
total time $(z) = \frac{1}{f} \times N^o$ gaps

$= \frac{1}{f} \times 6$

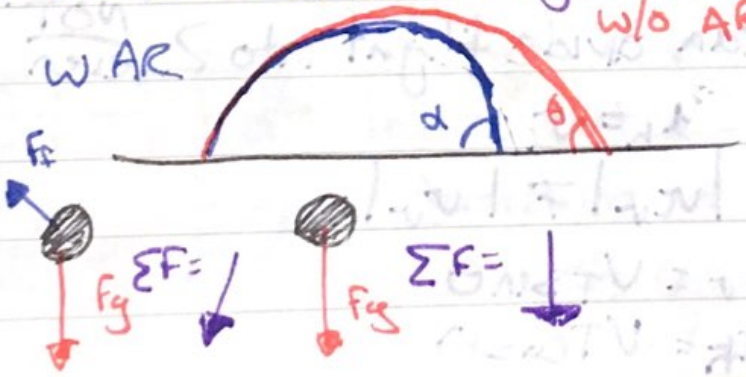
Measure everything with ruler and protractor!!

Projectiles + Air Resistance

Air Resistance • Acts oppositely to object motion

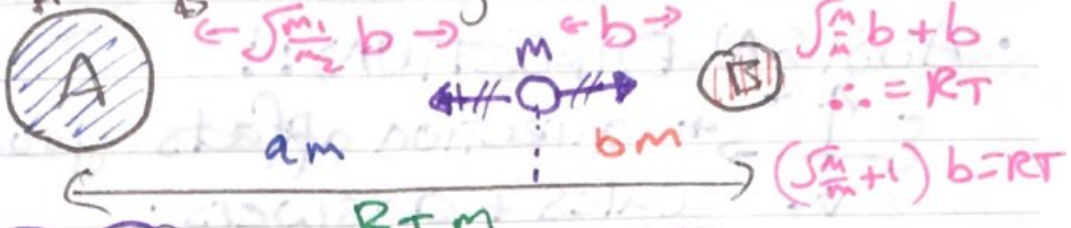


- Reduces calculated range (s_h ↓)
- Reduces calculated max height (s_v ↓)
- Increases descent angle (steeper descent)



Gravitational Null points

Point b/n two masses where $F_A = -F_B$ and they cancel out



METHOD 1

$$F_A = F_B$$

$$\frac{GM_A m}{a^2} = \frac{GM_B m}{b^2}$$

$$\frac{M_A}{a^2} = \frac{M_B}{b^2} \quad \therefore \quad \frac{a^2}{b^2} = \frac{M_A}{M_B}$$

$$a = \sqrt{\frac{b^2 M_A}{M_B}} = \sqrt{\frac{M_A}{M_B}}\, b$$

$$\left(\sqrt{\frac{M_A}{M_B}} + 1\right) b = R_T \Rightarrow \text{SOLVE}$$

METHOD 2

$$a + b = R_T \quad \therefore \quad b = R_T - a$$

$$F_A = F_B$$

$$\frac{GM_A m}{a^2} = \frac{GM_B m}{(R_T - a)^2}$$

$$\Rightarrow \frac{M_A}{a^2} = \frac{M_B}{(R_T - a)^2} \Rightarrow \frac{R_T - a}{a} = \sqrt{\frac{M_B}{M_A}}$$

$$R_T = a + a\sqrt{\frac{M_B}{M_A}}$$

$$R_T = a\left(1 + \sqrt{\frac{M_B}{M_A}}\right)$$

$$\therefore \quad a = \frac{R_T}{1 + \sqrt{\frac{M_B}{M_A}}}$$

Tips + Notes!!!

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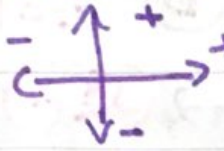
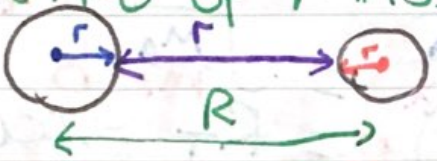
- CONSTRUCT DIAGRAMS!
  Sketch situations and include givens
- ASSIGN DIRECTION!!



direction affects your calcs + answers!

- VECTORS HAVE DIRECTION!!
  eg $-9.8 ms^{-2} \Rightarrow 9.8 ms^{-2}$ down 43m S 39° W
  $23.2 ms^{-1}$ 42° to the horizontal
- Force due to gravity acts from the CENTRE of MASSES!



$R = r + r + r$

- NEWTON'S 3RD LAW
  Every action has an equal and opposite reaction ∴ FORCE exerted on A by B = FORCE exerted on B by A

$$F_B = \frac{GM_BM_A}{r^2} = F_A = \frac{GM_AM_B}{r^2}$$

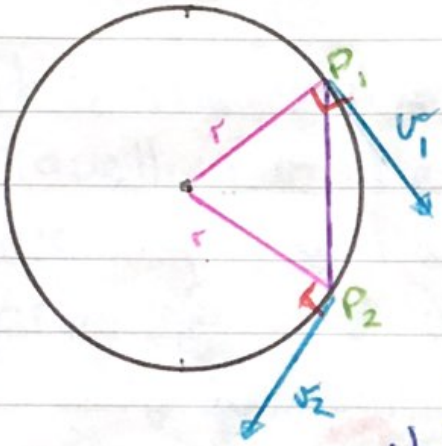
Acceleration is different as $F = Ma \Rightarrow a = \frac{F}{M}$
Mass is different.

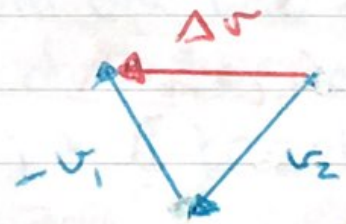
- Gravitational field Strength = $9.8 N kg^{-1}$
- Acceleration due to Gravity = $9.8 ms^{-2}$
  $= g$

Circular Motion

An object moving in a circle may travel with constant SPEED but its velocity will be constantly changing as its direction of motion is constantly changing. Because v is changing the object is accelerating

$$\Delta v = v - u$$
$$= v_2 - v_1$$





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

it follows that the object is accelerating in the direction of Δv (towards the centre)

- The radius is a position vector acting out from the centre
- Velocities (v_1, v_2) are a tangent to the circle ie. right angles to the radius
- Acceleration is always towards the centre
- Time to make 1 revolution is called the period (T)

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Distance around a circle $= 2\pi r$
Time for 1 revolution $= T$
$\therefore$ Speed $= v = \frac{s}{t} = \frac{2\pi r}{T}$

Centripetal acceleration

Acceleration is the change in velocity and as shown $\therefore$ always acts towards the circle centre.

$$a_c = \frac{v^2}{r}$$

$v = \frac{2\pi r}{T} \therefore a_c = \frac{4\pi^2 r}{T}$

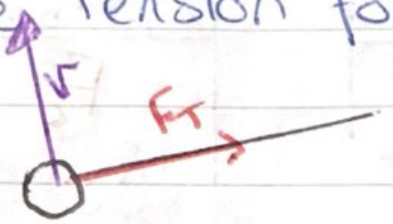
$s = \frac{vT}{2\pi} \therefore a_c = \frac{2\pi v}{T}$

Centripetal force

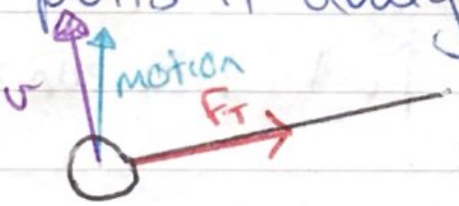
Centripetal (centre-seeking) force is simply the name given to any force directed toward a fixed centre.

eg ① If you swing a ball on a string in a circle the force of tension in the string is the

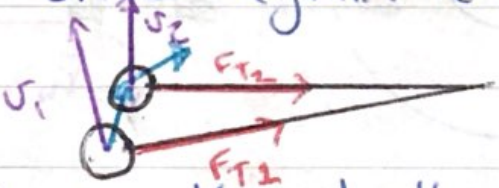
centripetal force directed towards your hand (the fixed centre)
At any given moment the balls velocity is tangential to the circle motion, and perpendicular to the tension force



Thus the ball will want to continue travelling in the direction of its velocity (inertia) but the tension force pulls it away.

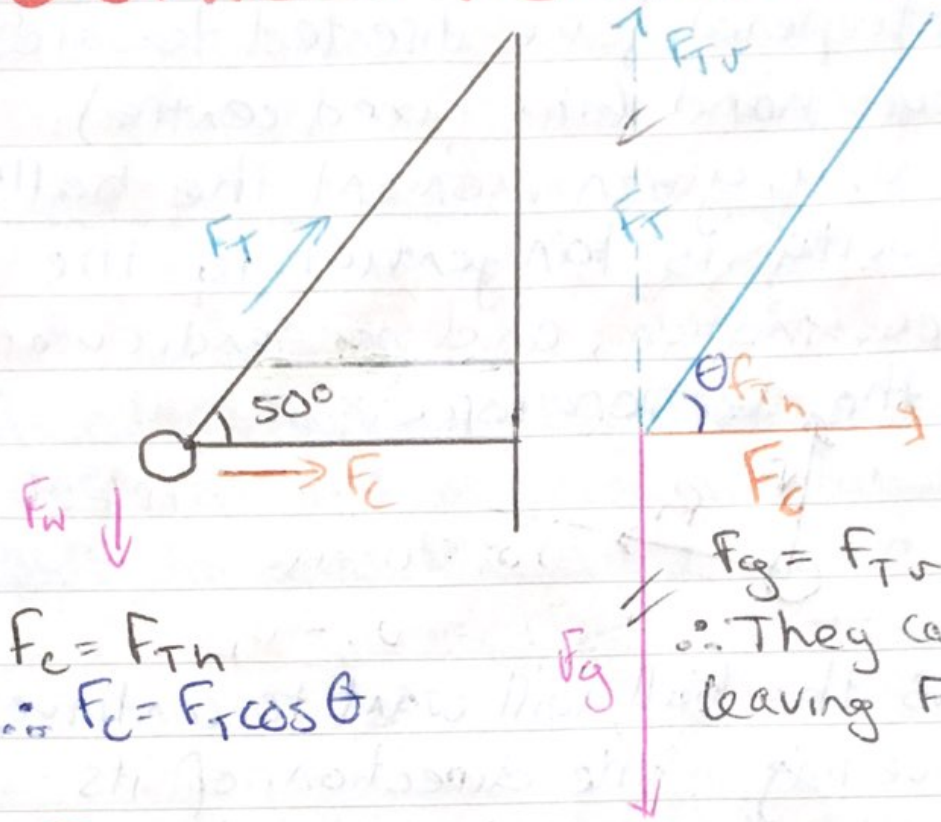


The ball then travels in its new direction, and wants to continue doing so, but once again tension pulls it away



And so the ball swings on a curved path.

Conical Pendulum



$F_C = F_{TH}$

$\therefore F_C = F_T \cos\theta$

$F_g = F_{TV}$

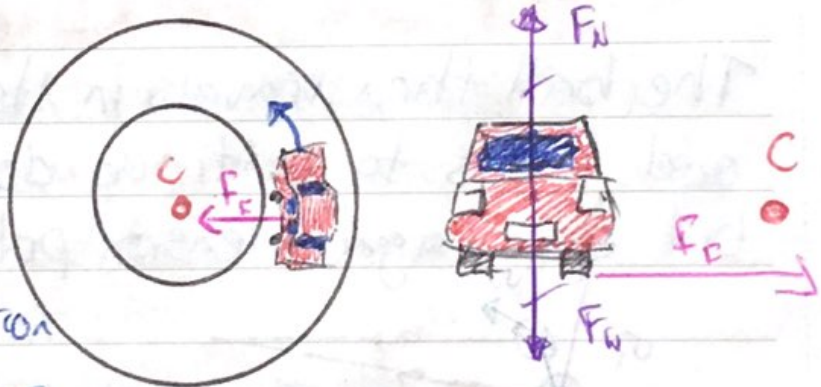
$\therefore$ They cancel leaving F_{TH}

Banked Tracks

On a normal, flat, horizontal circular track:

$F_C = F_{Net} = F_F$

Normal and weight force cancel, leaving Friction to supply centripetal force and maintain circular motion.



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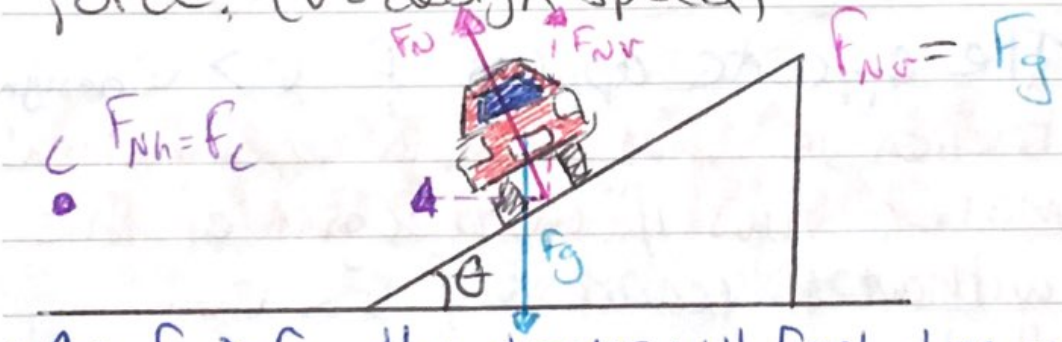
However on a banked curve F_N is no longer vertical, so has a horizontal component. The need for frictional force has been alleviated. in fact depending on the angle of banking (θ) at a certain constant v a car can go around the track with no ~~xxxx~~ sideways frictional force, F_{Nh} is the net and centripetal force. (v = design speed)



- As $F_N > F_g$, the driver will <u>feel</u> heavier
As friction is less of a requirement to round the curve, cars can go faster around banked curves without skidding.
- At design speed, no F_F up or down the track means it'd feel as though you were on a straight, flat track.

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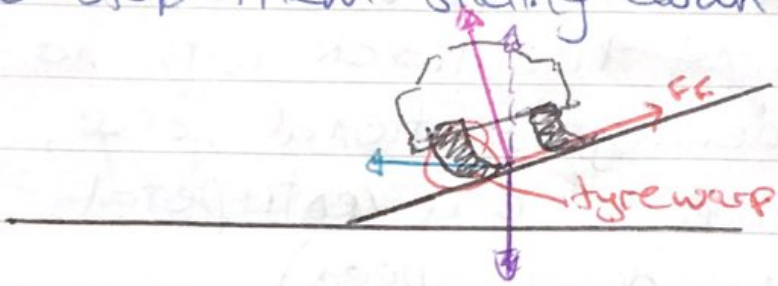
if a car were to go slower than design speed, gravity is the same but F_c and F_N are smaller.

$F_c = mv$ $F_c = \frac{mv^2}{r}$ $m, r =$ fixed

$v \downarrow \rightarrow F_c \downarrow$

The car would depend on friction to stop them sliding down the slope.



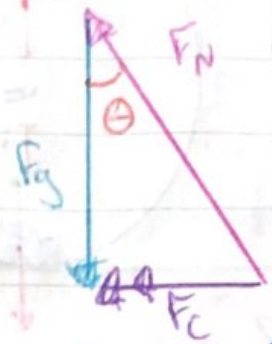
The opposite applies if $v > v_{design}$

Friction is what attempts to 'maintain' motion, thus if we thought of this without it (on ice) if $v < v_{design}$ the car would go down the slope, if $v > v_{design}$ it would go up.

To go above or below design speed and maintain frictionless motion, radius can be increased or decreased by going up/down the slope.

$F_c = \frac{mv^2}{r}$ if $r \uparrow$ $F_c \downarrow$ v can $\uparrow$ and F_c will not change

A derived formula for design speed:



REMEMBER θ is between F_g and F_N!

$\tan\theta = \frac{F_c}{F_g}$

$\tan\theta = \left(\frac{mv^2}{r}\right)\left(\frac{1}{mg}\right)$

$\tan\theta = \frac{v^2}{rg}$

$\therefore v = \sqrt{rg\tan\theta}$

OR $F_N = \frac{F_g}{\cos\theta}$

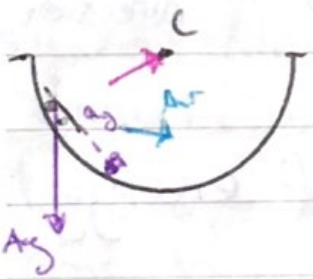
$F_N = \frac{F_c}{\sin\theta}$

$F_N = F_N$

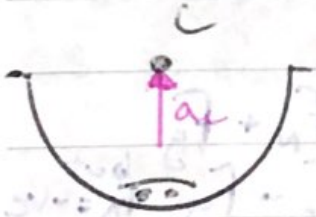
$\frac{F_g}{\cos\theta} = \frac{F_c}{\sin\theta}$

$\frac{\sin\theta}{\cos\theta} = \frac{F_c}{F_g}$

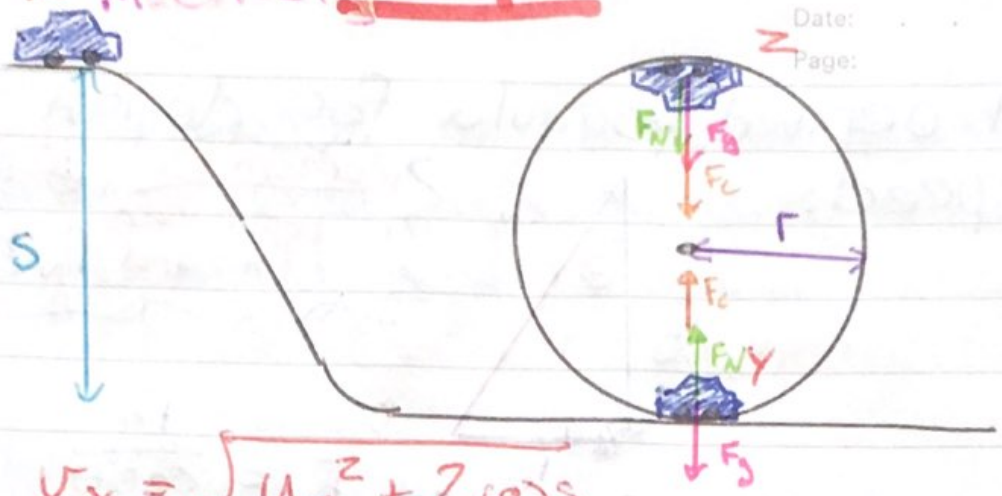
Circular Motion in a Vertical Plane



In a vertical plance, circular motion is not usually uniform. On a halfpipe a skater will gain v as they go down, thus there is a_g down the slope. However at the bottom they don't slow or speed up a is purely centripetal and easier to analyse.



Loops



$v_y = \sqrt{u_x^2 + 2(g)s}$

$F_c = \frac{mv_y^2}{r}$ $\quad F_c = F_N + F_g$

$a_c = \frac{v^2}{r}$ $\quad F_N = F_c - F_g$ $\quad F_g$ acts down $\therefore$ is -ve

$\therefore F_N > F_c$

$v_z = \sqrt{u_y^2 + 2(g)(s)^*}$ $\quad s = 2r$

$F_c = \frac{mv^2}{r}$ $\quad F_c = F_N + F_g$ $\quad F_g, F_c$ act in same direction

$a_c = \frac{v^2}{r}$ $\quad F_N = F_c - F_g$

$F_N < F_c$

$F_{NY} > F_{NZ}$

Can be done in terms of energy.

$E_{Total} = E_p + E_k$

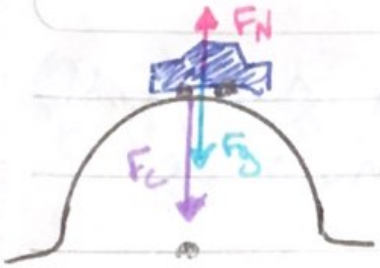
Dips + Bumps

$F_c = F_N + F_g$

$F_N = F_c - F_g$ but F_g = -ve

$\therefore F_N > F_g$

$\therefore$ You'll feel heavy at bottom



$F_c = F_N + F_g$

$F_N = F_c - F_g$

But F_c, F_g act in same direction

$\therefore F_N < F_g$

$\therefore$ you'll feel light at the top

Apparent Weight

$F_{aw} = m(g - a_c)$

At top, g, a_c act in same direction

$\therefore m(g - a_c) < mg$

$F_{aw} < F_g$

At bottom, g = -ve a_c = +ve

$\therefore m(g - (-a_c)) > mg$

$F_{aw} > F_g$

Satellite Motion

SYLLABUS: Newton's Law of Universal Gravitation is used to explain Kepler's Laws of Planetary Motion and to describe the motion of planets and other satellites, modelled as uniform circular motion.

$F_c = F_g$

$\frac{mv^2}{r} = \frac{GMm}{r^2}$ $\therefore \frac{m4\pi^2 r}{T^2} = \frac{GMm}{r^2}$

$v = \frac{2\pi r}{T}$ $\therefore \frac{r^3}{T^2} = \frac{GM}{4\pi^2}$

Since G and planetary mass (M_1) are constant, $\frac{r^3}{T^2}$ must be constant!

∴ The value of $\frac{r^3}{T^2}$ for one of a planet's moons, will be the same for every other moon.

Applying such formulae as:

$$v = \frac{2\pi r}{T} \quad a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2} = \frac{GM}{r^2} = g$$

$$F_g = \frac{Mv^2}{r} = \frac{4\pi^2 rm}{T^2} = \frac{GMm}{r^2} = mg.$$

$$\frac{r^3}{T^2} = \frac{GM}{4\pi^2}$$

Most orbital features of any satellite may be found.

CANNONBALL THOUGHT EXP.

Given enough v a cannonball fired above Earth can continually 'miss' the earth, be pulled into a circular motion by

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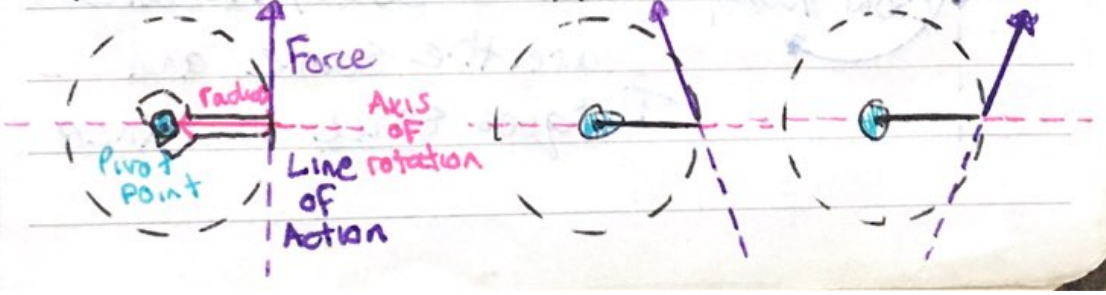
earth's gravity and thus orbit Earth. As such, objects orbiting earth are not experiencing 'zero gravity' but are in a state of perpetual free fall, g still acts on them.

Torque

Torque is the rotational counterpart of Force. Forces tend to change the motion of things, If you want to make a stationary object move, or a moving object change its velocity apply FORCE. Torques tend to twist or change the rotational motion of things, If you want to make a stationary object rotate, or a rotating object change its rotational velocity, apply TORQUE.

VOCAB and DIAGRAMS



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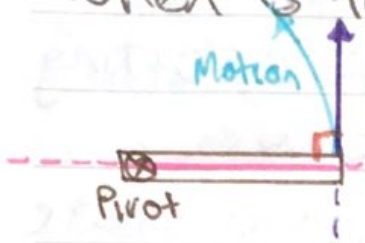
When is torque produced?



When the LINE OF ACTION goes through the pivot and axis of rotation:

No motion occurs

$\tau = rF\sin\theta$

$\sin 90 = 1$

$\tau = rF$ MAX τ!

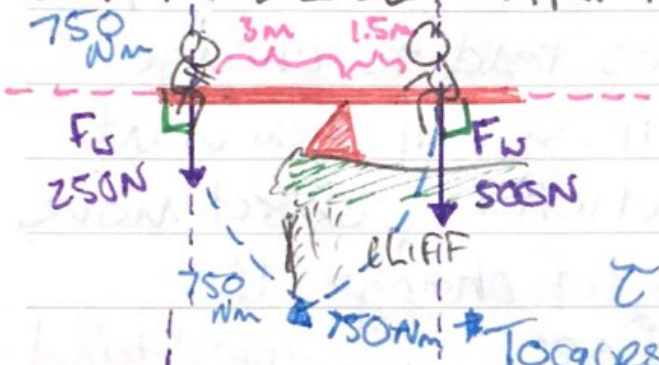
$\tau = rF\sin 0$

$\sin 0 = 0$

$\tau = 0$ NO τ!

TWO SOLVING STRATEGIES:

① THE LEVER ARM



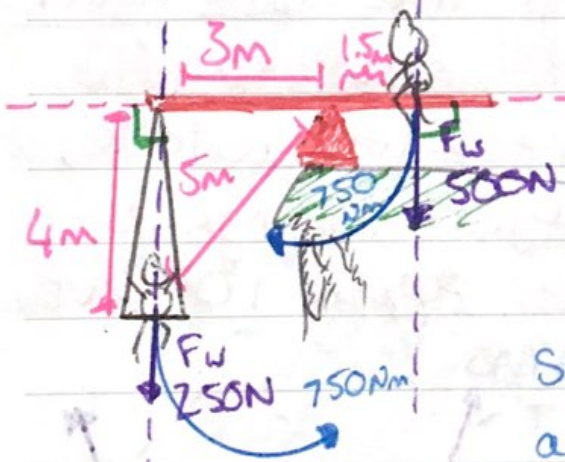
$\sum\tau = \tau_{CLOCKWISE} + \tau_{ACW}$

$= (500)(1.5) - (250)(3)$

$= 750 - 750$

$\tau_{CW} = \tau_{ACW}$

Torques balance, no rotation

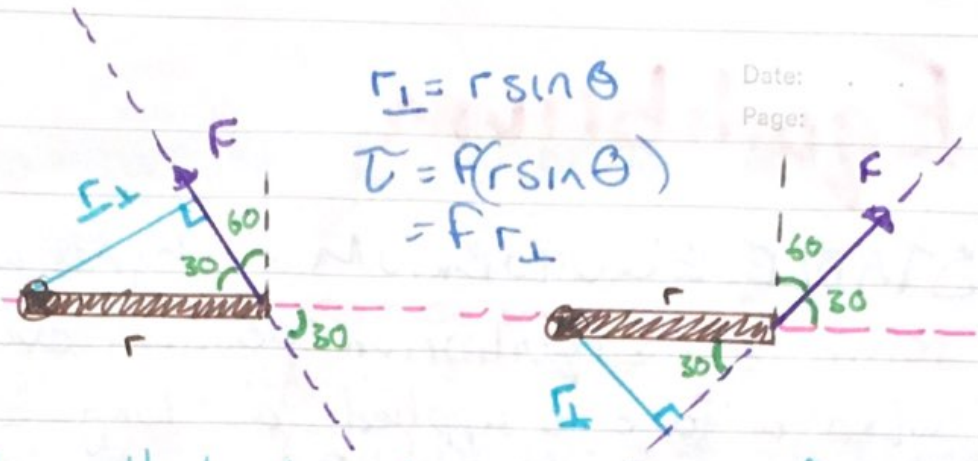


The line of action is STILL $\perp$ to the lever arm (axis of rotation) $\therefore$ r is the SAME (3m) $\therefore$ calcs are the same and Torques STILL balance

$r_\perp = r\sin\theta$

$\tau = F(r\sin\theta)$

$= F r_\perp$

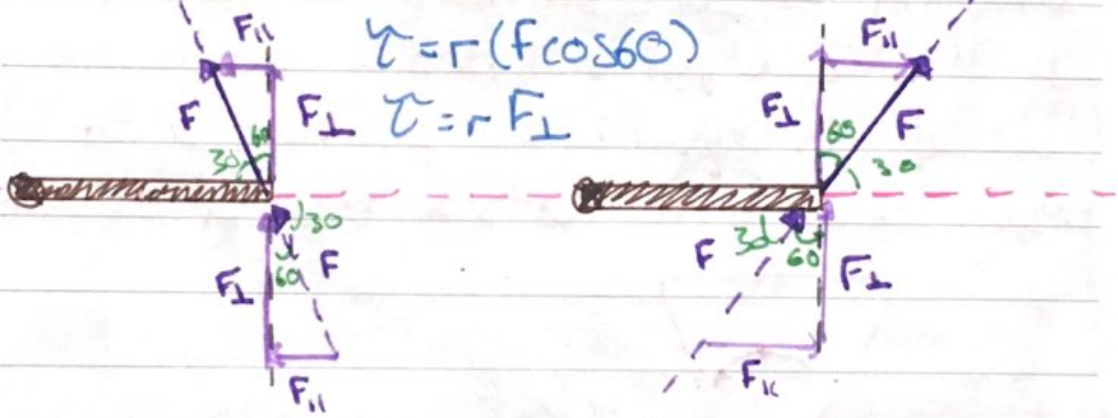


A hypothetical radius is drawn from the pivot point to form a 90° angle with line of action (force arm) this creates a 'perpendicular radius' the component of the radius $\perp^r$ to F

(2) PERPENDICULAR FORCE

$\tau = r(F\cos 60)$

$\tau = r F_\perp$



Alternatively we could consider the component of force $\perp^r$ to r. ie the component pulling the door, $F_{||}$ acts parallel so has no effect.

$\cos 60 = \sin 30 = \frac{1}{2}$ thus the answer would be the same.

Equilibrium

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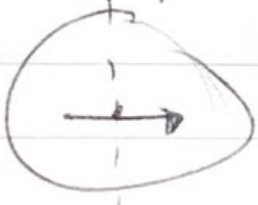
STABLE EQUILIBRIUM - object will return to its equilibrium position even when a force is applied, as long as the centre of mass is not moved outside the base of support

UNSTABLE EQUILIBRIUM - when force is applied object will readily accelerate out of its equilibrium position. Centre of mass easily moved outside base of support

NEUTRAL EQUILIBRIUM - will remain stationary no matter where placed, force applied has no effect of relations b/n c o f and base of support.

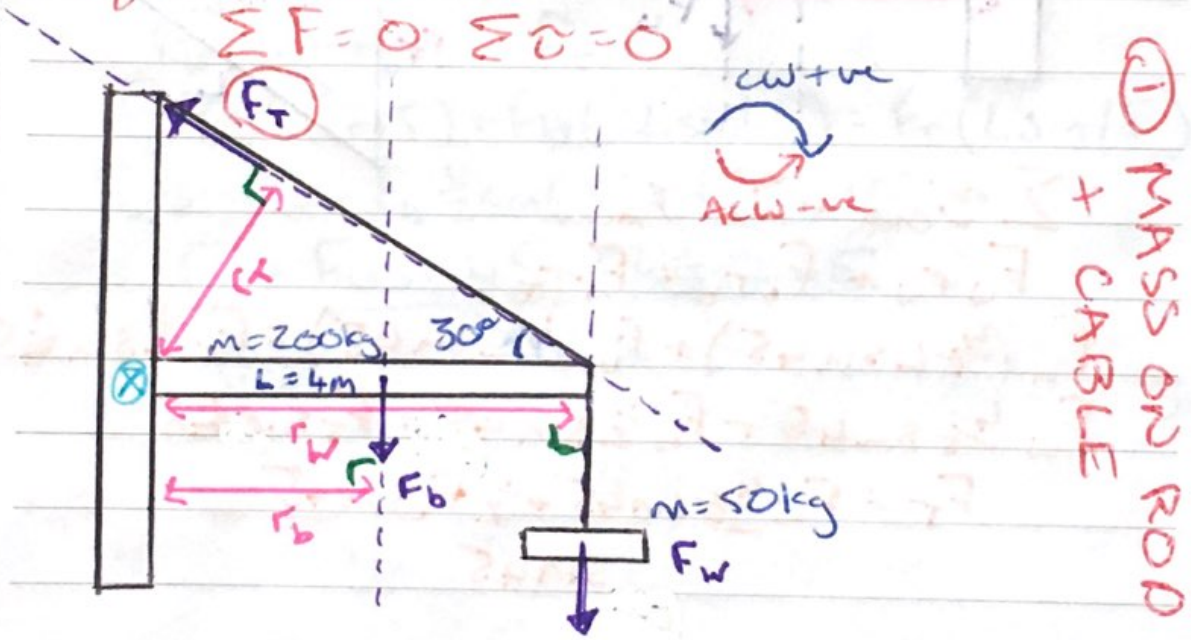


Translational Equilibrium: ΣF through centre $= 0$ ∴ no a
∴ object is stationary or at a constant velocity.

Rotational Equilibrium: $\Sigma \tau$ clockwise and anticlockwise $= 0$ about a reference point

Static Equilibrium: A system is not accelerating or rotating; it is in translational and rotational equilibrium.

$\Sigma F = 0 \quad \Sigma \tau = 0$



① MASS OF ROD + CABLE

$\Sigma \tau_{CW} = \Sigma \tau_{ACW}$

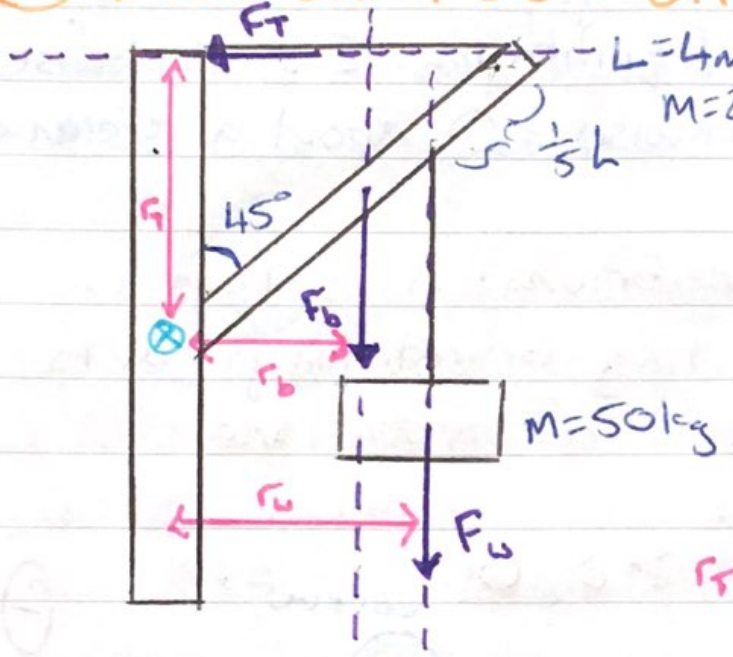
$F_W r_W + F_b r_b = F_T r_T$

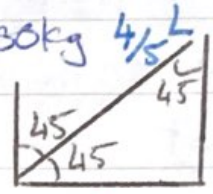
$F_W (L) + F_b (\frac{1}{2} L) = F_T (L \sin 30°)$

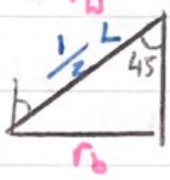
$$F_w + \frac{1}{2}F_b = F_T \sin 30$$

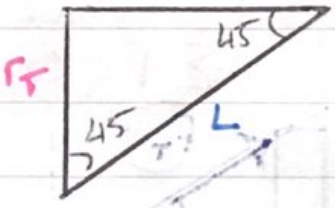
$$F_T = \frac{F_w + \frac{1}{2}F_b}{\sin 30}$$

(2) MASS ON ROD + CABLE









$$\sum \tau_{CW} = \sum \tau_{ACW}$$

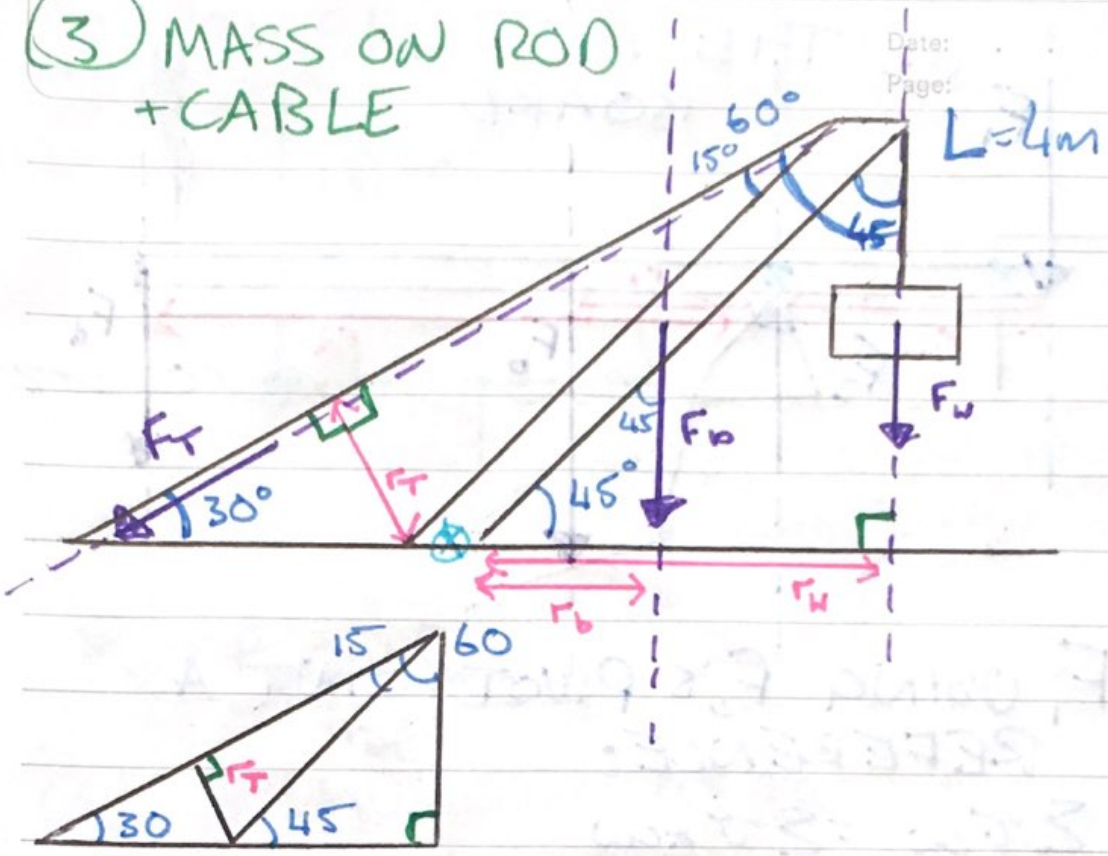
$$F_w r_w + F_b r_b = F_T r_T$$

$$F_w\left(\frac{4}{5}L\sin 45\right) + F_b\left(\frac{1}{2}L\sin 45\right) = F_T L \sin 45$$

$$F_w \frac{4}{5}\sin 45 + F_b \frac{1}{2}\sin 45 = F_T \sin 45$$

$$F_T = \frac{F_w \frac{4}{5}\sin 45 + \frac{1}{2}F_b \sin 45}{\sin 45}$$

(3) MASS ON ROD + CABLE



$$\sum \tau_{CW} = \sum \tau_{ACW}$$

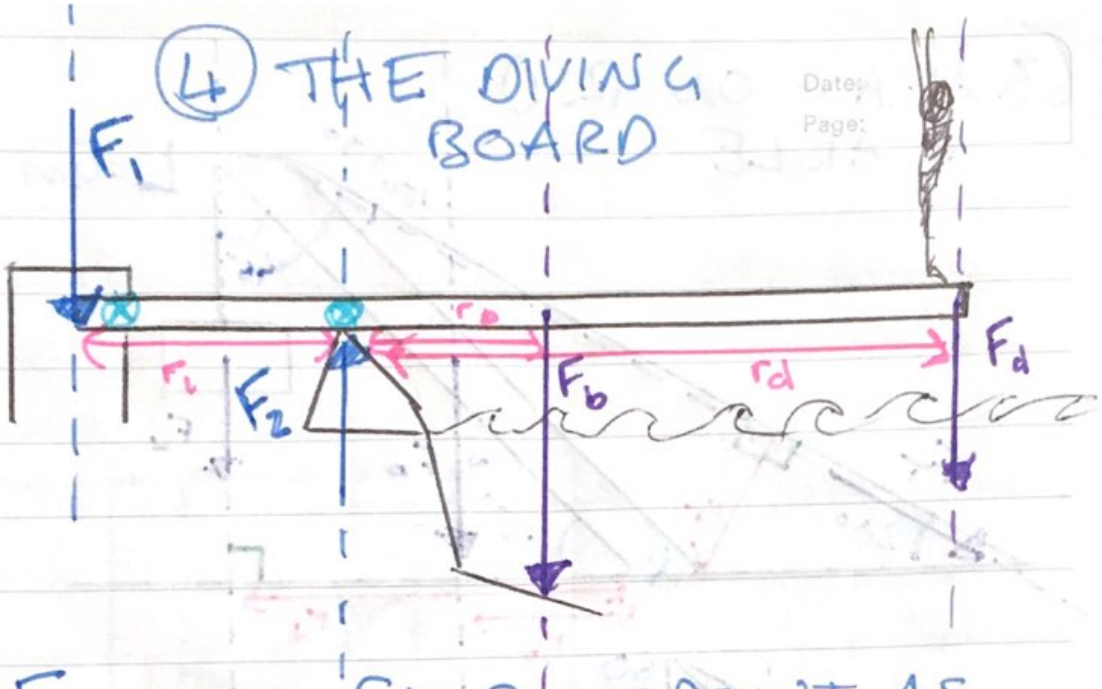
$$F_w r_w + F_b r_b = F_T r_T$$

$$F_w (L \sin 45) + F_b (\tfrac{1}{2} L \sin 45) = F_T (L \sin 15)$$

$$F_w \sin 45 + F_b \tfrac{1}{2} \sin 45 = F_T \sin 15$$

$$F_T = \frac{F_w \sin 45 + F_b \frac{1}{2} \sin 45}{\sin 15}$$

④ THE DIVING BOARD



F_1 USING F_2's PIVOT POINT AS REFERENCE:

$$\Sigma \tau_{CW} = \Sigma \tau_{ACW}$$

$$F_d r_d + F_b r_b = F_1 r_1$$

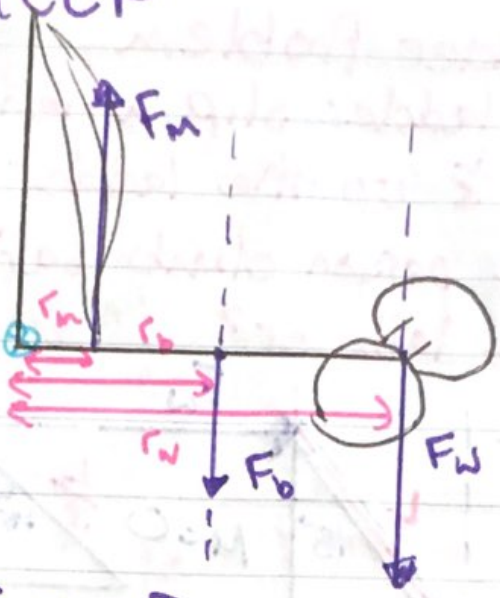
$$F_1 = \frac{F_d r_d + F_b r_b}{r_1}$$

F_2 USING ΣF_y

$$\Sigma F_{UP} = \Sigma F_{DOWN}$$

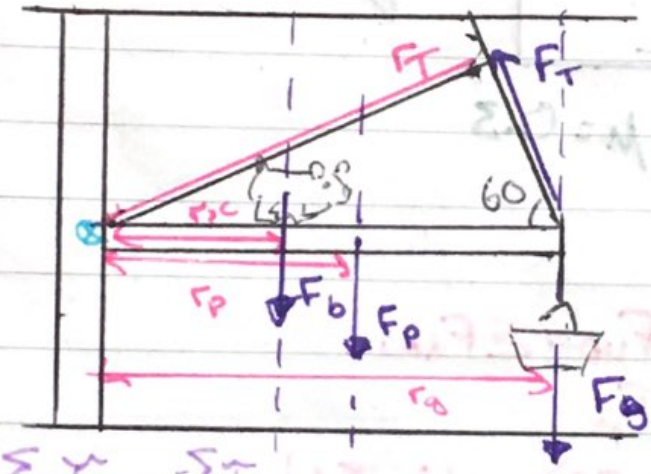
$$F_2 = F_1 + F_b + F_d$$

(5) BICEP



$$F_m = \frac{F_b r_b + F_w r_w}{r_m}$$

(6) THE HUNGRY BEAR



use r_g to find out how far the bear can get until F_T reaches max (N)

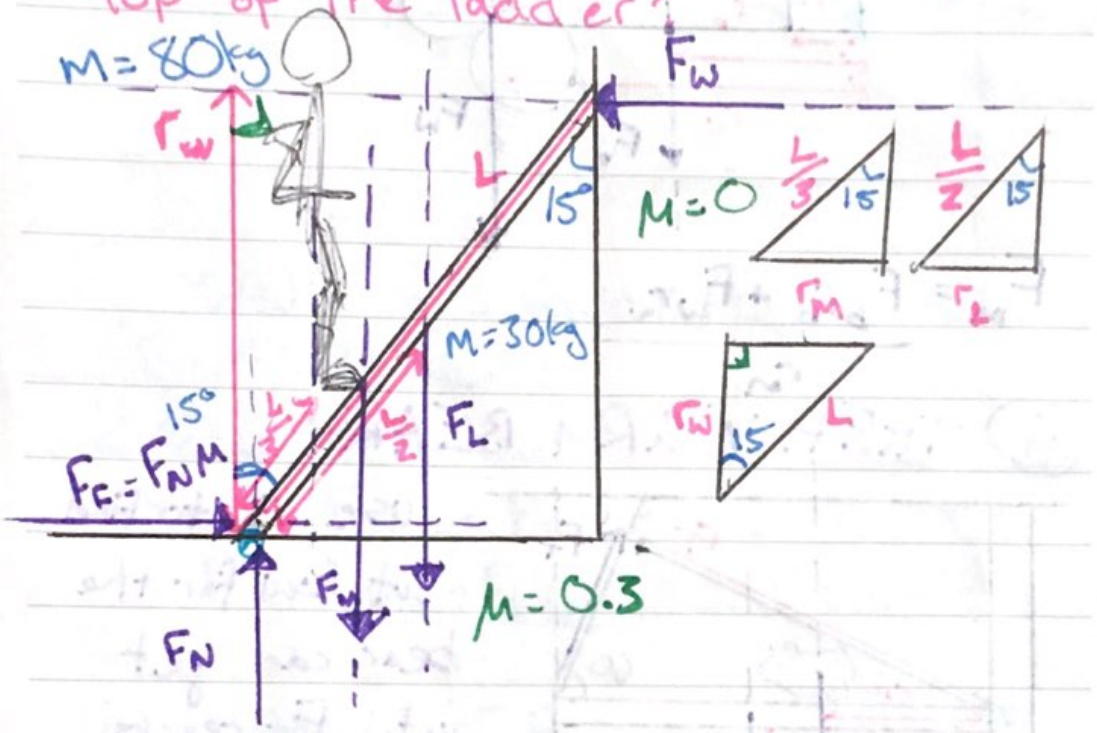
$$\Sigma \tau_{CW} = \Sigma \tau_{ACW}$$

$$F_g r_g + F_b r_b + F_p r_p = F_T r_T$$

(7) The ladder Problem

a) Will the ladder slip when the person is $\frac{1}{3}$ up the ladder

b) Can the person climb safely to the top of the ladder?



a) $\Sigma F_y = 0 \quad \Sigma F_{up} = \Sigma F_{down}$

$F_N = F_L + F_M$

$= g(80+30) = 1078\,N$

$F_F = F_N M$

$= (1078)(0.3) = 323.4$

$\Sigma \tau_{CW} = \Sigma \tau_{ACW}$

$F_M r_M + F_L r_L = F_w r_w$

$F_M \left(\frac{L}{3}\sin 15\right) + F_L \left(\frac{L}{2}\sin 15\right) = F_w (L \cos 15)$

$F_w = \dfrac{F_M \frac{1}{3}\sin 15 + F_L \frac{1}{2}\sin 15}{\cos 15}$

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$= 109.4\,N$

$\therefore F_W < F_F \therefore$ no slip

b) $\frac{L}{3}$ is now $L \therefore F_W$ will be larger

$$F_W = \frac{F_M \sin 15 + F_L \frac{1}{2} \sin 15}{\cos 15}$$

$= 246.2\,N$

$\therefore F_W < F_F \therefore$ will be safe

Electromagnetism

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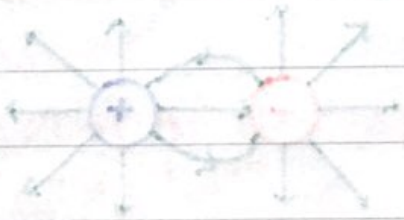

Electric Fields

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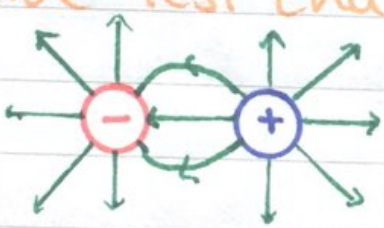
A field is a region of space where objects experience a force due to physical properties related to the field
An electric field surrounds charges/ charged objects and exerts a force on other charges within the field.

FIELD LINES

Diagramatically field lines are arrows representing the force on a positive test charge.



- Always 90° to start/end surface
- Density = strength
- 2D representations of 3D fields

FORCE + FIELD STRENGTH

$F = Eq$ $E\ (NC^{-1})$

E is the strength of an electric field (like q is the strength of a

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gravitational field)

Alternatively:

$E = \frac{F}{q} = \frac{V}{d}$ (NC^{-1}), (Vm^{-1})

$\Rightarrow Fd = Vq$

$(W = Fs) \Rightarrow W = Vq$

Coulomb's Law

$$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r^2}$$

Notice the similarities between the force between 2 charges, and that between 2 masses $(F_g = \frac{GMm}{r^2})$

- $F \propto \frac{1}{r^2}$ $F \propto q_1 q_2$
- Newton's 3rd law applies

ε_0 is the permittivity of free space, $= 8.8542 \times 10^{-12} C^2 N^{-1} m^{-2}$ in air or vacuum

$\frac{1}{4\pi\varepsilon_0}$ can be equated to k where $k = \frac{1}{4\pi\varepsilon_0} = 9.0 \times 10^9 Nm^2 C^{-2}$

Comparing this constant to G shows how much stronger the electromagnetic force is than gravity.

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Similarly to gravitation:

$F = F$

$E_{q_0} = k\frac{qq_0}{r^2}$ q_0 is a test charge, q is creating the field

$E = k\frac{q}{r^2}$

Electric field strength is dependent only on the magnitude of the charge creating the field and the distance from this charge. $E \propto \frac{1}{r^2}$ $E \propto q$

Work in an Electric Field

When a charged body moves or is moved in an electric field and its potential energy changes, work is done on the charge by the field.

Electrical potential energy is stored in an electric field, also a charge within an electric field has electrical potential energy. The field can do work on the charge to accelerate it, turning its electrical potential energy into kinetic energy.

$W = Vq$ $V = Ed$

$W = qEd$

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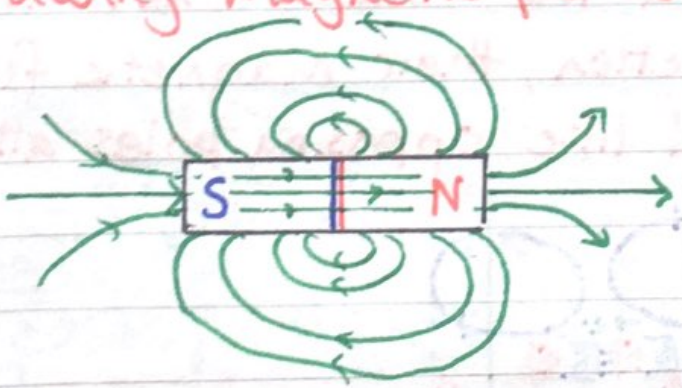
When a charge moves with the field, the field has done work on the charge. When a charge is moved (Forced) against the field, the charge has done work on the field.

Magnetic Fields

A magnetic field is produced by the motion of an electric charge.

In a magnet its magnetic field is produced by the motion of electrons in its atoms whose motion is such that each individual magnetic field created is built on as opposed to cancelled out like in other substances.

Drawing magnetic fields:



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Magnetic field strength is called magnetic flux density. Thinking of magnetic flux as lines from North to South, flux density is the amount of lines per unit area.

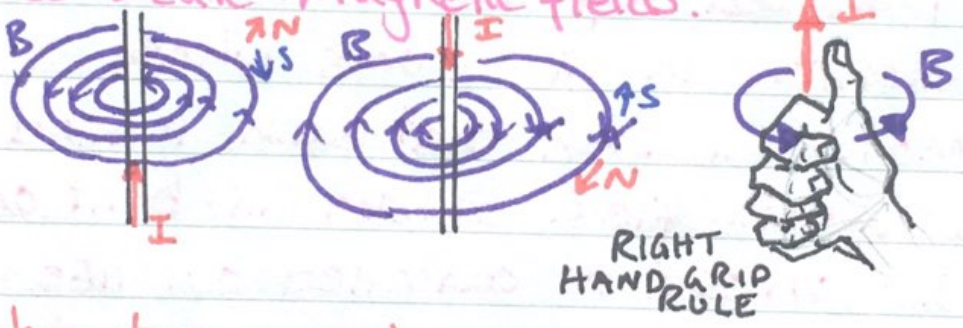
$$B = \frac{\Phi}{A_\perp}$$

Φ = flux (Wb)

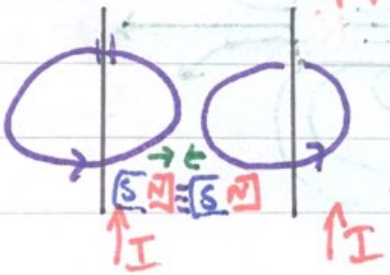
B = flux density (T) (Wbm^{-2})

AND CURRENT CARRYING WIRES

A current carrying wire contains electrons – charge carriers – moving through it. As such, current carrying wires create magnetic fields.



When two current carrying wires are parallel and the currents run in the same direction, their magnetic fields interact and like opposing poles attract.



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current in opposite directions repels

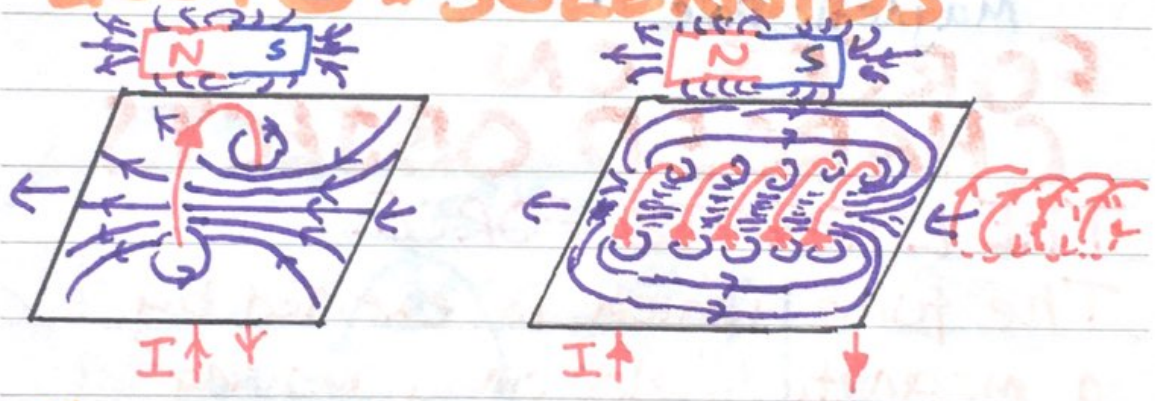
Magnetic flux density around a conductor / wire:

$$B = \frac{\mu_0 I}{2\pi r}$$

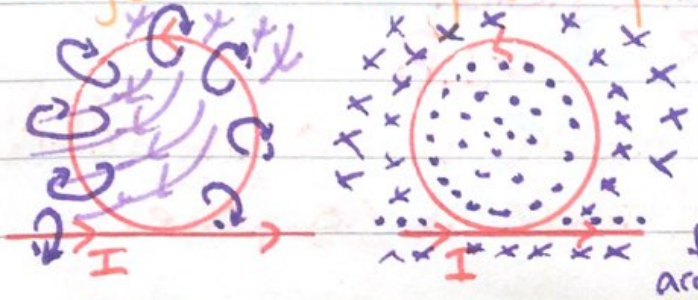
I: current (A)
r: dist from conductor (m)
$B \propto \frac{1}{r}$ $B \propto I$

μ_0 is the 'permeability of free space'
$= 4\pi \times 10^{-7}\ T\,m\,A^{-1}$

LOOPS + SOLENOIDS



The more loops of a solenoid, the more concentrated the flux through it, the higher the flux density, the stronger the magnetic field.



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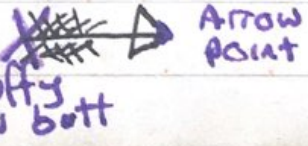

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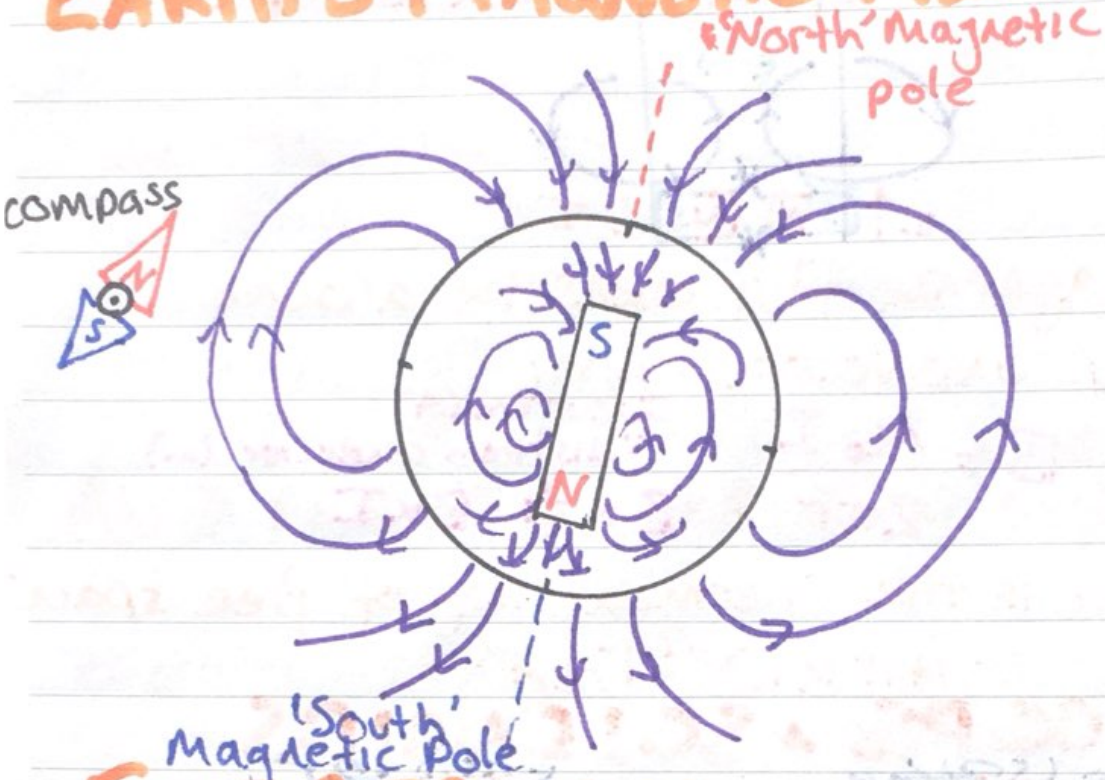
EARTH'S MAGNETIC FIELD



FORCES ON CHARGED OBJECTS

THE LORENTZ FORCE:

The force which is exerted by a magnetic field on a moving electric charge.

The force on a charged particle moving at a velocity PERPENDICULAR to a magnetic field.

$F = qvB \quad v \perp B$

When the charge is moving PARALLEL to the field there is no force.

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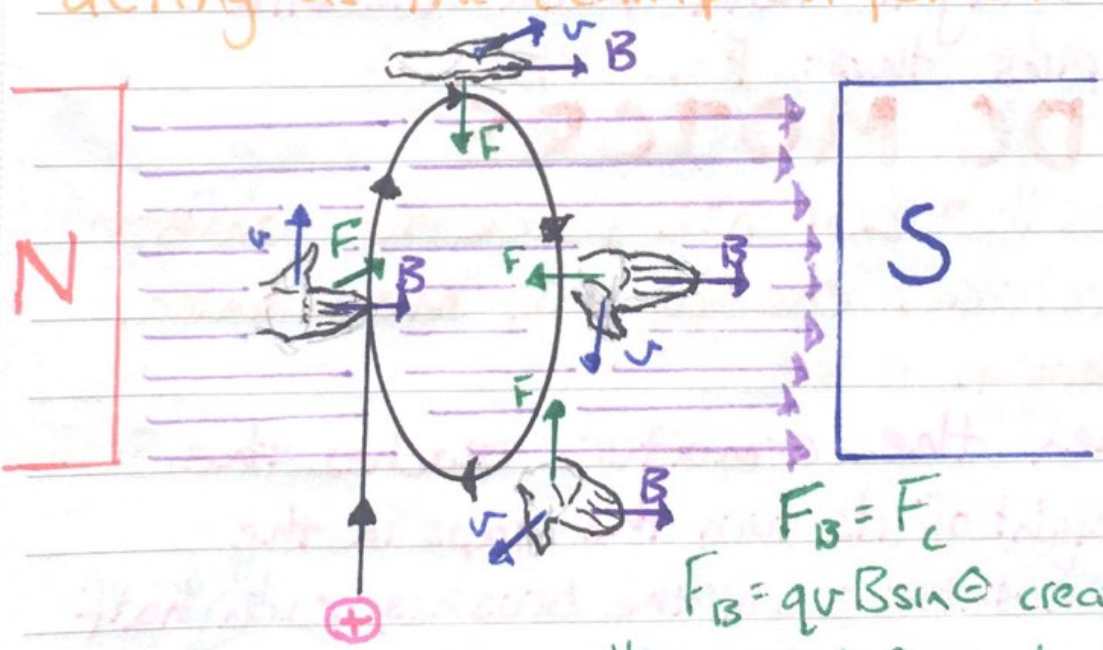
THE RIGHT HAND PALM RULE

$F \perp B \perp v$

The right hand palm rule shows the direction of the force on a POSITIVE test charge moving PERPENDICULAR to a magnetic field. For a NEGATIVE charge the force acts in the opposite direction.

AND CIRCULAR MOTION

The Lorentz force causes charges to move in circular paths, acting as the centripetal force.



$F_B = F_c$

$F_B = qvB\sin\theta$ creates the angled force to keep circular motion stable

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THE FORCE ON A CONDUCTOR

A conducting wire is essentially a stream of charged particles, as such it experiences a force in a magnetic field.

$t = \frac{q}{I}$, $t = \frac{\ell}{v}$

$\therefore \frac{q}{I} = \frac{\ell}{v} \Rightarrow qv = I\ell$

$qv = \frac{F}{B}$

$\Rightarrow I\ell = \frac{F}{B} \Rightarrow F = I\ell B$

For multiple loops of conductor:

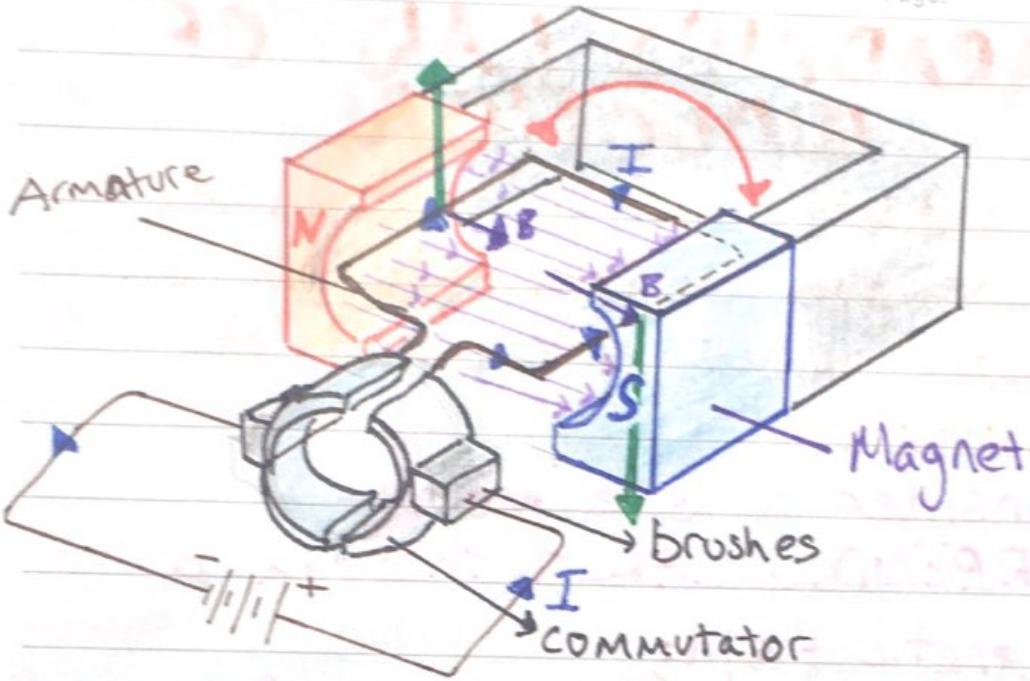
$F = nI\ell B$ $n = N^o$ loops

The right hand palm rule still applies thus: $F = nI\ell B \sin\theta$

DC MOTORS

Uses the Lorentz force to convert electrical energy into mechanical energy.

When the armature reaches the height of its turn the gaps in the commutator reach the brushes, each half of the commutator then contacts a different brush, the current in the



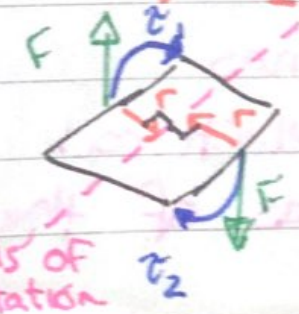
armature is reversed and so is the direction of the force, hence the armature continues to spin.

In larger motors the armature has many more coils to maximise torque at any given moment, and an electro-magnet is used to create a stronger field.

TORQUE

The force on the coil is up or down but the torque is clockwise

$\tau = r_1 F$



Total torque on armature:

$\Sigma\tau = \tau_1 + \tau_2$

$\Sigma\tau = 2\tau_{cw}$

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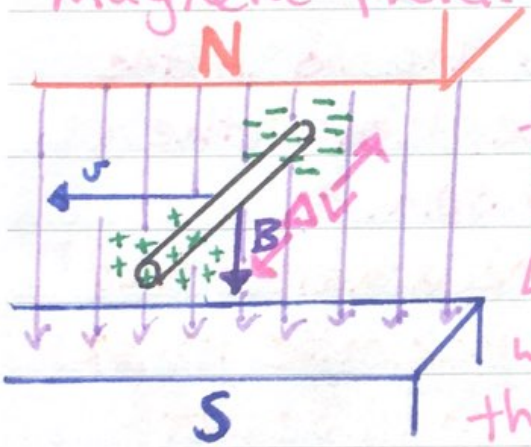
FARADAY'S LAW OF INDUCTION

An induced emf, $\mathcal{E}$, is produced by a changing magnetic flux in a process called electromagnetic induction.

Consider a wire moving PERPENDICULARLY through a magnetic field:



We know from the Lorentz force: $F = qvB$

Electrons in the wire are moving through a magnetic field and must experience a force from the field. The electrons carry their negative charge to one end of the wire, leaving a net positive charge at the other.

This charge seperation has created a <u>difference</u> in electrical potential between the ends of the

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wire, a POTENTIAL DIFFERENCE. The field has exerted a force on the electrons to move them a distance, it has done work on them, giving them electrical potential energy by bunching them together.

emf - ELECTROMOTIVE 'FORCE' caused the electrons to move, the magnetic field induced this emf in the wire, causing electrons and current to flow and a potential difference to be created.

{When the wire stops moving, the magnetic field around it is no longer changing, and is constant, no emf drives the electrons from the field and instead their potential difference in the wire produces an emf that causes them to flow in the opposite direction, charge becoming uniform across the wire, the ability to do work lost.} SPECULATIVE.

$W = Fs = qvBl$ NOTE: $B_\perp = B\cos\theta$

$\frac{W}{q} = \frac{qvBl}{q}$ emf = Work done / unit charge $\Rightarrow \boxed{\mathcal{E} = lv_\perp B}$

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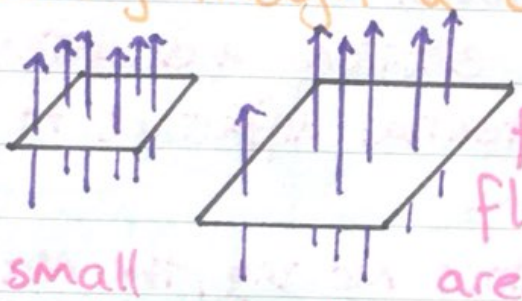
CHANGING MAGNETIC FLUX

To describe a 'change in magnetic field' its useful to describe an 'amount' of magnetic flux to give a value to this change.

$\Phi = BA_{\perp}$ Φ = Magnetic flux (Wb) (SCALAR)!

Magnetic flux can be thought of as a 'flow' of field of a particular density through a certain area.



A strong magnetic field of high flux density through a small area has the same flux (or 'flow') as a weak magnetic field of low flux density through a larger area. Flux is maximised when the area is perpendicular to the - 'flow' - the field.

$\Phi = BA\cos\theta$, θ is the angle between the normal of the plane of area and the magnetic field, $\cos 0 = 1$, $\cos 90 = 0$

NOTE: $1 cm^2 = 1 \times 10^{-4} m^2$

$1 m^2 = 1 \times 10^{4} cm^2$

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A greater change in magnetic field strength (magnetic flux density), the greater the change in flux, the greater the change in emf induced by the change. The greater the change in area through which the magnetic field 'flows', the greater the change in flux, the greater the change in emf.

The faster this change occurs will also cause a greater change in emf.

Hence the average emf induced by a changing magnetic flux is proportional to the RATE OF CHANGE of this flux, ie the magnitude of the change and the time in which this occurs

$\mathcal{E} = N\frac{\Phi_2 - \Phi_1}{t} = N\frac{\Delta\Phi}{t} = N\frac{\Delta(BA_\perp)}{t}$ Faradays Law of Induction

N = N° loops in the coil

If the coil is connected to an external circuit a current will flow. $I = \frac{V}{R}$

A coil not connected has emf but no current. (like a battery)

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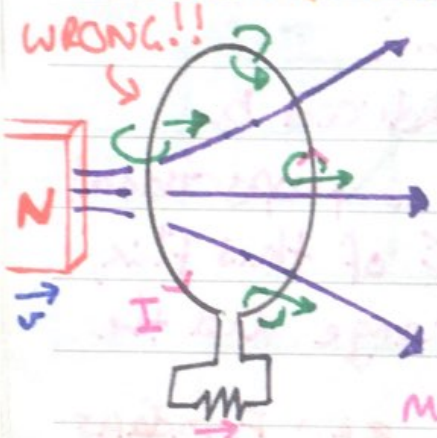
LENZ'S LAW

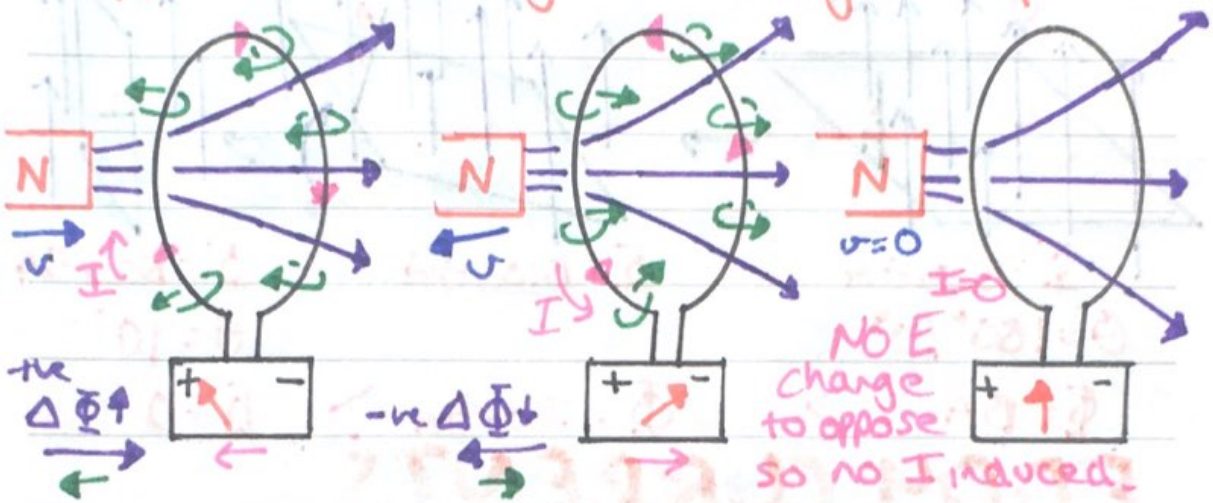
A changing magnetic flux will induce an emf in a wire, which can induce a current in the wire, but the magnetic field created by the moving charge in the wire must interact with the original magnetic field according to the principles of conservation of energy.



Suppose a magnet is moved toward a coil. Φ is increasing. Suppose the induced current flows anti-clockwise. The subsequent magnetic field would add to the existing field, the stronger original field would induce a larger current which would induce a larger magnetic field which would add even more energy to the original field until it had infinite energy. This does not abide by conservation of energy.

THUS; LENZ'S LAW: An induced

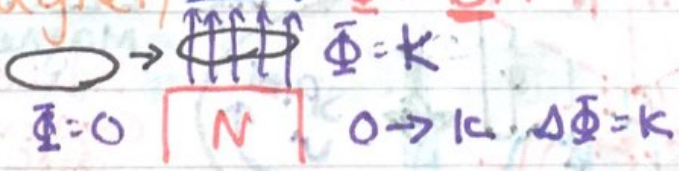
emf always gives rise to a current whose magnetic field will oppose the original change in flux.



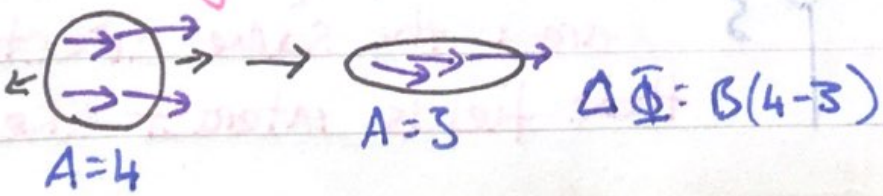
RIGHT HAND GRIP RULE APPLIES ↑

3 WAYS TO CREATE INDUCED emf:

1) Change the strength of the magnetic field ie move through spaces of varying magnetic flux density (in/out of a field, closer/further from a magnet) LS1 $\Phi = BA$ ↓



2) Change the area of the coil within the magnetic field $\Phi = BA$



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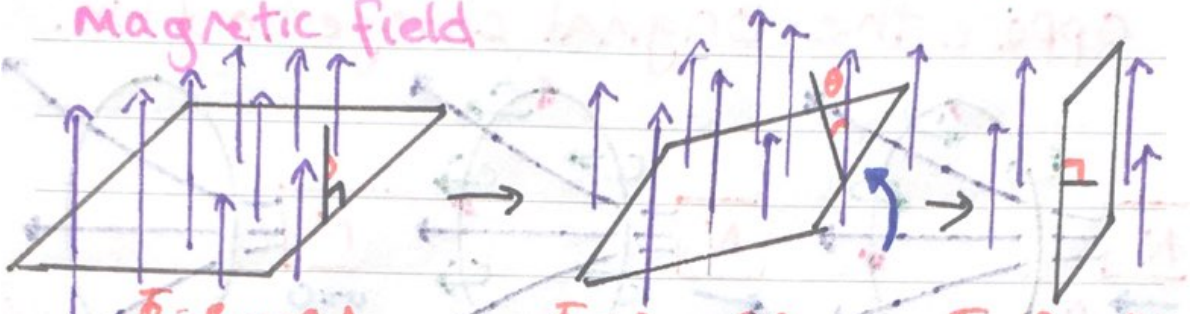
3) Change the orientation of the coil with respect to the direction of the magnetic field



$\Phi = B\cos\theta A$
$\theta = 180° / 0°$
$\Phi = BA$

$\Phi = B\cos\theta A$
$\Phi = B\cos\theta A$

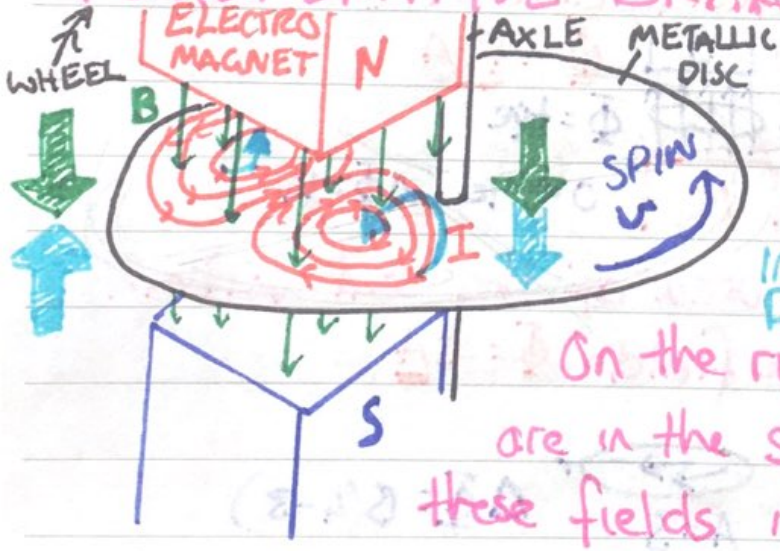
$\Phi = B\cos\theta A$
$\theta = 90°$
$\Phi = 0$

EDDY CURRENTS

An EDDY CURRENT is a circular electric current induced within a conductor by a changing magnetic field.

ABILITY TO OPPOSE MOTION

REGENERATIVE BRAKING



ELECTROMAGNET
Magnetic field B
Induced eddy current in disc I
Induced magnetic fields
On the right side ↓↓ are in the same direction, these fields interact like

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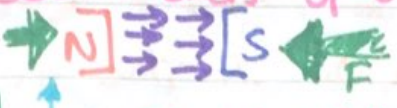
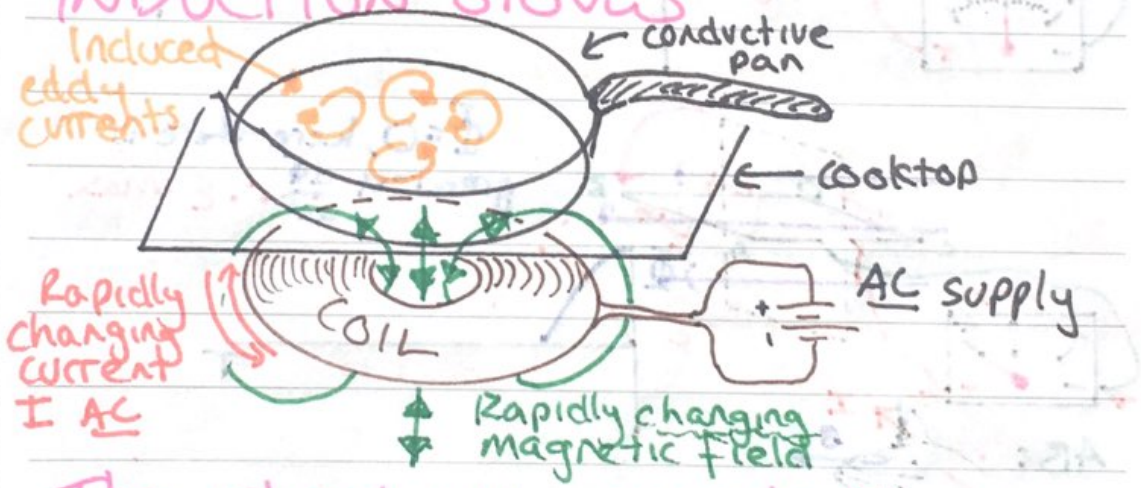
the North and South ends of a magnet and ATTRACT 

On the left: ↓ ↑ are in opposite directions, the fields interact like like poles of a magnet and REPEL


Both these forces oppose the disc's spin motion, slowing the motion, the axle, and the wheels, braking the vehicle

ABILITY TO GENERATE HEAT

INDUCTION STOVES



The induced eddy currents flow through highly resistive material. Resistance loses large amounts of electrical energy to HEAT, heating up the pan for cooking.

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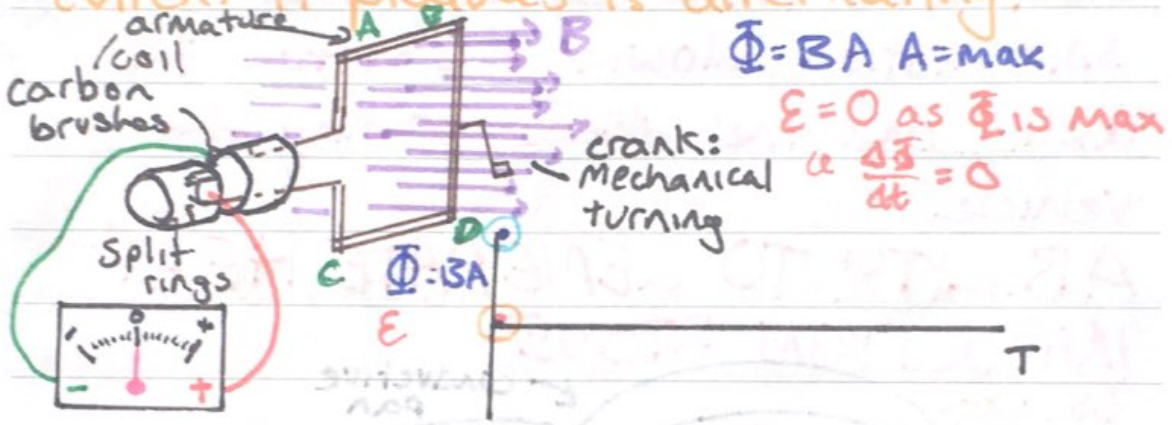
GENERATORS

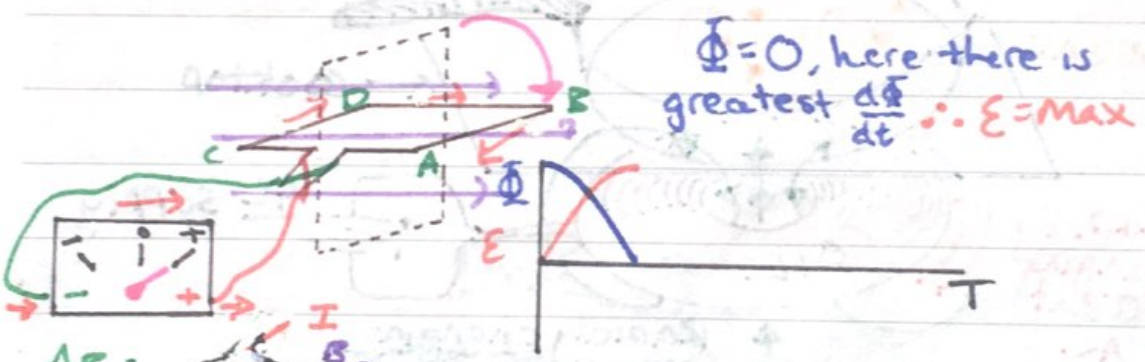
A generator is the inverse of a motor, ie it converts MECHANICAL Energy → ELECTRICAL energy. A generator is sometimes referred to as an ALTERNATOR as the current it produces is alternating.



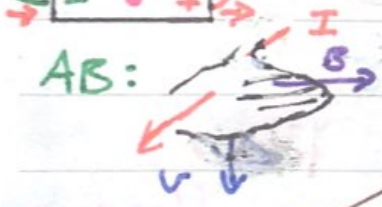
Φ=BA A=max

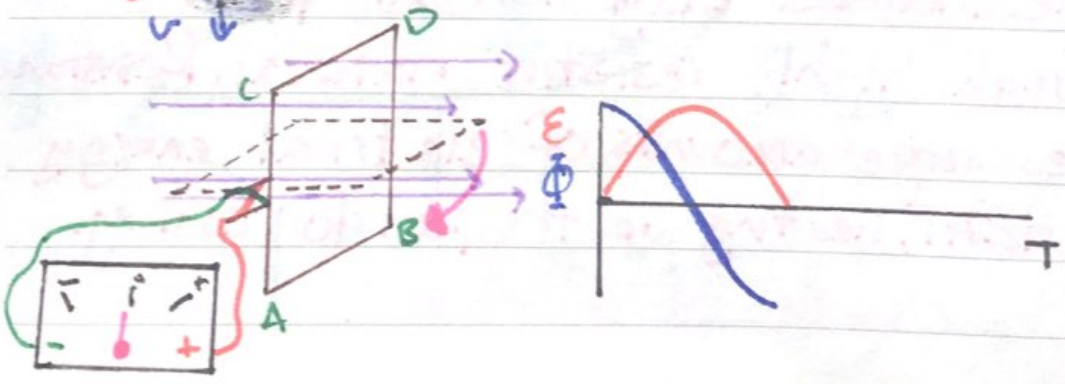
ε=0 as Φ is max

ie $\frac{d\Phi}{dt}=0$



Φ=0, here there is greatest $\frac{d\Phi}{dt}$ ∴ ε=max





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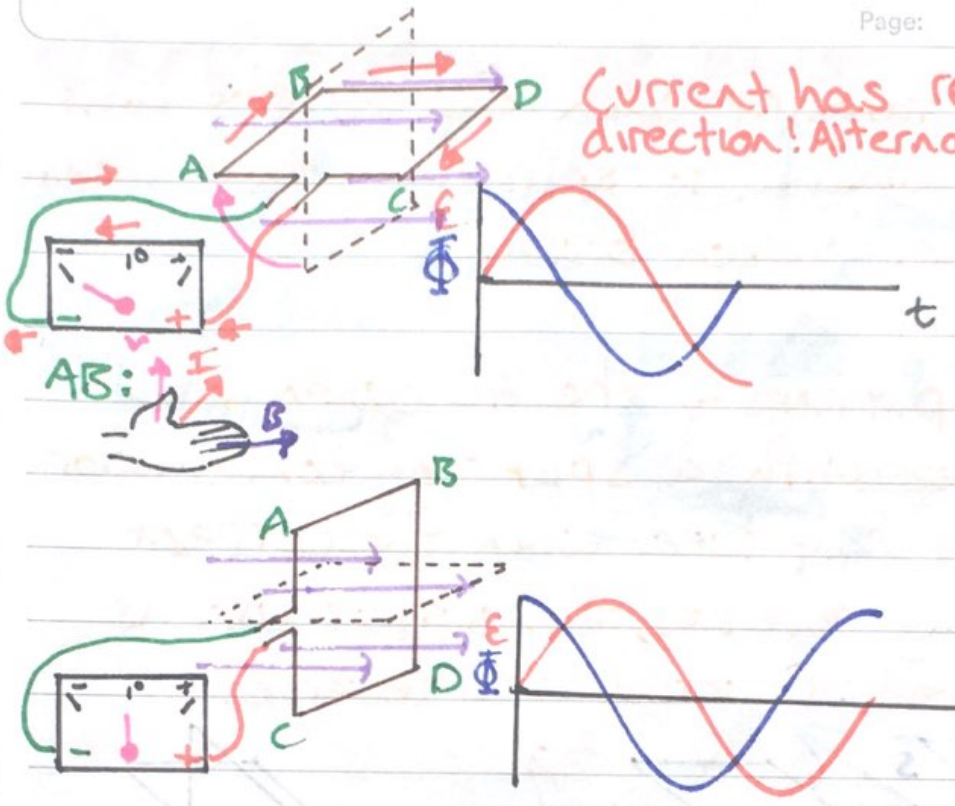


Current has reversed direction! Alternated

The maximum emf produced in a generator with loops rotating at a constant rate (max emf when rate of change of flux is highest → a no flux → flux):

$\mathcal{E}_{MAX} = 2\pi NBA_{\perp}f$ f = frequency of rotation (Hz)

This is the MAX emf not the average! ($\mathcal{E}_{AVG} = N\frac{\Delta\Phi}{t}$)

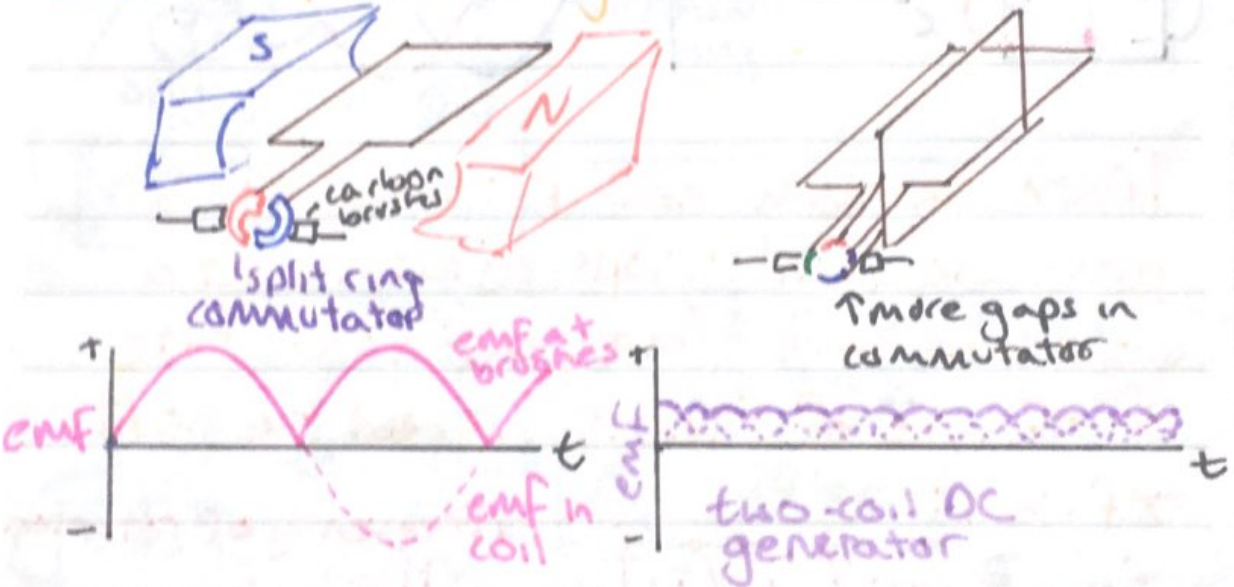
AC VS DC GENERATORS

AC - The current from an armature rotating in a magnetic field already alternates, to stop wires

from tangling each end of the coils are attached to split rings that rotate against carbon brushes.

DC

The split rings of the AC design are replaced with a split ring commutator. Every half turn when the current usually reverses, the output wire is switched, reversing the reverse.



Multiple armature windings smooth the output by making the proportion of time when a coil is in the position for generating max emf larger.

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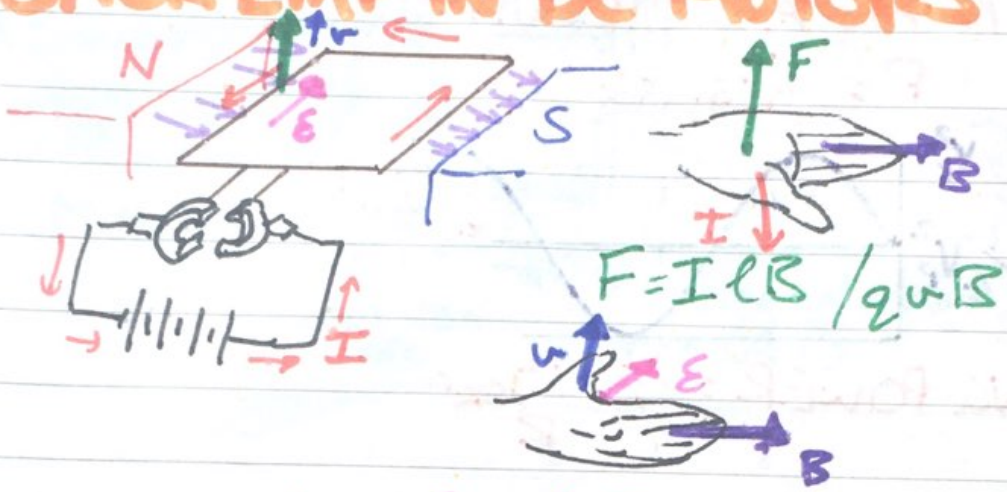
BACK EMF IN DC MOTORS



induced $\mathcal{E} = \ell v B$

The emf induced by the armature's motion through the magnetic field goes against the current (and existing emf) through it. Thus the net emf used by the motor < applied voltage $\mathcal{E}_{net} = V - \mathcal{E}_{back}$

ALTERNATING V AND I

AC generators produce current that varies sinusoidally over time, thus max emf is not constant. The values of CURRENT and VOLTAGE a DC supply would need to match the AVERAGE power output of AC supply are the ROOT ~~SQ~~ MEAN SQUARE values

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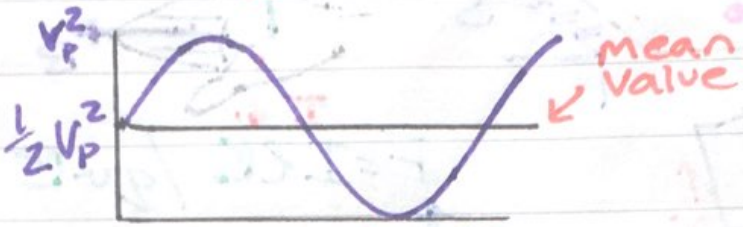
IN AN AC CIRCUIT

$P = \frac{V^2}{R}\sin^2\theta$



AVG POWER $= \frac{\frac{1}{2}V^2_{peak}}{R}$

If this same power were to be supplied by a steady DC source:

$$\frac{V^2_{AVG}}{R} = \frac{\frac{1}{2}V^2_{peak}}{R}$$

$$V_{AVG} = \frac{V_{peak}}{\sqrt{2}}$$

$$V_{RMS} = \frac{V_{MAX}}{\sqrt{2}}$$

This is the value of a steady voltage that would produce the same power as an alternating voltage with a peak value equal to $\sqrt{2}$ x as much.

$\mathcal{E} = \mathcal{E}_0 \sin\omega t$

the larger the velocity of the supply's armature the smaller the sin period the higher the frequency.

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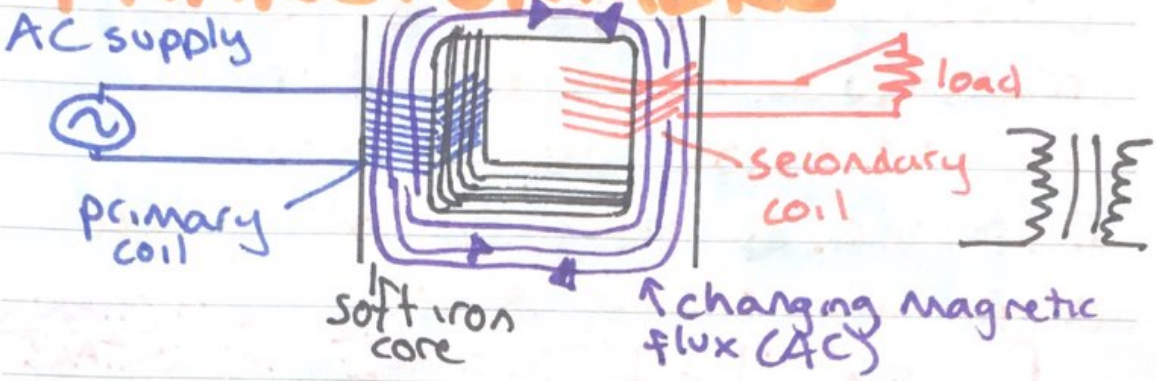
TRANSFORMERS



The changing magnetic field produced by the AC emf in the primary coil induces an AC emf in the secondary coil of the same frequency. The magnitude of the induced emf depends on the number of coils.

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \qquad \frac{I_p}{I_s} = \frac{N_s}{N_p}$$

Step-up: $N_s > N_p$; $V_s > V_p$

Step-down: $N_s < N_p$; $V_s < V_p$

In an ideal transformer input Power = output Power

i.e. $P_p = P_s$

due to Resistance

$P = VI \rightarrow V_p I_p = V_s I_s$

Electricity can be transported at ↑ V, ↓ I (less current heat loss) and transformed to ↓V, ↑I for commercial

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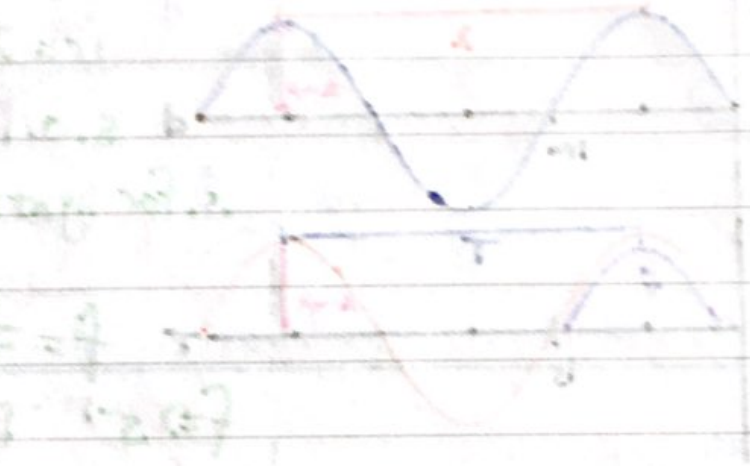
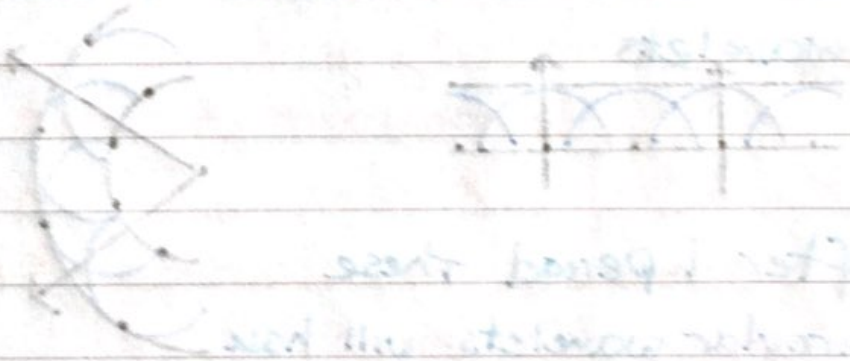
domestic use. Energy is lost by transmission over large distance by heat loss due to wire resistance. As energy is lost voltage drops and Power is lost.

$P_{loss} = \Delta V I = I^2 R = \frac{\Delta V^2}{R}$ ΔV = CHANGE IN VOLTAGE

From $P_{loss} = I^2 R$ we see that high currents cause large power losses

Wave Particle Duality and the Quantum Theory



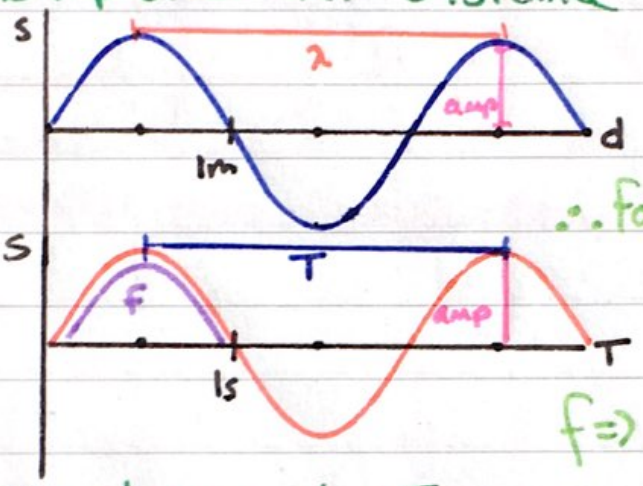


Wave Properties (+Revision)

TRANSVERSE WAVES

Transverse waves oscillate in a direction perpendicular to the direction of propagation.

Displacement-Distance



$v = \lambda f$

s.o.l = c

∴ for light: $c = \lambda f$

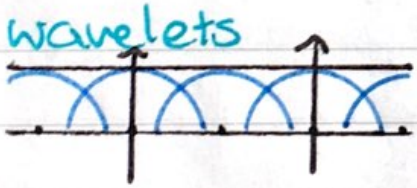
$f = \frac{1}{T}$

$f \Rightarrow s^{-1}$ $T \Rightarrow s$

Displacement-Time

HUYGEN'S PRINCIPLE

Each point on a wavefront can be considered as a source of secondary wavelets



After 1 period these circular wavelets will have advanced a distance of 1 wavelength when the amplitude of each is added the result is another wavefront.

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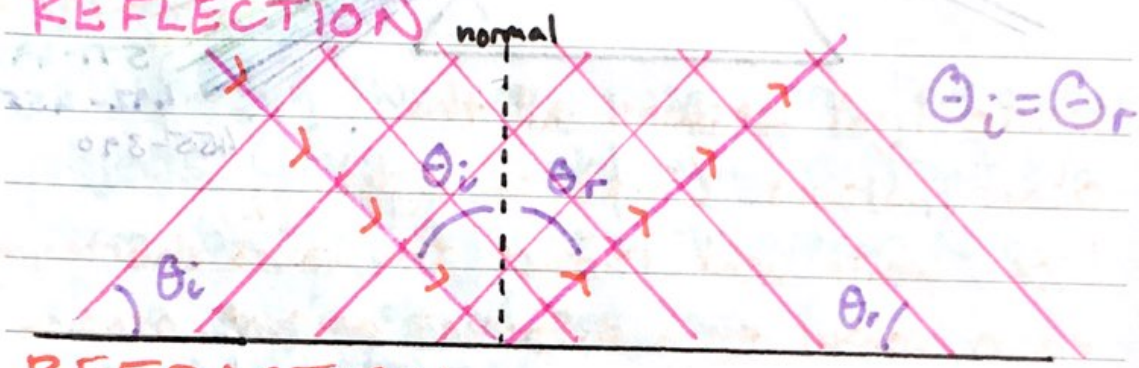
THE WAVE MODEL: PROPERTIES OF LIGHT

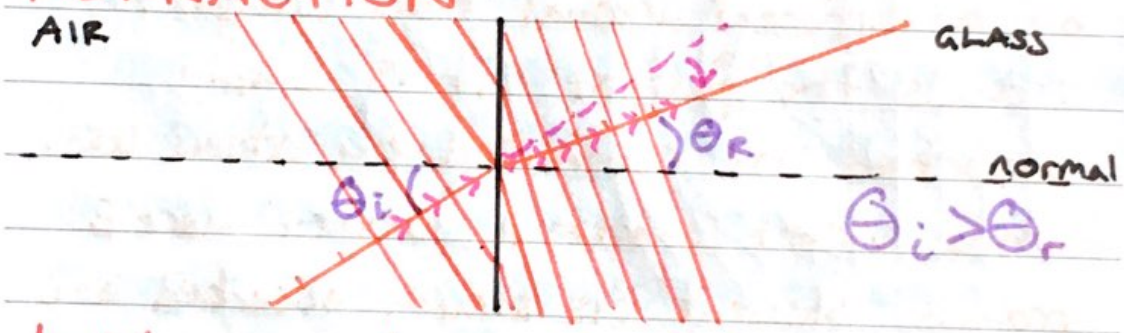
Evidence for the wave model:

Reflection Refraction Dispersion
Diffraction Polarisation

REFLECTION



REFRACTION



Light moves slower in glass than air, so bends towards the normal

Velocity Increase - Bend Away
Velocity Decrease - Bend Towards

In refracting λ changes but f doesn't

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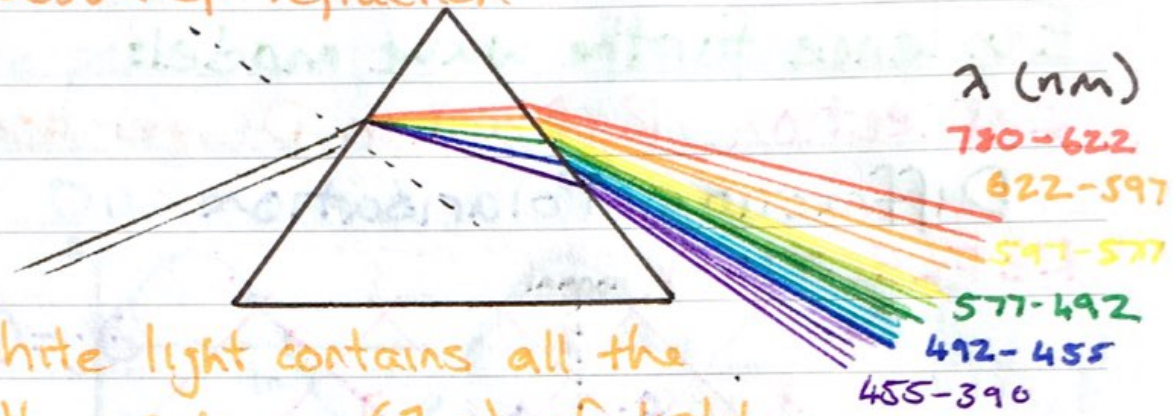
DISPERSION

- Result of refraction

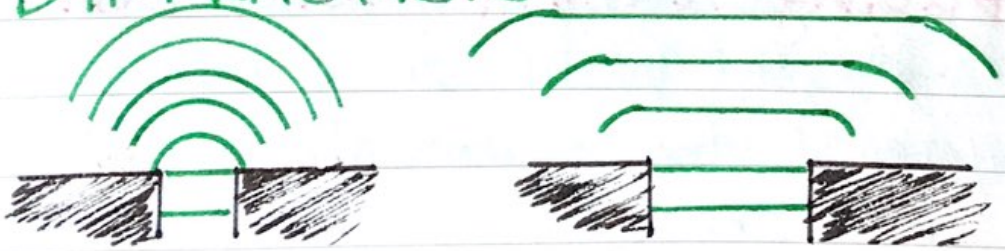


White light contains all the other colours (λs) of light.

When white light refract the waves (λ) shortening, each colour by a different amount, bending by a different amount. Red (longer λ) travels the 'fastest' (it is simply absorbed and re-emitted by atoms less) while violet (shorter λ, larger f, more E) travels 'slowest' (is simply absorbed and re-emitted by atoms more)

Chromatic aberration occurs when light is dispersed by lenses, distorting the picture of microscopes / telescopes

DIFFRACTION



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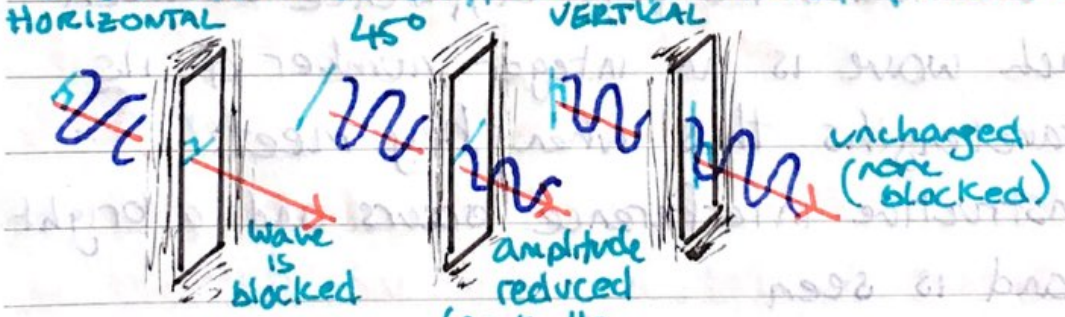
Diffraction occurs / is significant when the size of the opening or obstacle is similar to or smaller than the wavelength of the wave. As light λ is very small diffraction is hard to see (light will diffract around hair or cotton thread)

In imaging two very close, very far away objects (stars...), light may diffract b/n them, blurring the image to appear as one of a single object, not two.

POLARISATION

Occurs when a transverse wave is allowed to oscillate in only one direction.

Unpolarised (natural) light can be thought of as a collection of waves each with a different plane of polarisation.

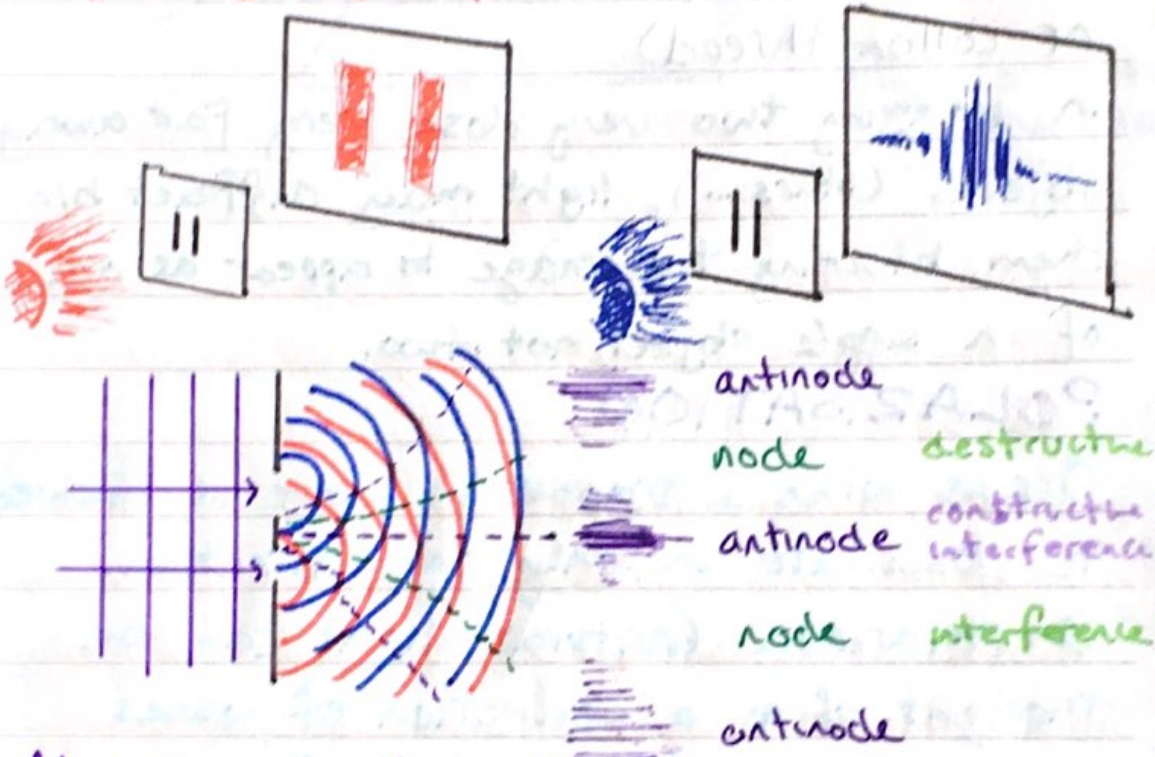


A transverse wave model is required to explain polarisation

THE WAVE MODEL: INTERFERENCE AND YOUNG'S DOUBLE SLIT

Light was shone through two thin slits and the result projected on a screen:

PARTICLE THEORY: ACTUAL RESULT:



At antinodes the path difference between each wave is an integer number of its wavelengths thus when they meet: ~ constructive interference occurs and a bright band is seen

At nodes the path difference is half a wavelength ($\frac{n\lambda}{2}$) thus: ~ destructive interference occurs and a dark band is seen.

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ELECTROMAGNETIC WAVES

A changing electric field produces a changing magnetic field perpendicular to it, which produces a changing $\vec{E}$ field, and the cycle repeats. Two mutually propagating fields that regenerate each other emanate into space - ELECTROMAGNETIC RADIATION.

$\vec{E}$ and $\vec{B}$ oscillate at the same f.

THE ELECTROMAGNETIC SPECTRUM

Changing the frequency or wavelength of EM waves changes ther properties, the EM spectrum divides these into bands according to their properties + uses

RADIO WAVES

$\lambda: 10^{7} \rightarrow 10^{-2}\,m$ $f: 10^{1} \rightarrow 10^{10}\,Hz$

RADIOS: radio transmitter converts signal (music/sound/data) to AC current of similar frequency. e^- oscillation in antenna created the wave, low E, can bounce off the atmosphere, reaches reciever → AC current → sound waves of the same frequency.

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MICROWAVES

$\lambda: 10^{1} \rightarrow 10^{-3}$ $f: 10^{8} \rightarrow 10^{11}$

INFRARED

$\lambda: 10^{-3} \rightarrow 10^{-6}$ $f: 10^{11} \rightarrow 10^{14}$

Longer λ than red light. They are emitted by objects (to varying degrees) due to their temperature. Radiant heat from the sun is transmitted as infrared ERR

ULTRAVIOLET LIGHT

$\lambda: 10^{-7} \rightarrow 10^{-8}$ $f: 10^{15} \rightarrow 10^{16}$

Shorter λ than violet light. Can penetrate human skin.

X-RAYS + GAMMA RAYS

$\lambda: 10^{-8} \rightarrow 10^{-10} \rightarrow$ $f: 10^{17} \rightarrow 10^{18} \rightarrow$

Can pass through human tissue. γ radiation is emitted by decaying radioactive substances and from the sun and space.

Light Quanta: Blackbody Radiation

All objects that have temperatures above absolute zero emit electromagnetic radiation At room temp, this is infrared, and invisible.

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At high temperatures the total amount of radiation emitted is larger AND a larger proportion is in the visible range.
At 3000K a large amount of E is emitted as red wavelengths → RED HOT
At 6000K, E is radiated evenly across λs of the visible spectrum, all λs are emitted → WHITE HOT
At 12000K → BLUE HOT
The shape of the emission spectrum depends on the type, ~~and~~ shape, and temp of the material.

BLACKBODY RADIATION

A <u>blackbody</u> is an ideal absorber, it absorbs <u>ALL</u> incident radiation. It is a <u>model</u> that asks what would we measure if we looked at the entire electromagnetic spectrum. A blackbody is in equilibrium with its surroundings - it radiates and absorbs E at the same time → its temp is <u>constant</u>.
Blackbody Radiation is the frequencies of light emitted by an object depending

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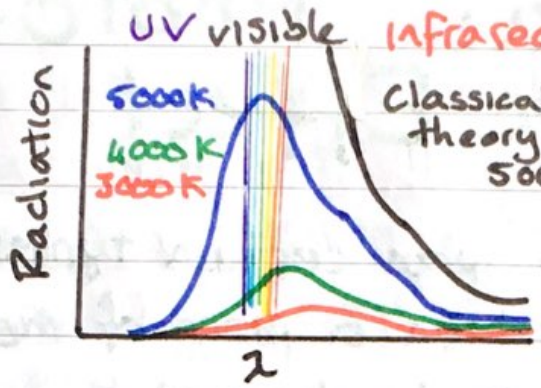
on temperature. The colour of a blackbody depends on its temp ONLY
If its not hot enough to emit visible light, it will be black.
A blackbody could be thought of as an oven emitting and absorbing thermal radiation. Standing waves of EMR are created in the oven as the temperature increases. Charges on the surface of the oven walls are accelerated, creating these EM waves. The 'Rayleigh-Jeans' Law gives the avg E per oscillating charge proportional to temperature. As temperature increases in the oven, the λ of radiation gets shorter and shorter and thus the amount of standing waves that can fit in the oven gets larger and larger. The energy density in the oven increases and approaches infinity. -WAVE THEORY
HOWEVER this is not the case experimentally.



E density = A below curve
For — → ∞

Experimentally, energy density dropped off where classical models predicted it would → ∞ ⇒ 'THE ULTRAVIOLET CATASTROPHE'

To solve the catastrophe, Max Planck had two postulates:

① Molecules vibrate at discrete E_s or f_s, given by: $E_n = nhf$

② Molecules emit and absorb radiation in discrete packets called PHOTONS, E of an individual photon: $E = hf$

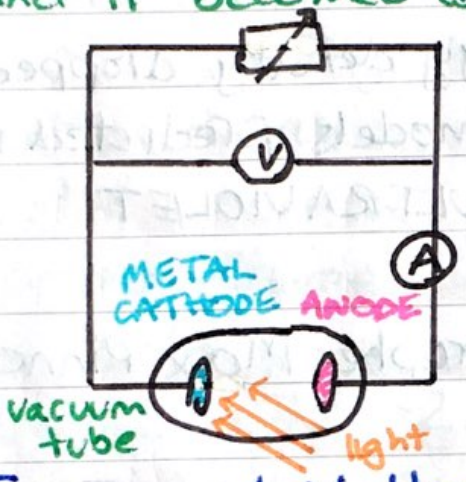
To gain E a molecule absorbs a photon and to lose E, emits a photon

He proposed that light existed in discrete E packets - quanta - the E of each quantum being:

$$E = hf$$

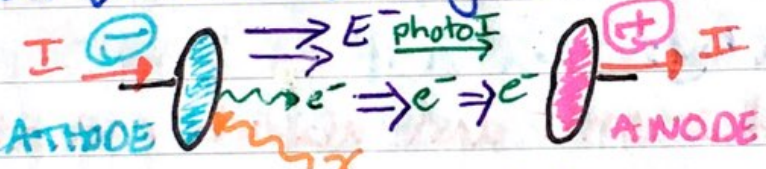
Light Quanta: The Photo-Electric Effect

The PEE occurs when certain types of EMR are incident on a piece of metal and it becomes ⊕-ly charged.



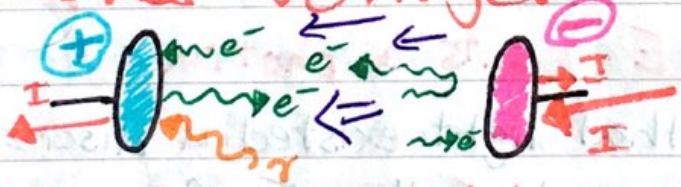
Incident light ejected e^- from the metal ⇒ photoelectrons, producing a photocurrent

Forward Voltage:



⊖ photoe^- are accelerated across gap to the ⊕ anode by the $\vec{E}$ resulting from the V

Reverse Voltage:



⊖ photoe^- are repelled by anode, slowing them, as rvs V↑, photoe^- repelled until none reach the anode and photoI ⇒ 0.

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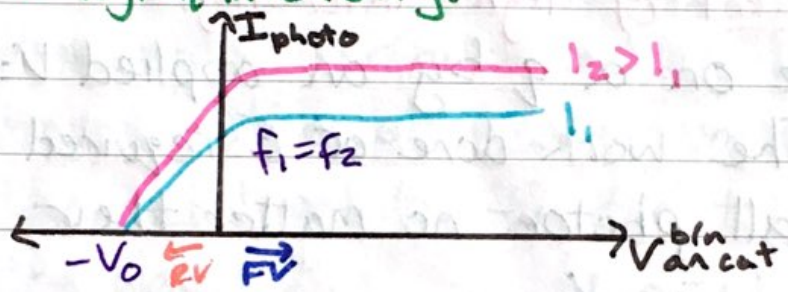
Using a colour filter, f of incident light can be varied. For a particular metal there is a certain f below which no photoe⁻ are emitted ⇒ threshold frequency (f_0)

$f_i < f_0$ ⇒ no photoI./photoe⁻

$f_i > f_0$ ⇒ photoI./photoe⁻!

For $f > f_0$, rate of photoe⁻ production ∝ light intensity:



This shows:

- As light intensity ↑, photoI ↑
- At 0 applied V, there is still a phI due to E_K of the phe⁻
- When applied V ⇒ ⊕ ($\vec{FV}$) phe⁻ attracted to collector (anode). A small FV is enough to ensure every available phe⁻ is collected ⇒ phI reaches max and plateaus, it stays constant even w more V applied
- When applied V ⇒ ⊖ (RV) phe⁻ repelled

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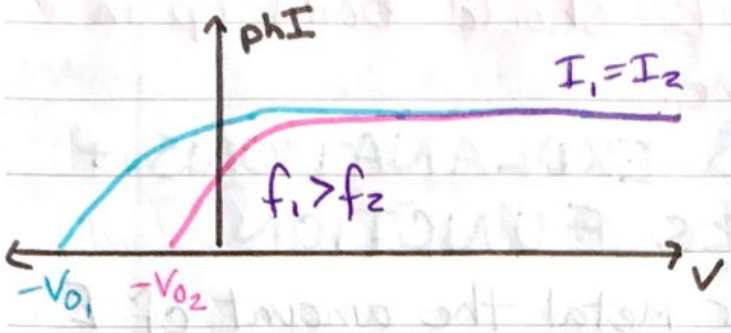
by ⊖ anode and attracted to ⊕ cathode from which they originated. As RV ↑ less and less phe⁻ have the E_K to overcome the opposing E potential ⇒ there is a V for which no phe⁻ reach the ⊖ collector anode & no phI ⇒ Stopping voltage (V_0) is characteristic of a metal and f of light + is Independent of light intensity.

Work done on a q by an applied V: $W = qV$. The work done or E required to stop all photoe⁻ no matter their speed: $W = q_e V_0$

As this is the E from the field that stops even photoe⁻ of max E_K, then the max E_K of emitted phe⁻:

$$E_K = W = q_e V_0$$

When light sources of = intensity but different f are used the same max phI is produced but ↑f = ↑V_0



As long as $f_i > f_o$ of cathode material, phe⁻ will be emitted with negligible time delay.

When $f_i > f_o$ e⁻ w max E_{Ks} are emitted from metal surface - and are least tightly bound. Other phe⁻ come from deeper in the metal and lose E_K due to collisions on the way out

⇒ emitted phe⁻ have a range of E_{Ks} from the max value down.

THE PEE AND THE WAVE THEORY

According to the wave model:

- f should be irrelevant (no f_o) as waves are a form of continuous E flow, so low f light should emit phe⁻ if left long enough to transfer the required E.
- There should be a time delay b/n light hitting the metal and phI flowing as

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the wave's E should build up in e^- first over time.

EINSTEIN'S EXPLANATIONS + THE WORK FUNCTION

for a particular metal the amount of E required to eject a phe$^-$ is a <u>constant value</u> that depends on the strength of the bonding within

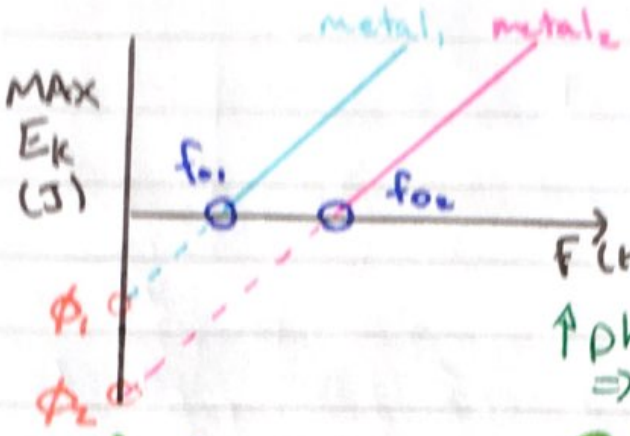
$\Rightarrow$ Work function (ϕ) (ionisation E)

- Light on a metal = bombardment of photons, each able to transfer its E to an e^- $\Rightarrow$ A <u>single</u> photon interacts w a <u>single</u> e^-, transferring all its E at once
- If photon $E < \phi \Rightarrow$ phe$^-$ <u>not</u> released.
- Each metal has a threshold frequency

$\therefore \phi = hf_0$

- If photon $E > \phi \rightarrow$ phe$^-$ released, excess photon $E > \phi$ = phe$^-$ E_k

$$E_{k\,MAX} = hf - \phi$$



$E_{KM} = hf - \phi$

At f_0 e^- no longer bound to metal but have no E_k

↑ photon f (∴ E)
⇒ ↑ phe⁻ E_k

Atomic Spectra

Emission and Absorption spectra are further evidence of the particle model of light.

The lines missing from the spectra of 'white' sunlight = Fraunhofer lines
⇒ corresponded to colours emitted when certain (g)s were heated to ↑ Ts.

- Dark lines of Absorption spectra are due to absorption of certain f/λ by gases as light passed through them
- Additional E can be applied to an element by ① heating to high temperatures ② passing through an E I ③ e^- bombardment ④ photon excitation by light ⇒ the element produces

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discrete Es of light

- Atom ⇒ unstable as it absorbs E and becomes excited! Promoted e⁻ falls back to ground state (stable) releasing E as a single photon
  ⇒ colour depends : $E = hf$
- Combination of colours produced is unique to that element.

BOHR MODEL OF THE ATOM

- Abs spec of H only capable of absorbing E of specific f (quantised)
- Emi spec of H showed it was only able to emit quanta of the exact E value it could absorb
- If E (and f) of incident light < certain value, light would pass straight through it (ligs)
- If light E > ionisation E ⇒ e⁻ removed
- Photons of light w all E_s > ionisation E value for H are absorbed.

$$\Delta E = hf = \frac{hc}{\lambda} = E_m - E_n$$

ΔE = photon E emitted

E_m = final E level, E_n = initial E level

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EMMISSION SPECTRA

- When e^- drops from higher E level to lower E level, a photon is emitted with E = to the difference in E b/n the levels

ABSORPTION OF PHOTONS

- Only incident light carrying just the right E to raise an e^- to an allowed level can be absorbed
- Incident light = E diff for e^- to be promoted
- If incident light > I_E for an atom, excess E becomes e^- E_K

ABSORPTION WITH ELECTRON EXCITATION

- E is transfereed from e^-, promoting bound e^- to a higher E level just as is with photons but E doesn't need to be exact as long as $E > \Delta E$, the excess energy ($E - \Delta E$) allowing the e^- to fly off.

The Quantum Nature of Light and Matter

WAVE PARTICLE DUALITY

- In some ways light ⇒ wave, and others light ⇒ particle.
- A double slit experiment with a stream of single photons produces the same interference as many protons (very dim vs bright light)

DE BROGLIE'S WAVE-PARTICLE THEORY

- If a wave ≈ particle
  ⇒ particle ≈ wave

∴ matter can also act like a wave.... but not very well:

$$\lambda = \frac{h}{p} \qquad \lambda = \text{De Broglie Wavelength}$$

ELECTRON DIFFRACTION PATTERNS

- When e^- were scattered of a piece of metal, ie reflecting off the metal's crystal structure, in detecting them an interference pattern was observed.

STANDING WAVES + MATTER

The stable orbitals of the H atom are those for which the circumference is exactly equal to the whole number

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of e^- wavelengths.

Evidence for the models of light

WAVE MODEL

* Reflection - bounce
* Refraction - bend through media
* Dispersion - bend into rainbow
* Diffraction - bend around corners
* Polarisation - transverse wave blocking
* Interference - Young's double slit

PARTICLE MODEL

* Blackbody Radiation - UV catastrophe solved by Planck's 2 postulates:
  ① Molecules vibrate at discrete E/f s
  $E_n = nhf$
  ② Molecules emit + absorb E in discrete packs (photons)
  $E_{photon} = hf$
* The Photoelectric Effect - light ejects e^- from metal under specific circumstance
* Atomic Spectra - e^-s transitioning through E levels ⇒ absorb + emit photons

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ATOM EXCITATION

(I) heating to ↑T

(II) Passing through an E current

(III) e^- bombardment ★

(IV) Photon excitation by light ★

Special Relativity

Einstein's Theory

GALILEO, NEWTON AND THE 'AETHER'

- Galilean relativity proposed the natural state of objects is not to be at rest but in a state of uniform motion.
  - You cannot tell if you are moving or not relative to other things without looking outside your own Frame of Reference
- Nature does not have a 'special' FOR, there is no ultimate or absolute velocity or frame. Everything is relative to everything else, not to one almighty stationary 'thing'.
  (its not possible to have a v relative to space itself, only other objects within space)
- James Clerk Maxwell formulated the classical theory of EMR, bringing together $\vec{E}$, $\vec{B}$, and light. He predicted a constant speed of light.
- Physicists interpreted this constant speed as relative to a medium through which light travelled, the

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'aether'

- This 'aether' would be an absolute reference frame in space, conflicting with Galilean relativity, so Einstein did away with it to accept both Maxwell's constant light speed and Galilean relativity.
- In uniting these ideas, Newton's assumptions, the basis of physics, conflicted.

Newton's assumptions:

① Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external. ⇒ time is constant, uniform, and straight.

② Absolute space, in its own nature, without relation to anything external, remains always similar and immovable ⇒ space is constant, uniform, and straight.

⇒ Einstein ignored these ideas to formulate his theory of special relativity.

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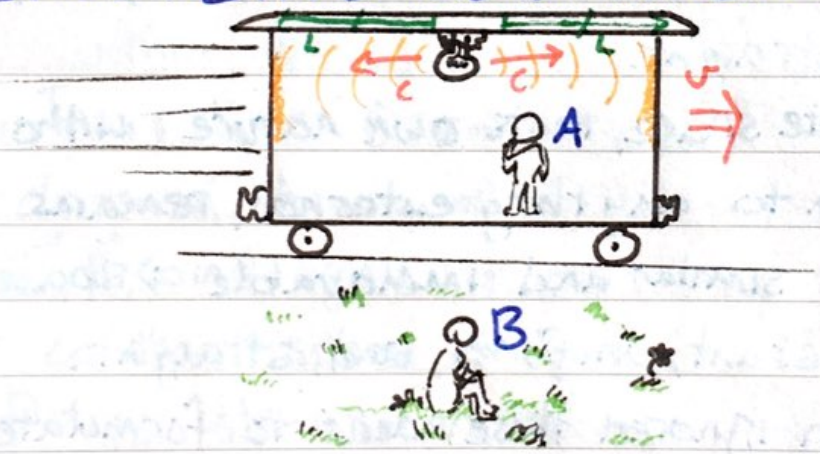
EINSTEIN'S POSTULATES

① The laws of physics are the same in all inertial (non-accelerating) frames of reference. ie there is no preferred FOR. 'No law of physics can identify a state of absolute rest.'

② The speed of light has a constant value for all observers regardless of their motion or the motion of the source.

For these two postulates to work together, space and time must be wibbily~wobbily.

EINSTEIN'S GEDANKEN TRAIN



To observer A light travels at c from the light source to hit the front

and back walls SIMULTANEOUSLY
However to observer B, since light travels at c regardless of FOR, the train moves away from the front beam while into the back beam. Observer B sees light hit the back then front wall.
The only reasonable explanation for this lack of simultaneity is that time itself is behaving strangely and must be different for each FOR

SPACETIME

Space and time are interrelated, 3 dimensions of space and one of time forms wibbly-wobbly SPACETIME

Time Dilation

DERIVING THE FORMULA:

A beam of light travels up and down vertically in a spaceship as a relatively stationary observer watches.

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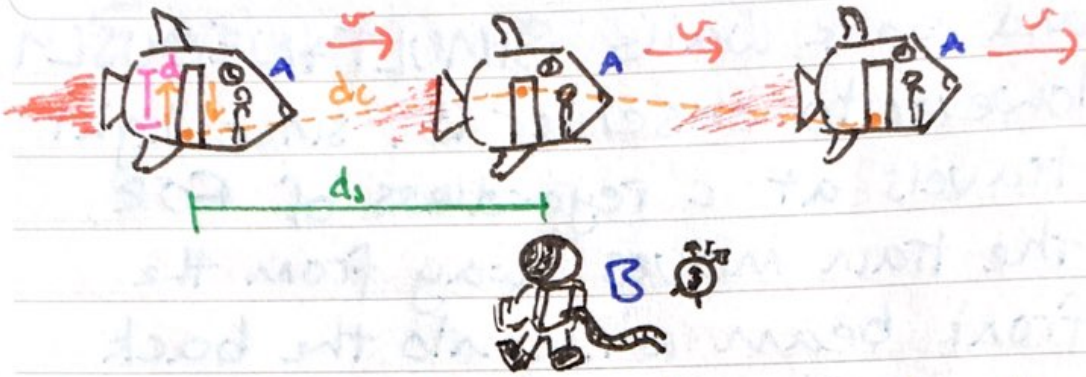

In one unit of time, B sees the ship travel $2d_s$

$$2d_s = v \times t_B$$

For $\frac{1}{2}$ an oscillation, the light pulse travels d as the ship moves through d_s

$$d_c^2 = d_s^2 + d^2$$

$$d_c = d^2 + \left(\frac{vt_c}{2}\right)^2$$

$$d_c = \sqrt{\left(d^2 + \left(\frac{vt_c}{2}\right)^2\right)}$$

B sees the light pulse travel $2d_c$ at speed c, in time t_c:

$$2d_c = c \times t_c$$

equate $\Rightarrow$

$$\frac{ct_c}{2} = \sqrt{d^2 + \left(\frac{vt_c}{2}\right)^2}$$

$$ct_c = \sqrt{\left(4d^2 + 4\left(\frac{vt_c}{2}\right)^2\right)}$$

$$t_c = \frac{\sqrt{4d^2 + (vt_c)^2}}{c}$$

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A sees the light pulse travel 2d at speed c in time t_a

$$d = \frac{ct_a}{2}$$

$$\Rightarrow t_c = \frac{\sqrt{4\left(\frac{ct_a}{2}\right)^2 + (vt_c)^2}}{c}$$

$$t_c^2 = \frac{c^2 t_a^2 + v^2 t_c^2}{c^2}$$

$$t_c^2 = t_a^2 + \frac{v^2 t_c^2}{c^2}$$

$$t_c^2\left(1 - \frac{v^2}{c^2}\right) = t_a^2$$

$$t_c = \frac{t_a}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$\therefore t = t_0\gamma$

$$\Rightarrow t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

t is the time a stationary observer sees pass on a stationary clock in THEIR FOR. t_0 is the PROPER TIME, it is the time a stationary observer sees pass on a clock in the MOVING FOR

To stationary observers time appears to run slowly in moving frames.

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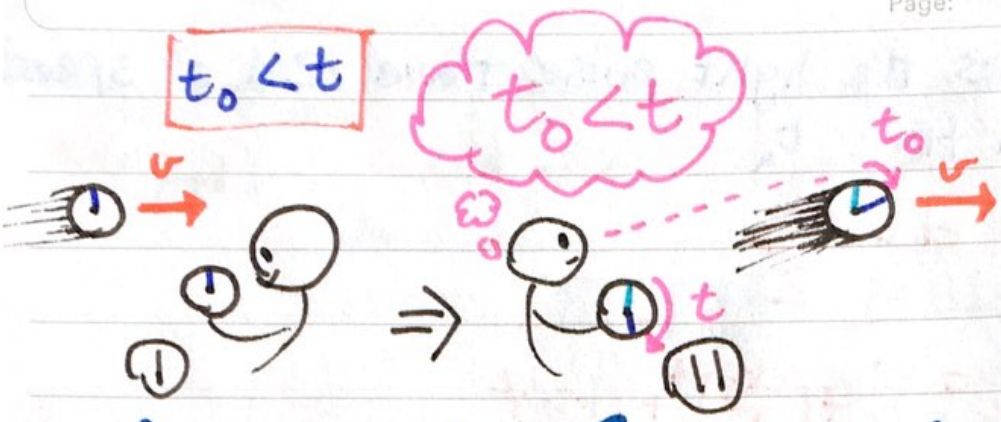

Length Contraction

Observer A sits in a gedanken train as it passes by a platform where observer B stands.
B measures the platform as length L_o, the train passes in time t:

$$t = \frac{L_o}{v_{train}}$$

A observes the platform passing in time t_o

$$t_o = t\sqrt{1-\frac{v^2}{c^2}}$$

$$t_o = \frac{L_o}{v}\sqrt{1-\frac{v^2}{c^2}}$$

A sees the platform move at speed v relative to them.

$$L = vt_o$$

$$\frac{L}{v} = \frac{L_0}{v}\sqrt{1-\frac{v^2}{c^2}}$$

$$\Rightarrow L = L_0\sqrt{1-\frac{v^2}{c^2}}$$

$$\therefore L = \frac{L_0}{\gamma}$$

$$\Rightarrow L = L_0\sqrt{1-\frac{v^2}{c^2}}$$

L_0 is the PROPER length, as seen in the stationary frame (in the same frame as the object being measured - ie 'REST LENGTH')

L is the length seen in the moving frame

$l < l_0$ - length is always observed as contracted from the rest length (l_0)

* The contraction is always PARALLEL to the direction of motion

$v = 99.999999999999\%\ c$

Relativistic Momentum and Energy

As a spaceship's speed approaches c its momentum increases... but this isn't reflected in an increase in speed

$F = ma$, $p = mv$

$$F = \frac{\Delta p}{\Delta t}$$

$$\Rightarrow Ft = mv$$

But t at $\uparrow v$ isn't constant

$$\frac{Ft}{\gamma} = mv$$

$$Ft = \gamma mv$$

$$p_v = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- $p \uparrow$ rapidly as $v \to c$
- $\left\{ m_r = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \right\}$ ∴ mass increases with an increase in v ∴ p also increases
- As $v \to c$ $m \uparrow$, $p \uparrow$, they become too large and the energy / force required to keep accelerating them $\to \infty$ so c is not

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achieved.

MASS-ENERGY EQUIVALENCE

$$E_K = \frac{1}{2}mv^2$$
$$= \frac{1}{2}mv \times v$$
$$= \frac{1}{2}pv$$

As $p \uparrow$, $E_k \uparrow$

$$E_K = (\gamma - 1)mc^2$$

$$\gamma mc^2 = E_K + mc^2$$

Total Energy — Kinetic Energy — rest energy

$$\therefore E_T = \gamma mc^2$$

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Rest mass doesn't depend on speed

$$E = mc^2$$

Mass has energy, energy has mass

RELATIVISTIC ADDITION OF VELOCITY

$$u = \frac{v + u'}{1 + \frac{vu'}{c^2}} \qquad u' = \frac{u - v}{1 - \frac{uv}{c^2}}$$

v is the velocity of the moving frame itself

u' is the velocity of the moving object

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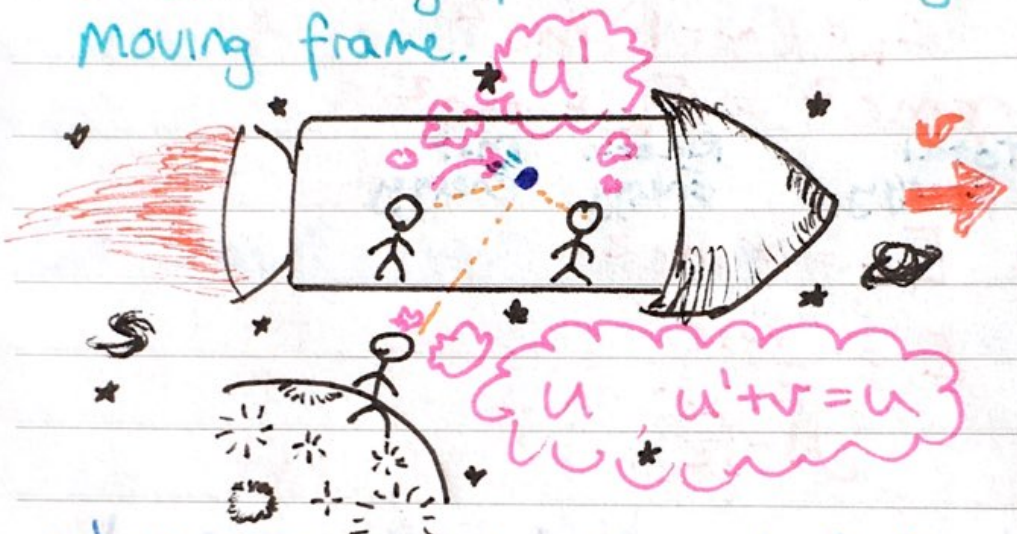
relative to the moving frame, u as seen by an observer sitting in the moving frame

u. is the velocity of the moving object as observed by an observer in a stationary frame observing the moving frame.



u' is seen as moving in both frames.

The Standard Model + Cosmology

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The Standard Model of Particle Physics

mass → MeV/c²
charge → 2
spin → 5 X

FERMIONS

QUARKS

2.3M, +2/3, 1/2, u, up	1.275G, +2/3, 1/2, c, charm	173.07G, +2/3, 1/2, t, top
4.8M, -1/3, 1/2, d, down	95M, -1/3, 1/2, s, strange	4.18G, -1/3, 1/2, b, bottom

GUAGE BOSONS

0, 0, 1, g, gluon

The strong interaction

Electromagnetism

LEPTONS

0.511M, -1, 1/2, e, electron	105.7M, -1, 1/2, μ, muon	1.777G, -1, 1/2, τ, tau	0, 0, 1, γ, photon
<2.2, 0, 1/2, ν_e, electron neutrino	<0.17M, 0, 1/2, ν_μ, muon neutrino	<15.5M, 0, 1/2, ν_τ, tau neutrino	91.2G, 0, 1, Z, Z boson
			80.4G, ±1, 1, W, W boson

The weak interaction

FERMIONS

All particles of matter are comprised of the 12 fundamental / elementary particles - Fermions

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All fermions obey Pauli's Exclusion Principle: no two particles can occupy the same quantum state at the same time (eg e^- in an atom's orbital)

QUARKS

All quarks experience the strong interaction and have fractional charges. 'Up' and 'down' are most common and make up most matter, (protons and neutrons)

LEPTONS

Leptons don't experience the strong interaction. Half have a charge of -1 and can interact via electromagnetism, the rest are neutrinos, they have no (0) charge.

GUAGE BOSONS

Bosons are 'force carriers' or 'exchange particles'. They mediate the fundamental forces that act on particles and govern their behaviour. Particles interact by the 'exchange' of bosons, where there's an interaction, there's a boson.

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THE STRONG INTERACTION - GLUONS

Gluons mediate the strong interaction which binds quarks to hadrons. 'Residual strong force' that gives protons and neutrons a slight '~force field~' due to the gluons binding them also binds protons and neutrons to the nucleus of an atom.

ELECTROMAGNETISM - PHOTONS

Photons mediate electromagnetism which is responsible for the attractive and repulsive interactions between charged particles. They are carried by electric and magnetic fields which allow photons to propagate through space as electromagnetic radiation.

THE WEAK INTERACTION - W, Z BOSONS

W and Z bosons mediate the 'weak nuclear force' which is responsible for radioactive decay. When something decays its charge is 'carried off' by one of the bosons: W^+, W^-, Z^0 to then further decay. It is the only force which may change the 'flavour' (type) of a quark, and the

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only force with massive (have mass) carrier particles.

GRAVITY - THEORISED 'GRAVITON'

Gravity is not included in the standard model as there is no quantum theory of gravity. There is a search for a grand unified theory that encompasses all the fundamental forces into one.

THE HIGGS BOSON - EXTREMELY SIMPLIFIED

Mass is an emergent behaviour of massless particles interaction with other massless particles, this gives the 'illusion of mass'. But certain particles have mass despite being alone and not interacting with stuff.

⇒ They are constantly interacting with the 'Higgs field' through its guage boson - the Higgs Boson.

GUAGE BOSONS + THE FOUNDATIONS OF THE STANDARD MODEL

Quantum mechanics and special relativity as well as guage bosons

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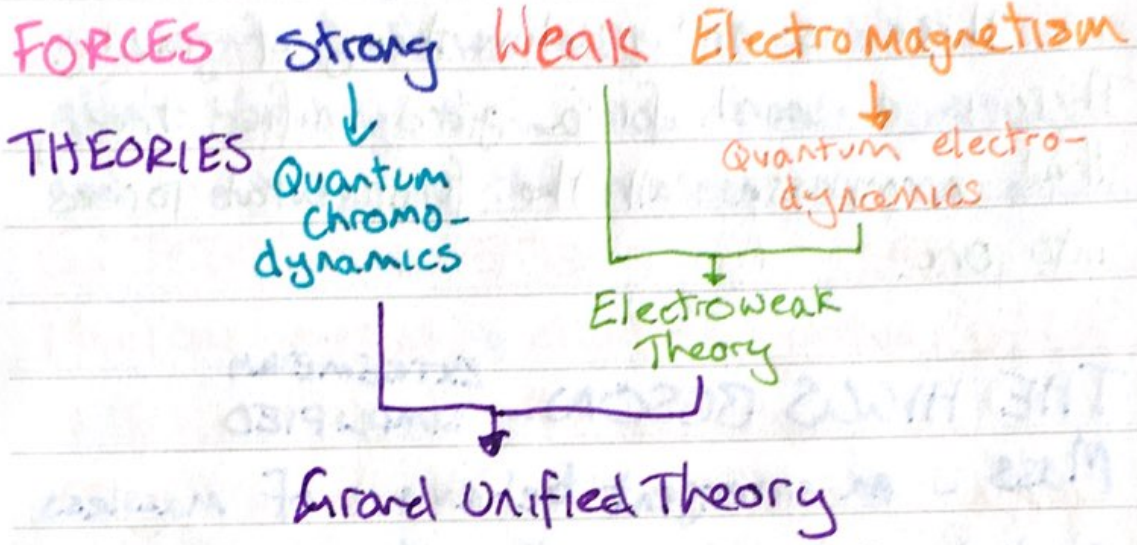
as exchange particles are the basis of the theories that make up the standard model



Fundamental Forces Summary:

Force	Nature	Rel. Strength	Range	Boson
Strong	Binds quarks	1	10^{-15}	g
EM	EM fields interactions of charges	$\frac{1}{137}$	∞	γ
Weak	Radioactive Decay	10^{-6}	10^{-18}	W^+, W^-, Z^0
Gravity	Mass attraction	6×10^{-39}	∞	graviton

HADRONS

Particles composed of quarks, quarks are never by themselves in nature, only under

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extreme circumstances. All hadrons experience the strong interaction as it is gluons that bind their quarks.

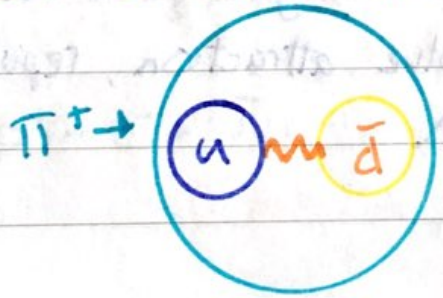
BARYONS

Baryons are 'composite fermions', all hadrons with an odd amount of quarks are fermions. Baryons are most commonly composed of 3 quarks.

MESONS

Mesons are comprised of a quarks, and an antiquark. Mesons are bosons, the Pauli Exclusion Principle doesn't apply to them and they may act as force mediating particles and can play a role in nuclear interaction and decay

Pions: π^+: $u\bar{d}$ π^0: $u\bar{u}$ or $d\bar{d}$ π^-: $d\bar{u}$



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ANTIMATTER

Antimatter is composed of antiparticles which have the same mass as their non-anti counterparts but opposite quantum numbers (charge, lepton number etc)
Particles are created and destroyed in particle-antiparticle pairs.

DARK MATTER

Some observations can only be explained in terms of an undiscovered source of mass that does not interact with electromagnetic radiation, so is 'invisible'.

Particle Interactions

The standard model was developed by observing interactions between particles using special relativity and conservation laws to analyse observations
Interactions produce changes = events.
Interactions can involve attraction, repulsion, decay, or annihilation.

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FEYNMAN DIAGRAMS

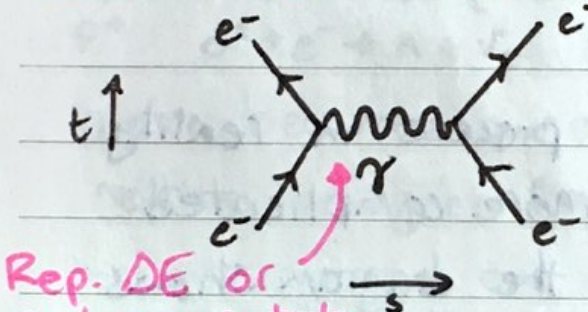
- 2D time-space diagrams simplifying interactions
- Arrows are NOT vectors, simply show travel through time.

(Non universal) Convention:

Fermion — Photon ~~~

Gluon eeeee — W Z bosons - - - - - -

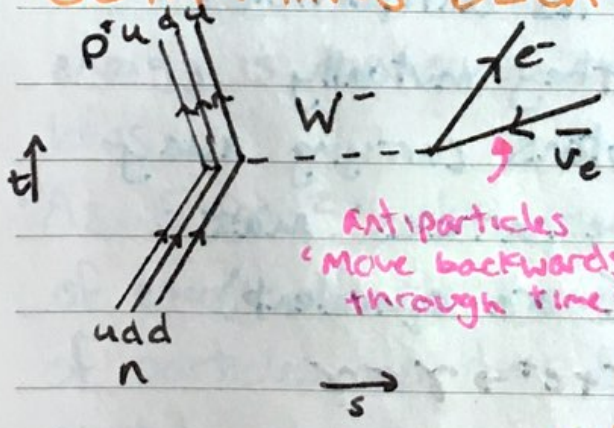
ELECTRON REPULSION



Two e⁻s approach, exchange a virtual γ, repel, and change direction

Rep. DE or exchange particle which has a brief / virtual existence

BETA-MINUS DECAY - β^-



antiparticles 'move backwards through time'

neutron → proton (β^- decay)

d quark → u quark

a W^- boson is emitted, decaying into an anti-electron neutrino and an electron

$n \rightarrow p^+ + e^- + \bar{\nu}_e$

e^- ↳ β^- particle

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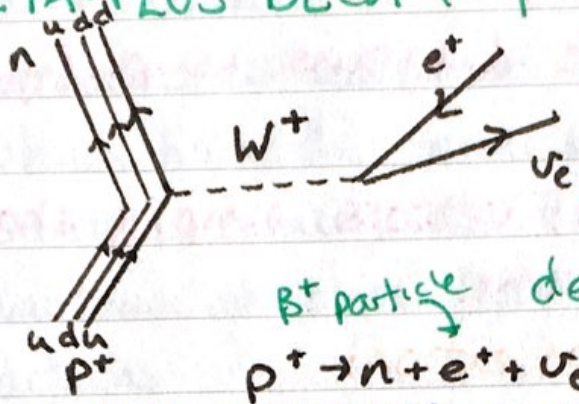
BETA-PLUS DECAY - β^+



Proton → neutron

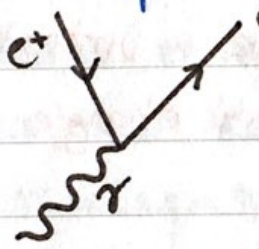
$u \rightarrow d$, a W^+ boson is emitted,

β^+ particle decaying into e^+ and ν_e

$p^+ \rightarrow n + e^+ + \nu_e$

PAIR PRODUCTION AND ANNIHILATION

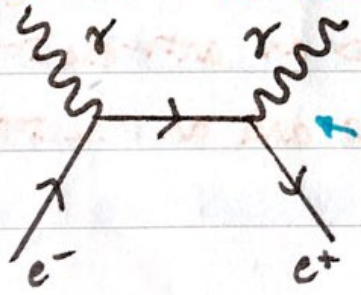
E as a γ can create a particle-anti particle pair provided it has $E \geq$ mass of the pair.



The process in reality is more complicated than the diagram shows

$\gamma \rightarrow e^- + e^+$

When a particle and its antiparticle counterpart collide, they mutually annihilate, two photons carrying away the E contained in the particles' mass. ($E = mc^2$ m and E are equivalent)



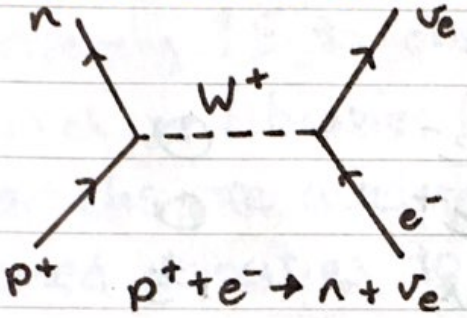
$e^- + e^+ \rightarrow \gamma + \gamma$

* Both particles have a rest $E \approx 0.511$ MeV, IF E_K is rel. negligible

this E_{rest} will become each photon E of the gamma rays produced

Momentum and energy are conserved with 1.022 MeV of gamma rays moving in OPPOSITE directions (conserves p).

ELECTRON CAPTURE



The p^+ rich nucleus of an electrically neutral atom absorbs an inner orbital electron, the proton becomes a neutron, an electron neutrino being emitted. An outer e^- replaces the missing inner one, emitting a photon.

CONSERVATION LAWS

In a particle interaction, momentum and energy is conserved as per their conservation laws

- As $E=mc^2$, when considering the conservation of energy, the total energy in the rest masses of particles and their E_K before and after must be considered.
- Charge is also conserved, total q of reactants = that of products

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Observations show only a small number of possible events actually occure as BARYON and LEPTON numbers must also be conserved.

CONSERVATION OF BARYON NUMBER:

Baryons: $B=+1$ Anti-Baryons: $B=-1$

All else: $B=0$

Particle:	B:		
p^+	$+1$	e^-	0
$\bar{p}^+ / p^-$	-1	e^+	0
n	$+1$	u	$+\frac{1}{3}$
$\bar{n}$	-1	$\bar{u}$	$-\frac{1}{3}$

CONSERVATION OF LEPTON NUMBER:

As well as overall Lepton number

(Leptons: $L=+1$ Antileptons: $L=-1$ Else $L=0$)

There are L_e for electron species, L_μ for muons and L_τ for tau.

$e^-, \nu_e : L_e=+1$ $e^+, \bar{\nu}_e : L_e=-1$ Else: $L_e=0$

$\mu^-, \nu_\mu : L_\mu=+1$ $\bar{\mu}, \bar{\nu}_\mu : L_\mu=-1$ Else: $L_\mu=0$

$\tau, \nu_\tau : L_\tau=+1$ $\bar{\tau}, \bar{\nu}_\tau : L_\tau=-1$ Else: $L_\tau=0$

Particle Accelerators

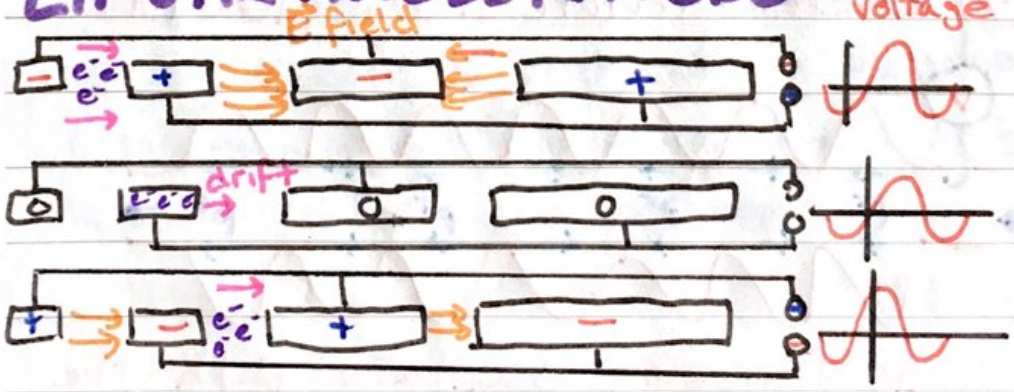
Before ↑E accelerators particle interactions were studied in cosmic rays ⇒ produce a cascade of ↑E particles upon striking the atmosphere. This is limited by natural Es and N° of events.

Particle accelerators accelerate matter to extremely ↑E to observe ↑E collisions in which new heavier particles are created.

Particles are accelerated to near light speed velocities to overcome repulsive forces, as well as increase momentum to give particles a shorter wavelength so finer detail can be seen, and a greater resolution studied.

⇒ De Broglie: $\lambda = \frac{h}{mv} = \frac{h}{p}$

LINEAR ACCELERATORS



Tubes get longer as e^- v ↑

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SYNCHROTRONS

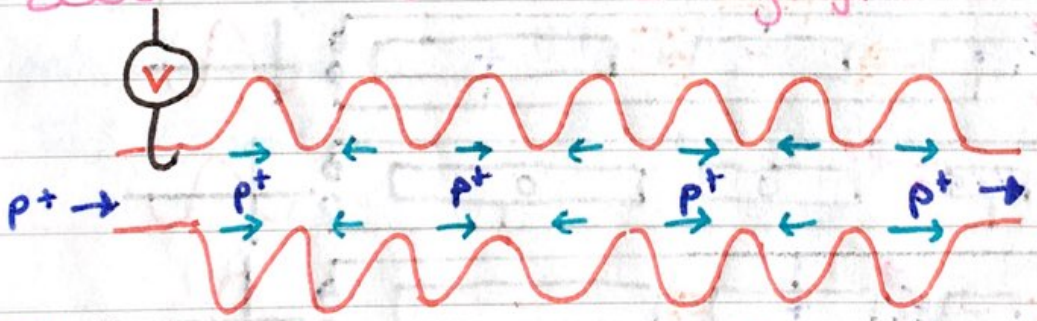
A large portion of E of a particle hitting a fixed target, as in a linear accelerator, is converted to the momentum of the product => E is wasted

In colliding particles from opposite directions, momentum before and after is zero, so more E is dedicated to the creation of the products themselves.

Particles are confined to a circular path of evacuated beams using bending magnets

ACCELERATION OF PROTONS IN THE LHC

p^+ in the LHC are accelerated around its circular ring using radio frequency (RF) cavities. One bunch = billions of p^+, 2000 bunches circulate at any given time



The radio frequency oscillates with the protons so they never experience a

force backwards, so they are constantly accelerated.

As a particle is accelerated to $\rightarrow c$, it takes increasingly more E to accelerate it, its relativistic energy increases. To a stationary observer this appears as an increase in mass.

$$E_T = \frac{M_0 c^2}{\sqrt{1-\frac{v^2}{c^2}}} \qquad M = \frac{M_0}{\sqrt{1-\frac{v^2}{c^2}}} \qquad r = \frac{mv}{qB}$$

Cosmology

HUBBLE'S FINDINGS

In some spiral nebulae are cepheid variables - very bright *s that slowly change brightness across a period. In comparing intrinsic brightness to apparent brightness across this period the distance to the nebula could be found.

It was also found the atomic spectra of different nebulae were shifted towards the red end of the EM spectrum, the greater

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the distance of the galaxy away, the greater the REDSHIFT

Hubble's Law: speed of recession $\propto$ distance away

$v = H_0 d$

$\Rightarrow H_0$ = Hubble's constant

$= 70\ kms^{-1} Mpc^{-1}$

EXPANSION OF THE UNIVERSE

At first it seemed the universe was uniform and infinite

$\Rightarrow$ Hubble: as all distant galaxies are receding from us, space itself is expanding, the galaxies aren't rushing away from us.

COSMIC MICROWAVE BACKGROUND RADIATION

T at beginning of big bang $\Rightarrow$ hot enough to fuse H nuclei $\Rightarrow$ hot universe was a blackbody and emitted blackbody radiation as intense $\uparrow E$ γ rays filling all space and radiating ever since.

As space expanded so did the wavelength into the microwave range ($\downarrow E$)

The CMBR we recieve from all parts of

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the sky, from all the space around us corresponds to the blackbody radiation of a hot new universe.
Close analysis shows slight variation in CMBR Temperature, this arises from slight variation in the structure of the universe ⇒ this allowed gravity to pull matter into clumps and stars eventually formed. Without variation in the structure of the early universe, nothing would form.

THE STANDARD BIG BANG MODEL

As the universe cooled, post big bang, composite particles formed. Strong force + EM bound nuclei and atoms ⇒ gravity pulled it all together into structures: galaxies, ★s, planets.
When the universe < size of proton, $T = 10^{32}$ K at 10^{-43} seconds gravity separated from the forces, having been unified.
After 10^{-35} s, strong force separated from electroweak, the E released caused inflation, expanding the universe to 10^{50} x its original size, preventing its collapse into

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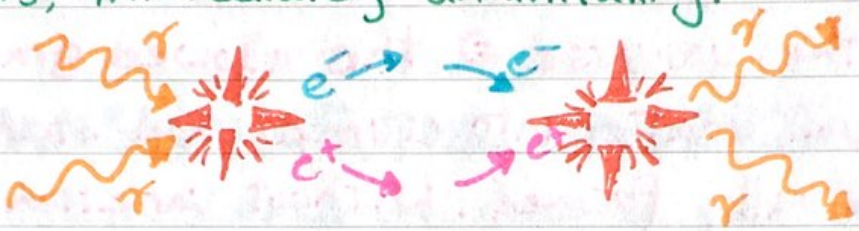
a black hole.

Heisenberg Uncertainty Principle:
Matter can pop into existence from nothing ⇒ always as matter-antimatter pairs, immediately annihilating.



CREATION ANNIHILATION

In a young hot universe matter + anti matter was constantly created and annihilated, the γ produced colliding to form more matter pairs..
Due to inflation produced pairs rapidly separated as space expanded, so couldn't annihilate.
After 0.0001s of expansion 10^{12}K was too cool for particle creation, particles annihilated en masse ⇒ LOTS of radiation, a fireball of EMR filling the universe ⇒ CMBR
However imbalance in par production ⇒ more matter than antimatter, 1 in 1 billion

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now making up the whole universe

1st Stars

1 billion years post BB, T = 15 K (COLD), uneven-ness in early universe caused clumping of matter, gravity pulling it into a crunch, collapsing atoms into a star, massive amounts of HEAT and E allowing heavier elements to begin being created (He, Li, →)