Session 1

General Tips and Tricks

1. (Do NOT use a calculator for this question)
   A rocket travels through space at a speed $v = \beta c$ relative to Earth such that it is length contracted to half its rest length. The equation for total energy is given by

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

By first considering the above energy equation when $v = 0$ (i.e. when it is at rest), calculate the ratio of the rocket's total energy to its rest energy.

$$E_R = \frac{mc^2}{\sqrt{1-\frac{0^2}{c^2}}} = \frac{mc^2}{\sqrt{1}} = mc^2$$

$$E_T : E_R = \frac{E_T}{E_R} = E_T \div E_R$$

$$= \frac{\cancel{mc^2}\,1}{\sqrt{1-\frac{v^2}{c^2}}} \div \cancel{mc^2} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$l = \underbrace{\frac{1}{2} l_0}_{\text{From question}} = \underbrace{l_0\sqrt{1-\frac{v^2}{c^2}}}_{\text{from formula sheet}}$$

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

$$\therefore \frac{E_T}{E_R} = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\frac{1}{2}} = 2$$

2. State 5 valid equations for Work which are on (or can be easily derived from) the formula sheet.
   Note that $W = \Delta E_k = \frac{1}{2}m(v_f^2 - v_i^2)$ is not valid as it is the definition of work.

① $W = F_{\parallel}s = Fs\cos\theta$

② $W = -\Delta U = -(U_f - U_i) = U_i - U_f$

③ $W = qV$

④ $W = qEd$

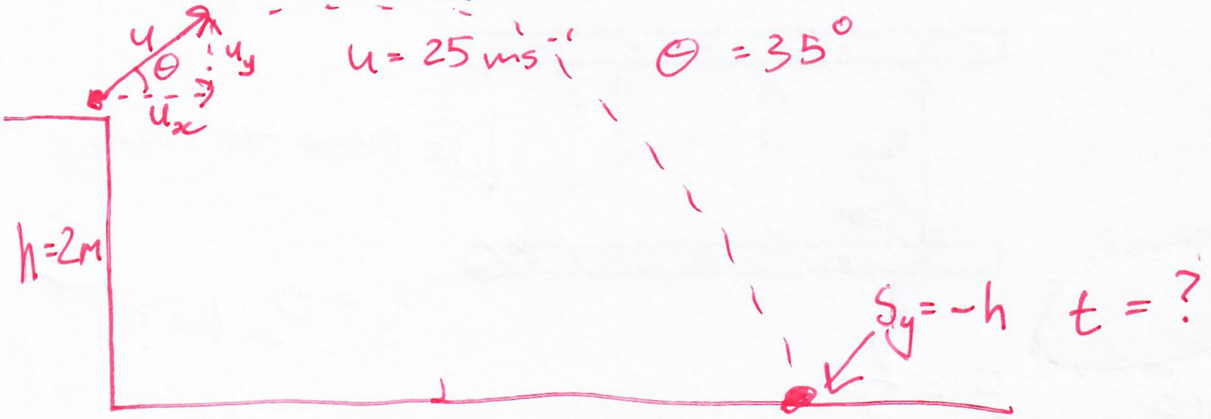
⑤ $W = (qv_{\perp}B)_{\parallel}s$

⑥ $W = (lI_{\perp}B)_{\parallel}s$

Any 5 are fine

Advanced Mechanics

1. A projectile is fired with intial velocity $u = 25\,m\,s^{-1}$ at an angle $\theta = 35°$ above the horizontal at an intial height of $h = 2\,m$ above the ground.
At what time will it hit the ground?



$$S_y = \frac{1}{2}a_y t^2 + u_y t \qquad a_y = -g$$

$$-h = \left(\frac{-g}{2}\right)t^2 + (u\sin\theta)t \qquad u_y = u\sin\theta$$

$$0 = \left(\frac{-g}{2}\right)t^2 + (u\sin\theta)t + h$$

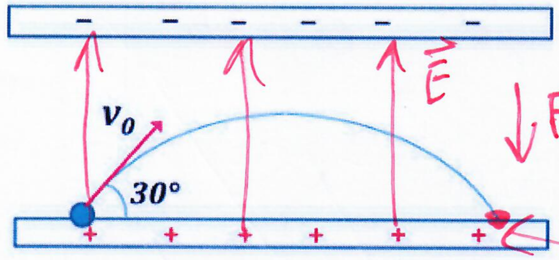
$$t = \frac{-u\sin\theta \pm \sqrt{u^2\sin^2\theta - 4\left(\frac{-g}{2}\right)(h)}}{2\left(\frac{-g}{2}\right)}$$

$$= \frac{-25\sin(35°) \pm \sqrt{25^2\sin^2(35°) + 2(g)(2)}}{-g}$$

$$t = 3.0598\ldots\ s \quad \text{or} \quad \cancel{t = -0.1333\ldots\ s} \rightarrow \text{no -ve times}$$

$$\therefore t = 3s \ (1\ \text{sig. fig.})$$

2. A particle with charge $q = -6.7 \times 10^{-5}\,C$ and mass $m = 1.2 \times 10^{-3} kg$ is fired from the positive plate of a capacitor at speed $v_0 = 10^{-2}\,m\,s^{-1}$ at an angle $\theta = 30°$ from the positive plate. If there is a potential difference of $30V$ and a gap between the plates of $d = 10^{-2}\,m$, calcualte the time it takes for the particle to touch the plate again.



$F = qE \qquad E = \frac{V}{d}$

$= \frac{qV}{d}$

$a_y = \frac{-F_E}{m}, \quad u_y = V_0 \sin\theta$

$S_y = \frac{1}{2} a_y t^2 + u_y t$

$0 = \left(\frac{-F_E}{2m}\right) t^2 + (V_0 \sin\theta) t + 0$

Method 1:

$\frac{F_E}{2m} t^{\cancel{2}} = V_0 \sin\theta \cancel{t}$

$t = \frac{2m V_0 \sin\theta}{F_E}$

$= \frac{2m V_0 \sin\theta}{\frac{qV}{d}}$

$= 5.9701\ldots \times 10^{-5} s$

$\approx \underline{6.0 \times 10^{-5} s}$

Method 2

$t = \frac{-V_0 \sin\theta \pm \sqrt{(V_0 \sin\theta)^2 - 4 \times 0}}{2\left(-\frac{F_E}{2m}\right)}$

$t = \frac{-V_0 \sin\theta \pm V_0 \sin\theta}{\frac{-qV}{dm}}$

$t = 0,\ \underline{6.0 \times 10^{-5} s}$

3. A satellite of mass $m = 1234\,kg$ is launched from Earth's surface with some velocity v to an orbital radius of $r_o = 9.87 \times 10^6\,m$.

(a) Calculate its change in gravitational potential energy.

$$\Delta U = U_f - U_i$$

$$r_f = r_o = 9.87 \times 10^6\,m$$

$$r_i = r_E = 6.371 \times 10^6\,m$$

$$M = M_e = 6 \times 10^{24}\,kg$$

$$= \left(-\frac{GMm}{r_o}\right) - \left(-\frac{GMm}{r_E}\right)$$

$$= (-5.004 \times 10^{10}) - (-7.751 \times 10^{10}) = 2.75 \times 10^{10}\,J$$

*must be positive

(b) If the satellite loses $5.00 \times 10^9\,J$ due to air resistance as heat and maintains a constant velocity throughout the trip, calculate the work done by the rocket.

GPE $\Delta K_u = -\Delta U = -2.75 \times 10^{10}$

Heat $\Delta K_Q = -Q = -5 \times 10^9$

Work $\Delta K_W = W$

$$\Delta K = \Delta K_W + \Delta K_u + \Delta K_Q$$

$$= W - \Delta U - Q$$

$\Delta K = 0$ (since constant velocity)

$$\therefore W - \Delta U - Q = 0$$

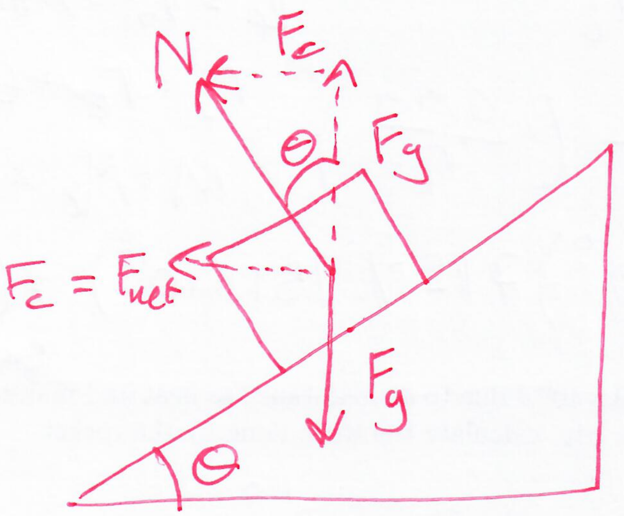
$$W = \Delta U + Q$$

$$= (2.75 \times 10^{10}) + (5 \times 10^9)$$

$$= 3.25 \times 10^{10}\,J$$

4. A cyclist is travelling with uniform speed at a constant height of $3\,m$ on a banked curve on a theoretically frictionless circular track.

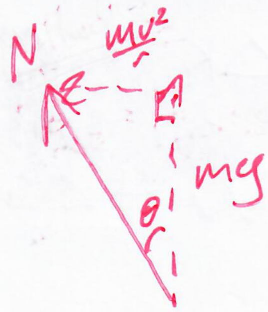
(a) Draw a free body diagram labelling the forces acting on the cyclist and showing the direction of the net force.



(b) If the banked curve was at an angle of $\theta = 25°$ with a radius of $r = 30\,m$, determine the net force acting on a $70\,kg$ cyclist.

Method 1

$$F_{net} = F_N \sin\theta = \frac{mv^2}{r}$$



$$\tan\theta = \frac{\left(\frac{\cancel{m}v^2}{r}\right)}{\cancel{m}g} = \frac{v^2}{rg}$$

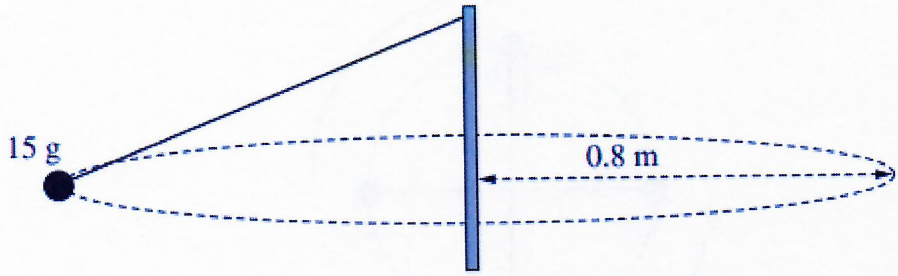
$$v^2 = rg\tan\theta$$

$$F_{net} = \frac{mv^2}{r} = \frac{m(\cancel{r}g\tan\theta)}{\cancel{r}}$$

$$= mg\tan\theta$$

$$= 319.9\,N$$

5. A 15 g metal ball bearing on a string is swung around a pole in a circle of radius $0.8\,m$. The plane of the circular path is horizontal. The angular velocity of the motion is $4\pi\,rad\,s^{-1}$.



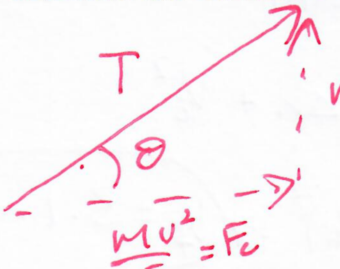
(a) Calculate the magnitude of the centripetal force on the ball bearing.

$v = \omega r = 4\pi \times 0.8$

$F_c = \frac{mv^2}{r} = \frac{m(\omega r)^2}{r} = \frac{m\omega^2 r^{\cancel{2}}}{\cancel{r}} = (15\times10^{-3}\,kg)\times(4\pi)^2\times 0.8$

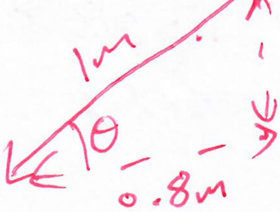
$= 1.89N$

(b) Calculate the tension in the string if the string is $1\,m$ long.



(vertical is mg since ball doesn't move down so cancels gravity)

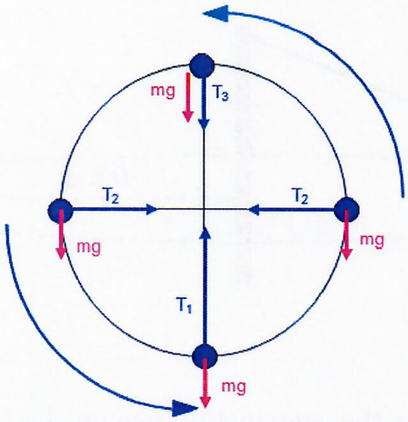
$\cos\theta = \frac{F_c}{T} \Rightarrow T = \frac{F_c}{\cos\theta}$



$\cos\theta = \frac{0.8}{1}$

$T = \frac{1.89}{0.8} = 2.37N$

6. A ball of mass $m = 50\,g$ is in circular motion in the vertical plane and is attached to a string of length $l = 20\,cm$. When the ball is at its highest position its velocity is $v_h = 1.4\,m\,s^{-1}$.



(a) Determine the tension in the string at the highest position.

At peak of orbit Tension and gravity point inwards

$$\therefore F_c = mg + T \Rightarrow T = \frac{mv^2}{l} - mg$$

$$= \frac{0.05 \times 1.4^2}{0.2} - 0.05 \times 9.8$$

$$T = 0$$

(b) What is the speed of the ball at the lowest point in its motion?

$$\Delta(\tfrac{1}{2}mv^2) = mg\Delta h$$

$$\tfrac{1}{2}\cancel{m}v_f^2 - \tfrac{1}{2}\cancel{m}v_i^2 = \cancel{m}g\Delta h \Rightarrow v_f^2 = 2g\Delta h + v_i^2$$

$$v_f^2 = 2g(2l) + (v_h)^2 \Rightarrow v_f = 3.1\,ms^{-1}$$

(c) Therefore, determine the tension in the string at the lowest point.

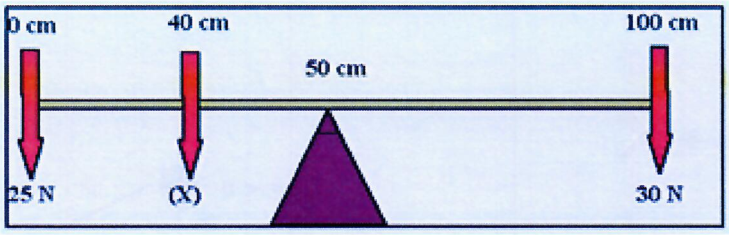
Tension is pointed towards centre and gravity is outwards

$$\therefore F_c = T - mg \Rightarrow T = F_c + mg$$

$$= \frac{mv^2}{l} + mg = \frac{0.05 \times 3.1^2}{0.2} + 0.05 \times 9.8$$

$$= 2.94\,N$$

7. Calculate the strength of the force X given the beam is of a uniform denstity and there is no net torque on the beam.



$$0.5 \times 25 + 0.1 \times X = 0.5 \times 30$$

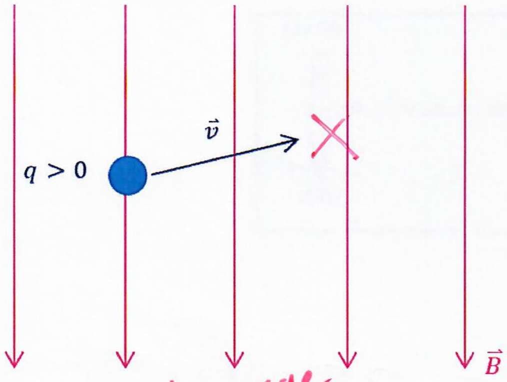
$$12.5 + 0.1X = 15$$

$$X = \frac{2.5}{0.1}$$

$$X = 25N$$

Electromagnetism

1. For each of the following, draw the resultant force vector



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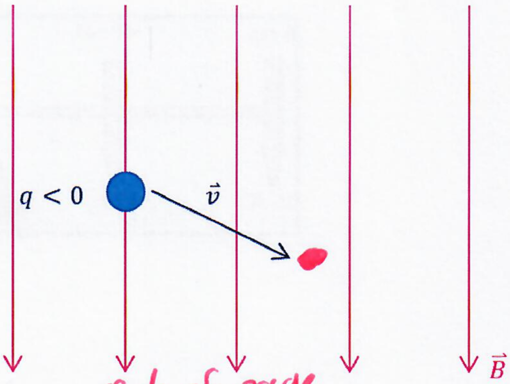

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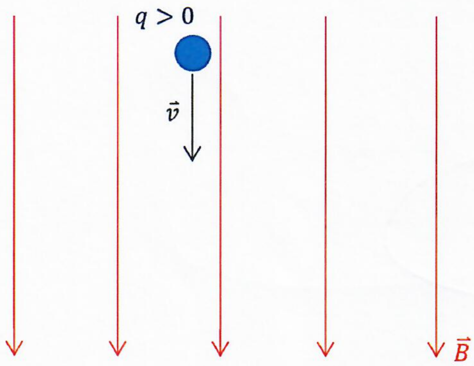
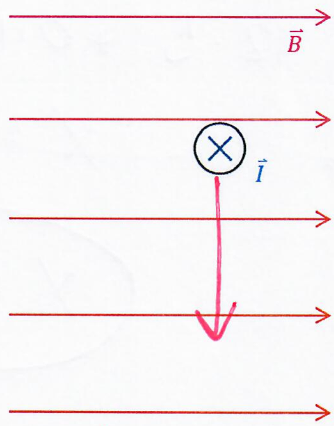


No force



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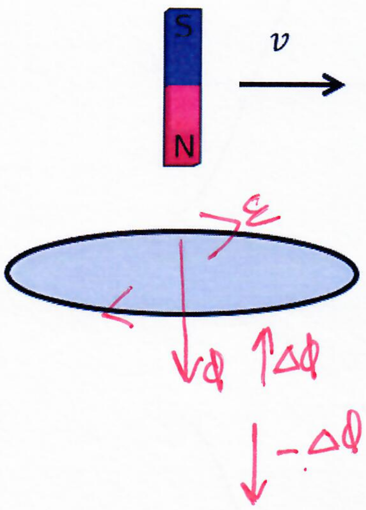
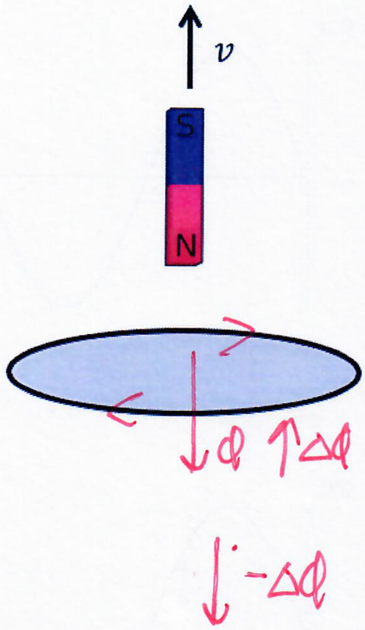
2. Draw the direction of the induced current and resultant magnetic field.

(a) Method 1

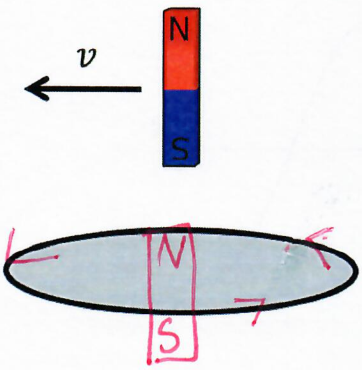


clockwise

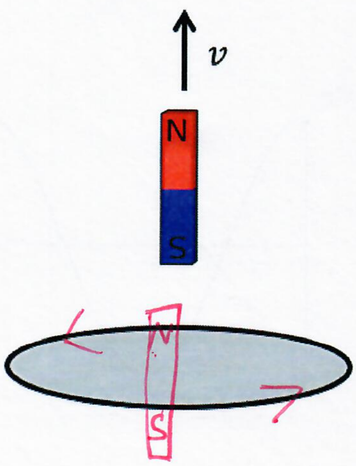


clockwise

(b) Method 2



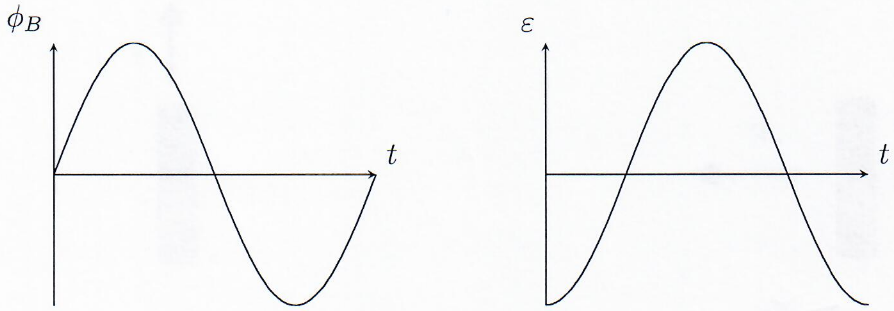
Anticlockwise



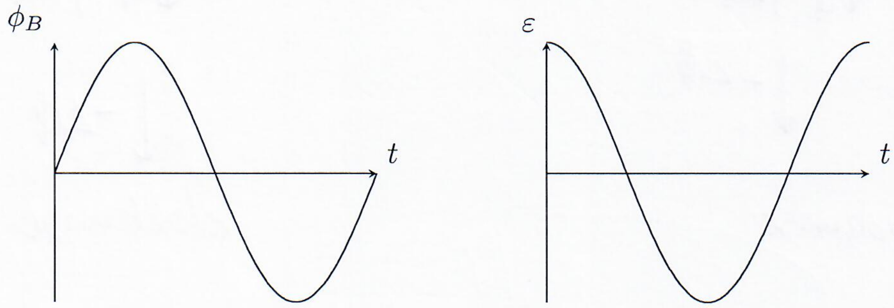
Anti-clockwise

3. Which of these pairs of graphs are accurate? (There are multiple)

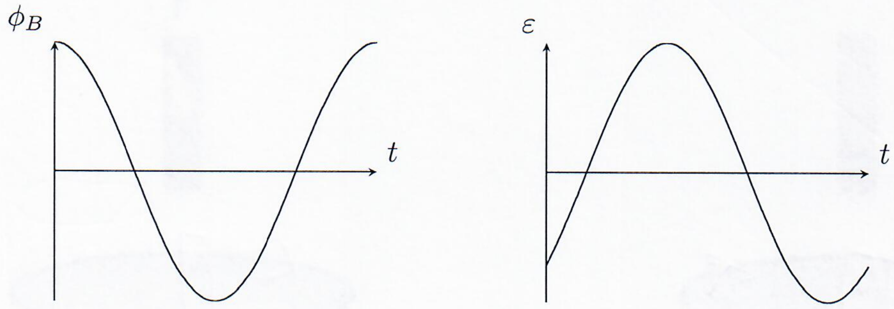
(a)



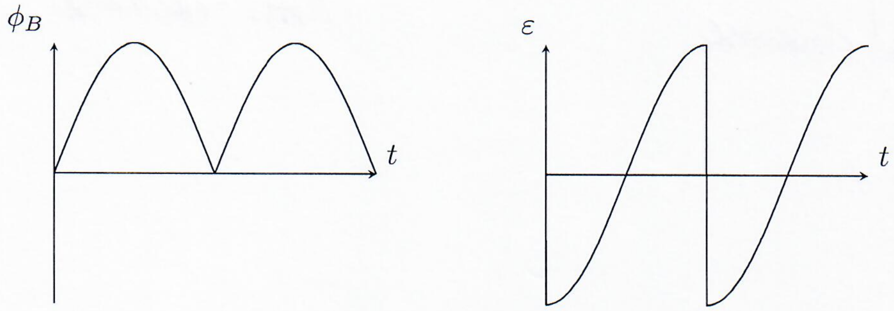
(b)



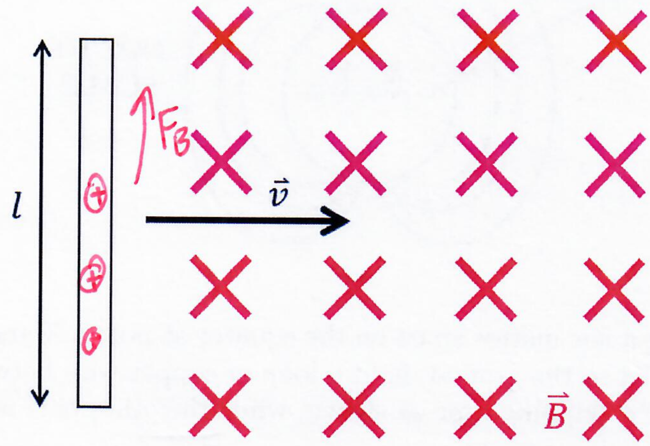
(c)



(d)



4. A rod of length $l = 0.2\,m$ moves through a magnetic field of strength $B = 4\,T$ at a speed $v = 2\,m\,s^{-1}$ as shown below.
Showing all working, calculate the induced EMF in the rod.



$W = qV \Rightarrow V = \frac{W}{q}$ $\qquad \varepsilon = V$

$W = F_{\parallel} s = (q v_{\perp} B)_{\parallel} l = q v B l$

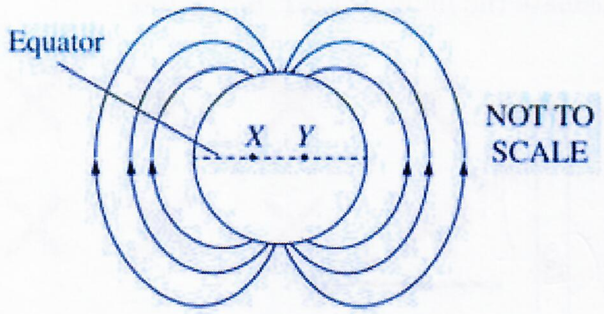
$\varepsilon = \frac{W}{q} = \frac{(\cancel{q} vBL)}{\cancel{q}}$

$\varepsilon = vBL$

$= 2 \times 4 \times 0.2$

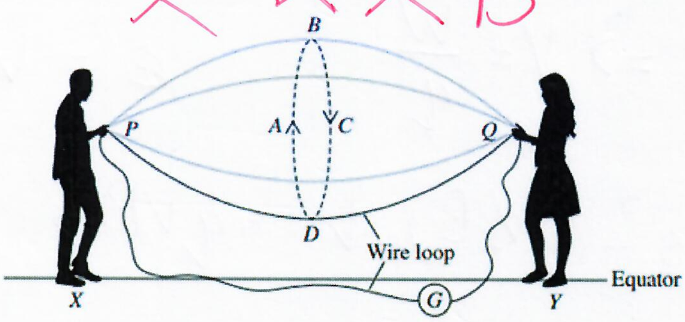
$= 1.6\,V$

5. The Earth's magnetic field is shown in the following diagram.



Two students standing a few metres apart on the equator at points X and Y, where Earth's magnetic field is parallel to the ground, hold a loop of copper wire between them. Part of the loop is rotated like a skipping rope as shown, while the other part is motionless on the ground.

$\times \quad \times \quad \times \; B$



At what point during the rotation of the wire does the maximum current flow in a direction from P to Q through the moving part of the wire?

A. A

B. B

C. C

D. D

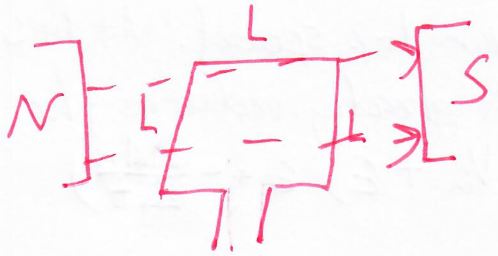
for $F = qv_\perp B$ to give a

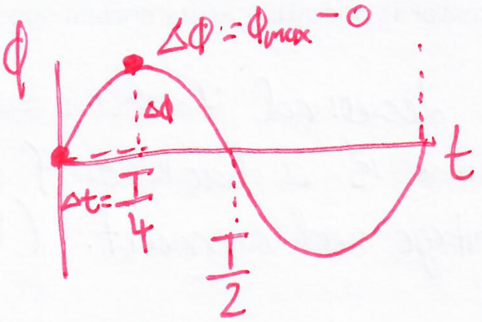
force from P to Q (by using right hand

rule) it must have a velocity down

$\therefore$ C

6. A square coil with perimeter $4L$ and n turns rotates in a uniform magnetic field of strength B. The frequency of its rotation is f.
What is the average induced EMF (ε)?





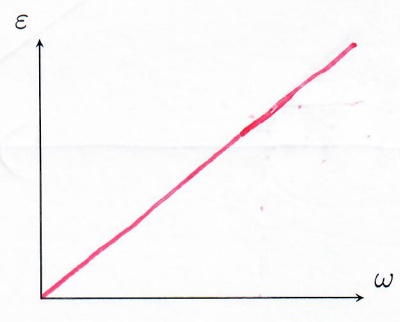
T is the period $(T = \frac{1}{f})$ $\Phi_{max} = BA = BL^2$

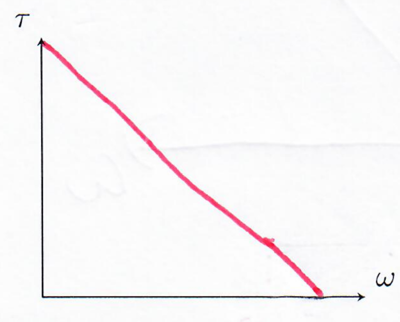
$$\varepsilon = -N\frac{\Delta\Phi_B}{\Delta t} = -n\frac{\Phi_{max}-0}{\frac{T}{4}-0} = -n\frac{BL^2}{\frac{T}{4}}$$

$$\varepsilon = \frac{-4nBL^2}{T} = \frac{-4nBL^2}{\frac{1}{f}}$$

$$= -4fnBL^2 \quad \text{or} \quad = 4fnBL^2$$

7. Sketch the graphs of emf and torque on a motor as a function of its angular velocity if the motor has a constant input voltage and is powering a fan.



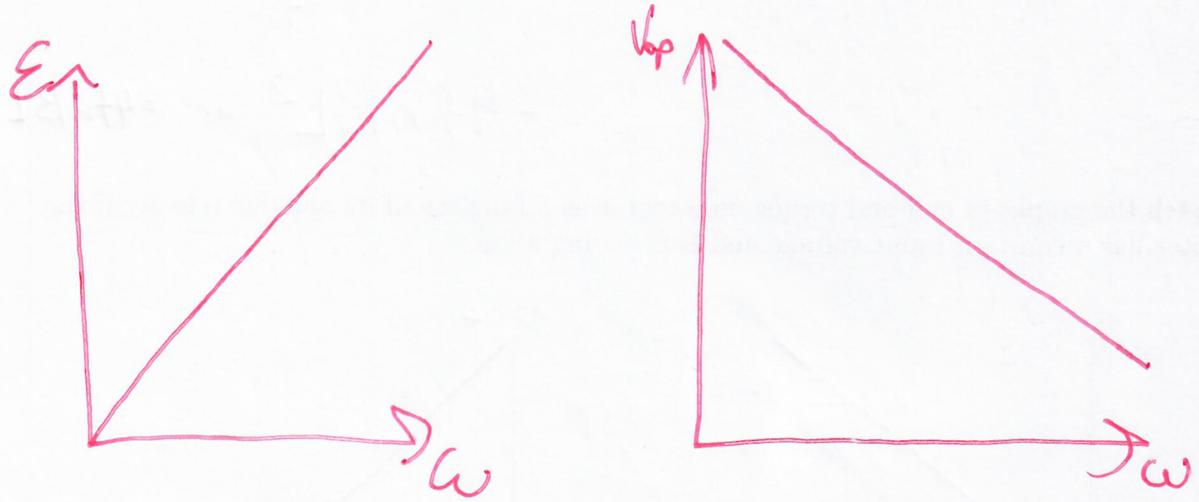


8. A big DC electric motor has a variable resistor in series with it. When the motor is switched on, a large resistance is set, and as the motor speeds up, this resistance is reduced to zero. Why is a large resistance needed when the motor is switched on but no resistance is needed when the motor is operating at its normal speed? (4)

Motors are designed to run at their top speed. At this top speed there is a back emf which greatly reduces the operating Voltage and current. ($V_{op} = V_{in} + \varepsilon$, $\varepsilon = -\frac{\Delta \Phi_B}{\Delta t}$)

As a motor begins spinning there is no ε and therefore the current is very high ($I_{op} = \frac{V_{op}}{R}$). To reduce this current and stop the coil in the motor from being damaged the resistance of the circuit is increased, reducing the current.

As the motor speeds up the ε reduces the operating voltage and current so there is no need for the resistor.

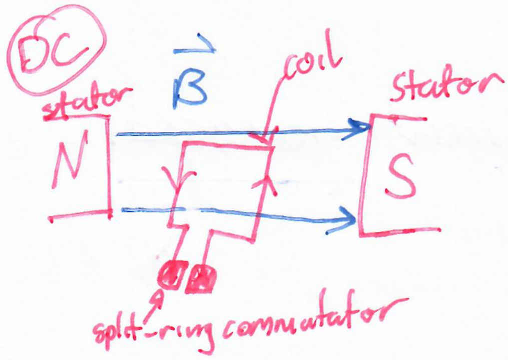


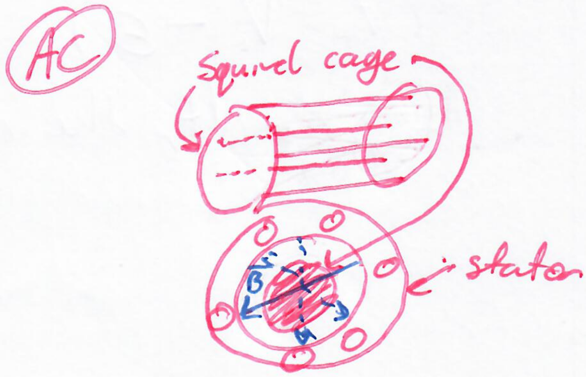
9. Compare the DC motor and the AC induction motor. Include: (6)

- Diagrams of AC and DC motors
- Explanation of the squirrel cage and its function
- Discussion about the differences in how/when they are used

A DC motor uses a coil inside a fixed stator ($\vec{B}$ field) to generate a torque via the motor effect ($\vec{F} = l\vec{I} \times \vec{B}$). As the motor speeds up the changing magnetic flux through the coil induces an emf (ε) which reduces the net Voltage and therefore the net current. This causes there to be a drop in torque as the speed increases.

An AC induction motor uses muti-phase power to create a rotating magnetic field inside the stator. The stator itself is made of multiple coils at an offset from each other such that the AC input induces a rotating B field through a squirrel cage. The changing magnetic flux through the loops of the cage induces a current through the cage. The induced currents flow such that they create a torque which reduces the relative motion of the coil with respect to the field (Lenz's law).
As the motor speeds up, the magnetic flux changes at a decreasing rate, reducing the induced currents ($\varepsilon = -\frac{\Delta \Phi_B}{\Delta t}$)



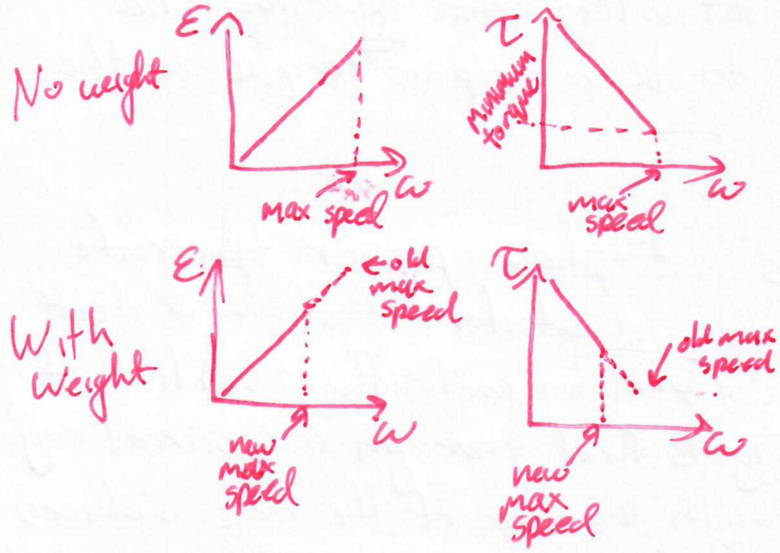


Since DC motors are able to provide much greater torques they are often used in high-power equipment, however the tendency for the commutator to wear out makes them expensive to maintain. Therefore AC motors are far more common in low cost electronics.

10. An electric motor is used to lift a load vertically. As the load is lifted, weights are added to increase the load.

(a) Explain how the rotation speed of the motor changes as the load increase. (2)

As the mass is increased the required torque to overcome gravity increases.
As a motor speeds up an emf is induced which reduces the current, reducing the max torque.



The increase in required minimum torque lowers the maximum speed of the motor

(b) Explain how the current in the coils change as the load increases. (2)

As the load increases, the maximum speed decreases. This reduces the rate of change of emf. This increases the operating voltage
$(V_{op} = V_i - \mathcal{E})$
As a result, the operating current increases.

11. Relate Lenz's Law to the law of conversation of energy and apply the law of conservation of energy to: (3)

- DC Motors
- Magnetic braking

To justify Lenz's law (that a changing magnetic field produces an electric field which, in turn, produces a magnetic field which opposes that change) we can consider the case where the induced B field does not oppose the change.

In this case, the new field would cause the change to increase, thereby increasing the induced field, causing more change, causing a greater field etc.
This would lead to an infinite field and infinite energy through the circuit.
So, to conserve energy, the induced field MUST oppose the change.

This can be seen in motors where the induced current opposes the input current, reducing the torque / work done by the magnetic field.

Similarly the eddy currents induced in a metal disk as it spins past a magnet ($\mathcal{E} = -\frac{\Delta\phi_B}{\Delta t}$) cause the disk to slow down rather than speed up.

12. Evaluate qualitatively the limitations of the ideal transformer model and the strategies used to improve transformer efficiency, including but not limited to: (4)

- Incomplete flux linkage
- Eddy currents and resistive heat production

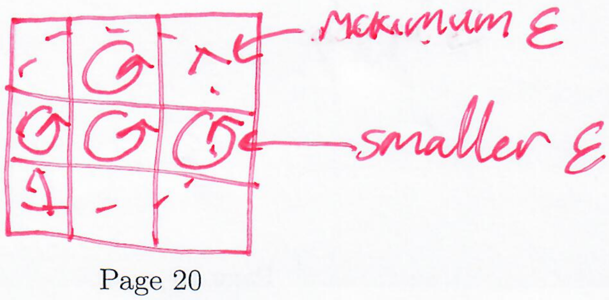
The ideal transformer model assumes that:

- All magnetic field lines produced inside the primary coil are channelled into the secondary coil
- No eddy currents are produced in the core.

In reality some of the B field lines loop outside the core, reducing the induced voltage in the secondary coil from its maximum theoretical value (this is called incomplete flux linkage)

Due to the AC, the B field produced by the primary coil changes with time. This induces eddy currents in the iron core ($\mathcal{E} = -\frac{\Delta \Phi_B}{\Delta t}$). These eddy currents cause energy loss due to heating the core and due to their opposition to the primary coil's field.

The eddy currents can be reduced by lining the core with non-conductive laminations which run perpendicular to the direction of the eddy currents. This reduces the effective area for the changing flux and therefore induces smaller currents.

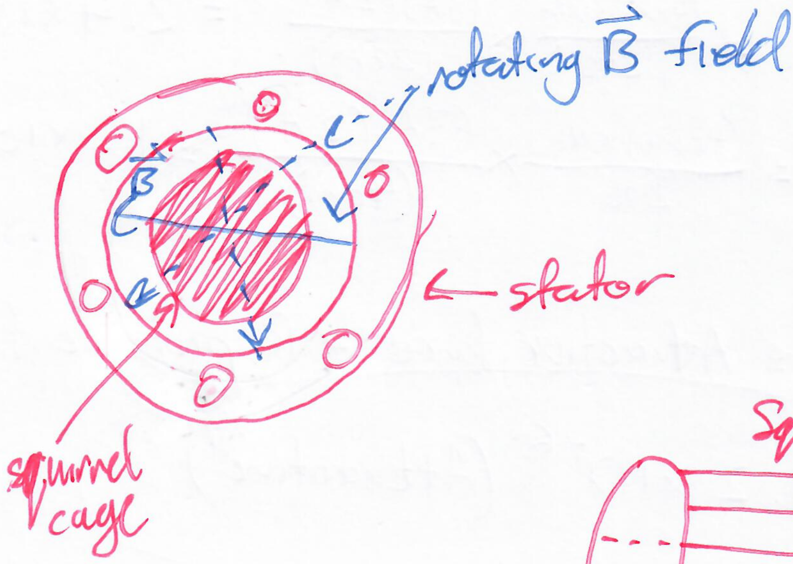


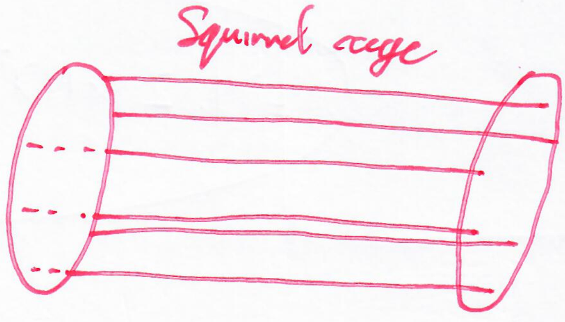
13. Most motors found in the household are AC induction motors. Describe the Physics behind the operation of an AC induction motor. Note a labelled diagram may help your explanation. (3)

An AC induction motor uses a fixed stator which creates a rotating magnetic field inside the coils of a squirrel cage.

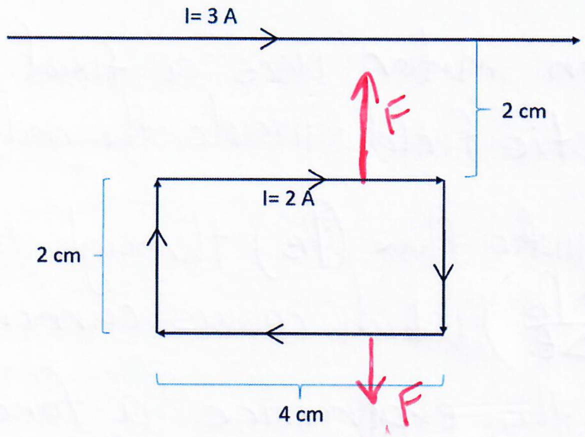
The changing magnetic flux (Φ_B) through the coils induces an emf ($\mathcal{E} = -\frac{\Delta \Phi_B}{\Delta t}$) which causes currents in the coils.

These currents then experience a force due to the magnetic field ($\vec{F} = L\vec{I} \times \vec{B}$), creating a torque ($\vec{\tau} = \vec{r} \times \vec{F}$) which causes the squirrel cage to rotate with the magnetic field.





14. A current carrying wire is near a current carrying loop.



Consider the situation shown in the diagram above where a wire carrying a current of $3A$ is placed near a rigid rectangular loop carrying a current of $2A$ (clockwise). Calculate the net force acting on the wire loop. (You may consider the wire to be parallel to the long side of the rectangle.)

$$\text{Attractive force} = \frac{(4cm)\times \mu_0}{2\pi} \times \frac{(3A)(2A)}{(2cm)} = 2.4\times10^{-6} N$$

$$\text{Repulsive force} = \frac{(4cm)\times \mu_0}{2\pi} \times \frac{(3A)(2A)}{(4cm)} = 1.2\times10^{-6}$$

$$\text{Net force} = \text{Attractive force} - \text{Repulsive force}$$

$$= 1.2\times10^{-6} \text{ (Attractive)}$$

Session 2

The Nature of Light

1. Explain how the model of light has progressed throughout history with reference to: (9)

   - Newton
   - Huygens
   - Young
   - Maxwell
   - Malus
   - Einstein
   - Schrodinger

Newton was the first person to publish a formal theory of light, describing light as a stream of 'corpuscles' (particles) travelling at an infinite speed.

Huygens proposed a wave model of light where he instead modelled it as a sort of ripple in some ever-present field. Linked to this theory were behaviours such as diffraction and refraction, with the only requirement that light have a finite speed.

Young's double slit experiment where he observed diffraction of light confirmed Huygens' theory that light is a wave.

Maxwell extended this theory, explaining what that wave was. He described light as an electromagnetic wave with speed $v = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$ (ε_0 is the resistivity of the electric field to the presence of charges and μ_0 the resistivity of the magnetic field to change)

Malus again gave support for the wave model with his law ($I = I_0 \cos^2\theta$) of polarisation.

Einstein proposed that light could still be modelled as a stream of packets or particles (called photons). This was due to the photo-electric effect where light could only transfer amounts of energy proportional to its frequency ($E = hf$)

Schrödinger extended on both theories, modelling light as a wave of probabilities which interacts with many properties akin to a particle.

2. Describe Maxwell's contribution to the development of the model of light. (3)

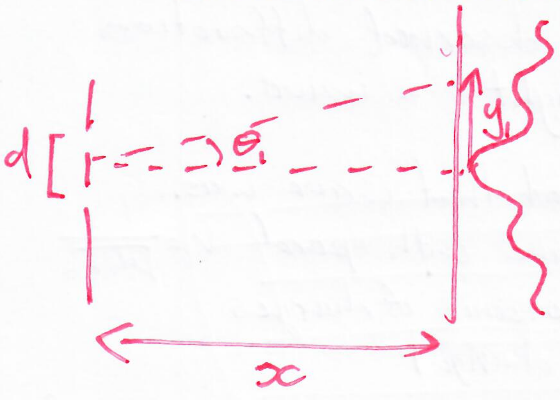
Maxwell's unification of Electromagnetism into 4 key equations allowed him to consider mathematically a situation without any charges or current:

$$\vec{\nabla} \times \vec{E} = -\frac{d\vec{B}}{dt} \qquad \vec{\nabla} \times \vec{B} = \mu_0 \varepsilon_0 \frac{d\vec{E}}{dt}$$

He was then able to show that a solution to these equations was a wave with mutually perpendicular $\vec{E}$ and $\vec{B}$ fields that moved at a speed $V = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}$

This speed was very close to Romer's measurement of lightspeed so it was then reasoned that light must be an electroMagnetic wave.

3. Using the formula for the angular location of a Maxima due to double slit diffraction ($d \sin \theta_m = m\lambda$) derive the formula for the distance of a single maxima from the centre and the distance between two slits.



$$d \sin \theta_m = m\lambda$$

(since θ_m is small $\sin \theta_m \approx \tan \theta_m$)

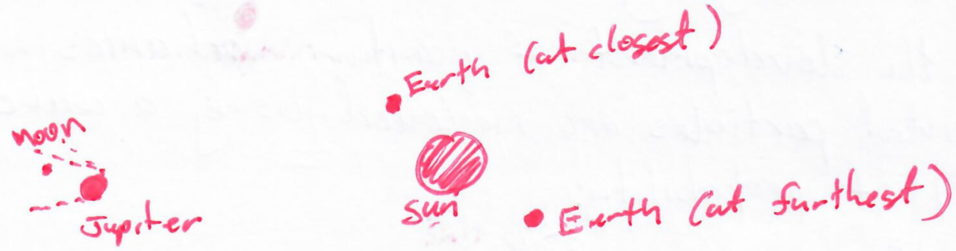
$$\tan \theta_m = \frac{y_m}{x}$$

$$\therefore d \frac{y_m}{x} = m\lambda$$

$$y_m = \frac{m\lambda x}{d}$$

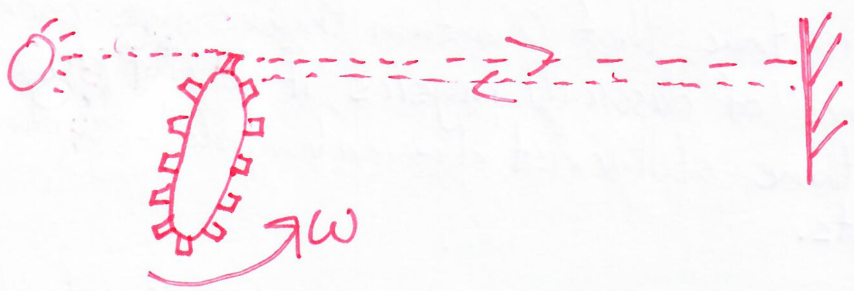
4. Describe TWO historical attempts to measure the sped of light. Include relevant diagrams. (4)

① Romer measured the speed of light by measuring the difference in the observed time of the eclipse of Jupiter's moon. By calculating the maximum difference in time between the eclipses and by assuming the extra distance was due to Earth moving to its opposite location in its orbit around the sun, he measured the speed of light to be $2.2 \times 10^8 ms^{-1}$!



② Fizeau used a spinning toothed wheel to measure the speed of light. By timing pulses of light such that they went through a gap between teeth and reflecting them back over a large distance he could control the amount of time the light had to get back to the sensor before it was blocked by the oncoming tooth.

Fizeau sped up the wheel from rest at fixed intervals and shone light through the gaps until the speed was great enough that the light was blocked by the tooth. In doing so he measured the speed of light to be $3.2 \times 10^8 ms^{-1}$!



5. Discuss the statement: "The limitations of classical physics gave birth to Quantum Physics." (6)

The 'classical model' of physics describes everything as being made of infinitely splittable pieces.
For example, the classical model says that for every length measured, there is always a smaller length you can measure.

However, discoveries such as the finite orbital radii of electrons in atoms and the finite energy of light (which can be modelled as coming in packets) required a theory which described everything as uncuttable.

This led to the development of quantum mechanics where all fundamental particles are modelled using a wave function (ψ) of probability:

$$-\frac{\hbar^2}{2m}\nabla\psi + V\psi = i\hbar\frac{\partial\psi}{\partial t}$$

This model explained the finite orbit of electrons (since waves must have an integer number of wavelengths) and also explained the growing body of evidence that electrons diffract.

Despite this, many classical concepts such as field theories and Gravity have remained unchanged.
Einstein's General Relativity has avoided all attempts to become a quantum theory, with the continuous description of spacetime still giving the most accurate match to experiment.

So while it is true that Quantum Physics was born out of the failures of classical physics, it is not an all encompassing model and there still exist classical models without any apparent faults.

** Alternative answers could include UV catastrophe, LHC / standard model or closer attention to experiments

6. Describe how limitations in the classical model of physics led to the Quantum Model. Discuss with reference to the Photoelectric Effect. (4)

The classical model of light describes it as a continuous electromagnetic wave with some amplitude and frequency.
This model led to four predictions:

① That light could give energy in a continuous manner (i.e. the more time light was shone on something the more energy it would give it).

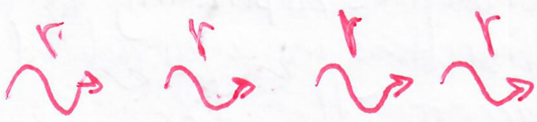
② That the energy in a wave was proportional to its amplitude squared ($P \propto A^2$)

③ That the energy in a wave was proportional to its frequency ($P \propto f$)

④ And that light should be continually emitted by an accelerating charged particle.

Experiments relating to the photoelectric effect revealed that the energy and power output of light was only proportional to its frequency and that the time it was shone on a material did not affect the energy given. (disproving ① and ②). Einstein realised this meant that light must come in discrete 'packets' now called photons, (Contradicting ④) with energy $E = hf$.

This is further supported by Bohr's realisation that light was only emitted at fixed energy amounts with a frequency proportional to that energy. (Further contradicting ④)



A modern model of a light ray as a stream of photons.

7. Describe how the spectra of stars can provide information on FOUR of the star's properties. (4)

① Density → Denser stars have greater gravitational pulls at their surface. This causes them to accumulate denser atmospheres. The denser atmosphere has more atoms in the way of leaving photons which gives them a greater chance of being absorbed. This makes spectral absorption lines darker.

② Surface Temperature → Stars emit light with a peak in brightness at the wavelength $\lambda_{max} = \frac{b}{T}$ (where T is its surface temperature). Therefore the location of the peak in the spectra can tell you its temperature.

③ Chemical Composition → The chemical composition of the atmosphere of a star affects what frequencies are absorbed. Therefore the locations of absorption lines in the spectra can inform us what elements are in its atmosphere.

④ Rotational + Translational Velocity → A star moving in relative motion to Earth will have its spectra doppler shifted. Parts of a star can have different relative velocities depending on the stars rotation, resulting in a gradient of doppler shift accross the star. The total average doppler shift therefore informs us of linear velocity and the gradient informs us of its rotation.

Special Relativity

1. State Einstein's two postulates. (2)

That the laws of physics are the same in all inertial reference frames.

That the speed of light is therefore constant in all inertial reference frames.

2. Relate the speed of light to the fundamental properties of the universe.

ε_0 represents the resistivity to change in the electric field

$\frac{1}{\mu_0}$ represents the proclivity (desire) to change for the magnetic field

The formula for speeds of transverse waves through materials is $v = \sqrt{\frac{T}{\mu}}$ where μ is the density (resistivity to motion) and T is the tension (proclivity for motion) in the material.

$\therefore$ The formula $c = \sqrt{\frac{1}{\mu_0 \varepsilon_0}}$ represents the speed of light as a function of the fundamental properties of the electric and magnetic fields (similar to the tension and density in a material).

3. Analyse and evaluate the evidence for Special Relativity. (4)

Atmospheric Muons → Muons are created when protons from space collide with atoms. The Muons have a maximum lifetime on the order of 10^{-6} s, (as predicted by Quantum Physics), far too short to reach Earth by traditional physics.

Relativistic time-dialation due to the Muon's motion relative to earth extends the lifetime long enough for muons to reach Earth's surface.

From the Muon's perspective the relative motion of the Earth causes the distance between the upper atmosphere and the surface to be length contracted, allowing Earth to hit the Muon. Without these effects muons could not be detected at Earth's surface therefore this confirms both relativistic effects.

Hafele-Keating

→ Hafele and Keating used atomic clocks to measure the effects of special and General Relativity.

The atomic clocks were originally syncronised with clocks on Earth and then taken on a plane flight.

The discrepency between the clocks after the trip was predicted exactly by Relativity* (time dilation) confirming the theory's predictions.

* The experiment actually resulted in a speeding up of the clocks which is predicted by General Relativity (since the plane was further out of Earth's gravitational well). HOWEVER, this is not necessary to mention to get the marks.

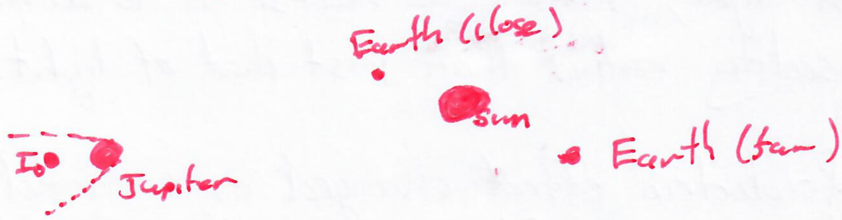
4. How did Einstein's theory of special relativity and his explanation of the photoelectric effect lead to the reconceptualisation of the model of light? (6)

The confirmation of Einstein's theories of relativity confirmed that light had a finite speed which is the same in all reference frames.
The implication of this is that the universe will change all other measurements (including time and distance) to conserve this speed.
The conclusion is, therefore, that the speed of light is actually the maximum speed of information in the universe.
So, in summary, relativity changed our perspective of the speed of light, making us realise it is actually the speed of causality rather than just that of light.

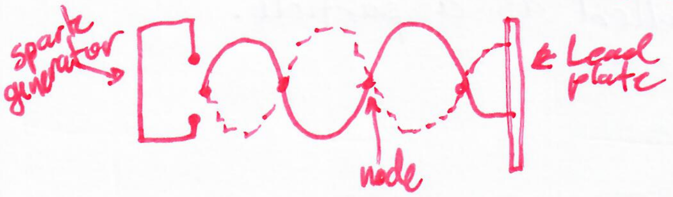
The photoelectric effect changed our model of light from a purely wave model to one of a wave-particle duality.
The realisation that light must deliver energy in discrete amounts forced Einstein to conclude that light is made of individual parts.
This led to the quantisation of light as a particle called a photon. Photons are still waves and have a corresponding wave function, allowing them to diffract, however the photon itself can be modelled as a particle.

5. Describe investigations of historical and contemporary methods used to determine the speed of light. (6)

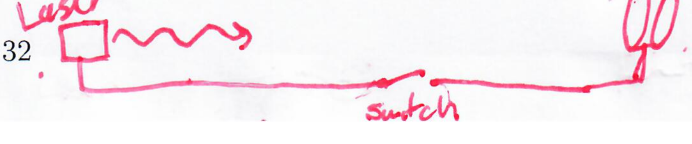
Romer, in measuring the eclipse of Io (Jupiter's moon), noticed that the event happened 22 minutes later at one point in the year and slowly returned to its predicted time over 6 months. He hypothesised that this must be due to the finite speed of light and the extra time it takes for it to cover the diameter of Earth's solar orbit. He used this to measure the speed of light to be $2.2 \times 10^8 ms^{-1}$.



Hertz used Maxwell's prediction that light is an electromagnetic wave to measure the speed using the frequency and wavelength ($v = f\lambda$). He used light of a known frequency in a standing wave pattern. The anti-nodes induced an emf in a coil due to the oscillating B field so the location of nodes was found by measuring where there was no emf ($\epsilon = -\frac{\Delta \phi_B}{\Delta t}$). He used the distance between two nodes as $\frac{\lambda}{2}$ and then measured $v \approx 3.4 \times 10^8 ms^{-1}$.

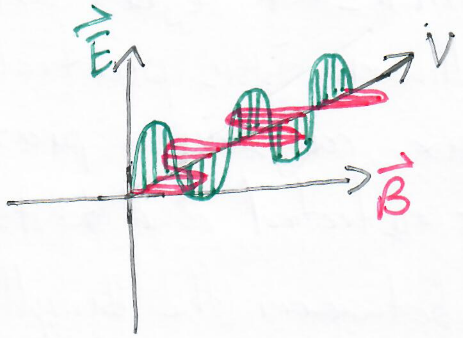


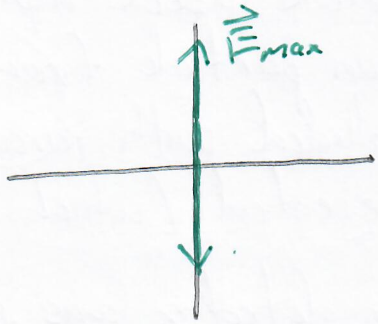
Modern experiments use a button which has an equal amount of wire between it, a laser and a detector. The button simultaneously triggers the laser and the detector and the time taken for the light to reach the detector is measured. Since the speed is measurable to the nearest cm per second, this is used to define a meter where $1m = \frac{c}{3 \times 10^8 s^{-1}}$



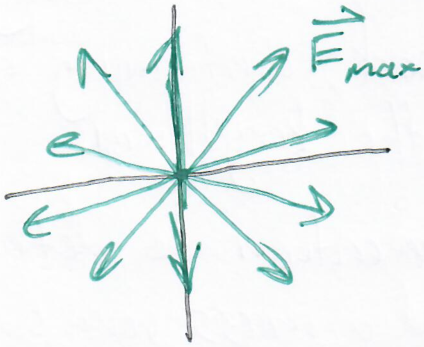
6. With the aid of a diagram, explain the difference between polarised and unpolarised light. (3)

Polarised light has an electric field which oscillates along one axis and a corresponding perpendicular magnetic field.





Unpolarised light has an electric field which oscillates along all axes randomly* (it appears random)



From the Universe to the Atom

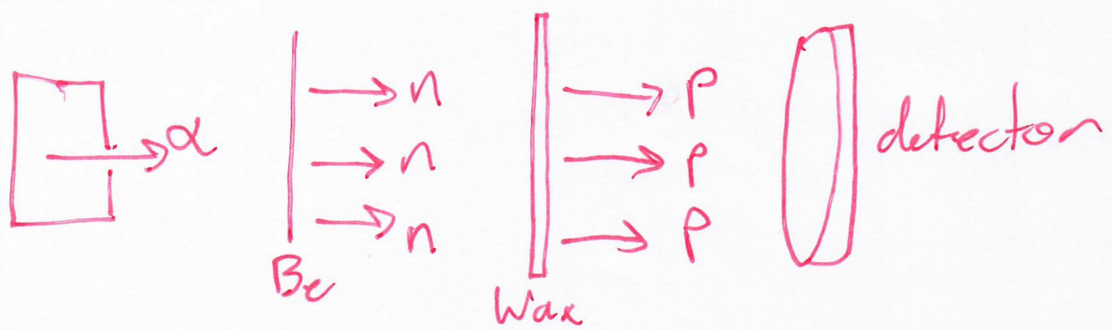
1. Describe the experimental setup Chadwick used to discover the neutron. Include relevant diagrams. (3)

Chadwick used alpha particles to eject an unknown particle from Beryllium. This particle then collided with Paraffin wax, causing a proton to be ejected (which can be detected due to its charge)

When the detector was placed between the beryllium it did not detect anything, confirming the alpha particles were not getting through. and that it had no charge.

By placing a lead block in the way the emission of protons was stopped, confirming a particle was being emitted from the Beryllium.

Using conservation of momentum he determined that this neutral particle had a mass very similar to a proton and reasoned that it must be the theorised neutron.



* For the sake of space I have not discussed Chadwick or drawn diagrams, though I strongly recommend this in an exam.

2. Describe the historical progression of the atom, refer to all key models and the experiments which led to their development. (8)

Dalton was the first to publish a formal theory of the atom and he believed each atom was its own type of 'billiard ball'

Thompson used cathode rays to show that all metal atoms appeared to contain the same negatively charged particle. He did this by using electric and magnetic fields to measure the charge-mass ratio of the ejected particle. From this he created the 'plum pudding' model where the atom is a positively charged 'billiard ball' with negative electrons dispersed throughout.

Geiger and Marsden used alpha particles and fired them at a very thin sheet of Gold foil. Surprising to them was that most particles passed through undeflected, with only a small fraction being deflected but at a large ($\theta > 90^\circ$) angle. From this Rutherford developed the planetary model where the nucleus is a very dense and positively charged, with the light electrons orbiting in the empty space around it. This, however, failed to explain how electrons orbit, since the accelerating electrons should be constantly losing energy as light in a continuous spectra.

Bohr used the discrete spectra of atoms to develop a theory of the atom where electrons orbit at fixed orbits with $mvr = \frac{nh}{2\pi}$. This provided a logical explanation for atomic spectra, (with mathematical support for single electron atoms provided by experiment) though he could not explain why this was true.

de Broglie took Einstein's idea of light being both a particle and a wave and applied it to the electron. de Broglie was able to show that if the electron were a standing wave wrapped around the nucleus, it must have fixed orbits for the wave to be continuous (i.e. have n ($n \in \mathbb{Z}^+$) wavelengths).

The evidence for single electrons diffracting when passing through a double slit provided evidence for a wave model and allowed Schrödinger to develop his probability wave model of the electron. This led to the modern model of the atom where there is a dense nucleus of protons and neutrons with a 'cloud' of electrons around it (where the clouds represent probability densities).

3. Outline the properties of a Proton and its constituent parts and the resulting interactions that the proton can partake in. (6)

A proton is made of three Quarks:

Proton

Quarks have electric charge and can therefore interact via the electromagnetic force. This force is mediated by the exchange of photons.

Quarks have colour charge and can therefore interact via the strong force. this force is mediated by the exchange of gluons.

As a result of this, protons can also trade quarks with other protons or neutrons through the nuclear interaction. This creates an attractive force about 100x stronger than electromagnetic repulsion between protons inside the nucleus.

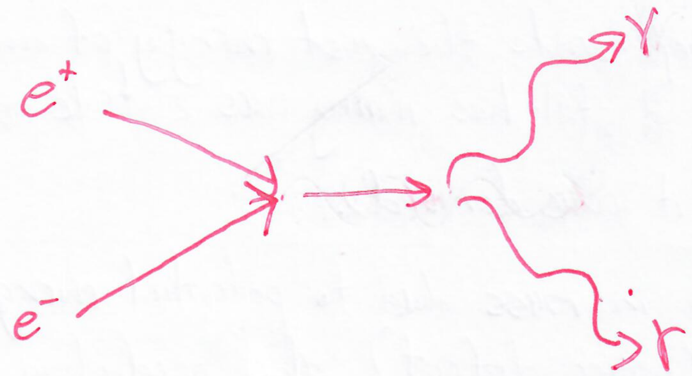
Quarks can also interact via the weak force which results in a change of flavour of the quarks. This force is mediated by W^+, W^- and Z^0 bosons.

Last of all, quarks and the gluon fields between them has mass. This allows the proton to participate in gravitation attraction.

4. If an electron and positron each moving at speed $0.25c$ and with kinetic energy $E_k = \frac{1}{32} m_e c^2$ annihilate, calculate the total energy of the released photons. ($E = mc^2$ gives intrinsic rest energy)

$$E_{e^-} = m_e c^2 + \frac{1}{32} m_e c^2 \quad \text{(rest + kinetic energy)}$$

$$E_{e^+} = m_e c^2 + \frac{1}{32} m_e c^2$$



Since the particles are annihilated all energy is converted.

$$\Delta E = E_{e^-} + E_{e^+} = 2\left(m_e c^2 + \frac{1}{32} m_e c^2\right)$$

$$\approx 1.69 \times 10^{-13} \text{ J}$$

5. One of the most important equations in Physics is $E = mc^2$. Justify this statement. (7)

From NESA:

Answers could include:

The equivalence of mass and energy, as summarised in Einstein's $E = mc^2$, is a hugely important concept in physics and helps to explain a range of phenomena and concepts such as:

- nuclear fission and nuclear fusion processes, and the common source of their energy output
- binding energy and mass defect, where apparently 'missing mass' goes
- radioactive decay and the energy associated with it
- mass dilation of objects approaching the speed of light
- nuclear bombs and nuclear reactors, as the fundamental principle upon which they operate
- processes which explain the sources of energy in stars, through nuclear fusion and mass transforming into energy
- processes which allow us to further investigate the structure of matter through particle accelerators, through the high energies of collisions transforming into a range of short-lived particles.

$E = mc^2$ therefore is justified in being called one of the most important equations in physics, as it plays a fundamental role in a range of fields that make up our current understanding and application of physics. Other 'famous' equations like Newton's Universal Law of Gravity do not have the same breadth of impact. Maxwell's equations as a group perhaps have a similar impact as $E = mc^2$, however, the single equation $E = mc^2$ can be considered as one of the most important equations in physics.

6. Describe THREE fusion processes used by stars. Include relevant equations and diagrams where they are useful.

Proton - Proton

① $^{1}_{1}H + ^{1}_{1}H \rightarrow ^{2}_{1}H + ^{0}_{1}e^{+} + ^{0}_{0}\nu_e$

② $^{2}_{1}H + ^{1}_{1}H \rightarrow ^{3}_{2}He + ^{0}_{0}\gamma$

③ $^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + 2\,^{1}_{1}H$

The proton-proton chain combines 4 Hydrogen nuclei ($^{1}_{1}H$) into Helium ($^{4}_{2}He$)

CNO

① $^{12}_{6}C + ^{1}_{1}H \rightarrow ^{13}_{7}N + ^{0}_{0}\gamma$

② $^{13}_{7}N \rightarrow ^{13}_{6}C + ^{0}_{1}e^{+} + ^{0}_{0}\nu_e$

③ $^{13}_{6}C + ^{1}_{1}H \rightarrow ^{14}_{7}N + ^{0}_{0}\gamma$

④ $^{14}_{7}N + ^{1}_{1}H \rightarrow ^{15}_{8}O + ^{0}_{0}\gamma$

⑤ $^{15}_{8}O \rightarrow ^{15}_{7}N + ^{0}_{1}e^{+} + ^{0}_{0}\nu_e$

⑥ $^{15}_{7}N + ^{1}_{1}H \rightarrow ^{12}_{6}C + ^{4}_{2}He$

The CNO cycle uses carbon-12 as a catylist to fuse 4 Hydrogen ($^{1}_{1}H$) nuclei into Helium-4 ($^{4}_{2}He$)

Triple α

① $^{4}_{2}He + ^{4}_{2}He \rightarrow ^{8}_{4}Be + ^{0}_{0}\gamma$

② $^{8}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + ^{0}_{0}\gamma$

This process fuses three Helium-4 nuclei ($^{4}_{2}He$) into carbon-12 ($^{12}_{6}C$)

7. Explain FOUR requirements necessary for a controlled fission chain reaction of Uranium-235 to be sustained. (4)

1. Enrichment

- enrichment is the process of increasing the proportion of required molecules within the reaction vessel, thus increasing the chance of a favourable reaction and collision between a neutron and a U-235 neutron.

2. Moderator

- the moderator is a material rich in nuclides that have slightly large masses than neutrons. The moderator decreases the kinetic energy of the U-235 neutron to increase the probability of collision and reaction with a U-235 nucleus and not a U-238 nucleus.

3. Reactor vessel

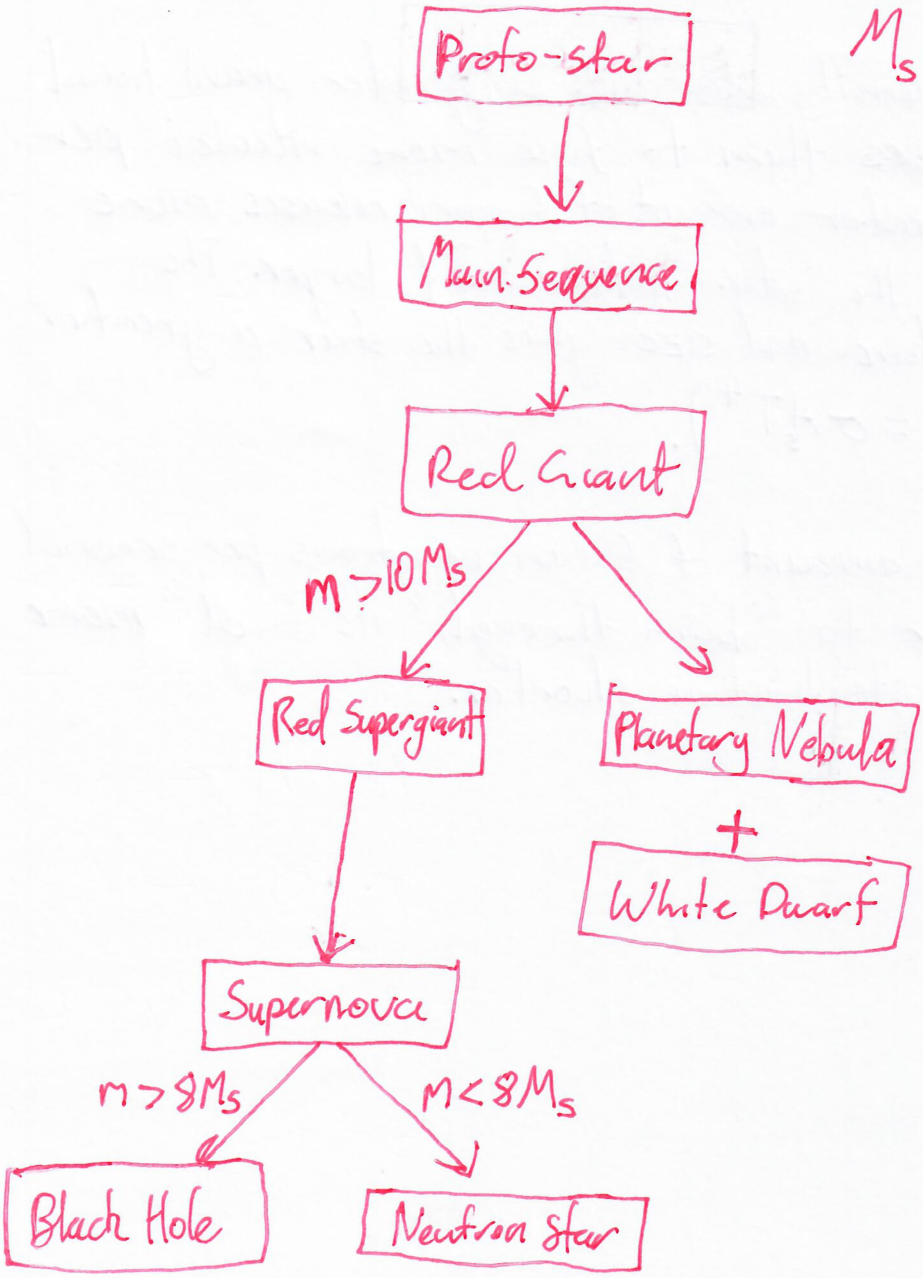
- the reactor vessel is the container in which the fission reaction takes place. There is a requirement for the vessel to have a particular surface area-to-volume ratio for an ideal reaction rate and the interior surface often has a high-nucleon-number material to readily reflected back into the sample.

4. Control rods

- control rods are a material, such as boron-10, cadmium, that absorbs neutrons which slow the rate of reaction when inserted, thus controlling the reaction if it threatens to "run away" to equalise the number of neutrons produced with the number of fission-producing neutrons.

8. Draw a flow chart to outline the various lifecycles of stars.

M_s = mass of sun



9. Describe the relationship between the masses of main sequence stars, their luminosities and lifetimes. (3)

A large mass/density star has a greater gravitational pull. This causes them to fuse more nuclei per second. The greater amount of fusion releases more energy, making the star hotter and larger. The greater temperature and size gives the star a greater luminosity ($L = \sigma A_s T^4$).

But the greater amount of fusion reactions per second causes the star to "burn through" its "fuel" more quickly, making its lifetime shorter.