IBO IB DIPLOMA PROGRAMME
PROGRAMME DU DIPLÔME DU BI
PROGRAMA DEL DIPLOMA DEL BI

PHYSICS
HIGHER LEVEL
PAPER 3

Candidate number

Wednesday 12 November 2003 (morning)

1 hour 15 minutes

INSTRUCTIONS TO CANDIDATES

- Write your candidate number in the box above.
- Do not open this examination paper until instructed to do so.
- Answer all of the questions from two of the Options in the spaces provided. You may continue your answers on answer sheets. Write your candidate number on each answer sheet, and attach them to this examination paper and your cover sheet using the tag provided.
- At the end of the examination, indicate the letters of the Options answered in the candidate box on your cover sheet and indicate the number of answer sheets used in the appropriate box on your cover sheet.

OPTION D — BIOMEDICAL PHYSICS

D1. This question is about scaling.

(a) There is a very large variation in the size of different land mammals. They vary from about 2 cm to 4 m in length.

(i) Estimate the ratio

$$\frac{\text{rate of energy loss per unit mass from the smallest land mammal}}{\text{rate of energy loss per unit mass from the largest land mammal}}.$$ *[4]*

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(ii) State **one** assumption that you have made in your estimation. *[1]*

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(b) State, and explain, **one** reason why no land mammals are found in nature that are

(i) smaller than about 2 cm in length. *[2]*

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(ii) larger than about 4 m in length. *[2]*

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D2. This question is about the hearing abilities of two different people, where one is much older than the other.

Carmen is just able to hear a sound of frequency 1000 Hz when its intensity is 10^{-12} W m^{-2}. Her grandfather, Jorge, cannot hear this sound frequency until its intensity is increased to 10^{-6} W m^{-2}.

(a) Determine the ratio

$$\frac{\textbf{amplitude} \text{ of the sound wave just heard by Carmen}}{\textbf{amplitude} \text{ of the sound wave just heard by Jorge}}.$$ *[2]*

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(b) Determine Jorge's hearing loss in dB at this frequency compared with Carmen. *[2]*

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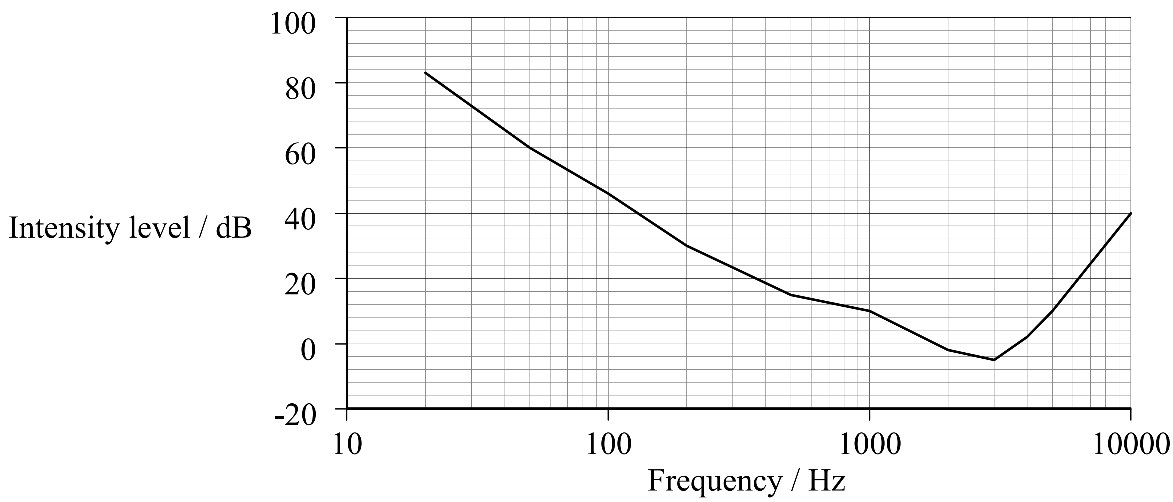
The graph below shows the threshold of hearing for Carmen as a function of frequency.



(c) Using the data from the graph, state and explain the frequency to which Carmen's ear is most sensitive. *[2]*

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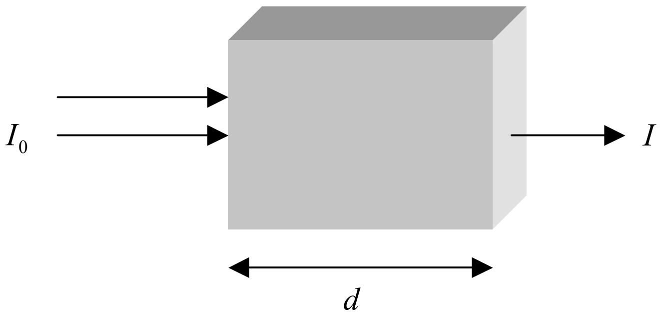
(d) Using your answer to (b), mark on the graph Jorge's threshold of hearing at a frequency of 1000 Hz. *[1]*

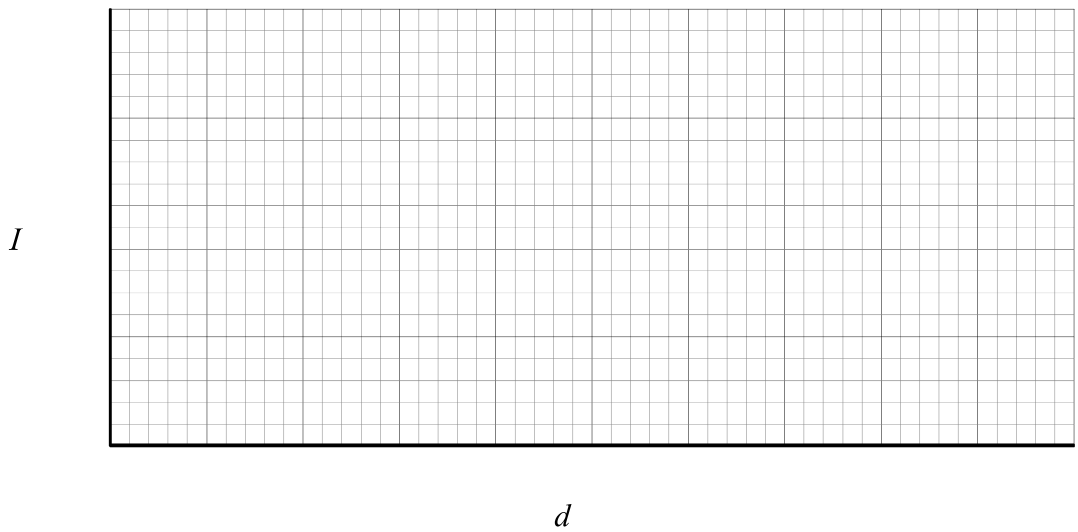
D3. This question is about X-rays.

When an X-ray beam passes through matter, the beam is attenuated.

The diagram below shows a parallel beam of X-rays of intensity I_0 entering a sample of material of thickness *d*. The intensity of the emergent beam is *I*.



(a) Using the grid below, sketch a graph to show the variation with thickness *d* of the intensity *I*. *[2]*



The attenuation of X-rays depends not only on the nature of the material through which they travel but also on the photon energy. For photons with energy of about 30 keV, the *half-value thickness* of muscle is about 50 mm and for photons of energy 5 keV, it is about 10 mm.

(b) Explain which photon energy would be most suitable for obtaining a sharp picture of a broken leg. *[2]*

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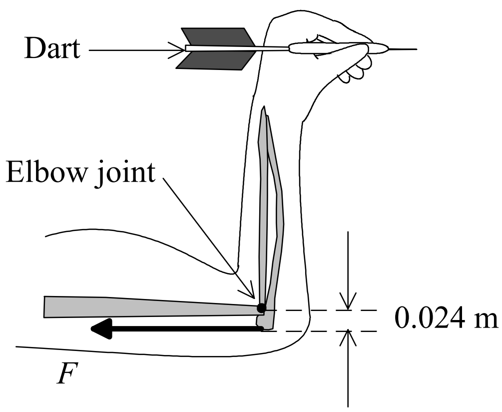
D4. This question is about the forces acting on the forearm while throwing a dart.

The following diagram shows the human arm with the forearm raised and about to throw a dart. The forearm behaves like a lever that can rotate about an axis through the elbow joint.



(a) The line of action of the force F exerted by the muscles is horizontal and acts 0.024 m from the elbow joint. At the start of a throw, the arm is vertical. A moment of 12 N m is exerted about the elbow joint. Calculate the magnitude of force F. *[2]*

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(b) This design for the forearm acts at a mechanical disadvantage, as the force F is much larger than the weight of the whole arm and dart. Describe and explain what **advantages** result from this design for the forearm. *[3]*

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D5. This question is about the biological effectiveness of radiation.

(a) Explain the term *quality factor (relative biological effectiveness).* *[1]*

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(b) A beam of protons is directed at a tumour of mass 0.015 kg. In order to kill the tumour, a dose equivalent of 240 J kg^{-1} is required.

Using the data below, determine the exposure time, assuming all the incident protons are absorbed within the tumour.

Energy of each proton = 4.0 MeV.
Number of protons incident on the tumour per second = 1.8×10^{10}.
Quality factor for protons of this energy = 14. *[4]*

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OPTION E — THE HISTORY AND DEVELOPMENT OF PHYSICS

E1. This question is about Newton's contribution to understanding the motion of heavenly bodies.

Newton believed that the nature of the force that causes the acceleration of objects close to the surface of the Earth was the same as that of the force that keeps the Moon in orbit about the Earth. To support his argument, he assumed that the force F exerted by the Earth on an object distance R from the centre of the Earth may be expressed as

$$F = \frac{K}{R^2}$$

where K is a constant.

(a) The distance from the centre of the Moon to the centre of the Earth is about $60R_E$ where R_E is the radius of the Earth.

(i) Use the above expression to estimate the acceleration of the Moon in orbit about the Earth (the acceleration due to gravity at the surface of the Earth $g = 10\ \text{m}\,\text{s}^{-2}$). *[4]*

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(This question continues on the following page)

(Question E1 continued)

The acceleration of the Moon in orbit may also be determined from the following data.

orbital period of the Moon $= 2.4 \times 10^6$ s
radius of the Earth $= 6.4 \times 10^6$ m

(ii) Use the above data to calculate the acceleration of the Moon. *[4]*

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(iii) In view of your answers to (i) and (ii), explain whether Newton was correct in his assumption about the nature of the force that causes the acceleration of objects close to the surface of the Earth being the same as that of the force that keeps the Moon in orbit about the Earth. *[1]*

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(b) Newton proposed that the force law $F = \frac{K}{R^2}$ is a universal force law. Explain what is meant by *universal* in this context. *[2]*

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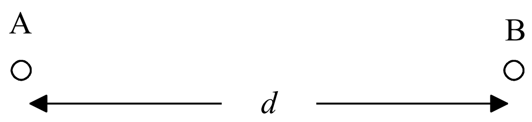
E2. This question is about the experimental verification of Coulomb's law.

A small metal sphere A is given a charge $+Q$. It is then brought into contact with an identical, uncharged metal sphere B. The two spheres are then held at a distance d apart as shown below.



The distance d is much greater than the radius of the spheres.

(a) Assuming that the spheres are isolated from any other charges, write down an expression for the electrostatic force F on either sphere. *[1]*

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Sphere B is now discharged and once more brought into contact with sphere A after which the spheres are again held at a distance d apart.

(b) Write down an expression, in terms of F, for the new electrostatic force on either sphere. *[1]*

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(c) State why the answers you have given in (a) and (b) depend on the fact that d is much greater than the radius of the spheres. *[1]*

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(d) Outline how the above procedure enabled Coulomb to establish that the force between two point charges is proportional to the product of their magnitudes. *[2]*

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(This question continues on the following page)

(Question E2 continued)

(e) Describe briefly, with the aid of a diagram, how Coulomb was able to measure the electrostatic force between two small, charged metal spheres. *[4]*

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E3. This question is about the Bohr model of the hydrogen atom and the Heisenberg uncertainty principle.

(a) A postulate of the Bohr model of the hydrogen atom is that the electron revolves about the proton in stable, circular orbits. State **two** other postulates of the Bohr model. *[2]*

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In the n^{th} energy state, the hydrogen atom has energy E_n and the electron orbits with speed v_n in an orbit of radius r_n. E_n, r_n and v_n are given by the following relationships.

$$E_n = -\frac{13.606}{n^2}\ \text{eV}$$

$$r_n = 0.0529n^2\ \text{nm}$$

$$v_n = \frac{2.19\times10^6}{n}\ \text{m s}^{-1}$$

(b) Apply the expressions above, to hydrogen in its ground state, to determine the ground state energy, the radius of the electron orbit and the electron speed. *[2]*

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(Question E3 continued)

(c) According to the Schrödinger model, the position and the speed of an electron are not well defined. It can be assumed that the uncertainty in the position of the electron in a hydrogen atom is equal to the radius of the electron orbit in the $n = 1$ state.

(i) Apply the Heisenberg uncertainty principle to hydrogen in this state to show that the **uncertainty** in the speed of the electron is approximately equal to the electron speed as calculated in (b). *[3]*

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(ii) Explain why the result in (i) above suggests that the idea of electron orbits, as used in the Bohr model, is a poor one. *[3]*

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OPTION F — ASTROPHYSICS

F1. This question is about some facts regarding some of the planets in the Solar system.

Four of the planets in the Solar system are Jupiter, Earth, Mars and Pluto.

(a) List these four planets in order of increasing distance from the Sun. *[2]*

	→		→		→	

nearest → furthest

increasing distance from Sun

(b) List these four planets in order of increasing diameter. *[2]*

	→		→		→	

smallest → largest

increasing diameter

F2. This question is about some of the properties of Barnard's star.

Barnard's star, in the constellation Ophiuchus, has a *parallax angle* of 0.549 arc-second as measured from Earth.

(a) With the aid of a suitable diagram, explain what is meant by *parallax angle* and outline how it is measured. *[6]*

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(b) Deduce that the distance of Barnard's star from the Sun is 5.94 ly. *[2]*

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(Question F2 continued)

(c) The ratio $\frac{\text{apparent brightness of Barnard's star}}{\text{apparent brightness of the Sun}}$ is 2.6×10^{-14}.

(i) Define the term *apparent brightness*. *[2]*

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(ii) Determine the value of the ratio $\frac{\text{luminosity of Barnard's star}}{\text{luminosity of the Sun}}$ *[4]*

$(1 \text{ ly} = 6.3 \times 10^4 \text{ AU})$.

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(d) The surface temperature of Barnard's star is about 3 500 K. Using this information and information about its luminosity, explain why Barnard's star cannot be

(i) a white dwarf. *[1]*

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(ii) a red giant. *[1]*

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F3. This question is about the evolution of stars.

(a) Outline the process that provides the source of energy for stars while on the main sequence. *[2]*

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(b) State the conditions required for the above process to take place. *[1]*

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(c) State the reason why stars leave the main sequence. *[1]*

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(Question F3 continued)

(d) Main sequence stars eventually evolve to form red giants. With reference to the Chandrasekhar limit, describe and distinguish between the **subsequent** evolutionary paths of **red giant** stars that have evolved from main sequence stars of mass

(i) about two times that of the Sun. *[3]*

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(ii) about ten times that of the Sun. *[3]*

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OPTION G — RELATIVITY

G1. This question is about evidence to support the Special Theory of Relativity and relativistic mass increase.

The following is an extract from an article on Relativity.

> *"…The **proper length** of an object and the **proper time** interval between events can never be measured directly by the same **inertial observer**."*

(a) Define the following terms.

(i) *Proper length* *[1]*

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(ii) *Proper time* *[1]*

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(iii) *Inertial observer* *[1]*

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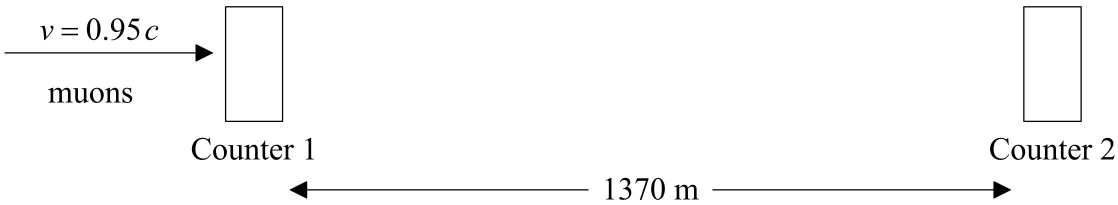
(Question G1 continued)

An experiment is set-up in which muons are accelerated to a speed of 0.95 c, as measured by a laboratory observer. They are counted by the particle counter 1 and the muons that do not decay are counted by counter 2, a distance 1370 m from counter 1 as shown below.



N muons pass through counter 1 in a given time and $\frac{N}{2}$ pass through counter 2 in the same given time.

(b) Determine

(i) the half-life of the muons as measured by a laboratory observer. *[2]*

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(ii) the half-life of the muons as measured in the reference frame in which the muons are at rest. *[2]*

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(iii) the separation of the counters as determined in the reference frame in which the muons are at rest. *[1]*

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(c) Use your answers in (b) to explain what is meant by the terms *time dilation* and *length contraction*. *[4]*

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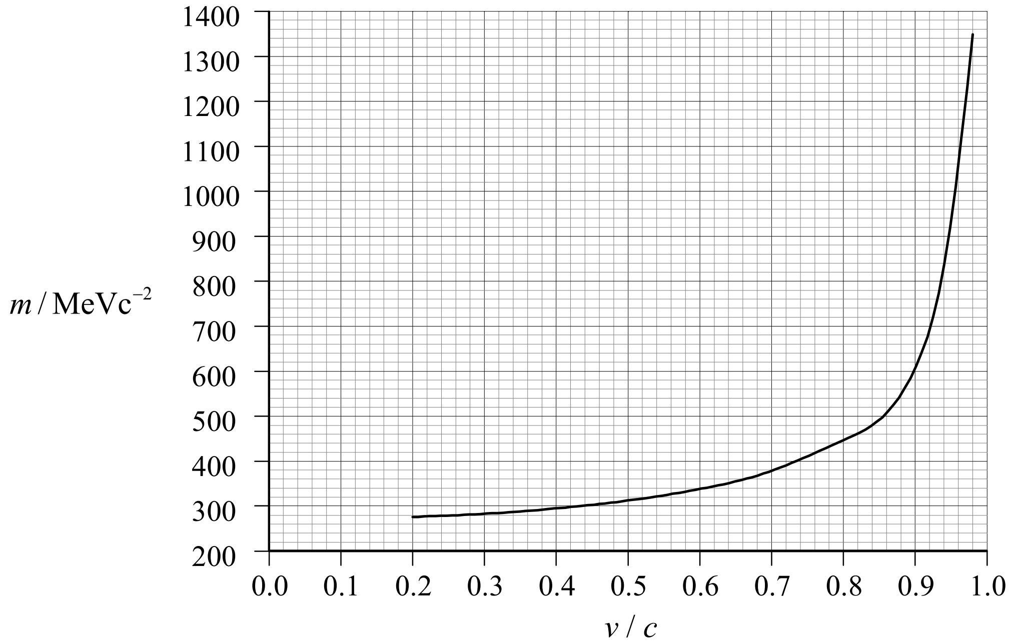
(Question G1 continued)

A muon has a mass m when its speed is v as measured in the laboratory reference frame. The graph below shows the variation with ratio $\frac{v}{c}$ of the mass m. The rest mass of the muon is m_0.



(d) (i) Write down an equation for the above curve. *[1]*

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(ii) Use this equation to explain why a muon can never attain the speed of light. *[2]*

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(e) Use the graph above to determine

(i) the rest mass of a muon. *[1]*

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(ii) the mass of a muon when it is moving with speed of 0.95 c. *[1]*

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(This question continues on the following page)

(Question G1 continued)

(f) State the total energy in MeV of a muon when it has a speed of 0.95 c. *[1]*

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(g) The charge on a muon is -1.6×10^{-19} C. Calculate the potential difference through which the muon must be accelerated in order to attain a speed of 0.95 c. *[2]*

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G2. This question is about the equivalence principle.

(a) In a famous "thought experiment" relating to general relativity, Einstein considered a "spaceship" in a gravity-free region of space accelerating uniformly with respect to an inertial observer, in a direction perpendicular to its "base". A narrow beam of light is initially directed parallel to the base. The diagrams below show this situation.

Diagram 1: View with respect to the inertial observer

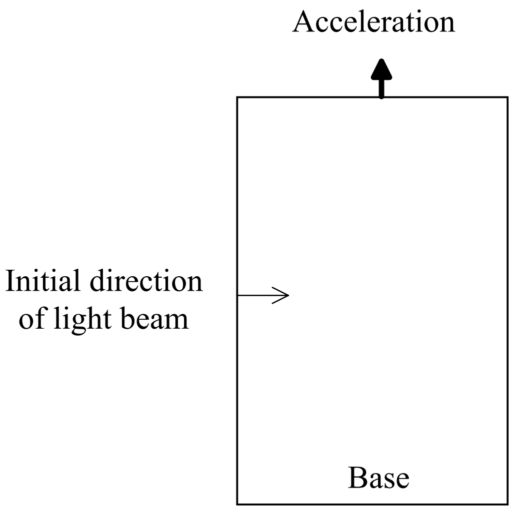
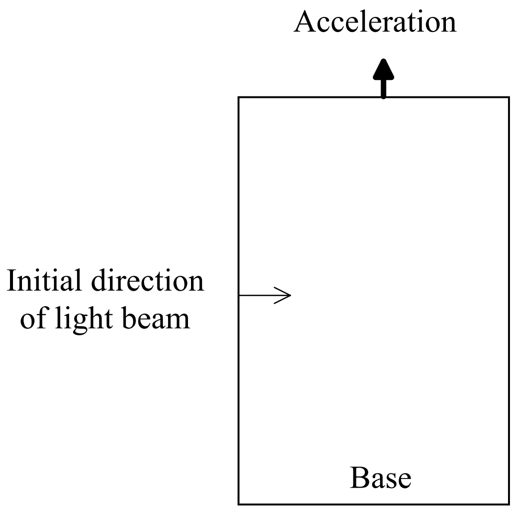


Diagram 2: View with respect to the observer in the spaceship



(i) Draw on **Diagram 1**, the path taken by the light beam as observed by an inertial observer. *[1]*

(ii) Draw on **Diagram 2**, the path taken by the light beam as observed from within the space ship. *[1]*

(iii) Explain the shape of the paths you have drawn. *[3]*

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(b) Explain how this "thought experiment" relates to the equivalence principle. *[2]*

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G3. The total energy of a particle is always given by $E = mc^2$. Calculate the speed at which a particle is travelling if its total energy is equal to three times its rest mass energy. *[3]*

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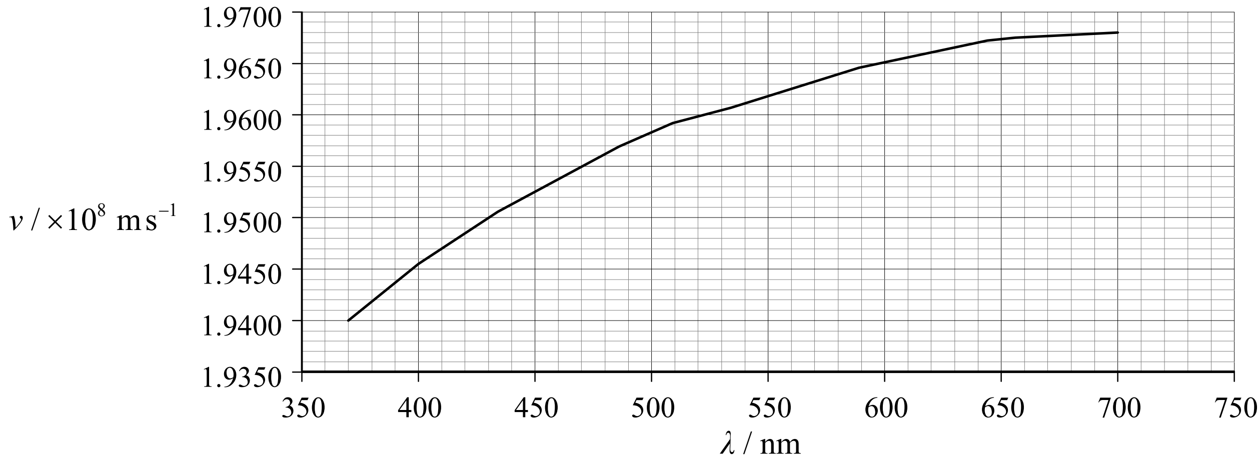
OPTION H — OPTICS

H1. This question is about optical dispersion.

The graph below shows the variation with wavelength λ of the speed v of light in one type of glass.



(a) Use data from the graph to determine, to the correct number of significant digits, the refractive index for blue light of wavelength 400 nm in this type of glass (free space speed of light $c = 2.9979 \times 10^8\ \text{m s}^{-1}$). *[2]*

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(b) The refractive index of red light of wavelength 650 nm in this type of glass is about 1.52. Use this fact and your answer in (a) to explain optical dispersion. *[2]*

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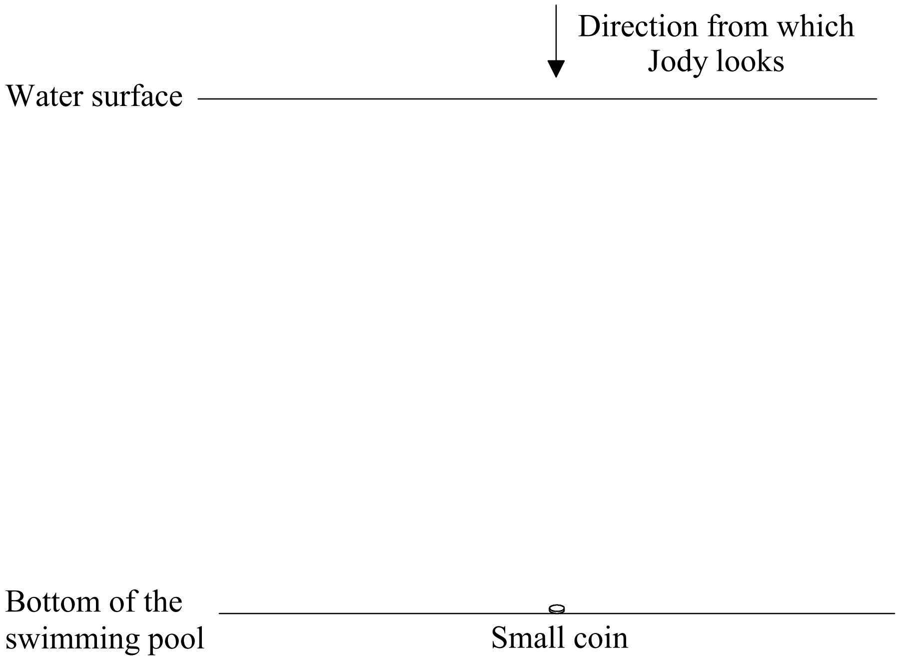
H2. This question is about real and apparent depth.

Jody looks straight down on to the surface of the water in a swimming pool. A small coin is lying on the bottom of the swimming pool. The situation is represented in the diagram below.



(a) On the diagram above, draw appropriate rays to show the position of the image of the coin as seen by Jody. *[2]*

(b) Explain whether the image that Jody observes is real **or** virtual. *[1]*

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The real depth d and the apparent depth a are related by the expression $\frac{d}{a} = n$ where n is the refractive index of the water.

The refractive index of the water in the swimming pool is 1.3 and the coin is at a depth of 3.0 m.

(c) Determine the position of the image, relative to the bottom of the pool, as observed by Jody. *[3]*

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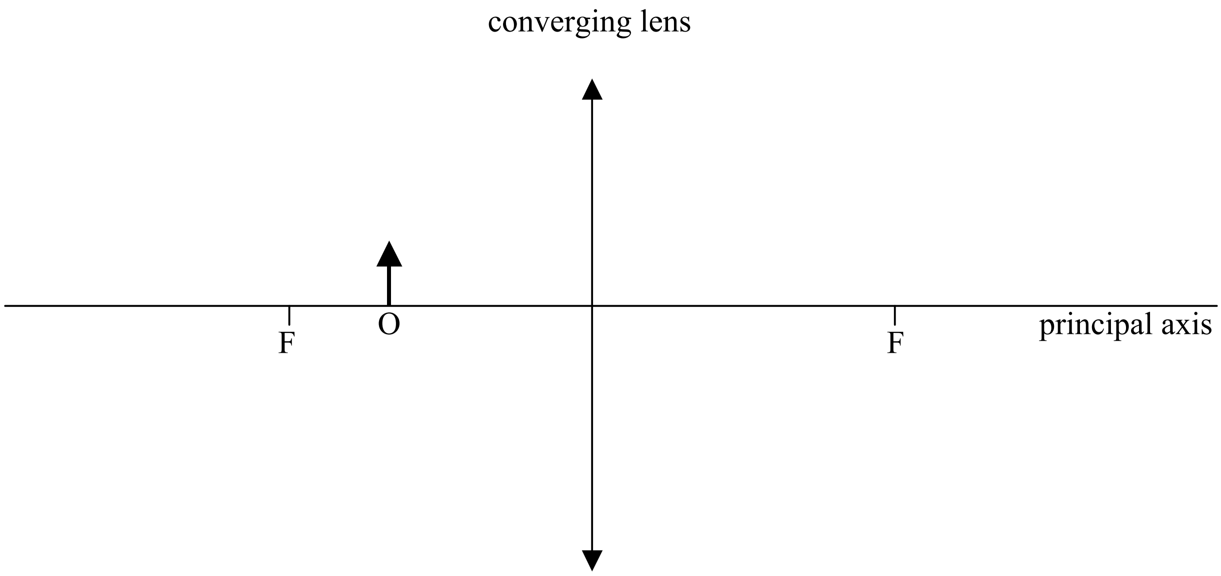
H3. This question is about the simple magnifying glass.

An object O is placed in front of a converging lens in the position shown in the diagram below. The principal foci of the lens are marked F.



(a) On the diagram,

(i) construct rays to locate the position of the image. *[1]*

(ii) draw in the image and label it I. *[1]*

(iii) show on the diagram where the eye must be placed in order to view this image. *[1]*

(This question continues on the following page)

(Question H3 continued)

For a particular lens, the focal length is 10.0 cm and the distance of O from the lens is such that the image is formed at the *near point* of the eye. The distance of the lens from the eye is 3.0 cm.

(b) (i) Explain what is meant by the term *near point*. *[1]*

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(ii) Calculate the distance of the object from the lens if the near point is 25.0 cm from the eye. *[4]*

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(iii) State, and explain, where the object should be placed if the image is to be formed at the *far point*. *[2]*

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H4. This question is about the formation of coloured fringes when white light is reflected from thin films.

(a) Name the wave phenomenon that is responsible for the formation of regions of different colour when white light is reflected from a thin film of oil floating on water. *[1]*

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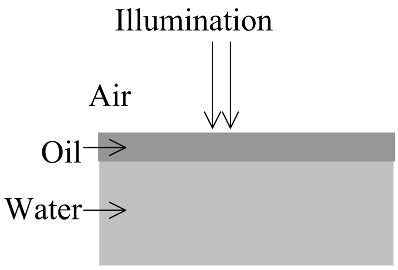
(b) A film of oil of refractive index 1.45 floats on a layer of water of refractive index 1.33 and is illuminated by white light at normal incidence.



When viewed at near normal incidence a particular region of the film looks red, with an average wavelength of about 650 nm. An equation relating this dominant average wavelength λ, to the minimum film thickness of the region t, is $\lambda = 4nt$.

(i) State what property n measures and explain why it enters into the equation. *[2]*

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(ii) Calculate the minimum film thickness. *[1]*

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(This question continues on the following page)

(Question H4 continued)

(iii) Describe the change to the conditions for reflection that would result if the oil film was spread over a flat sheet of glass of refractive index 1.76, rather than floating on water. *[2]*

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H5. This question is about resolution.

(a) State the name of the wave phenomenon that limits the resolution of any optical instrument. *[1]*

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(b) Explain with the aid of a diagram, the Rayleigh criterion. *[3]*

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