SL Paper 3

Observer A detects the creation (event 1) and decay (event 2) of a nuclear particle. After creation, the particle moves at a constant speed relative to A.

As measured by A, the distance between the events is 15 m and the time between the events is 9.0×10^{-8} s.

Observer B moves with the particle.

For event 1 and event 2,

a. Explain what is meant by the statement that the spacetime interval is an invariant quantity. [1]

b.i. calculate the spacetime interval. [1]

b.ii. determine the time between them according to observer B. [2]

c. Outline why the observed times are different for A and B. [1]

Markscheme

a. quantity that is the same/constant in all inertial frames

[1 mark]

b.i. spacetime interval = $27^2 - 15^2 = 504$ «m^2»

[1 mark]

b.ii. ***ALTERNATIVE 1***

Evidence of $x' = 0$

t' «$\frac{\sqrt{504}}{c}$» = 7.5×10^{-8} «s»

ALTERNATIVE 2

$\gamma = 1.2$

t' «= $\frac{9 \times 10^{-8}}{1.2}$» = 7.5×10^{-8} «s»

[2 marks]

c. observer B measures the proper time and this is the shortest time measured

OR

time dilation occurs «for B's journey» according to A

OR

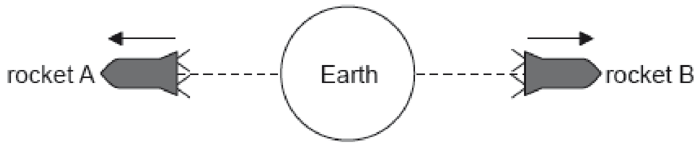
observer B is stationary relative to the particle, observer A is not

[1 mark]

Examiners report

a. [N/A]
b.i. [N/A]
b.ii. [N/A]
c. [N/A]

Rocket A and rocket B are travelling in opposite directions from the Earth along the same straight line.



In the reference frame of the Earth, the speed of rocket A is 0.75*c* and the speed of rocket B is 0.50*c*.

a.i. Calculate, for the reference frame of rocket A, the speed of rocket B according to the Galilean transformation. [1]

a.ii. Calculate, for the reference frame of rocket A, the speed of rocket B according to the Lorentz transformation. [2]

b. Outline, with reference to special relativity, which of your calculations in (a) is more likely to be valid. [1]

Markscheme

a.i. 1.25*c*

[1 mark]

a.ii. ***ALTERNATIVE 1***

$u' = \frac{(0.50+0.75)}{1+0.5\times0.75}c$

0.91*c*

ALTERNATIVE 2

$u' = \frac{-0.50-0.75}{1-(-0.5\times0.75)}c$

–0.91*c*

[2 marks]

b. nothing can travel faster than the speed of light (therefore (a)(ii) is the valid answer)

OWTTE

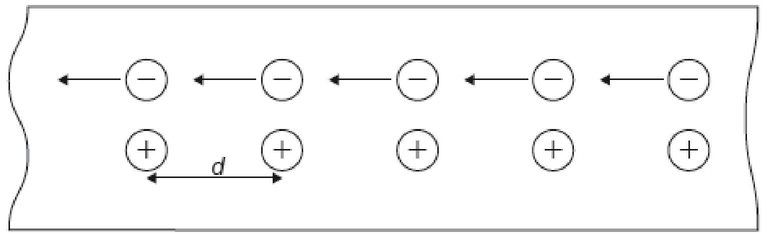
[1 mark]

Examiners report

a.i. [N/A]
a.ii. [N/A]
b. [N/A]

The diagram shows the motion of the electrons in a metal wire carrying an electric current as seen by an observer X at rest with respect to the wire.

The distance between adjacent positive charges is *d*.



Observer Y is at rest with respect to the electrons.

a. State whether the field around the wire according to observer X is electric, magnetic or a combination of both. [1]

b.i. Discuss the change in *d* according to observer Y. [2]

b.ii. Deduce whether the overall field around the wire is electric, magnetic or a combination of both according to observer Y. [2]

Markscheme

a. magnetic field

[1 mark]

b.i. «according to Y» the positive charges are moving «to the right»

d decreases

For MP1, movement of positive charges must be mentioned explicitly.

[2 marks]

b.ii. positive charges are moving, so there is a magnetic field

the density of positive charges is higher than that of negative charges, so there is an electric field

The reason must be given for each point to be awarded.

[2 marks]

Examiners report

a. [N/A]
b.i. [N/A]
b.ii. [N/A]

Identical twins, A and B, are initially on Earth. Twin A remains on Earth while twin B leaves the Earth at a speed of 0.6*c* for a return journey to a point three light years from Earth.

a. Calculate the time taken for the journey in the reference frame of twin A as measured on Earth. [1]

b. Determine the time taken for the journey in the reference frame of twin B. [2]

c. Draw, for the reference frame of twin A, a spacetime diagram that represents the worldlines for both twins. [1]

d. Suggest how the twin paradox arises and how it is resolved. [2]

Markscheme

a. «0.6 ct = 6 ly» so t = 10 «years»

Accept: If the 6 ly are considered to be measured from B, then the answer is 12.5 years.

b. ***ALTERNATIVE 1***

$10^2 - 6^2 = t^2 - 0^2$

so t is 8 «years»
Accept: If the 6 ly are considered to be measured from B, then the answer is 10 years.

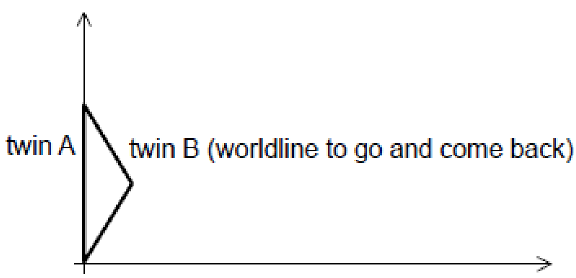
ALTERNATIVE 2

gamma is $\frac{5}{4}$

$10 \times \frac{4}{5} = 8$ «years»

Allow ECF from a
Allow ECF for incorrect γ in mp1

c. three world lines as shown



*Award mark only if axes **OR** world lines are labelled.*

d. according to both twins, it is the other one who is moving fast therefore clock should run slow

Allow explanation in terms of spacetime diagram.

«it is not considered a paradox as» twin B is not always in the same inertial frame of reference

OR

twin B is actually accelerating «and decelerating»

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]

Muons are created in the upper atmosphere of the Earth at an altitude of 10 km above the surface. The muons travel vertically down at a speed of 0.995*c* with respect to the Earth. When measured at rest the average lifetime of the muons is 2.1 μs.

a.i. Calculate, according to Galilean relativity, the time taken for a muon to travel to the ground. [1]

a.ii. Deduce why only a small fraction of the total number of muons created is expected to be detected at ground level according to Galilean relativity. [1]

b.i. Calculate, according to the theory of special relativity, the time taken for a muon to reach the ground in the reference frame of the muon. [2]

b.ii. Discuss how your result in (b)(i) and the outcome of the muon decay experiment support the theory of special relativity. [2]

Markscheme

a.i. «$\frac{10^4}{0.995\times3\times10^8}$ =» 34 «μs»

Do not accept $10^4/c$ = 33 μs.

[1 mark]

a.ii. time is much longer than 10 times the average life time «so only a small proportion would not decay»

[1 mark]

b.i. $\gamma = 10$

$\Delta t_0 =$ «$\frac{\Delta t}{\gamma} = \frac{34}{10}$ =» 3.4 «μs»

[2 marks]

b.ii. the value found in (b)(i) is of similar magnitude to average life time

significant number of muons are observed on the ground

«therefore this supports the special theory»

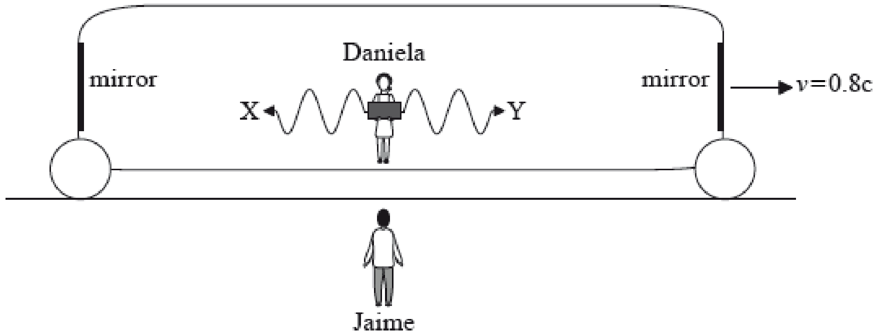
[2 marks]

Examiners report

a.i. [N/A]
a.ii. [N/A]
b.i. [N/A]
b.ii. [N/A]

This question is about simultaneity.

Daniela is standing in the middle of a train that is moving at a constant velocity relative to Jaime, who is standing on the platform. At the moment the train passes Jaime, two beams of light, X and Y, are emitted simultaneously from a device held by Daniela. Both beams are reflected by mirrors at the end of the train and then return to Daniela.



a. State and explain the order of arrival of X and Y at the mirrors according to Jaime. [3]

b. Outline whether the return of X and Y to Daniela are simultaneous according to Jaime. [2]

Markscheme

a. beam X will reach the mirror first;

the speed of light of each beam is constant for all inertial observers;

the left mirror moves towards the beam X while the right mirror moves away from the beam Y;

b. the beams returning to Daniela occur at one point in space;

if this is simultaneous to Daniela, the event will also be simultaneous to Jaime;

or

beam X has less to go to the mirror and then longer to Daniela, whilst beam Y has longer to the mirror and less to Daniela;

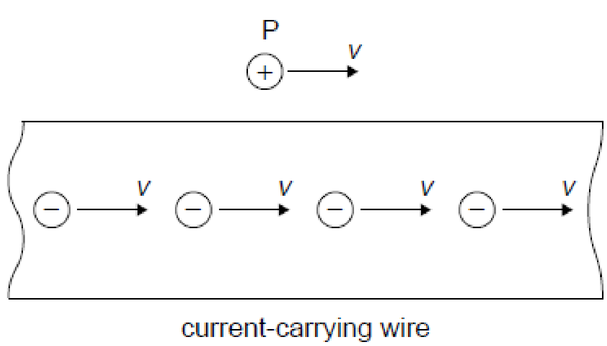
the sum of the times are the same because Daniela is in the middle so they arrive at the same time;

Examiners report

a. Usually candidates gave acceptable answers to (a) but forgot that the speed of light must be constant for their statements to be true.

b. Very few answered (b) well.

A long current-carrying wire is at rest in the reference frame S of the laboratory. A positively charged particle P outside the wire moves with velocity v relative to S. The electrons making up the current in the wire move with the same velocity v relative to S.



a. State what is meant by a reference frame. [1]

b.i. State and explain whether the force experienced by P is magnetic, electric or both, in reference frame S. [2]

b.ii. State and explain whether the force experienced by P is magnetic, electric or both, in the rest frame of P. [3]

Markscheme

a. a set of coordinate axes and clocks used to measure the position «in space/time of an object at a particular time»

OR

a coordinate system to measure x,y,z, and t / OWTTE

[1 mark]

b.i. magnetic only

there is a current but no «net» charge «in the wire»

[2 marks]

b.ii. electric only

P is **stationary** so experiences no magnetic force

relativistic contraction will increase the density of protons in the wire

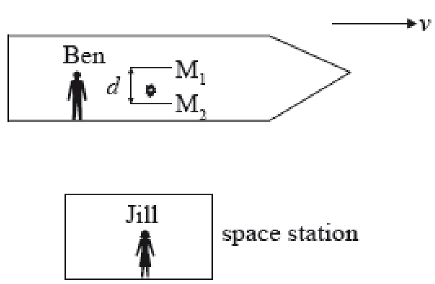
[3 marks]

Examiners report

a. [N/A]
b.i. [N/A]
b.ii. [N/A]

This question is about a Galilean transformation and time dilation.

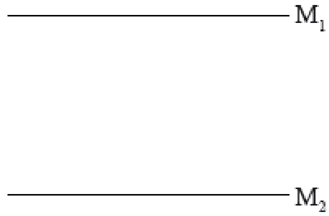
Ben is in a spaceship that is travelling in a straight-line with constant speed v as measured by Jill who is in a space station.



Ben switches on a light pulse that bounces vertically (as observed by Ben) between two horizontal mirrors M_1 and M_2 separated by a distance d. At the instant that the mirrors are opposite Jill, the pulse is just leaving the mirror M_2. The speed of light in air is c.

The time for the light pulse to travel from M_2 to M_1 as measured by Jill is Δt.

a. On the diagram, sketch the path of the light pulse between M_1 and M_2 as observed by Jill. [1]



b. (i) State, according to Jill, the distance moved by the spaceship in time Δt. [3]

(ii) Using a Galilean transformation, derive an expression for the length of the path of the light between M_2 and M_1.

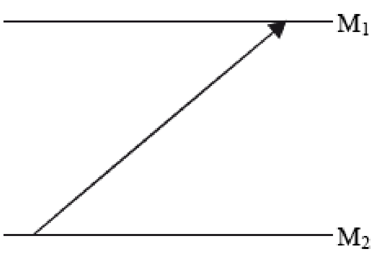
c. State, according to special relativity, the length of the path of the light between M_1 and M_1 as measured by Jill in terms of c and Δt. [1]

d. The time for the pulse to travel from M_2 to M_1 as measured by Ben is $\Delta t'$. Use your answer to (b)(i) and (c) to derive a relationship between Δt and $\Delta t'$. [3]

e. According to a clock at rest with respect to Jill, a clock in the spaceship runs slow by a factor of 2.3. Show that the speed v of the spaceship is 0.90c. [2]

Markscheme

a. any diagonal line as shown;



b. (i) $v\Delta t$;

(ii) speed of pulse $(c^2+v^2)^{\frac{1}{2}}$;

distance $=(c^2+v^2)^{\frac{1}{2}}\Delta t$;

*Award **[2]** for bald correct answer.*

c. $c\Delta t$;

d. $d=c\Delta t'$;

from Pythagoras $d^2=c^2\Delta t'^2=c^2\Delta t^2-v^2\Delta t^2$;

$\Delta t=\frac{\Delta t'}{\sqrt{1-\frac{v^2}{c^2}}}$;

e. recognize that $2.3=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$;

some evidence of rearranging *e.g.* $v=\sqrt{\frac{[2.3]^2-1}{[2.3]^2}}$;

$=0.90\mathrm{c}$

Examiners report

a. Most candidates were able to draw the correct path of the light.

b. Parts (b), (c) and (d) effectively dealt with the derivation of the time dilation formula and here many candidates had problems often relying on guesswork and half-remembered proofs rather than follow the logical development of the questions. The calculation was often done well but with the usual confusion between the times.

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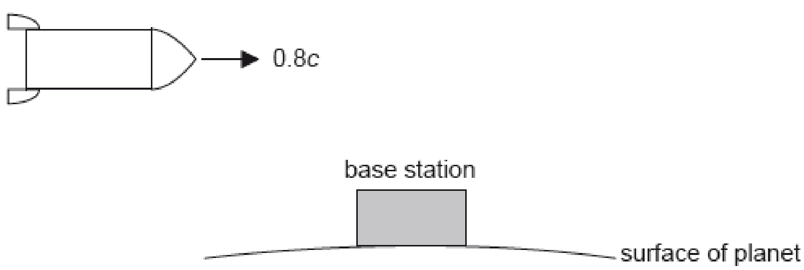
e. [N/A]

This question is about relativistic kinematics.

A spacecraft is flying in a straight line above a base station at a speed of 0.8*c*.



Suzanne is inside the spacecraft and Juan is on the base station.

a. [N/A] [[N/A

b.i. [N/A] [[N/A

b.ii. While moving away from the base station, Suzanne observes another spacecraft travelling towards her at a speed of 0.8*c*. Using Galilean transformations, calculate the relative speed of the two spacecraft. [1]

b.iii. Using the postulates of special relativity, state and explain why Galilean transformations cannot be used in this case to find the relative speeds of the two spacecraft. [2]

b.iv. Using relativistic kinematics, the relative speeds of the two spacecraft is shown to be 0.976*c*. Suzanne measures the other spacecraft to have a length of 8.00 m. Calculate the proper length of the other spacecraft. [2]

c. Suzanne's spacecraft is on a journey to a star. According to Juan, the distance from the base station to the star is 11.4 ly. Show that Suzanne measures the time taken for her to travel from the base station to the star to be about 9 years. [2]

Markscheme

a. [N/A]

b.i. [N/A]

b.ii. 1.6*c*;

b.iii. (one of the) postulates states that the speed of light in a vacuum is the same for all inertial observers;

Galilean transformation will give a relative speed greater than the speed of light;

b.iv. $\gamma = \frac{1}{\sqrt{1-0.976^2}}$ $(= 4.59)$;

$l_0 = (4.56 \times 8.00 =)\ 36.7\ (\text{m})$;

***Note**: the final answer for SP3 is different to the HP3.*

c. $t = \frac{s}{v} = \frac{11.4}{0.8} = 14.25\ (\text{years})$;

$\Delta t_0 = \frac{\Delta t}{\gamma} = \frac{14.25}{1.67} = 8.6\ (\text{years})$;

Allow ECF from (b).

Accept length contraction with the same result.

Examiners report

a. Only HL Questions 12(a), (b)(i) and (c) were common with SL questions 12(a), (b)(i) and (c). Many did not address “frame of reference”, only explaining “inertial”. Most could identify the postulate relevant to Galilean transformations but few could earn full marks. The calculation was well done by those who attempted the question.

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Muons are unstable particles with a proper lifetime of 2.2 μs. Muons are produced 2.0 km above ground and move downwards at a speed of 0.98*c* relative to the ground. For this speed γ = 5.0. Discuss, with suitable calculations, how this experiment provides evidence for time dilation.

Markscheme

ALTERNATIVE 1 *— for answers in terms of time*

overall idea that more muons are detected at the ground than expected «without time dilation»

«Earth frame transit time = $\frac{2000}{0.98c}$» = 6.8 «μs»

«Earth frame dilation of proper half-life = 2.2 μs x 5» = 11 «μs»
OR
«muon's proper transit time = $\frac{6.8\mu s}{5}$» = 1.4 «μs»

ALTERNATIVE 2 *– for answers in terms of distance*
overall idea that more muons are detected at the ground than expected «without time dilation»

«distance muons can travel in a proper lifetime = 2.2 μs x 0.98*c*» = 650 «m»

«Earth frame lifetime distance due to time dilation = 650 m x 5» = 3250 «m»
OR
«muon frame distance travelled = $\frac{2000}{5}$» = 400 «m»

Accept answers from ***one*** *of the alternatives.*

[3 marks]

Examiners report

[N/A]

An electron is emitted from a nucleus with a speed of 0.975*c* as observed in a laboratory. The electron is detected at a distance of 0.800m from the emitting nucleus as measured in the laboratory.

a. For the reference frame of the electron, calculate the distance travelled by the detector. [2]

b. For the reference frame of the laboratory, calculate the time taken for the electron to reach the detector after its emission from the nucleus. [2]

c. For the reference frame of the electron, calculate the time between its emission at the nucleus and its detection. [2]

d. Outline why the answer to (c) represents a proper time interval. [1]

Markscheme

a. γ=4.503

$\ll \frac{0.800}{4.50} = \gg 0.178\text{m}$

b. $\text{time} = \frac{0.800}{2.94\times10^8}$

2.74 ns

c. $\frac{2.74}{4.5}$ ***OR*** $\frac{0.178}{2.94\times10^8}$

0.608 ns

d. it is measured in the frame of reference in which both events occur at the same position

OR

it is the shortest time interval possible

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]

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a. Define *proper length.* [1]

b. A charged pion decays spontaneously in a time of 26 ns as measured in the frame of reference in which it is stationary. The pion moves with a velocity of 0.96*c* relative to the Earth. Calculate the pion's lifetime as measured by an observer on the Earth. [2]

c. In the pion reference frame, the Earth moves a distance X before the pion decays. In the Earth reference frame, the pion moves a distance Y before the pion decays. Demonstrate, with calculations, how length contraction applies to this situation. [3]

Markscheme

a. the length of an object in its rest frame

b. $\frac{1}{\sqrt{(1-0.96^2)}}$ ***OR*** $\gamma = 3.6$

ECF for wrong γ

93 «ns»
Award ***[2]*** *for a bald correct answer.*

c. «X is» 7.5 «m» in frame on pion

«Y is» 26.8 «m» in frame on Earth

identifies proper length as the Earth measurement
OR
identifies Earth distance according to pion as contracted length
OR
a statement explaining that one of the length is shorter than the other one

Examiners report

[N/A]

b. [N/A]
c. [N/A]

Outline the conclusion from Maxwell's work on electromagnetism that led to one of the postulates of special relativity.

Markscheme

light is an EM wave

speed of light is independent of the source/observer

Examiners report

[N/A]

One of the postulates of special relativity states that the laws of physics are the same in all inertial frames of reference.

a. State what is meant by inertial in this context. [1]

b. An observer is travelling at velocity v towards a light source. Determine the value the observer would measure for the speed of light emitted by the source according to [2]

(i) Maxwell's theory.

(ii) Galilean transformation.

Markscheme

a. not being accelerated

OR

not subject to an unbalanced force

OR

where Newton's laws apply

b. (i) c

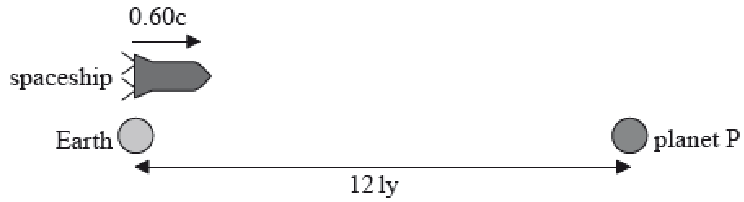
(ii) $c+v$

Examiners report

a. [N/A]
b. [N/A]

This question is about relativistic kinematics.

The diagram shows a spaceship as it moves past Earth on its way to a planet P. The planet is at rest relative to Earth.



The distance between the Earth and planet P is 12 ly as measured by observers on Earth. The spaceship moves with speed 0.60c relative to Earth.

Consider two events:

Event 1: when the spaceship is above Earth

Event 2: when the spaceship is above planet P

Judy is in the spaceship and Peter is at rest on Earth.

Judy considers herself to be at rest. According to Judy, the Earth and planet P are moving to the left.

a. State the reason why the time interval between event 1 and event 2 is a proper time interval as measured by Judy. [1]

b. (i) Calculate the time interval between event 1 and event 2 according to Peter. [3]

(ii) Calculate the time interval between event 1 and event 2 according to Judy.

c. (i) Calculate, according to Judy, the distance separating the Earth and planet P. [3]

(ii) Using your answers to (b)(ii) and (c)(i), determine the speed of planet P relative to the spaceship.

(iii) Comment on your answer to (c)(ii).

d. Determine, according to Judy in the spaceship, which signal is emitted first. [3]

Markscheme

a. because the events occur at the same place/point in space for this observer;

Do not allow "events within the same reference frame".

b. (i) $t = \left(\frac{12}{0.60\text{c}} =\right) 20(\text{yr});$

(ii) $\gamma = \left(\frac{1}{\sqrt{1-0.60^2}} =\right) 1.25;$ *(allow implicit value)*

$t_{\text{rocket}} = \left(\frac{20\text{yr}}{\gamma} =\right) 16(\text{yr});$ *(allow ECF)*

*Award **[2]** for a bald correct answer.*

c. (i) $L = \left(\frac{12\text{ly}}{\gamma} =\right) 9.6(\text{ly});$ *(allow ECF from (b)(ii))*

(ii) $v = \left(\frac{9.6\text{ly}}{16\text{y}} =\right) 0.60\text{c};$ *(allow ECF from (b)(ii) and (c)(i))*

(iii) (by principle of relativity this should be the) same as the speed of the spaceship relative to Earth;

d. both signals travel at the same speed c;

Judy must agree that the signals arrive at S simultaneously / *OWTTE*;

for Judy, observer S moves away from the signal traveling from P/towards the signal traveling from Earth;

for Judy the signal from P has further to travel to reach S – so was emitted first;

Do not accept explanations based on Judy approaching P or seeing/receiving the signal from P first as this is irrelevant.

Award **[0]** *for a bald correct answer.*

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]

This question is about a light clock.

One of the postulates of special relativity refers to the speed of light. State the other postulate of special relativity.

Markscheme

the laws of physics are the same for all inertial observers;

Examiners report

(a) was well answered.

This question is about relativistic kinematics.

a. An observer at rest relative to Earth observes two spaceships. Each spaceship is moving with a speed of 0.85 c but in opposite directions. The observer measures the rate of increase of distance between the spaceships to be 1.7 c. Outline whether this observation contravenes the theory of special relativity. [2]

b. The observer on Earth in (a) watches one spaceship as it travels to a distant star at a speed of 0.85 c. According to observers on the spaceship, this journey takes 8.0 years. [8]

(i) Calculate, according to the observer on Earth, the time taken for the journey to the star.

(ii) Calculate, according to the observer on Earth, the distance from Earth to the star.

(iii) At the instant when the spaceship passes the star, the observer on the spaceship sends a radio message to Earth. The spaceship continues to move at a speed of 0.85 c. Determine, according to the spaceship observer, the time taken for the message to arrive on Earth.

Markscheme

a. theory suggests that no object can travel faster than light;

the 1.7c is not the speed of a physical object;

so is not in violation of the theory;

b. (i) $y = 1.90$;

interval on Earth $=$ $y \times$ interval on spaceship;

(interval on Earth 1.90×8 years $=$)15 years;

*Award **[3]** for a bald correct answer.*

(ii) observer on Earth thinks spaceship has travelled for 15 years;
so distance is $0.85c \times 15 = 12.8 \approx 13$ly;
*Award **[2]** for a bald correct answer*

or

the spaceship observer observes the distance moved by the Earth $= 0.85c \times 8.0$ yr;
proper distance $= 1.90 \times 0.85c \times 8.0$yr $= 12.9 \approx 13$ly ;
*Award **[2]** for a bald correct answer*

(iii) *(take time for message to arrive at Earth in spaceship frame to be T)*
distance moved by Earth in spaceship frame before message arrives = $0.85cT$;
distance of Earth from spaceship when message sent=$0.85c \times 8.0$=6.8(ly);

$(cT = 0.85cT + 6.8)$ so $T = \frac{6.8}{0.15} = 45.3$ years

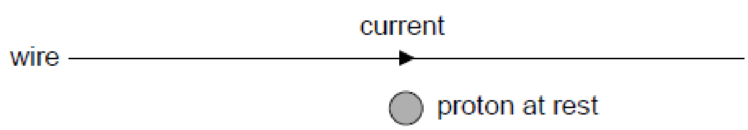
Examiners report

a. [N/A]
b. [N/A]

---

a. State **one** prediction of Maxwell's theory of electromagnetism that is consistent with special relativity. [1]

b. A current is established in a long straight wire that is at rest in a laboratory. [3]



A proton is at rest relative to the laboratory and the wire.

Observer X is at rest in the laboratory. Observer Y moves to the right with constant speed relative to the laboratory. Compare and contrast how observer X and observer Y account for any non-gravitational forces on the proton.

Markscheme

a. the speed of light is a universal constant/invariant

OR

c does not depend on velocity of source/observer

electric and magnetic fields/forces unified/frame of reference dependant

[1 mark]

b. observer X will measure zero «magnetic or electric» force

observer Y must measure both electric and magnetic forces

which must be equal and opposite so that observer Y also measures zero force

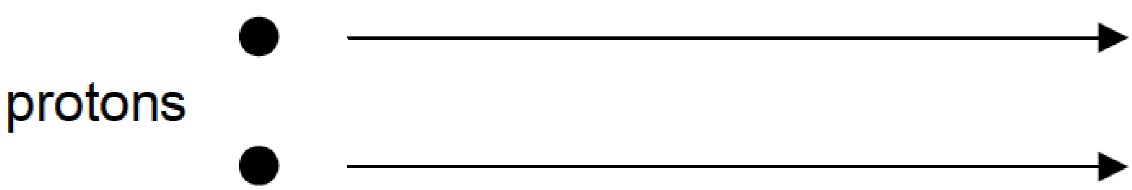
*Allow **[2 max]** for a comment that both X and Y measure zero resultant force even if no valid explanation is given.*

[3 marks]

Examiners report

a. [N/A]
b. [N/A]

Two protons are moving with the same velocity in a particle accelerator.



Observer X is at rest relative to the accelerator. Observer Y is at rest relative to the protons.

Explain the nature of the force between the protons as observed by observer X **and** observer Y.

Markscheme

Y measures electrostatic repulsion only

protons are moving relative to X «but not Y» ***OR*** protons are stationary relative to Y

moving protons create magnetic fields around them according to X

X also measures an attractive magnetic force ***OR*** relativistic/Lorentz effects also present

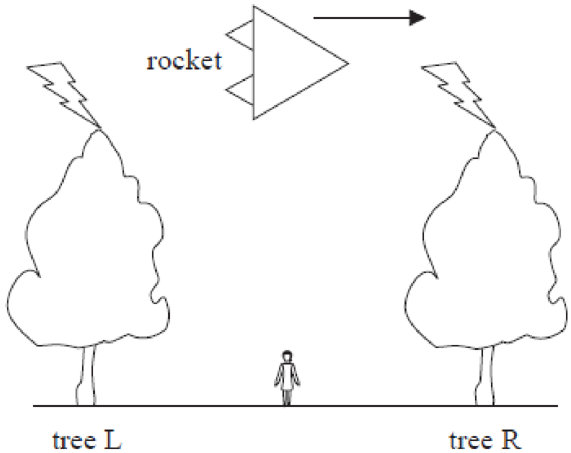
Examiners report

[N/A]

This question is about simultaneity.

a. State the postulate of special relativity that is related to the speed of light. [1]

b. A rocket moving at a relativistic speed passes an observer who is at rest on the ground equidistant from two trees L and R. At the moment that an observer in the rocket is opposite the ground observer, lightning strikes L and R at the same time according to the ground observer. Light from the strikes reaches the observer in the rocket as well as the observer on the ground. [4]



(i) Explain why, according to the observer in the rocket, light from the two strikes will reach the ground observer at the same time.

(ii) Using your answer to (a) and (b)(i), outline why, according to the rocket observer, tree R was hit by lightning before tree L.

Markscheme

a. the speed of light in a vacuum is the same for all inertial observers/observers in uniform motion;

b. (i) ground observer measures a zero proper time interval for the two arrivals;

all other observers measure a time interval of $\gamma \times 0 = 0$;

hence the arrivals are simultaneous for all observers, including rocket

*Award **[1]** for statement that "events that are simultaneous for one observer*

and occur at the same place are simultaneous for all observers".

(ii) according to the rocket observer, the ground observer moves towards the signal from tree L and away from the signal from tree R;
since the signals move at the same speed and they arrive at the same time according to the rocket observer;
signal from tree R must have been emitted first

Examiners report

a.

b.

A train is passing through a tunnel of proper length 80 m. The proper length of the train is 100 m. According to an observer at rest relative to the tunnel, when the front of the train coincides with one end of the tunnel, the rear of the train coincides with the other end of the tunnel.

a. Explain what is meant by proper length. [1]

b. Draw a spacetime diagram for this situation according to an observer at rest relative to the tunnel. [3]

c. Calculate the velocity of the train, according to an observer at rest relative to the tunnel, at which the train fits the tunnel. [2]

d. For an observer on the train, it is the tunnel that is moving and therefore will appear length contracted. This seems to contradict the observation made by the observer at rest to the tunnel, creating a paradox. Explain how this paradox is resolved. You may refer to your spacetime diagram in (b). [2]

Markscheme

a. the length of an object in its rest frame

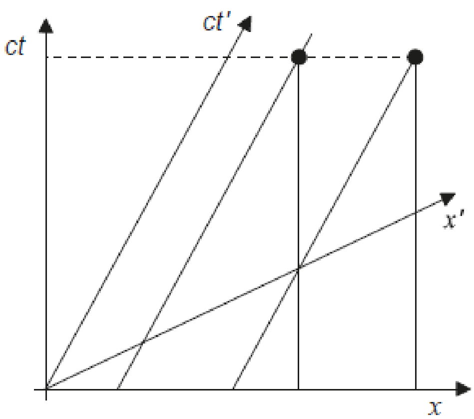
OR

the length of an object measured when at rest relative to the observer

b. world lines for front and back of tunnel parallel to *ct* axis

world lines for front and back of train

which are parallel to *ct′* axis



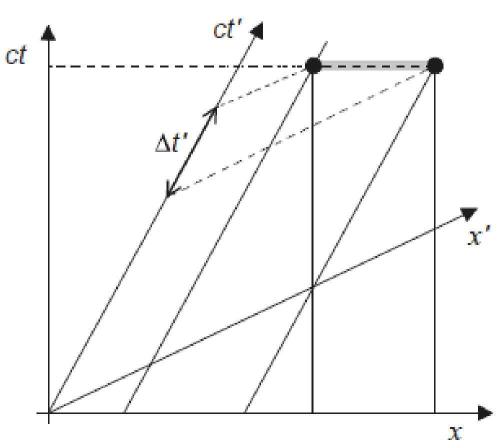
c. realizes that gamma = 1.25

0.6*c*

d. ***ALTERNATIVE 1***

indicates the two simultaneous events for *t* frame

marks on the diagram the different times «for both spacetime points» on the *ct′* axis «shown as Δ*t′* on each diagram»



ALTERNATIVE 2: (no diagram reference)

the two events occur at different points in space

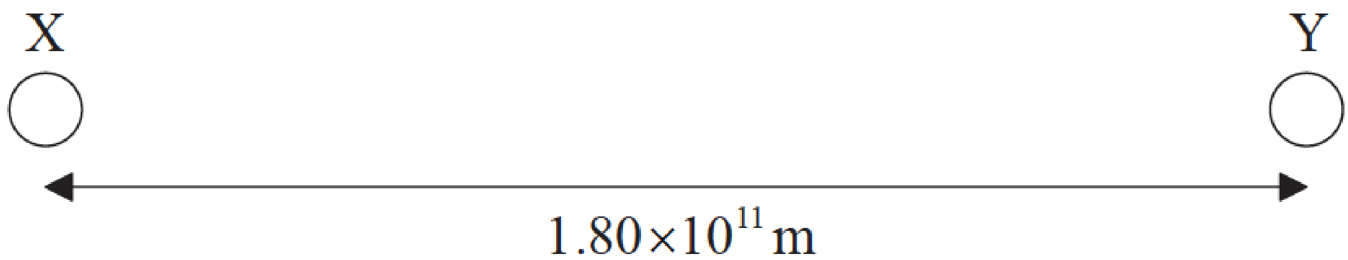
statement that the two events are not simultaneous in the t' frame

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]

This question is about time dilation.

a. Two space stations X and Y are at rest relative to each other. The separation of X and Y as measured in their frame of reference is 1.80×10^{11}m. [1]



State what is meant by a frame of reference.

b. A radio signal is sent to both space stations in (a) from a point midway between them. On receipt of the signal a clock in X and a clock in Y are each set to read zero. A spaceship S travels between X and Y at a speed of 0.750c as measured by X and Y. In the frame of reference of S, station X passes S at the instant that X's clock is set to zero. A clock in S is also set to zero at this instant. [9]

(i) Calculate the time interval, as measured by the clock in X, that it takes S to travel from X to Y.

(ii) Calculate the time interval, as measured by the clock in S, that it takes S to travel from X to Y.

(iii) Explain whether the clock in X **or** the clock in S measures the proper time.

(iv) Explain why, according to S, the setting of the clock in X and the setting of the clock in Y does not occur simultaneously.

Markscheme

a. a set of coordinates that can be used to locate events/position of objects;

b. (i) $\frac{1.80\times10^{11}}{0.750\times3\times10^{8}}$;

=800(s);

*Award **[2]** for a bald correct answer.*

(ii) $\gamma = \left(\frac{1}{\sqrt{1-0.750^2}} =\right) 1.51;$

$\text{time} = \left(\frac{800}{1.51} =\right) 530\ (\text{s});$

Watch for ECF from (b)(i) or first marking point in (b)(ii).
*Award **[2]** for a bald correct answer.*

(iii) only S's clock measures proper time;
because S's clock is at both events / events occur at same place in S's frame;

(iv) according to S, Y moves towards/X moves away from the radio signal;
the signal travels at the same speed/at the speed of light in each direction;
therefore according to S's clock the signal reaches Y before it reaches X/X after reaching Y;

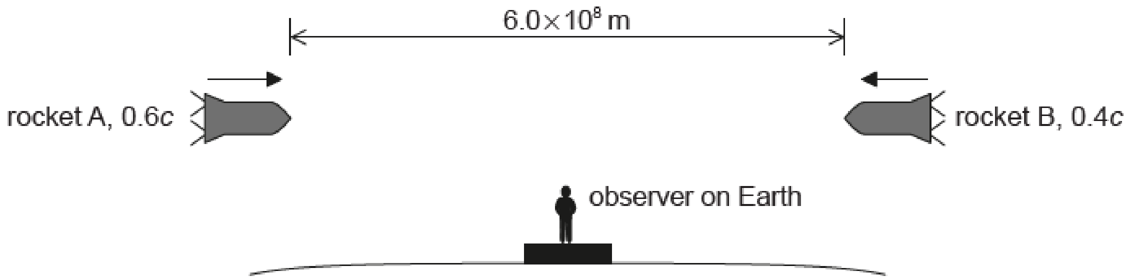
or

S's frame is different/moving relative to the X and Y frame;
the two events/arrival of signals are separated in space;
so if simultaneous for XY, cannot be simultaneous for S;

Examiners report

a. [N/A]
b. [N/A]

Two rockets, A and B, are moving towards each other on the same path. From the frame of reference of the Earth, an observer measures the speed of A to be 0.6*c* and the speed of B to be 0.4*c*. According to the observer on Earth, the distance between A and B is 6.0 x 10^8 m.



a. Define frame of reference. [1]

b. Calculate, according to the observer on Earth, the time taken for A and B to meet. [2]

c. Identify the terms in the formula. [1]

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

d. Determine, according to an observer in A, the velocity of B. [2]

e.i. Determine, according to an observer in A, the time taken for B to meet A. [2]

e.ii. Deduce, without further calculation, how the time taken for A to meet B, according to an observer in B, compares with the time taken for the same event according to an observer in A. [2]

Markscheme

a. a co-ordinate system in which measurements «of distance and time» can be made

Ignore any mention to inertial reference frame.

b. closing speed = *c*

2 «s»

c. *u* and *v* are velocities with respect to the same frame of reference/Earth ***AND*** *u′* the relative velocity

Accept 0.4c and 0.6c for u and v

d. $\frac{-0.4-0.6}{1+0.24}$

«–» 0.81*c*

e.i. γ = 1.25

so the time is *t* = 1.6 «s»

e.ii. gamma is smaller for B

so time is greater than for A

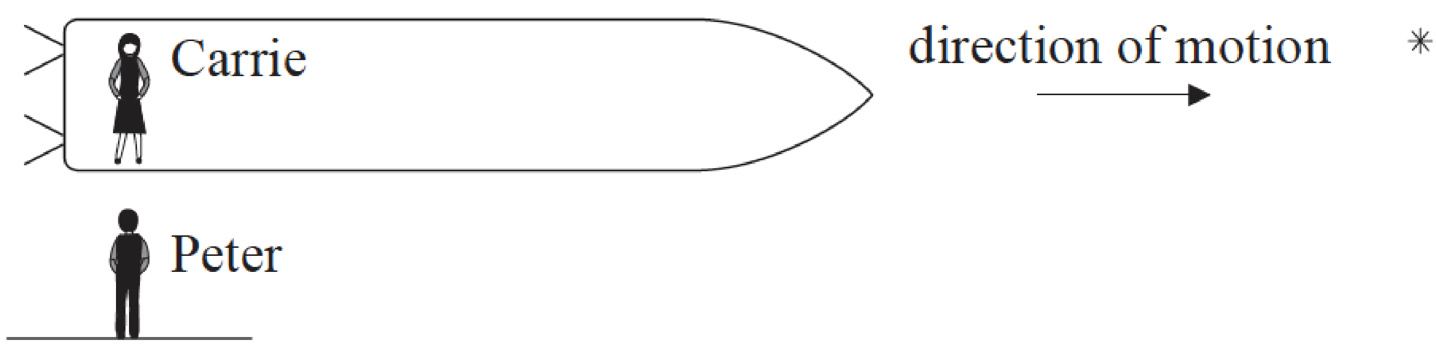
Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]
e.i. [N/A]
e.ii. [N/A]

This question is about relativity.

Carrie is in a spaceship that is travelling towards a star in a straight-line at constant velocity as observed by Peter. Peter is at rest relative to the star.

a. Carrie measures her spaceship to have a length of 100m. Peter measures Carrie’s spaceship to have a length of 91m. [3]



(i) Explain why Carrie measures the proper length of the spaceship.

(ii) Show that Carrie travels at a speed of approximately 0.4 c relative to Peter.

b. According to Carrie, it takes the star ten years to reach her. Using your answer to (a)(ii), calculate the distance to the star as measured by Peter. [2]

c. According to Peter, as Carrie passes the star she sends a radio signal. Determine the time, as measured by Carrie, for the message to reach Peter. [3]

Markscheme

a. (i) proper length is measured by observer at rest relative to object / Carrie is at rest relative to spaceship;

(ii) $\gamma = \left(\frac{100}{91} =\right) 1.1$;

evidence of algebraic manipulation *e.g.* $\frac{v^2}{c^2} = 1 - \frac{1}{1.1^2}$ to give *v*=0.42c;

≈0.4c

b. travel time measured by Peter = (10×γ=)11years;

4.6ly ***or*** 4.4ly *(if 0.4 c used)*;

c. moves away at 0.42 c so is 4.2ly away when signal emitted; *(allow ECF from (a)(ii))*

signal travel time *t* where *ct*=4.2+0.42*ct*;

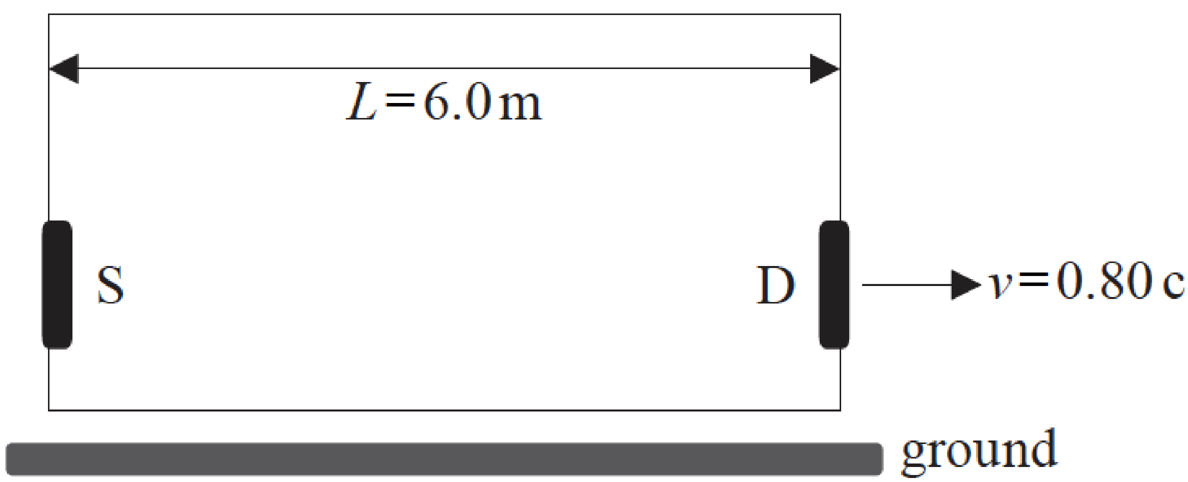
7.2y ***or*** 7y *(if 0.4 c used)*;

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

This question is about relativistic kinematics.

A source of light S and a detector of light D are placed on opposite walls of a box as shown in the diagram.



According to an observer in the box the distance *L* between S and D is 6.0m. The box moves with speed *v*= 0.80c relative to the ground.

Consider the following events.

Event 1: a photon is emitted by S towards D
Event 2: the photon arrives at D

a. In the context of the theory of relativity, state what is meant by an event. [1]

b. (i) Calculate the time interval *t* between event 1 and event 2 according to an observer in the box. [3]

(ii) According to an observer on the ground the time interval between event 1 and event 2 is T. One student claims that $T=\frac{t}{\sqrt{1-\frac{v^2}{c^2}}}$ and another that $T=t\sqrt{1-\frac{v^2}{c^2}}$.

Explain why both students are wrong.

c. Relative to an observer on the **ground**, [6]

(i) calculate the distance between S and D.

(ii) state the speed of the photon leaving S.

(iii) state an expression for the distance travelled by detector D in the time interval *T* (*T* is the interval in (b)(ii)).

(iv) determine *T*, using your answers to (c)(i), (ii) and (iii).

Markscheme

a. a point in spacetime / something happening at a particular time and a particular point in space;

b. (i) $t=\frac{6.0}{3.0\times10^8}=2.0\times10^{-8}\text{s};$

(ii) for either formula to be used one of the time intervals must be a proper time interval;
the two events occur at different points in space and so neither observer measures a proper time interval;
the proper time interval is that of the photons;

c. (i) $\gamma=\frac{1}{\sqrt{1-0.80^2}}=\frac{5}{3}=1.67;$
$l=\frac{L}{\gamma}=\frac{6.0}{1.67}=3.6\text{m};$

*Award **[2]** for a bald correct answer.*

(ii) *c*;

(iii) *vT **or*** 0.80*cT*;

(iv) *cT*=0.80*cT*+3.6;
$T=\frac{3.6}{0.20\times3.0\times10^8}=6.0\times10^{-8}\text{s};$
*Award **[2]** for a bald correct answer.*

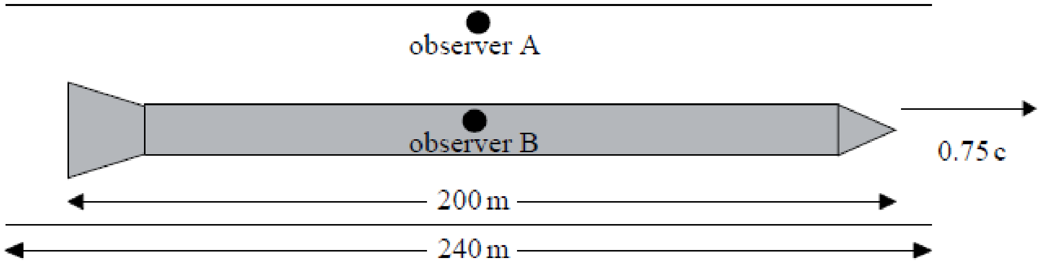
Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

This question is about length contraction and simultaneity.

a. Define *proper length*. [1]

b. A spaceship is travelling to the right at speed 0.75 c, through a tunnel which is open at both ends. Observer A is standing at the centre of one side of the tunnel. Observer A, for whom the tunnel is at rest, measures the length of the tunnel to be 240 m and the length of the spaceship to be 200 m. The diagram below shows this situation from the perspective of observer A. [5]



Observer B, for whom the spaceship is stationary, is standing at the centre of the spaceship.

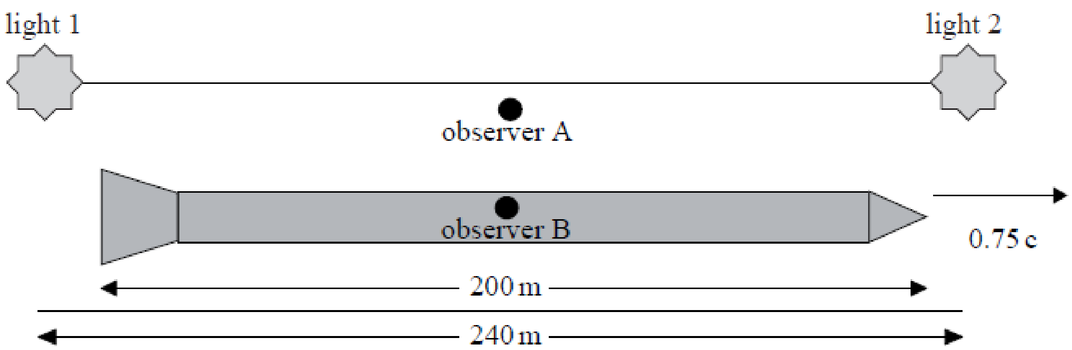
(i) Calculate the Lorentz factor, γ, for this situation.

(ii) Calculate the length of the tunnel according to observer B.

(iii) Calculate the length of the spaceship according to observer B.

(iv) According to observer A, the spaceship is completely inside the tunnel for a short time. State and explain whether or not, according to observer B, the spaceship is ever completely inside the tunnel.

c. Two sources of light are located at each end of the tunnel. The diagram below shows this situation from the perspective of observer A. [4]



According to observer A, at the instant when observer B passes observer A, the two sources of light emit a flash. Observer A sees the two flashes simultaneously. Discuss whether or not observer B sees the two flashes simultaneously.

Markscheme

a. the length of an object as measured by an observer who is at rest relative to the object;

b. (i) $\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-0.75^2}} = 1.5$;

(ii) $L = \frac{L_0}{\gamma} = \frac{240}{1.5} = 160\text{m}$;

(iii) $L_0 = \gamma L = 1.5 \times 200 = 300\text{m}$;

(iv) the spaceship is never completely inside the tunnel;
because (according to observer B) the spaceship is longer than the tunnel;
Apply ECF in all parts of question (b).

c. observer B will not see the two flashes simultaneously;

according to B, light 2 is moving to the left/towards observer B;

since the speed of light is the same for both sources;

the flash from light 2 reaches B before the flash from light 1;

or

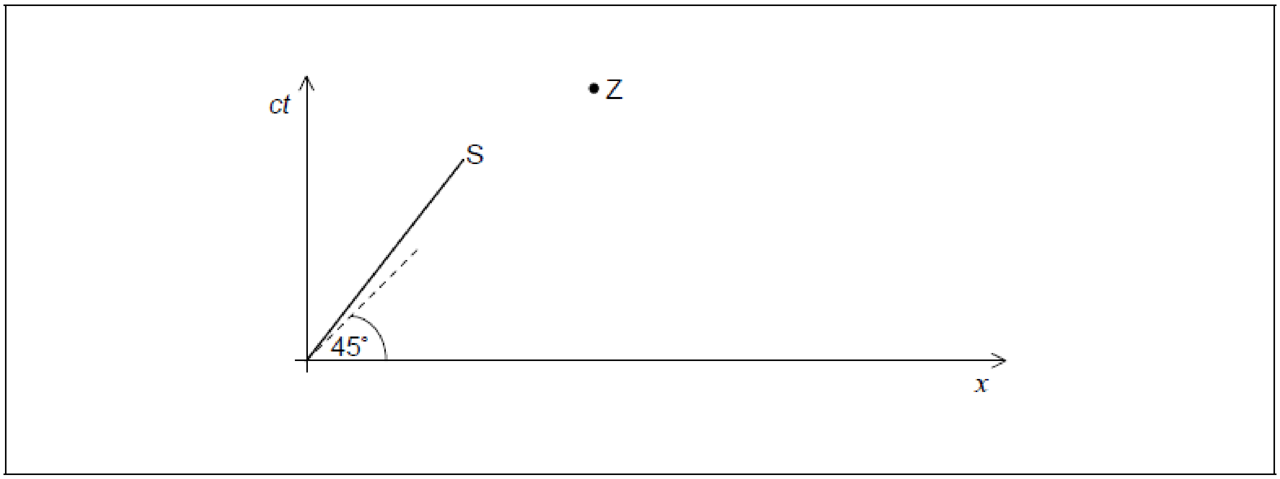
according to B, the two flashes arrive at A simultaneously;
according to B, A is moving to the left/away from light 2;
since light from both sources moves with the same speed;

for the flashes to be received by A at the same time, the flash from light 2 must be emitted first;
Accept any equivalent discussion.

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

A spaceship S leaves the Earth with a speed v = 0.80c. The spacetime diagram for the Earth is shown. A clock on the Earth and a clock on the spaceship are synchronized at the origin of the spacetime diagram.



a. Calculate the angle between the worldline of S and the worldline of the Earth. [1]

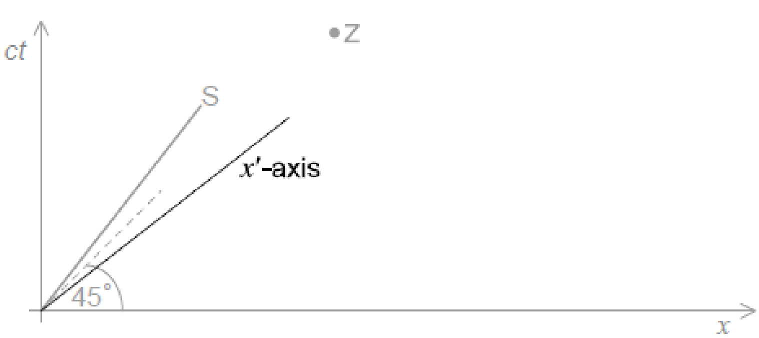
b. Draw, on the diagram, the x'-axis for the reference frame of S. [1]

c. An event Z is shown on the diagram. Label the co-ordinates of this event in the reference frame of S. [1]

Markscheme

a. angle = $\tan^{-1}$ «$\frac{0.8}{1}$» = 39 «°» ***OR*** 0.67 «rad»

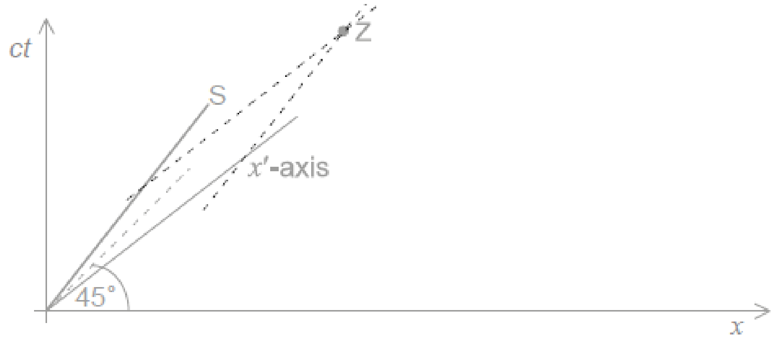
b. adds x'-axis as shown



Approximate same angle to v = c as for ct′.

Ignore labelling of that axis.

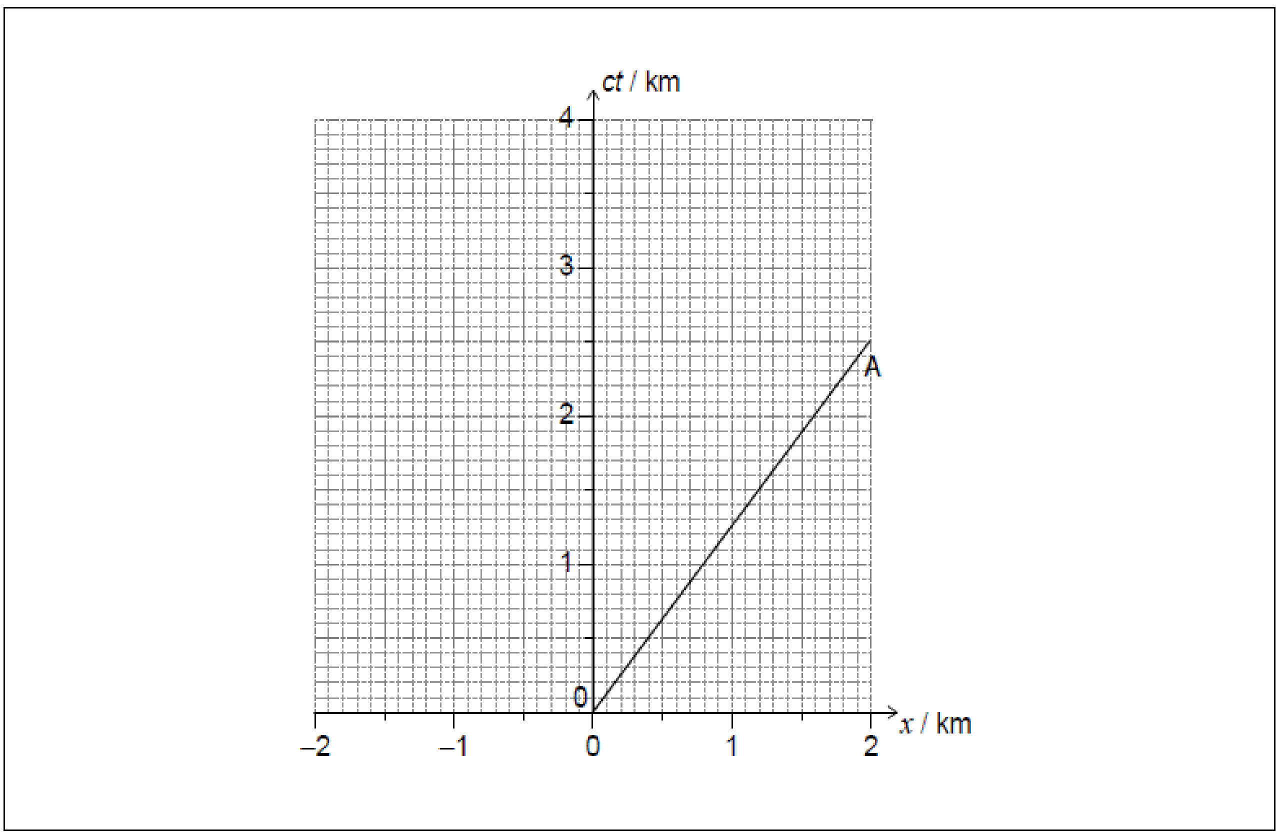
c. adds two lines parallel to ct' and x' as shown indicating coordinates



Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

An observer on Earth watches rocket A travel away from Earth at a speed of 0.80c. The spacetime diagram shows the worldline of rocket A in the frame of reference of the Earth observer who is at rest at x = 0.



Another rocket, B, departs from the same location as A but later than A at ct = 1.2 km according to the Earth observer. Rocket B travels at a constant speed of 0.60c in the opposite direction to A according to the Earth observer.

Rocket A and rocket B both emit a flash of light that are received simultaneously by the Earth observer. Rocket A emits the flash of light at a time coordinate ct = 1.8 km according to the Earth observer.

a. Draw on the spacetime diagram the worldline of B according to the Earth observer and label it B. [2]

b. Deduce, showing your working on the spacetime diagram, the value of *ct* according to the Earth observer at which the rocket B emitted its flash of light. [3]

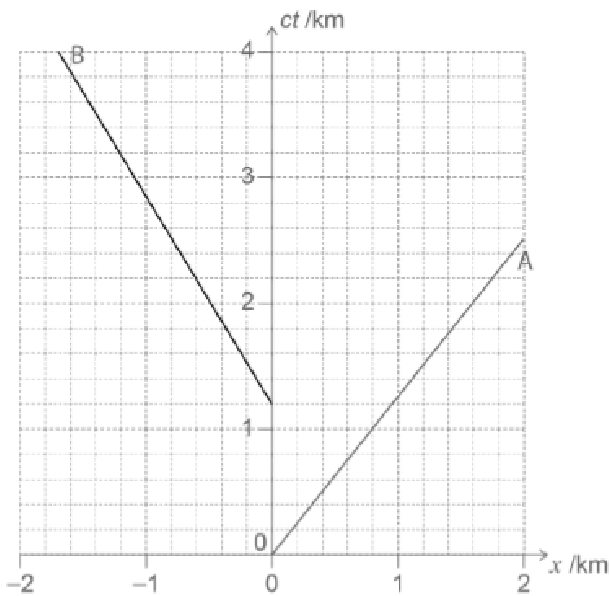
c. Explain whether or not the arrival times of the two flashes in the Earth frame are simultaneous events in the frame of rocket A. [2]

d. Calculate the velocity of rocket B relative to rocket A. [2]

Markscheme

a. straight line with negative gradient with vertical intercept at *ct* = 1.2 «km»

through (–0.6, 2.2) *ie* gradient = –1.67



Tolerance: Allow gradient from interval –2.0 to –1.4, (at ct = 2.2, x from interval 0.5 to 0.7).

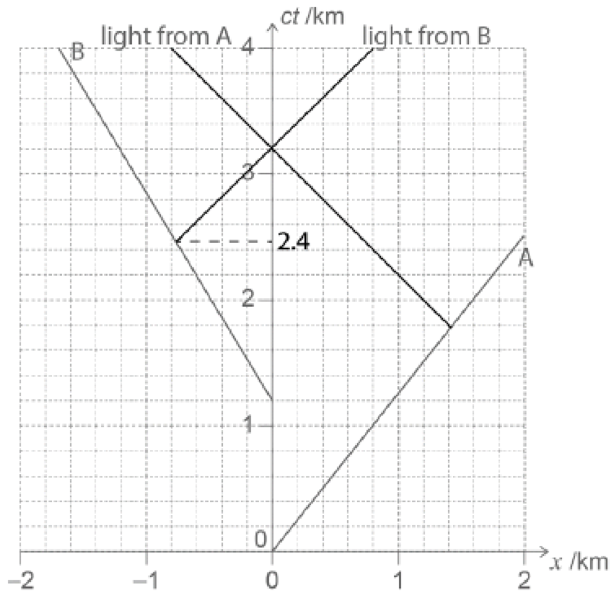
If line has positive gradient from interval 1.4 to 2.0 and intercepts at ct = 1.2 km then allow ***[1 max]****.*

[2 marks]

b. line for the flash of light from A correctly drawn

line for the flash of light of B correctly drawn

correct reading taken for time of intersection of flash of light and path of B, *ct* = 2.4 «km»



Accept values in the range: 2.2 to 2.6.

[3 marks]

c. the two events take place in the same point in space at the same time

so all observers will observe the two events to be simultaneous / so zero difference

Award the second MP only if the first MP is awarded.

[2 marks]

d. $u' = \frac{-0.6-0.8}{1-(-0.6)\times0.8}$

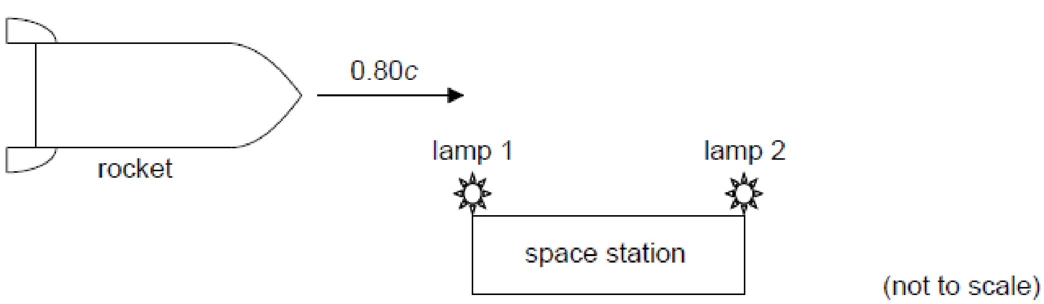
= «–»0.95 «*c*»

[2 marks]

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d. [N/A]

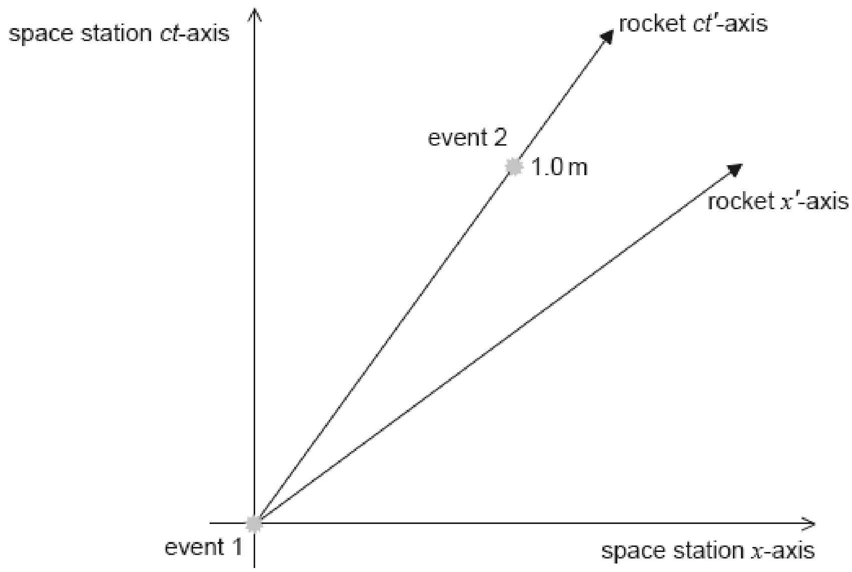
A rocket of proper length 450 m is approaching a space station whose proper length is 9.0 km. The speed of the rocket relative to the space station is 0.80*c*.



X is an observer at rest in the space station.

Two lamps at opposite ends of the space station turn on at the same time according to X. Using a Lorentz transformation, determine, according to an observer at rest in the rocket,

The rocket carries a different lamp. Event 1 is the flash of the rocket's lamp occurring at the origin of **both** reference frames. Event 2 is the flash of the rocket's lamp at time *ct'* = 1.0 m according to the rocket. The coordinates for event 2 for observers in the space station are *x* and *ct*.



a.i. Calculate the length of the rocket according to X. [2]

a.ii. A space shuttle is released from the rocket. The shuttle moves with speed 0.20*c* **to the right** according to X. Calculate the **velocity** of the shuttle relative to the rocket. [2]

b.i. the time interval between the lamps turning on. [2]

b.ii. which lamp turns on first. [1]

c.i. On the diagram label the coordinates *x* and *ct*. [2]

c.ii. State and explain whether the *ct* coordinate in (c)(i) is less than, equal to **or** greater than 1.0 m. [2]

c.iii. Calculate the value of $c^2t^2 - x^2$. [2]

Markscheme

a.i. the gamma factor is $\frac{5}{3}$ ***or*** 1.67

$L = \frac{450}{\frac{5}{3}} = 270$ «m»

Allow ECF from MP1 to MP2.

[2 marks]

a.ii $u' =$ «$\frac{u-v}{1-\frac{uv}{c^2}}$ =» $\frac{0.20c-0.80c}{1-0.20\times0.80}$

OR

$0.2c = \frac{0.80c+u'}{1+0.80u'}$

$u' =$ «–»$0.71c$

Check signs and values carefully.

[2 marks]

b.i. $\Delta t' =$ «$\gamma\left(\Delta t - \frac{v\Delta x}{c^2}\right)$ =» $\frac{5}{3}\times\left(0-\frac{(0.80c\times9000)}{c^2}\right)$

$\Delta t' =$ «–»4.0×10^{-5} «s»

Allow ECF for use of wrong γ from (a)(i).

[2 marks]

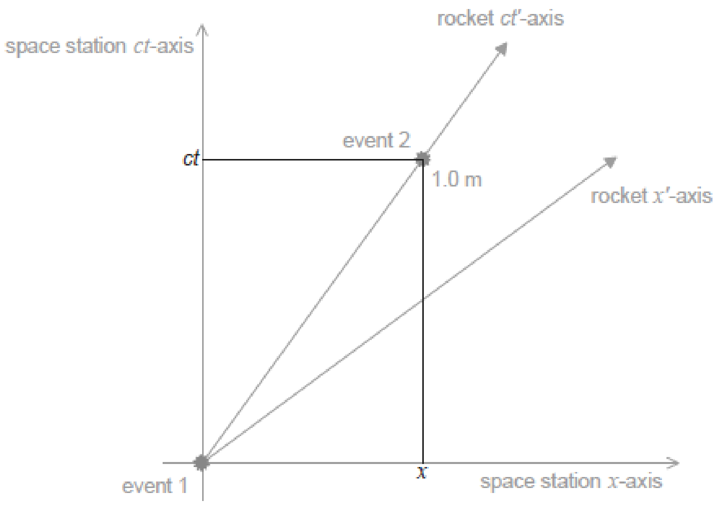
b.ii lamp 2 turns on first

Ignore any explanation

[1 mark]

c.i. *x* coordinate as shown

ct coordinate as shown



Labels must be clear and unambiguous.

Construction lines are optional.

[2 marks]

c.ii. «in any other frame» *ct* is greater

the interval $ct' = 1.0$ «m» is proper time
OR
ct is a dilated time
OR
$ct = \gamma ct'$ «$= \gamma$»

MP1 is a statement

MP2 is an explanation

[2 marks]

c.iiiuse of $c^2t^2 - x^2 = c^2t'^2 - x'^2$

$c^2t^2 - x^2 = 1^2 - 0^2 = 1$ «m^2»

for MP1 equation must be used.

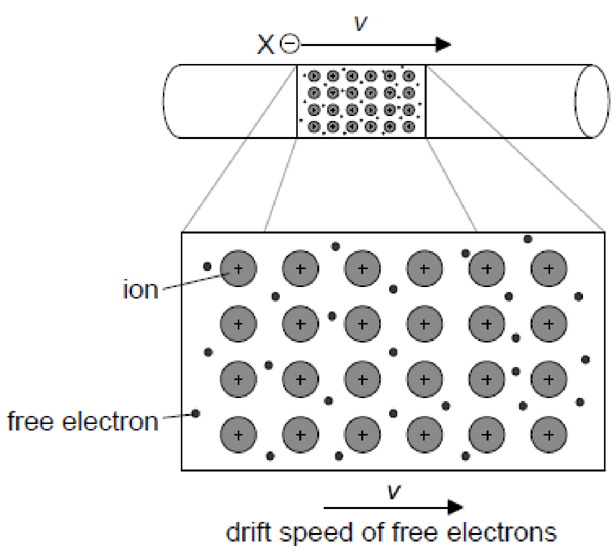
*Award **[2]** for correct answer that first finds x (1.33 m) and ct (1.66 m)*

[2 marks]

Examiners report

a.i. [N/A]
a.ii.[N/A]
b.i. [N/A]
b.ii.[N/A]
c.i. [N/A]
c.ii.[N/A]
c.iii.[N/A]

An electron X is moving parallel to a current-carrying wire. The positive ions and the wire are fixed in the reference frame of the laboratory. The drift speed of the free electrons in the wire is the same as the speed of the external electron X.



a. Define *frame of reference.* [1]

b. In the reference frame of the laboratory the force on X is magnetic. [4]

(i) State the nature of the force acting on X in this reference frame where X is at rest.

(ii) Explain how this force arises.

Markscheme

a. a coordinate system

OR

a system of clocks and measures providing time and position relative to an observer

OWTTE

b. i

electric
OR
electrostatic

ii

«as the positive ions are moving with respect to the charge,» there is a length contraction

therefore the charge density on ions is larger than on electrons

so net positive charge on wire attracts X

For candidates who clearly interpret the question to mean that X is now at rest in the Earth frame accept this alternative MS for bii
the magnetic force on a charge exists only if the charge is moving
an electric force on X , if stationary, only exists if it is in an electric field
no electric field exists in the Earth frame due to the wire
and look back at b i, and award mark for there is no electric or magnetic force on X

Examiners report

a. [N/A]
b. [N/A]

This question is about special relativity, simultaneity and length contraction.

a. One of the two postulates of special relativity may be stated as: [2]

> "The laws of physics are the same for all observers in inertial reference frames."

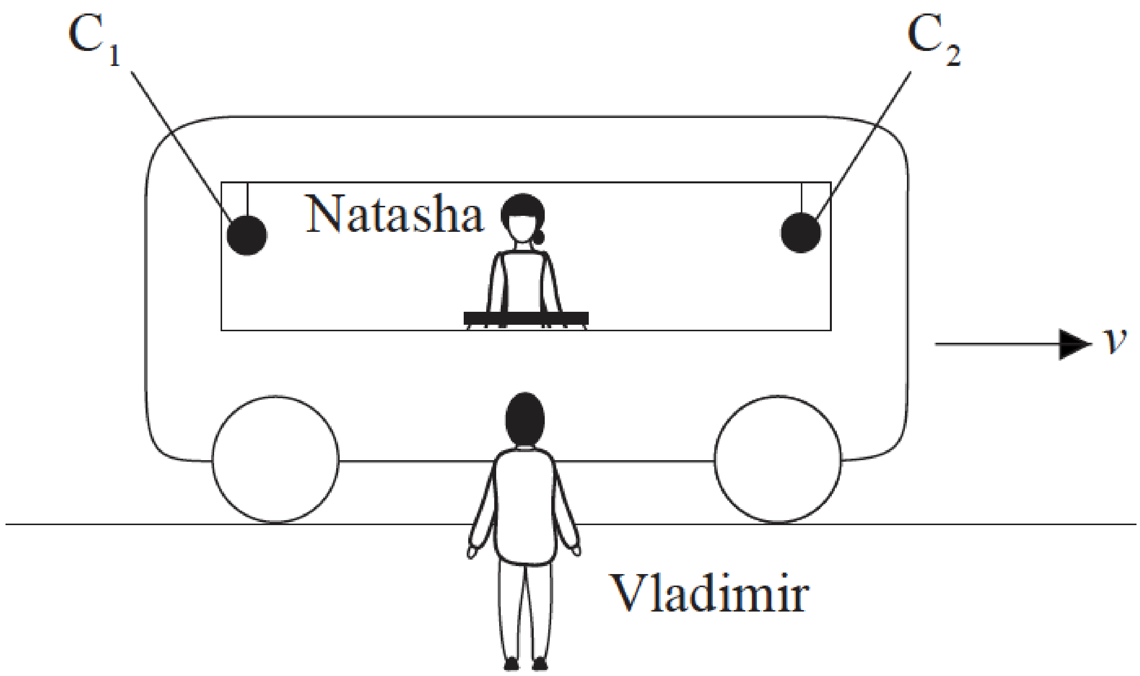
State

(i) what is meant by an inertial frame of reference.

(ii) the other postulate of special relativity.

b. In a thought experiment to illustrate the concept of simultaneity, Vladimir is standing on the ground close to a straight, level railway track. [4]

Natasha is in a railway carriage that is travelling along the railway track with constant speed *v* in the direction shown.



Natasha is sitting on a chair that is equidistant from each end of the carriage. At either end of the carriage are two clocks C_1 and C_2. Next to Natasha is a switch that, when operated, sends a signal to each clock. The clocks register the time of arrival of the signals. At the instant that Natasha and Vladimir are opposite each other, Natasha operates the switch. According to Natasha, C_1 and C_2 register the same time of arrival of each signal.

Explain, according to Vladimir, whether or not C_1 and C_2 register the same time of arrival for each signal.

c. The speed *v* of the carriage is 0.70c. Vladimir measures the length of the table at which Natasha is sitting to be 1.0 m. [4]

(i) Calculate the length of the table as measured by Natasha.

(ii) Explain which observer measures the proper length of the table.

Markscheme

a. (i) (a reference frame) in which Newton's first law holds true/that is not accelerating/that is moving with constant velocity;

(ii) the speed of light in a vacuum/free space is the same for all inertial observers;

b. *Look for these main points:*

signal from switch travels at same speed *c* to each lamp;

but during signal transfer C_1 moves closer to/C_2 moves away from source of signal;

since speed of light is independent of speed of source, signal reaches C_1 before C_2/C_2 after C_1;

according to Vladamir C_1 registers arrival of signal before C_2/C_2 registers arrival of signal after C_1;

c. (i) $\gamma = \frac{1}{\sqrt{1-(0.70)^2}} = 1.4;$

$L_0 = \gamma L$;

=1.4m;

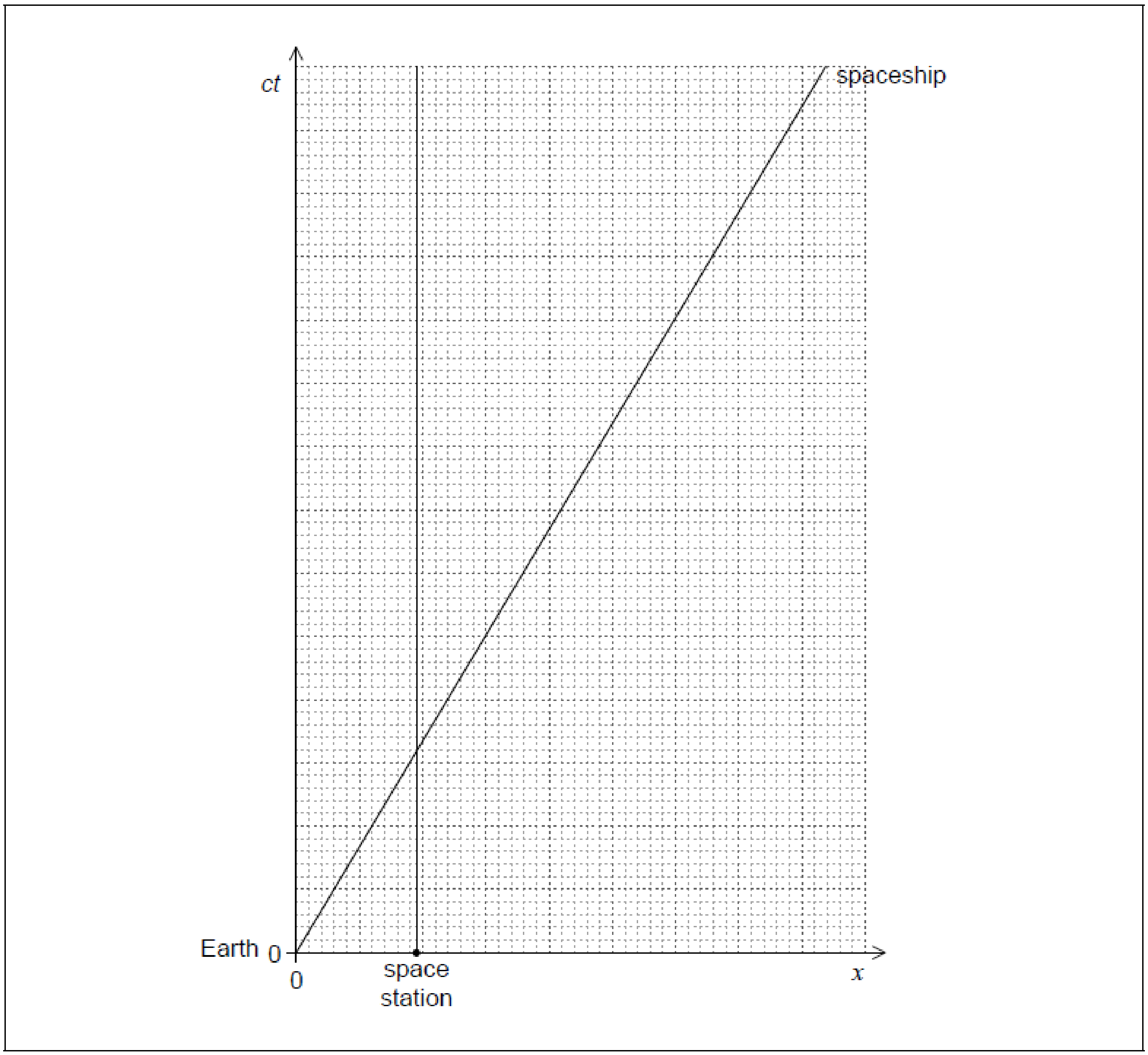
(ii) Natasha
since proper length is defined as the length of the object measured by the observer at rest with respect to the object;

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

When a spaceship passes the Earth, an observer on the Earth and an observer on the spaceship both start clocks. The initial time on both clocks is 12 midnight. The spaceship is travelling at a constant velocity with $\gamma = 1.25$. A space station is stationary relative to the Earth and carries clocks that also read Earth time.

Some of the radio signal is reflected at the surface of the Earth and this reflected signal is later detected at the spaceship. The detection of this signal is event B. The spacetime diagram is shown for the Earth, showing the space station and the spaceship. Both axes are drawn to the same scale.



a. Calculate the velocity of the spaceship relative to the Earth. [1]

b. The spaceship passes the space station 90 minutes later as measured by the spaceship clock. Determine, for the reference frame of the Earth, the distance between the Earth and the space station. [3]

c. As the spaceship passes the space station, the space station sends a radio signal back to the Earth. The reception of this signal at the Earth is event A. Determine the time on the Earth clock when event A occurs. [2]

d.i. Construct event A and event B on the spacetime diagram. [3]

d.ii. Estimate, using the spacetime diagram, the time at which event B occurs for the spaceship. [2]

Markscheme

a. $0.60c$

OR

1.8×10^8 «m s^{-1}»

[1 mark]

b. ***ALTERNATIVE 1***

time interval in the Earth frame = 90 × γ = 112.5 minutes

«in Earth frame it takes 112.5 minutes for ship to reach station»

so distance = 112.5 × 60 × $0.60c$

$1.2 \times 10m^{12}$ «m»

ALTERNATIVE 2

Distance travelled according in the spaceship frame = 90 × 60 × $0.6c$

= 9.72×10^{11} «m»

Distance in the Earth frame «= 9.72×10^{11} × 1.25» = 1.2×10^{12} «m»

[3 marks]

c. signal will take «112.5 × 0.60 =» 67.5 «minutes» to reach Earth «as it travels at *c*»

OR

signal will take «$\frac{1.2\times10^{12}}{3\times10^{8}}$ =» 4000 «*s*»

total time «= 67.5 + 112.5» = 180 minutes ***or*** 3.00 h or 3:00am

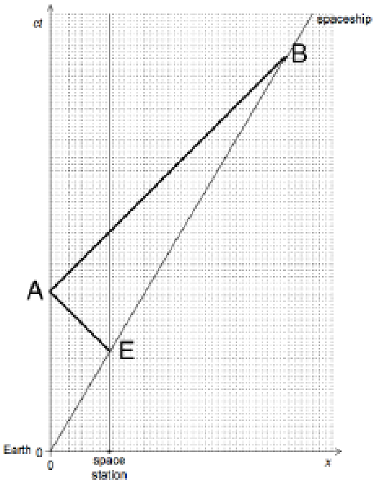
[2 marks]

d.i. line from event E to A, upward and to left with A on *ct* axis (approx correct)

line from event A to B, upward and to right with B on *ct*' axis (approx correct)

both lines drawn with ruler at 45 (judge by eye)

eg:



[3 marks]

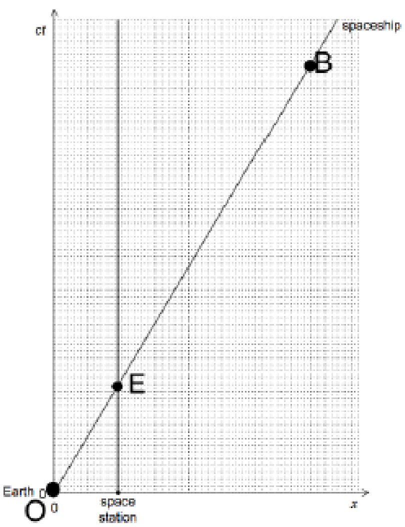
d.ii ***ALTERNATIVE 1***

«In spaceship frame»

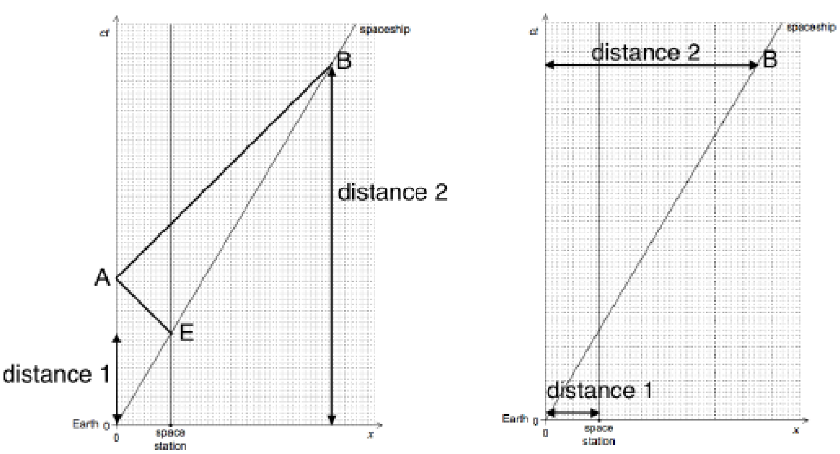
Finds the ratio $\frac{OB}{OE}$ (or by similar triangles on *x* or *ct* axes), value is approximately 4

hence time elapsed ≈ 4 × 90 mins ≈ 6h «so clock time is ≈ 6:00»

Alternative 1:



Allow similar triangles using x-axis or ct-axis, such as $\frac{distance\ 2}{distance\ 1}$ *from diagrams below*



ALTERNATIVE 2

«In Earth frame»

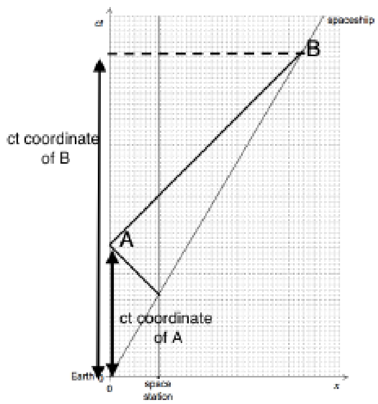
Finds the ratio

$\frac{ct \text{ coordinate of B}}{ct \text{ coordinate of A}}$, value is approximately 2.5

hence time elapsed ≈ $\frac{2.5 \times 3\text{h}}{1.25}$ ≈ 6h

«so clocktime is ≈ 6:00»

ALTERNATIVE 2:



[2 marks]

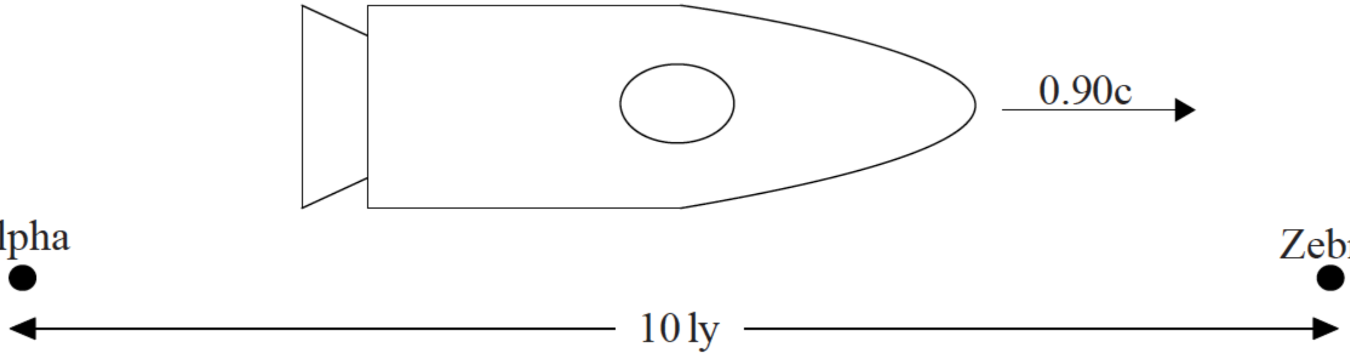
Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d.i. [N/A]
d.ii. [N/A]

This question is about relativistic kinematics.

a. State what is meant by an inertial frame of reference. [1]

b. A spaceship travels from space station Alpha to space station Zebra at a constant speed of 0.90c relative to the space stations. The distance from Alpha to Zebra is 10ly according to space station observers. At this speed *γ*=2.3. [3]



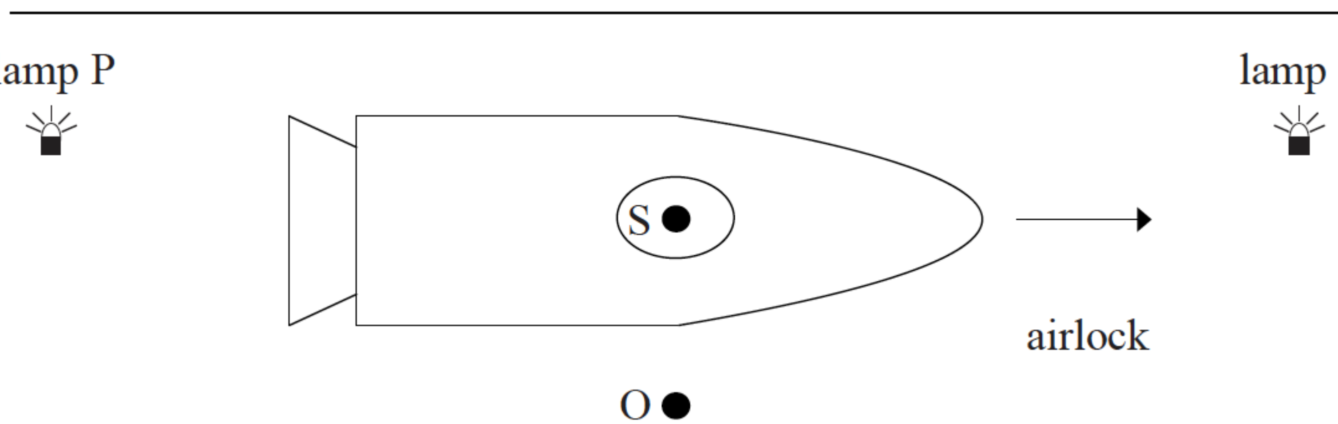
Calculate the time taken to travel between Alpha and Zebra in the frame of reference of an observer

(i) on the Alpha space station.

(ii) on the spaceship.

c. Explain which of the time measurements in (b)(i) and (b)(ii) is a proper time interval. [2]

d. The spaceship arrives at Zebra and enters an airlock at constant speed. O is an observer at rest relative to the airlock. Two lamps P and Q emit a flash simultaneously according to the observer S in the spaceship. At that instant, O and S are opposite each other and midway between the lamps. [3]



Discuss whether the lamps flash simultaneously according to observer O.

Markscheme

a. a co-ordinate system (in which measurements of distance and time can be made);

which is not accelerating;

in which Newton's laws are valid;

b. (i) $\left(\frac{10}{0.90c} =\right) 11\text{yr};$

$\left(= 3.5 \times 10^8\text{s}\right);$

This is a question testing units for this option. Do not award mark for an incorrect or missing unit.

(ii) distance according to spaceship observer $= \frac{10}{2.3} (= 4.3\text{ly});$
so time for spaceship $= \frac{4.3}{0.90} = 4.8\,(\text{yr});$

c. between two events occurring at the same point in space / shortest time measured;

so proper time interval measured by observer on spaceship;

Do not award second marking point unless a reason has been attempted.

d. speed of light is the same for both observers O and S / events simultaneous in stationary reference frame are not (necessarily) simultaneous in moving reference frame;

S is moving so PS will be longer than QS when light reaches S;

so if light arrives simultaneously then light from P will have been in transit for longer than Q;

therefore P emits a flash before Q;

Examiners report

a. There were a large variety of answers to (a). Many candidates stated that the frame of reference is not accelerated. Many candidates did not explain the term “frame of reference” in terms of a “co-ordinate system”. It was a rare answer that earned more than one mark.

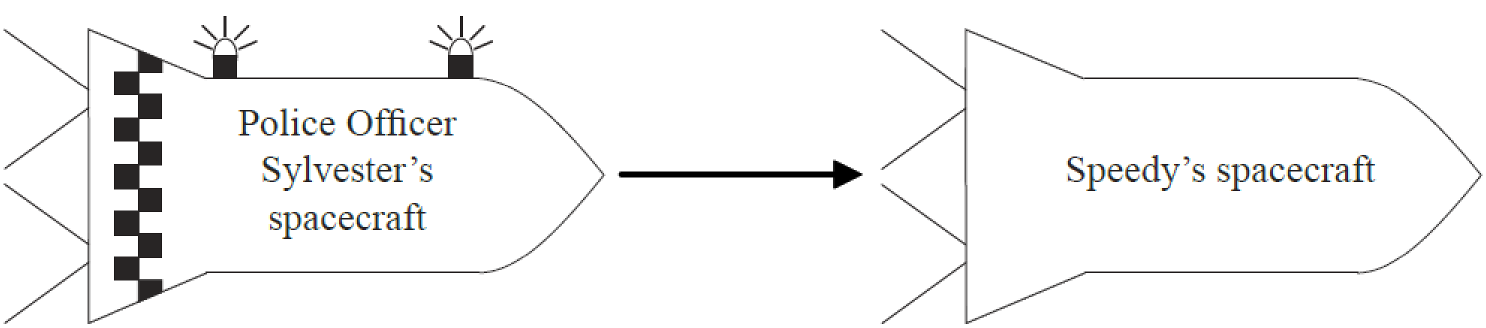
b. In (b)(i), the majority of candidates properly calculated the time. Some wrote the incorrect unit (ly) instead of y or s. There is room for improvement in responses to (b)(ii). The vast majority of candidates used the formula for time dilation. They did not notice that it is not normal for the observer on the spaceship to know the time measured on the space station. The correct calculation, length and speed measured, appeared only very rarely.

c. There was a good variety of answers to (c). Many candidates still do not know the term proper time interval, clearly defined in relativity. Many incorrectly referred to both events occurring in one frame of reference rather than one point in space in their answer. Most did attempt a reason.

d. In (d) many candidates proved that they understood the concept of simultaneity. However, many did not respond to the command term “discuss”. Many candidates were confused between object (in a specific frame of reference) and event.

This question is about relativistic kinematics.

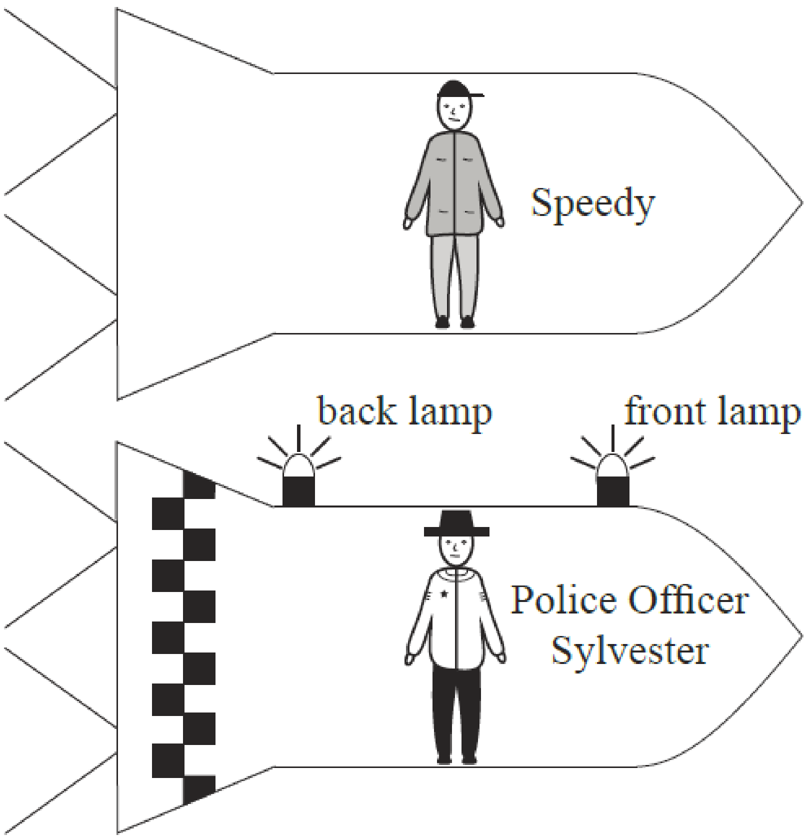
Speedy is in a spacecraft being chased by Police Officer Sylvester. In Officer Sylvester’s frame of reference, Speedy is moving directly towards Officer Sylvester at 0.25c.



a. Describe what is meant by a frame of reference. [2]

b. At a later time the police spacecraft is alongside Speedy's spacecraft. The police spacecraft is overtaking Speedy's spacecraft at a constant velocity. [4]

Officer Sylvester is at a point midway between the flashing lamps, both of which he can see. At the instant when Officer Sylvester and Speedy are opposite each other, Speedy observes that the blue lamps flash simultaneously.



State and explain which lamp is observed to flash first by Officer Sylvester.

c. The police spacecraft is travelling at a constant speed of 0.5c relative to Speedy's frame of reference. The light from a flash of one of the lamps travels across the police spacecraft and is reflected back to the light source. Officer Sylvester measures the time taken for the light to return to the source as 1.2×10^{-8}s. [4]

(i) Outline why the time interval measured by Officer Sylvester is a proper time interval.

(ii) Determine, as observed by Speedy, the time taken for the light to travel across the police spacecraft and back to its source.

Markscheme

a. a coordinate system / set of rulers / clocks;

in which measurements of distance/position and time can be made;

b. light travels at same speed for both observers;

during transit time Officer Sylvester moves towards point of emission at front/away from point of emission at back;

light from front arrives first as distance is less / light from back arrives later as distance is more;

Officer Sylvester observes the front lamp flashes first;

*Award **[0]** for a bald correct answer without correct explanation*

c. (i) the two events occur at the same place (in the same frame of reference) / shortest measured time;

(ii) $y = \left(\frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \right) 1.15;$

Δt=1.15 x Δt_0;

1.48 x 10^{-8}(s);

Examiners report

a. There were some good, clear answers to (a) but there were many vague statements about “point of view”.

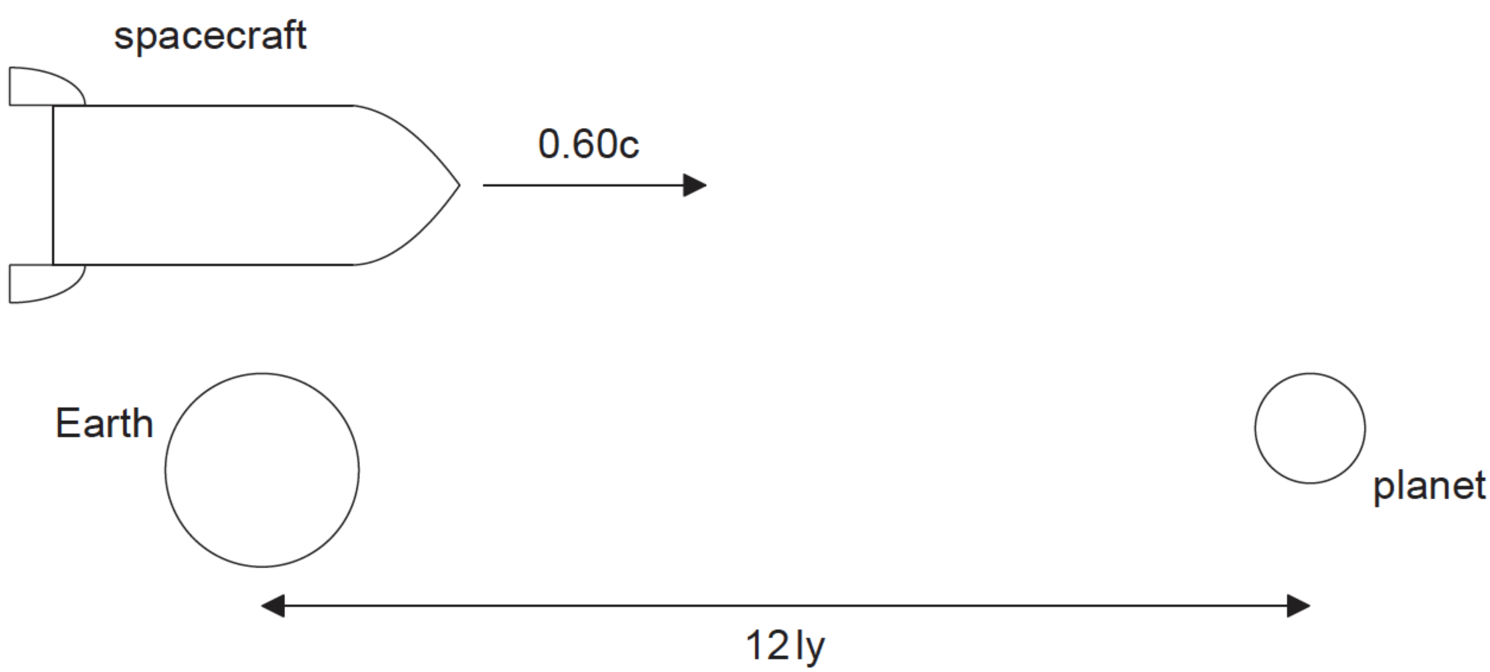
b. There were also some good answers to (b) but most candidates struggled. It was rarely stated that light travels at the same speed for all observers.

c. (i) was well done and

(ii) was very well done.

This question is about relativistic kinematics.

A spacecraft leaves Earth and moves towards a planet. The spacecraft moves at a speed 0.60c relative to the Earth. The planet is a distance of 12ly away according to the observer on Earth.



a. Determine the time, in years, that it takes the spacecraft to reach the planet according to the [3]

(i) observer on Earth.

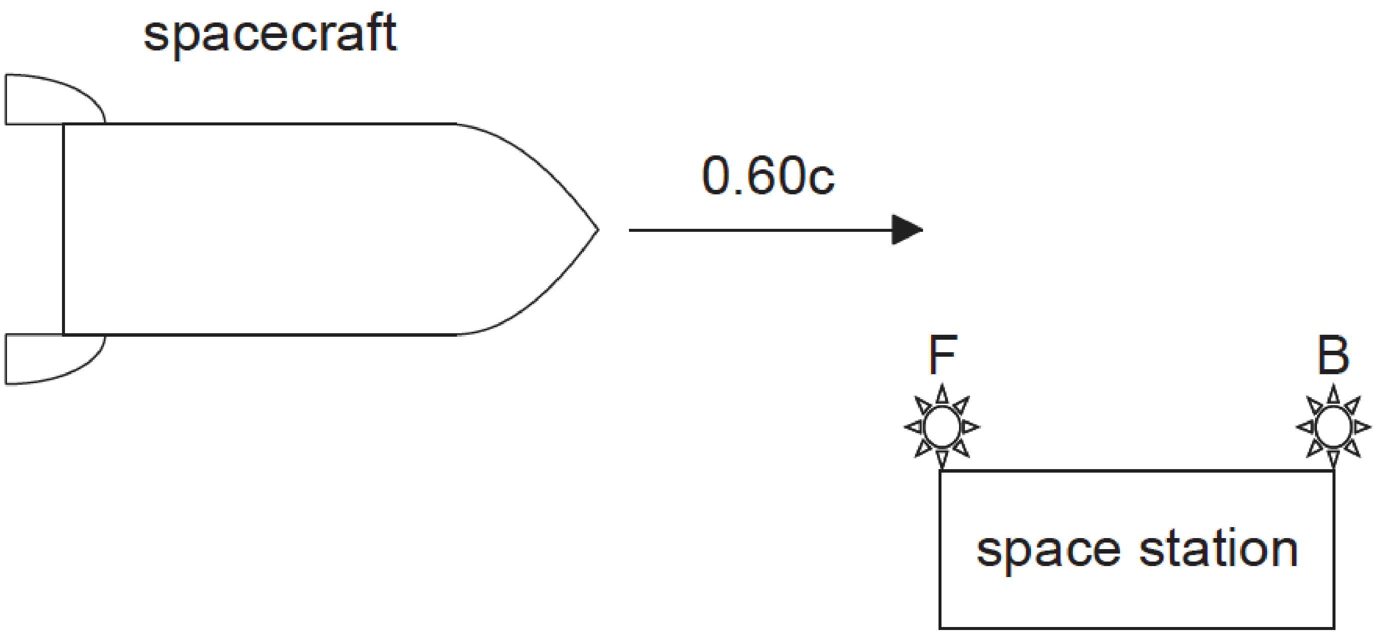
(ii) observer in the spacecraft.

b. The spacecraft passes a space station that is at rest relative to the Earth. The proper length of the space station is 310 m. [3]

(i) State what is meant by proper length.

(ii) Calculate the length of the space station according to the observer in the spacecraft.

c. F and B are two flashing lights located at the ends of the space station, as shown. As the spacecraft approaches the space station in (b), F and B turn on. The lights turn on simultaneously according to the observer on the space station who is midway between the lights. [4]



State and explain which light, F **or** B, turns on first according to the observer in the **spacecraft**.

Markscheme

a. (i) $\left(\frac{12\text{ly}}{0.60\text{c}}=\right) 20\ (\text{yr})$ ***or*** 6.3×10^{8} (s);

(ii) $y=\left(\frac{1}{\sqrt{1-0.60^2}}=\right) 1.25;$

$\Delta t_0=\left(\frac{\Delta t}{y}=\frac{20}{1.25}=\right) 16\ (\text{yr})$ ***or*** 5.0×10^{8} (s); *(allow ECF from (a)(i));*

*This question is worth **[2]**, but it is easy to accidentally award **[1]**.*

b. (i) the length of a body in the rest frame of the body;

Do not accept "event" instead of "object/body".

Do not accept "in the same frame" unless rest (OWTTE) is mentioned.

(ii) $l=\frac{310}{1.25}$; *(allow ECF from (a)(ii))*
=250(m);
*This question is worth **[2]**, but it is easy to accidently award **[1]**.*

c. according to the spacecraft observer, the space station observer receives light from B and F at the same time;

for the spacecraft observer the space station observer moves away from the waves from B/towards the waves from F;

but the speed of light is constant;

according to the spacecraft observer light from B must be emitted first;

Do not award second marking point for answers that refer to light the spacecraft observer SEES or to distances to the spacecraft.

Examiners report

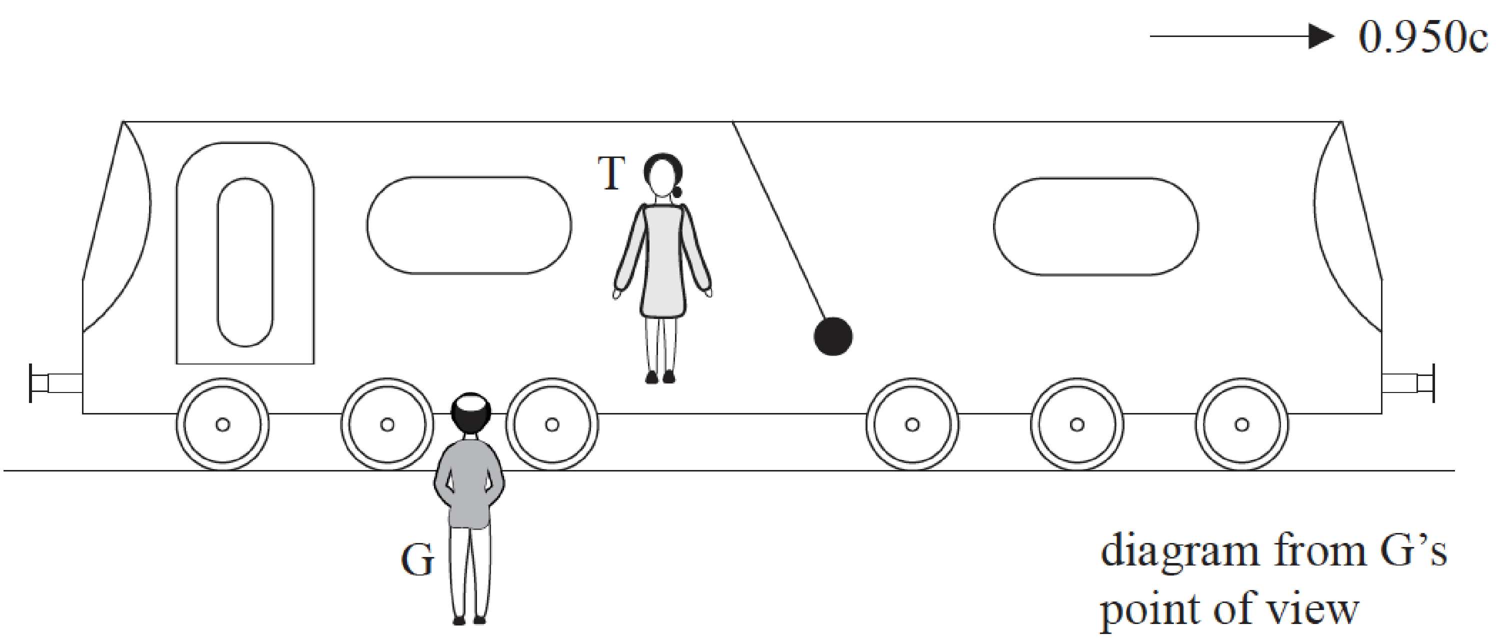
a. Part (a) was answered very well. This year almost nobody worked in seconds and so the answers were easily obtained. As usual there were candidates who got time dilation the wrong way round. The time interval for the Earth clocks is dilated (longer) but some candidates think that the time interval on the "moving" clock is dilated. It is best not to think of motion, but to realise that the single clock at both events records the shortest time interval.

b. In (b) a very common misconception with proper length is to just say that the object must be measured in the same frame of reference as the observer. Well this is always true of course, but only if the object is at rest in the observer's frame is it proper length. Everything is in everything else's frame. Gradually more and more candidates are answering simultaneity questions correctly. This year almost 3% could correctly explain why light B emits waves before light F as perceived from the spacecraft frame. The other 97% thought that the question was asking about which light the spacecraft observer sees first.

c. [N/A]

This question is about relativistic kinematics.

In a thought experiment, a train is moving at a speed of 0.950c relative to the ground. A pendulum attached to the ceiling of the train is set into oscillation.

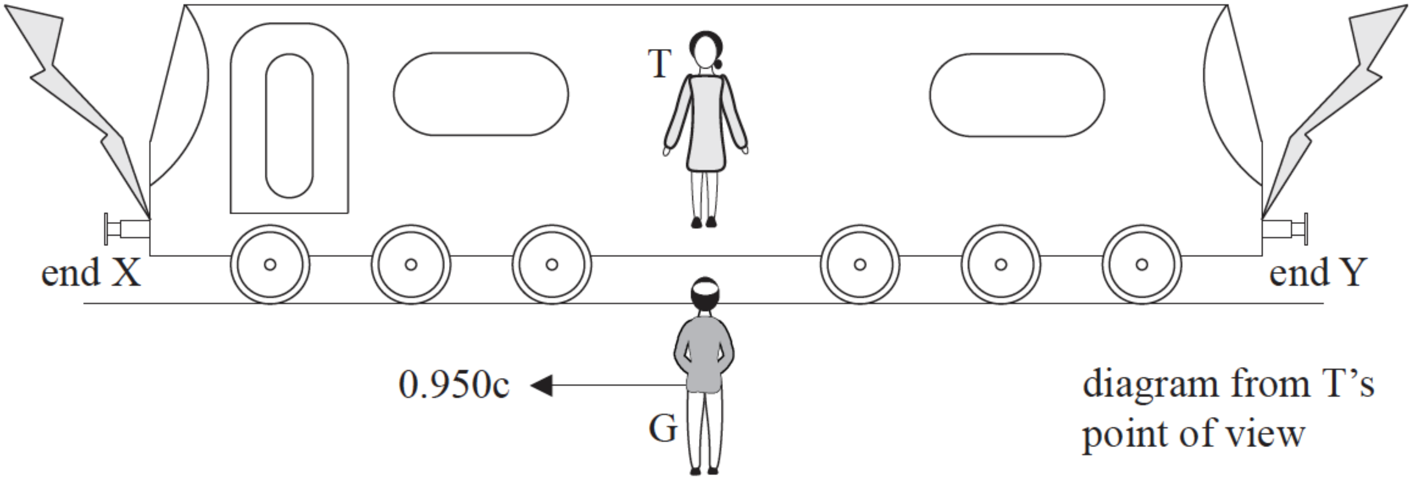


An observer T on the train and an observer G on the ground measure the period of oscillation of the pendulum.

a. State and explain whether the pendulum period is a proper time interval for observer T, observer G **or** both T and G. [2]

b. Observer T measures the period of oscillations of the pendulum to be 0.850s. Calculate the period of oscillations according to observer G. [2]

c. Observer T is standing in the middle of a train watched by observer G at the side of the track. Two lightning strikes hit the ends of the train. The strikes are simultaneous **according to observer T.** [4]



Light from the strikes reaches both observers.

(i) Explain why, according to observer G, light from the two strikes reaches observer T at the same time.

(ii) Using your answer to (i), explain why, according to observer G, end X of the train was hit by lightning first.

Markscheme

a. only T measures the proper time interval;

for T the pendulum is (a single clock) at rest/same point in space;

Do NOT simply allow that the pendulum is in the same frame as T.

b. $\gamma = \left(\frac{1}{\sqrt{1-0.95^2}} =\right) 3.20;$

$T = (\gamma T_0 = 3.20 \times 0.85 =) \, 2.72\text{s};$

c. (i) the arrivals at T of the light from the two strikes occurs at the same point in space for T and are simultaneous for T;

so the arrivals of the light are simultaneous for all other observers as well;

or

T measures a zero proper time interval for the arrivals of the light;
so G measures a time interval equal to γ×0=0 also;

(ii) according to G, T is moving away from the light from the left strike and yet receives the light at the same time as the light from the right strike;
since the speed of light is the same for light from both strikes;
the left strike occurred first
No marks for just stating left strike is first. Given.

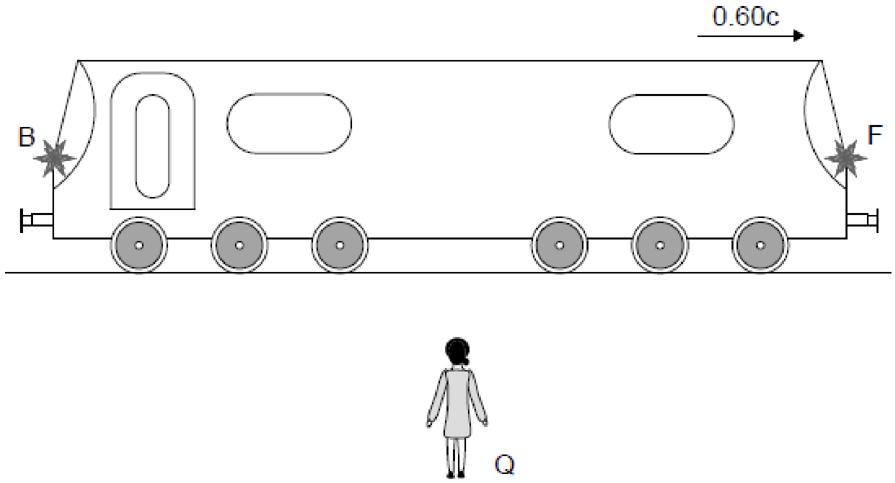
Examiners report

a. [N/A]
b. [N/A]
c. [N/A]

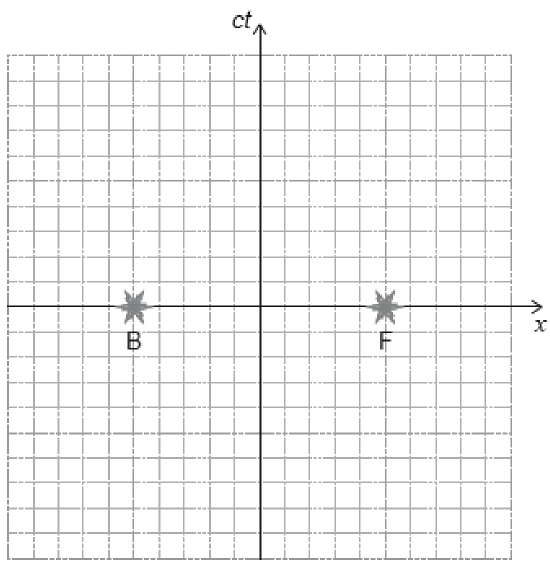
An observer P sitting in a train moving at a speed *v* measures that his journey takes a time Δt_P. An observer Q at rest with respect to the ground measures that the journey takes a time Δt_Q.

According to Q there is an instant at which the train is completely within the tunnel.

At that instant two lights at the front and the back of the train are turned on simultaneously according to Q.



The spacetime diagram according to observer Q shows event B (back light turns on) and event F (front light turns on).



a. State which of the two time intervals is a proper time. [1]

b. Calculate the speed *v* of the train for the ratio $\frac{\Delta t_{\mathrm{P}}}{\Delta t_{\mathrm{Q}}} = 0.30.$ [2]

c. Later the train is travelling at a speed of 0.60c. Observer P measures the length of the train to be 125 m. The train enters a tunnel of length 100 m according to observer Q. [2]

Show that the length of the train according to observer Q is 100 m.

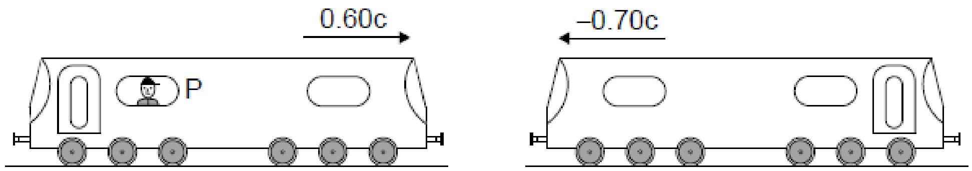
d.i. Draw the time ct' and space x' axes for observer P's reference frame on the spacetime diagram. [1]

d.ii. Deduce, using the spacetime diagram, which light was turned on first according to observer P. [3]

d.iii. Apply a Lorentz transformation to show that the time difference between events B and F according to observer P is 2.5 × 10^{-7} s. [1]

d.iv. Demonstrate that the spacetime interval between events B and F is invariant. [2]

e. A second train is moving at a velocity of –0.70c with respect to the ground. [2]



Calculate the speed of the second train relative to observer P.

Markscheme

a. Δt_P / observer sitting in the train

[1 mark]

b. $\gamma = \frac{\Delta t_Q}{\Delta t_P}$ = «$= \frac{1}{0.30}$» = 3.3

to give v = 0.95c

[2 marks]

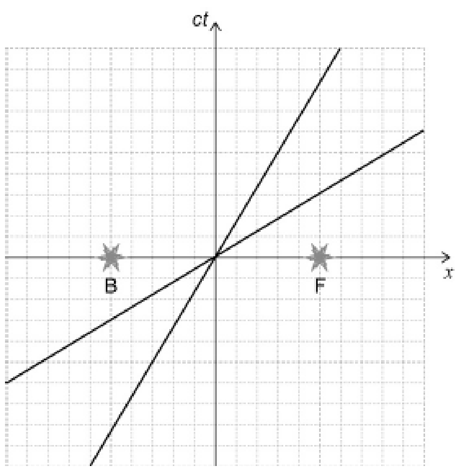
c. γ = 1.25

«length of train according Q» = 125/1.25

«giving 100m»

[2 marks]

d.i.

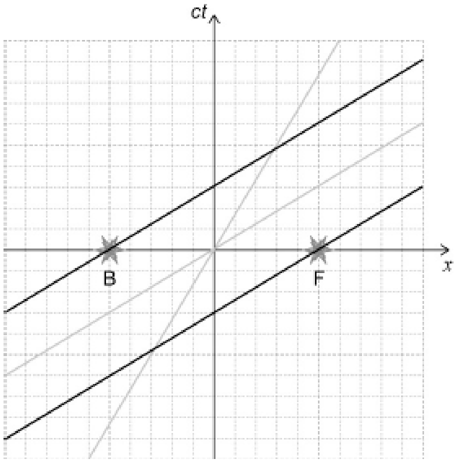


axes drawn with correct gradients of $\frac{5}{3}$ for ct' and 0.6 for x'

*Award **[1]** for one gradient correct **and** another approximately correct.*

[1 mark]

d.ii.



lines parallel to the x' axis and passing through B and F

intersections on the ct' axis at B' and F' shown

light at the front of the train must have been turned on first

[3 marks]

d.iii. $\Delta t' = 1.25 \times \frac{0.6\times100}{3\times10^8}$

«2.5 × 10^{-7}»

Allow ECF for gamma from (c).

[1 mark]

d.iv. according to P: $\left(3\times10^8\times2.5\times10^{-7}\right)^2 - 125^2 =$ «–» 10000

according to Q: $\left(3\times10^8\times0\right)^2 - 100^2 =$ «–» 10000

[2 marks]

e. $u' = \frac{-0.7-0.6}{1+0.7\times0.6}$ **c**

= «–» 0.92c

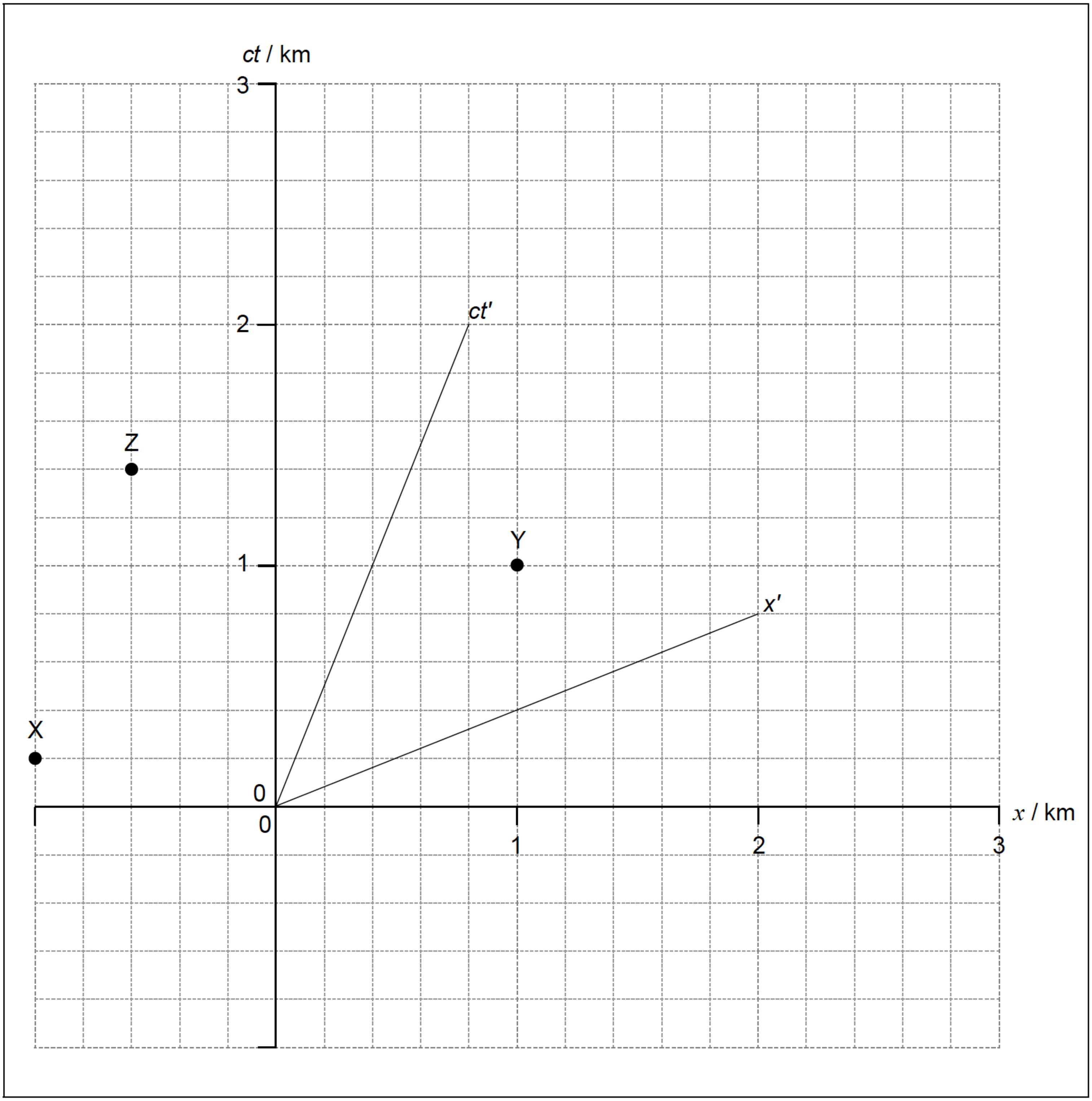
[2 marks]

Examiners report

a. [N/A]
b. [N/A]
c. [N/A]
d.i. [N/A]
d.ii. [N/A]
d.iii. [N/A]
d.iv. [N/A]
e. [N/A]

An observer on Earth watches a rocket A. The spacetime diagram shows part of the motion of A in the reference frame of the Earth observer. Three flashing light beacons, X, Y and Z, are used to guide rocket A. The flash events are shown on the spacetime diagram.

The diagram shows the axes for the reference frames of Earth and of rocket A. The Earth observer is at the origin.



a. For the reference frame of the Earth observer, calculate the speed of rocket A in terms of the speed of light *c*. [2]

b. Using the graph opposite, deduce the order in which [4]

(i) the beacons **flash** in the reference frame of rocket A.

(ii) the Earth observer **sees** the beacons flash.

Markscheme

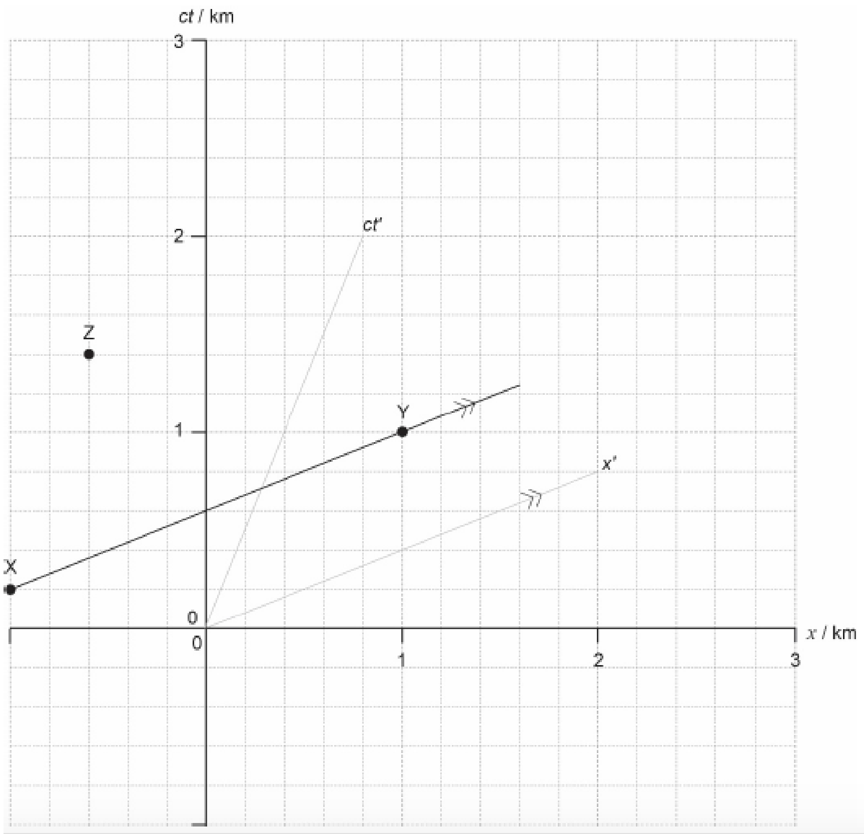
a. Δct=2.0km ***AND*** Δx=0.8km

$v = \frac{\Delta x}{\Delta ct} = \frac{0.8}{2.0} = 0.4c$

Allow any correct read-off from graph.
Accept answers from 0.37c to 0.43c.

b. (i) events at same perpendicular distance from x' axis of rocket are simultaneous ***OR*** line joining X to Y is parallel to x' axis

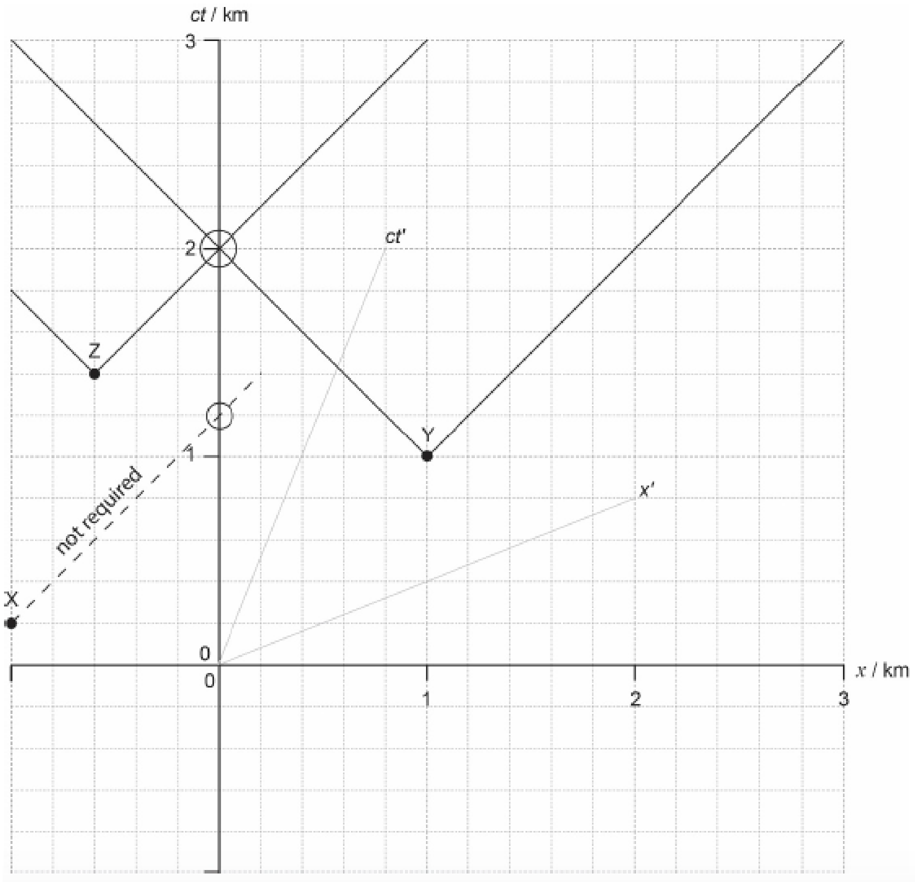
X and Y simultaneously then Z



MP1 may be present on spacetime diagram.

(ii) constructs light cones to intersect worldline of observer

X first followed by Y and Z simultaneously



Only Y and Z light cones need to be seen.

Examiners report

a. [N/A]
b. [N/A]