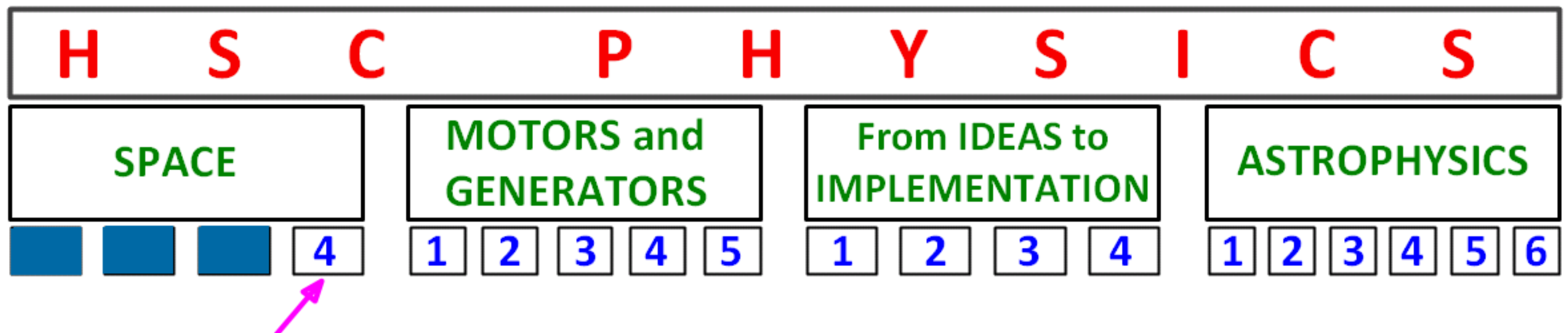


# SPACE

1<sup>st</sup> Quarter; Module 1

## PERIOD 22

Inertial Frames of Reference, Principle of Relativity



## Space 4

Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light

*Students learn to:*

- outline the features of the aether model for the transmission of light
- describe and evaluate the Michelson-Morley attempt to measure the relative velocity of the Earth through the aether
- discuss the role of the Michelson-Morley experiments in making determinations about competing theories
- outline the nature of inertial frames of reference
- discuss the principle of relativity
- describe the significance of Einstein's assumption of the constancy of the speed of light
- identify that if  $c$  is constant then space and time become relative
- discuss the concept that length standards are defined in terms of time in contrast to the original metre standard
- explain qualitatively and quantitatively the consequence of special relativity in relation to:
  - the relativity of simultaneity
  - the equivalence between mass and energy
  - length contraction
  - time dilation
  - mass dilation
- discuss the implications of mass increase, time dilation and length contraction for space travel



## Space 4

**Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light**

*Students:*

- gather and process information to interpret the results of the Michelson-Morley experiment
- perform an investigation to help distinguish between non-inertial and inertial frames of reference
- analyse and interpret some of Einstein's thought experiments involving mirrors and trains and discuss the relationship between thought and reality
- analyse information to discuss the relationship between theory and the evidence supporting it, using Einstein's predictions based on relativity that were made many years before evidence was available to support it
- solve problems and analyse information using:

$$E = mc^2$$

$$l_v = l_0 \sqrt{1 - \frac{v^2}{c^2}}$$

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

$$m_v = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

# AETHER MODEL

## Why the need for such a model?

- ✦ Having concluded that light travels as a wave, nineteenth-century physicists turned to other wave motions in order to better understand light.
- ✦ There were many others known, including sound waves, waves in a spring, water waves, and earthquake waves.
- ✦ All of these waveforms need a medium through which to travel, and so it was believed that **light waves would also require a medium**.
- ✦ Nobody could find such a medium but belief in its existence was so strong that it was given a name, the **'luminiferous aether'**, and its properties were identified.

## The aether:

- ✦ filled all of space, had low density and was perfectly transparent
- ✦ permeated all matter and yet was completely permeable to material objects
- ✦ had great elasticity to support and propagate the light waves.

## Then

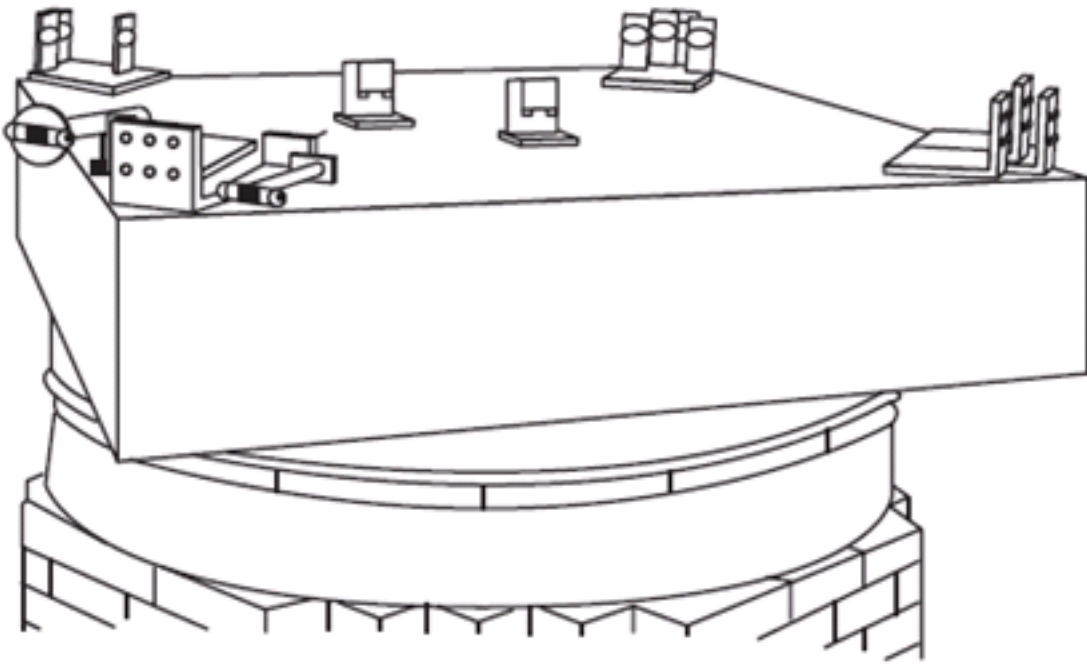
- ✦ The search for the aether was to occupy physicists for several decades before it was finally accepted that;
  - (a) **the aether does not actually exist**, and
  - (b) electromagnetic waves (including light) are unique in that they **do not require a medium** of any sort in order to move.



## Michelson-Morley Experiment

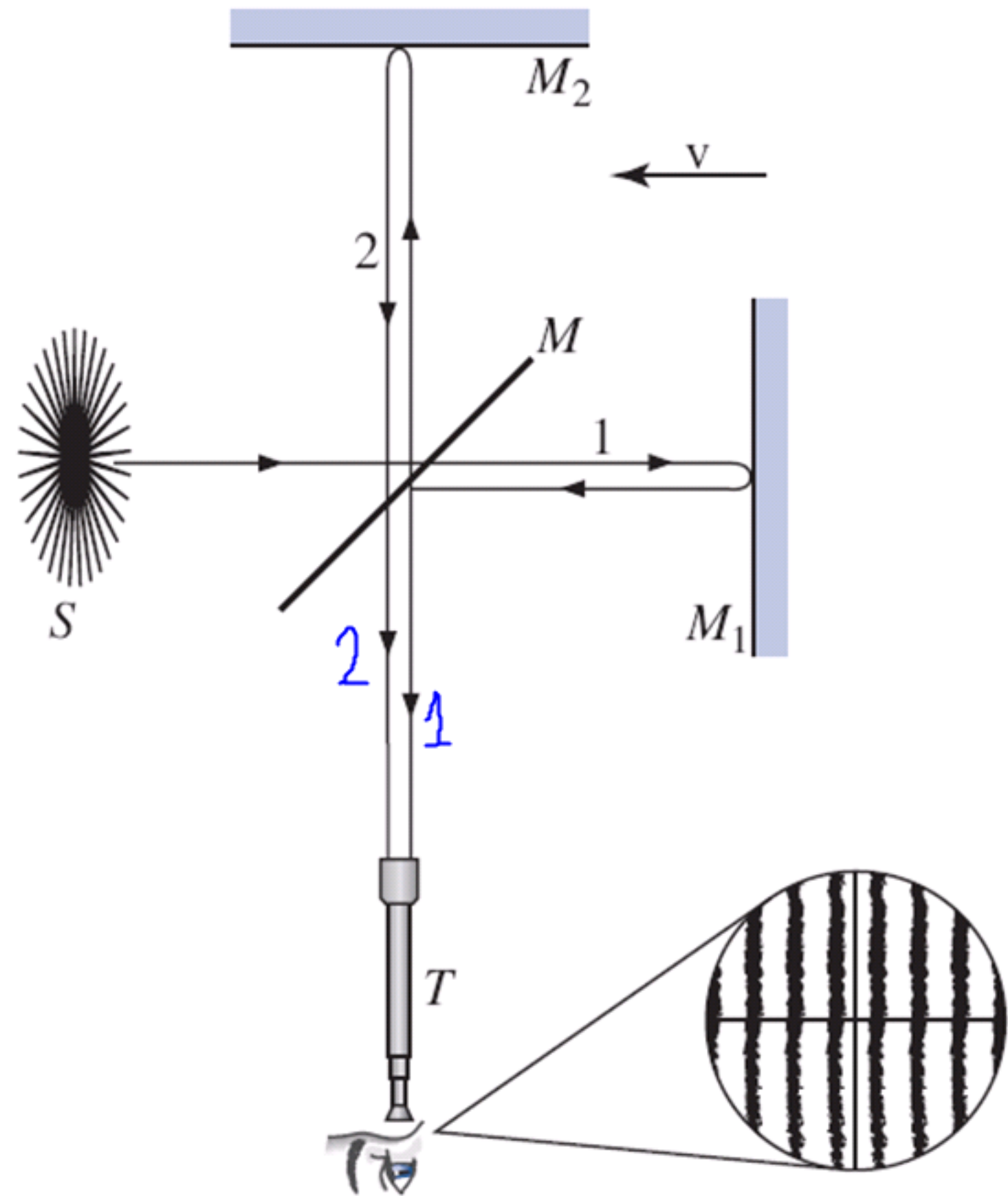
Aim: to measure the speed of Earth through aether

*Their apparatus*

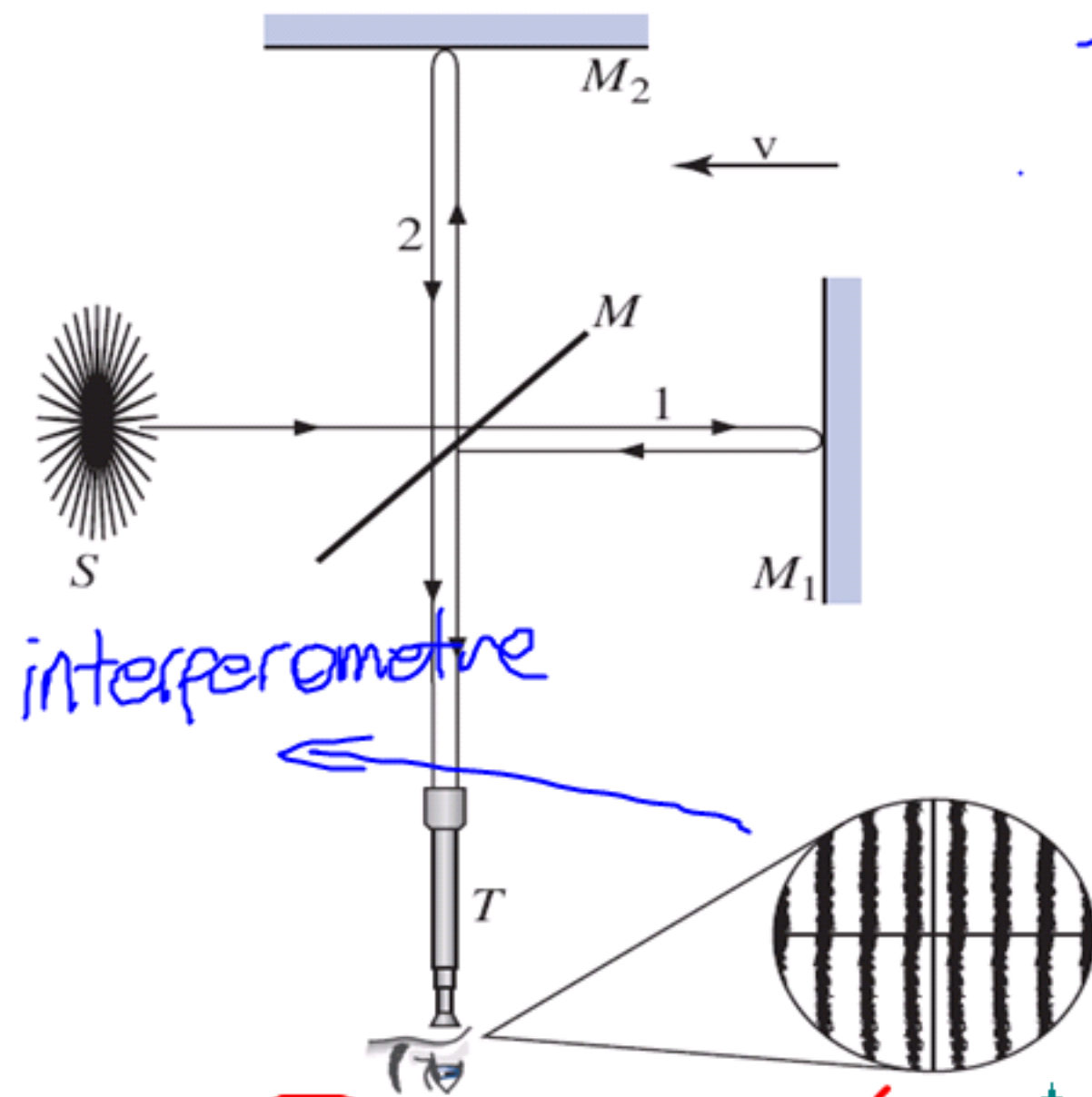


**Figure 5.4** *The apparatus of the Michelson–Morley experiment set up on a large stone block, to keep it rigid, and floating on mercury so that it can be easily rotated 90 degrees*

*The diagram*



## BACK TO M-M



\* path 1 is against the "ether wind"  
 \* so it is expected that light from path 1 to arrive the interferometer after the light from path 2.

\* there must be a "path difference" which causes an interference pattern.

\* as the device rotated by  $90^\circ$  the fringes must "swap" (interpose)

+ The method of comparing the light rays involves a very sensitive effect called 'interference', and hence this apparatus is referred to as an 'interferometer'.

+ Essentially, when looking into the telescope a pattern of light and dark bands will be seen, as shown in figure.

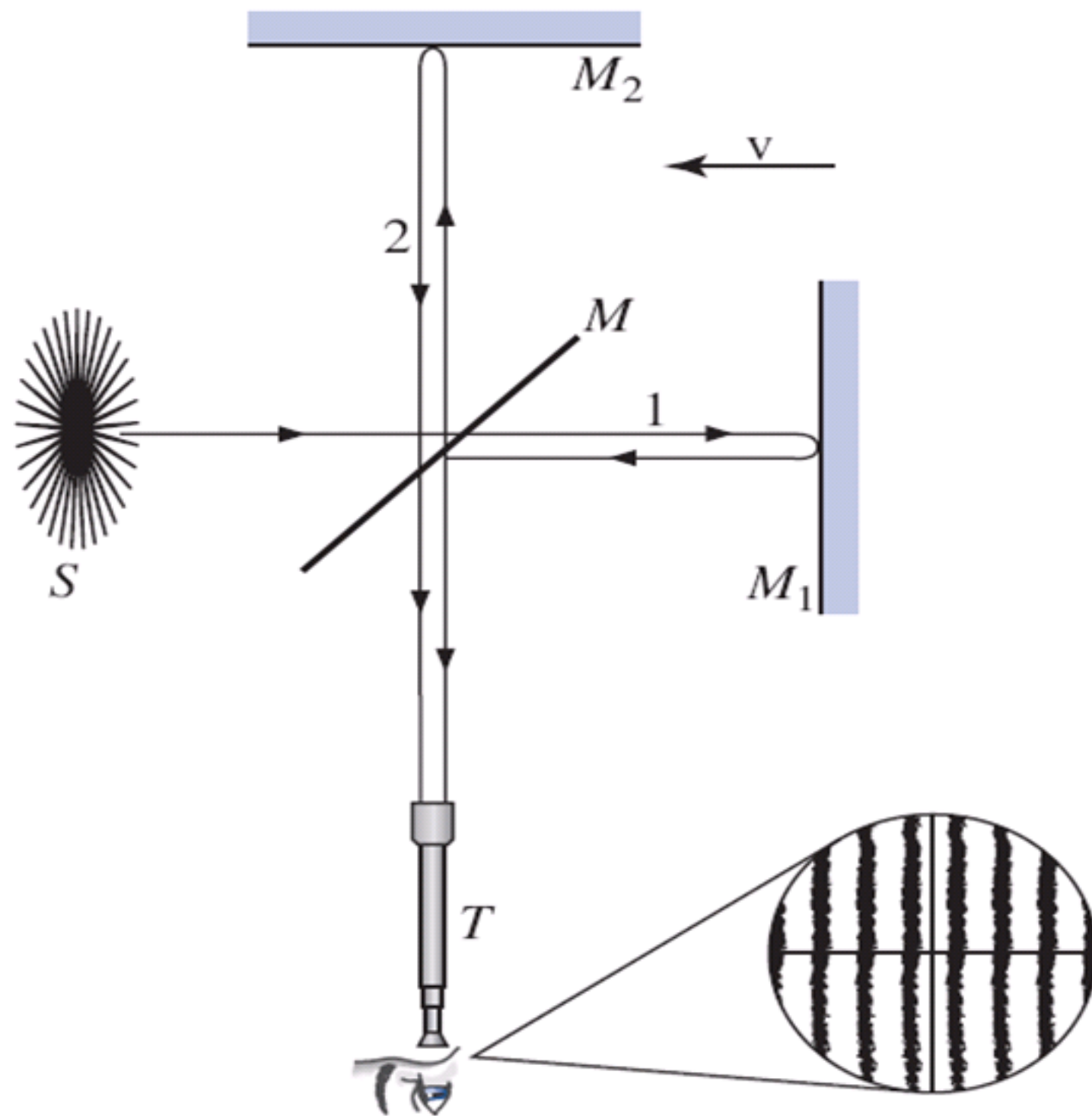
+ If the ether wind exists, so that one light ray is indeed faster than the other, then when the apparatus is rotated, so that the rays are interposed, the interference pattern should be seen to shift.

However, no such shift was observed.

→ null result

they expected to observe a "swap" of black/bright fringes, as the device was rotated  $90^\circ$ .

# MICHELSON & MORLEY EXPERIMENT REVISITED



- ✦ The method of comparing the light rays involves a very sensitive effect called 'interference', and hence this apparatus is referred to as an 'interferometer'.
- ✦ Essentially, when looking into the telescope a pattern of light and dark bands will be seen, as shown in figure.
- ✦ If the aether wind exists, so that one light ray is indeed faster than the other, then when the apparatus is rotated, so that the rays are interposed, the interference pattern should be seen to shift.
- ✦ **However, no such shift was observed.**



## FRAMES OF REFERENCE

Inertial Frames of Reference  
(**IFR**)

IFRs are either moving  
at constant velocity

or Stationary

$$v = \text{constant}$$

OR

$$v = 0$$

non-Inertial  
Frames of Reference

nIFRs ~~are~~ have  
acceleration,  
they are accelerating  
frames of reference.





## THE PRINCIPLE OF RELATIVITY [PROPOSED BY GALILEO NOT EINSTEIN!]

Three hundred years before Einstein, Galileo posed a simple idea, now called the 'principle of relativity', which states that all steady motion is relative and cannot be detected without reference to an outside point. The idea can be found built into Newton's First Law of Motion as well. Put another way, if you are travelling inside a vehicle you cannot tell if you are moving at a steady velocity or standing still without looking out the window. You may have experienced this personally when sitting in a train and an adjacent train begins to roll — at first you may think that your own train is moving until you look out of a window on the other side of the carriage.

There are two points that must be reinforced:

- The principle of relativity applies only for non-accelerated steady motion; that is, standing at rest or moving with a uniform velocity. This is referred to as an **inertial frame of reference**. Situations that involve acceleration are called non-inertial frames of reference.
- This principle states that within an inertial frame of reference you cannot perform any mechanical experiment or observation that would reveal to you whether you were moving with uniform velocity or standing still.

As an example, if you were seated in a very smooth train and you held up a string with a small object tied to the end, the object would hang so that the string was vertical. However, as the train pulled away from the station you would notice the object swing backward so that the string was no longer vertical. This would continue until the train reached its cruising speed and stopped accelerating, at which point the object would move forward so that the string was once again vertical. When rounding bends in the track you would notice the string leaning one way or the other, but once the track straightened out the string would once again be vertical, just as it was when standing at the station. This plumb bob is operating as a simple accelerometer but it is unable to distinguish between being motionless and steady motion.

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# INERTIAL FRAMES OF REFERENCE > NEWTON vs EINSTEIN

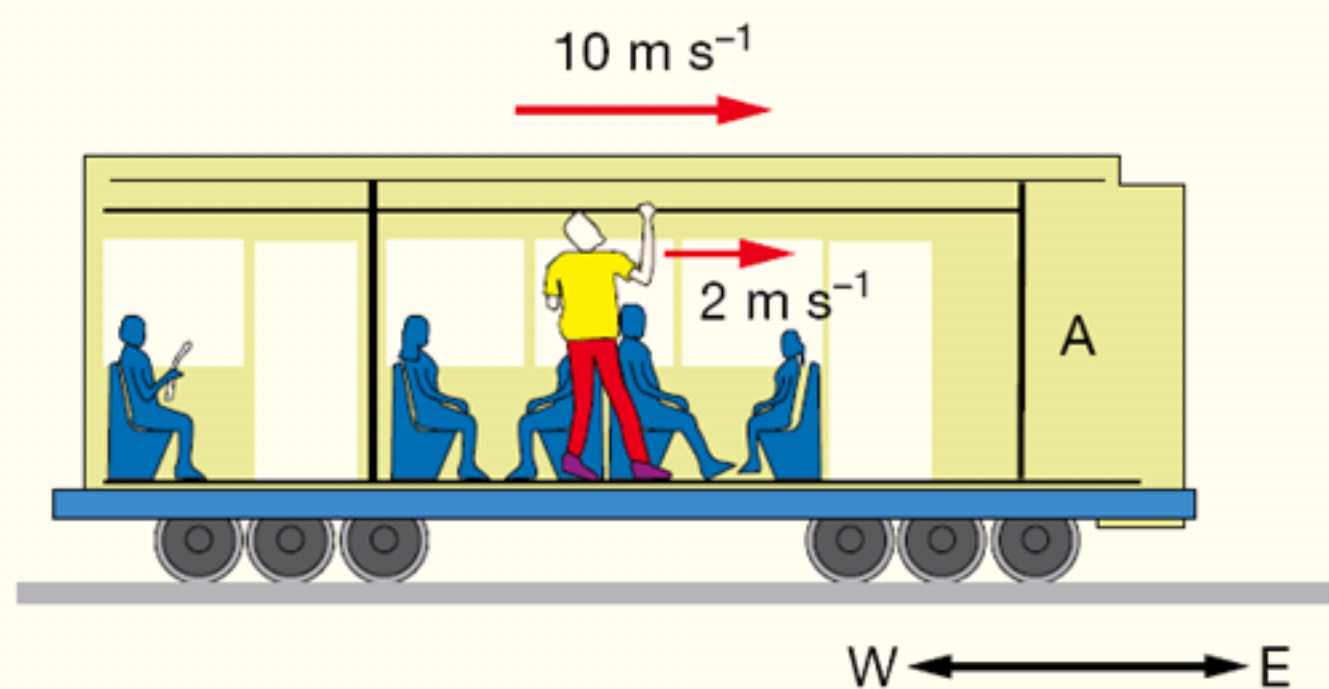
Newtonian physics

Imagine that you are in a car that is travelling along a straight, flat stretch of freeway at 100 km/h. You have an apple in your hand that you toss up and down and side to side. In the car, we can say that your frame of reference is moving with a constant velocity relative to the ground. Now, say that you repeat exactly the same actions on the apple when the car is stationary. The motion of the apple, its mass and acceleration are exactly the same in this stationary reference frame as they were when the car was moving with constant velocity.

A stationary frame of reference and a frame of reference with constant velocity are called inertial frames of reference. Newton's laws of motion are valid in these inertial frames of reference. Newton also assumed that physical quantities such as mass, time, distance and so on were absolute quantities. This means that their values did not change whatever the frame of reference. This would seem to make sense. After all, the mass of an apple and the length of a metre ruler don't change as they travel faster-or do they?

About 200 years after Newton published his laws of motion, Albert Einstein showed that Newton's laws did not work at speeds approaching the speed of light. In fact, at these high speeds, the mass of an object is greater, time slows down and lengths shrink! These ideas are outlined in Einstein's theory of special relativity. In this theory, Newton's ideas of the absolute nature of space and time were replaced by Einstein's ideas of the relative nature of space and time. In fact, history has shown that Newton's laws were a special case of Einstein's theories, applying only to situations involving comparatively slow-moving objects.

Einstein



**Figure 1.7** The velocity of this person relative to the ground is  $12 \text{ m s}^{-1}$  east, but their velocity relative to the other passengers is  $2 \text{ m s}^{-1}$  east.



## SOLUTIONS OF P21

**A1.**

$$F = Gm^2/R^2$$

$$\text{then } m^2 = FR^2/G$$

$$= (2.94 \times 10^{-59} \text{ N})(1.0 \times 10^{-2} \text{ m})^2 / (6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2})$$

$$\text{and } m = 6.64 \times 10^{-27} \text{ kg}$$

**A2.**

$$F = GMm/R^2$$

$$\text{then } R^2 = GMm/F$$

$$= (6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2})(5.69 \times 10^{26} \text{ kg})(1.05 \times 10^{21} \text{ kg}) / (2.79 \times 10^{20} \text{ N})$$

$$\text{and } R = 3.78 \times 10^8 \text{ m}$$

**A3.**

At a height of 2.00 Earth radii above the Earth's surface, a person is a distance of 3.00 Earth radii from the centre of the Earth.

$$\text{Then } F = 900 \text{ N}/3^2 = 900 \text{ N}/9 = 100 \text{ N}$$

**A4.**

$$M/(0.8R)^2 = m/(0.2R)^2$$

$$\text{and } M/m = 1/4^2 = 1 : 16 = 0.063$$

**A5.**

$$\text{a } g = GM/R^2$$

$$= (6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2})(1.02 \times 10^{26} \text{ kg}) / (2.48 \times 10^7 \text{ m})^2$$

$$= 11.1 \text{ N kg}^{-1}$$

**b** It will accelerate at a rate given by the gravitational field strength, i.e. at  $11.1 \text{ m s}^{-2}$ .

**A6.**

The orbital speed of the Moon around the Earth is given by:

$$v = (GM/R)^{1/2}$$

$$= [(6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2})(5.98 \times 10^{24} \text{ kg}) / (3.84 \times 10^8 \text{ m})]^{1/2}$$

$$= 1.019 \text{ km s}^{-1}$$

The period of the Moon around the

$$\text{Earth } T = 2\pi R/v$$

$$= 2\pi(3.84 \times 10^8 \text{ m}) / (1.019 \times 10^3 \text{ m s}^{-1})$$

$$= (2.367 \times 10^6 \text{ s}) / (3.6 \times 10^3)$$

$$= 657.6 \text{ hours} = 657.6 \text{ hours}/24 = 27.4 \text{ days}$$

**A7.**

$$\text{a } v = (GM/R)^{1/2}$$

$$= [(6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2})(1.90 \times 10^{27} \text{ kg}) / (1.10 \times 10^{10} \text{ m})]^{1/2} = 3.39 \times 10^3 \text{ m s}^{-1}$$

$$\text{b } a = v^2/R$$

$$= (3.39 \times 10^3 \text{ m s}^{-1})^2 / (1.10 \times 10^{10} \text{ m})$$

$$= 1.05 \times 10^{-3} \text{ m s}^{-2} \text{ towards Jupiter}$$

$$\text{c } T = 2\pi R/v$$

$$= 2\pi(1.10 \times 10^{10} \text{ m}) / (3.39 \times 10^3 \text{ m s}^{-1})$$

$$= 2.0388 \times 10^7 \text{ s} = 235 \text{ days}$$

**A8.**

**a** A satellite is said to be in a geosynchronous orbit if its orbital period is the same as that of the Earth's rotation (i.e. 24 hours).

**b** This satellite will always be directly above the same point on the Earth's surface, and can therefore transmit radio signals to any point that can see it.

$$\text{c } R^3 = GMT^2/4\pi^2,$$

$$\text{then } R^3 = (6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2})(6.0 \times 10^{24} \text{ kg})(24 \text{ h})(3.6 \times 10^3 \text{ s h}^{-1})^2/4\pi^2$$

$$\text{and } R = 4.2 \times 10^7 \text{ m}$$

**A9.**

$$\text{a } R^3 = GMT^2/4\pi^2$$

$$= (6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2})(3.30 \times 10^{23} \text{ kg})(5.07 \times 10^6 \text{ s})^2/4\pi^2$$

$$\text{and } R = 2.43 \times 10^8 \text{ m}$$

$$\text{b } v = 2\pi R/T$$

$$= 2\pi(2.429 \times 10^8 \text{ m}) / (5.07 \times 10^6 \text{ s}) = 3.01 \times 10^2 \text{ m s}^{-1}$$

$$\text{c } a = v^2/r$$

$$= (301 \text{ m s}^{-1})^2 / (2.429 \times 10^8 \text{ m}) = 3.73 \times 10^{-4} \text{ m s}^{-2} \text{ towards Mercury}$$

**A10.**

**a** The increase in the kinetic energy of the rock

$$= \text{area under the graph from } R = 2.5 \times 10^6 \text{ m to } R = 3.0 \times 10^6 \text{ m}$$

$$= 2.8 \times 10^7 \text{ J}$$

$$\text{b } \text{The initial } E_K = 0.5mv^2$$

$$= 0.5(20 \text{ kg})(1.0 \times 10^3 \text{ m s}^{-1})^2 = 1.0 \times 10^7 \text{ J}$$

$$\text{The final } E_K = 2.8 \times 10^7 \text{ J} + 1.0 \times 10^7 \text{ J} = 3.8 \times 10^7 \text{ J}$$

$$\text{c } 3.8 \times 10^7 \text{ J} = 0.5(20 \text{ kg})v^2$$

$$\text{and } v = 1.9 \times 10^3 \text{ m s}^{-1}$$

**A11.**

Transposing  $GMm/R^2 = mv^2/R$  to make  $v$  the subject gives:

$$v = \sqrt{GM/R}$$

$$v_{\text{ISS}}/v_{\text{GMS}} = R_{\text{GMS}}/R_{\text{ISS}} = \sqrt{(6.4 \times 10^6 + 3.6 \times 10^7) / (6.4 \times 10^6 + 3.8 \times 10^5)} = 2.5$$

**A12.**

Transposing  $GMm/R^2 = 4\pi^2 Rm/T^2$  to make  $T$  the subject gives:

$$T = \sqrt{(4\pi^2 R^3/GM)}$$

$$T_{\text{ISS}}/T_{\text{GMS}} = \sqrt{(R_{\text{ISS}}^3/R_{\text{GMS}}^3)} = 0.064$$

**A13.**

$$a_{\text{ISS}}/a_{\text{GMS}} = (GM/R_{\text{ISS}}^2)/(GM/R_{\text{GMS}}^2) = R_{\text{GMS}}^2/R_{\text{ISS}}^2 = 0.026$$

**A14.**

$$\text{a } (T_1/T_2)^2 = (R_1/R_2)^3$$

$$\text{and } T_1/T_2 = (R_1/2R)^{3/2} = 1/\sqrt{8} = 0.35$$

$$\text{b } v_1/v_2 = (T_2/T_1)(R_1/R_2) = \sqrt{8}/2 = \sqrt{2}$$

$$= 1.4$$

$$\text{c } a_1/a_2 = (v_1/v_2)^2(R_2/R_1) = 2 \times 2 = 4$$

**A15.**

Transposing  $GMm/R^2 = 4\pi^2 Rm/T^2$  to make  $M$  the subject gives:  $M = 4\pi^2 R^3 m/GT^2$ .

Substituting into this using  $R = 1.5 \times 10^{11} \text{ m}$  and  $T = 365.25 \times 24 \times 60 \times 60$  gives  $M = 2.0 \times 10^{30} \text{ kg}$ .

**A16.**

A is correct because the units of area  $(\text{N})(\text{m}) = (\text{Nm})$ .

**A17.**

C is the correct answer. The area under the graph gives the energy change. In this example, the satellite is falling closer to Earth, so it is losing gravitational potential energy.

**A18.**

This can be determined by finding the area under the graph between  $R = 2 \times 10^5 \text{ m}$  and  $R = 6 \times 10^5 \text{ m}$ .

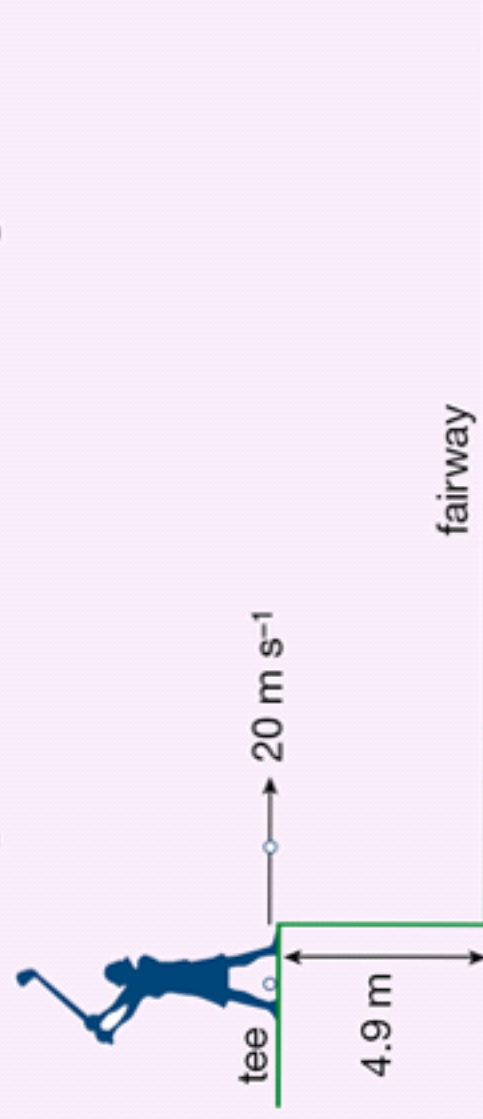
Counting squares give area  $= 35 \times 1 \times 10^5 \times 1 \times 10^3 = 3.5 \times 10^9 \text{ J}$ .



For the following questions, assume that the acceleration due to gravity is  $9.8 \text{ m s}^{-2}$  and ignore the effects of air resistance unless otherwise stated.

**1** A golfer practising on a range with an elevated tee  $4.9 \text{ m}$  above the fairway is able to strike a ball so that it leaves the club with a horizontal velocity of  $20 \text{ m s}^{-1}$ .

- a** How long after the ball leaves the club will it land on the fairway?
- b** What horizontal distance will the ball travel before striking the fairway?
- c** What is the acceleration of the ball  $0.50 \text{ s}$  after being hit?
- d** Calculate the speed of the ball  $0.80 \text{ s}$  after it leaves the club.
- e** With what speed will the ball strike the ground?

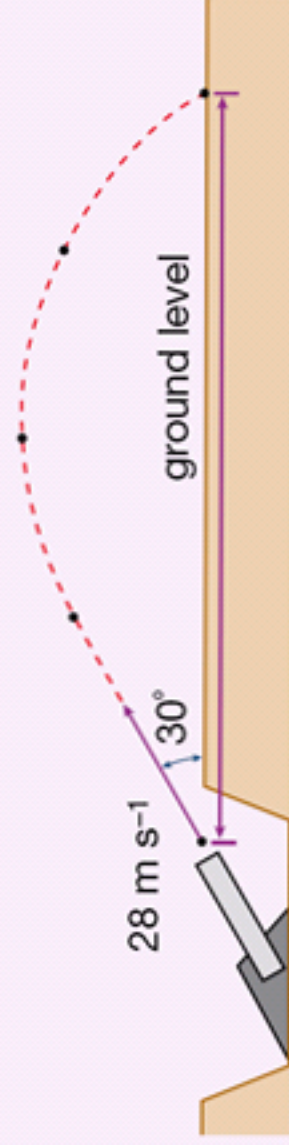


**2** A bowling ball of mass  $7.5 \text{ kg}$  travelling at  $10 \text{ m s}^{-1}$  rolls off a horizontal table  $1.0 \text{ m}$  high.

- a** Calculate the ball's horizontal velocity just as it strikes the floor.
- b** What is the vertical velocity of the ball as it strikes the floor?
- c** Calculate the velocity of the ball as it reaches the floor.
- d** What time interval has elapsed between the ball leaving the table and striking the floor?
- e** Calculate the horizontal distance travelled by the ball as it falls.
- f** Draw a diagram showing the forces acting on the ball as it falls towards the floor.

The following information applies to questions 3–8.

A senior physics class conducting a research project on projectile motion constructs a device that can launch a cricket ball. The launching device is designed so that the ball can be launched at ground level with an initial velocity of  $28 \text{ m s}^{-1}$  at an angle of  $30^\circ$  to the horizontal.



**3** Calculate the horizontal component of the velocity of the ball:

- a** initially
- b** after  $1.0 \text{ s}$
- c** after  $2.0 \text{ s}$ .

**4** Calculate the vertical component of the velocity of the ball:

- a** initially
- b** after  $1.0 \text{ s}$
- c** after  $2.0 \text{ s}$ .

**5 a** At what time will the ball reach its maximum height?

**b** What is the maximum height that is achieved by the ball?

**c** What is the acceleration of the ball at its maximum height?

**6 a** At which point in its flight will the ball experience its minimum speed?

**b** What is the minimum speed of the ball during its flight?

**c** At what time does this minimum speed occur?

**d** Draw a diagram showing the forces acting on the ball at the maximum height.

**7 a** At what time after being launched will the ball return to the ground?

**b** What is the velocity of the ball as it strikes the ground?

**c** Calculate the horizontal range of the ball.

**8** If the effects of air resistance were taken into account, which one of the following statements would be correct?

**A** The ball would have travelled a greater horizontal distance before striking the ground.

**B** The ball would have reached a greater maximum height.

**C** The ball's horizontal velocity would have been continually decreasing.

**9** A softball of mass  $250 \text{ g}$  is thrown with an initial velocity of  $16 \text{ m s}^{-1}$  at an angle  $\theta$  to the horizontal. When the ball reaches its maximum height, its kinetic energy is  $16 \text{ J}$ .

**a** What is the maximum height achieved by the ball from its point of release?

**b** Calculate the initial vertical velocity of the ball.

**c** What is the value of  $\theta$ ?

**d** What is the speed of the ball after  $1.0 \text{ s}$ ?

**e** What is the displacement of the ball after  $1.0 \text{ s}$ ?

**f** How long after the ball is thrown will it return to the ground?

**g** Calculate the horizontal distance that the ball will travel during its flight.

**10** During training, an aerial skier takes off from a ramp that is inclined at  $40.0^\circ$  to the horizontal and lands in a pool that is  $10.0 \text{ m}$  below the end of the ramp. If she takes  $1.50 \text{ s}$  to reach the highest point of her trajectory, calculate:

**a** the speed at which she leaves the ramp

**b** the maximum height above the end of the ramp that she reaches

**c** the time for which she is in mid-air.



# HOMEWORK

- ✦ Homework is an integral part of your "Learning Curve", take it seriously!
- ✦ Target minimum 1 hour of Physics everyday
- ✦ Divide your physics home study in three segments;
  - ✓ Revision (past)
  - ✓ Homework (present)
  - ✓ Tomorrow (future)
- ✦ Homework is due next period, unless otherwise stated
- ✦ If you cannot do all, at least do a few from each piece

*Apart from **reading the relevant pages from the textbook and solving the rest of the questions in this booklet** your homework is:*

- ✓ Study CSU Space 4 notes
- ✓ 10 questions in this booklet
- ✓ Relevant pages in Multiple Choice Dot Points Book (DPB)
- ✓ New Dot Points booklet (pages 24-27)
- ✓ Chapter 4 all questions
- ✓ 20 questions of P21
- ✓ 12 questions of P19
- ✓ 12 questions of P18
- ✓ 8 questions of P17
- ✓ Experiment 5 Report
- ✓ Chapter 3 all questions

**NEXT PERIOD > CONSTANCY OF SPEED OF LIGHT**