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t = top, *b* = bottom, l = left, *r* = right

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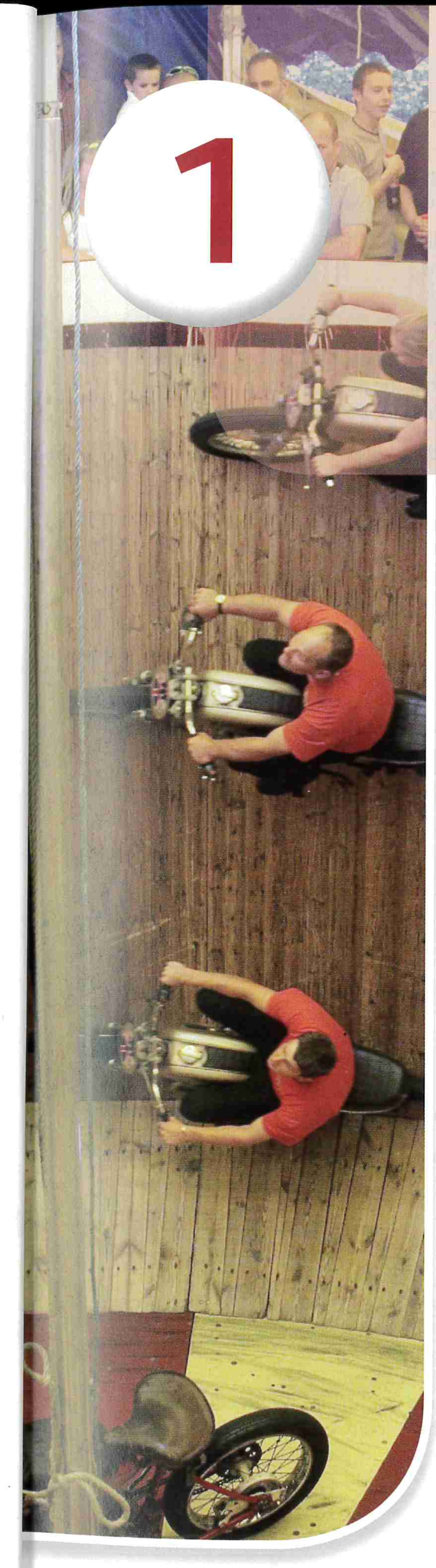


1 Circular motion

PRIOR KNOWLEDGE

Before you start, make sure that you are confident in your knowledge and understanding of the following points:

$$\text{Acceleration} = \frac{\text{change of velocity}}{\text{time}}$$

- Resultant force = mass × acceleration.
- You need to recall that a vector quantity has magnitude and direction: force, velocity and acceleration are vectors.
- Resolving a vector into components.
- Circumference of a circle = 2π × radius of circle, $c = 2\pi r$.
- Newton's first law of motion: a body remains at rest or continues to move in a straight line at a constant speed unless acted on by an unbalanced force.

TEST YOURSELF ON PRIOR KNOWLEDGE

1 a) Explain the difference between speed and velocity.
b) Explain why acceleration is a vector quantity.

2 The three diagrams in Figure 1.1 show three separate examples of how a vehicle's velocity changes from v_1 to v_2 over a time of 10 s. Use the equation $a = \frac{v_2 - v_1}{t}$ to calculate the magnitude and direction of the acceleration in each case.

3 The vehicle in question 2 has a mass of 2 kg. In each case shown in Figure 1.1, calculate the average resultant force that caused the acceleration of the vehicle.

4 An unbalanced force acts on a moving vehicle. Explain three changes that could occur to the vehicle's velocity.

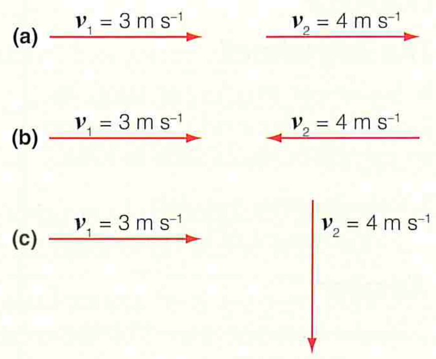


Figure 1.1

5 You walk a quarter of the way round a circle of diameter 20 m.
a) Calculate the distance you have walked.
b) Calculate your displacement if you started at the north of the circle and walked to the eastern side of the circle.

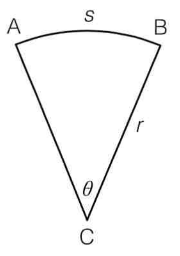


Figure 1.2

Radian The radian measure of a central angle of a circle, θ, is defined as the ratio of the arc length, s, subtended by the angle θ, to the radius r:

$$\theta = \frac{s}{r}$$

Angular displacement The angle (measured in radians) through which a line rotates about a fixed point.

Angular velocity The rate of change of angular displacement (measured in radians per second).

Circular measure

You are used to measuring angles in degrees, but in physics problems involving rotations we use a different measure.

In Figure 1.2, an arc AB is shown. The length of the arc is s, and the radius of the circle is r. We define the angle θ as

$$\theta = \frac{s}{r}$$

The advantage of this measure is that θ is a ratio of lengths, so it has no unit. However, to avoid the confusion that the angle might be measured in degrees, we give this measure the unit **radian**, abbreviated to rad.

Since the circumference of a circle is $2\pi r$, it follows that 2π radians is the equivalent of 360°:

$$2\pi \text{ rad} = 360°$$

so

$$1 \text{ rad} = \frac{360°}{2\pi} = 57.3°$$

Equations of rotation

When something rotates about a fixed point we use the term **angular displacement** to measure how far the object has rotated. For example, in Figure 1.2, when an object rotates from A to B, its angular displacement is θ radians.

The term **angular velocity**, ω, is used to measure the rate of angular rotation. Angular velocity has units of radians per second or rad s^{-1}:

$$\omega = \frac{\theta}{t}$$

or

$$\omega = \frac{\Delta\theta}{\Delta t}$$

where $\Delta\theta$ is the small angle turned into a small time Δt.

In general, there is a useful relationship connecting the time period of one complete rotation, T, and angular velocity, ω, because after one full rotation the angular displacement is 2π:

$$\omega = \frac{2\pi}{T}$$

or

$$\omega = 2\pi f$$

where f is the frequency of rotation. There is a further useful equation, which connects angular velocity with the velocity of rotation. Since

$$s = \theta r$$

EXAMPLE

The 'big wheel'

A 'big wheel' at a funfair takes its passengers for a ride, completing six complete revolutions in 120 s.

1 Calculate the angular displacement of the wheel.

Answer

$\theta = 6 \times 2\pi = 12\pi \text{ rad} = 37.7 \text{ rad}$

2 Calculate the average angular velocity during the ride.

Answer

$$\omega = \frac{12\pi}{120 \text{ s}} = 0.1\pi = 0.31 \text{ rad s}^{-1}$$

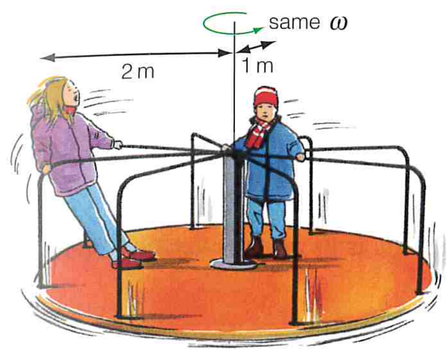


Figure 1.3

and

$$v = \frac{\Delta s}{\Delta t} = \frac{\Delta\theta}{\Delta t} r$$

then

$$v = \omega r$$

This equation shows that the rotational speed of something is faster further away from the centre. For example, all the children on a roundabout in a playground have the same angular velocity ω, but the ones near the edge are moving faster (Figure 1.3).

TEST YOURSELF

1 The Earth has a radius of 6400 km. The Shetland Isles are at latitude of 60°.
   a) Calculate the angular velocity of the Earth.
   b) Calculate the velocity of rotation of a point on the equator.
   c) Calculate the velocity of rotation of the Shetland Isles.

2 A proton in a synchrotron travels round a circular path of radius 85 m at a speed of close to 3.0×10^8 m s^{-1}.
   a) Calculate the time taken for one revolution of the synchrotron.
   b) Calculate the frequency of rotation of the protons.
   c) Calculate the proton's angular velocity.

3 The Sun rotates around the centre of our Galaxy, the Milky Way, once every 220 million years, in an orbit of about 30 000 light years.
   a) Calculate the angular velocity of the Sun about the centre of the Milky Way.
   Calculate the velocity of the Sun relative to the centre of the Galaxy.
   [1 light year = 9.47×10^{15} m; 1 year = 3.16×10^7 s]

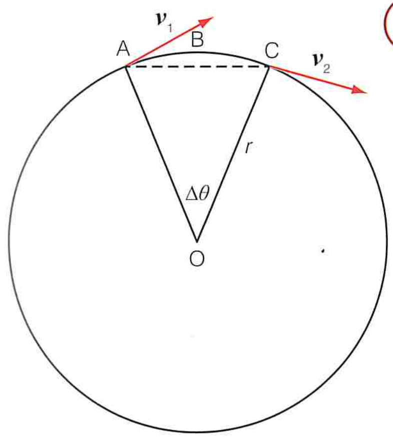


Figure 1.4 A particle moving round a circular path with a constant speed is always accelerating.

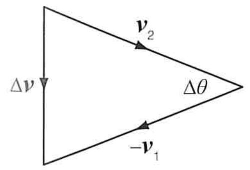


Figure 1.5

Centripetal acceleration

In Figure 1.4 a particle is moving round a circular path at a constant speed v, and because it is continually changing direction the particle is always accelerating.

It is easier to understand the acceleration when you recall the formula:

$$\text{acceleration} = \frac{\text{change of velocity}}{\text{time}}$$

Velocity is a vector quantity, so if the direction of the motion changes, even though there is no change of speed, there must be an acceleration.

Figure 1.5 shows the direction of the acceleration. In going from position A to position C, the particle's velocity changes from v_1 to v_2. So the change in velocity, $\Delta \boldsymbol{v}$, is the vector sum $\boldsymbol{v}_2 - \boldsymbol{v}_1$.

The diagram shows the change in velocity, $\Delta \boldsymbol{v}$, which is directed along the line BO, towards the centre of the circle. So, as the particle moves around the circular path, there is an acceleration towards the centre of the circle. This is called the **centripetal acceleration**. Because this acceleration is at right angles to the motion, there is no speeding up of the particle, just a change of direction.

Centripetal acceleration When a particle moves in a circular path of radius r, at a constant speed v, there must be a centripetal acceleration towards the centre of the circle, given by

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

The size of the acceleration, a, is calculated using this formula:

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

or because $v = \omega r$

$$a = \omega^2 r$$

Here v is the constant speed of the particle, ω is its angular velocity, and r is the radius of the path.

MATHS BOX

You are not expected to be able to derive the formula for centripetal acceleration, but it is given here for those who want to know where the formula comes from.

In Figure 1.4, the particle moves from A to C in a small time Δt. We now look at the instantaneous acceleration at the point B, by considering a very small angle $\Delta\theta$. The distance travelled round the arc AC, Δs, is given by

$$\Delta s = v\Delta t \quad \text{and} \quad \Delta s = r\Delta\theta$$

so

$$r\Delta\theta = v\Delta t \quad \text{and} \quad \Delta\theta = \frac{v}{r}\Delta t \qquad \text{(i)}$$

In Figure 1.5 the angle θ is given by

$$\Delta\theta = \frac{\Delta v}{v} \qquad \text{(ii)}$$

provided $\Delta\theta$ is very small. Then by combining equations (i) and (ii), it follows that

$$\frac{\Delta v}{v} = \frac{v}{r}\Delta t$$

or

$$a = \frac{\Delta v}{\Delta t} = \frac{v^2}{r}$$

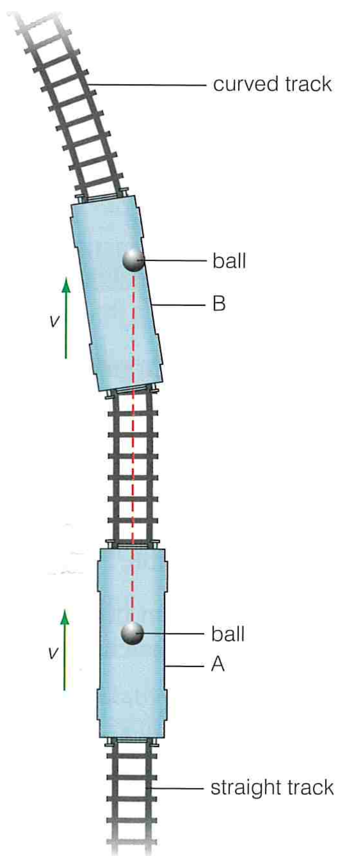


Figure 1.6 A train carriage turns a corner, but a ball on the floor of the carriage keeps on moving in a straight line.

Centripetal force

Figure 1.6 illustrates the path of a railway carriage as it turns round a corner (part of a circle), moving from A to B at a constant speed v. The rails provide a force to change the direction of the carriage. However, a ball that is placed on the floor behaves differently. The ball carries on moving in a straight line until it meets the side of the carriage. The ball experiences no force, so, as predicted by Newton's first law of motion, it carries on moving in a straight line at a constant speed, until the side of the carriage exerts a force on it.

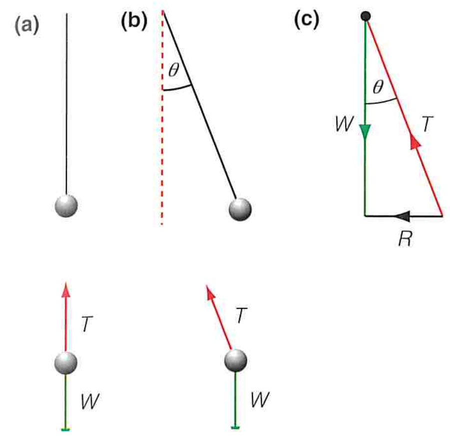


Figure 1.7 Views of a ball suspended from the back of the train carriage looking forwards. (a) When the train moves along a straight track, the ball hangs straight down. (b) When the train moves around the curved track, as in Figure 1.6, the ball is displaced to the right. (c) There is a resultant unbalanced force R acting on the ball.

Centripetal force When an object moves around a circular path, there must be a centripetal force acting towards the centre of the circle. Something must provide this force, such as a pull from a string or a push from the road.

Now suppose that the ball is suspended from the ceiling of the carriage and the experiment is repeated. Figure 1.7 illustrates what happens now as the carriage moves from a straight track to a curved track. In Figure 1.7(a) the carriage moves along a straight track at a constant speed. The ball hangs straight down and the forces acting on it balance: the tension of the string, T, upwards, balances the ball's weight, W, downwards.

In Figure 1.7(b) the train turns the corner. The ball keeps moving in a straight line until tension in the string acts to pull the ball round the corner. Now the forces acting on the ball do *not* balance. The vector sum of the tension T and the weight W provides an unbalanced force R, which acts towards the centre of the circle (Figure 1.7c).

This unbalanced force R provides the centripetal acceleration. So we can write

$$R = \frac{mv^2}{r}$$

where R is the unbalanced **centripetal force**, m is the mass of the ball, v is the ball's forward speed, and r is the radius of the (circular) bend it is going round.

It is important to understand that a centripetal force does not exist because something is moving round a curved path. It is the other way around – according to Newton's second law of motion, to make something change direction a force is required to make the object accelerate. In the example you have seen here, the tension in the string provides the centripetal force, which is necessary to make the ball move in a circular path. When a car turns a corner, the frictional force from the road provides the centripetal force to change the car's direction. When a satellite orbits the Earth, the gravitational pull of the Earth provides the centripetal force to make the satellite orbit the Earth – there is no force acting on the satellite other than gravity.

A common misunderstanding

Figure 1.8 shows the same ball discussed earlier held hanging, at rest, at an angle in the laboratory. Now it is kept in place by the balance of three forces: the tension in the string, T, its weight, W, and a sideways push, P, from a student's finger.

If the student removes his finger, the ball will accelerate and begin moving to the left, because there is now an unbalanced force acting on it, exactly as there was in Figure 1.7.

However, the situations are different. In Figure 1.8 the ball is stationary until the finger is removed, and it begins to accelerate and move in the direction of the unbalanced force. In Figure 1.7 the ball is moving forwards and the action of the unbalanced force is to change the direction of the ball.

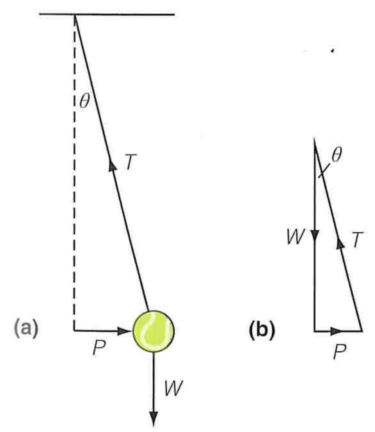


Figure 1.8

TEST YOURSELF

4 Explain how a force can change the velocity of a body without increasing its speed.

5 The force of gravity makes things fall towards the ground. Explain why the Earth's gravity does not make the Moon fall towards the Earth.

6 A satellite is in orbit around the Earth, at a distance of 7000 km from the Earth's centre. The mass of the satellite is 560 kg and the gravitational field strength at that height is $8.2\,N\,kg^{-1}$.
  a) Draw a diagram to show the direction and magnitude of the force (or forces) that act(s) on it.
  b) Calculate the centripetal acceleration of the satellite.
  c) Calculate
    i) the speed of the satellite
    ii) the time period of its orbit.

7 This question refers to the suspended ball in the train, illustrated in Figure 1.7. The ball has a mass of 0.15 kg.
  a) The train accelerates forwards out of the station along a straight track at a rate of $2\,m\,s^{-2}$.
    i) Explain why the ball is displaced backwards.
    ii) Calculate the resultant force on the ball.
    iii) Show that the angle at which the ball hangs to the vertical is about 11.5°.
  b) The train reaches a speed of $55\,m\,s^{-1}$ and travels round a curved piece of the track. At this moment, the ball is deflected sideways by about 11.5°.
    i) State and explain the direction and magnitude of the resultant force on the ball.
    ii) Explain why the ball is accelerating. In which direction is the acceleration? Calculate the magnitude of the acceleration.
    iii) Explain why the ball's speed remains constant.
    iv) Calculate the radius of the bend the train is going round.
  c) The train carriage that carries the ball has a mass of 40 tonnes.
    i) Calculate the centripetal force that acts on the carriage as it turns the corner. What provides this force?
    ii) Explain why trains go round tight bends at reduced speeds.

ACTIVITY

Investigating centripetal forces

Figure 1.9 shows a way in which you can investigate centripetal forces. The idea is that you whirl a rubber bung around your head in a horizontal circle. The bung is attached by a thin string to a plastic tube, which is held vertically. A weight is hung on the bottom of the string. This causes the tension to provide the necessary centripetal force to keep the bung moving in its circular path.

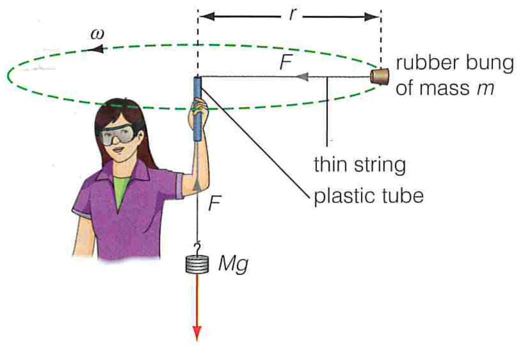


Figure 1.9

- Use a bung, of mass m, of about 50 g to 100 g.
- Wear safety glasses (useful to protect yourself from others doing the same experiment).
- A suitable plastic tube is an old case from a plastic ballpoint pen.
- The time of rotation, T, can be calculated by measuring the time for 10 rotations, $10T$.
- The radius r can be measured after you have finished 10 rotations by pinching the string with your finger, then measuring the length from the top of the tube to the centre of the bung.
- We assume that there is no friction between the plastic tube and the string.
- It is assumed that the string is horizontal, although this will not be entirely possible, so it is important to try to meet this condition as far as you can.

Table 1.1 shows some data measured by a student doing this experiment.

1 Copy and complete Table 1.1 by filling in the gaps. Comment on how well the results support the hypothesis that the weight on the end of the string causes the centripetal force to keep the bung in its circular path. In this experiment the bung has a mass of 0.09 kg.

Table 1.1

M/kg	F/N	$10T$/s	ω/rad s^{-1}	r/m	$m\omega^2 r$/N
0.1		18.8		0.94	
0.2		11.5		0.78	
0.2		10.2		0.56	
0.3		8.6		0.61	
0.3		7.9		0.52	
0.4		5.4		0.31	

2 Discuss the sources of error in this experiment. Suggest how the errors can be minimised.

3 To improve the reliability of the data, it might be helpful to plot a graph.
  a) Plot a graph of F against $m\omega^2 r$.
  b) Explain why this should be a straight line. What gradient do you expect to get when you measure it?

EXAMPLE

Round in circles

1 A physics teacher, shown in Figure 1.10, demonstrates a well-known trick. She puts a beaker of water on a tray, suspended by four strings at its corners. Then she whirls the tray round in a vertical circle, so that the beaker is upside down at the top. She then asks why the water does not fall at the top of the swing. A student (who has not been paying attention) says 'the pull of gravity is balanced by an outwards force'. Explain why this is *not* correct.

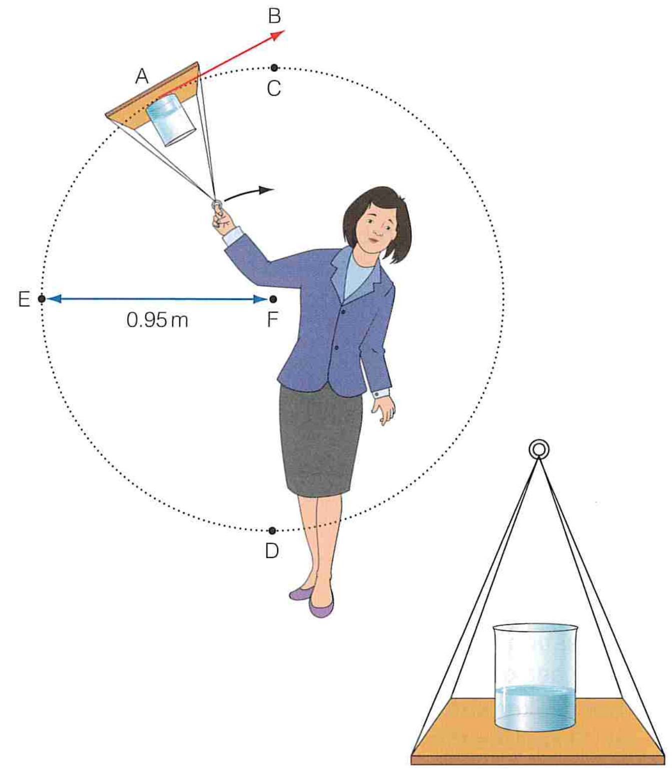


Figure 1.10

Answer

The teacher gives this explanation: At the top, the water and the beaker are falling together. Look at Figure 1.10. At point A, the beaker is travelling along the direction AB. The string pulls the beaker down in the direction BC so at the top it has fallen to point C.

The teacher repeated the demonstration and asked the students to time the revolutions. The students determined that the tray completed 10 revolutions in 8.3 s. They measure the radius of the circle to be 0.95 m.

The speed of the tray is

$$v = \frac{2\pi r}{T}$$

$$= \frac{2\pi \times 0.95\,m}{0.83\,s}$$

$$= 7.2\,m\,s^{-1}$$

So, while the beaker rotates, it has a centripetal acceleration of

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

$$= \frac{(7.2\,m\,s^{-1})^2}{0.95\ m}$$

$$= 55\,m\,s^{-2}$$

This tells us that the water is accelerating all the time at $55\,m\,s^{-2}$ (more than five times the gravitational acceleration). So the water does not fall out ofthe beaker at the top, because it is already falling with an acceleration greater than gravitational acceleration.

2 A cyclist is cycling at $14.5\,m\,s^{-1}$ in a velodrome where the track is bankedat an angle of 40° to the horizontal (Figure 1.11). The track is curved so that the cyclist is turning in a horizontal circle of radius 25 m. The cyclist and bicycle together have a mass of 110 kg.

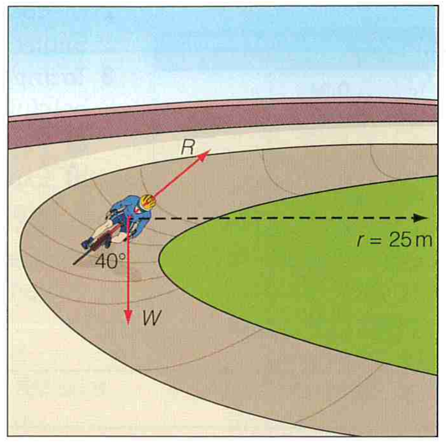
a) Calculate the centripetal force acting on the cyclist.

Answer

$$F = \frac{mv^2}{r}$$

$$= \frac{110\,kg \times (14.5\,m\,s^{-1})^2}{25\,m}$$

$$= 930\,N\ (2\ s.f.)$$



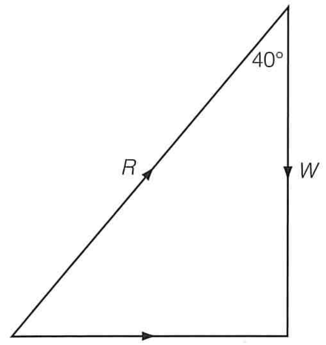


Figure 1.11

b) Calculate the contact force R from the track on the bicycle.

Answer

Figure 1.11 shows the two forces acting on the bicycle and cyclist: the contact force R and the weight W. The forces combine to produce the unbalanced centripetal force, which keeps the cyclist moving round her horizontal circular path.

Force R may be resolved horizontally and vertically as follows:

$$R_v = R\cos 40°$$

$$R_h = R\sin 40°$$

The vertical component R_v balances the weight, and the horizontal component provides the unbalanced centripetal force. (It is important to realise that the cyclist can only lean her bicycle as shown because she is accelerating towards the centre of the circle. She would fall over if she were stationary.) So

$$R\sin 40° = 930\,N$$

$$R = \frac{930\,N}{\sin 40°}$$

$$= 1440\,N$$

TEST YOURSELF

8 This question refers to the teacher's demonstration with the beaker of water shown in Figure 1.10.

a) The beaker and water have a combined mass of 0.1 kg. Use this information, together with the information in the text, to calculate the centripetal force required to keep the beaker in the circular path that the teacher used.

b) The only two forces that act on the beaker and water are their weight, W, and the contact force, R, from the tray. Calculate the size and direction of R at the following points shown in Figure 1.10:

i) C **ii)** D **iii)** E.

c) The water will fall out of the beaker at point C if the beaker moves so slowly that the required centripetal acceleration is less than g.

Assuming the teacher still rotates the beaker in a circle of 0.95 m radius, calculate the minimum speed at which the water does not fall out of the beaker at point C.

9 Formula 1 (F1) racing cars are designed to enable them to corner at high speeds. Traction between the tyres and the road surface is increased by using soft rubber tyres, which provide a large frictional force, and by using wings to increase the down force on the car.

The tyres of an F1 car can provide a maximum frictional force to resist sideways movement of 15 500 N. The car's mass (including the driver) is 620 kg.

Calculate the maximum cornering speed of the car going round a bend of

a) radius 30 m **b)** radius 120 m.

Practice questions

1 The orbit of an electron in a hydrogen atom may be considered to be a circle of radius $5 \times 10^{-11}\,m$. The period of rotation of the electron is $1.5 \times 10^{-16}\,s$. The speed of rotation of the electron is

A $2 \times 10^5\,m\,s^{-1}$ **C** $2 \times 10^6\,m\,s^{-1}$

B $4 \times 10^5\,m\,s^{-1}$ **D** $4 \times 10^7\,m\,s^{-1}$

2 From the information in question 1, the centripetal acceleration of the electron is

A $3 \times 10^{22}\,m\,s^{-2}$ **C** $12 \times 10^{22}\,m\,s^{-2}$

B $9 \times 10^{22}\,m\,s^{-2}$ **D** $30 \times 10^{22}\,m\,s^{-2}$

3 The Moon orbits the Earth once every 29 days with a radius of orbit of 380 000 km. The angular velocity of the Moon is

A $2.5 \times 10^{-6}\,rad\,s^{-1}$ **C** $8.5 \times 10^{-6}\,rad\,s^{-1}$

B $5.0 \times 10^{-6}\,rad\,s^{-1}$ **D** $25 \times 10^{-6}\,rad\,s^{-1}$

4 From the information in question 3, the Moon's centripetal acceleration is

A $2.4\,mm\,s^{-2}$ **C** $7.6\,mm\,s^{-2}$

B $4.0\,mm\,s^{-2}$ **D** $24\,mm\,s^{-2}$

5 The centripetal acceleration of a car moving at a speed of $30\,m\,s^{-1}$ round a bend of radius 0.45 km is

A $1.0\,m\,s^{-2}$ **C** $100\,m\,s^{-2}$

B $2.0\,m\,s^{-2}$ **D** $200\,m\,s^{-2}$

6 A satellite is in orbit around the Earth in a circular orbit of radius 10 000 km. The angular velocity of the satellite is $6.4 \times 10^{-4}\,rad\,s^{-1}$. The time of orbit of the satellite is

A 4800 s **C** 8400 s

B 6800 s **D** 9800 s

7 From the information in question 6, the centripetal acceleration of the satellite is

A $2\,m\,s^{-2}$ **C** $4\,m\,s^{-2}$

B $3\,m\,s^{-2}$ **D** $8\,m\,s^{-2}$

8 A student swings a bucket of water in a vertical circle of radius 1.3 m. The bucket and water have a mass of 2.5 kg. The bucket rotates once every 1.4 s. When the bucket is upside down, the water does not fall out. Which of the following gives a correct explanation of why the water stays in the bucket.

A The weight of the water is balanced by a centrifugal force.

B The centripetal force and the weight of the water balance.

C The water and bucket are falling at the same rate.

D The bucket moves so fast that the water has no time to fall.

9 From the information in question 8, the centripetal force on the swinging bucket is

A 6 N **C** 52 N

B 36 N **D** 65 N

10 From the information in question 8, for the swinging bucket, at the bottom of the swing the rope exerts a force on the student's hand of

A 90 N **C** 52 N

B 63 N **D** 36 N

11 An astronaut undergoes some training to test his tolerance to acceleration. He is placed in a rotor, which carries him in a circle of radius 7.0 m. The rotor completes 10 revolutions in 24.3 s, moving at a constant speed.

a) Explain why the astronaut is accelerating, although his speed is constant. (2)

b) Calculate the size of the astronaut's acceleration. (3)

12 (Synoptic question: you need to think about energy transformations to help solve this question.)

A large steel ball of mass 2100 kg is used to demolish buildings. The ball is suspended on a cable of length 8 m, and is pulled back to a height of 4 m above its lowest point, before being released to hit a building.

a) Calculate the maximum speed of the ball just prior to hitting the building. (3)

b) Calculate the tension in the cable when the ball is at its lowest point. (4)

13 Figure 1.12 shows an aircraft propeller that is undergoing tests in a laboratory.

The propeller is made out of high-strength, low-density carbon-fibre-reinforced plastic (CFRP). In a test, it is rotating at a rate of 960 times per minute.

a) Calculate the angular velocity of the propeller. (2)

b) Calculate the speed of the propeller blade at these two positions. (2)

i) A

ii) B

c) Explain why the propeller blade is made of CFRP. (2)

d) At which point is the blade more likely to fracture, A or B? Explain your answer. (2)

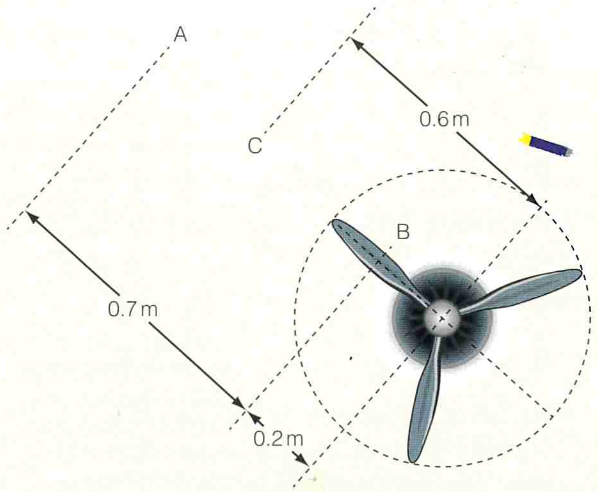


Figure 1.12

e) Estimate the centripetal force required to keep a propeller blade rotating at a rate of 960 times per second, if its centre of mass is 0.6 m from the centre of rotation and the mass of the blade is 3.5 kg. (3)

Stretch and challenge

14 This question is about apparent weight. Your weight is the pull of gravity on you. But what gives you the sensation of weight is the reaction force from the floor you are standing on.

a) A man has a mass of 80 kg. Calculate his apparent weight (the reaction from the floor) when he is in a lift that is

i) moving at a constant speed of $3\,m\,s^{-1}$

ii) accelerating upwards at $1.5\,m\,s^{-2}$

iii) accelerating downwards at $1.5\,m\,s^{-2}$.

b) A designer plans the funfair ride shown in Figure 1.13. A vehicle in an inverting roller coaster leaves point A with a very low speed before reaching point B, the bottom of the inverting circle. It then climbs to point C, 14 m above B, before leaving the loop and travelling to point D.

Assuming that no energy is transferred to other forms due to frictional forces, show that

i) the speed of the vehicle at B is $20\,m\,s^{-1}$

ii) the speed of the vehicle at C is $11\,m\,s^{-1}$.

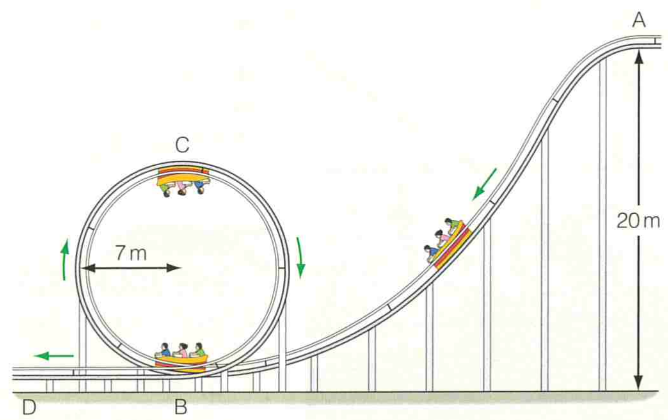


Figure 1.13

c) Use your answers to (b) to calculate the centripetal acceleration required to keep the vehicle in its circular path

i) at B **ii)** at C.

d) Now calculate the apparent weight of a passenger of mass 70 kg

i) at B **ii)** at C.

In the light of your answers, discuss whether or not this is a safe ride.

e) Figure 1.14 shows the design of a space station. It rotates so that it produces an artificial gravity. The reaction force from the outer surface provides a force to keep people in their circular path.

Use the information in the diagram to calculate the angular velocity required to provide an apparent gravity of $9.8\,m\,s^{-2}$.

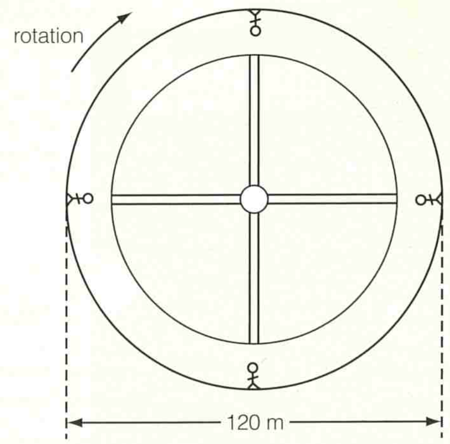


Figure 1.14