

Pearson Edexcel AS and A level Further Mathematics

Further Mechanics 2

FM2

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● = A level only

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Overarching themes

The following three overarching themes have been fully integrated throughout the Pearson Edexcel AS and A level Mathematics series, so they can be applied alongside your learning and practice.

1. Mathematical argument, language and proof

- Rigorous and consistent approach throughout
- Notation boxes explain key mathematical language and symbols
- Dedicated sections on mathematical proof explain key principles and strategies
- Opportunities to critique arguments and justify methods

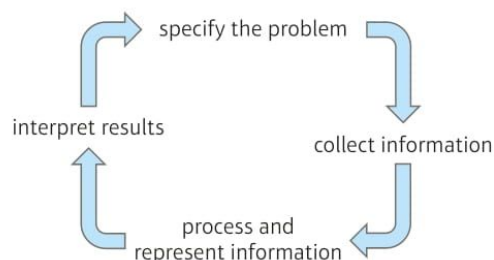
2. Mathematical problem solving

- Hundreds of problem-solving questions, fully integrated into the main exercises
- Problem-solving boxes provide tips and strategies
- Structured and unstructured questions to build confidence
- Challenge boxes provide extra stretch

3. Mathematical modelling

- Dedicated modelling sections in relevant topics provide plenty of practice where you need it
- Examples and exercises include qualitative questions that allow you to interpret answers in the context of the model
- Dedicated chapter in Statistics & Mechanics Year 1/AS explains the principles of modelling in mechanics

The Mathematical Problem-solving cycle



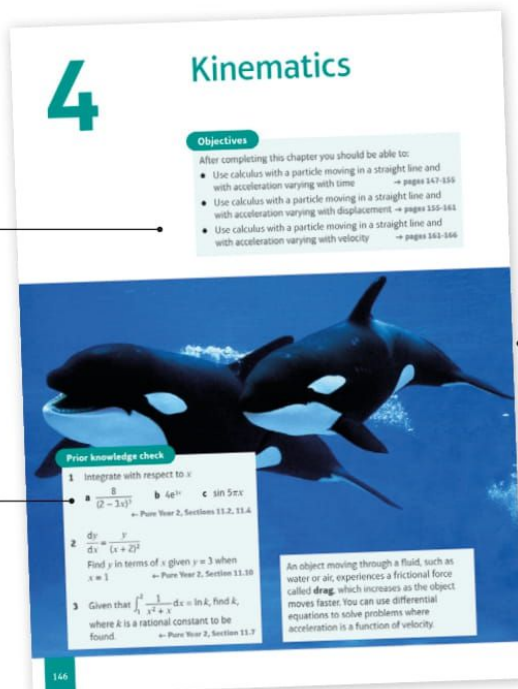
Finding your way around the book

Access an online digital edition using the code at the front of the book.



Each chapter starts with a list of objectives

The *Prior knowledge check* helps make sure you are ready to start the chapter



The real world applications of the maths you are about to learn are highlighted at the start of the chapter with links to relevant questions in the chapter

Exercise questions are carefully graded so they increase in difficulty and gradually bring you up to exam standard

Exercises are packed with exam-style questions to ensure you are ready for the exams

Challenge boxes give you a chance to tackle some more difficult questions

Exam-style questions are flagged with **E**

Problem-solving questions are flagged with **P**

A level content is clearly flagged with **A**

Chapter 2

Centres of mass of plane figures

Exercise 7 A 3.5 m ladder is modelled as a framework made of uniform wire as shown in the diagram. The rungs are 50 cm wide and are 50 cm apart and the top and bottom rungs are 50 cm from the base and the top of the ladder respectively. The base of the ladder rests on horizontal ground and the ladder stands vertically.

a Find the height of the centre of mass above the ground. (2 marks)

b Show that the height of the centre of mass of the ladder has increased by $\frac{1}{5}$ m. (4 marks)

Challenge

A metal framework $ABCDE$ is made from two congruent right-angled triangles such that ACD and BCE are straight lines, as shown in the diagram.

Given that $AB = 4$ cm and $CD = 3$ cm, work out the distance between C and the centre of mass of the framework.

2.6 Lamina in equilibrium

You can solve problems involving a lamina in equilibrium. A lamina can be suspended by means of a string attached to some point of the lamina, or can be allowed to pivot freely about a horizontal axis which passes through some point of the lamina.

• When a lamina or framework is suspended freely from a fixed point or pivots freely about a horizontal axis it will rest in equilibrium in a vertical plane with its centre of mass vertically below the point of suspension or the pivot.

Hint The first lamina is suspended from a fixed point. There are only two forces acting on it: the weight of the lamina and the tension in the string. Both forces pass through the point of suspension.

The second lamina is free to rotate about a fixed horizontal pivot. There are only two forces acting on it: the weight of the lamina and the reaction of the pivot on the lamina. Both pass through the pivot.

The resultant of the moments about O in both laminas is zero.

Example 16

Find the angle that the line AB makes with the vertical if this L-shaped uniform lamina is freely suspended from:

a A
b B
c E

First find the centre of mass of the lamina.
Split the lamina along CD .
Take A as the origin and axes along AB and AF .

$\bar{x} = \frac{2(4)}{12} + \frac{1(1)}{12} = \frac{9}{12} = \frac{3}{4}$
 $\bar{y} = \frac{2(2)}{12} + \frac{1(1)}{12} = \frac{5}{12}$
 $\tan \theta = \frac{\bar{y}}{\bar{x}} = \frac{5/12}{3/4} = \frac{5}{9}$
 $\theta = 29.1^\circ$ (3 s.f.)

θ is the angle required.

Problem-solving

You do not need to draw the lamina hanging.
Draw a line from the point of suspension to the centre of mass. Mark this in as the vertical.

Each section begins with explanation and key learning points

Step-by-step worked examples focus on the key types of questions you'll need to tackle

Each chapter ends with a *Mixed exercise* and a *Summary of key points*

Problem-solving boxes provide hints, tips and strategies, and *Watch out* boxes highlight areas where students often lose marks in their exams

Every few chapters a *Review exercise* helps you consolidate your learning with lots of exam-style questions

Review exercise

1

1 A circular flywheel of diameter 7 cm is rotating about the axis through its centre and perpendicular to its plane with constant angular speed 1000 revolutions per minute. Find, in m s^{-1} to 3 significant figures, the speed of a point on the rim of the flywheel. (2) **E**

2 A particle P of mass 0.5 kg is attached to one end of a light inextensible string of length 1.5 m. The other end of the string is attached to a fixed point A . The particle is moving, with the string taut, in a horizontal circle with centre O vertically below A . The particle is moving with constant angular speed 2.7 rad s^{-1} . Find:

a the tension in the string (4)

b the angle, to the nearest degree, that AP makes with the downward vertical. (4)

3 A particle P of mass m is attached to one end of a light string. The other end of the string is attached to a fixed point A . The particle moves in a horizontal circle with constant angular speed ω , and with the string inclined at an angle of 60° to the vertical, as shown in the diagram above. (4) **E**

4 A car moves round a bend which is banked at a constant angle of 10° to the horizontal. When the car is travelling at a constant speed of 18 m s^{-1} , there is no sideways frictional force on the car. The car is modelled as a particle moving in a horizontal circle of radius r metres. Calculate the value of r . (6) **E**

5 A cyclist is travelling around a circular track which is banked at 25° to the horizontal. The coefficient of friction between the cycle's tyres and the track is 0.6. The cyclist moves with constant speed in a horizontal circle of radius 40 m, without the tyres slipping. Find the maximum speed of the cyclist. (9) **E**

6 A light inextensible string of length l has its ends fixed to two points A and B , where A is vertically above B . A small smooth ring of mass m is threaded on the string. The ring is moving with constant speed. (4) **E**

Exam-style practice

Further Mathematics

A Level

Further Mechanics 2

Time: 1 hour and 30 minutes

You must have: Mathematical Formulae and Statistical Tables, Calculator

1 In a harbour, sea level at low tide is 10 m below the level of the sea at high tide. At low tide the depth of the water in the harbour is 8 m. On a particular day, low tide occurs at 1 p.m. and the next low tide occurs at 1.30 p.m. A ship can remain in the harbour safely when the depth of water is at least 12 m. The sea level is modelled as rising and falling with simple harmonic motion.

a Write down the

i period (2)

ii amplitude of the motion.

A 'safe mooring height' marker is attached to the harbour wall at a depth of 12 m.

b Find the speed, in metres per hour, at which the water level is rising when it passes this marker. (4)

c Find the total length of time between two consecutive low tides for which the water in the harbour is at a safe mooring depth. (4)

2 A uniform rectangular piece of card $ABCD$ has $AB = 2a$ and $AD = a$. Corner C is folded down to meet side AB as shown in the diagram.

a Find the distance of the centre of mass of the lamina from

i AD ii AB (7)

The lamina is freely suspended by a string attached to the point A and hangs at rest.

b Find, to the nearest degree, the angle between DE and the vertical. (4)

3 A particle P of mass m moves along the positive x -axis. At time t seconds, the acceleration of the particle is $-2t^2 + 2t \text{ m s}^{-2}$ where $t \geq 0$. The particle is at O and $v = 2U$. The particle passes through the point A with velocity U .

a Find the distance OA . (6)

b Show that the time P takes to travel from O to A is $\frac{1}{2U} \left(\arctan \frac{2U}{k} - \arctan \frac{U}{k} \right)$. (5)

AS and A level practice papers at the back of the book help you prepare for the real thing.

Extra online content

Whenever you see an *Online* box, it means that there is extra online content available to support you.



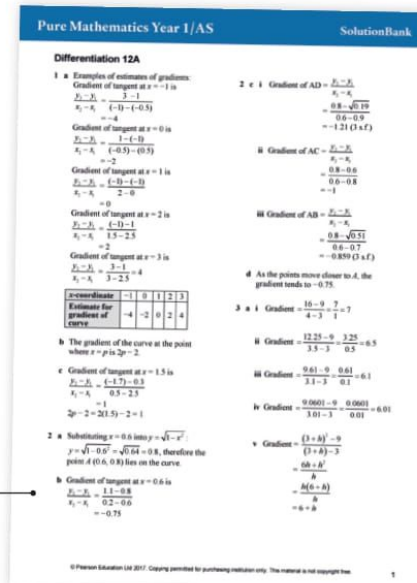
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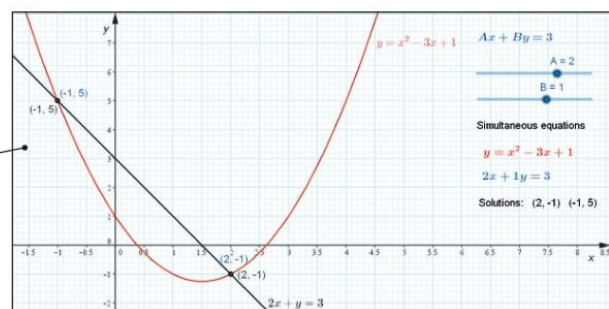
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Circular motion

1

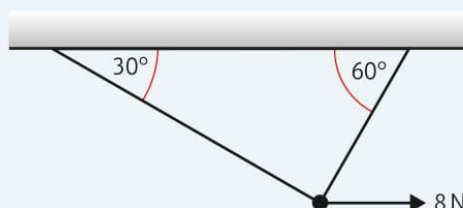
Objectives

After completing this chapter you should be able to:

- Understand and calculate angular speed of an object moving in a circle → pages 2–4
- Understand and calculate angular acceleration of an object moving on a circular path → pages 5–10
- Solve problems with objects moving in horizontal circles → pages 11–18
- Solve problems with objects moving in vertical circles → pages 19–25
- Solve problems when objects do not stay on a circular path → pages 26–30

Prior knowledge check

- 1** A smooth ring is threaded on a light inextensible string. The ends of the string are attached to a horizontal ceiling, and make angles of 30° and 60° with the ceiling respectively. The ring is held in equilibrium by a horizontal force of magnitude 8 N.



Find

- a** the tension in the string **b** the mass of the ring.

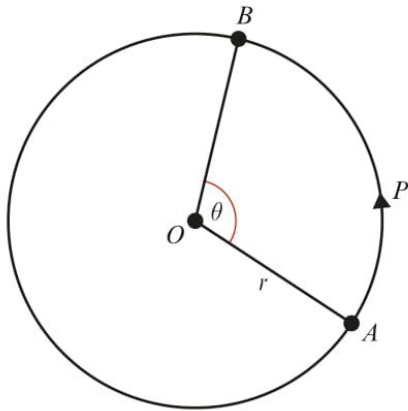
← Statistics and Mechanics 2, Section 7.1

- 2** A box of mass 4 kg is projected with speed 10 m s^{-1} up the line of greatest slope of a rough plane, which is inclined at an angle of 20° to the horizontal. The coefficient of friction between the box and the plane is 0.15. Find:
- a** the distance travelled by the box before it comes to instantaneous rest
- b** the work done against friction as the box reaches instantaneous rest. ← Further Mechanics 1, Section 2.3

A car travelling around a bend can be modelled as a particle on a circular path. Police use models such as this to determine likely speeds of cars following accidents. → Exercise 1C, Q18

1.1 Angular speed

When an object is moving in a straight line, the speed, usually measured in m s^{-1} or km h^{-1} , describes the rate at which distance is changing. For an object moving on a circular path, you can use the same method for measuring speed, but it is often simpler to measure the speed by considering the rate at which the radius is turning.



As the particle P moves from point A to point B on the circumference of a circle of radius r m, the radius of the circle turns through an angle θ radians.

The distance moved by P is $r\theta$ m, so if P is moving at v m s^{-1} we know that $v = \frac{d}{dt}(r\theta) = r \frac{d\theta}{dt} = r \times \dot{\theta}$

Notation

$\dot{\theta}$ is the rate at which the radius is turning about O .

It is called the **angular speed of the particle** about O .

The angular speed of a particle is usually denoted by ω , and measured in rad s^{-1} .

- If a particle is moving around a circle of radius r m with linear speed v m s^{-1} and angular speed ω rad s^{-1} then $v = r\omega$.

Example 1

A particle moves in a circle of radius 4 m with speed 2 m s^{-1} . Calculate the angular speed.

Using $v = r\omega$, $2 = 4\omega$, so $\omega = 0.5 \text{ rad s}^{-1}$

Example 2

Express an angular speed of 200 revolutions per minute in radians per second.

Each complete revolution is 2π radians, so 200 revolutions is 400π radians per minute. Therefore the angular speed is

$$\frac{400\pi}{60} = 20.9 \text{ rad s}^{-1} \text{ (3 s.f.)}$$

Watch out Sometimes an angular speed is described in terms of the number of revolutions completed in a given time.

Example 3

A particle moves round a circle in 10 seconds at a constant speed of 15 m s^{-1} . Calculate the angular speed of the particle and the radius of the circle.

The particle rotates through an angle of 2π radians in 10 seconds, so $\omega = \frac{2\pi}{10} = 0.628 \text{ rad s}^{-1}$ (3 s.f.)

Using $v = r\omega$, $r = \frac{v}{\omega} = \frac{15}{0.628} = 23.9 \text{ m}$ (3 s.f.)

Exercise 1A

- 1 Express:
 - a an angular speed of 5 revolutions per minute in rad s^{-1}
 - b an angular speed of 120 revolutions per minute in rad s^{-1}
 - c an angular speed of 4 rad s^{-1} in revolutions per minute
 - d an angular speed of 3 rad s^{-1} in revolutions per hour.
- 2 Find the speed in m s^{-1} of a particle moving on a circular path of radius 20 m at:
 - a 4 rad s^{-1}
 - b 40 rev min^{-1}
- 3 A particle moves on a circular path of radius 25 cm at a constant speed of 2 m s^{-1} . Find the angular speed of the particle:
 - a in rad s^{-1}
 - b in rev min^{-1}
- 4 Find the speed in m s^{-1} of a particle moving on a circular path of radius 80 cm at:
 - a 2.5 rad s^{-1}
 - b 25 rev min^{-1}
- 5 An athlete is running round a circular track of radius 50 m at 7 m s^{-1} .
 - a How long does it take the athlete to complete one circuit of the track?
 - b Find the angular speed of the athlete in rad s^{-1} .
- 6 A disc of radius 12 cm rotates at a constant angular speed, completing one revolution every 10 seconds. Find:
 - a the angular speed of the disc in rad s^{-1}
 - b the speed of a particle on the outer rim of the disc in m s^{-1}
 - c the speed of a particle at a point 8 cm from the centre of the disc in m s^{-1} .

- 7 A cyclist completes two circuits of a circular track in 45 seconds. Calculate:
- his angular speed in rad s^{-1}
 - the radius of the track given that his speed is 40 km h^{-1} .
- 8 Anish and Bethany are on a fairground roundabout. Anish is 3 m from the centre and Bethany is 5 m from the centre. If the roundabout completes 10 revolutions per minute, calculate the speeds with which Anish and Bethany are moving.
- 9 A model train completes one circuit of a circular track of radius 1.5 m in 26 seconds. Calculate:
- the angular speed of the train in rad s^{-1}
 - the linear speed of the train in m s^{-1} .
- 10 A train is moving at 150 km h^{-1} round a circular bend of radius 750 m. Calculate the angular speed of the train in rad s^{-1} .
- (P) 11 The hour hand on a clock has radius 10 cm, and the minute hand has radius 15 cm. Calculate:
- the angular speed of the end of each hand
 - the linear speed of the end of each hand.
- 12 The drum of a washing machine has diameter 50 cm. The drum spins at $1200 \text{ rev min}^{-1}$. Find the linear speed of a point on the drum.
- 13 A gramophone record rotates at 45 rev min^{-1} . Find:
- the angular speed of the record in rad s^{-1}
 - the distance from the centre of a point moving at 12 cm s^{-1} .
- (P) 14 The Earth completes one orbit of the sun in a year. Taking the orbit to be a circle of radius $1.5 \times 10^{11} \text{ m}$, and a year to be 365 days, calculate the speed at which the Earth is moving.
- (P) 15 A bead moves around a hoop of radius $r \text{ m}$ with angular velocity 1 rad s^{-1} . The bead moves at a speed greater than 5 m s^{-1} . Find the range of possible values for r .

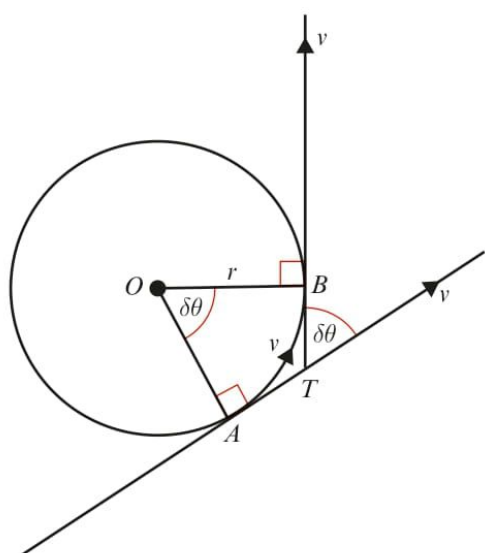
Challenge

Two separate circular turntables, with different radii, are both mounted horizontally on a common vertical axis which acts as the centre of rotation for both. The smaller turntable, of radius 18 cm, is uppermost and rotates clockwise. The larger turntable has radius 20 cm and rotates anticlockwise. Both turntables have constant angular velocities, with magnitudes in the same ratio as their radii.

A blue dot is placed at a point on the circumference of the smaller turntable, and a red dot likewise on the larger one. Starting from the instant that the two dots are at their closest possible distance apart, it is known that 10 seconds later these dots are at their maximum distance apart for the first time. Find the exact angular velocity of the larger turntable.

1.2 Acceleration of an object moving on a horizontal circular path

When an object moves round a horizontal circular path at constant speed, the direction of the motion is changing. If the direction is changing, then, although the speed is constant, the velocity is not constant. If the velocity is changing then the object must have an acceleration.



Suppose that the object is moving on a circular path of radius r at constant speed v .

Let the time taken to move from A to B be δt , and the angle AOB be $\delta\theta$.

At A , the velocity is v along the tangent AT . At B , the velocity is v along the tangent TB .

The velocity at B can be resolved into components:

$v \cos \delta\theta$ parallel to AT and

$v \sin \delta\theta$ perpendicular to AT .

We know that acceleration = $\frac{\text{change in velocity}}{\text{time}}$, so to find the acceleration of the object at the instant when it passes point A , we need to consider what happens to $\frac{v \cos \delta\theta - v}{\delta t}$ and $\frac{v \sin \delta\theta - 0}{\delta t}$ as $\delta t \rightarrow 0$. These will be the components of the acceleration parallel to AT and perpendicular to AT respectively. For a small angle $\delta\theta$ measured in radians, $\cos \delta\theta \approx 1$ and $\sin \delta\theta \approx \delta\theta$, so the acceleration parallel to AT is zero, and the acceleration perpendicular to AT is $v \frac{\delta\theta}{\delta t} = v\omega$.

Using $v = r\omega$, $v\omega$ can be written as $r\omega^2$ or $\frac{v^2}{r}$.

- **An object moving on a circular path with constant linear speed v and constant angular speed ω has acceleration $r\omega^2$ or $\frac{v^2}{r}$, towards the centre of the circle.**

Example 4

A particle is moving on a horizontal circular path of radius 20 cm with constant angular speed 2 rad s^{-1} . Calculate the acceleration of the particle.

Acceleration

$$= 0.2 \times 2^2$$

$$= 0.8 \text{ m s}^{-2} \text{ towards the centre of the circle.}$$

The radius needs to be measured in metres if the answer is to be in m s^{-2} .

Using $a = r\omega^2$.

A

Given that the rod remains on the surface of the sphere,

- b** show that the time taken for the particle to make one complete revolution is at least $\pi\sqrt{\frac{6r}{g}}$.
(3 marks)
- c** Without further calculation, state how your answer to part **b** would change if the particle was moved:
- up the rod towards the pivot
 - down the rod away from the pivot.
- (2 marks)

E/P

- 11** A rough disc rotates in a horizontal plane with constant angular velocity ω about a fixed vertical axis. A particle P of mass m lies on the disc at a distance $\frac{3}{5}a$ from the axis. The coefficient of friction between P and the disc is $\frac{3}{7}$. Given that P remains at rest relative to the disc,

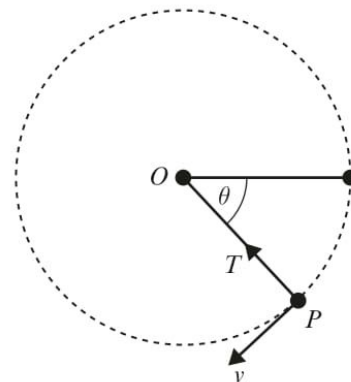
- a** prove that $\omega^2 \leq \frac{5g}{7a}$ (7 marks)

The particle is now connected to the axis by a horizontal light elastic string of natural length $\frac{a}{2}$ and modulus of elasticity $\frac{5mg}{2}$. The disc again rotates with constant angular velocity ω about the axis and P remains at rest relative to the disc at a distance $\frac{3}{5}a$ from the axis.

- b** Find the range of possible values of ω^2 . (8 marks)

- 12** A particle P of mass m is attached to one end of a light inextensible string of length a . The other end of the string is fixed at a point O . The particle is held with the string taut and OP horizontal. It is then projected vertically downwards with speed u , where $u^2 = \frac{4}{3}ga$. When OP has turned through an angle θ and the string is still taut, the speed of P is v and the tension in the string is T , as shown in the diagram. Find:

- an expression for v^2 in terms of a , g and θ
- an expression for T in terms of m , g and θ
- the value of θ when the string becomes slack to the nearest degree.
- Explain why P would not complete a vertical circle if the string were replaced by a light rod.



- 13** A particle P of mass 0.4 kg is attached to one end of a light inelastic string of length 1 m. The other end of the string is fixed at point O . P is hanging in equilibrium below O when it is projected horizontally with speed u m s⁻¹. When OP is horizontal it meets a small smooth peg at Q , where $OQ = 0.8$ m. Calculate the minimum value of u if P is to describe a complete circle about Q .

E/P

- 14** A smooth solid hemisphere is fixed with its plane face on a horizontal table and its curved surface uppermost. The plane face of the hemisphere has centre O and radius a . The point A is the highest point on the hemisphere. A particle P is placed on the hemisphere at A .

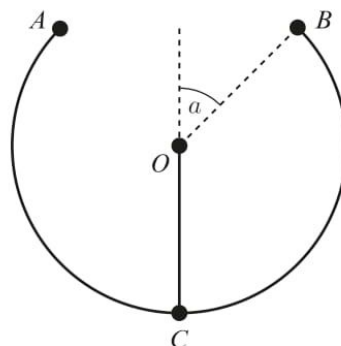
It is then given an initial horizontal speed u , where $u^2 = \frac{ag}{2}$. When OP makes an angle θ with OA , and while P remains on the hemisphere, the speed of P is v .

- A**
- a** Find an expression for v^2 . (2 marks)
- b** Show that P is still on the hemisphere when $\theta = \arccos 0.9$. (2 marks)
- c** Find the value of:
- $\cos \theta$ when P leaves the hemisphere
 - v when P leaves the hemisphere. (3 marks)

After leaving the hemisphere P strikes the table at B , find:

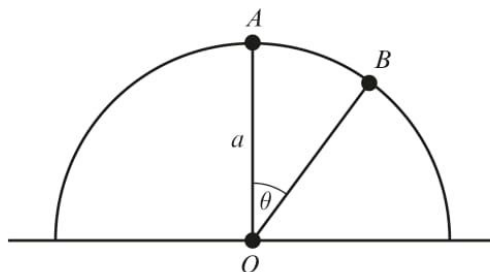
- d** the speed of P at B (2 marks)
- e** the angle, to the nearest degree, at which P strikes the table. (3 marks)

- E/P** **15** Part of a hollow spherical shell, centre O and radius r , is removed to form a bowl with a plane circular rim. The bowl is fixed with the circular rim uppermost and horizontal. The point C is the lowest point of the bowl. The point B is on the rim of the bowl and OB is at an angle α to the upward vertical as shown in the diagram. Angle α satisfies $\tan \alpha = \frac{4}{3}$. A smooth small marble of mass m is placed inside the bowl at C and given an initial horizontal speed u . The direction of motion of the marble lies in the vertical plane COB . The marble stays in contact with the bowl until it reaches B . When the marble reaches B it has speed v .



- a** Find an expression for v^2 . (4 marks)
- b** If $u^2 = 4gr$, find the normal reaction of the bowl on the marble as the marble reaches B . (3 marks)
- c** Find the least possible value of u for the marble to reach B . (3 marks)
- The point A is the other point of the rim of the bowl lying in the vertical plane COB .
- d** Find the value of u which will enable the marble to leave the bowl at B and meet it again at A . (4 marks)

- E/P** **16** A particle is at the highest point A on the outer surface of a fixed smooth hemisphere of radius a and centre O . The hemisphere is fixed to a horizontal surface with the plane face in contact with the surface. The particle is projected horizontally from A with speed u , where $u < \sqrt{ag}$. The particle leaves the sphere at the point B , where OB makes an angle θ with the upward vertical, as shown in the diagram.



- a** Find an expression for $\cos \theta$ in terms of u , g and a . (3 marks)
- The particle strikes the horizontal surface with speed $\sqrt{\frac{5ag}{2}}$.
- b** Find the value of θ , to the nearest degree. (4 marks)

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Further Mechanics 2

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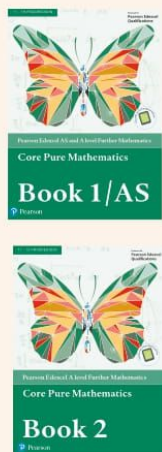


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