

# Stage 3 Physics:

## Motion and Force in a Gravitational Field

### Student workbook Part 2

#### Contexts:

- Movement in sport, funfairs and play-grounds
- Motion of satellites, planetary motion and the universe
- Structures, bridges and buildings

#### Plan For Unit.

This workbook will give you an outline of the content to be covered and the related text pages. It is expected that you will follow the workbook and read the related text, experiments and investigations **before** the lesson. It will be assumed that you have read the text and have some introductory knowledge of the work to be covered each lesson; failure to do so may affect your progress in class. Your teacher will then teach you the concepts and show you how to do the examples in the workbook thus ensuring you have exemplars when completing additional questions from the workbook and texts. Your teacher also has all the worked answers to the additional questions in this workbook and you must check your answers when you complete the questions.

In addition to the work set for homework, it is essential that you set up a study plan and regularly review the work covered. This plan should be set up from day one. Regular reviewing not only makes study easy, it ensures good grades.

Wk	Content	Text Reference	Exploring Physics		Assessments
			Problem Sets	Experiments & Investigations	
1	<b>Students start Monday</b> 1. describe and apply the principle of conservation of energy 2. resolve, add and subtract vectors in one plane 3. draw free body diagrams, showing the forces acting on objects, from descriptions of real life situations involving forces acting in one plane 4. explain and apply the concept of centre of mass	CD Pg. 416-419  CD Pg. 421  CD Pg. 420	Set 1: Vectors	Expt: 1.1 Expt: 1.2	
2-3	5. describe and apply the concepts of distance and displacement, speed and velocity, acceleration, energy and momentum in the context of motion in a plane, including the trajectories of projectiles in the absence of air resistance —this will include <i>applying the relationships</i> : $v_{av} = \frac{s}{t}, \quad v_{av} = \frac{v + u}{2}, \quad a = \frac{v - u}{t},$ $s = ut + \frac{1}{2}at^2, \quad v^2 = u^2 + 2as$ $p = mv, \quad \sum p_{before} = \sum p_{after},$ $F\Delta t = mv - mu$ $E_k = \frac{1}{2}mv^2, \quad E_p = mg\Delta h, \quad W = Fs,$ $W = \Delta E$ 6. describe qualitatively the effects of air resistance on projectile motion	Stage 2 Review CD Pg. 422-432 CD Pg. 433-444 Pg. 7-14 Pg. 19-22  Pg. 26-32	Set 2: Projectile Motion	Expt: 2.1 Expt: 2.2 (both needs camera and stroboscope lamp)	

Wk	Content	Text Reference	Exploring Physics		Assessments
			Problem Sets	Experiments & Investigations	
4	<p>7. explain and apply the concepts of centripetal acceleration and centripetal force, as applied to uniform circular motion—this will include <i>applying the relationships</i>:</p> $a_c = \frac{v^2}{r}, \quad \text{resultant } F = ma = \frac{mv^2}{r}$	Pg. 33-51	Set 3: Circular Motion	Expt: 3.1 Invest: 3.2 (home research)	
5	<p><b>Week 5 Monday Holidays</b></p> <p>8. describe and interpret the radial gravitational field distribution around a single (point) mass</p> <p>9. explain and apply Newton's Law of Universal Gravitation and the concept of gravitational acceleration, <math>g</math>, as gravitational field strength—this will include <i>applying the relationships</i>:</p> $F_g = G \frac{m_1 m_2}{r^2}, \quad g = G \frac{M}{r^2}$	<p>Pg. 58-62</p> <p>Pg. 54-62</p>		Expt: 4.1 Optional: Expt: 4.2 Expt: 4.3	<b>Task 6:</b> Test Projectile motion and circular motion
6	<p>10. explain the conditions for a satellite to remain in a stable circular orbit in a gravitational field, and calculate the parameters of satellites in stable circular orbits—this will include <i>applying the relationships</i>:</p> $v_{av} = \frac{s}{t}, \quad a_c = \frac{v^2}{r},$ $\text{resultant } F = ma = \frac{mv^2}{r},$ $F_g = G \frac{m_1 m_2}{r^2}, \quad g = G \frac{M}{r^2}.$ <p>11. describe and explain the impact of satellites and associated technologies on everyday life</p>	<p>Pg. 63-68</p> <p>Pg. 68-71</p>	Set 4: Gravitation and Satellites		
7-8	<p>12. explain and apply the concept of torque or moment of a force about a point, and the principle of moments, and their application to situations where the applied force is perpendicular to the lever arm—this will include <i>applying the relationships</i>:</p> $\tau = rF \quad \text{and} \quad \Sigma \tau = 0.$ <p>13. explain and apply the concept of a rigid body in equilibrium—this will include <i>applying the relationships</i>:</p> $\Sigma F = 0, \quad \tau = rF \quad \text{and} \quad \Sigma \tau = 0$ <p><b>Unit Test</b></p>	<p>Pg. 72-76</p> <p>Pg. 77-91</p>	Set 5: Moments and Equilibrium	Expt: 5.1 Expt: 5.2	<b>Task 7:</b> Test Motion and forces in a gravitational field

**Outcome 7:** explain and apply the concepts of centripetal acceleration and centripetal force, as applied to uniform circular motion—this will include *applying the relationships*:

$$a_c = \frac{v^2}{r}, \quad \text{resultant } F = ma = \frac{mv^2}{r}$$

## Going Around In Circles

### Going Around at a Constant Speed      Text Reference pg. 33-36

An object moving in a circle may travel with constant speed, but its velocity will be constantly changing because its direction of motion is constantly changing. Because the velocity is changing, the object will be accelerating. As there is acceleration there must be a net force acting to produce the circle motion.

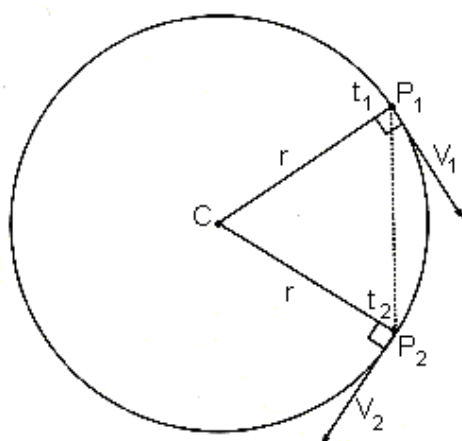
There are two types of motion:

- \_\_\_\_\_
- \_\_\_\_\_

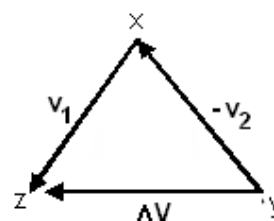
For this unit we will only consider motion (a)

### Terminology and Equations:

(a)



(b)



- The radius ( $r$ ) is a position vector acting out from the centre.
- The velocities ( $V_1$  and  $V_2$ ) are a tangent to the circle, and at right angles to the radius.
- Diagram (b) shows the change in velocity or acceleration (a).
- The acceleration is always towards the centre.
- The time ( $t$ ) taken to move once around the circle is called the period ( $T$ ).
- The frequency ( $f$ ) can be found by  $1/T$ .
- The distance travelled is the circumference of the circle -  $2\pi r$  therefore  $v = \frac{s}{t} = \frac{2\pi r}{T}$

Your teacher will work through this example with you.

### Example:

You may feel like you are not moving but the earth takes one year to complete its revolution around the sun. Assuming it moves at a constant speed in a circle at a distance of  $1.50 \times 10^8$  km from the sun, at what speed does the earth travel in  $\text{kms}^{-1}$ .

## Equations for acceleration:

Equation for centripetal acceleration is  $a_c = \frac{v^2}{r}$

Using main equation and substituting in other equations for  $v$  and  $r$ , two other equations can be found.

$$a_c = \frac{v^2}{r} \xrightarrow{\text{substitute } v = \frac{2\pi r}{T}} a_c = \frac{4\pi^2 r}{T^2} \xrightarrow{\text{substitute } r = \frac{vT}{2\pi}} a_c = \frac{2\pi v^2}{T}$$

### Example:

A side show attraction is racing cars. Assuming that the track is circular and that a boy is driving a car at an average velocity of  $20.0 \text{ kmh}^{-1}$ ,  $3.00 \text{ m}$  from the centre, what is the size of the acceleration to move around the track? (Helpful hint: Don't forget to change to SI units.)

## Centripetal Force:

As shown before, because acceleration occurs in circular motion, there must be a force acting and this must act along the direction of the acceleration e.g. towards the centre. This centre-seeking force is called the *centripetal force*. As the force and acceleration are in the same direction we can now call our acceleration the centripetal acceleration,  $a_c$ .

We know from Newton's Second Law that  $F = ma$

Now in the case of centripetal acceleration,  $a_c = \frac{v^2}{r}$

Therefore  $F_c = \frac{mv^2}{r}$  which is the equation for the centripetal force

Note also as  $v = \frac{2\pi r}{T}$  then in addition,  $F_c = \frac{m4\pi^2 r}{T^2}$

### Example:

Annie rides her bicycle at a constant speed around a circular track of radius  $50.0 \text{ m}$ . She completes one revolution of the track each minute.

a. What is her speed?	b. What is the magnitude of the centripetal acceleration acting on the rider?	c. If the rider and cycle have a combined mass of $70.0 \text{ kg}$ , what is the size of the force causing the circular motion?

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## Centrifugal – An outward directing force?

Writers will often describe a centrifugal force or centre-fleeing force. “A *centripetal force*”, they say “acts towards the centre of the circle, so there must be a force acting away from the centre – we can feel it so it must exist.” IT DOES NOT!!

Let us consider Newton’s First Law – objects will keep doing what they are doing unless acted upon by an external force. As the velocity of an object travelling in a circle is at a tangent to the circle so is the direction of travel. While the external force keeps acting, the object will keep travelling in a circle. If the external force is no longer available then the object will shoot off at a tangent to the circle NOT away from the centre. So although you may be able to feel a force acting away from the centre, for the reason above, physicists call it a “*fictitious force*” unlike the forces of gravity, etc.

## Back to Centripetal Forces

Text Reference pg. 36

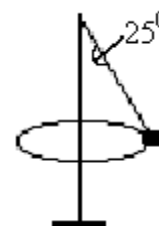
Examples of Centripetal forces are:

- Loops in roller coaster.
- Rides at the Royal Show
- Buses or cars suddenly turning a corner
- Many sports such as hammer throwing
- Gravitational attraction between Earth and Moon.
- Planes doing loops in the air

Your teacher will work through the examples on the following pages with you.

### Example:

In a game of totem tennis, a 0.120 kg ball is moving at a constant velocity in a horizontal circle around the pole as shown. The rope forms an angle of  $25.0^\circ$  to the pole and the horizontal radius of the ball is 1.20 m. The ball takes 0.800 s for one revolution.



a. Draw and label the forces acting on the ball.

b. What is holding the ball up? \_\_\_\_\_

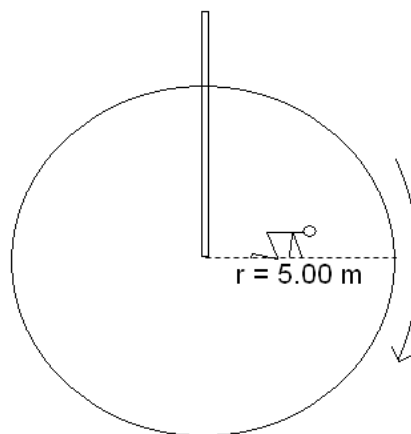
c. What is the ball’s acceleration?

d. What is the tension in the string?

Example:

A fun ride at the Busselton Show consists of a giant disk, which rotates, in a horizontal plane. While the disk is stationary, the riders sit in the centre of the disk. When the disk is rotating at full speed, the riders must start to crawl towards the perimeter of the disk. The first rider to reach the perimeter without being flung off the disk wins a prize. The disk rotates at 10 revolutions per minute and its radius is 5.00 m.

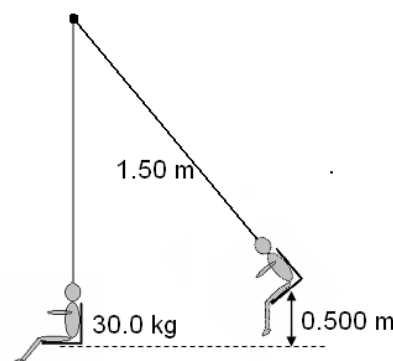
One rider of mass 70.0 kg can provide a maximum frictional force between their hands and feet and the disk of 425 N, what radius will the rider reach before being flung off the disk?



Example:

A child is sitting on a swing and has been pulled back so that the seat is 0.500 m above the lowest point in the swing. The seat is then released.

- Calculate the velocity of the swing at its lowest point.
- Calculate the tension in the ropes of the swing when a 30.0 kg child is moving through the lowest point in the swing, which has a length of 1.50 m.



**Exploring Physics Stage 3:**

• **Experiment 3.1**

## Going around a circular curve Text Reference pg. 37-40

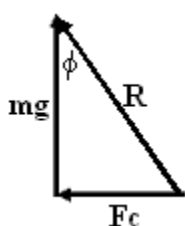
Why do road and race track designers sometimes bank the road when it curves?

When a car rounds a curve that is horizontal, the frictional force between the tyres and road surface supply the necessary centripetal force. The reaction force (or normal) is the force of the road on the car due to its weight ( $mg$ ). See Figure 1.

If the road is banked at an angle to the horizontal as shown in Figure 2, the horizontal component of the reaction force,  $R$ , supplies the centripetal force. The vertical component of  $R$  is equal to the weight of the car. See Figure 3.

In other words, the banking of curves can reduce the chance of skidding because the normal force of the road will have a component towards the centre of the circle thus reducing the need for friction. For a given angle of banking, there will be one speed for which no friction at all is required. This will be the case when the horizontal component of the normal force,  $F_n \sin \phi$ , is just equal to the force required to give a vehicle its centripetal acceleration – that is when  $F_n \sin \phi = mv^2/r$ . The banking angle of a road,  $\phi$ , is chosen so that this condition holds for a particular speed, called the “design speed”. Which is why you shouldn’t speed around curves as they have been designed for a particular maximum speed!

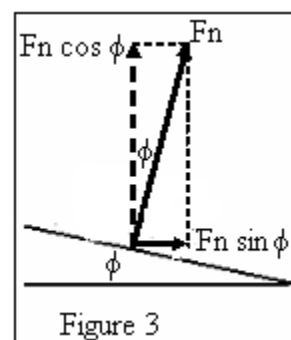
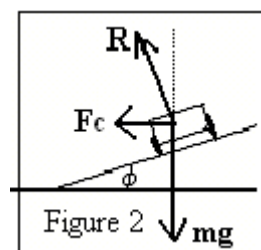
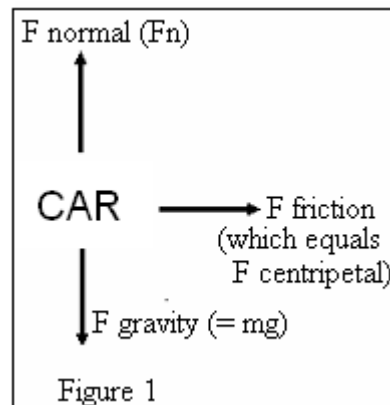
From Figure 2, the reaction force can be resolved into its compounds as shown below and from the triangle you can see that:



$$\tan \phi = \frac{F_c}{mg} = \frac{mv^2/r}{mg}$$

so  $\tan \phi = \frac{v^2}{rg}$

where  $\phi$  = angle of track  
 $v$  = optimum speed for banked track  
 $r$  = radius of curvature  
 $g = 9.8 \text{ ms}^{-2}$

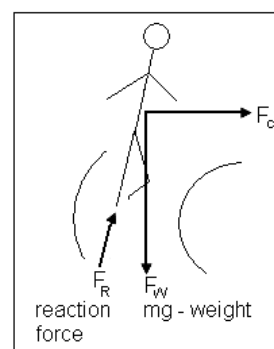


A typical type question could be, given the angle and radius of a bank, what is the maximum speed for this bank. Or you could be asked to compare two situations, one in which a curve is not banked and one in which it is and compare the maximum speeds.

**Helpful Hint:** The formula above can also be used for objects that lean on a flat surface e.g. runners going around a corner will lean to enable them to increase their speed, likewise, motor cycles will lean when going around bends for the same reason.

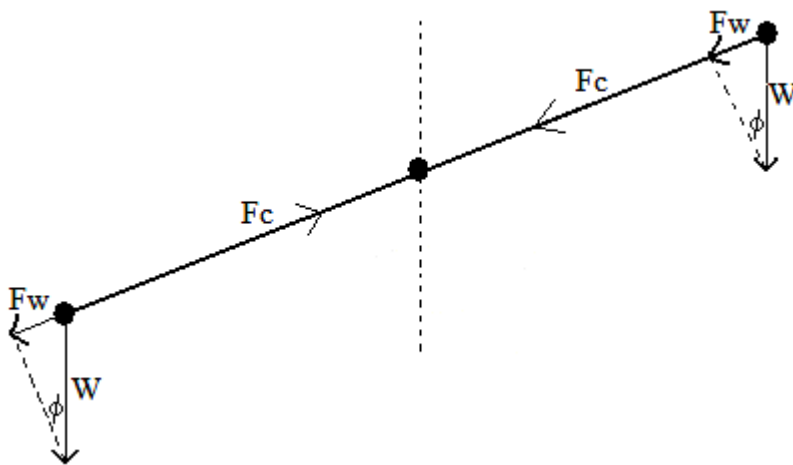
### Example:

A civil engineer has to design a road in which there is a curve with a radius of  $3.00 \times 10^2 \text{ m}$ . The road will have a maximum speed limit of  $1.10 \times 10^2 \text{ kmh}^{-1}$ . At what angle should the road bank on the curve so that no frictional force is needed by a vehicle, travelling at the speed limit, to move round it.



### Increasing Angle But Maintaining The Same Speed:

The diagram below shows how the different tensions can be calculated when the circular motion is not horizontal. The situation is swinging a ball ready to release such as in hammer throwing at athletic events.



At the highest point, gravity is helping as the ball starts to fall so there is less tension in the wire:

$$F_t = F_c - F_w$$

$$F_t = F_c - W \sin \phi$$

At lowest point, gravity needs to be overcome as the ball raises so tension is higher:

$$F_t = F_c + F_w$$

$$F_t = F_c + W \sin \phi$$

#### Example:

A hammer thrower is swinging his 7.25 kg hammer at an angle of  $40.0^\circ$  to the horizontal at a speed of  $10.0 \text{ ms}^{-1}$ . If the length of his arms are 0.500 m and the length of the wire is 0.700 m, calculate:

a. the centripetal acceleration.

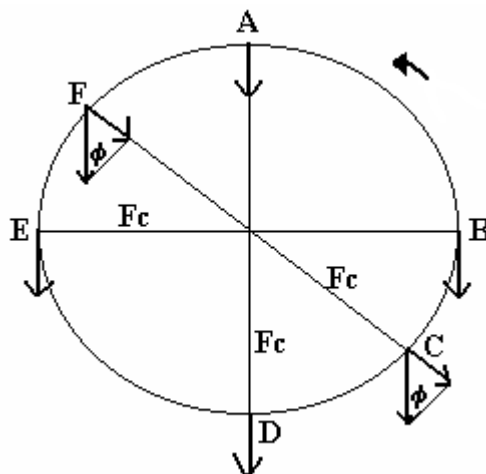
b. the centripetal force.

c. the tension in the wire at the top of the swing just as the ball is on the way down.

d. The tension in the wire at the bottom of the swing just as the ball is on the way up.



## A Vertical Circle Text Reference pg. 42-47



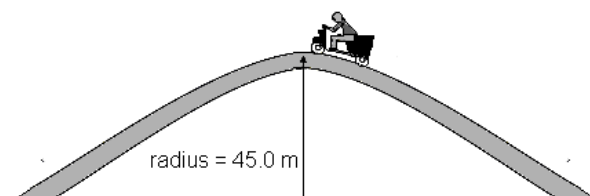
In a horizontal circle, the force applied is always constant. However, in a vertical circle the force of gravity must be considered. As gravity is the same value and always acts downwards sometimes it assists the motion and sometimes it acts against the motion. Consider each of the points above on a vertical circle turning anticlockwise.

A - gravity helps so	$F_t = F_c - W$ $F_t = F_c - mg$
B - no component of $F_c$ so	$F_t = F_c$
C - component added to $F_c$ so	$F_t = F_c + F_w$ $F_t = F_c + W \sin \phi$
D - gravity adds force so	$F_t = F_c + W$ $F_t = F_c + mg$
E - same as B	
F - Component along $F_c$ so	$F_t = F_c - F_w$ $F_t = F_c - W \sin \phi$

Your text page 183 gives an example.

### Example:

A hump back bridge is constructed so it has a radius of 45.0 m. What is the maximum speed a motorcyclist can travel across the bridge without 'lifting off the bridge'?



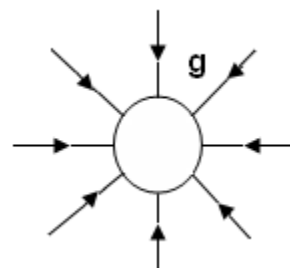
### Exploring Physics Stage 3:

- Set 3 Circular Motion
- Investigation 3.2 (home research)

**Outcome 8:** describe and interpret the radial gravitational field distribution around a single (point) mass

### Diagrammatic representation of gravitational fields pg. 59

We can describe a field as an area in which an object will experience a force. You have already drawn electrical fields around charged particles in Stage 2 Physics; Electrical Fundamentals, this is no different. Gravitational fields are regions in which a mass will experience a force. The diagram to the right shows the radial gravitational field distribution around an object, for example, the Earth.



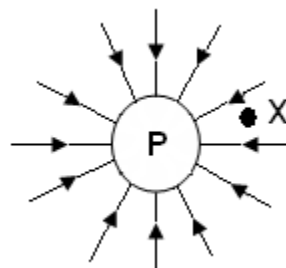
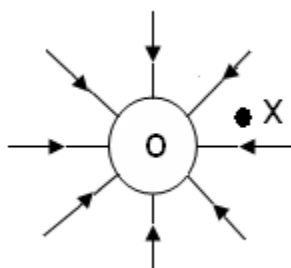
- Gravitational forces are vector quantities and can be represented by vector arrows.
- The arrow shows that the direction of the gravitational force is towards the object.
- The more arrows, the greater the mass of the object and therefore the greater the gravitational field.
- The closeness of the arrows indicates the size of the field at any point within the field.

Most fields obey the “inverse square rule” which is that the force is proportional to the inverse of the distance squared:

$$F = \frac{1}{r^2}. \text{ Gravitational fields are no different.}$$

#### Example:

Consider the two field diagrams that represent the gravitational fields around two planets O and P which have the same radius. X represents a mass which is exactly the same distance above the planets.



Which of the following statements is true? Where the statement is false, write in a correct answer. If true, justify your answer.

- A. The planets have the same radius so must have the same acceleration due to gravity at the surface of the planets.

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- B. The gravitational force is weaker on mass 'X' above planet P.

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- C. The mass of planet O is less than the mass of planet P.

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**Outcome 9:** explain and apply Newton's Law of Universal Gravitation and the concept of gravitational acceleration,  $g$ , as gravitational field strength—this will include *applying the relationships*:

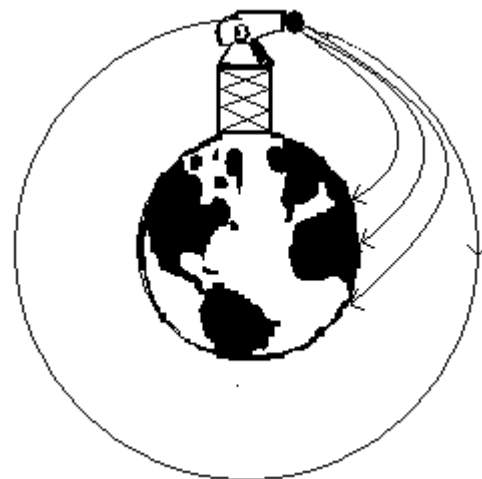
$$F_g = G \frac{m_1 m_2}{r^2}, \quad g = G \frac{M}{r^2}$$

## Gravitation Fields and Universal Gravitation

Consider a tower several miles high with a horizontal canon on top. The velocity at which the cannon ball is fired is increased every time.

Each time it falls back to the ground except the last time where it keeps falling towards the Earth but the Earth curves away from it as it falls. It is in orbit.

All satellites, both artificial and natural, are in free fall and their acceleration depends only on where they are. Close to Earth the acceleration is  $9.8 \text{ ms}^{-2}$ . In much higher orbits they move slower and have a lower acceleration.



### Gravitational Fields Text Reference pg. 54-62

Newton's talent for clear thinking provided most of the logical framework for our modern understanding of motion of everyday objects. He explained the forces which attract falling objects towards the Earth and why satellites stay in orbit. He found that all objects *attract each other with a force which is proportional to the product of their masses and inversely proportional to the square of their distance apart*.

$$\text{So } F_g \propto \frac{m_1 m_2}{r^2}$$

This is known as **Newton's Law of Universal Gravitation**.

To turn a proportionality into an equation you need to add a constant, in this case,  $G$  – the gravitational constant.

$$F_g = G \frac{m_1 m_2}{r^2} \quad \text{where} \quad \begin{aligned} F_g &= \text{force in newtons (N)} \\ m_1 \text{ \& } m_2 &= \text{masses of objects (kg)} \\ r &= \text{distance apart (m)} \\ G &= \text{gravitational constant, } 6.67 \times 10^{-11} \text{ Nm}^2\text{kg}^{-2} \end{aligned}$$

*Your teacher will work through the following examples with you.*

Helpful hint: A common error for students is to forget to square the radius.

Example:

The mass of the Earth is  $6.00 \times 10^{24} \text{ kg}$ . If the centres of the Earth and moon are  $3.90 \times 10^8 \text{ m}$  apart, the gravitational force between them is about  $1.90 \times 10^{20} \text{ N}$ . What is the approximate mass of the moon?

Example:

Calculate the force of attraction between yourself and your nearest neighbour. List your assumptions.

*Helpful Hint:* When dealing with estimation questions, you must make reasonable estimates. For example, you could estimate your friend's mass as 60 kg or 65 but not 64.5 kg – this is too accurate for an estimate. Most estimate questions have only 1 or 2 significant figures in the answer.

## Calculating Gravitational Field Strength      Text Reference pg. 60-62

We know that the force that causes an object to fall towards Earth is the gravitational force between that object and the Earth, otherwise known as *weight*. The weight follows the Universal Gravitational Laws hence:

$$\text{Weight} = F_g = G \frac{m_E m_o}{r^2} \quad \text{Where } m_E = \text{mass of Earth and } m_o = \text{mass of object}$$

Now                      weight = mass of object x gravity    or    weight =  $m_s g$

So                       $mg = G \frac{m_1 m_2}{r^2}$

$M_o$  cancels out on each side so;     $g = \frac{Gm_E}{r^2}$     or     $g' = \frac{Gm_E}{r^2}$  (see note 3 below)

**NOTE:**

1. This implies that the value of “g” is independent of the mass of the object.
2. For any object on the Earth's surface, G,  $m_E$ , and r are constant so ‘g’ is the same value.
3. Values of “g” above the Earth's surface are often referred to as g’ (g prime) to distinguish them from “g” on Earth.

Example:

Determine the acceleration due to gravity on a rocket of mass  $6.0 \times 10^3$  kg when it is on the Earth and when it is in orbit 250 km above the Earth.

*Helpful Hint:* Sometimes a value you are looking for is a constant and is found in your data sheet.

*Helpful Hint:* Don't forget to change km to m when dealing with distance above Earth and add to radius of Earth (or other large mass).

## Exploring Physics Stage 3

### Experiment 4.1

**Outcome 10:** explain the conditions for a satellite to remain in a stable circular orbit in a gravitational field, and calculate the parameters of satellites in stable circular orbits—this will include *applying the relationships*:

$$v_{av} = \frac{s}{t}, \quad a_c = \frac{v^2}{r}, \quad \text{resultant } F = ma = \frac{mv^2}{r}, \quad F_g = G \frac{m_1 m_2}{r^2}, \quad g = G \frac{M}{r^2}.$$

### Satellite motion

Text Reference pg. 63-70

Newton believed that the force of attraction between the Earth and the Moon made the Moon continually fall towards the Earth instead of travelling off into space.

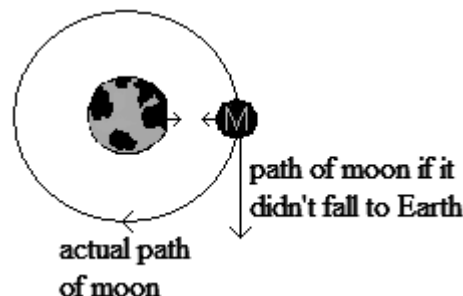
The Earth provides a centripetal force on the moon that maintains its circular path around the Earth. This same force explains why planets maintain their orbits around the sun. From circular motion we know that the centripetal force is

equal to  $F_c = \frac{mv^2}{r}$

but we also know that the two bodies exert a force on each other  $F_g = G \frac{m_1 m_2}{r^2}$

In circular motion these forces are the same value so  $F_c = F_g$

There  $\frac{m_0 v^2}{r} = G \frac{m_E m_0}{r^2}$ ; cancel  $m_0$  then  $v^2 = G \frac{m_E}{r}$



### Why Do Satellites Stay in Space?

1. It must be high enough above the Earth so that it escapes falling back to Earth.
2. Its horizontal velocity must be such that it makes a complete circular orbit of the Earth. Any less, it falls to Earth, any more, it escapes orbit.

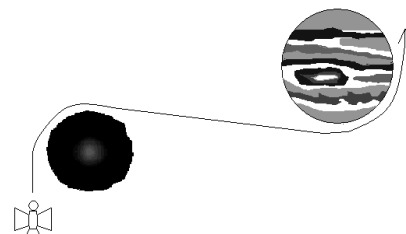
*Note: At this point the tangential velocity is perpendicular to the force of gravity and travelling parallel to the curve of the Earth – no component of 'g' to change the speed.*

3. As centripetal force pulls the satellite to Earth it continually falls down towards the Earth's surface which is itself continually curving away. The satellite swings in a circle above the Earth at a constant distance.
4. Mathematically for a stable orbit,  $F_c = F_g$ ,

### Gravitational Force Fields

Remember, a force field can be thought of as a region of influence. Each body in space has its own force field and any object travelling in space experiences these forces. The nearer to the body an object moves, the stronger the gravitational pull and visa versa.

Space travel has to take into account the effects of numerous gravitational fields. These can hinder progress by pulling a spacecraft off course or be used to advantage to sling-shot a craft into a new course without the use of fuel. Many space probes use the "sling-shot" approach when exploring our solar system to both change direction and increase speed.



### Main formulas for satellites are:

$$F_c = F_g; \quad F_c = \frac{mv^2}{r} = \frac{m4\pi^2 r}{T^2}; \quad F_g = G \frac{m_1 m_2}{r^2}; \quad v = \frac{2\pi r}{T}$$

these can be used to derive the following:

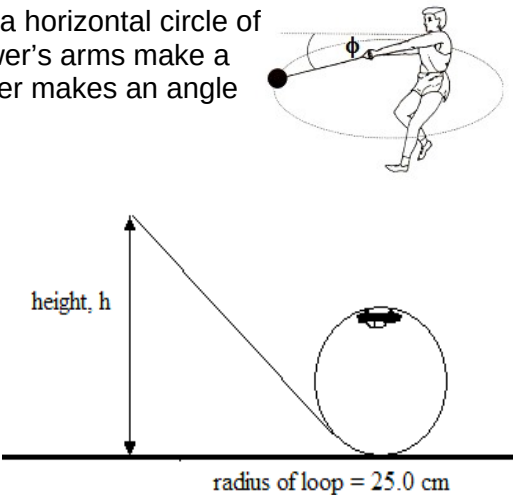
$$v^2 = \frac{Gm}{r}; \quad r^3 = \frac{GmT^2}{4\pi^2}; \quad T = \frac{Gm4\pi^2}{v^3}$$

you should know how to derive these! (See pages 65-68 of text.)

**Outcome 11:** describe and explain the impact of satellites and associated technologies on everyday life

Read page 70 of your text, Physics Content and Contexts Units 3A & 3B, and also appropriate websites on satellites and write notes on the impact of satellite technology on our world. Be prepared to use this research to make a mind map during class time.

## Revision Questions

- A car is travelling at  $72.0 \text{ kmh}^{-1}$  East when it rounds a corner to finally be travelling at  $64.8 \text{ kmh}^{-1}$  North. If the change of velocity took place in  $1.56 \text{ s}$ , what was the car's acceleration?
- A light plane, flying at  $20.0^\circ$  above the horizontal has an airspeed of  $136.8 \text{ kmh}^{-1}$ . Find the plane's rate of climb (vertical velocity).
- You are travelling in a hot-air balloon at  $7.00 \text{ ms}^{-1}$ , which is the same speed as the wind. If you hold a small flag in your hand, which way will the flag wave? Briefly explain.
- The pilot of a small plane is flying feedstock (bails of hay) to a stranded flock of sheep, trapped by rising floodwaters. The pilot skilfully flies at an altitude of  $1.00 \times 10^2 \text{ m}$  when, travelling at  $151.2 \text{ kmh}^{-1}$  horizontally, she releases a bail of hay. How far horizontally from the flock of sheep must she release the feedstock so that the bail of hay strikes the ground just before the sheep?
- An archer fires an arrow from a height of  $1.20 \text{ m}$  above the ground. If the initial velocity of the arrow was  $32.0 \text{ ms}^{-1}$ , and the archer fires the arrow at an angle of  $28^\circ$  to the ground. How far away from him will the arrow hit the ground?
  - Explain one way in which the archer could have fired the arrow a greater distance without increasing the initial velocity.
- At the Olympics, a hammer thrower spins the  $7.26 \text{ kg}$  hammer in a horizontal circle of radius  $1.45 \text{ m}$ , rotating 10 times every  $13.4 \text{ s}$ . The hammer thrower's arms make a straight line with the hammer handle and at this speed the hammer makes an angle of  $\phi$  to the horizontal as shown in the diagram.
  - Calculate the centripetal force on the hammer.
  - Calculate the tension in the wire handle of the hammer.
  - Calculate the angle  $\phi$ .
- A toy designer is in the process of designing a "loop the loop" racetrack for small toy cars. The designer is neglecting friction during the initial design phase. A sketch of the planned track is shown. Perform the necessary calculations that would show the starting height,  $h$ , required for the car to **just** complete one loop.
 
- A cyclist racing at a velodrome can corner at a speed of  $60.0 \text{ kmh}^{-1}$  around a  $40.0 \text{ m}$  radius bend that is banked. Calculate the angle of the track to the horizontal.
- A planet with a small radius, A, has a large mass while a planet with a large radius, B, has a lower mass. Draw the fields around each planet.
- A satellite is orbiting  $270 \text{ km}$  above the Earth. Determine the acceleration due to gravity on the satellite.

11. Calculate the force between the Earth and the Moon.

### Exploring Physics Stage 3

#### • Set 4 Gravitation and Satellites

**Outcome 12:** explain and apply the concept of torque or moment of a force about a point, and the principle of moments, and their application to situations where the applied force is perpendicular to the lever arm—this will include *applying the relationships*:  $\tau = rF$  and  $\Sigma\tau = 0$ .

## Torque and Equilibrium

All structures can experience forces, some of these forces are:

- COMPRESSION - this is a squashing force
- TENSION - this is a stretching force (sometimes referred to as a tensile force)
- SHEARING - this is a sideways force
- TORSIONAL STRESS - a twisting force
- BENDING FORCES - usually looked at in beams under load.

### A review of centre of mass

The closer the centre of mass of an object is to the ground and the larger the base, the more stable the object is. Greatest stability comes from low centre of mass and large area (base) over which the centre of mass acts. A large force is then required to move the centre of mass beyond the base.

#### **Stable:**

Stable position with centre of mass over the base. Slight movement has no overall effect - centre of mass may be raised but object returns to its original position

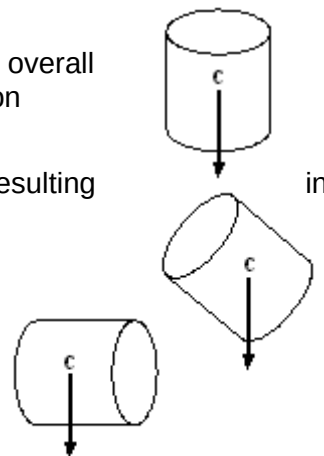
#### **Unstable:**

Centre of mass is over the pivot. Slight movement causes object to move resulting a new, often lower, centre of mass.

#### **Neutral:**

Centre of mass is over the pivot. Slight movement causes object to move to a new position although the centre of mass usually remains at the same height.

*Work through these questions with your teacher.*



### Moment of a Force or Torque

1. Explain why you pick up a long object at the centre. \_\_\_\_\_
2. Give some examples of a turning force. \_\_\_\_\_
3. What is the name given to this turning force? \_\_\_\_\_
4. Three factors affect the amount of turning force, they are:
  - a. \_\_\_\_\_
  - b. \_\_\_\_\_
  - c. \_\_\_\_\_
5. Explain the equation  $M = Fr_{\perp}$  (also  $\tau = Fr_{\perp}$ ) \_\_\_\_\_

What are the units for moment? \_\_\_\_\_

6. What is a *cantilever*? \_\_\_\_\_

Diagram:

## Torque Text Reference pg. 72-75

A *torque* or *moment of a force* is a turning effect created when a linear force is applied to a lever arm with a pivot and the object rotates. In this course, the linear force is applied perpendicular to the lever arm so the formula is:

$$\tau = F \times r_{\perp}$$

where

$\tau$  = torque or moment in Nm

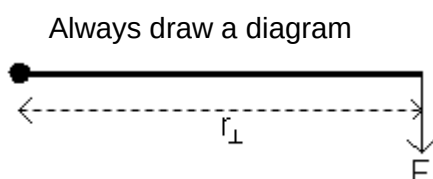
$F$  = applied force at  $90^\circ$  in N

$r_{\perp}$  = perpendicular distance of point of application of force from pivot point

### Example:

You pick up a hammer which has a mass of 1.25 kg. You are holding it 15.0 cm from the centre of mass. What is the value of the moment of force you are applying to keep the hammer horizontal?

$$\begin{aligned} F &= mg \\ &= 1.25 \times 9.8 \\ &= 12.25 \text{ N} \\ r &= 0.150 \text{ m} \end{aligned}$$



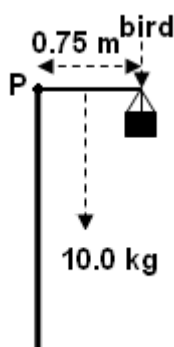
$$\begin{aligned} \tau &= Fr_{\perp} \\ &= 12.25 \times 0.150 \\ &= 1.8375 \\ \tau &= \underline{1.84 \text{ Nm}} \end{aligned}$$

### Activity:

Jasmine, who has a mass of 35.0 kg, is sitting on a uniform seesaw which is 5.00 m long and pivoted in the middle. She is sitting 0.545 m from one end. What torque does she produce?

### Activity:

A 24.0 kg pelican is sitting at the end of a uniform horizontal support pole for a street lamp. The support pole is 0.750 m long and has a mass of 10.0 kg. Calculate the torque on the pivot point of the street lamp.





## Exploring Physics Stage 3

### • Experiment 5.1

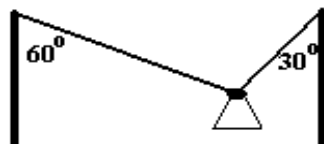
## Resolving Vector Forces

You need to have an understanding of resolving vector forces.

Your teacher will work through the example below with you.

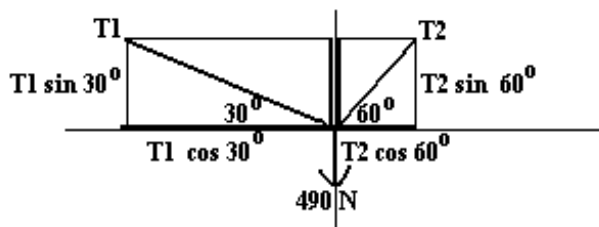
Example:

A street lamp weighing 50 kg, hangs from two poles as shown below. Calculate the tension in each wire.



**Answer:**

1. Firstly resolve the forces into horizontal and vertical components.



2. Then add the horizontal forces. As the lamp is not moving, we know that the left side minus the right side must equal zero ( $\Sigma X = 0$ ).

$$T1 \cos 30^\circ - T2 \cos 60^\circ = 0$$

$$0.866 T1 - 0.5 T2 = 0$$

$$\text{therefore } T1 = 0.5774 T2 \rightarrow \text{equation 1}$$

3. Then add the vertical forces. As the lamp is not moving, we know that the sum of the forces must be zero ( $\Sigma Y = 0$ )

$$T1 \sin 30^\circ + T2 \sin 60^\circ - 490 = 0$$

$$0.5 T1 + 0.866 T2 - 490 = 0 \rightarrow \text{equation 2}$$

substitute equation (1) into equation (2)

$$0.5 (0.5774 T2) + 0.866 T2 - 490 = 0$$

$$0.2887 T2 + 0.866 T2 - 490 = 0$$

$$1.1547 T2 - 490 = 0$$

$$T2 = 424 \text{ N}$$

4. Substitute for T2 back into equation (1)

$$T1 = 0.5774 T2$$

$$= 0.5774 \times 424$$

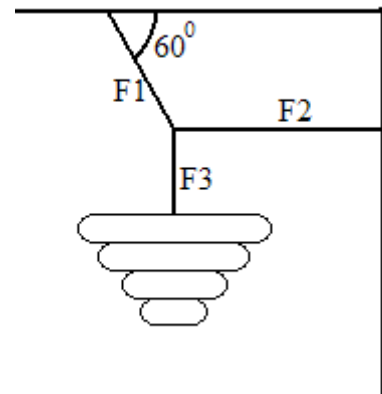
$$= 245 \text{ N}$$

5. Write down answer:  $T2 = 424 \text{ N}$

$$T1 = 245 \text{ N}$$

Example 2:    *Try this one yourself*

A chandelier is hanging from a ceiling as shown. The mass of the chandelier is 200 kg. Find the forces  $F_1$ ,  $F_2$  and  $F_3$ .



- Experiment 1.2

## Conditions for Equilibrium Text Reference pg. 77-89

The simplest turning situation is a seesaw. The point about which the turning occurs is called the **fulcrum** or **pivot**. The Magnitude of the weights (**force**) placed either side of the fulcrum as well as where the weights are placed (**perpendicular distance of force**) can cause an imbalance. When a turning force is in balance e.g. in a seesaw balanced horizontally with masses on either side, we say that it is in a state of stable (or static) equilibrium.

At this point two conditions exist. The sum of the forces equals zero and the sum of the moments equals zero.

$$\square\square\square\square\square\square\square\square\square\square\Sigma M = 0$$

sum of the clockwise moments = sum of anti-clockwise moments

$$\Sigma CM = \Sigma ACM$$

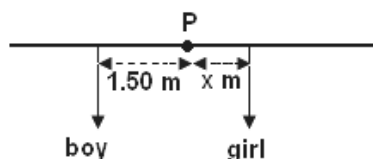
$$\Sigma F = 0$$

sum of forces up = sum of forces down

$$\Sigma F_{up} = \Sigma F_{down}$$

Example 1: A boy of mass 45.0 kg sits 1.50 m from the pivot point of a seesaw on the right hand side. Where must a girl of mass 40.0 kg sit in order for the seesaw to balance?

Always draw a diagram



BOY  $F = ma$

$$F = 45 \times 9.8$$

$$F = 441 \text{ N}$$

$$r_{\perp} = 1.5 \text{ m}$$

GIRL  $F = 40 \times 9.8$

$$F = 392 \text{ N}$$

$$r_{\perp} = ?$$

take moments about P  
for balance  $\Sigma M = 0$   
therefore  $\Sigma CM = \Sigma ACM$

$$Fr_{\perp}(\text{boy}) = Fr_{\perp}(\text{girl})$$

$$441 \times 1.5 = 392 \times r(\text{girl})$$

$$r(\text{girl}) = \frac{441 \times 1.5}{392}$$

$$r(\text{girl}) = 1.69 \text{ m}$$

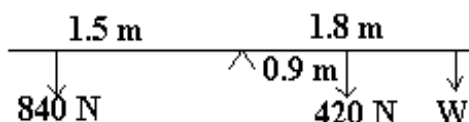
Girl is sitting 1.69 m from the left of the centre (fulcrum)

Helpful Hint: Always state where you are taking the moments from. This is particularly important in your WACE Examination. In last year's TEE, 1 mark was given for this in a difficult question.

Your teacher will work through the following examples with you.

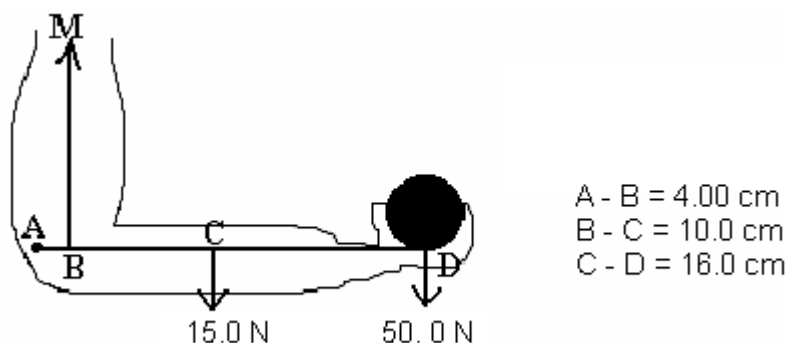
Example 2:

A man weighing 840 N sits on a seesaw 1.50 m from the pivot. His son and daughter sit on the other side and balance it. The girl weighs  $4.20 \times 10^2 \text{ N}$  and is 0.900 m from the pivot. What is the weight of the boy who sits 1.80 m from the pivot?



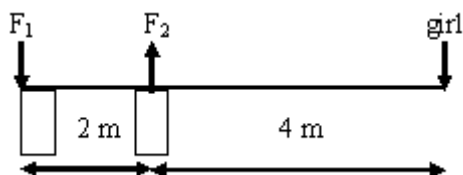
Example 3:

A man holds a 50.0 N ball in his arm as shown below. The pivot point is the elbow and the forearm weighs 15.0 N. Calculate the force the muscles (M) must apply for the arm to hold the ball horizontal.

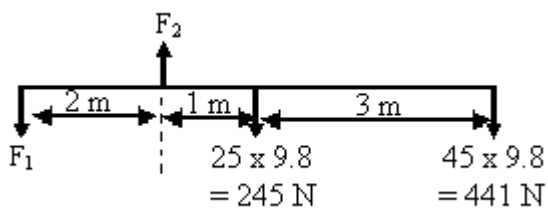


Example 4:

What are the forces  $F_1$  and  $F_2$  that the supports exert on the diving board shown in the diagram below, when a 45.0 kg girl stands at the end of the board, if the mass of the board is 25.0 kg?



1. Firstly, always redraw diagram.



Helpful Hint: Forces are vector quantities so you should include a direction.

## Before we continue, a suggested approach to problem solving

Follow this procedure in all problems and you will find them easier to do. Marks are awarded for working and if you go through this process you can often get more than 50% of the marks, even if you cannot solve the equations, perhaps even if you get the equations wrong. You must always show all working.

1. Read question carefully and form a mental picture of the situation then identify the object that is in equilibrium including its pivot point.
2. Draw a large clear fully labelled diagram. Use a ruler and pencil.
3. Identify the forces acting on the object that is in equilibrium and put them in the diagram in correct position.
4. Identify the unknown forces and angles required by the question and mark them in the diagram. Give them a symbol.
5. Check that you have all the forces correctly shown. Show only forces acting on the object in question.
6. Take moments about the point of action of the force with unknown direction (if applicable).
7. Equate the components of the forces horizontally and vertically to zero.  $\Sigma F_H = 0$   $\Sigma F_V = 0$
8. Solve for the unknowns. Be careful with the mathematics.
9. Give direction of vector. Check you have the correct number of significant figures & the correct units.

## Back to equilibrium

We know that for a body to be in equilibrium (not moving at all),

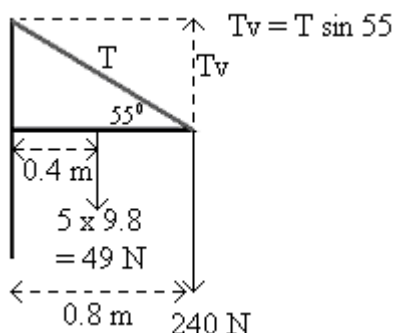
$$\Sigma M = 0 \text{ (sum of moments equals zero) and } \Sigma F = 0 \text{ (sum of forces equals zero).}$$

These are known as the conditions for equilibrium.

*Your teacher will work through the following with you giving you clear steps to follow and a better understanding of equilibrium.*

### Example 1:

The diagram below shows a sign hanging in front of a shop. If the sign weighs  $2.40 \times 10^2 \text{ N}$  and the angle the rope makes with the bar is  $55^\circ$  (angle near the coffee sign), how much tension is in the rope? (Assume the bar weighs  $5.00 \text{ kg}$  and is  $0.800 \text{ m}$  long.)

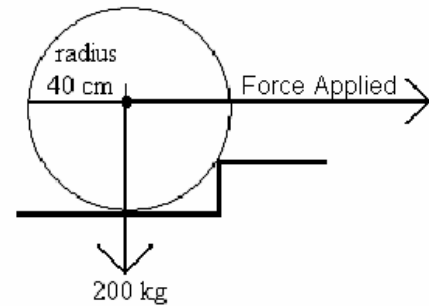


*Helpful Hint:* When dealing with angles in moments, students sometimes forget to multiply by the distance. For example, in the example above, the anticlockwise moment is  $(T \sin 55 \times 0.80)$

Example 2:

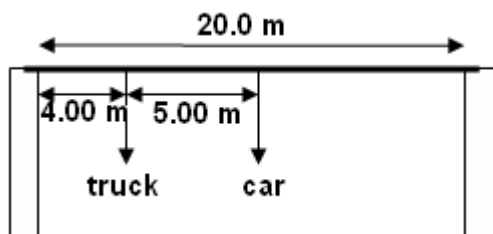
A lawn roller of mass  $2.00 \times 10^2$  kg and radius 40.0 cm is being pulled over a step as shown. The step is 8.00 cm high and the handle is horizontal.

- What force is required to cause the roller to begin moving
- At what angle to the horizontal will the least force be needed to pull the roller over the step. Justify your answer with appropriate calculations.



**Example 3:**

A 20.0 m long bridge is supported at each end by pillars. The bridge has a mass of  $3.52 \times 10^4$  kg. On the bridge is a truck which has a mass of  $2.60 \times 10^3$  kg and a car which has mass of 985 kg. The truck is 4.00 m from one end and the car is 5.00 m behind the truck. Calculate the force on each pillar.



**Exploring Physics Stage 3**

• **Experiment 5.2**

**Questions:**

1. If you stand with your left side and left foot against the wall you will fall over if you lift your right foot. Explain, using the concept of torque then estimate the amount of torque causing you to fall over in the situation described above.

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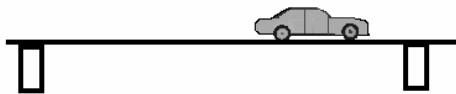
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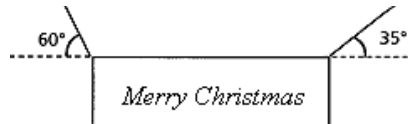
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2. A long bridge of mass  $1.00 \times 10^4$  kg is supported by two large columns as shown. The centre of mass of each column is 24.0 m apart. If a  $9.00 \times 10^2$  kg car is two-thirds of the way across the bridge, what is the force each column is supporting?



3. A large uniform sign of mass 40.0 kg is suspended over Victoria Street in Bunbury as part of the Christmas decorations. It is supported by two cables attached to buildings either side of the street. Calculate the tensions in the cables.





NOTE: You will not have questions involving resolution of forces with a moments problems but this problem does show how the two concepts work together.

4. The diagram shows a wall bracket used to hang a sign from a wall. The dimensions of the wall bracket are as follows:

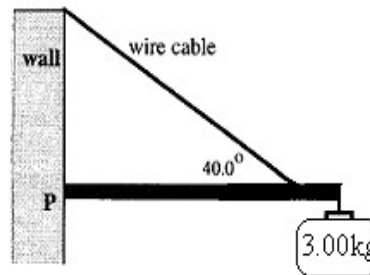
*Mass beam = 1.50 kg*

*Length beam = 1.00 m*

*Wire attached 0.750 m along beam*

Find:

- The tension in the wire cable.
- The compression in the beam.
- The reaction at the wall, point P.



### Exploring Physics Stage 3:

- Set 5: Moments and Equilibrium

## **Text Questions page 90-91**

### **Task 7: Test Motion and forces in a gravitational field**