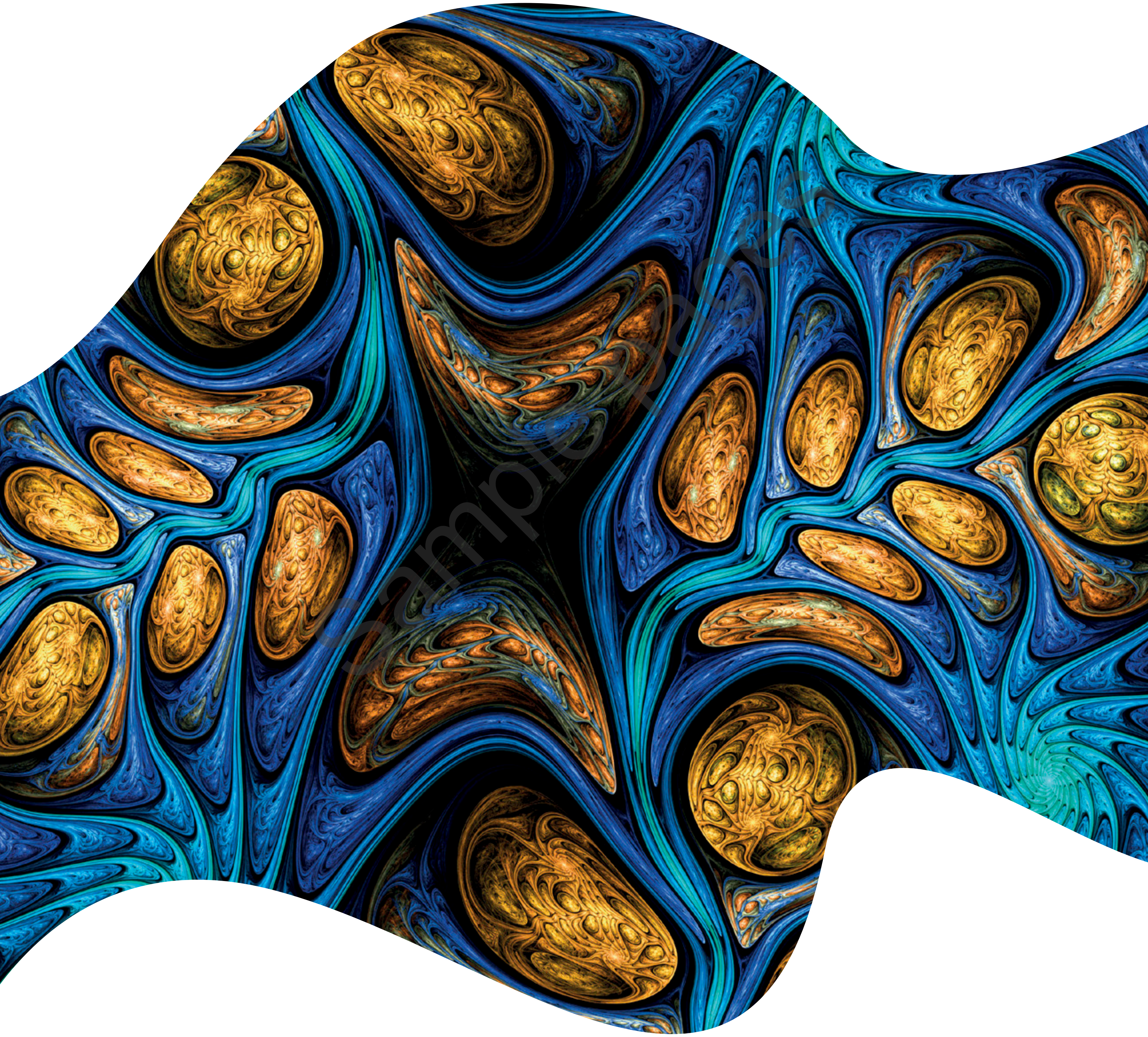
PEARSON

PHYSICS

WESTERN AUSTRALIA

STUDENT BOOK

12



Contents

UNIT 3 Gravity and electromagnetism

AREA OF STUDY 1

Gravity and motion

CHAPTER 1 **The force due to gravity** **3**
1.1 Newton's law of universal gravitation 4
1.2 Gravitational fields 18
1.3 Work in a gravitational field 27
Chapter 1 Review **36**

CHAPTER 2 **Motion in a gravitational field** **39**
2.1 Inclined planes 40
2.2 Projectiles launched horizontally 46
2.3 Projectiles launched obliquely 55
2.4 Circular motion in a horizontal plane 63
2.5 Circular motion on banked tracks 73
2.6 Circular motion in a vertical plane 78
2.7 Satellite motion 87
Chapter 2 Review **94**

CHAPTER 3 **Equilibrium of forces** **97**
3.1 Torque 98
3.2 Equilibrium of forces 109
3.3 Static equilibrium 118
Chapter 3 Review **131**

AREA OF STUDY 2

Electromagnetism

CHAPTER 4 **Electric fields** **133**
4.1 Electric fields 134
4.2 Coulomb's law 139
4.3 Work done in an electric field 144
Chapter 4 Review **148**

CHAPTER 5 **Magnetic field and force** **151**
5.1 The magnetic field 152
5.2 Forces on charged objects 163
5.3 The force on a conductor 169
Chapter 5 Review **179**

CHAPTER 6 **Magnetic field and emf** **181**
6.1 Induced emf in a conductor moving in a magnetic field 182
6.2 Induced emf from a changing magnetic flux 187
6.3 Lenz's law 193
6.4 Transforming voltage using changing magnetic field 203
Chapter 6 Review **220**

Unit 3 Review **225**

UNIT 4 Revolutions in modern physics

AREA OF STUDY 3

Wave-particle duality and the quantum theory

CHAPTER 7 **Wave-particle duality and the quantum theory** **230**

7.1 Properties of waves in two dimensions 232

7.2 Interference: Further evidence for the wave model of light 248

7.3 Electromagnetic waves 254

7.4 Light quanta: Blackbody radiation and the photoelectric effect 260

7.5 Atomic spectra 271

7.6 The quantum nature of light and matter 285

Chapter 7 Review **298**

AREA OF STUDY 4

Special relativity

CHAPTER 8 **Special relativity** **303**

8.1 Einstein's theory of special relativity 304

8.2 Time dilation 317

8.3 Length contraction 325

8.4 Relativistic momentum and energy 331

Chapter 8 Review **339**

AREA OF STUDY 5

The Standard Model

CHAPTER 9 **The Standard Model** **341**

9.1 Particles of the Standard Model 342

9.2 Interactions between particles 350

9.3 Particle accelerators 358

9.4 Expansion of the universe 370

Chapter 9 Review **384**

AREA OF STUDY 6

Science inquiry skills

CHAPTER 10 **Practical investigation** **386**

10.1 Designing and planning the investigation 388

10.2 Conducting investigations, and recording and presenting data 396

10.3 Discussing investigations and drawing evidence-based conclusions 403

Chapter 10 Review **409**

Unit 4 Review **410**

APPENDIX A SI units **415**

APPENDIX B Understanding measurement **417**

APPENDIX C Mathematical skills for physics ATAR **428**

ANSWERS **448**

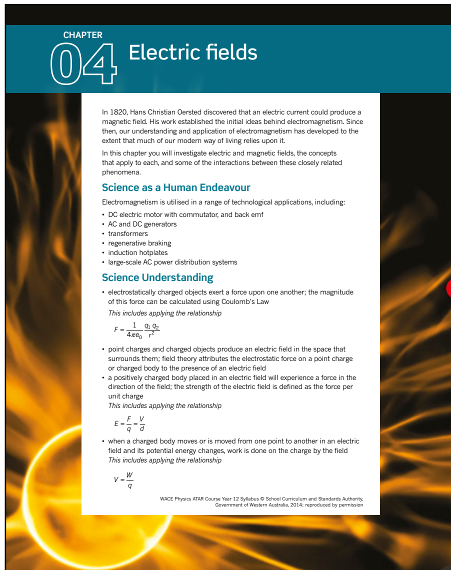
GLOSSARY **461**

INDEX **465**

ATTRIBUTIONS **473**

Pearson Physics 12 Western Australia

Pearson Physics 12 Western Australia has been written to the *WACE Physics ATAR Course, Year 12 Syllabus 2017*. Each chapter is clearly divided into manageable sections of work. Best practice literacy and instructional design are combined with high quality, relevant photos and illustrations. Explore how to use this book below.


CHAPTER 04 Electric fields

Science as a Human Endeavour

Science Understanding

Chapter opening page

The chapter opening page links the syllabus to the chapter content. Science Understanding and Science as a Human Endeavour addressed in the chapter is clearly listed.


2.1 Inclined planes

REVISION

Newton's third law

REVISION

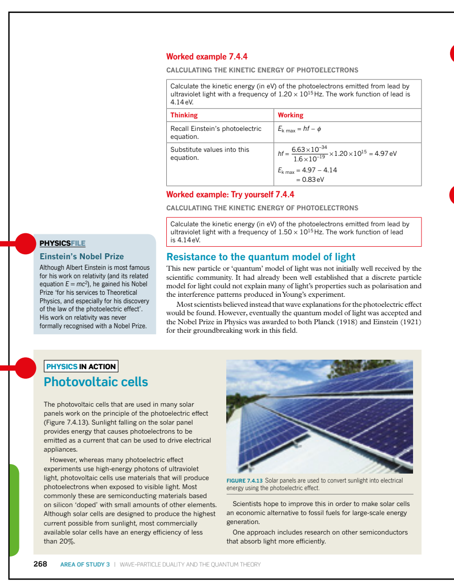
Revises important concepts from Year 11

PHYSICSFILE

PhysicsFiles include a range of interesting information and real world examples.

PHYSICS IN ACTION

Physics in Action boxes place physics in an applied situation or relevant context and encourage students to think about the development of physics and its use and influence of physics in society.


Worked example 7.4.4

Worked example: Try yourself 7.4.4

Resistance to the quantum model of light

PHYSICSFILE Einstein's Nobel Prize

PHYSICS IN ACTION Photovoltaic cells

Worked examples

Worked examples are set out in steps that show both thinking and working. This enhances student understanding by clearly linking underlying logic to the relevant calculations.

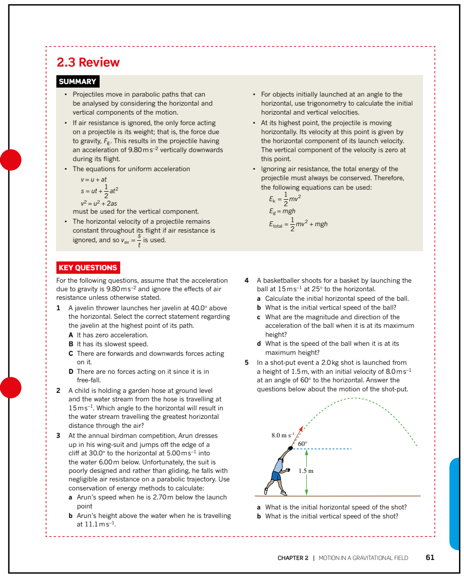
Each Worked example is followed by a Try yourself: Worked example. This mirror problem allows students to immediately test their understanding.

Section summary

Each section includes a summary to assist students consolidate key points and concepts.

Section review questions

Each section finishes with questions to test students' understanding and ability to recall the key concepts of the section.

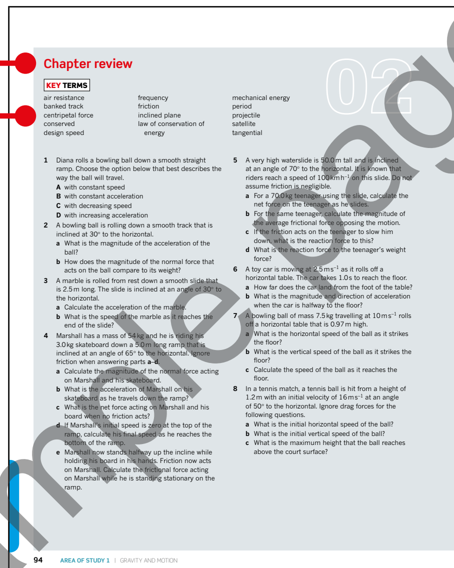


Chapter review

Each chapter finishes with a set of higher order questions to test students' ability to apply the knowledge gained from the chapter.

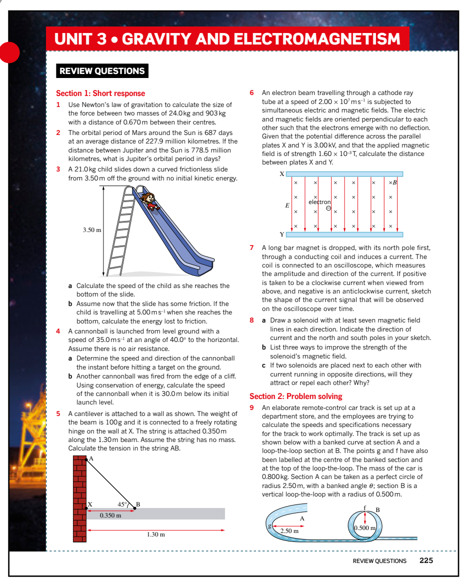
Key terms and glossary

Key terms are shown in bold and listed at the end of each chapter. A comprehensive glossary at the end of the book includes and defines all the key terms.



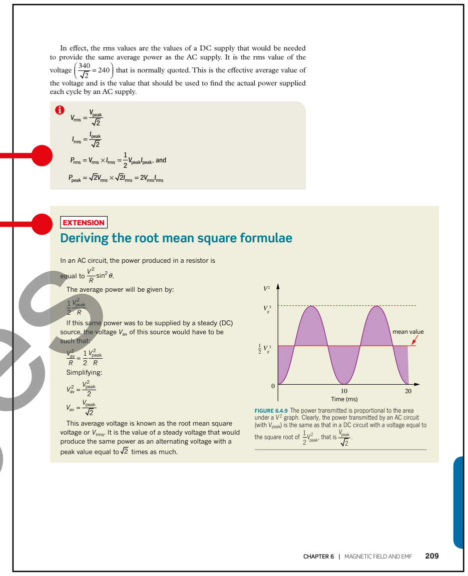
Unit review

Each unit finishes with a comprehensive set of exam-style questions that assist students to draw together their knowledge and understanding and apply it to this style of question.



Highlight box

Focuses students' attention on important information such as key definitions, formulae and summary points.



EXTENSION

Extension boxes include material that goes beyond the core content of the syllabus. They are intended for students who wish to expand their depth of understanding in a particular area.

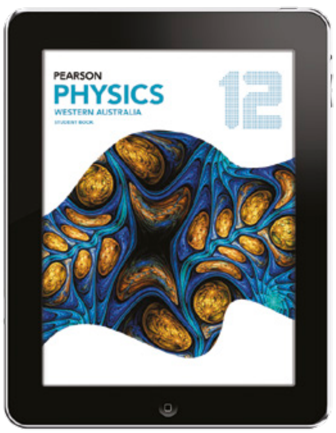
Answers

Numerical answers and key short response answers are included at the back of the book. Comprehensive answers and fully worked solutions for all section review questions, Try yourself: Worked examples, chapter review questions and Unit review questions are provided via *Pearson Physics 12 Western Australia Reader+* and *Teacher Resource*

Pearson Physics 12 Western Australia

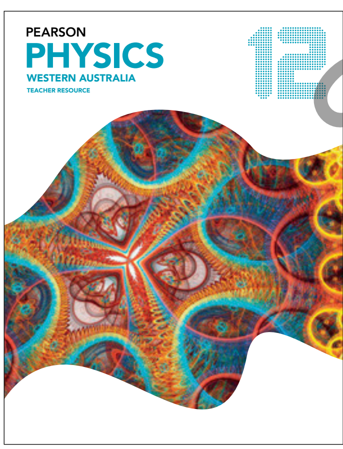
Student Book

Pearson Physics 12 Western Australia has been written to fully align with the *WACE Physics ATAR Course, Year 12 Syllabus 2017.* The series includes the very latest developments and applications of physics and incorporates best practice literacy and instructional design to ensure the content and concepts are fully accessible to all students.



Reader+

Pearson Reader+ lets you use the Student Book online or offline on any device. Pearson Reader+ includes interactive activities and videos to enhance learning and test understanding. The teacher version includes support material to assist planning and implementing the syllabus.



Teacher Resource

The Pearson Physics 12 Western Australia Teacher Resource consists of a print book and online resources, and provides comprehensive teacher support including teaching programs, fully worked solutions to all questions and chapter tests and practice exams.

PearsonDigital

Browse and buy at **pearson.com.au**
Access the ProductLink at **pearsonplaces.com.au**

CHAPTER 01

The force due to gravity

Gravity is the force that drives the universe. It was gravity that first caused particles to coalesce into atoms, and atoms to congregate into nebulas, planets and stars. An understanding of gravity is fundamental to understanding the universe.

This chapter centres on Newton's law of universal gravitation. This will be used to predict the size of the force experienced by an object at various locations on the Earth and other planets. It will also be used to develop the idea of a gravitational field and to refine the understanding of gravitational potential energy developed in Year 11. Since the field concept is also used to describe other basic forces such as electromagnetism and the strong and weak nuclear forces, this will provide an important foundation for further areas of study later in this unit.

Science as a Human Endeavour

Artificial satellites are used for communication, navigation, remote-sensing and research. Their orbits and uses are classified by altitude (low, medium or high Earth orbits) and by inclination (equatorial, polar and sun-synchronous orbits). Communication via satellite is now used for global positioning systems (GPS), satellite phones and television. Navigation services support management and monitoring of traffic and aircraft movement. Geographic information science uses data from satellites to monitor population movement, biodiversity and ocean currents.

Science Understanding

- all objects with mass attract one another with a gravitational force; the magnitude of gravitational force, F_g, can be calculated using Newton's Law of Universal Gravitation
  This includes applying the relationship

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

- gravitational field strength is defined as the net force per unit mass at a particular point in the field
  This includes applying the relationships

  $$g = \frac{F_g}{m} = G\frac{M}{r^2}$$

- the movement of free-falling bodies in Earth's gravitational field is predictable
- objects with mass produce a gravitational field in the space that surrounds them; field theory attributes the gravitational force on an object to the presence of a gravitational field
  This includes applying the relationship

  $$F_{weight} = mg$$

- when a mass moves or is moved from one point to another in a gravitational field and its potential energy changes, work is done on the mass by the field
  This includes applying the relationships

  $$E_p = mg\Delta h,\ W = Fs,\ W = \Delta E,\ E_k = \frac{1}{2}mv^2$$

1.1 Newton's law of universal gravitation

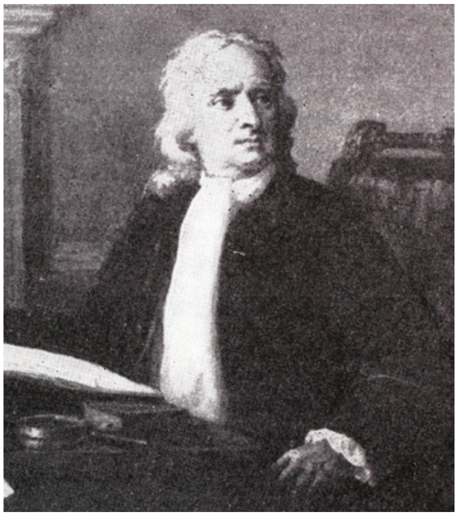


FIGURE 1.1.1 Sir Isaac Newton was one of the most influential physicists who ever lived.

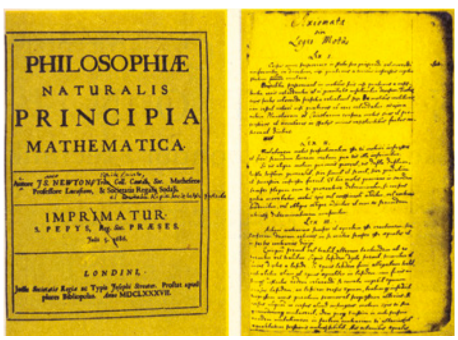


FIGURE 1.1.2 The *Principia* is one of the most influential books in the history of science.

In 1687, Sir Isaac Newton (Figure 1.1.1) published a book that changed the world. Entitled *Philosophiæ Naturalis Prinicipia Mathematica* (Mathematical Principles of Natural Philosophy), Newton's book (Figure 1.1.2) used a new form of mathematics, now known as calculus, and outlined his famous laws of motion.

The *Principia* also introduced Newton's law of universal gravitation. This was particularly significant because, for the first time in history, it was possible to scientifically explain the motion of the planets. This led to a change in humanity's understanding of its place in the universe.

UNIVERSAL GRAVITATION

Newton's law of universal gravitation states that any two bodies in the universe attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

As the radius, r, appears in the denominator of Newton's law of universal gravitation, the relationship indicates an inverse relationship. Since r is also squared, this relationship is known as an **inverse square law**. The implication is that as r increases, F_g will decrease dramatically. This law will reappear again later in the chapter when gravitational fields are examined in detail.

Mathematically, Newton's law of universal gravitation can be expressed as:

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

where F_g is the gravitational force (N)
m_1 is the mass of object 1 (kg)
m_2 is the mass of object 2 (kg)
r is the distance between the centres of m_1 and m_2 (m)
G is the gravitational constant, $6.67 \times 10^{-11}\ \mathrm{N\,m^2\,kg^{-2}}$

PHYSICS IN ACTION

Measuring the gravitational constant, *G*

The **gravitational constant**, G, was first accurately measured by the British scientist Henry Cavendish in 1798, over a century after Newton's death. Cavendish used a **torsion balance** (Figure 1.1.3), a device that can measure very small twisting forces. Cavendish's experiment could measure forces smaller than 1 μN (i.e. 10^{-6} N). He used this balance to measure the force of attraction between lead balls held a small distance apart. Once the size of the force was known for a given combination of masses at a known separation distance, a value for G could be determined.

FIGURE 1.1.3 Henry Cavendish used a torsion balance to measure the small twisting force created by the gravitational attraction of lead balls. A very similar method is still in use in introductory labs in senior secondary schools and universities today.

The law of universal gravitation predicts that *any* two objects that have mass *will attract each other*. However, because the value of G is so small, the **gravitational force** between two everyday objects, such as you and the person seated next to you, is too small to be noticed.

Worked example 1.1.1

GRAVITATIONAL ATTRACTION BETWEEN SMALL OBJECTS

A man with a mass of 90 kg and a woman with a mass of 75 kg have a distance of 80 cm between their centres. Calculate the force of gravitational attraction between them.

Thinking	Working
Recall the formula for Newton's law of universal gravitation.	$F_g = G\dfrac{m_1 m_2}{r^2}$
Identify the information required, and convert values into appropriate units when necessary.	$G = 6.67 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$ $m_1 = 90\,\mathrm{kg}$ $m_2 = 75\,\mathrm{kg}$ $r = 80\,\mathrm{cm} = 0.80\,\mathrm{m}$
Substitute the values into the equation.	$F_g = 6.67 \times 10^{-11} \times \dfrac{90 \times 75}{0.80^2}$
Solve the equation.	$F_g = 7.0 \times 10^{-7}\,\mathrm{N}$

Worked example: Try yourself 1.1.1

GRAVITATIONAL ATTRACTION BETWEEN SMALL OBJECTS

Two bowling balls are sitting next to each other on a shelf so that the centres of the balls are 60 cm apart. Ball 1 has a mass of 7.0 kg and ball 2 has a mass of 5.5 kg. Calculate the force of gravitational attraction between them.

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Gravitational forces between everyday objects are so small (as seen in Worked example 1.1.1) that they are hard to detect without specialised equipment, and can usually be considered as negligible.

For the gravitational force to become significant, at least one of the objects must have a very large mass—for example, our planet Earth (Figure 1.1.4).

FIGURE 1.1.4 Gravitational forces become significant when at least one of the objects has a large mass. Both the Earth and the Moon have significant mass.

Worked example 1.1.2

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Calculate the force of gravitational attraction between the Sun and the Earth, given the following data:

$m_{Sun} = 2.0 \times 10^{30}\,\mathrm{kg}$

$m_{Earth} = 6.0 \times 10^{24}\,\mathrm{kg}$

$r_{Sun–Earth} = 1.5 \times 10^{11}\,\mathrm{m}$

Thinking	Working
Recall the formula for Newton's law of universal gravitation.	$F_g = G\dfrac{m_1 m_2}{r^2}$

Identify the information required.	$G = 6.67 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$ $m_1 = 2.0 \times 10^{30}\,\mathrm{kg}$ $m_2 = 6.0 \times 10^{24}\,\mathrm{kg}$ $r = 1.5 \times 10^{11}\,\mathrm{m}$
Substitute the values into the equation.	$F_g = 6.67 \times 10^{-11} \times \dfrac{2.0 \times 10^{30} \times 6.0 \times 10^{24}}{(1.5 \times 10^{11})^2}$
Solve the equation.	$F_g = 3.6 \times 10^{22}\,\mathrm{N}$

Worked example: Try yourself 1.1.2

GRAVITATIONAL ATTRACTION BETWEEN MASSIVE OBJECTS

Calculate the force of gravitational attraction between the Earth and the Moon, given the following data: $m_{Earth} = 6.0 \times 10^{24}\,\mathrm{kg}$ $m_{Moon} = 7.3 \times 10^{22}\,\mathrm{kg}$ $r_{Moon\text{–}Earth} = 3.8 \times 10^{8}\,\mathrm{m}$

The force in Worked example 1.1.2 is much greater than that in Worked example 1.1.1, illustrating the difference in the gravitational force when at least one of the objects has a much larger mass.

EXTENSION

Understanding the structure of the solar system

In the century before Newton, there had been some controversy about the structure of the solar system. In 1543, the commonly accepted geocentric (i.e. Earth-centred) model of the solar system had been challenged by the Polish astronomer Nicolaus Copernicus. He proposed that the Sun was the centre of the solar system. Unfortunately, some faulty assumptions meant that the predictions of Copernicus' Sun-centred or heliocentric model (shown in Figure 1.1.5) did not match observations any better than the geocentric model.

The Danish astronomer Tycho Brahe had been observing and studying the heavens for many years, accumulating a comprehensive collection of data. Using Brahe's documentation, his assistant, German mathematician Johannes Kepler, refined the Copernican model to reflect actual observations.

Through these calculations, Kepler discovered that the orbits of the planets around the Sun are elliptical and not circular as previously thought (Figure 1.1.6). At the time, this discovery challenged conventional beliefs about the 'perfection' of heavenly bodies, and, as a consequence, Kepler's ideas were not widely accepted. In fact, in some countries his books were banned and publicly burned.

One of Newton's great achievements was that he was able to use his law of universal gravitation to mathematically derive all of Kepler's planetary laws.

This allowed Newton to accurately explain the motion of the planets in terms of gravitational attraction. Within a few years of the publication of Newton's work, the geocentric model of our solar system had largely been abandoned in favour of the heliocentric model.

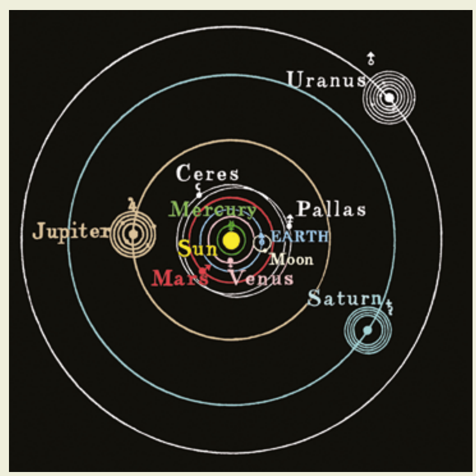


FIGURE 1.1.5 Nicolaus Copernicus proposed a heliocentric model of the solar system.

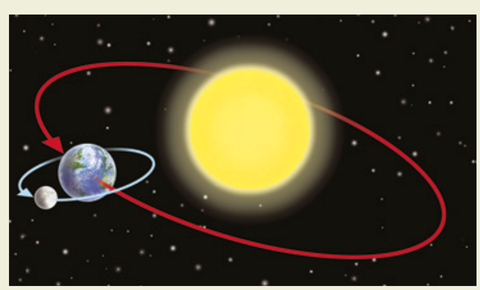


FIGURE 1.1.6 Johannes Kepler discovered that the orbits of planets around the Sun are elliptical.

EFFECT OF GRAVITY

According to Newton's third law of motion, forces occur in action–reaction pairs. An example of such a pair is shown in Figure 1.1.7. The Earth exerts a gravitational force on the Moon and, conversely, the Moon exerts an equal and opposite force on the Earth. Using Newton's second law of motion, you can see that the effect of the gravitational force of the Moon on the Earth will be much smaller than the corresponding effect of the Earth on the Moon. This is because of the Earth's larger mass.

FIGURE 1.1.7 The Earth and Moon exert gravitational forces on each other.

Worked example 1.1.3

ACCELERATION CAUSED BY A GRAVITATIONAL FORCE

The force of gravitational attraction between the Moon and the Earth is approximately 2.0×10^{20} N. Calculate the acceleration of the Earth and the Moon caused by this force. Compare these accelerations by calculating the ratio $\frac{a_{Moon}}{a_{Earth}}$.

Use the following data:

$m_{Earth} = 6.0 \times 10^{24}$ kg

$m_{Moon} = 7.3 \times 10^{22}$ kg

Thinking	Working
Recall the formula for Newton's second law of motion.	$F = ma$
Transpose the equation to make *a* the subject.	$a = \frac{F}{m}$
Substitute values into this equation to find the accelerations of the Moon and the Earth.	$a_{Earth} = \frac{2.0 \times 10^{20}}{6.0 \times 10^{24}} = 3.3 \times 10^{-5}\ \text{m s}^{-2}$ $a_{Moon} = \frac{2.0 \times 10^{20}}{7.3 \times 10^{22}} = 2.7 \times 10^{-3}\ \text{m s}^{-2}$
Compare the two accelerations.	$\frac{a_{Moon}}{a_{Earth}} = \frac{2.7 \times 10^{-3}}{3.3 \times 10^{-5}} = 82$ The acceleration of the Moon is 82 times greater than the acceleration of the Earth.

Worked example: Try yourself 1.1.3

ACCELERATION CAUSED BY A GRAVITATIONAL FORCE

The force of gravitational attraction between the Sun and the Earth is approximately 3.6×10^{22} N. Calculate the acceleration of the Earth and the Sun caused by this force. Compare these accelerations by calculating the ratio $\frac{a_{Earth}}{a_{Sun}}$.

Use the following data:

$m_{Earth} = 6.0 \times 10^{24}$ kg

$m_{Sun} = 2.0 \times 10^{30}$ kg

Gravity in the solar system

Although the accelerations caused by gravitational forces in Worked example 1.1.3 are small, over billions of years they have created the motion of the solar system.

In the Earth–Moon system, the acceleration of the Moon is many times greater than that of the Earth, which is why the Moon orbits the Earth. Although the Moon's gravitational force causes a much smaller acceleration of the Earth, it does have other significant effects, such as causing the tides.

Similarly, the Earth and other planets orbit the Sun because their masses are much smaller than the Sun's mass. However, the combined gravitational effect of the planets of the solar system (and Jupiter in particular) causes the Sun to wobble slightly as the planets orbit it.

PHYSICSFILE

Extrasolar planets

In recent years, scientists have been interested in discovering whether other stars have planets like those in our own solar system. One of the ways in which these 'extrasolar planets' (or 'exoplanets') can be detected is from their gravitational effect.

When a large planet (Jupiter-sized or larger) orbits a star, it causes the star to wobble. This causes variations in the star's appearance, which can be detected on Earth. Hundreds of exoplanets have been discovered using this technique, including one orbiting the closest star to our Sun, Proxima Centauri, in the potentially habitable zone where temperatures are similar to those on Earth.

WEIGHT AND GRAVITATIONAL FORCE

In Year 11 Physics the **weight** of an object was calculated using the formula $F_{weight} = mg$. Weight is another name for the gravitational force acting on an object near the Earth's surface.

Worked example 1.1.4 below shows that the formula $F_{weight} = mg$ and Newton's law of universal gravitation give the same answer for the gravitational force acting on objects on the Earth's surface. It is important to note that the distance used in these calculations is the distance between the centres of the two objects, which is effectively the radius of the Earth.

Worked example 1.1.4

GRAVITATIONAL FORCE AND WEIGHT

Compare the weight of an 80 kg person calculated using $F_{weight} = mg$ with the gravitational force calculated using $F_g = G\frac{m_1 m_2}{r^2}$.

Use the following dimensions of the Earth in your calculations:

$g = 9.80\ \text{m s}^{-2}$

$m_{Earth} = 6.0 \times 10^{24}\ \text{kg}$

$r_{Earth} = 6.4 \times 10^6\ \text{m}$

Thinking	Working
Apply the weight equation.	$F_{weight} = mg$ $= 80 \times 9.80$ $= 784\ \text{N}$ $= 780\ \text{N}$ (to two significant figures)
Apply Newton's law of universal gravitation.	$F_g = G\frac{m_1 m_2}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{6.0 \times 10^{24} \times 80}{(6.4 \times 10^6)^2}$ $= 780\ \text{N}$
Compare the two values.	The equations give the same result to two significant figures.

Worked example: Try yourself 1.1.4

GRAVITATIONAL FORCE AND WEIGHT

Compare the weight of a 1.0 kg mass on the Earth's surface calculated using the formulae $F_{weight} = mg$ and $F_g = G\frac{m_1 m_2}{r^2}$. Use the following dimensions of the Earth where necessary:

$g = 9.80\ \text{m s}^{-2}$

$m_{Earth} = 6.0 \times 10^{24}\ \text{kg}$

$r_{Earth} = 6.4 \times 10^6\ \text{m}$

Worked example 1.1.4 shows that the constant for the **acceleration due to gravity**, g, can be derived directly from the dimensions of the Earth. An object with mass m sitting on the surface of the Earth is a distance of 6.4×10^{6} m from the centre of the Earth.

Given that the Earth has a mass of 6.0×10^{24} kg, then:

$$F_{\text{weight}} = F_{\text{g}}$$

$$\therefore \; mg = G\frac{m_{\text{Earth}} m}{(r_{\text{Earth}})^2}$$

$$= mG\frac{m_{\text{Earth}}}{(r_{\text{Earth}})^2}$$

$$\therefore \quad g = G\frac{m_{\text{Earth}}}{(r_{\text{Earth}})^2}$$

$$= 6.67 \times 10^{-11} \times \frac{6.0 \times 10^{24}}{(6.4 \times 10^{6})^2}$$

$$= 9.8\,\text{m}\,\text{s}^{-2}$$

EXTENSION

Multi-body systems

So far, only gravitational systems involving two objects have been considered, such as the Moon and the Earth. In reality, all objects experience gravitational force from every other object around them. Usually, most of these forces are negligible and only the gravitational effect of the largest object nearby (i.e. the Earth) needs to be considered.

When there is more than one significant gravitational force acting on a body, the gravitational forces must be added together as vectors to determine the net gravitational force (Figure 1.1.8).

The direction and relative magnitude of the net gravitational force in a multi-body system depends entirely on the masses and the positions of the attracting objects (i.e. m_1, m_2 and m_3 in Figure 1.1.8).

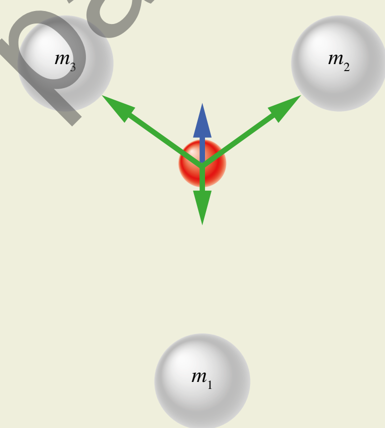


FIGURE 1.1.8 For the three masses $m_1 = m_2 = m_3$, the gravitational forces acting on the central red ball are shown by the green arrows. The vector sum of the green arrows is shown by the blue arrow. This will be the direction of the net (or resultant) gravitational force on the red ball due to the other three masses.

The rate of acceleration of objects near the surface of the Earth is a result of the Earth's mass and radius. A planet with a different mass and/or different radius will have a different value for g. Likewise, if an object is above the Earth's surface, the value of r will be greater and the value of g will be smaller (due to the inverse square law). This explains why the strength of the Earth's gravity reduces as you travel away from the Earth.

APPARENT WEIGHT

Scientists use the term 'weight' simply to mean 'the force due to gravity'. It is also correct to interpret weight as the contact force (or **normal reaction force**) between an object and the Earth's surface. In most situations these two definitions are effectively the same. However, there are some cases, for example when a person is accelerating up or down in an elevator, where they give different results. In these situations, the normal force (F_{N}) is referred to as the **apparent weight** since you do not feel the force you apply to the floor, you will only experience with your senses the forces that are applied on *you*. What you feel is the normal force acting up on you from the floor. Normally, when you stand on a surface that is either stationary or in constant vertical motion, your apparent weight is constant and equal to your weight force (Figure 1.1.9).

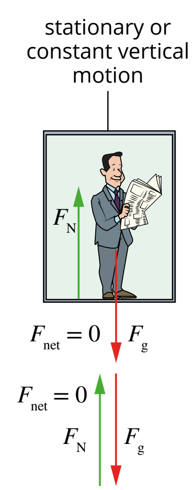


FIGURE 1.1.9 In this case, the forces that act on the person, F_{N} and F_{g}, are equal in size. The person will 'feel' his or her normal apparent weight.

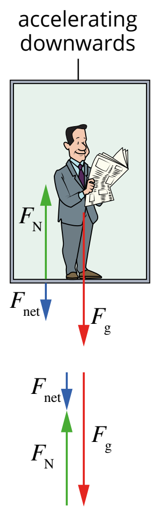


FIGURE 1.1.10 In this case, the forces that act on the person in the lift cause him to feel lighter than his normal apparent weight. When accelerating downwards, $F_N < F_g$.

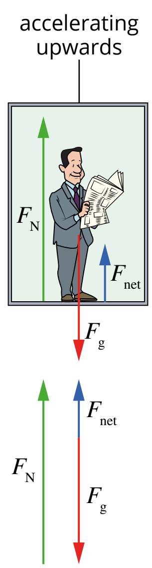


FIGURE 1.1.11 In this case, the forces that act on the person in the lift cause him to feel heavier than his normal apparent weight. When accelerating upwards, $F_N > F_g$.

The apparent weight that you experience changes when the surface you are standing on is accelerating upwards or downwards. If the floor is accelerating downwards at a rate less than 9.80 m s^{-2}, your feet will be pressing less firmly on the surface than when the floor was not accelerating. Therefore, the normal force is also less and so your apparent weight appears to be less. That is, you would feel lighter than usual (Figure 1.1.10).

The opposite happens when the floor is accelerating upwards. In this case, the floor is pushing up against your feet with a greater force than the normal reaction force due to your weight alone. The upwards push of the floor must provide the force to accelerate you upwards. This accelerating force adds to the normal force to make it appear that your apparent weight is greater than it would be if you weren't accelerating. That is, you would feel heavier than usual (Figure 1.1.11).

The normal reaction force (felt as apparent weight) and the force due to gravity (weight force) add as vectors to give the net force that causes the acceleration.

$F_{net} = F_N + F_{weight}$

where F_N is the apparent weight force that acts upwards on your feet
F_{weight} is the weight force due to gravity (which never changes)
F_{net} is the net force causing the acceleration

Worked example 1.1.5

CALCULATING APPARENT WEIGHT

A 79.0 kg student rides a lift up to the top floor of an office block. During the journey, the lift accelerates upwards at 1.26 m s^{-2} before travelling at a constant velocity of 3.78 m s^{-1} and then finally decelerating at 1.89 m s^{-2}.

a Calculate the apparent weight of the student in the first part of the journey while accelerating upwards at 1.26 m s^{-2}.

Thinking	Working
Ensure that the variables are in their standard units.	m = 79.0 kg a = 1.26 m s^{-2} up g = 9.80 m s^{-2} down
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	m = 79.0 kg a = +1.26 m s^{-2} g = −9.80 m s^{-2}
Apply the equation for apparent weight (the normal force).	$F_{net} = F_N + F_g$ $F_N = F_{net} - F_g$ $= ma - mg$ $= (79.0 \times 1.26) - (79.0 \times -9.80)$ $= 99.54 + 774.2$ $= 874$ N

b Calculate the apparent weight of the student in the second part of the journey while travelling at a constant speed of 3.78 m s^{-1}.

Thinking	Working
Ensure that the variables are in their standard units.	m = 79.0 kg a = 0 m s^{-2} g = 9.80 m s^{-2} down

Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 79.0\,\text{kg}$ $a = 0\,\text{m s}^{-2}$ $g = -9.80\,\text{m s}^{-2}$
Apply the equation for apparent weight (the normal force).	$F_{net} = F_N + F_{weight}$ $F_N = F_{net} - F_{weight}$ $= ma - mg$ $= (79.0 \times 0) - (79.0 \times -9.80)$ $= 0 + 774.2$ $= 774\,\text{N}$

c Calculate the apparent weight of the student in the last part of the journey while travelling upwards and decelerating at $1.89\,\text{m s}^{-2}$.

Thinking	**Working**
Ensure that the variables are in their standard units. Also consider that deceleration is a negative acceleration.	$m = 79.0\,\text{kg}$ $a = -1.89\,\text{m s}^{-2}$ up $g = 9.80\,\text{m s}^{-2}$ down
Apply the sign and direction convention for motion in one dimension. Up is positive and down is negative.	$m = 79.0\,\text{kg}$ $a = -1.89\,\text{m s}^{-2}$ $g = -9.80\,\text{m s}^{-2}$
Apply the equation for apparent weight (the normal force).	$F_{net} = F_N + F_{weight}$ $F_N = F_{net} - F_{weight}$ $= ma - mg$ $= (79.0 \times -1.89) - (79.0 \times -9.80)$ $= -149.3 + 774.2$ $= 625\,\text{N}$

Worked example: Try yourself 1.1.5

CALCULATING APPARENT WEIGHT

A 79.0 kg student rides a lift down from the top floor of an office block to the ground. During the journey the lift accelerates downwards at $2.35\,\text{m s}^{-2}$, before travelling at a constant velocity of $4.08\,\text{m s}^{-1}$ and then finally decelerating at $4.70\,\text{m s}^{-2}$.

a Calculate the apparent weight of the student in the first part of the journey while accelerating downwards at $2.35\,\text{m s}^{-2}$.

b Calculate the apparent weight of the student in the second part of the journey while travelling at a constant speed of $4.08\,\text{m s}^{-1}$.

c Calculate the apparent weight of the student in the last part of the journey while travelling downwards and decelerating at $4.70\,\text{m s}^{-2}$.

From Worked example 1.1.5, you can see that:

- when accelerating upwards the student will feel heavier than normal ($F_N > mg$) (Note: this is the same as decelerating while travelling downwards)
- when accelerating downwards, the student will feel lighter than normal ($F_N < mg$) (Note: this is the same as decelerating while travelling upwards)
- when travelling upwards or downwards at a constant velocity, the student will feel their normal weight, just as they would if the lift was stationary ($F_N = mg$).

Apparent weightlessness

Defining apparent weight makes it possible to identify the situations in which you will experience **apparent weightlessness**. Your apparent weight is a contact reaction force that acts upwards on you from a surface because gravity is pulling you down on that surface. So if you are not standing on a surface, you will experience zero apparent weight; that is, apparent weightlessness. This means that you will experience apparent weightlessness the moment you step off the top platform of a diving pool or as you skydive from a plane, although the rushing air will hardly let you experience the sensation of floating as you skydive.

Felix Baumgartner experienced apparent weightlessness as he fell from his balloon 39 km above the Earth (Figure 1.1.12). This vertical height is equivalent to the distance from Perth to the west end of Rottnest.

FIGURE 1.1.12 Felix Baumgartner experienced apparent weightlessness on his return to Earth from 39 000 m.

Astronauts also experience apparent weightlessness in the International Space Station, which orbits about 370 km above the surface of the Earth (about the horizontal distance from Perth to Albany).

Whenever you are in **free-fall**, you experience apparent weightlessness. It follows then that whenever you experience apparent weightlessness, you must be in free-fall. When astronauts experience apparent weightlessness, they are not floating in space as they orbit the Earth. They are actually in free-fall. Astronauts and their spacecraft are both falling, but not directly towards the Earth like Baumgartner. The astronauts are actually moving horizontally, as shown in Figure 1.1.13. Baumgartner stayed approximately above the same place on the Earth from where he departed. Astronauts, on the other hand, are moving at a velocity relative to the Earth, so they are moving across the sky at the same time as they are falling. The combined effect is that they fall in a curved path that almost mirrors the curve of the Earth. So they fall, but continually miss the Earth as the surface of the Earth curves away from their path.

Importantly there is a significant difference between apparent weightlessness and true weightlessness. True weightlessness only occurs when the gravitational field strength is zero and hence $F_{weight} = 0$. This only occurs in deep space, far enough away from any planets so that their gravitational effect is zero. Apparent weightlessness, however, can occur when still under the influence of a gravitational field.

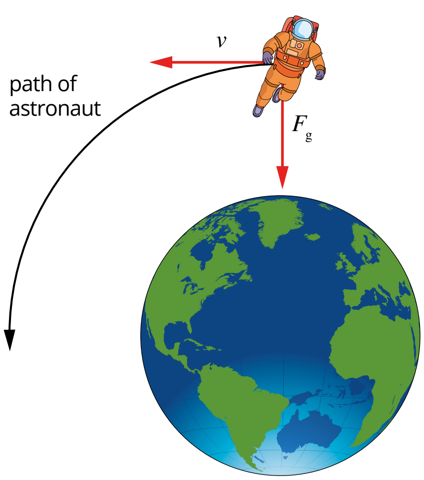


FIGURE 1.1.13 Astronauts are in free-fall while orbiting the Earth.

EXTENSION

Falling at constant speed

Galileo was able to show, more than 400 years ago, that the mass of a body does not affect the rate at which it falls towards the ground. However, our common experience is that not all objects behave in this way. A light object, such as a feather or a balloon, does not accelerate at $9.80\,\text{m}\,\text{s}^{-2}$ as it falls. It drifts slowly to the ground, far slower than other dropped objects. Parachutists and skydivers also eventually fall with a constant speed. However, they can change their falling speed by changing their body profile, as pictured in Figure 1.1.14. If they assume a tuck position, they will fall faster, and if they spread out their arms and legs, they will fall slower. This enables them to form spectacular patterns as they fall.

FIGURE 1.1.14 Skydivers performing intricate manoeuvres in free-fall.

Skydivers, base-jumpers and air-surfers are able to use the force of air resistance to their advantage. As a skydiver first steps out of the plane, the forces acting on them are drag (air resistance), F_{ar}, and weight due to gravity, F_{weight}. Since their speed is low, the drag force is small, as shown in Figure 1.1.15(a). There is a large net force (F_{net}) downwards, so they will experience a large downwards acceleration of just less than $9.80\,\text{m}\,\text{s}^{-2}$, causing them to speed up. This causes the drag force to increase because they are colliding harder with the air molecules. In fact, the drag force increases in proportion to the square of the speed, $F_{ar} \propto v^2$. This results in a smaller net force downwards as shown in Figure 1.1.15(b). Their downwards acceleration is therefore reduced. (It is important to remember that they are still speeding up, but at a reduced rate.)

As their speed continues to increase, so too does the magnitude of the drag force. Eventually, the drag force becomes as large as the weight force due to gravity, as shown in Figure 1.1.15(c). When this happens, the net force is zero and the skydiver will fall with a constant velocity. As the velocity is now constant, the drag force will also remain constant and the motion of the skydiver will not change, as shown in Figure 1.1.15(d). This velocity is commonly known as the *terminal velocity*.

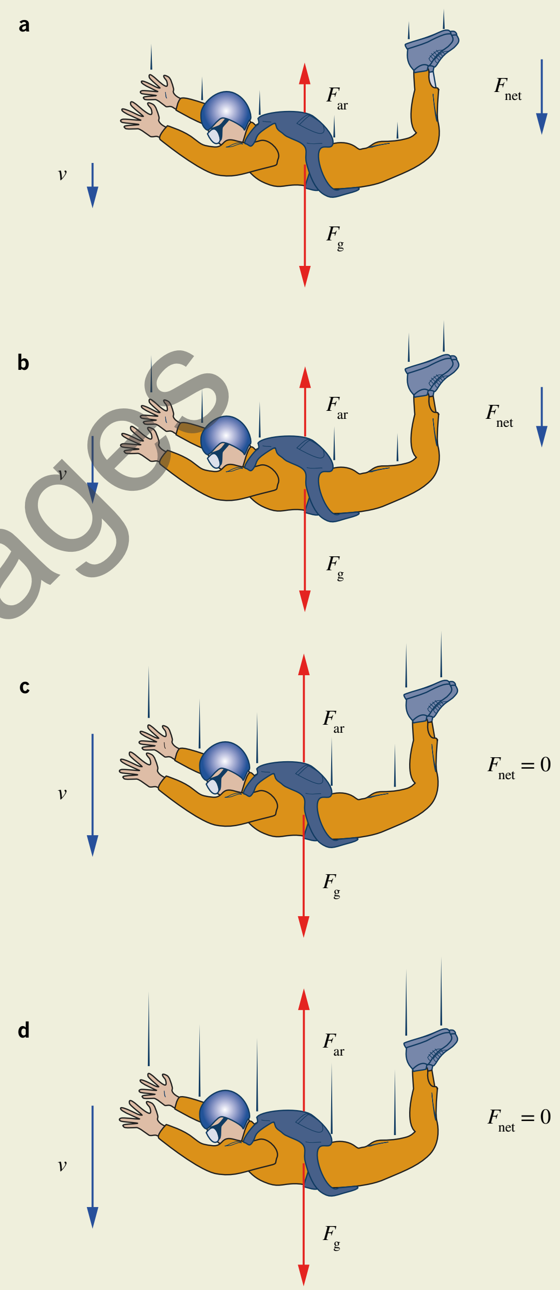


FIGURE 1.1.15 The forces involved in skydiving.

PHYSICS IN ACTION

Satellites

Natural satellites have existed throughout the universe for billions of years. The planets and asteroids of the solar system are natural satellites of the Sun.

Earth has one natural satellite: the Moon. The largest planets—Jupiter and Saturn—each have more than sixty natural satellites in orbit around them. Most of the stars in the Milky Way galaxy have planets and more of these exoplanets are being discovered each year.

Since the space age began in 1957 with the launch of Sputnik, about 6000 **artificial satellites** have been launched into orbit around the Earth. Today there are about 4000 artificial satellites still in orbit, although only about 1200 of these are operational.

Satellites in orbit around the Earth are classified as being in low, medium or high orbit.

- Low orbit: 180 km to 2000 km **altitude**. Most satellites orbit in this range (an example is shown in Figure 1.1.16). These include the Hubble Space Telescope, which is used by astronomers to view objects right at the edge of the universe.
- Medium orbit: 2000 km to 36 000 km altitude. The most common satellites in this region are the global positioning system (GPS) satellites used to run navigation systems.
- High orbit: 36 000 km altitude or greater. Australia uses the Optus satellites for communications, and deep-space weather pictures come from the Japanese Himawari-8 satellite. The satellites that sit at an altitude of 36 000 km and orbit with a period of 24 hours are known as **geostationary satellites** (or geosynchronous satellites). Most communications satellites are geostationary.

Earth satellites can have different orbital paths depending on their function:

- equatorial orbits in which the satellite always travels above the equator
- polar or near-polar orbits in which the satellite travels over or close to the North and South poles as it orbits
- inclined orbits, which lie between equatorial and polar orbits.

Satellites are used for a multitude of different purposes, with 60% used for communications. Many low-orbit American NOAA satellites have an inclination of 99° and an orbit that allows them to pass over each part of the Earth at the same time each day. These satellites are also known as Sun-synchronous satellites.

Artificial and natural satellites are not propelled by rockets or engines. They orbit in free-fall, and the only force acting on them is the gravitational attraction between the satellite and the body about which it orbits. This means that the satellites have a **centripetal acceleration** that is equal to the gravitational field strength at their location (Figure 1.1.18). Centripetal acceleration is covered in more detail in Chapter 2 'Motion in a gravitational field'.

Artificial satellites are often equipped with tanks of propellant that is squirted in the appropriate direction when the orbit of the satellite needs to be adjusted.

Artificial satellites of particular value to Australia

Geostationary meteorological satellites Himawari-8 and 9

The Himawari-8 satellite was launched from the Tanegashima Space Centre, Japan, on 7 October 2014, and orbits at approximately 35 786 km directly over the equator in a geostationary orbit of 24 hours. At its closest point to the Earth (perigee), its altitude is 35 784 km. At its furthest point from the Earth (apogee), it is at 35 789 km. Himawari-8 orbits at a longitude of around 140.7°E, so it is just to the north of Cape York. At this position it is ideally located for use by Australian forecasters.

Scans from Himawari-8 are made every 10 minutes and transmitted in near real-time to a satellite dish on the roof of the head office at the Bureau of Meteorology in Perth. Himawari-8 is the first geostationary weather satellite to take true-colour pictures at a much greater resolution than previous satellites. 16 different types of image show the temperature variations in the atmosphere and are invaluable in weather forecasting. Himawari-8 is box-like and measures about 2.6 m along each side. It had a mass of 3500 kg when it was launched, and is powered by solar panels that, when deployed, take its overall length to approximately 8 m. Himawari-9 was launched on 2 November 2016 and is positioned very near to Himawari-8. Its role is to remain on standby until 2022, when Himawari-8 will switch from observing to standing-by while Himawari-9 takes over.

FIGURE 1.1.16 A low-orbit satellite called the Soil Moisture and Ocean Salinity (SMOS) probe was launched in August 2014. Its role is to measure water movements and salinity levels on Earth as a way of monitoring climate change. It was launched from northern Russia by the European Space Agency (ESA).

Hubble Space Telescope (HST)

This cooperative venture between NASA and the European Space Agency (ESA) was launched by the crew of the space shuttle Discovery on 25 April 1990. The HST is a permanent unoccupied space-based observatory with a 2.4 m-diameter reflecting telescope, spectrographs and a faint-object camera. It orbits above the Earth's atmosphere, producing images of distant stars and galaxies far clearer than those from ground-based observatories (Figure 1.1.17). The HST is in a low-Earth orbit inclined at 28° to the equator. Its expected life span was originally around 15 years, but service and repair missions have extended its life and it is still in use today.

FIGURE 1.1.17 In August 2014, astronomers used the Hubble Space Telescope to detect the blue companion star of a white dwarf in a distant galaxy. The white dwarf slowly siphoned fuel from its companion, eventually igniting a runaway nuclear reaction in the compact star, which produced a supernova blast.

National Oceanic and Atmospheric Administration Satellite (NOAA-19)

Many of the US-owned and operated NOAA satellites are located in low-altitude near-polar orbits. This means that they pass close to the poles of the Earth as they orbit. NOAA-19 was launched in February 2009 and orbits at an inclination of 99° to the equator. Its low altitude means that it captures high-resolution pictures of small bands of the Earth. The data is used in local weather forecasting as well as to provide enormous amounts of information for monitoring global warming and climate change.

Table 1.1.1 provides data for the three satellites discussed in this section.

Seeing the International Space Station (ISS) and other satellites

It is easy to see low-orbit satellites if you are away from city lights. The best time to look is just after sunset. If you can, go outside and look for any slow-moving objects passing across the star background.

There are also many websites that will allow you to track and predict the real-time paths of satellites. You can use the NASA 'Spot the Station' website to see when the ISS is passing over your part of the planet. The ISS is so bright that it is easy to see from most locations.

FIGURE 1.1.18 The only force acting on these artificial and natural satellites is the gravitational attraction of the Earth. Both orbit with a centripetal acceleration equal to the gravitational field strength at their locations.

TABLE 1.1.1 A comparison of the three satellites discussed in this section

Satellite	Orbit	Inclination	Perigee (km)	Apogee (km)	Period
Himawari-8	equatorial	0°	35 784	35 789	1 day
Hubble	inclined	28°	591	599	96.6 min
NOAA-19	near polar	99°	846	866	102 min

1.1 Review

SUMMARY

- All objects with mass attract one another with a gravitational force.
- The gravitational force acts equally on each of the masses.
- The magnitude of the gravitational force is given by Newton's law of universal gravitation:

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

- Gravitational forces are usually negligible unless one of the objects is massive, e.g. a planet.
- The weight of an object on the Earth's surface is due to the gravitational attraction of the Earth, i.e. weight = F_{weight}.
- The acceleration due to gravity of an object near the Earth's surface can be calculated using the dimensions of the Earth:

$$g = G\frac{m_{\text{Earth}}}{(r_{\text{Earth}})^2} = 9.80\,\text{m s}^{-2}$$

- Objects can have an apparent weight that is greater or less than their normal weight. This occurs when they are accelerating vertically.
- Artificial satellites are used for communication, navigation, remote-sensing and research. Their orbits and uses are classified by altitude (low-, medium- or high-Earth orbits) and by inclination (equatorial, polar and Sun-synchronous orbits).

KEY QUESTIONS

1 Newton's law of universal gravitation links the relationships (or proportionalities) between several key factors influencing the force due to gravity between two objects. What are the individual proportionalities?

2 What does the symbol *r* represent in Newton's law of universal gravitation?

3 Calculate the force of gravitational attraction between the Sun and Mars, given the following data:
$m_{\text{Sun}} = 2.0 \times 10^{30}$ kg
$m_{\text{Mars}} = 6.4 \times 10^{23}$ kg
$r_{\text{Sun–Mars}} = 2.2 \times 10^{11}$ m

4 The force of gravitational attraction between the Sun and Mars is 1.8×10^{21} N. Calculate the acceleration of Mars given that $m_{\text{Mars}} = 6.4 \times 10^{23}$ kg.

5 On 14 April 2014, Mars came within 93 million km of Earth. Its gravitational effect on the Earth was the strongest it had been for over 6 years. Use the following data to answer the questions below.
$m_{\text{Sun}} = 2.0 \times 10^{30}$ kg
$m_{\text{Earth}} = 6.0 \times 10^{24}$ kg
$m_{\text{Mars}} = 6.4 \times 10^{23}$ kg

a Calculate the gravitational force between the Earth and Mars on 14 April 2014.
b Calculate the force of the Sun on the Earth if the distance between them was 153 million km.
c Compare your answers to parts (a) and (b) above by expressing the Mars–Earth force as a percentage of the Sun–Earth force.

6 The acceleration of the Moon caused by the gravitational force of the Earth is much larger than the acceleration of the Earth due to the gravitational force of the Moon. What is the reason for this?

7 Calculate the acceleration of an object dropped near the surface of Mercury if this planet has a mass of 3.3×10^{23} kg and a radius of 2500 km. Assume that the gravitational acceleration on Mercury can be calculated similarly to that on Earth.

8 Calculate the weight of a 65 kg cosmonaut standing on the surface of Mars, given that the planet has a mass of 6.4×10^{23} kg and a radius of 3.4×10^{6} m.

9 In your own words, explain the difference between the terms 'weight' and 'apparent weight', giving an example of a situation where the magnitudes of these two forces would be different.

10 Calculate the apparent weight of a 50 kg person in an elevator under the following circumstances.
a accelerating upwards at $1.2\,\text{m s}^{-2}$
b moving upwards at a constant speed of $5\,\text{m s}^{-1}$

11 Calculate the apparent weight of a 45.0 kg child standing in a lift that is decelerating at $3.15\,\text{m s}^{-2}$ while travelling upwards.

12 Which statement best describes the motion of astronauts when orbiting the Earth?
- **A** They float in a zero-gravity environment.
- **B** They float in a reduced gravity environment.
- **C** They fall down very slowly due to the very small gravity.
- **D** They fall in a reduced gravity environment.

13 Select the statement below that correctly describes how a satellite in a stable circular orbit 200 km above the Earth will move.
- **A** It will have an acceleration of $9.80\,\mathrm{m\,s^{-2}}$.
- **B** It will have constant velocity.
- **C** It will have zero acceleration.
- **D** It will have acceleration of less than $9.80\,\mathrm{m\,s^{-2}}$.

14 What can be said about an object if that object is orbiting the Earth in space and appears to be weightless?
- **A** It is in free-fall.
- **B** It is in zero gravity.
- **C** It has no mass.
- **D** It is floating.

15 A geostationary satellite orbits above Singapore, which is on the equator. Which of the following statements about the satellite is correct?
- **A** It is in a low orbit.
- **B** It is in a high orbit.
- **C** It passes over the North Pole.
- **D** It is not moving.

1.2 Gravitational fields

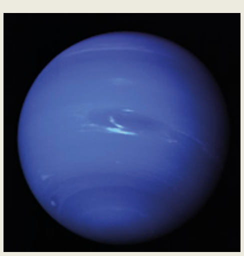
Newton's law of universal gravitation describes the force acting between two mutually attracting bodies. In reality, complex systems like the solar system involve a number of objects (i.e. the Sun and planets shown in Figure 1.2.1) that are all exerting attractive forces on each other at the same time.

In the 18th century, to simplify the process of calculating the effect of simultaneous gravitational forces, scientists developed a mental construct known as the gravitational field. In the following centuries, the idea of a **field** was also applied to other forces and has become a very important concept in physics.

FIGURE 1.2.1 The solar system is a complex gravitational system.

PHYSICS IN ACTION

Discovery of Neptune



The planet Neptune was discovered through its gravitational effect on other planets. Two astronomers, Urbain Le Verrier of France and John Couch Adams of England, each independently identified that the observed orbit of Uranus varied significantly from predictions made based on the gravitational effects of the Sun and other known planets. Both suggested that this was due to the influence of a distant, undiscovered planet.

Le Verrier sent a prediction of the location of the new planet to Gottfried Galle at the Berlin Observatory and, on 23 September 1846, Neptune was discovered within 1° of Le Verrier's prediction (Figure 1.2.2).

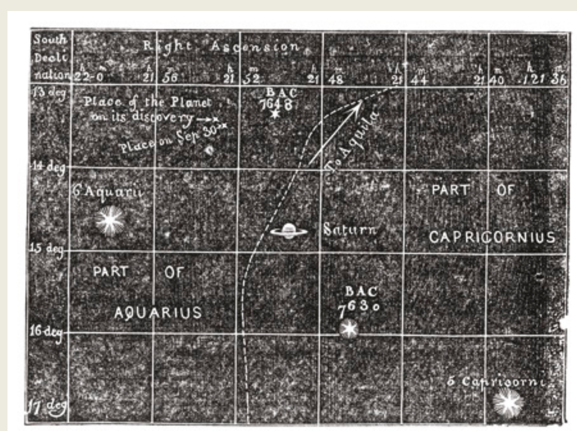


FIGURE 1.2.2 This star chart published in 1846 shows the location of Neptune in the constellation Aquarius when it was discovered on 23 September, and its location one week later.

GRAVITATIONAL FIELDS

A **gravitational field** is a region in which a gravitational force is exerted on all matter within that region. Every physical object has an accompanying gravitational field. For example, the space around your body contains a gravitational field because any other object that comes into this region will experience a (small) force of gravitational attraction to your body.

The gravitational field around a large object such as a planet is much more significant than that around a small object. The Earth's gravitational field exerts a significant influence on objects on its surface and even up to thousands of kilometres into space.

REPRESENTING GRAVITATIONAL FIELDS

Over time, scientists have developed a commonly understood method of representing fields using a series of arrows known as field lines (Figure 1.2.3). For gravitational fields, these are constructed as follows:

- The direction of the arrowhead indicates the direction of the gravitational force.
- The space between the field lines indicates the relative magnitude of the field.
  - Closely spaced field lines indicate a strong field.
  - Widely spaced field lines indicate a weaker field.
  - Parallel field lines indicate constant or **uniform** field strength.

An infinite number of field lines could be drawn, so only a few are chosen to represent the rest. The size of the gravitational force acting on a mass in the region of a gravitational field is determined by the strength of the field, and the force acts in the direction of the field.

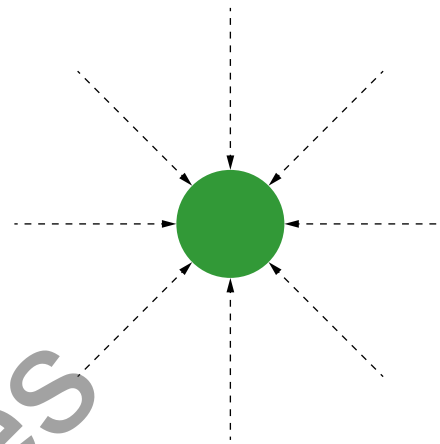
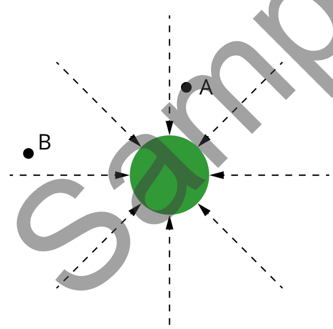


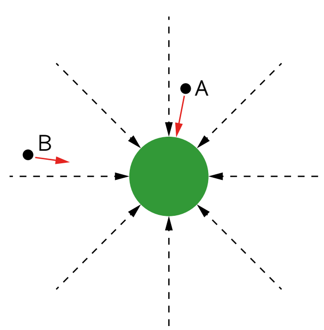
FIGURE 1.2.3 The arrows in this gravitational field diagram indicate that objects will be attracted towards the mass in the centre; the spacing of the lines shows that force will be strongest at the surface of the central mass and weaker further away from it.

Worked example 1.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a moon.



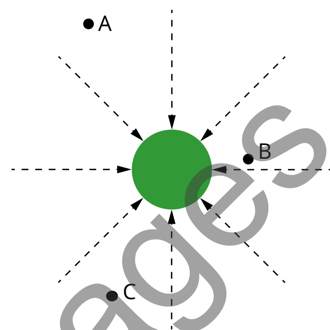
a Use arrows to indicate the magnitude and direction of the gravitational force acting at points A and B.	
Thinking	**Working**
The direction of the field arrows indicates the direction of the gravitational force, which is inwards towards the centre of the moon.	

b Describe the relative strength of the gravitational field at each point.	
Thinking	**Working**
The closer the field lines, the stronger the force. The field lines are closer together at point A than they are at point B, as point A is closer to the moon.	The field is stronger at point A than at point B.

Worked example: Try yourself 1.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a planet.



a Use arrows to indicate the magnitude and direction of the gravitational force acting at points A, B and C.

b Describe the relative strength of the gravitational field at each point.

GRAVITATIONAL FIELD STRENGTH

In theory, gravitational fields extend infinitely out into space. However, since the magnitude of the gravitational force decreases with the square of the distance, eventually these fields become so weak as to become negligible.

In Section 1.1, it was shown that it is possible to calculate the acceleration due to gravity of objects near the Earth's surface using the dimensions of the Earth:

$$g = G\frac{m_{\text{Earth}}}{(r_{\text{Earth}})^2} = 9.80\,\text{m}\,\text{s}^{-2}$$

The constant g can also be used as a measure of the strength of the gravitational field. When understood in this way, the constant is written with the equivalent units of $\text{N}\,\text{kg}^{-1}$ rather than $\text{m}\,\text{s}^{-2}$. This means $g_{\text{Earth}} = 9.80\,\text{N}\,\text{kg}^{-1}$.

These units indicate that objects on the surface of the Earth experience 9.80 N of gravitational force for every kilogram of their mass.

Accordingly, the familiar equation $F_{\text{weight}} = mg$ can be transposed so that the **gravitational field strength**, g, can be calculated.

$$g = \frac{F_{\text{weight}}}{m}$$

where g is gravitational field strength ($\text{N}\,\text{kg}^{-1}$)

F_{weight} is the force due to gravity (N)

m is the mass of an object in the field (kg)

PHYSICSFILE

$\text{N}\,\text{kg}^{-1} = \text{m}\,\text{s}^{-2}$

It can be shown that $\text{N}\,\text{kg}^{-1}$ and $\text{m}\,\text{s}^{-1}$ are equivalent units.

From Newton's second law, $F = ma$, you will remember that:

$$1\,\text{N} = 1\,\text{kg}\,\text{m}\,\text{s}^{-2}$$

$$\therefore\ 1\,\text{N}\,\text{kg}^{-1} = 1\,\text{kg}\,\text{m}\,\text{s}^{-2} \times \text{kg}^{-1} = 1\,\text{m}\,\text{s}^{-2}$$

Worked example 1.2.2

CALCULATING GRAVITATIONAL FIELD STRENGTH

When a student hangs a 1.0 kg mass from a spring balance, the balance measures a downwards force of 9.80 N. According to this experiment, what is the gravitational field strength of the Earth in this location?	
Thinking	**Working**
Recall the equation for gravitational field strength.	$g = \frac{F_{weight}}{m}$
Substitute in the appropriate values.	$g = \frac{9.8}{1.0}$
Solve the equation.	$g = 9.8\ \text{N kg}^{-1}$

Worked example: Try yourself 1.2.2

CALCULATING GRAVITATIONAL FIELD STRENGTH

A student uses a spring balance to measure the weight of a piece of wood as 2.5 N.

If the piece of wood is thought to have a mass of 260 g, calculate the gravitational field strength indicated by this experiment.

Newton's law of universal gravitation can be written as $F_g = G\frac{Mm}{r^2}$, to indicate the difference in mass between the large central body and the smaller object within the gravitational field. This formula can be used to develop the formula for gravitational field strength:

$$g = \frac{F_{weight}}{m} = \frac{G\frac{Mm}{r^2}}{m}$$

This simplifies to:

$$g = G\frac{M}{r^2}$$

where g is the gravitational field strength (N kg^{-1})

G is the gravitational constant, $6.67 \times 10^{-11}\ \text{N m}^2\ \text{kg}^{-2}$

M is the mass of the planet or moon (the central body; kg)

r is the radius of the planet or moon (m)

REVISION

Inverse square law

The concept of a field is a very powerful tool for understanding forces that act at a distance. It has also been applied to forces such as the electrostatic force between charged objects and the force between two magnets.

The study of gravitational fields introduces the concept of the inverse square law. From the point source of a field, whether it be gravitational, electric or magnetic, the field will spread out radially in three dimensions. When the distance from the source is doubled, the field will be spread over four times the original area.

In Figure 1.2.4, going from r to $2r$ to $3r$, the area shown increases from one square to four squares (2^2) to nine squares (3^2). Using the inverse part of the inverse square law, at a distance $2r$ the strength of the field will be reduced to a quarter of that at r, as is the force that the field would exert. At $3r$ from the source, the field will be reduced to one-ninth of that at the source, and so on.

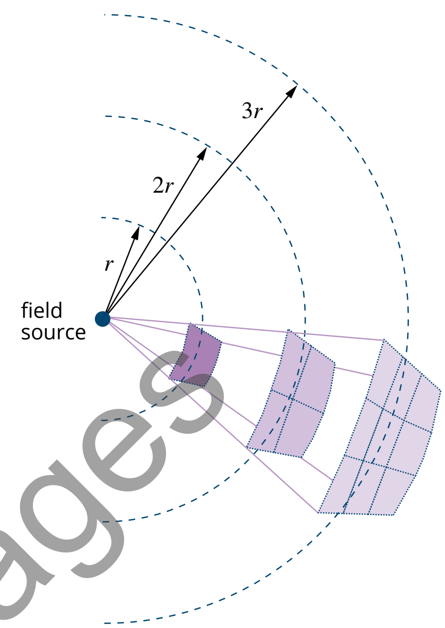


FIGURE 1.2.4 As the distance from the source of a field increases, the field is spread over an area that increases with the square of the distance from the source, resulting in the strength of the field decreasing by the same ratio.

In terms of the gravitational field, the strength of the force varies inversely with the square of the distance between the objects:

$$F \propto \frac{M}{r^2}$$

where F is the force

r is the distance from the source of the gravitational field.

This is referred to as the inverse square law.

One key difference between the gravitational force and other inverse square forces is that the gravitational force is always attractive, whereas like charges or magnetic poles repel one another.

Inverse square laws are an important concept in physics, not only in the study of fields but also for other phenomena where energy is moving away from its source in three dimensions, such as in sound and other waves.

Variations in gravitational field strength of the Earth

The gravitational field strength of the Earth, g, is usually assigned a value of $9.81\,\text{N kg}^{-1}$ (and generally rounded further to $9.80\,\text{N kg}^{-1}$ for Physics exams). However, the field strength experienced by objects on the surface of the Earth can vary between $9.76\,\text{N kg}^{-1}$ and $9.83\,\text{N kg}^{-1}$, depending on location.

Geological formations can also create differences in gravitational field strength, depending on their composition. Geologists use a sensitive instrument known as a **gravimeter** (Figure 1.2.5) that detects small local variations in gravitational field strength to indicate underground features. Rocks with above-average density, such as those containing mineral ores, create slightly stronger gravitational fields, whereas less-dense sedimentary rocks produce weaker fields.

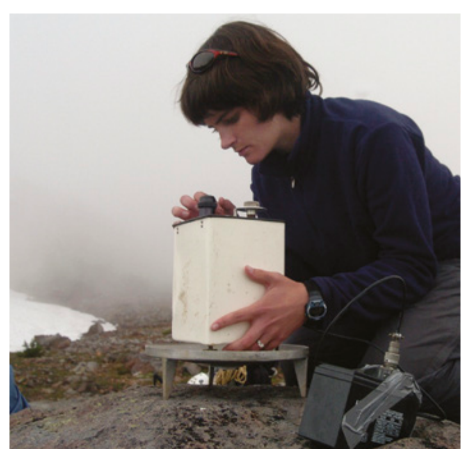


FIGURE 1.2.5 A gravimeter can be used to measure the strength of the local gravitational field.

If the surface of the Earth is considered a flat surface as it appears in everyday life, then the gravitational field lines are approximately parallel, indicating a uniform field (Figure 1.2.6).

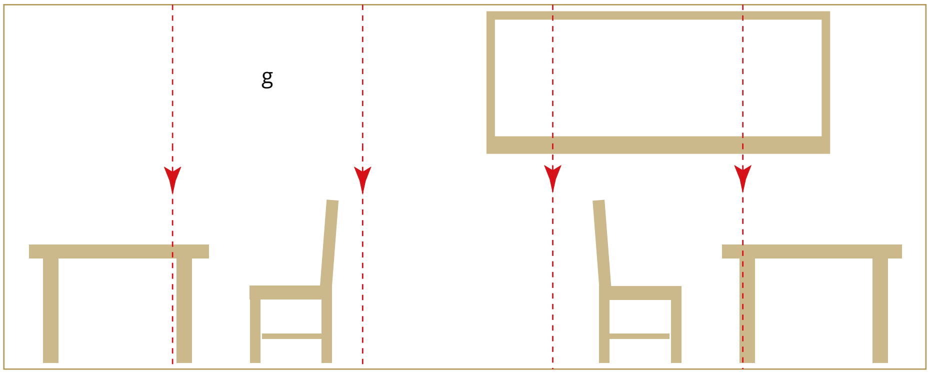


FIGURE 1.2.6 The uniform gravitational field, g, is represented by evenly spaced parallel lines in the direction of the force.

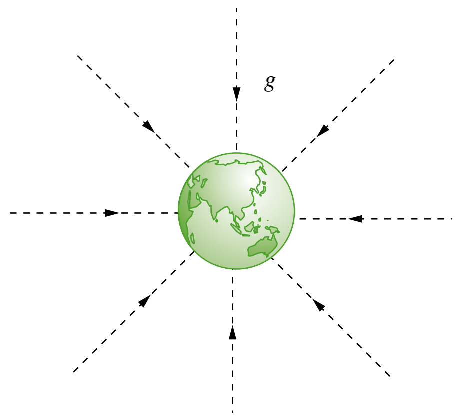


FIGURE 1.2.7 The Earth's gravitational field becomes progressively weaker out into space.

However, when the Earth is viewed from a distance as a sphere, it becomes clear that the Earth's gravitational field is not uniform at all (Figure 1.2.7). The increasing distance between the field lines indicates that the field becomes progressively weaker out into space.

This is because gravitational field strength, like gravitational force, is governed by the inverse square law:

$$g = G\frac{M_{\text{Earth}}}{(r_{\text{Earth}})^2}$$

The gravitational field strength at different altitudes can be calculated by adding the altitude to the radius of the Earth to calculate the distance of the object from Earth's centre (Figures 1.2.8 and 1.2.9).

$$g = \frac{GM_{\text{Earth}}}{(r_{\text{Earth}} + \text{alititude})^2}$$

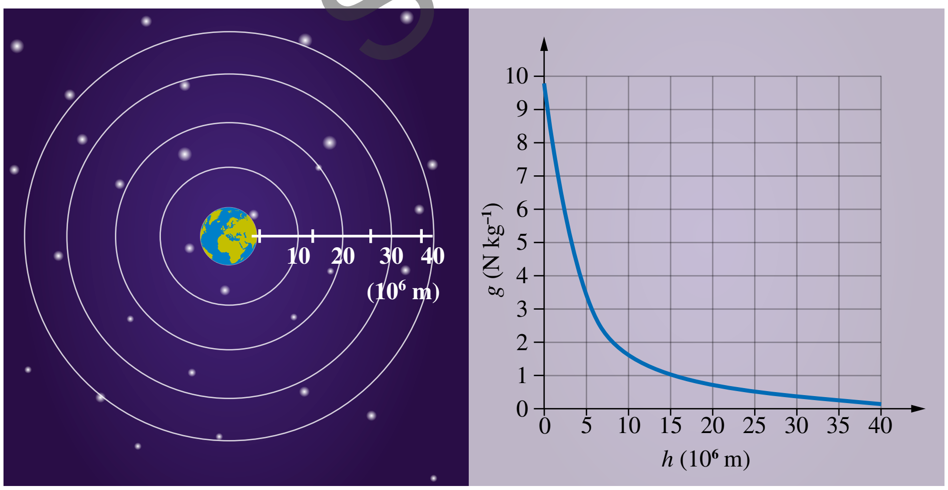


FIGURE 1.2.8 As the distance from the surface of the Earth is increased from 0 to 40×10^6 m, the value for g decreases rapidly from $9.80\,\text{N kg}^{-1}$, according to the inverse square law. The blue line on the graph gives the value of g at various altitudes (h).

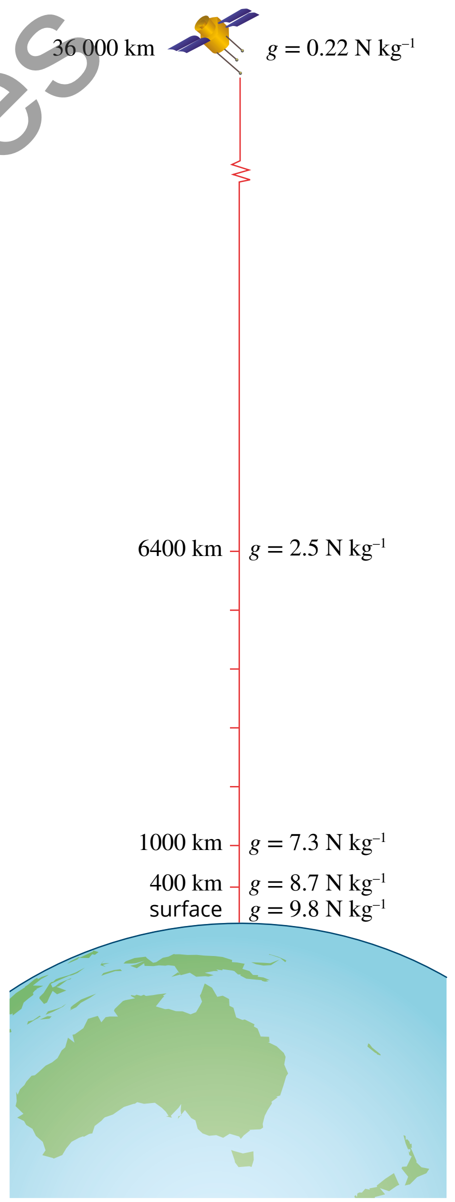


FIGURE 1.2.9 The Earth's gravitational field strength is weaker at higher altitudes.

PHYSICSFILE

Variations in gravitational field strength

The Earth's gravitational field strength is not the same at every point on the Earth's surface. As the Earth is not a perfect sphere, objects near the equator are slightly further from the centre of the Earth than objects at the poles. This means that the Earth's gravitational field is slightly stronger at the poles than at the equator.

The shape of the Earth is known as an oblate spheroid (Figure 1.2.10). Mathematically, this is the shape that's made when an ellipse is rotated around its minor axis. The diameter of the Earth between the North and South poles is approximately 40 km shorter than its diameter at the equator.

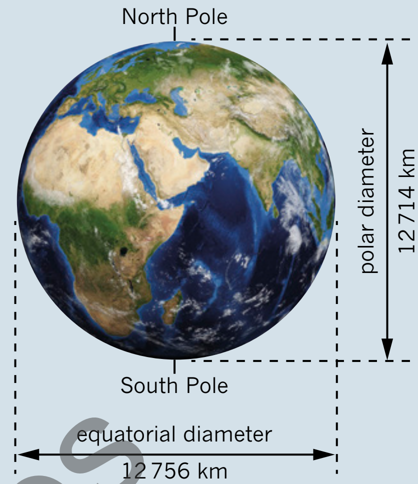


FIGURE 1.2.10 The Earth is a flattened sphere, which means its gravitational field is slightly stronger at the poles.

Worked example 1.2.3

CALCULATING GRAVITATIONAL FIELD STRENGTH AT DIFFERENT ALTITUDES

Calculate the strength of the Earth's gravitational field at the top of Mt Everest using the following data:

$r_{Earth} = 6.38 \times 10^6$ m

$m_{Earth} = 5.97 \times 10^{24}$ kg

height of Mt Everest = 8850 m

Thinking	Working
Recall the formula for gravitational field strength.	$g = G\frac{M}{r^2}$
Add the height of Mt Everest to the radius of the Earth.	$r = 6.38 \times 10^6 + 8850$ m $= 6.389 \times 10^6$ m
Substitute the values into the formula.	$g = G\frac{M}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{5.97 \times 10^{24}}{(6.389 \times 10^6)^2}$ $= 9.76\ \text{N kg}^{-1}$

Worked example: Try yourself 1.2.3

CALCULATING GRAVITATIONAL FIELD STRENGTH AT DIFFERENT ALTITUDES

Commercial airlines typically fly at an altitude of 11 000 m. Calculate the gravitational field strength of the Earth at this height using the following data:

$r_{Earth} = 6.38 \times 10^6$ m

$m_{Earth} = 5.97 \times 10^{24}$ kg

Gravitational field strengths of other planets

The gravitational field strength on the surface of the Moon is much less than on Earth, at approximately 1.6 N kg^{-1}. This is because the Moon's mass is smaller than that of the Earth.

The formula $g = G\frac{M}{r^2}$ can be used to calculate the gravitational field strength on the surface of any astronomical object, such as Mars (Figure 1.2.11).

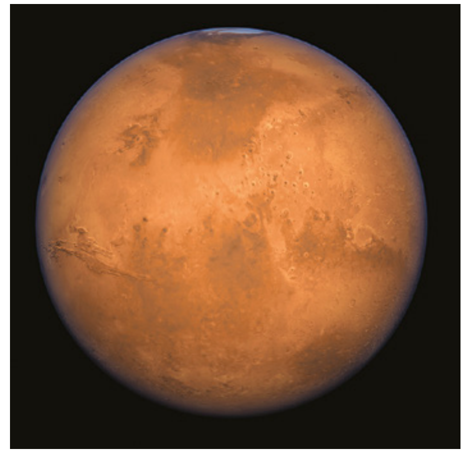


FIGURE 1.2.11 The gravitational field strength on the surface of Mars (shown here) is different from the gravitational field strength on the Earth, which, in turn, is different from that on the Moon.

Worked example 1.2.4

GRAVITATIONAL FIELD STRENGTH ON ANOTHER PLANET OR MOON

Calculate the strength of the gravitational field on the surface of the Moon given that the Moon's mass is 7.35×10^{22} kg and its radius is 1740 km. Give your answer correct to two significant figures.	
Thinking	**Working**
Recall the formula for gravitational field strength.	$g = G\frac{M}{r^2}$
Convert the Moon's radius to m.	$r = 1740$ km $= 1740 \times 1000$ m $= 1.74 \times 10^6$ m
Substitute values into the formula.	$g = G\frac{M}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{7.35 \times 10^{22}}{(1.74 \times 10^6)^2}$ $= 1.6$ N kg^{-1}

Worked example: Try yourself 1.2.4

GRAVITATIONAL FIELD STRENGTH ON ANOTHER PLANET OR MOON

Calculate the strength of the gravitational field on the surface of Mars.

$m_{Mars} = 6.42 \times 10^{23}$ kg

$r_{Mars} = 3390$ km

Give your answer correct to two significant figures.

PHYSICSFILE

Moon walking

Walking is a process of repeatedly stopping yourself from falling over. When astronauts first tried to walk on the Moon, they found that they fell too slowly to walk easily. Instead, they invented a kind of shuffling jump that was a much quicker way of moving around in the Moon's weak gravitational field (Figure 1.2.12). This type of 'moon walk' should not be confused with the famous dance move of the same name!

FIGURE 1.2.12 Astronauts had to invent a new way of walking to deal with the Moon's weak gravitational field.

1.2 Review

SUMMARY

- A gravitational field is a region in which a gravitational force is exerted on all matter within that region.
- A gravitational field can be represented by a gravitational field diagram:
  - The arrowheads indicate the direction of the gravitational force.
  - The spacing of the field lines indicates the relative strength of the field. The closer the line spacing, the stronger the field.
- The strength of a gravitational field can be calculated using the following formulae:

$$g = \frac{F_{weight}}{m} \quad \text{or} \quad g = G\frac{M}{r^2}$$

- The gravitational field strength on the Earth's surface is approximately 9.80 N kg^{-1}. This varies from location to location and with altitude.
- The gravitational field strength on the surface of any other planet depends on the mass and radius of the planet.

KEY QUESTIONS

1 What is the most appropriate unit for measuring gravitational field strength in the context of gravitational fields?

2 Students use a spring balance to measure the weight of a 150 g set of slotted masses to be 1.4 N. According to this measurement, what is the gravitational field strength in their classroom?

3 A gravitational field, g, is measured as 5.5 N kg^{-1} at a distance of 40 000 km from the centre of a planet. The distance from the centre of the planet is then increased to 120 000 km. What would be the ratio of the magnitude of the gravitational field at this new distance to the magnitude of original measurement?

4 Different types of satellite have different types of orbit, as shown in the table below. Calculate the strength of the Earth's gravitational field in each orbit.

r_{Earth} = 6380 km

$m_{Earth} = 5.97 \times 10^{24}$ kg

	Type of orbit	Altitude (km)
a	low-Earth orbit	2 000
b	medium-Earth orbit	10 000
c	semi-synchronous orbit	20 200
d	geosynchronous orbit	35 786

5 On 12 November 2014, the Rosetta spacecraft landed a probe on the comet 67P/Churyumov–Gerasimenko. Assuming this comet is a roughly spherical object with a mass of 1×10^{13} kg and a diameter of 1.8 km, calculate the gravitational field strength on its surface.

6 The masses and radii of three planets are given in the following table. Calculate the gravitational field strength, g, at the surface of each planet.

Planet	Mass (kg)	Radius (m)
Mercury	3.30×10^{23}	2.44×10^{6}
Saturn	5.69×10^{26}	6.03×10^{7}
Jupiter	1.90×10^{27}	7.15×10^{7}

7 There are bodies outside our solar system, such as neutron stars, that produce very large gravitational fields. A typical neutron star can have a mass of 3.0×10^{30} kg and a radius of just 10 km. Calculate the gravitational field strength at the surface of such a star.

8 A newly discovered solid planet located in a distant solar system is found to be distinctly non-spherical in shape. Its polar radius is 5000 km, and its equatorial radius is 6000 km.

The gravitational field strength at the poles is 8.0 N kg^{-1}. How would the gravitational field strength at the poles compare with the strength at the equator?

9 There is a point between the Earth and the Moon where the total gravitational field is zero. The significance of this is that returning lunar missions are able to return to Earth under the influence of the Earth's gravitational field once they pass this point. Given that the mass of Earth is 6.0×10^{24} kg, the mass of the Moon is 7.3×10^{22} kg and the radius of the Moon's orbit is 3.8×10^{8} m, calculate the distance of this point from the centre of the Earth.

10 An astronaut travels away from Earth to a region in space where the gravitational force due to Earth is only 1.0% of that at Earth's surface. What distance, in Earth radii, is the astronaut from the centre of the Earth?

Chapter review

01

KEY TERMS

acceleration due to gravity
altitude
apparent weight
apparent weightlessness
artificial satellites
centripetal acceleration
field
free-fall
geostationary satellite
gravimeter
gravitational constant
gravitational field
gravitational field strength
gravitational force
gravitational potential energy
inverse square law
kinetic energy
natural satellite
Newton's law of universal gravitation
normal reaction force
torsion balance
uniform
weight

1 Use Newton's law of universal gravitation to calculate the gravitational force acting on a person with a mass of 75 kg. Use the following data:
$m_{Earth} = 6.0 \times 10^{24}$ kg
$r_{Earth} = 6400$ km

2 The gravitational force of attraction between Saturn and Dione, a moon of Saturn, is equal to 2.79×10^{20} N. Calculate the orbital radius of Dione. Use the following data:
mass of Dione = 1.05×10^{21} kg
mass of Saturn = 5.69×10^{26} kg

3 Of all the planets in the solar system, Jupiter exerts the largest force on the Sun: 4.2×10^{23} N. Calculate the acceleration of the Sun due to this force, using the following data: $m_{Sun} = 2.0 \times 10^{30}$ kg.

4 The planet Jupiter and the Sun exert gravitational forces on each other.
a Compare, qualitatively, the force exerted on Jupiter by the Sun to the force exerted on the Sun by Jupiter.
b Compare, qualitatively, the acceleration of Jupiter caused by the Sun to the acceleration of the Sun caused by Jupiter.

5 Calculate the acceleration due to gravity on the surface of Mars if it has a mass of 6.4×10^{23} kg and a radius of 3400 km.

6 Calculate the apparent weight of a 50 kg person in an elevator under the following circumstances.
a accelerating downwards at 0.6 m s^{-2}
b moving downwards at a constant speed of 2 m s^{-1}

7 A comet of mass 1000 kg is plummeting towards Jupiter. Jupiter has a mass of 1.90×10^{27} kg and a planetary radius of 7.15×10^{7} m. If the comet is about to crash into Jupiter, calculate the:
a magnitude of the gravitational force that Jupiter exerts on the comet
b magnitude of the gravitational force that the comet exerts on Jupiter
c acceleration of the comet towards Jupiter
d acceleration of Jupiter towards the comet.

8 A person standing on the surface of the Earth experiences a gravitational force of 900 N. What gravitational force will this person experience at a height of two Earth radii above the Earth's surface?
A 900 N
B 450 N
C zero
D 100 N

9 During a space mission, an astronaut of mass 80 kg initially accelerates at 30 m s^{-2} upwards, then travels in a stable circular orbit at an altitude where the gravitational field strength is 8.2 N kg^{-1}.
a What is the apparent weight of the astronaut during lift-off?
A zero
B 780 N
C 2400 N
D 3200 N
b During the lift-off phase, the astronaut will feel:
A lighter than usual
B heavier than usual
C the same as usual
c The weight of the astronaut during the lift-off phase is:
A lower than usual
B greater than usual
C the same as usual
d During the orbit phase, the apparent weight of the astronaut is:
A zero
B 780 N
C 2400 N
D 660 N
e During the orbit phase, the weight of the astronaut is:
A zero
B 780 N
C 2400 N
D 660 N

10 Describe the main rules to follow when drawing gravitational field lines.

11 A set of bathroom scales is calibrated so that when the person standing on it has a weight of 600 N, the scales read 61.5 kg. What gravitational field strength has been assumed in this setting?

12 The Earth is a slightly flattened sphere. Its radius at the poles is 6357 km compared to 6378 km at the equator. The Earth's mass is 5.97×10^{24} kg.

a Calculate the Earth's gravitational field strength at the equator.

b Using the information in part (a), calculate how much stronger the gravitational field would be at the North Pole compared with at the equator. Give your answer as a percentage of the strength at the equator.

13 Neptune has a planetary radius of 2.48×10^{7} m and a mass of 1.02×10^{26} kg.

a Calculate the gravitational field strength on the surface of Neptune.

b A 250 kg lump of ice is falling directly towards Neptune. What is its acceleration as it nears the surface of Neptune? Ignore any drag effects.

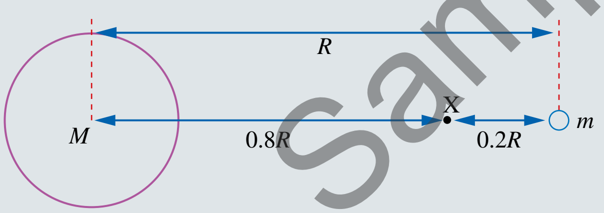
A $9.80\,\mathrm{m\,s^{-2}}$

B zero

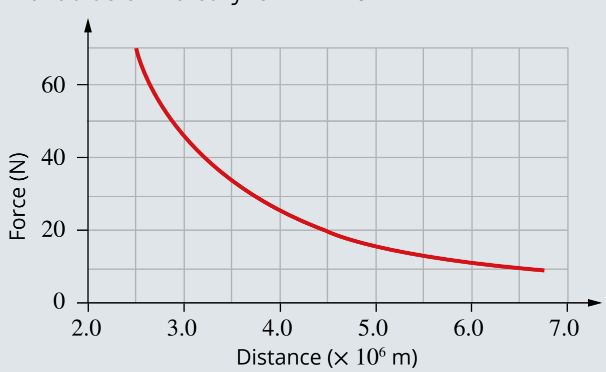
C $11\,\mathrm{m\,s^{-2}}$

D $1.6\,\mathrm{m\,s^{-2}}$

14 Two stars of masses M and m are in orbit around each other. As shown in the following diagram, they are a distance R apart. A spacecraft located at point X experiences zero net gravitational force from these stars. Calculate the value of the ratio $\frac{M}{m}$.



15 A 20 kg rock is speeding towards Mercury. The following graph shows the force on the rock as a function of its distance from the centre of the planet. The radius of Mercury is 2.4×10^{6} m.



When the rock is 3.0×10^{6} m from the centre of the planet, its speed is estimated at $1.0\,\mathrm{km\,s^{-1}}$. Using the graph, estimate the:

a increase in kinetic energy of the rock as it moves to a point that is just 2.5×10^{6} m from the centre of Mercury

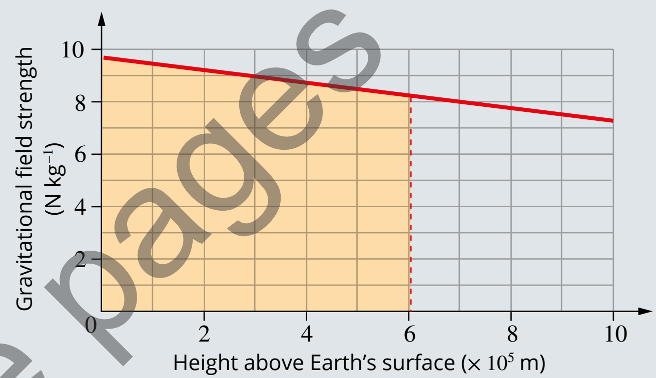
b kinetic energy of the rock at this closer point

c speed of the rock at this point

d gravitational field strength at 2.5×10^{6} m from the centre of Mercury.

The following information relates to questions 16–20.

The diagram shows the gravitational field strength and distance near the Earth. A wayward satellite of mass 1000 kg is drifting towards the Earth.



16 What is the gravitational field strength at an altitude of 300 km?

17 Which of the following units is associated with the area under this graph?

A J

B $\mathrm{m\,s^{-2}}$

C J s

D $\mathrm{J\,kg^{-1}}$

18 Which one of the following quantities is represented by the shaded area on the graph? (Ignore air resistance.)

A the kinetic energy per kilogram of the satellite at an altitude of 600 km

B the loss in gravitational potential energy of the satellite

C the loss in gravitational potential energy per kilogram of the satellite as it falls to the Earth's surface

D the increase in gravitational potential energy of the satellite as it falls to the Earth's surface

19 How much kinetic energy does the satellite gain as it travels from an altitude of 600 km to an altitude of 200 km?

20 In reality, would the satellite gain the amount of kinetic energy that you have calculated in Question 19? Explain your answer.