Heinemann

PHYSICS 12

4TH EDITION

VCE Units 3 & 4

Written for the VCE Physics Study Design 2017–2021

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Please be aware that these images might cause sadness or distress in Aboriginal or Torres Strait Islander communities.

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4TH EDITION

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Unit 4: How can two contradictory models explain both light and matter?

AREA OF STUDY 1
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and AREA OF STUDY 2
How are light and matter similar?

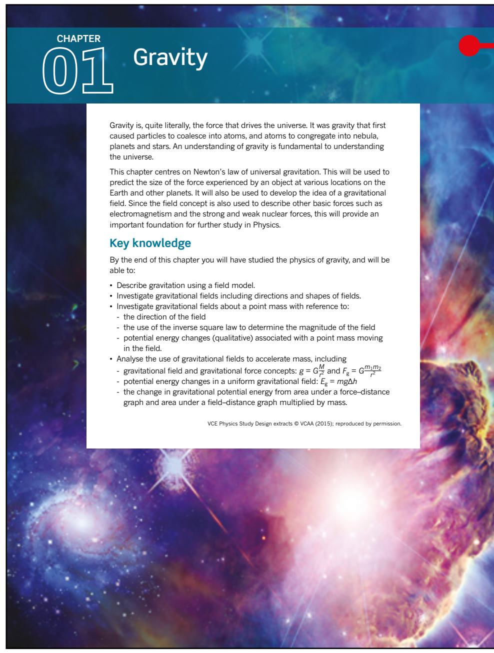
AREA OF STUDY 3: PRACTICAL INVESTIGATION

Heinemann Physics 12 4th Edition ProductLink provides extensive support material for Unit 4 Area of Study 3 Practical Investigation. This includes teacher notes and advice, logbook template and sample logbook, poster template and sample poster, rubrics, checklists and more.

How to use this book

Heinemann Physics 12 4th Edition

Heinemann Physics 12 4th Edition has been written to the new VCE Physics Study Design 2017–2021. The book covers Units 3 and 4 in an easy-to-use resource. Explore how to use this book below.


CHAPTER 01 Gravity

Gravity is, quite literally, the force that drives the universe. It was gravity that first caused particles to coalesce into atoms, and atoms to congregate into nebula, 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. 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 study in Physics.

Key knowledge

By the end of this chapter you will have studied the physics of gravity, and will be able to:

- Describe gravitation using a field model.
- Investigate gravitational fields including directions and shapes of fields.
- Investigate gravitational fields about a point mass with reference to:
  - the direction of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass moving in the field.
- Analyse the use of gravitational fields to accelerate mass, including
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
  - the change in gravitational potential energy from area under a force–distance graph and area under a field–distance graph multiplied by mass.

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Chapter opener

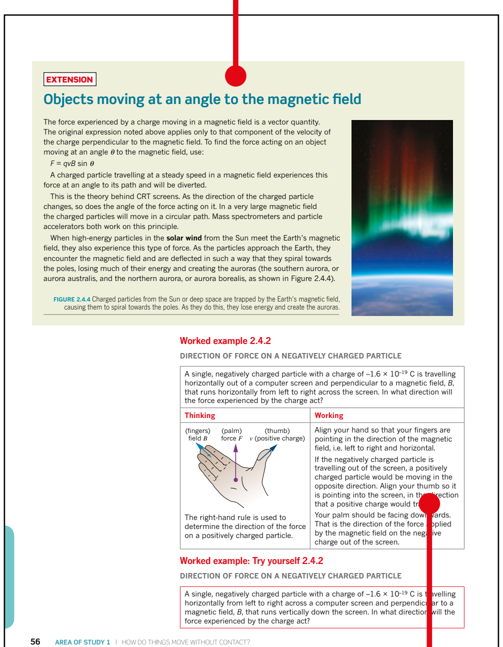
Chapter opening pages links the Study Design to the chapter content. Key knowledge addressed in the chapter is clearly listed.

Extension

The extension boxes include material that goes beyond the core content of the Study Design and are intended for students who wish to expand their depth of understanding.

Physics in Action

Physics in Action place physics in an applied situation or relevant context. These refer to the nature and practice of physics, applications of physics and the associated issues and the historical development of concepts and ideas.


EXTENSION

Objects moving at an angle to the magnetic field

The force experienced by a charge moving in a magnetic field is a vector quantity. The original expression noted above applies only to that component of the velocity of the charge perpendicular to the magnetic field. To find the force acting on an object moving at an angle θ to the magnetic field, use:

$F = qvB \sin \theta$

A charged particle travelling at a steady speed in a magnetic field experiences this force at an angle to its path and will be diverted.

This is the theory behind CRT screens. As the direction of the charged particle changes, so does the angle of the force acting on it. In a very large magnetic field the charged particles will move in a circular path. Mass spectrometers and particle accelerators both work on this principle.

When high-energy particles in the **solar wind** from the Sun meet the Earth's magnetic field, they also experience this type of force. As the particles approach the Earth, they encounter the magnetic field and are deflected in such a way that they spiral towards the poles, losing much of their energy and creating the auroras (the southern aurora, or aurora australis, and the northern aurora, or aurora borealis, as shown in Figure 2.4.4).

FIGURE 2.4.4 Charged particles from the Sun or deep space are trapped by the Earth's magnetic field, causing them to spiral towards the poles. As they do this, they lose energy and create the auroras.

Worked example 2.4.2

DIRECTION OF FORCE ON A NEGATIVELY CHARGED PARTICLE

A single, negatively charged particle with a charge of -1.6×10^{-19} C is travelling horizontally out of a computer screen and perpendicular to a magnetic field, B, that runs horizontally from left to right across the screen. In what direction will the force experienced by the charge act?

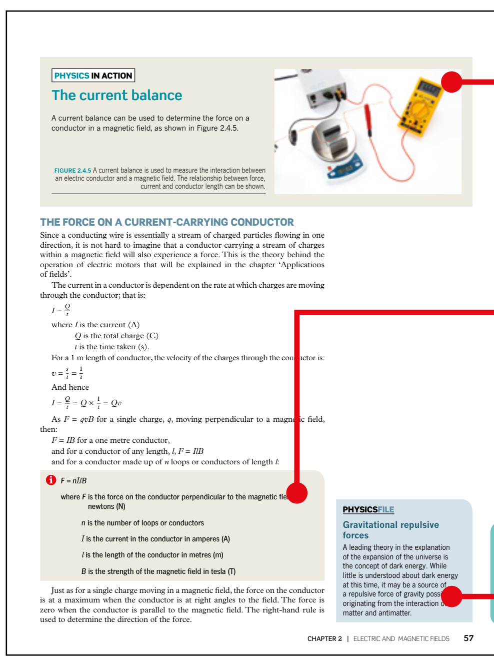
Thinking	Working
(fingers) field B (palm) force F (thumb) v (positive charge) The right-hand rule is used to determine the direction of the force on a positively charged particle.	Align your hand so that your fingers are pointing in the direction of the magnetic field, i.e. left to right and horizontal. If the negatively charged particle is travelling out of the screen, a positively charged particle would be moving in the opposite direction. Align your thumb so it is pointing into the screen, in the direction that a positive charge would tr[illegible]. Your palm should be facing downwards. That is the direction of the force applied by the magnetic field on the negative charge out of the screen.

Worked example: Try yourself 2.4.2

DIRECTION OF FORCE ON A NEGATIVELY CHARGED PARTICLE

A single, negatively charged particle with a charge of -1.6×10^{-19} C is travelling horizontally from left to right across a computer screen and perpendicular to a magnetic field, B, that runs vertically down the screen. In what direction will the force experienced by the charge act?

56 AREA OF STUDY 1 | HOW DO THINGS MOVE WITHOUT CONTACT?


PHYSICS IN ACTION

The current balance

A current balance can be used to determine the force on a conductor in a magnetic field, as shown in Figure 2.4.5.

FIGURE 2.4.5 A current balance is used to measure the interaction between an electric conductor and a magnetic field. The relationship between force, current and conductor length can be shown.

THE FORCE ON A CURRENT-CARRYING CONDUCTOR

Since a conducting wire is essentially a stream of charged particles flowing in one direction, it is not hard to imagine that a conductor carrying a stream of charges within a magnetic field will also experience a force. This is the theory behind the operation of electric motors that will be explained in the chapter 'Applications of fields'.

The current in a conductor is dependent on the rate at which charges are moving through the conductor; that is:

$I = \frac{Q}{t}$

where I is the current (A)

Q is the total charge (C)

t is the time taken (s).

For a 1 m length of conductor, the velocity of the charges through the conductor is:

$v = \frac{s}{t} = \frac{1}{t}$

And hence

$I = \frac{Q}{t} = Q \times \frac{1}{t} = Qv$

As $F = qvB$ for a single charge, q, moving perpendicular to a magnetic field, then:

$F = IB$ for a one metre conductor,

and for a conductor of any length, l, $F = IlB$

and for a conductor made up of n loops or conductors of length l:

$F = nIlB$

where F is the force on the conductor perpendicular to the magnetic fie[illegible] newtons (N)

n is the number of loops or conductors

I is the current in the conductor in amperes (A)

l is the length of the conductor in metres (m)

B is the strength of the magnetic field in tesla (T)

Just as for a single charge moving in a magnetic field, the force on the conductor is at a maximum when the conductor is at right angles to the field. The force is zero when the conductor is parallel to the magnetic field. The right-hand rule is used to determine the direction of the force.

PHYSICSFILE

Gravitational repulsive forces

A leading theory in the explanation of the expansion of the universe is the concept of dark energy. While little is understood about dark energy at this time, it may be a source of a repulsive force of gravity possi[illegible] originating from the interaction o[illegible] matter and antimatter.

CHAPTER 2 | ELECTRIC AND MAGNETIC FIELDS 57

Highlight

The highlight boxes provide important information such as key definitions, formulae and summary points.

PhysicsFile

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

Worked examples

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

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

The fully worked solution to each **Worked example: Try Yourself** is available on *Heinemann Physics 12 4th edition ProductLink*.

Chapter review

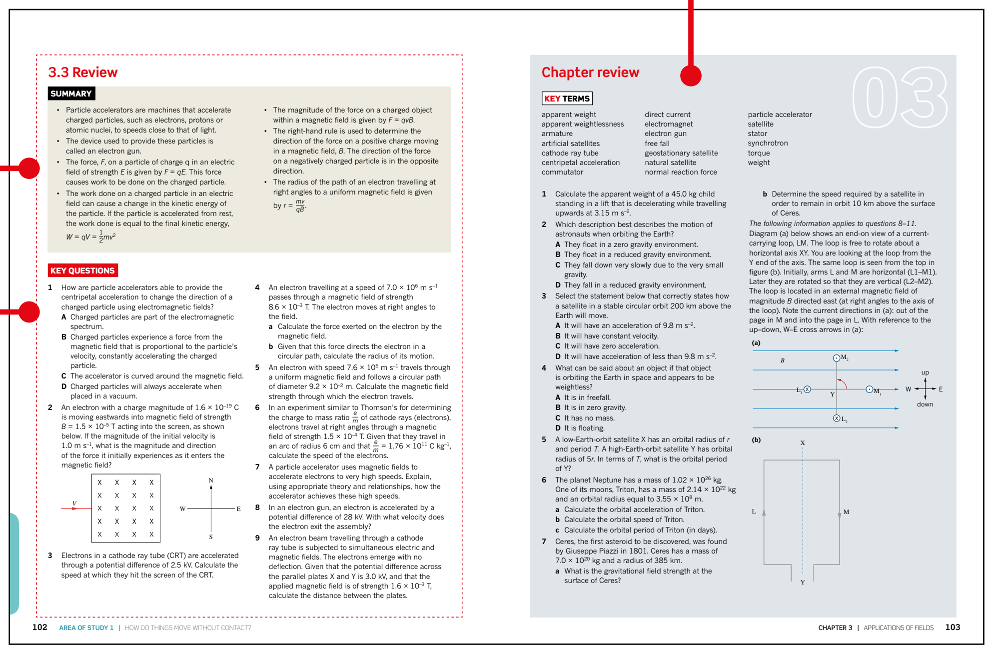
A set of higher order questions are provided at the end of each chapter to test students' ability to apply the knowledge gained from the chapter.

Section summary

A summary is provided at the end of each section to assist students consolidate key points and concepts.

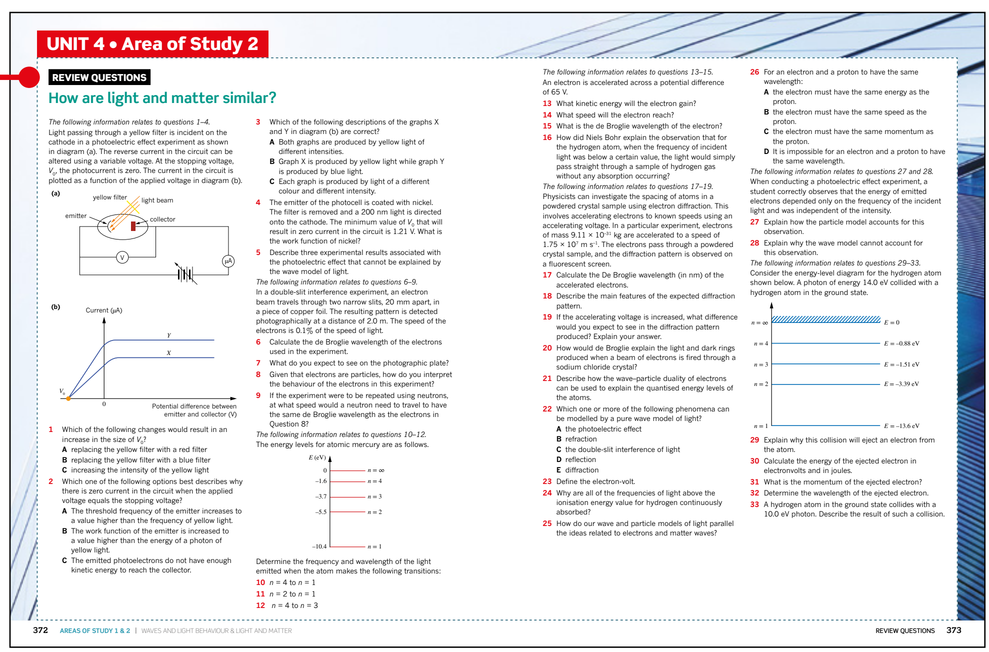
Section review

A set of 'key questions' are provided at the end of each section to test students' understanding and ability to recall the key concepts of the section as well as highlight areas that they need to revise.



Area of Study review

A comprehensive set of exam-style questions, including multiple choice and extended response are provided at the end of each Area of Study section. The questions are designed to assist students in to apply their knowledge and understanding across the entire Area of Study.



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, each Worked example: Try Yourself, chapter review questions and Area of Study review questions are provided via *Heinemann Physics 12 4th edition ProductLink.*

Glossary

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

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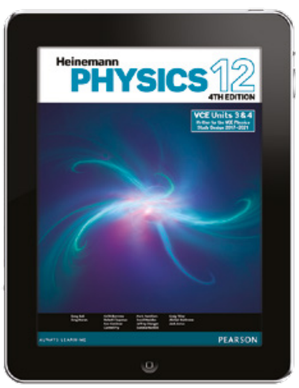
Student Book

Heinemann Physics 12 4th Edition has been written to fully align with the *2017–2021 VCE Physics Study Design*.



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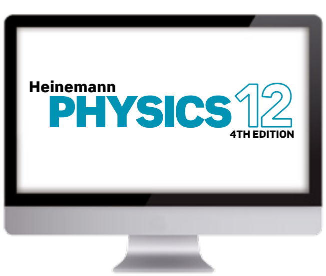

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UNIT 3 How do fields explain motion and electricity?

AREA OF STUDY 1

How do things move without contact?

Outcome 1: On completion of this unit the student should be able to analyse gravitational, electric and magnetic fields, and use these to explain the operation of motors and particle accelerators and the orbits of satellites.

AREA OF STUDY 2

How are fields used to move electrical energy?

Outcome 2: On completion of this unit the student should be able to analyse and evaluate an electricity generation and distribution system.

AREA OF STUDY 3

How fast can things go?

Outcome 3: On completion of this unit the student should be able to investigate motion and related energy transformations experimentally, analyse motion using Newton's laws of motion in one and two dimensions, and explain the motion of objects moving at very large speeds using Einstein's theory of special relativity.

CHAPTER

01 Gravity

Gravity is, quite literally, 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. 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 study in Physics.

Key knowledge

By the end of this chapter you will have studied the physics of gravity, and will be able to:

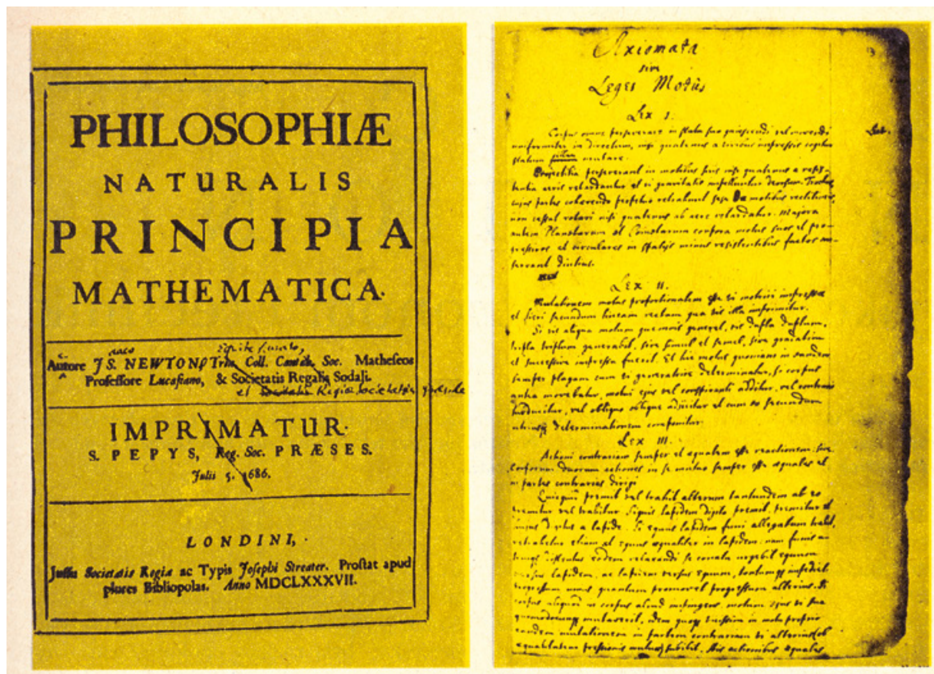
- describe gravitation using a field model
- investigate gravitational fields including directions and shapes of fields
- investigate gravitational fields about a point mass with reference to:
  - the direction of the field
  - the use of the inverse square law to determine the magnitude of the field
  - potential energy changes (qualitative) associated with a point mass moving in the field
- analyse the use of gravitational fields to accelerate mass, including
  - gravitational field and gravitational force concepts: $g = G\frac{M}{r^2}$ and $F_g = G\frac{m_1 m_2}{r^2}$
  - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
  - the change in gravitational potential energy from area under a force–distance graph and area under a field–distance graph multiplied by mass.

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.

In 1687, Sir Isaac Newton (see Figure 1.1.1) published a book that changed the world. Entitled *Philosophiæ Naturalis Prinicipia Mathematica* (Mathematical Principles of Natural Philosophy), Newton's book (shown in 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 scientifically explained the motion of the planets. This led to a change in humanity's understanding of its place in the universe.



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J. S. NEWTON, Trin. Coll. Cantab. Soc. Matheseos Professore Lucasiano, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, Reg. Soc. PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas. Anno MDCLXXXVII.

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

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.

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, 6.67×10^{-11} N m^2 kg^{-2}

The fact that r appears in the denominator of Newton's law of universal gravitation 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.

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** (shown in 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.

As its name suggests, 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 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.	$F_g = G\frac{m_1 m_2}{r^2}$
Identify the information required, and convert values into appropriate units when necessary.	$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2} $m_1 = 90$ kg $m_2 = 75$ kg $r = 80$ cm $= 0.80$ m
Substitute the values into the equation.	$F_g = 6.67 \times 10^{-11} \times \frac{90 \times 75}{0.80^2}$
Solve the equation.	$F_g = 7.0 \times 10^{-7}$ 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 to be negligible.

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

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

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:

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

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

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

Thinking	Working
Recall the formula for Newton's law of universal gravitation.	$F_g = G\frac{m_1 m_2}{r^2}$
Identify the information required.	$G = 6.67 \times 10^{-11}$ N m² kg⁻² $m_1 = 2.0 \times 10^{30}$ kg $m_2 = 6.0 \times 10^{24}$ kg $r = 1.5 \times 10^{11}$ m
Substitute the values into the equation.	$F_g = 6.67 \times 10^{-11} \times \frac{2.0 \times 10^{30} \times 6.0 \times 10^{24}}{(1.5 \times 10^{11})^2}$
Solve the equation.	$F_g = 3.6 \times 10^{22}$ 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:

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

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

$r_{Moon–Earth} = 3.8 \times 10^{8}$ m

The forces in Worked example 1.1.2 are much greater than those in Worked example 1.1.1, illustrating the difference in the gravitational force when at least one of the objects has a very large mass.

EXTENSION

Understanding the structure of the universe

In the century before Newton, there had been some controversy about the structure of the universe. In 1543, the commonly accepted geocentric (i.e. Earth-centred) model of the universe had been challenged by a Polish astronomer called Nicolaus Copernicus. He proposed that the Sun was the centre of the universe. 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.

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

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

Through these calculations, Kepler discovered that the orbit of the planets around the Sun was elliptical and not circular as previously thought (see 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.

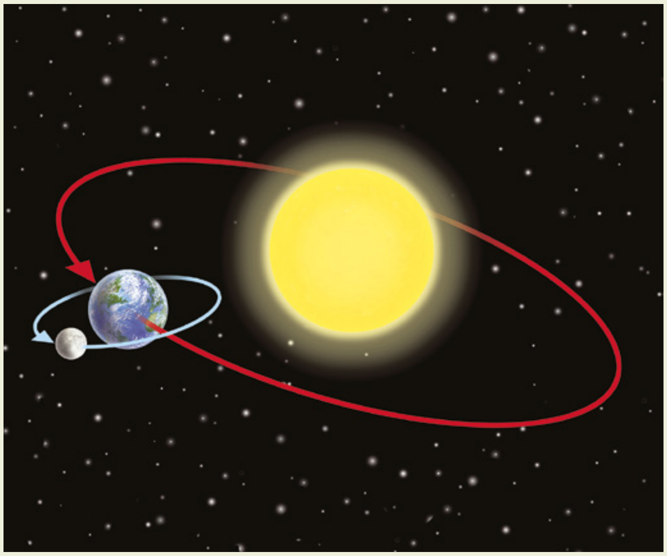


FIGURE 1.1.6 Johannes Kepler discovered that the orbit of planets around the Sun was elliptical.

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 had largely been abandoned in favour of the heliocentric model.

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.

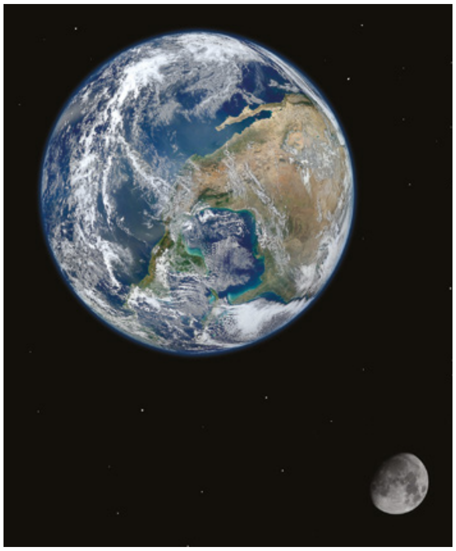


FIGURE 1.1.7 The Earth and Moon exert gravitational forces on each other.

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.	$a_{Earth} = \frac{2.0 \times 10^{20}}{6.0 \times 10^{24}} = 3.3 \times 10^{-5}$ m s^{-2} $a_{Moon} = \frac{2.0 \times 10^{20}}{7.3 \times 10^{22}} = 2.7 \times 10^{-3}$ 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

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 (i.e. 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.

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 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 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.

WEIGHT AND GRAVITATIONAL FORCE

In Unit 2 Physics the **weight** of an object was calculated using the formula $W = F_g = mg$. 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 $F_g = mg$ 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 $F_g = mg$ 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:
$g = 9.8 \text{ m s}^{-2}$
$m_{Earth} = 6.0 \times 10^{24}$ kg
$r_{Earth} = 6.4 \times 10^6$ m

Thinking	Working
Apply the weight equation.	$F_g = mg$ $= 80 \times 9.8$ $= 784$ N $= 780$ N (to two significant figures)
Apply Newton's law of universal gravitation.	$F_g = G\frac{m_1 m_2}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{6.0 \times 10^{24} \times 80}{(6.4 \times 10^6)^2}$ $= 780$ N
Compare the two values.	Both 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 formulas $F_g = mg$ and $F_g = G\frac{m_1 m_2}{r^2}$. Use the following dimensions of the Earth where necessary:
$g = 9.8 \text{ m s}^{-2}$
$m_{Earth} = 6.0 \times 10^{24}$ kg
$r_{Earth} = 6.4 \times 10^6$ 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:

$$\text{Weight} = F_g$$

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

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

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

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

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

So, 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 therefore 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 is why the strength of the Earth's gravity reduces as you travel away from the Earth.

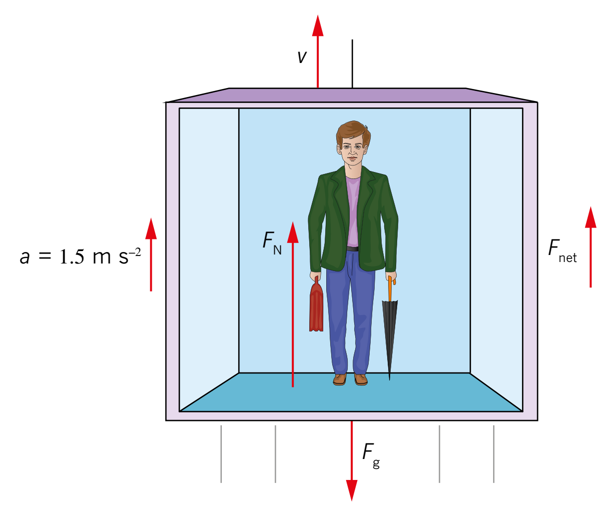
APPARENT WEIGHT

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 this is the force that the person will feel through their feet.

Worked example 1.1.5

APPARENT WEIGHT

A 74 kg person is standing in an elevator which is accelerating upwards at 1.5 m s^{-2}. Calculate the weight and apparent weight of the person. Use g = 9.8 m s^{-2}.



Thinking	Working
Calculate the weight of the person using $F_g = mg$.	$F_g = mg = 74 \times 9.8 = 725$ N
Calculate the force required to accelerate the person upwards at 1.5 m s^{-2}.	$F_{net} = ma = 74 \times 1.5 = 111$ N
The net force that causes the acceleration results from the normal reaction force (upwards) and the weight force (downwards). Since the elevator is accelerating upwards, $F_N > F_g$. Recall that the normal reaction force gives the apparent weight.	$F_{net} = 111$ $F_N - F_g = 111$ $F_N - 725 = 111$ $F_N = 725 + 111$ F_N = apparent weight = 836 N

Worked example: Try yourself 1.1.5

APPARENT WEIGHT

Calculate the apparent weight of a 90 kg person in an elevator which is accelerating downwards at 0.8 m s^{-2}. Use g = 9.8 m 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, 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 (see Figure 1.1.8).

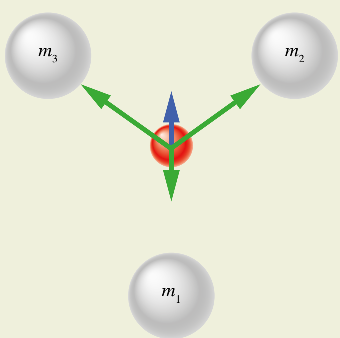


FIGURE 1.1.8 For the three masses $m_1 = m_2 = m_3$, the gravitational forces acting on the central red ball are shown by the green arrows. The vector sum of the green arrows is shown by the blue arrow. This will be the direction of the net (or resultant) gravitational force on the red ball due to the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

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

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_g.
- The acceleration due to gravity of an object near the Earth's surface can be calculated using the dimensions of the Earth:

  $g = G\frac{m_{Earth}}{(r_{Earth})^2} = 9.8 \text{ m s}^{-2}$
- Objects can have an apparent weight that is greater or less than their normal weight. This occurs when they are accelerating vertically.

KEY QUESTIONS

1 What are the proportionalities in Newton's law of universal gravitation?

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:
$m_{Sun} = 2.0 \times 10^{30}$ kg
$m_{Mars} = 6.4 \times 10^{23}$ kg
$r_{Sun–Mars} = 2.2 \times 10^{11}$ 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 $m_{Mars} = 6.4 \times 10^{23}$ 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.
$m_{Sun} = 2.0 \times 10^{30}$ kg
$m_{Earth} = 6.0 \times 10^{24}$ kg
$m_{Mars} = 6.4 \times 10^{23}$ 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 m s^{-2}
- **b** moving upwards at a constant speed of 5 m s^{-1}

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.

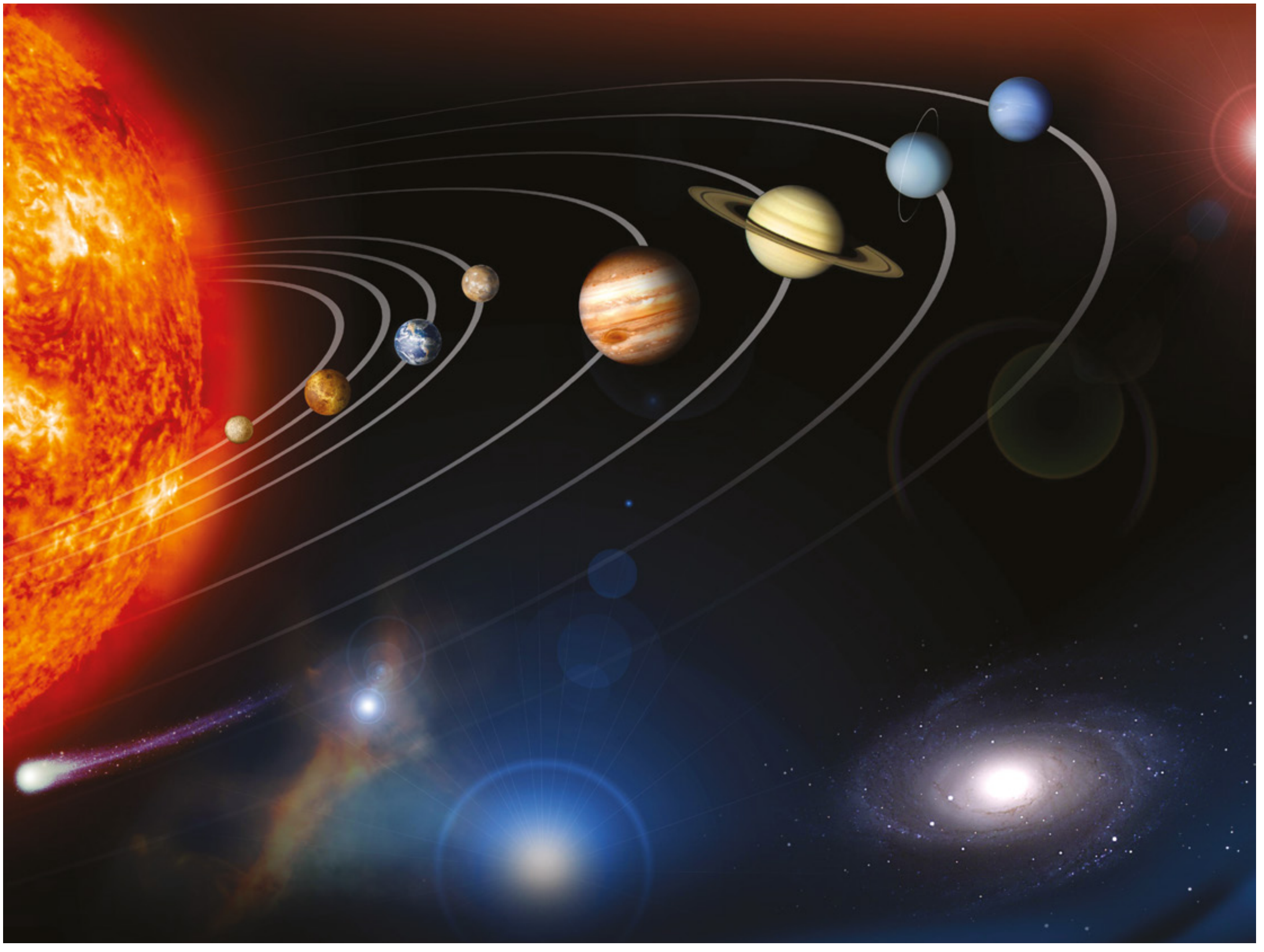


FIGURE 1.2.1 The solar system is a complex gravitational system.

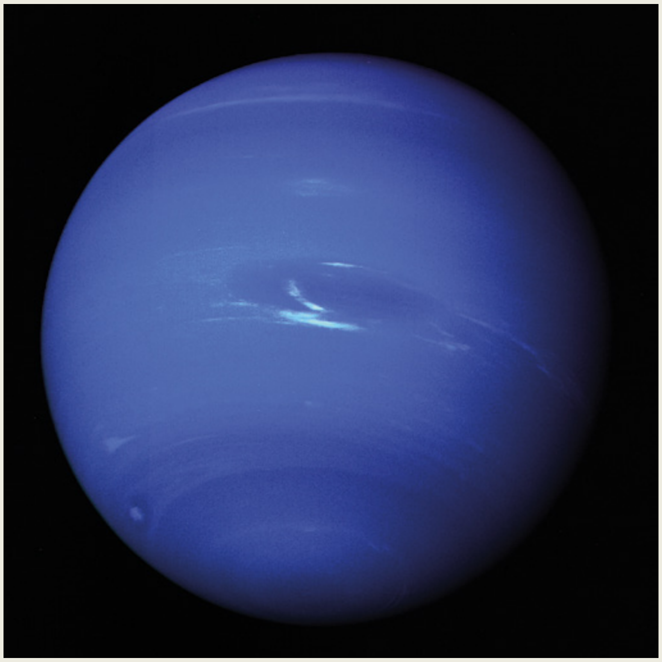
GRAVITATIONAL FIELDS

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 like 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.

PHYSICS IN ACTION

Discovery of Neptune



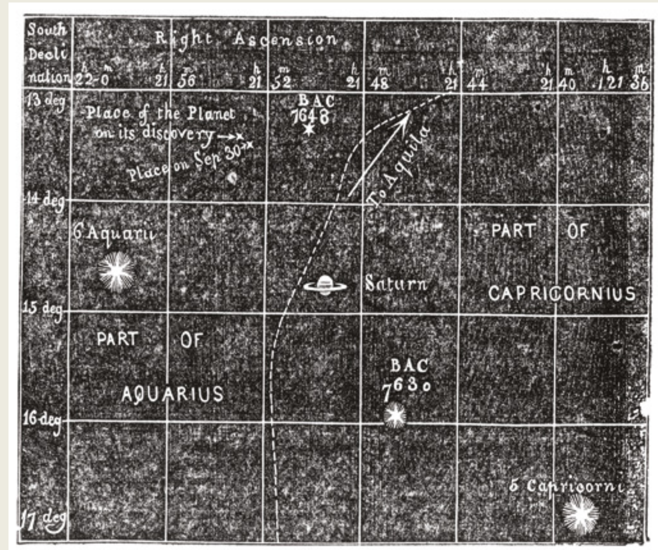


FIGURE 1.2.2 This star chart published in 1846 shows the location of Neptune in the constellation Aquarius when it was discovered on 23 September, and its location one week later.

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 (see Figure 1.2.2).

Representing gravitational fields

Over time, scientists have developed a commonly understood method of representing fields using a series of arrows known as field lines (see 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 arrows indicates the relative magnitude of the field:
  - closely spaced arrows indicate a strong field
  - widely spaced arrows 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.

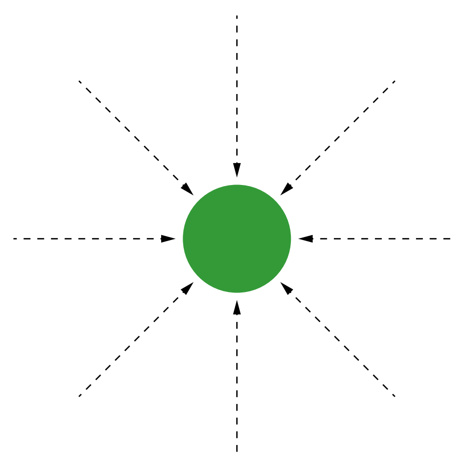
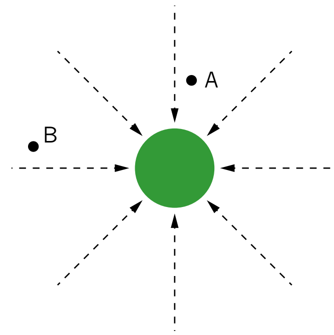


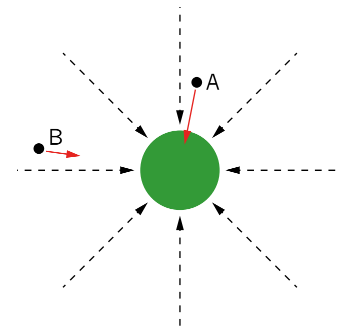
FIGURE 1.2.3 The arrows in this gravitational field diagram indicate that objects will be attracted towards the mass in the centre; the spacing of the lines shows that force will be strongest at the surface of the central mass and weaker further away from it.

Worked example 1.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a moon.



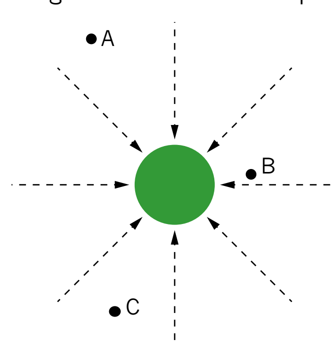
a Use arrows to indicate the direction of the gravitational force acting at points A and B.	
Thinking	**Working**
The direction of the field arrows indicates the direction of the gravitational force, which is inwards towards the centre of the moon.	

b Indicate 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 direction of the gravitational force acting at points A, B and C.

b Indicate 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 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:

$$g = G\frac{m_{\text{Earth}}}{(r_{\text{Earth}})^2} = 9.8 \text{ m s}^{-2}$$

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 N kg^{-1} rather than m s^{-2}. This means $g_{\text{Earth}} = 9.8$ N kg^{-1}.

These units indicate that objects on the surface of the Earth experience 9.8 N of gravitational force for every kilogram of their mass.

Accordingly, the familiar equation $F_g = mg$ can be transposed so that the **gravitational field strength**, g, can be calculated:

$$g = \frac{F_g}{m}$$

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

F_g is the force due to gravity (N)

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

PHYSICS FILE

N kg^{-1} = m s^{-2}

It is a simple matter to show that N kg^{-1} and m s^{-2} are equivalent units.

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

1 N = 1 kg m s^{-2}

∴ 1 N kg^{-1} = 1 kg m s^{-2} × kg^{-1}

= 1 m s^{-2}

Worked example 1.2.2

CALCULATING GRAVITATIONAL FIELD STRENGTH

When a student hangs a 1 kg mass from a spring balance, the balance measures a downwards force of 9.8 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.	$g = \frac{F_g}{m}$
Substitute in the appropriate values.	$g = \frac{9.8}{1}$
Solve the equation.	$g = 9.8$ 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.

The formula for gravitational field strength, $g = \frac{F_g}{m}$, can be combined with Newton's law of universal gravitation, $F_g = G\frac{Mm}{r^2}$, to develop the formula for gravitational field strength:

$$g = \frac{F_g}{m} = \frac{\left(G\frac{Mm}{r^2}\right)}{m}$$

Therefore:

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

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

G is the gravitational constant, 6.67×10^{-11} N m^2 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)

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.

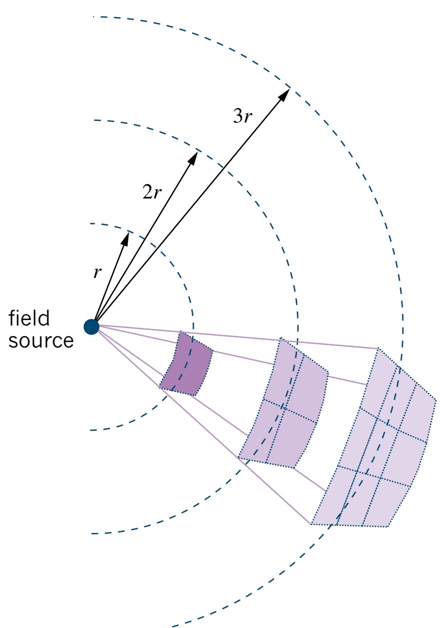


FIGURE 1.2.4 As the distance from the source of a field increases, the field is spread over an area that increases with the square of the distance from the source, resulting in the strength of the field decreasing by the same ratio.

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

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

where F is the force and 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 magnets 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 N kg^{-1}. However, the field strength experienced by objects on the surface of the Earth can actually vary between 9.76 N kg^{-1} and 9.83 N kg^{-1}, depending on the location.

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.

Geological formations can also create differences in gravitational field strength, depending on their composition. Geologists use a sensitive instrument known as a **gravimeter** (see Figure 1.2.6) 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 1.2.6 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 (see Figure 1.2.7).

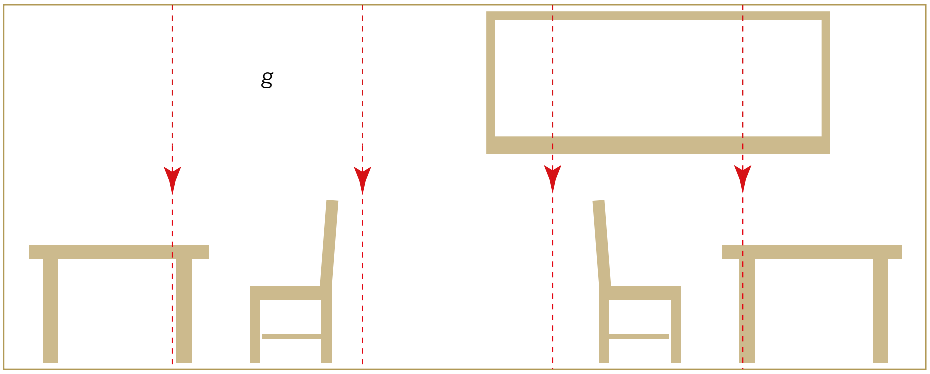


FIGURE 1.2.7 The uniform gravitational field, g, is represented by evenly spaced parallel lines in the direction of the force.

PHYSICSFILE

The shape of the Earth

The shape of the Earth is known as an oblate spheroid (see Figure 1.2.5). 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.

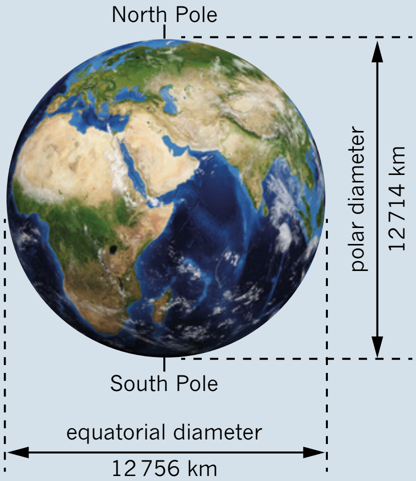


FIGURE 1.2.5 The Earth is a flattened sphere, which means its gravitational field is slightly stronger at the poles.

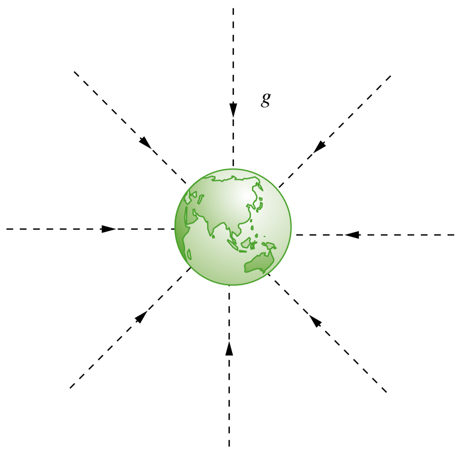


FIGURE 1.2.8 The Earth's gravitational field becomes progressively weaker out into space.

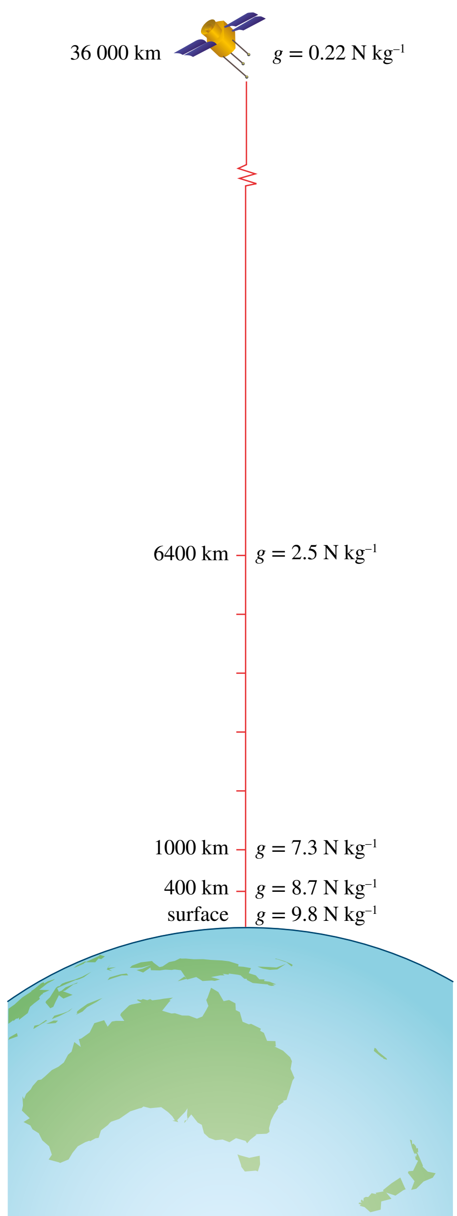


FIGURE 1.2.9 The Earth's gravitational field strength is weaker at higher altitudes.

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 (see Figure 1.2.8). 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:

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

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 (see Figures 1.2.9 and 1.2.10).

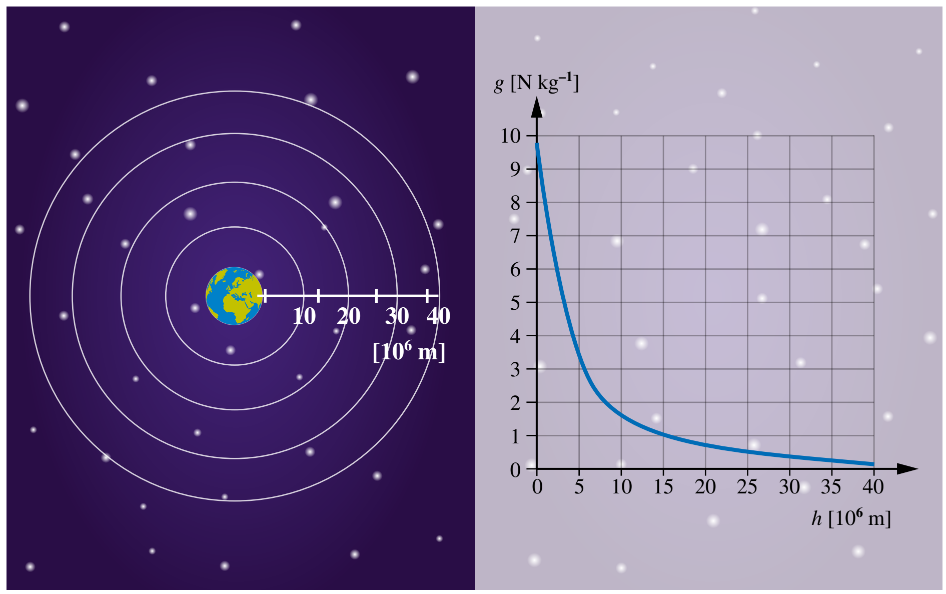


FIGURE 1.2.10 As the distance from the surface of the Earth is increased from 0 to 40 × 10^6 m, the value for g decreases rapidly from 9.8 N kg^{-1}, according to the inverse square law. The blue line on the graph gives the value of g at various altitudes (h).

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

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.	$g = G\frac{M}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{5.97 \times 10^{24}}{(6.389 \times 10^6)^2}$ $= 9.76$ 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

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

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 the Earth's.

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 (see Figure 1.2.11).

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. 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 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 formulas:
  $g = \frac{F_g}{m}$ or $g = G\frac{M}{r^2}$
  The gravitational field strength on the Earth's surface is approximately 9.8 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 Give the most appropriate unit for measuring gravitational field strength.

2 A group of 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 400 km from the centre of a planet. The distance from the centre of the planet is then increased to 1200 km. What would the ratio of the magnitude of the gravitational field be at this new distance compared to the 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 × 10^{24} kg

	Type of orbit	Altitude (km)
a	low Earth orbit	2000
b	medium Earth orbit	10000
c	semi-synchronous orbit	20200
d	geosynchronous orbit	35786

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.

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}

Calculate the gravitational field strength, g, at the surface of each planet.

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?