

Heinemann

PHYSICS 12

4TH EDITION

VCE Units 3 & 4

Written for the VCE Physics
Study Design 2017–2021

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Heinemann
PHYSICS **12**
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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.

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.

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 deflected. 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 particle work?

Thinking Working

(Fingers) field B (thumb) force F (positive charge)



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 be moving. Your palm should be facing down towards the screen. 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?



Chapter opener

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

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.

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 l m length of conductor, the velocity of the charges through the conductor is:

$$v = \frac{l}{t}$$

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,

$$F = IB$$

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 field, 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 is 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 originating from the interaction of matter and antimatter.

Highlight **i**

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

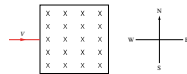
A set of 'key questions' are provided at the end of each section to test students' understanding and ability to recall the key concepts of the section as well as highlight areas that they need to revise.

3.3 Review

SUMMARY

- Particle accelerators are machines that accelerate charged particles, such as electrons, protons or atomic nuclei, to speeds close to that of light. The device used to provide these particles is called an electron gun.
- The force, F , on a particle of charge q in an electric field of strength E is given by $F = qE$. This force causes work to be done on the charged particle. The work done on a charged particle in an electric field can cause a change in the kinetic energy of the particle. If the particle is accelerated from rest, the work done is equal to the final kinetic energy, $W = qV = \frac{1}{2}mv^2$.
- The magnitude of the force on a charged object within a magnetic field is given by $F = qvB \sin \theta$.
- The right-hand rule is used to determine the direction of the force on a positive charge moving in a magnetic field. The direction of the force on a negatively charged particle is in the opposite direction.
- The radius of the path of an electron travelling at right angles to a uniform magnetic field is given by $r = \frac{mv}{qB}$.

KEY QUESTIONS

- How are particle accelerators able to provide the centripetal acceleration to change the direction of a charged particle using electromagnetic fields?
 - Charged particles are part of the electromagnetic spectrum.
 - Charged particles experience a force from the magnetic field that is proportional to the particle's velocity, constantly accelerating the charged particle.
 - The accelerator is curved around the magnetic field.
 - Charged particles will always accelerate when placed in a vacuum.
- An electron with a charge magnitude of 1.6×10^{19} C is moving eastwards into a magnetic field of strength $B = 1.5 \times 10^{-4}$ T acting into the screen, as shown below. If the magnitude of the initial velocity is 1.0 m s^{-1} , what is the magnitude and direction of the force it initially experiences as it enters the magnetic field?
 
- Electrons in a cathode ray tube (CRT) are accelerated through a potential difference of 25 kV. Calculate the speed at which they hit the screen of the CRT.
- An electron travelling at a speed of $7.0 \times 10^6 \text{ m s}^{-1}$ passes through a magnetic field of strength 8.6×10^{-2} T. The electron moves at right angles to the field.
 - Calculate the force exerted on the electron by the magnetic field.
 - Given that this force directs the electron in a circular path, calculate the radius of its motion.
- An electron with speed $7.6 \times 10^6 \text{ m s}^{-1}$ travels through a uniform magnetic field and follows a circular path of diameter 9.2×10^{-2} m. Calculate the magnetic field strength through which the electron travels.
- In an experiment similar to Thomson's for determining the charge to mass ratio $\frac{e}{m}$ of cathode rays (electrons), electrons travel at right angles through a magnetic field of strength 1.5×10^{-4} T. Given that they travel in an arc of radius 6 cm and that $\frac{e}{m} = 1.76 \times 10^{11} \text{ C kg}^{-1}$, calculate the speed of the electron.
- A particle accelerator uses magnetic fields to accelerate electrons to very high speeds. Explain, using appropriate theory and relationships, how the accelerator achieves these high speeds.
- In an electron gun, an electron is accelerated by a potential difference of 28 kV. With what velocity does the electron exit the assembly?
 - An electron beam travelling through a cathode ray tube is subjected to simultaneous electric and magnetic fields. The electrons emerge with no deflection. Given that the potential difference across the parallel plates X and Y is 3.0 kV and that the applied magnetic field is of strength 1.6×10^{-2} T, calculate the distance between the plates.

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

Chapter review

KEY TERMS

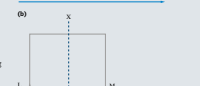
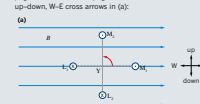
- apparent weight
- artificial satellites
- centrifugal acceleration
- commutator
- direct current electromagnet
- electron gun
- fall full
- geostationary satellite
- natural satellite
- normal reaction force

- Calculate the apparent weight of a 45.0 kg child standing in a lift that is accelerating while travelling upwards at 1.5 m s^{-2} .
- Which description best describes the motion of astronauts when orbiting the Earth?
 - They float in a zero gravity environment.
 - They float in a reduced gravity environment.
 - They fall down very slowly due to the very small gravity.
 - They fall in a reduced gravity environment.

- Select the statement below that correctly states how a satellite in a stable circular orbit 200 km above the Earth will move.
 - It will have an acceleration of 9.8 m s^{-2} .
 - It will have constant velocity.
 - It will have acceleration of less than 9.8 m s^{-2} .
- What can be said about an object if that object is orbiting the Earth in space and appears to be weightless?
 - It is in free fall.
 - It is in zero gravity.
 - It has no mass.
 - It is floating.
- A low-Earth-orbit satellite X has an orbital radius of r and period T . A high-Earth-orbit satellite Y has orbital radius of $5r$. In terms of T , what is the orbital period of Y?
 - $5T$
 - $25T$
 - $125T$
 - $625T$
- The planet Neptune has a mass of 1.02×10^{26} kg. One of its moons, Triton, has a mass of 2.14×10^{22} kg and an orbital radius equal to 3.55×10^8 m.
 - Calculate the orbital acceleration of Triton.
 - Calculate the orbital speed of Triton.
 - Calculate the orbital period of Triton (in days).
- Ceres, the first asteroid to be discovered, was found by Giuseppe Piazzi in 1801. Ceres has a mass of 7.0×10^{22} kg and a radius of 385 km.
 - What is the gravitational field strength at the surface of Ceres?

- Determine the speed required by a satellite in order to remain in orbit 10 km above the surface of Ceres.

The following information applies to questions 8–11. Diagram (a) below shows an end-on view of a current-carrying loop, LM. The loop is free to rotate about a horizontal axis XY. You are looking at the loop from the Y end of the axis. The same loop is seen from the top in figure (b). Initially, arms L and M are horizontal (L1–M1). Later they are rotated so that they are vertical (L2–M2). The loop is located in an external magnetic field of magnitude B directed east (at right angles to the axis of the loop). Note the current directions in (a); out of the page in M and into the page in L. With reference to the up-down, W-E cross arrows in (a):



- Calculate the torque on the loop when the arms are horizontal.
- Calculate the torque on the loop when the arms are vertical.
- Calculate the work done in rotating the loop from horizontal to vertical.
- Calculate the average force exerted on the loop when the arms are vertical.

CHAPTER 3 | APPLICATIONS OF FIELDS 103

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.

UNIT 4 • Area of Study 2

REVIEW QUESTIONS

How are light and matter similar?

- The following information relates to questions 1–4. Light passing through a yellow filter is incident on the cathode in a photoelectric effect experiment as shown in diagram (a). The reverse current in the circuit can be altered using a variable voltage. At the stopping voltage, V_s , the photocurrent is zero. The current in the circuit is plotted as a function of the applied voltage in diagram (b).
-
-
- Which of the following changes would result in an increase in the size of V_s ?
 - replacing the yellow filter with a red filter
 - replacing the yellow filter with a blue filter
 - increasing the intensity of the yellow light
 - Which one of the following options best describes why there is zero current in the circuit when the applied voltage equals the stopping voltage?
 - The threshold frequency of the emitter increases to a value higher than the frequency of yellow light.
 - The work function of the emitter is increased to a value higher than the energy of a photon of yellow light.
 - The emitted photoelectrons do not have enough kinetic energy to reach the collector.
 - Which of the following descriptions of the graphs X and Y in diagram (b) are correct?
 - Both graphs are produced by yellow light of different intensities.
 - Graph X is produced by yellow light while graph Y is produced by blue light.
 - Each graph is produced by light of a different colour and different intensity.
 - The emitter of the photocell is coated with nickel. The filter is removed and a 200 nm light is directed onto the cathode. The minimum value of V_s that will result in zero current in the circuit is 1.21 V. What is the work function of nickel?
 - Describe three experimental results associated with the photoelectric effect that cannot be explained by the wave model of light.
- The following information relates to questions 5–6. In a double-slit interference experiment, an electron beam travels through two narrow slits, 20 nm apart, in a piece of copper foil. The resulting pattern is detected photographically at a distance of 2.0 m. The speed of the electrons is 0.1% of the speed of light.
- Calculate the de Broglie wavelength of the electrons used in the experiment.
 - What do you expect to see on the photographic plate?
 - Given that electrons are particles, how do you interpret the behaviour of the electrons in this experiment?
 - If the experiment were to be repeated using neutrons, at what speed would a neutron need to travel to have the same de Broglie wavelength as the electrons in Question 5f?
 - The following information relates to questions 7–12. The energy levels for atomic mercury are as follows.
-
- Determine the frequency and wavelength of the light emitted when the atom makes the following transitions:
- $n = 4$ to $n = 1$
 - $n = 2$ to $n = 1$
 - $n = 4$ to $n = 3$

372 AREAS OF STUDY 1 & 2 | WAVES AND LIGHT BEHAVIOUR OF LIGHT AND MATTER

The following information relates to questions 13–15.

- An electron is accelerated across a potential difference of 65 V.
- What kinetic energy will the electron gain?
 - What speed will the electron reach?
 - What is the de Broglie wavelength of the electron?
- How did Niels Bohr explain the observation that for the hydrogen atom, when the frequency of incident light was below a certain value, the light would simply pass through a sample of hydrogen gas without any absorption occurring?
- The following information relates to questions 17–19. Physicists can investigate the spacing of atoms in a powdered crystal sample using electron diffraction. This involves accelerating electrons to known speeds using an accelerating voltage. In a particular experiment, electrons of mass 9.11×10^{-31} kg are accelerated to a speed of $1.75 \times 10^7 \text{ m s}^{-1}$. The electrons pass through a powdered crystal sample, and the diffraction pattern is observed on a fluorescent screen.
- Calculate the de Broglie wavelength (in nm) of the accelerated electrons.
 - Describe the main features of the expected diffraction pattern.
 - If the accelerating voltage is increased, what difference would you expect to see in the diffraction pattern produced? Explain your answer.
 - How would de Broglie explain the light and dark rings produced when a beam of electrons is fired through a sodium chloride crystal?
 - Describe how the wave-particle duality of electrons can be used to explain the quantised energy levels of the atoms.
 - Which one or more of the following phenomena can be modelled by a pure wave model of light?
 - the photoelectric effect
 - reflection
 - the double-slit interference of light
 - Define the electron-volt.
 - Why are all of the frequencies of light above the Lyman series energy value for hydrogen continuously absorbed?
 - How do our wave and particle models of light parallel the ideas related to electrons and matter waves?

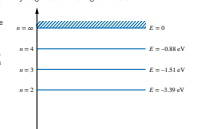
- For an electron and a proton to have the same wavelength:
 - the electron must have the same energy as the proton.
 - the electron must have the same speed as the proton.
 - the electron must have the same momentum as the proton.
 - it is impossible for an electron and a proton to have the same wavelength.

The following information relates to questions 27 and 28. When conducting a photoelectric effect experiment, a student correctly observes that the energy of emitted electrons depended only on the frequency of the incident light and was independent of the intensity.

27 Explain why the wave model cannot account for this observation.

28 Explain why the photon model can account for this observation.

The following information relates to questions 29–32. Consider the energy level diagram for the hydrogen atom shown below. A photon of energy 14.0 eV collides with a hydrogen atom in the ground state.



- Explain why this collision will eject an electron from the atom.
- Calculate the energy of the ejected electron in electronvolts and in joules.
- What is the momentum of the ejected electron?
- Determine the wavelength of the ejected electron.
- A hydrogen atom in the ground state collides with a 10.0 eV photon. Describe the result of such a collision.

REVIEW QUESTIONS 373

Answers

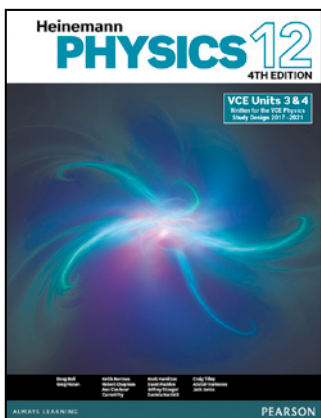
Numerical answers and key short response answers are included at the back of the book. Comprehensive answers and fully worked solutions for all section review questions, each Worked example: Try Yourself, chapter review questions and Area of Study review questions are provided via *Heinemann Physics 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.

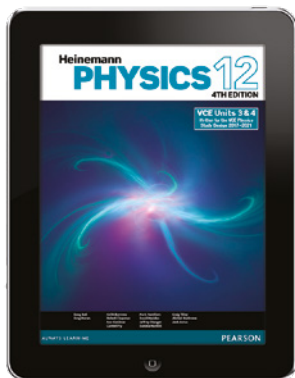
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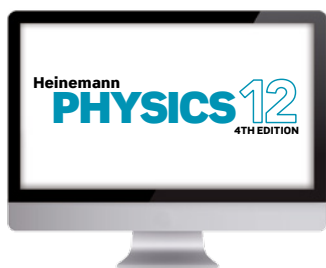
Student Book

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



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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 nebulae, 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 $F_g = G\frac{m_1m_2}{r^2}$
 - 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 Principia 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.

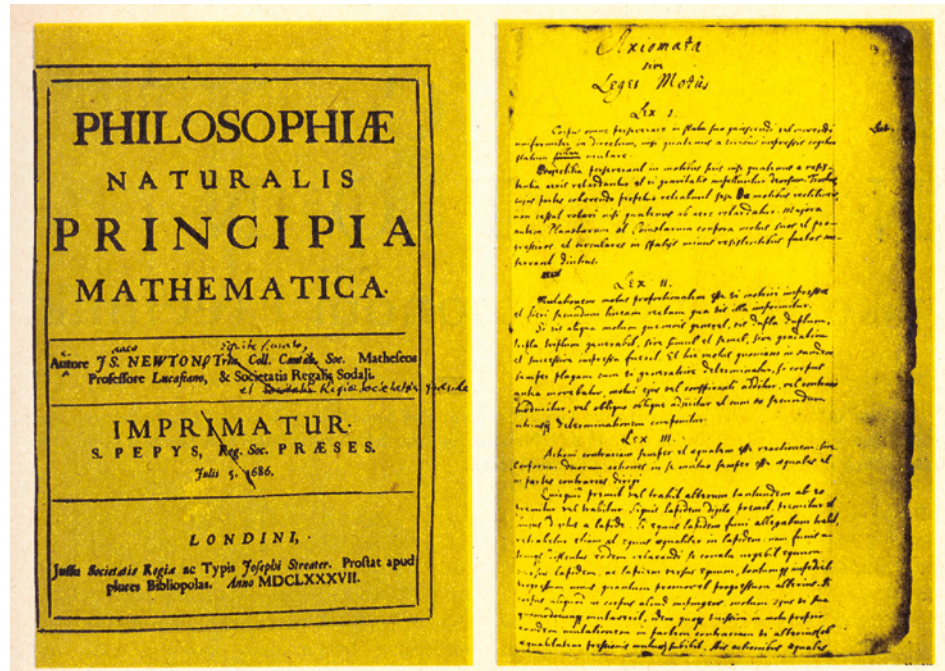


FIGURE 1.1.2 The *Principia* is one of the most influential books in the history of science.

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.

i 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, $6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$

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 $1 \mu\text{N}$ (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.	$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$ $m_1 = 90 \text{ kg}$ $m_2 = 75 \text{ kg}$ $r = 80 \text{ cm} = 0.80 \text{ m}$
Substitute the values into the equation.	$F_g = 6.67 \times 10^{-11} \times \frac{90 \times 75}{0.80^2}$
Solve the equation.	$F_g = 7.0 \times 10^{-7} \text{ N}$

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:

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

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

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

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.	$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$ $m_1 = 2.0 \times 10^{30} \text{ kg}$ $m_2 = 6.0 \times 10^{24} \text{ kg}$ $r = 1.5 \times 10^{11} \text{ m}$
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.	$F_g = 3.6 \times 10^{22} \text{ N}$

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:

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

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

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

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.

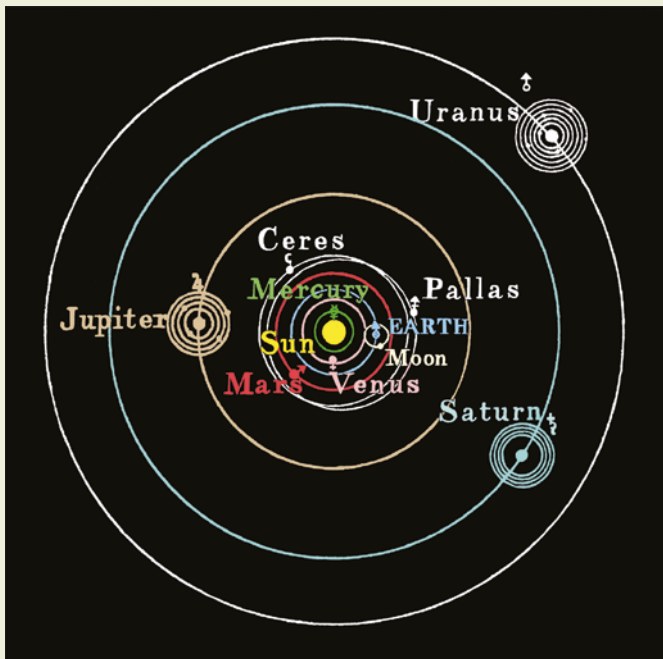


FIGURE 1.1.5 Nicolaus Copernicus' proposed heliocentric model of the solar system.

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.

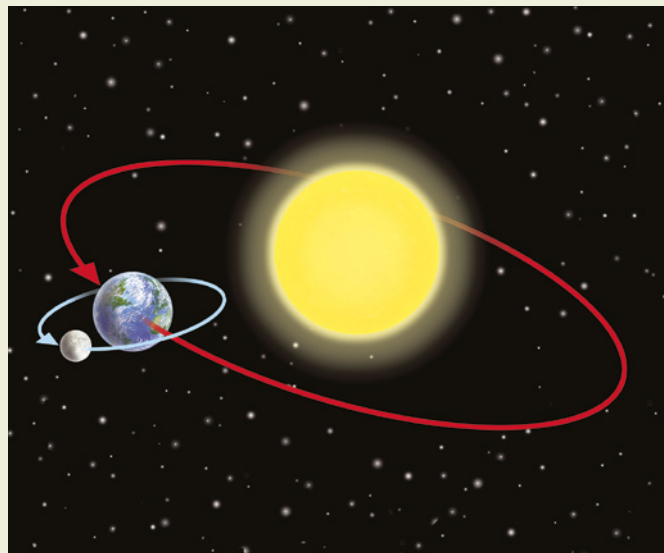


FIGURE 1.1.6 Johannes Kepler discovered that the orbit of planets around the Sun was elliptical.

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.

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 $\frac{a_{\text{Moon}}}{a_{\text{Earth}}}$. Use the following data:

$m_{\text{Earth}} = 6.0 \times 10^{24}$ kg
 $m_{\text{Moon}} = 7.3 \times 10^{22}$ 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.	$a_{\text{Earth}} = \frac{2.0 \times 10^{20}}{6.0 \times 10^{24}} = 3.3 \times 10^{-5} \text{ m s}^{-2}$ $a_{\text{Moon}} = \frac{2.0 \times 10^{20}}{7.3 \times 10^{22}} = 2.7 \times 10^{-3} \text{ m s}^{-2}$
Compare the two accelerations.	$\frac{a_{\text{Moon}}}{a_{\text{Earth}}} = \frac{2.7 \times 10^{-3}}{3.3 \times 10^{-5}} = 82$ <p>The acceleration of the Moon is 82 times greater than the acceleration of the Earth.</p>

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 $\frac{a_{\text{Earth}}}{a_{\text{Sun}}}$. Use the following data:

$m_{\text{Earth}} = 6.0 \times 10^{24}$ kg
 $m_{\text{Sun}} = 2.0 \times 10^{30}$ 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 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.



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

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.

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

<p>Compare the weight of an 80 kg person calculated using $F_g = mg$ with the gravitational force calculated using $F_g = G\frac{m_1m_2}{r^2}$.</p> <p>Use the following dimensions of the Earth in your calculations:</p> <p>$g = 9.8 \text{ m s}^{-2}$</p> <p>$m_{\text{Earth}} = 6.0 \times 10^{24} \text{ kg}$</p> <p>$r_{\text{Earth}} = 6.4 \times 10^6 \text{ m}$</p>	
Thinking	Working
Apply the weight equation.	$F_g = mg$ $= 80 \times 9.8$ $= 784 \text{ N}$ $= 780 \text{ N (to two significant figures)}$
Apply Newton's law of universal gravitation.	$F_g = G\frac{m_1m_2}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{6.0 \times 10^{24} \times 80}{(6.4 \times 10^6)^2}$ $= 780 \text{ N}$
Compare the two values.	Both equations give the same result to two significant figures.

Worked example: Try yourself 1.1.4

GRAVITATIONAL FORCE AND WEIGHT

<p>Compare the weight of a 1.0 kg mass on the Earth's surface calculated using the formulas $F_g = mg$ and $F_g = G\frac{m_1m_2}{r^2}$. Use the following dimensions of the Earth where necessary:</p> <p>$g = 9.8 \text{ m s}^{-2}$</p> <p>$m_{\text{Earth}} = 6.0 \times 10^{24} \text{ kg}$</p> <p>$r_{\text{Earth}} = 6.4 \times 10^6 \text{ m}$</p>

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 $6.4 \times 10^6 \text{ m}$ from the centre of the Earth.

Given that the Earth has a mass of $6.0 \times 10^{24} \text{ kg}$, then:

$$\text{Weight} = F_g$$

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

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

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

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

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

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).

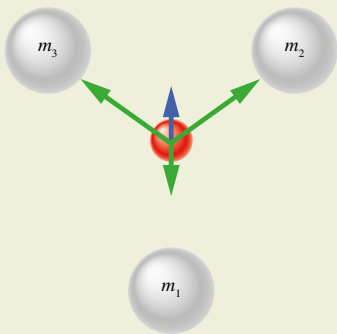


FIGURE 1.1.8 For the three masses $m_1 = m_2 = m_3$, the gravitational forces acting on the central red ball are shown by the green arrows. The vector sum of the green arrows is shown by the blue arrow. This will be the direction of the net (or resultant) gravitational force on the red ball due to the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

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.

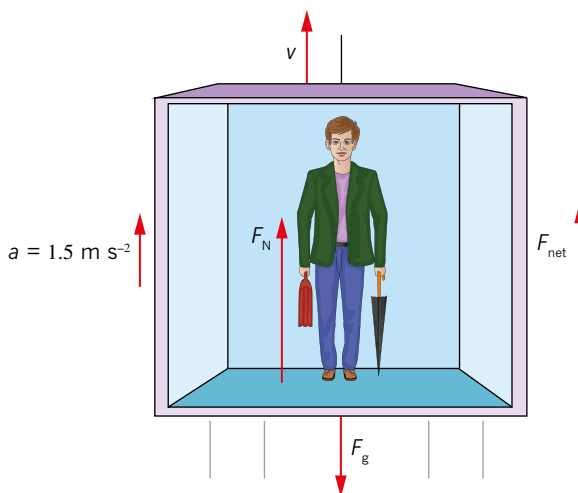
APPARENT WEIGHT

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



Thinking

Calculate the weight of the person using $F_g = mg$.

Calculate the force required to accelerate the person upwards at 1.5 m s^{-2} .

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.

Working

$$F_g = mg = 74 \times 9.8 = 725 \text{ N}$$

$$F_{\text{net}} = ma = 74 \times 1.5 = 111 \text{ N}$$

$$\begin{aligned} F_{\text{net}} &= 111 \\ F_N - F_g &= 111 \\ F_N - 725 &= 111 \\ F_N &= 725 + 111 \\ F_N &= \text{apparent weight} = 836 \text{ N} \end{aligned}$$

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

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. $\text{weight} = F_g$.
- The acceleration due to gravity of an object near the Earth's surface can be calculated using the dimensions of the Earth:

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

- 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:
 $m_{\text{Sun}} = 2.0 \times 10^{30} \text{ kg}$
 $m_{\text{Mars}} = 6.4 \times 10^{23} \text{ kg}$
 $r_{\text{Sun-Mars}} = 2.2 \times 10^{11} \text{ m}$
- 4 The force of gravitational attraction between the Sun and Mars is $1.8 \times 10^{21} \text{ N}$. Calculate the acceleration of Mars given that $m_{\text{Mars}} = 6.4 \times 10^{23} \text{ kg}$.
- 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.
 $m_{\text{Sun}} = 2.0 \times 10^{30} \text{ kg}$
 $m_{\text{Earth}} = 6.0 \times 10^{24} \text{ kg}$
 $m_{\text{Mars}} = 6.4 \times 10^{23} \text{ kg}$
 - 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 $3.3 \times 10^{23} \text{ kg}$ 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 $6.4 \times 10^{23} \text{ kg}$ and a radius of $3.4 \times 10^6 \text{ m}$.
- 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.

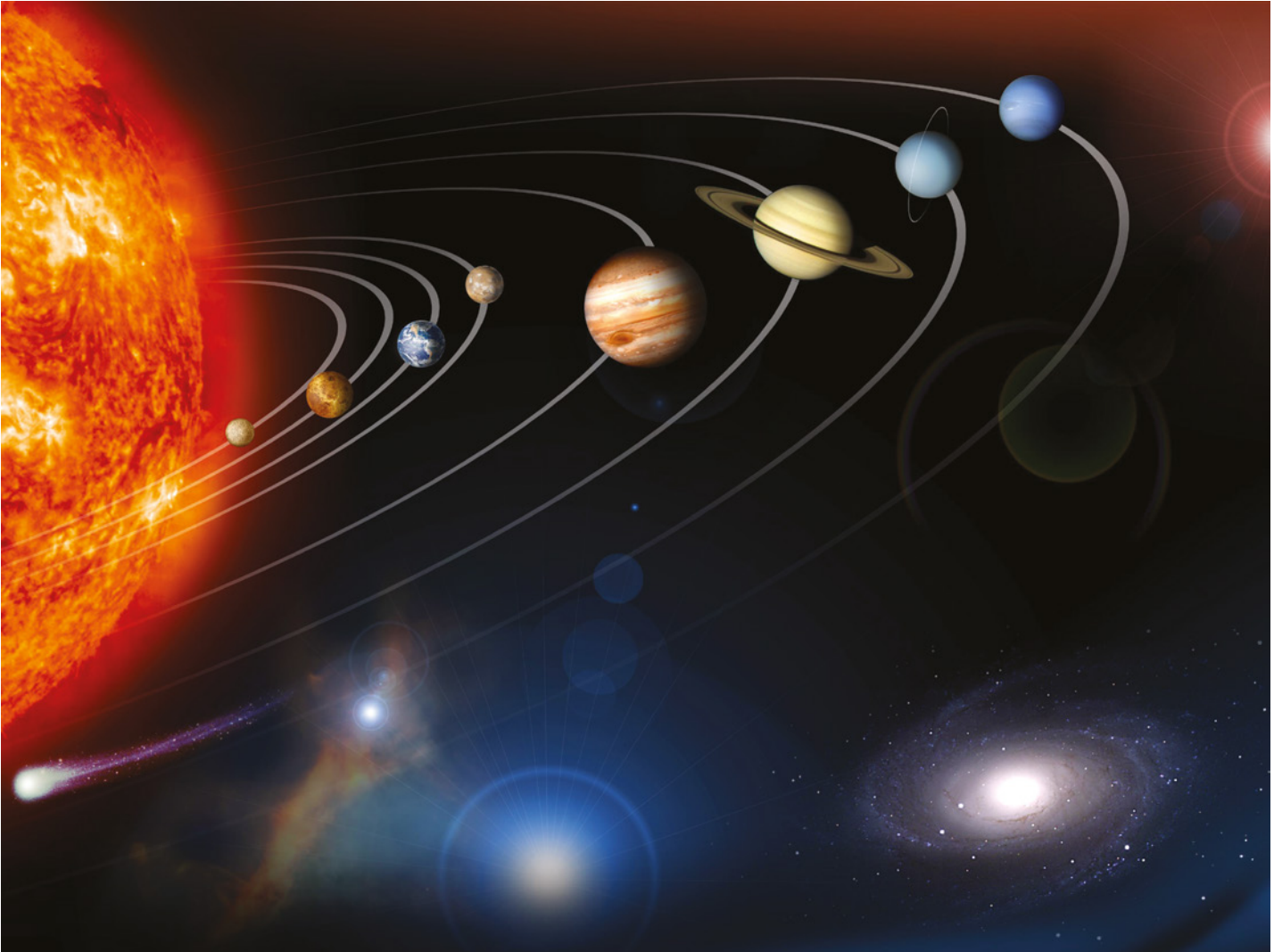


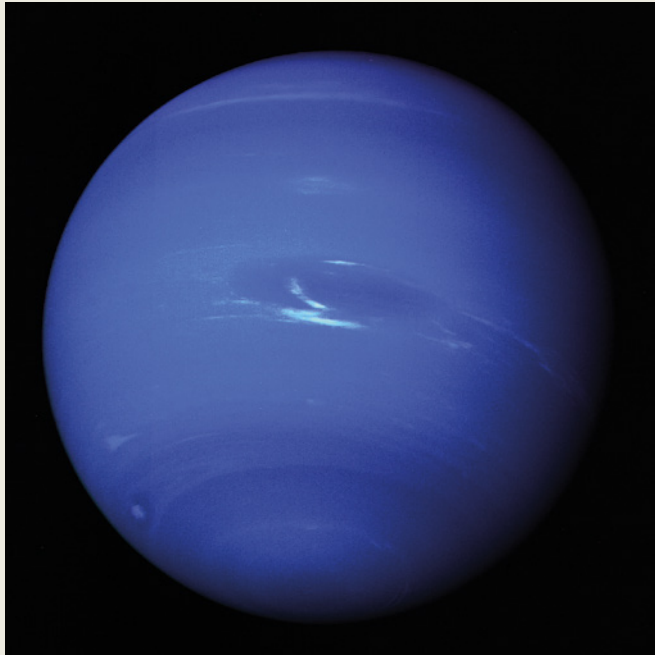
FIGURE 1.2.1 The solar system is a complex gravitational system.

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.

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

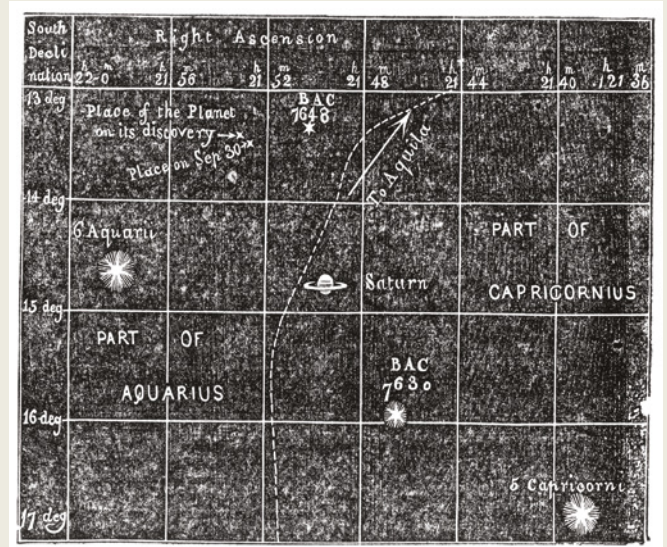


FIGURE 1.2.2 This star chart published in 1846 shows the location of Neptune in the constellation Aquarius when it was discovered on 23 September, and its location one week later.

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.

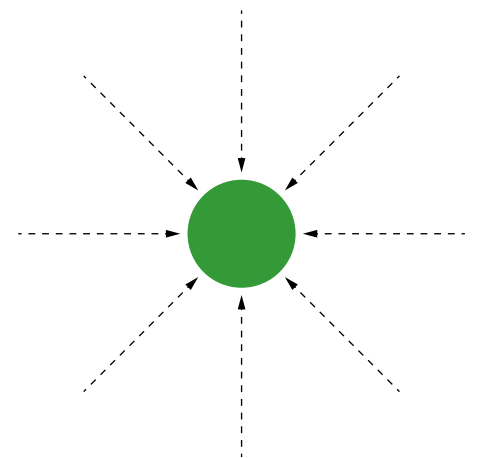
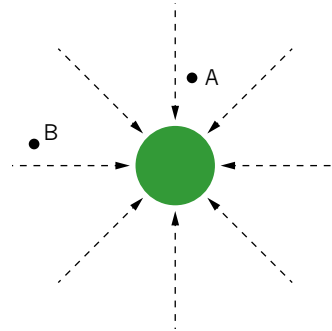


FIGURE 1.2.3 The arrows in this gravitational field diagram indicate that objects will be attracted towards the mass in the centre; the spacing of the lines shows that force will be strongest at the surface of the central mass and weaker further away from it.

Worked example 1.2.1

INTERPRETING GRAVITATIONAL FIELD DIAGRAMS

The diagram below shows the gravitational field of a moon.

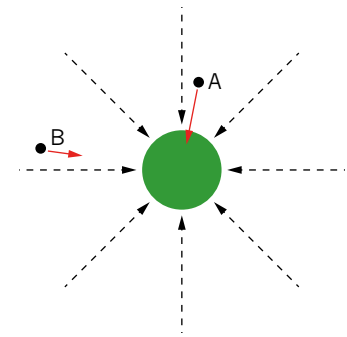


a Use arrows to indicate the direction of the gravitational force acting at points A and B.

Thinking

The direction of the field arrows indicates the direction of the gravitational force, which is inwards towards the centre of the moon.

Working



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

Thinking

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.

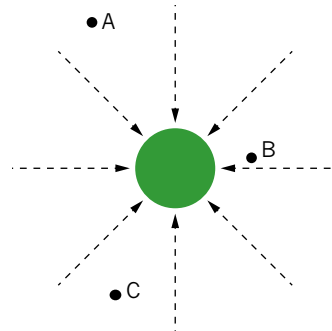
Working

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 $g_{\text{Earth}} = 9.8 \text{ N kg}^{-1}$.

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:

$$\mathbf{i} \quad g = \frac{F_g}{m}$$

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)

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

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:

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

$$\begin{aligned} \therefore 1 \text{ N kg}^{-1} &= 1 \text{ kg m s}^{-2} \times \text{kg}^{-1} \\ &= 1 \text{ m s}^{-2} \end{aligned}$$

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.	$g = 9.8 \text{ N kg}^{-1}$

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.

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:

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

i Therefore:

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

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)

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.

i 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.

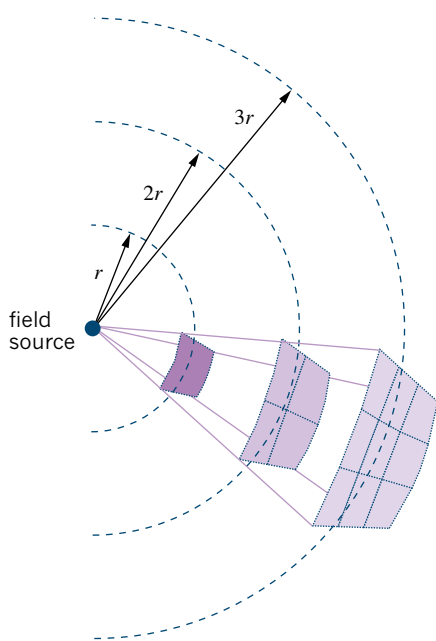


FIGURE 1.2.4 As the distance from the source of a field increases, the field is spread over an area that increases with the square of the distance from the source, resulting in the strength of the field decreasing by the same ratio.

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.

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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).

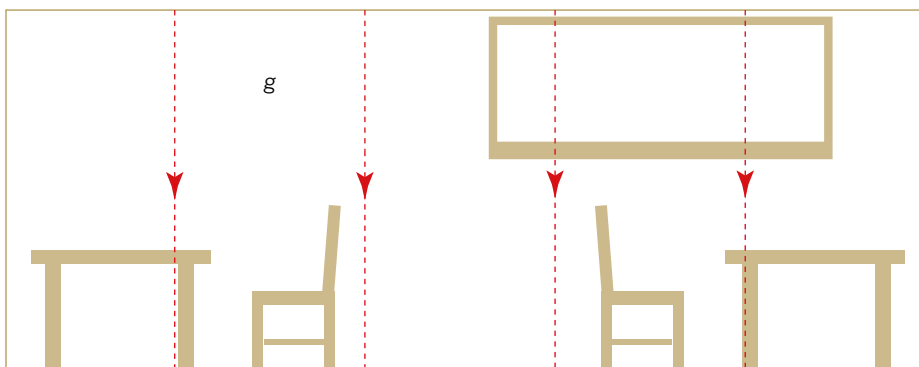


FIGURE 1.2.7 The uniform gravitational field, g , is represented by evenly spaced parallel lines in the direction of the force.

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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.

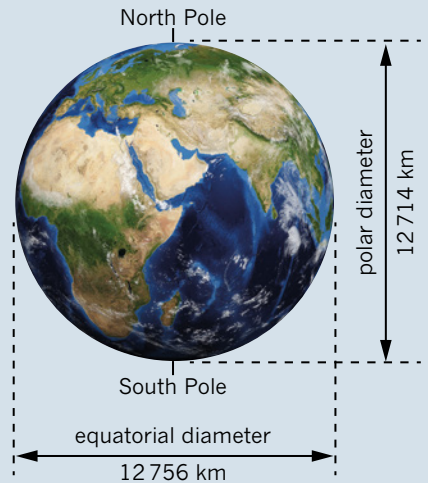


FIGURE 1.2.5 The Earth is a flattened sphere, which means its gravitational field is slightly stronger at the poles.

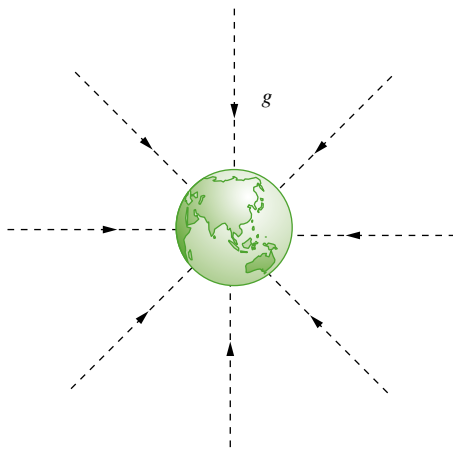


FIGURE 1.2.8 The Earth's gravitational field becomes progressively weaker out into space.

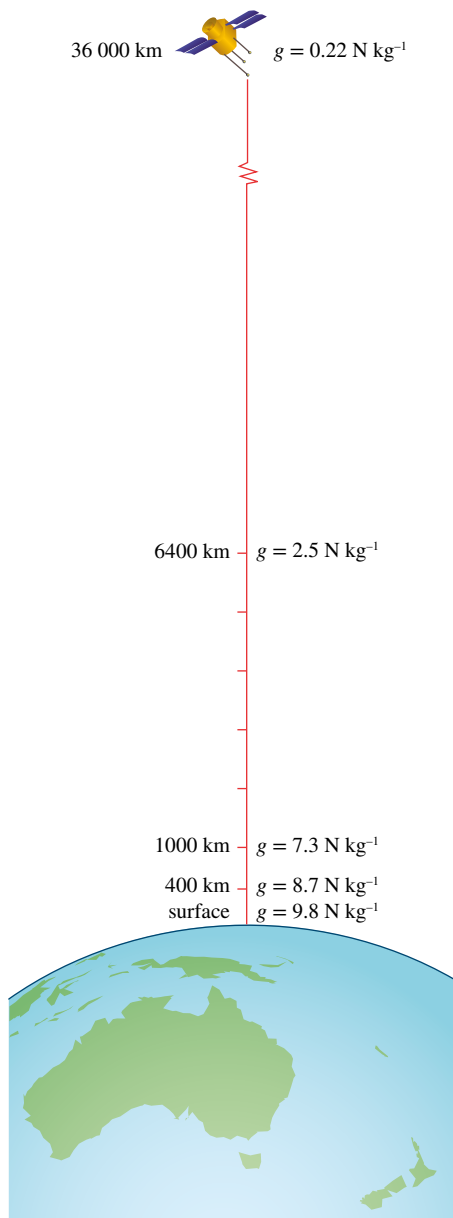


FIGURE 1.2.9 The Earth's gravitational field strength is weaker at higher altitudes.

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:

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

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 (see Figures 1.2.9 and 1.2.10).

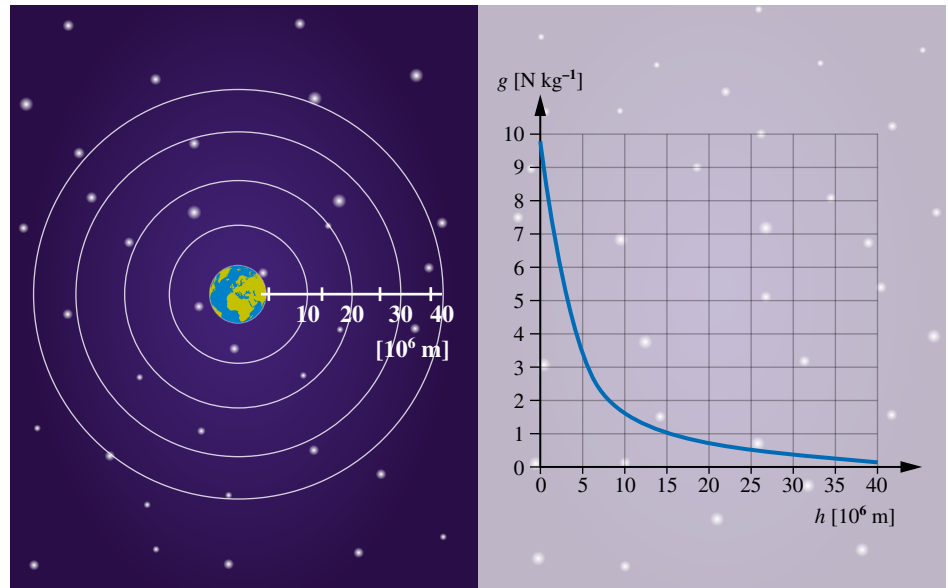


FIGURE 1.2.10 As the distance from the surface of the Earth is increased from 0 to 40×10^6 m, the value for g decreases rapidly from 9.8 N kg^{-1} , according to the inverse square law. The blue line on the graph gives the value of g at various altitudes (h).

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

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:

- $r_{\text{Earth}} = 6.38 \times 10^6 \text{ m}$
- $m_{\text{Earth}} = 5.97 \times 10^{24} \text{ kg}$
- 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.	$r = 6.38 \times 10^6 + 8850 \text{ m}$ $= 6.389 \times 10^6 \text{ m}$
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:

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

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

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 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 $7.35 \times 10^{22} \text{ kg}$ 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.	$r = 1740 \text{ km}$ $= 1740 \times 1000 \text{ m}$ $= 1.74 \times 10^6 \text{ m}$
Substitute values into the formula.	$g = G\frac{M}{r^2}$ $= 6.67 \times 10^{-11} \times \frac{7.35 \times 10^{22}}{(1.74 \times 10^6)^2}$ $= 1.6 \text{ N kg}^{-1}$

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.

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

$$r_{\text{Mars}} = 3390 \text{ km}$$

Give your answer correct to two significant figures.



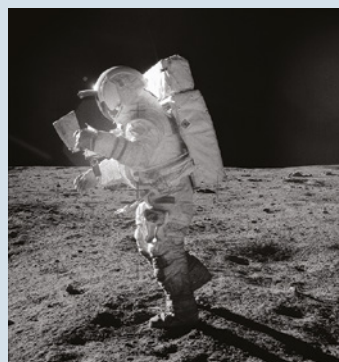
FIGURE 1.2.11 The gravitational field strength on the surface of Mars (shown here) is different to the gravitational field strength on the surface of the Earth, which, in turn, is different from that on the Moon.

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

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.

$$r_{\text{Earth}} = 6380 \text{ km}$$

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

	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 $1 \times 10^{13} \text{ kg}$ 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 $3.0 \times 10^{30} \text{ kg}$ 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 $6.0 \times 10^{24} \text{ kg}$, the mass of the Moon is $7.3 \times 10^{22} \text{ kg}$ and the radius of the Moon's orbit is $3.8 \times 10^8 \text{ m}$, 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?