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7.1 Gravitational Fields

PHYSICS

AQA A Level Revision Notes

A Level Physics AQA

7.1 Gravitational Fields

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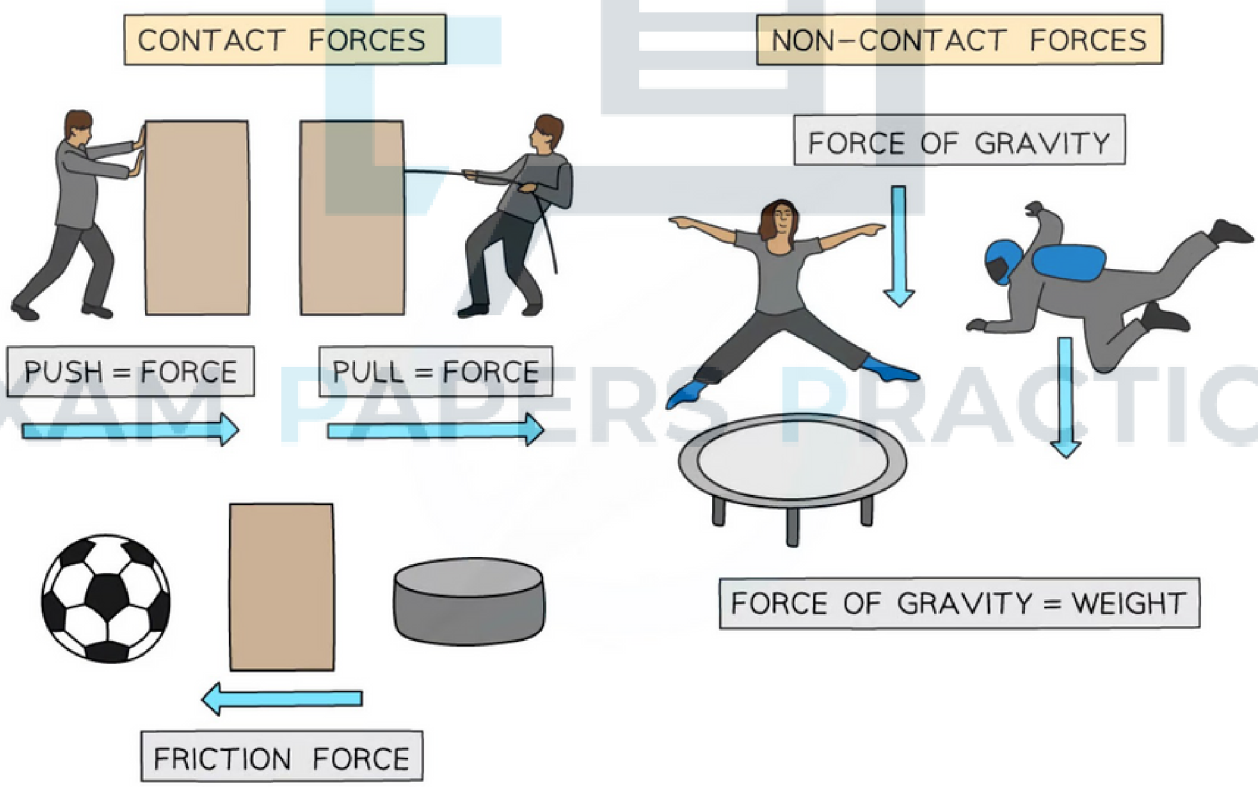
7.1.1 Force Fields

Concept of a Force Field

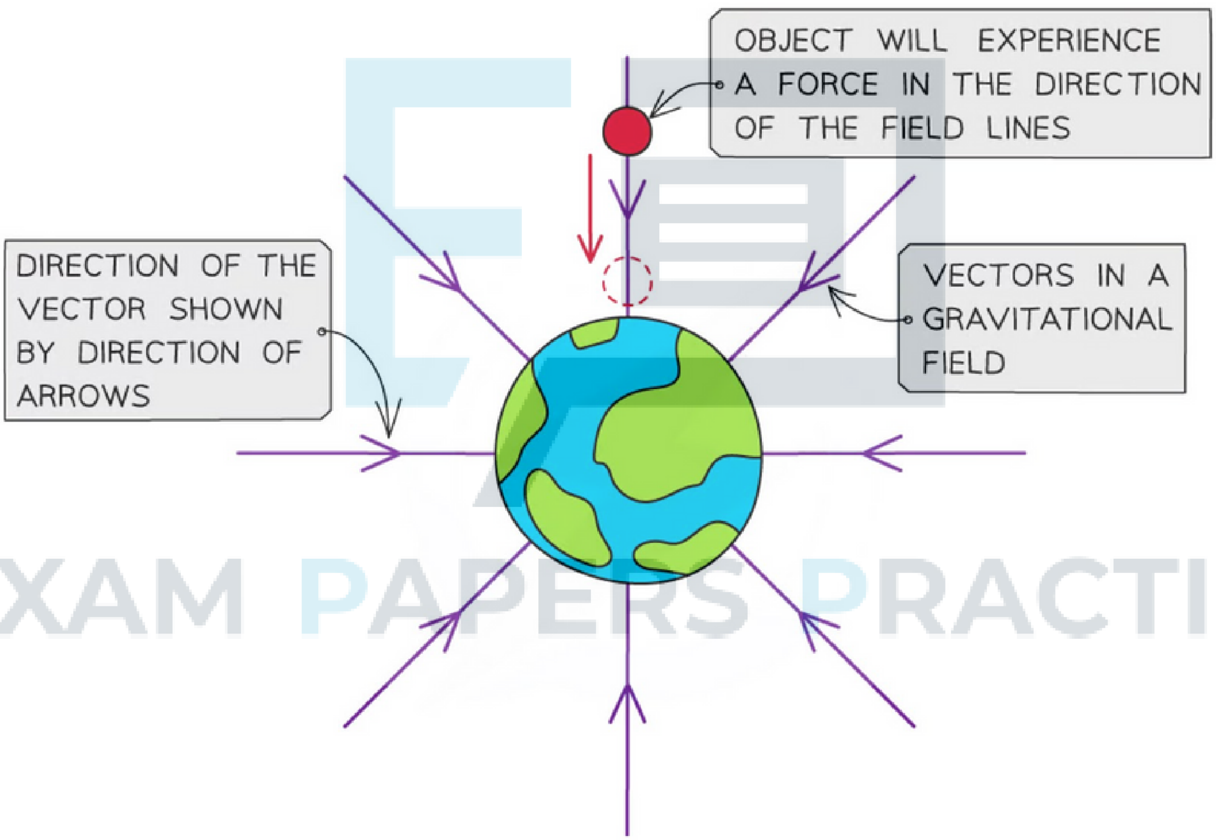
- A force field is any region of space where a body will experience a non-contact force
  - This will cause the body to move, interact or be deformed in some way
- A non-contact force is a force that acts without physical contact
  - Pushing a trolley is a contact force
  - A fridge magnet being attracted to the metal on a fridge is a non-contact force
- Force fields arise from the interactions between bodies or particles
  - **Static** or **moving charged** particles experience a force in an electric field
  - **Moving charged** particles experience a force in a magnetic field
  - Particles with **mass** experience a force in a gravitational field
- For example, the effects of the Moon and Sun's gravitational fields can be seen on Earth, such as the cause of tides



Examples of contact and non-contact forces

Direction of a Force Field

- The direction of a force field can be represented as a **vector**, the direction of which must be determined by inspection
- The direction of the vector shows the direction of the force that would be exerted on that body if it was placed in that position in the field
- The direction of a force field is shown by **field lines** (or 'lines of force'), which are represented by arrows
- A force field on a three-dimensional object is the force acting over the whole three-dimensional object
    - For spherical objects, such as a planet, the object can be approximated to a point mass



The direction of the gravitational force is shown by the vector field lines

7.1.2 Gravitational Field Strength

Gravitational Force

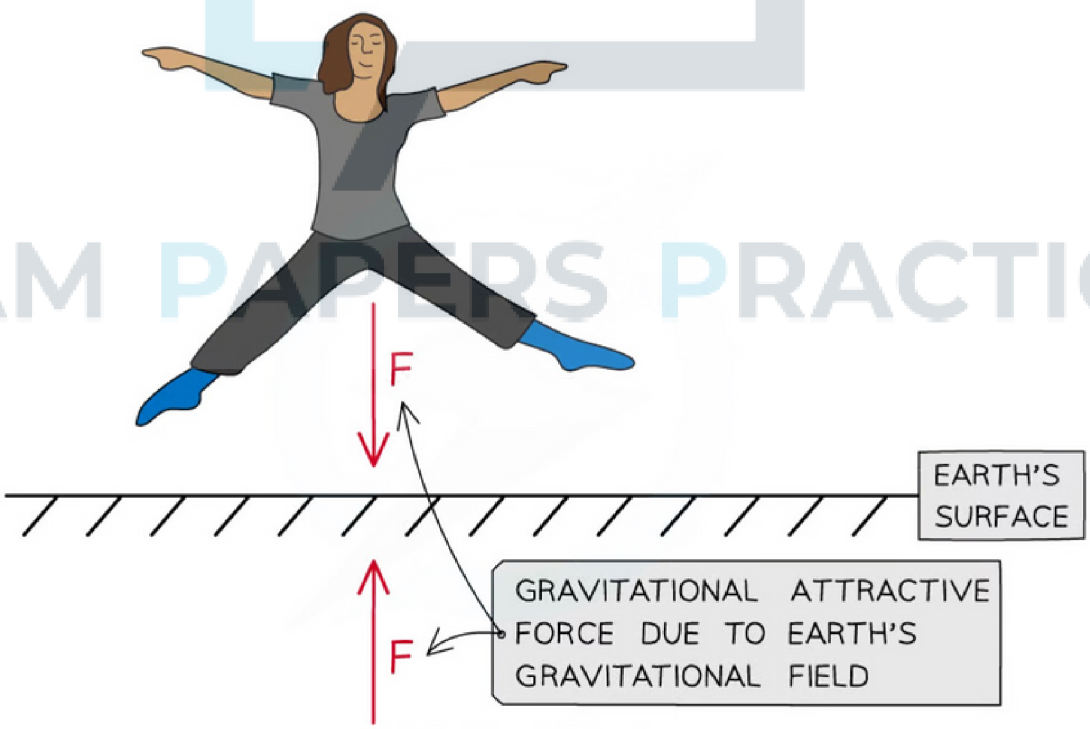
- There is a universal force of attraction between all matter with **mass**
  - This force is known as the 'force due to gravity' or the weight

- The Earth's gravitational field is responsible for the weight of all objects on Earth
- A gravitational field is defined as:

  A region of space where a mass experiences a force due to the gravitational attraction of another mass

- The direction of the gravitational field is always towards the centre of the mass
  - Gravitational forces **cannot** be repulsive

- Gravity has an infinite range, meaning it affects all objects in the universe
  - There is a greater gravitational force around objects with a large mass (such as planets)
  - There is a smaller gravitational force around objects with a small mass (almost negligible for atoms)



The Earth's gravitational field produces an attractive force

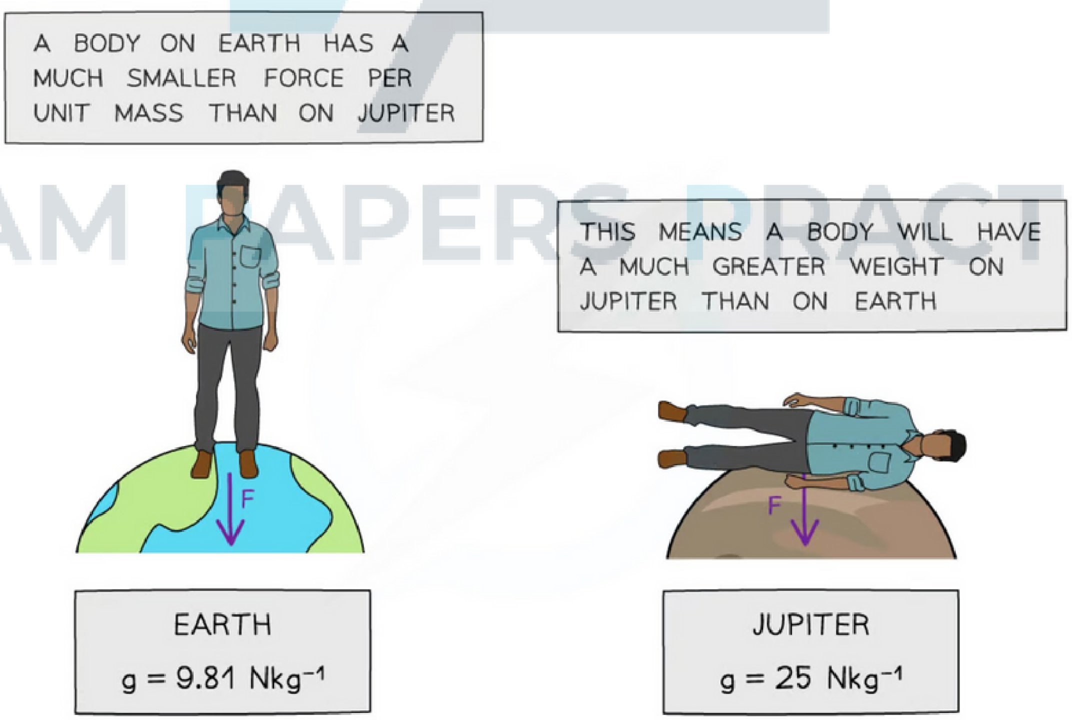
Gravitational Field Strength

- The strength of this gravitational field *g* at a point is the force *F* per unit mass *m* of an object at that point:

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

- Where:
  - *g* = gravitational field strength (N kg^{-1})
  - *F* = force due to gravity, or weight (N)
  - *m* = mass (kg)

- This equation shows that:
  - The larger the mass of an object, the greater its pull on another object
  - On planets with a large value of *g*, the gravitational force per unit mass is **greater** than on planets with a smaller value of *g*
- An object's mass remains the same at all points in space
  - However, on planets such as Jupiter, the weight of an object will be a lot greater than on a less massive planet, such as Earth
  - This means the gravitational force would be so high that humans, for example, would not be unable to fully stand up

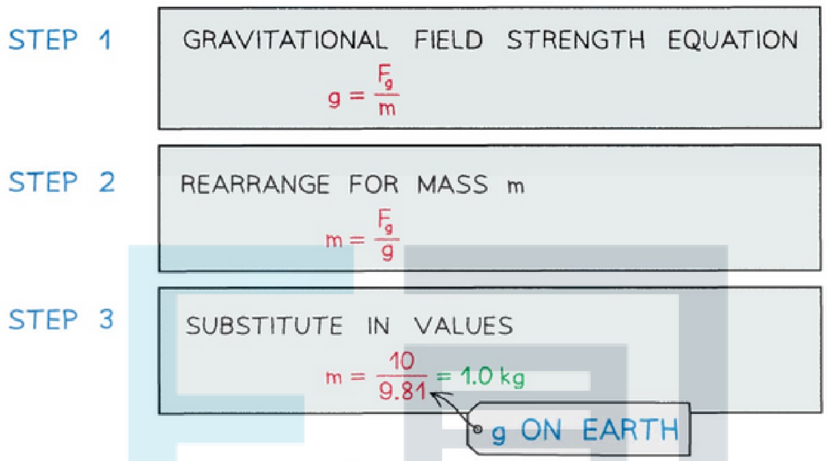


A person's weight on Jupiter would be so large that a human would be unable to fully stand up

- Factors that affect the gravitational field strength at the surface of a planet are:
  - The **radius** (or diameter) of the planet
  - The **mass** (or density) of the planet

Worked Example

Calculate the mass of an object with weight 10 N on Earth.



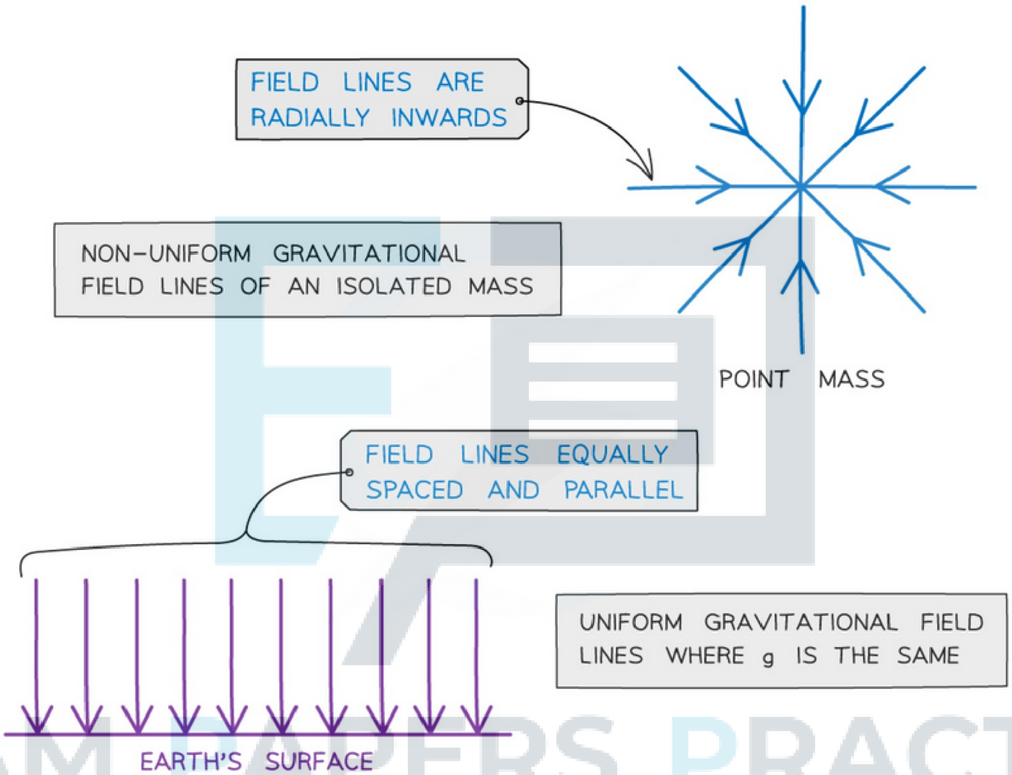
Exam Tip

There is a big difference between *g* and *G* (sometimes referred to as 'little g' and 'big G' respectively), *g* is the gravitational field strength and *G* is Newton's gravitational constant. Make sure not to use these interchangeably!Remember the equation density ρ = mass m ÷ volume V, which may come in handy with some calculations

7.1.3 Representing Gravitational Fields

Gravitational Field Lines

- The direction of a gravitational field is represented by gravitational field lines
- The gravitational field lines around a point mass are **radially inwards**
- The gravitational field lines of a uniform field, where the field strength is the same at all points, is represented by **equally spaced parallel lines**
  - For example, the fields lines on the Earth's surface



Gravitational field lines for a point mass and a uniform gravitational field

- Radial fields are considered **non-uniform fields**
  - The gravitational field strength *g* is different depending on how far you are from the centre
- Parallel field lines on the Earth's surface are considered a **uniform field**
  - The gravitational field strength *g* is the same throughout

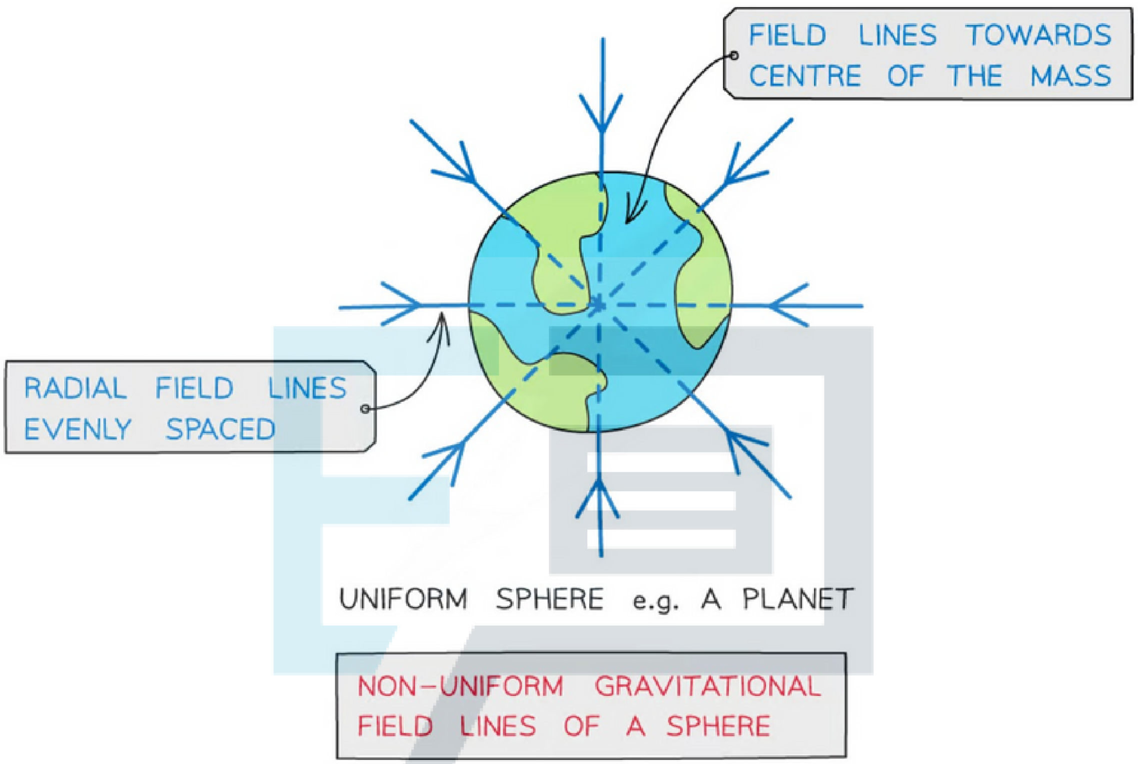
Point Mass Approximation

- For a point outside a uniform sphere, the mass of the sphere may be considered to be a **point mass** at its centre
  - A uniform sphere is one where its mass is **distributed evenly**
- The gravitational field lines around a uniform sphere are therefore **identical to those around a point mass**

- An object can be regarded as point mass when:

  A body covers a very large distance as compared to its size, so, to study its motion, its size or dimensions can be neglected

- An example of this is field lines around planets



Gravitational field lines around a uniform sphere are identical to those on a point mass

- Radial fields are considered **non-uniform** fields
  - So, the gravitational field strength *g* is different depending on how far an object is from the centre of mass of the sphere

Exam Tip

Always label the arrows on the field lines! Gravitational forces are **attractive only**. Remember:

- For a **radial field**: it is towards the centre of the sphere or point charge
- For a **uniform field**: towards the surface of the object e.g. Earth

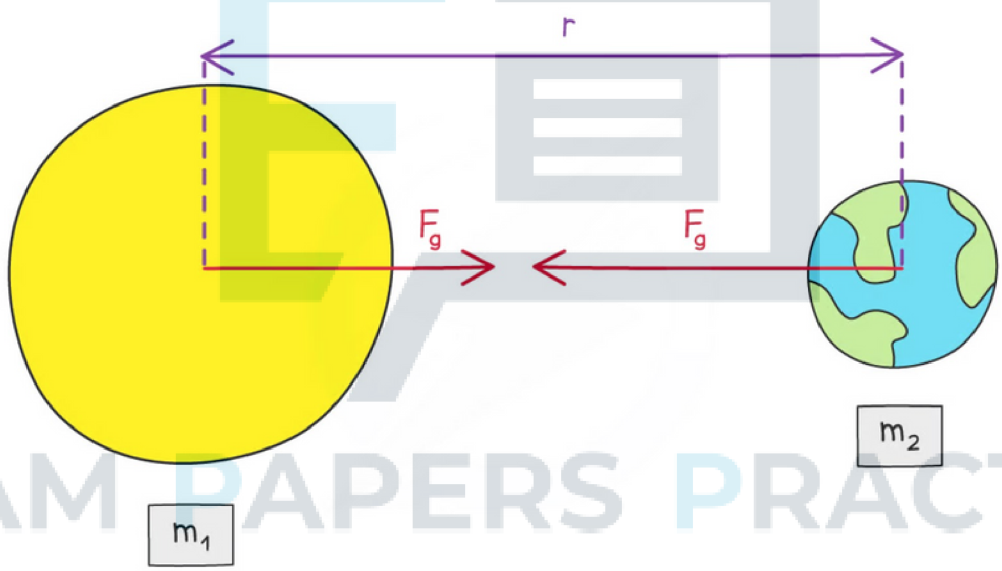
Newton's Law of Gravitation

- The gravitational force between two bodies outside a uniform field, e.g. between the Earth and the Sun, is defined by Newton's Law of Gravitation
  - Recall that the mass of a uniform sphere can be considered to be a point mass at its centre
- Newton's Law of Gravitation states that:

  The gravitational force between two point masses is proportional to the product of the masses and inversely proportional to the square their separation

- In equation form, this can be written as:

$$F_G = \frac{Gm_1 m_2}{r^2}$$



The gravitational force between two masses outside a uniform field is defined by Newton's Law of Gravitation

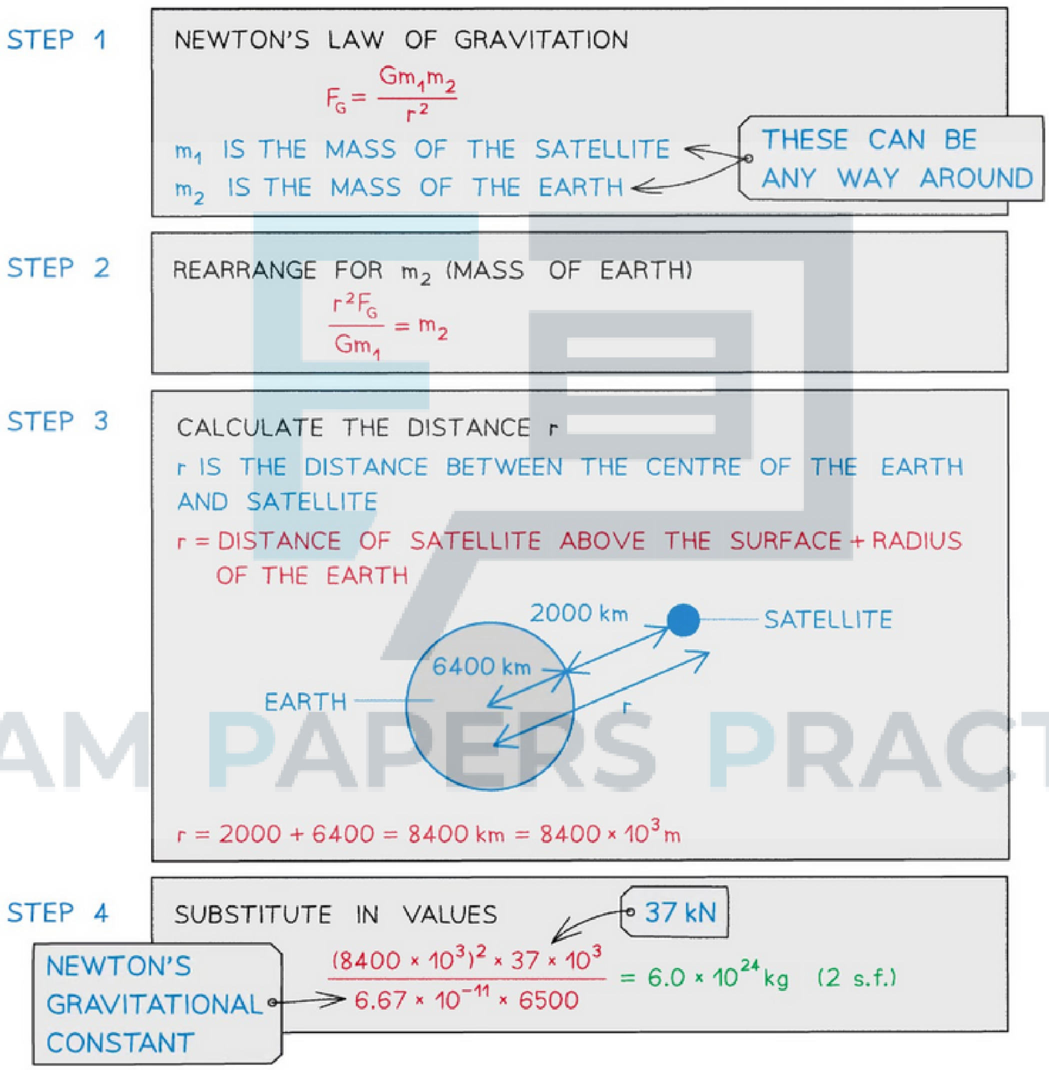
- Where:
  - F_G = gravitational force between two masses (N)
  - G = Newton's gravitational constant
  - m_1 and m_2 = two points masses (kg)
  - r = distance between the centre of the two masses (m)

- Although planets are not point masses, their separation is much larger than their radius
  - Therefore, Newton's law of gravitation applies to planets orbiting the Sun
- The $1/r^2$ relation is called the 'inverse square law'

- This means that when a mass is twice as far away from another, its force due to gravity reduces by $(½)^2 = ¼$

Worked Example

A satellite with mass 6500 kg is orbiting the Earth at 2000 km above the Earth's surface. The gravitational force between them is 37 kN. Calculate the mass of the Earth. Radius of the Earth = 6400 km.



Exam Tip

A common mistake in exams is to forget to **add together** the distance from the surface of the planet and its radius to obtain the value of *r*. The distance *r* is measured from the **centre** of the mass, which is from the **centre** of the planet.

7.1.5 Gravitational Field Strength in a Radial Field

Gravitational Field Strength in a Radial Field

- The gravitational field strength, *g* at a point describes how **strong or weak a gravitational field is** at that point
- *g* in a **radial** field (such as a planet) is calculated using the equation:

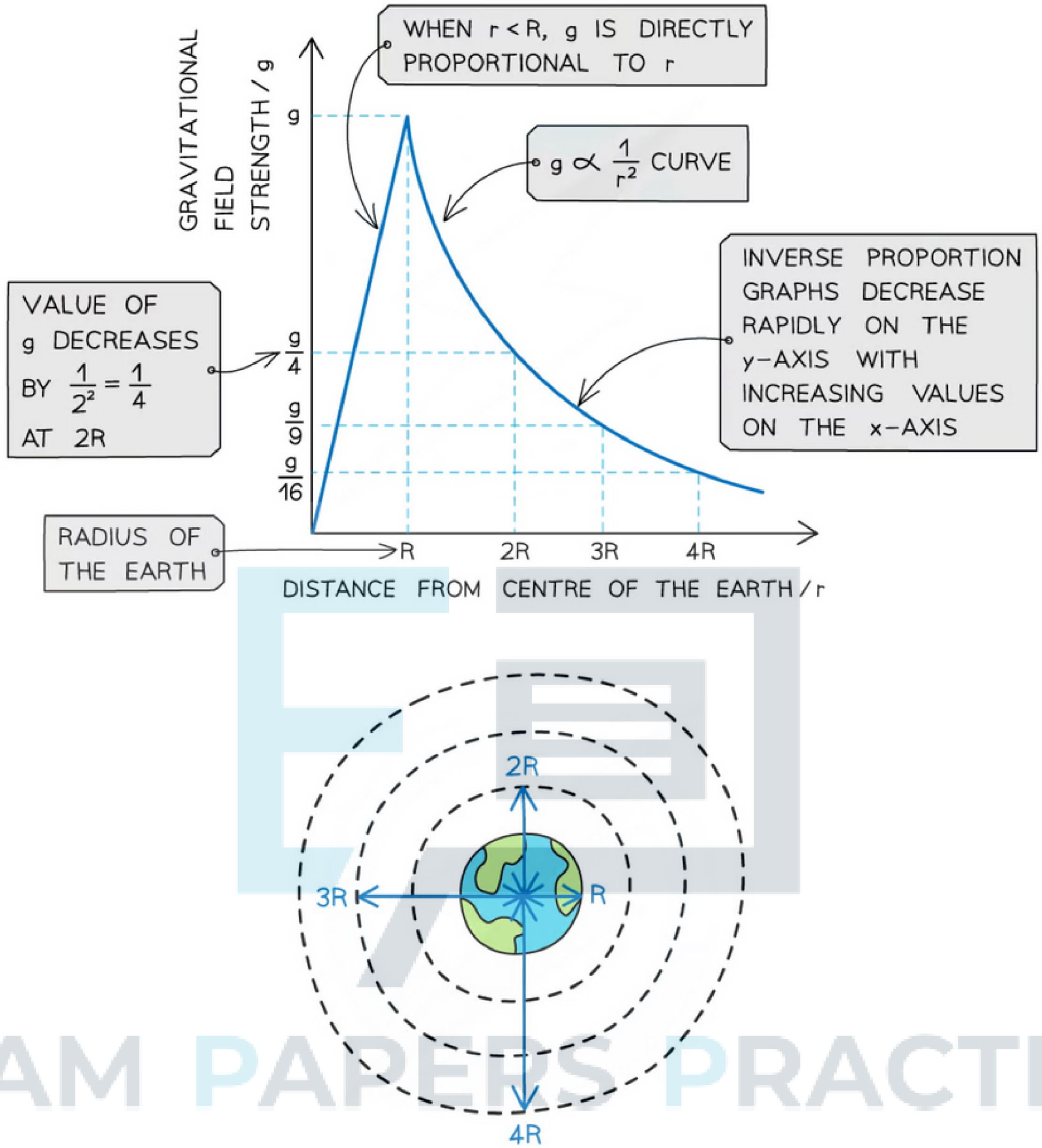
$$g = \frac{GM}{r^2}$$

- Where:
  - g = gravitational field strength ($N\ kg^{-1}$)
  - G = Newton's Gravitational Constant
  - M = mass of the body producing the gravitational field (kg)
  - r = distance from the mass where you are calculating the field strength (m)

- Gravitational field strength, *g*, is a vector quantity
- The direction of *g* is always towards the centre of the body creating the gravitational field
  - This is the same direction as the gravitational field lines

- On the Earth's surface, *g* has a constant value of $9.81\ N\ kg^{-1}$
- However, outside the Earth's surface, ***g* is not constant**
  - *g* decreases as *r* increases by a factor of $1/r^2$
  - This is an **inverse square law relationship** with distance

- When *g* is plotted against the distance from the centre of a planet, r has two parts:
  - When $r < R$, the radius of the planet, *g* is directly proportional to *r*
  - When $r > R$, *g* is inversely proportional to r^2 (this is an 'L' shaped curve and shows that *g* decreases rapidly with increasing distance *r*)



Graph showing how gravitational field strength varies at greater distance from the Earth's surface

- Sometimes, g is referred to as the 'acceleration due to gravity' with units of m s^{-2}
  - Any object that falls freely in a uniform gravitational field on Earth has an acceleration of 9.81 m s^{-2}

Worked Example

The mean density of the Moon is 3/5 times the mean density of the Earth. The gravitational field strength on the Moon is 1/6 of the value on Earth. Determine the ratio of the Moon's radius r_M and the Earth's radius r_E.

Step 1: Write down the known quantities

$$\rho_M = \frac{3}{5}\rho_E$$
$$g_M = \frac{1}{6}g_E$$

g_M = gravitational field strength on the Moon, ρ_M = mean density of the Moon

g_E = gravitational field strength on the Earth, ρ_E = mean density of the Earth

Step 2: The volumes of the Earth and Moon are equal to the volume of a sphere

$$V = \frac{4}{3}\pi r^3$$

Step 3: Write the density equation and rearrange for mass M

$$\rho = \frac{M}{V}$$

$$M = \rho V$$

Step 4: Write the gravitational field strength equation

$$g = \frac{GM}{r^2}$$

Step 5: Substitute M in terms of ρ and V

$$g = \frac{G\rho V}{r^2}$$

Step 6: Substitute the volume of a sphere equation for V, and simplify

$$g = \frac{G\rho 4\pi r^3}{3r^2} = \frac{G\rho 4\pi r}{3}$$

Step 7: Find the ratio of the gravitational field strength

$$\frac{g_M}{g_E} = \frac{G\rho_M 4\pi r_M}{3} \div \frac{G\rho_E 4\pi r_E}{3} = \frac{\rho_M r_M}{\rho_E r_E}$$

Step 8: Rearrange and calculate the ratio of the Moon's radius r_M and the Earth's radius r_E

$$\frac{r_M}{r_E} = \frac{\rho_E g_M}{\rho_M g_E} = \frac{\rho_E(\frac{1}{6}g_E)}{3 \ldots}$$

$$r_E \qquad \rho_M g_E \qquad (\tfrac{5}{3}\rho_E) g_E$$

$$\frac{r_M}{r_E} = \frac{5}{3} \times \frac{1}{6} = \frac{5}{18} = \mathbf{0.28} \text{ (2 s.f.)}$$

Exam Tip

Remember that *r* is always taken from the **centre** of mass of the object creating the gravitational field.Also, make sure you're comfortable with drawing the inverse square law graph of *g* against *r*, since this is a common exam question