CHAPTER 4

Gravity extends throughout the universe.

Learning Expectations

By the end of this chapter, you will:

Developing Skills of Investigation and Communication

- use appropriate terminology related to forces
- analyze the relationships between acceleration and forces such as the force of gravity, and solve related problems using free-body diagrams
- analyze and solve problems involving the relationship between the force of gravity and acceleration for objects in free fall

Understanding Basic Concepts

- distinguish between different forces
- explain how the discoveries of Galileo and Newton advanced knowledge about forces and motion
- describe, in qualitative and quantitative terms, the relationships among mass, gravitational field strength, and force of gravity

In 1665, Isaac Newton began his study of gravity in order to understand the Moon's orbit. Several centuries later, his theories have led to the success of various space missions such as the Cassini-Huygens mission to Saturn and the New Horizons mission to Pluto and beyond (Figure 4.1). Gravitational force between all objects in the universe attracts them to one another. It holds you to Earth and keeps Earth in its orbit around the Sun. Gravity is one of the four basic forces of nature, called **fundamental forces**, that physicists think underlie all interactions in the universe.

Scientists who plan space missions take advantage of gravitational forces in our solar system to change the speed and direction of spacecraft. A space probe leaving Earth to study Jupiter and Saturn and their moons takes many years to arrive there. If several planets are moving in the same direction and their positions are aligned, the probe can save years of travel time by passing near as many of those planets as possible. Each time the probe gets near enough to a planet, its gravitational field deflects the space probe. If the probe is moving in the same direction as the planet, the speed of the probe after its planetary encounter will increase. This use of planetary gravitational forces is called a **gravity assist**.

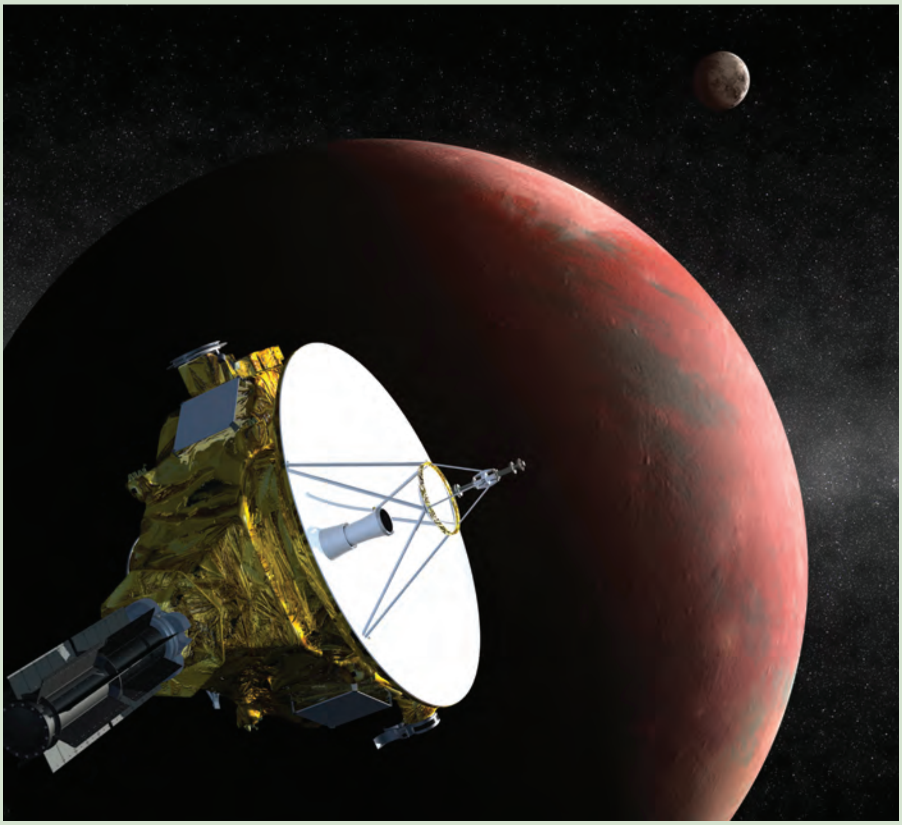

Figure 4.1 On July 14, 2015, New Horizons will become the first spacecraft to encounter Pluto. Its journey will have taken nine and a half years.

4.1 The Nature of Force

Section Summary

- There are four fundamental forces.
- Forces are vector quantities.
- Free-body diagrams are used to analyze forces.
- A net force results from the addition of all forces acting on an object.

Fundamental Forces

You experience a **force** when you push or pull an object. A push or a pull can have different magnitudes and can be in different directions. For this reason, force is a vector quantity.

Forces are all around us. Forces help keep our atoms and molecules together, and allow us to interact with our environment. The four fundamental forces, of which gravity is one, all play an important role in shaping the world around us.

The strongest of the fundamental forces, called the strong force, holds the nucleus of an atom together. Particles must be very close together in order for this force to be significant. It is very strong but has a very short range, less than 10^{-15} m, or about the width of an atomic nucleus. The next strongest, the electromagnetic force, holds atoms and molecules together. It also causes atoms and molecules to repel each other if they get too close. The electromagnetic force is caused by electric charges and has an infinite range. Most forces that you would notice in your daily life are electromagnetic in origin. The weak force is responsible for some kinds of radioactive decay. Like the strong force, it also has a very short range, less than 10^{-18} m, or $\frac{1}{1000}$ the range of the strong force.

These three fundamental forces share something in common: they can all attract or repel. The fourth fundamental force, **gravity**, attracts objects to each other due to their mass. Although the weakest of the four forces, gravity is very significant because of two important properties:

1. It has an infinite range.
2. It always attracts.

Table 4.1 summarizes the four types of forces.

Table 4.1 Fundamental Forces

Force	Relative Strength	Range	Function
Strong	1	Less than 10^{-15} m	Holds protons and neutrons together
Electromagnetic	$\frac{1}{137}$	Infinite	Holds atoms and molecules together Causes atoms and molecules to repel each other if they get too close
Weak	10^{-5}	Less than 10^{-18} m	Involved in radioactive decay
Gravitational	6×10^{-39}	Infinite	Mutual attraction of matter

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Explore More

What images do each of the four fundamental forces suggest?

The force of gravity is important for large objects such as stars and planets. It controls their motions and holds them in their orbits. The gravitational attraction between everyday objects is not noticeable since the force is very weak. It requires at least one of the masses to be very large, such as a planet, in order to be significant. The force of gravitational attraction between you and the person sitting beside you is less than a millionth of the force on each of you due to Earth's gravity, which holds you in your seats.

Force Is a Vector Quantity

In general, any force acting on an object can change the shape and/or velocity of the object. If you want to deform an object yet keep it stationary, at least two forces must be present (Figure 4.2(a)).

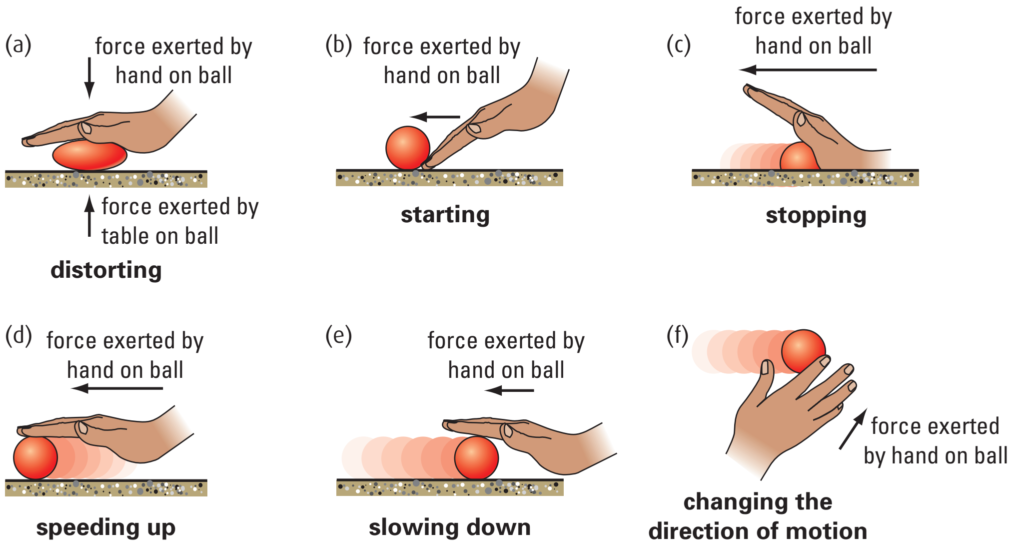

Figure 4.2 Different forces acting on a ball change either the shape or the motion of the ball.

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Suggested Activity

- B1 Quick Lab Overview on page 102

The symbol for force is $\vec{F}$ and the SI unit for force is the newton (symbol: N), named in honour of physicist Isaac Newton (1642–1727) who first defined the modern concept of force. One newton is equal to one kilogram-metre per second squared (1 kg·m/s^2), which is the force required to move a 1-kg object with an acceleration of 1 m/s^2. One newton is also about the amount of force required to hold an apple in your hand.

The direction of a force is described using reference coordinates that you choose for a particular situation. For example, you may use [forward] or [backward], [up] or [down], or compass directions (Figure 4.3).

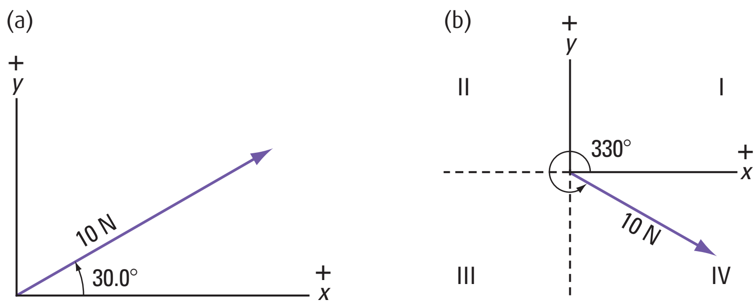

Figure 4.3 Two vectors of the same magnitude but with different directions. (a) 10 N [30°] (b) 10 N [330°]

Representing Forces Using Free-Body Diagrams

A free-body diagram is a powerful tool that can be used to analyze situations involving forces. A **free-body diagram** is a sketch that shows the object by itself, isolated from all others with which it may be interacting (Figure 4.4). Only the force vectors exerted *on* the object are included. In this physics course, the vectors are drawn with their tails meeting at the approximate centre of the object. However, this does not necessarily mean that the centre of the object is *where* the forces act.

When drawing a free-body diagram, it is important to always include which directions you will choose as positive. Figure 4.5 shows the steps for drawing free-body diagrams.

Usually you will be working with forces that all lie in one dimension, for example with directions such as [forward] and [backward], or [up] and [down]. You can simply add or subtract the magnitudes of the forces in one-dimensional problems. Sometimes you may encounter forces in the directions [forward], [backward], [up], and [down], or [N], [S], [E], and [W]. In this case, you can work with the [forward]-[backward] or [E]-[W] forces separately from the other pairs of forces.

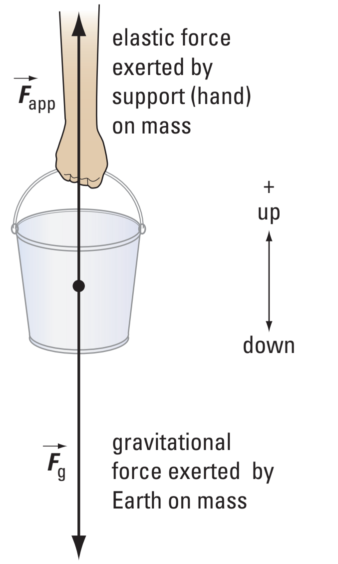

Figure 4.4 The free-body diagram for a bucket held stationary in Earth's gravitational field

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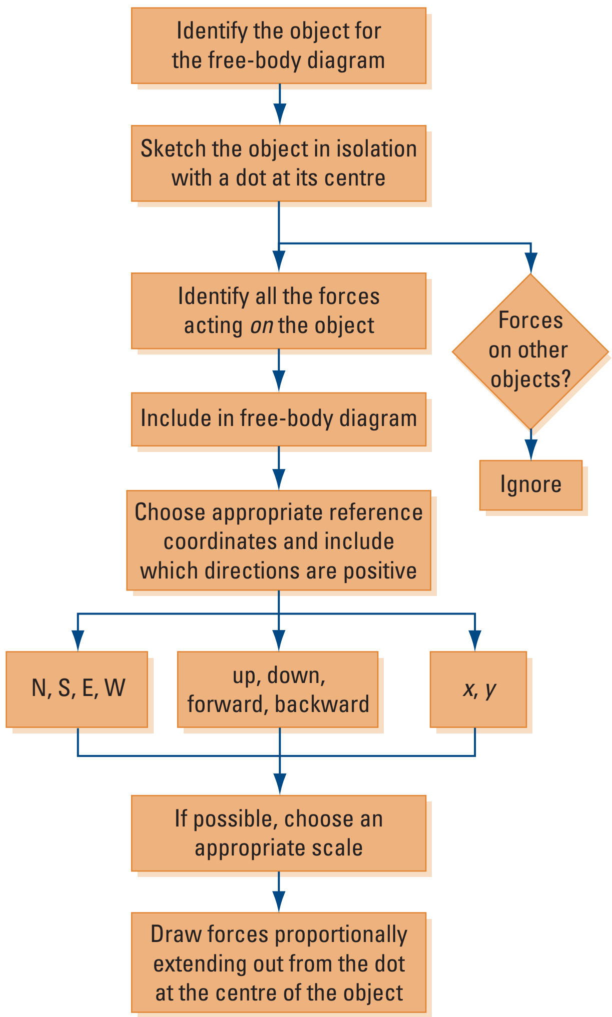

Figure 4.5 Flow chart summarizing the steps for drawing a free-body diagram

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Suggested Activity

- B2 Quick Lab Overview on page 102

Examples of Forces

There are different types of forces, and scientists distinguish among these forces by giving them particular names. When one object is in contact with another, the objects will have a common surface of contact, and the two objects will exert a normal force on each other. This **normal force**, $\vec{F}_N$, is a force that is perpendicular to this common surface. Depending on the situation, friction may be present. **Friction**, $\vec{F}_f$, is a force that acts parallel to the common surface of contact, resisting motion between the two surfaces.

The adjective "normal" simply means perpendicular. Figure 4.6(a) shows a book at rest on a level table. The normal force exerted by the table on the book is represented by the vector directed upward. If the table top were slanted as in Figure 4.6(b), the normal force acting on the book would not be directed vertically upward. Instead, it would be slanted, but still perpendicular to the contact surface.

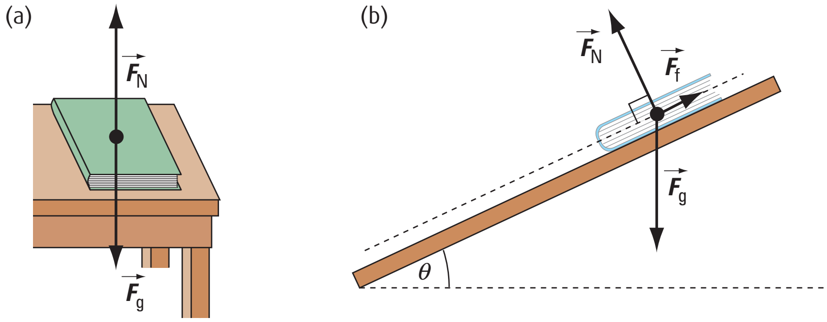

Figure 4.6 Forces acting (a) on a stationary book on a level table and (b) on a book resting on a slanted table.

A stationary object may experience an applied force, $\vec{F}_{app}$, if, say, a person pushes against the object (Figure 4.7). An **applied force** is a force acting on an object. In this case, the force of friction acting on the object will oppose the direction of possible motion. For example, if the applied force is directed forward, the force of friction acts backward because it resists the motion that the applied force tends to cause.

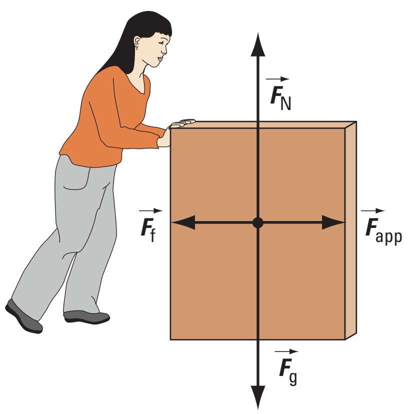

Figure 4.7 The forces acting on a stationary box

Example 4.1 demonstrates how to draw a free-body diagram for a car experiencing different types of forces. In this situation, the normal force acting on the car is equal in magnitude to the force of gravity $\vec{F}_g$ acting on the car.

Example 4.1

A car experiencing a gravitational force $\vec{F}_g$ of 10 000 N [down] is coasting on a level road. The car experiences a normal force $\vec{F}_N$ of 10 000 N [up], a force of air resistance $\vec{F}_{air}$ of 2500 N [backward], and a force of friction $\vec{F}_f$ exerted by the road on the tires of 500 N [backward]. Draw a free-body diagram for this situation.

Analysis and Solution

While the car is coasting, there is no forward force acting on it. The free-body diagram shows four forces (Figure 4.8).

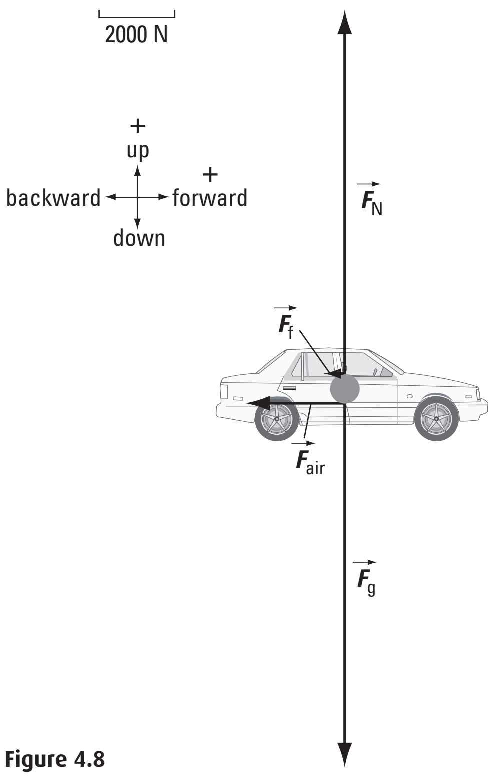

Figure 4.8

Practice Problems

1. The driver in Example 4.1 sees a pedestrian and brakes. The force of air resistance remains 2500 N [backward]. With the brakes engaged, the force of friction exerted on the car is 5000 N [backward]. Draw a free-body diagram for this situation.
2. A car moving at constant velocity starts to speed up. The gravitational force on the car is 12 000 N [down]. The force of air resistance is 3600 N [backward]. With the engine engaged, the force of friction exerted on the road by the tires is 7200 N [forward]. Draw a free-body diagram for this situation.

Answers

See Answers on page 451 of this book.

Using Free-Body Diagrams to Find Net Force

Free-body diagrams are very useful when you need to calculate the net force, $\vec{F}_{net}$, on an object. The **net force** is a vector sum of all the forces acting simultaneously on an object. This means that the magnitude of the force as well as its direction must be considered. Force vectors that are parallel can be added using a vector diagram that looks similar to a number line.

Concept Check

1. Can the net force on an object ever equal zero? Explain using an example and a free-body diagram.
2. What would happen to the object's velocity in that case?
3. If the object's velocity does change, what does that tell you about the net force?

Adding Collinear Forces

Vectors that are parallel are *collinear*, even if they have opposite directions. Example 4.2 demonstrates how to find the net force on an object given two or more collinear forces. In this example, a canoe is dragged using two ropes. The magnitude of the force $\vec{F}_T$ exerted by a rope on an object at the point where the rope is attached to the object is called the **tension** in the rope.

In this physics course, there are a few assumptions that you need to make about ropes or cables to simplify calculations. These assumptions and the corresponding inferences are listed in Table 4.2. Note that a "light" object means one that has negligible mass. Astronauts have performed experiments to understand how tension can be kept in a long tether between two orbiting spacecraft (Figure 4.9).

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Take It Further

How do physicists think "dark energy" might counter the attractive effect of gravity throughout the universe?

Table 4.2 Assumptions about Ropes or Cables

Assumption	Inference
The mass of the rope is negligible.	The force of tension $\vec{F}_T$ is uniform throughout the length of the rope.
The rope has a negligible thickness.	$\vec{F}_T$ acts parallel to the rope and is directed away from the object to which the rope is attached.
The rope is taut and does not stretch.	Any objects attached to the rope will have the same magnitude of acceleration as the rope.

Figure 4.9 In this experiment, astronauts investigated whether a tether between their spacecraft (not shown) and a target spacecraft could be kept taut in orbit.

Example 4.2

Two people are dragging a canoe out of a lake onto a beach using light ropes (Figure 4.10). Each person applies a force of 60.0 N [forward] on the rope. The force of friction exerted by the beach on the canoe is 85.0 N [backward]. Starting with a free-body diagram, calculate the net force on the canoe.

Given

$\vec{F}_{T_1} = 60.0$ N [forward]

$\vec{F}_{T_2} = 60.0$ N [forward]

$\vec{F}_{f} = 85.0$ N [backward]

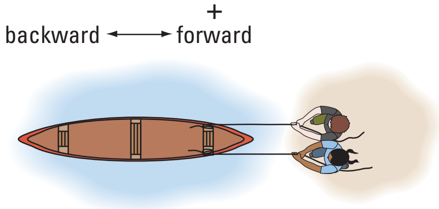

Figure 4.10

Required

net force on canoe ($\vec{F}_{net}$)

Analysis and Solution

Draw a free-body diagram for the canoe (Figure 4.11). Notice the [forward] direction is chosen to be positive.

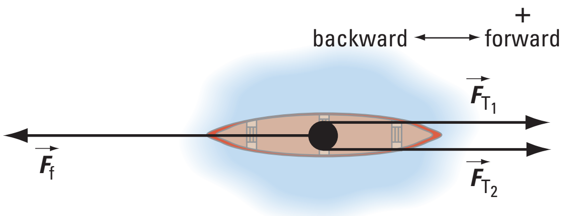

Figure 4.11

Add the force vectors shown in the vector addition diagram (Figure 4.12).

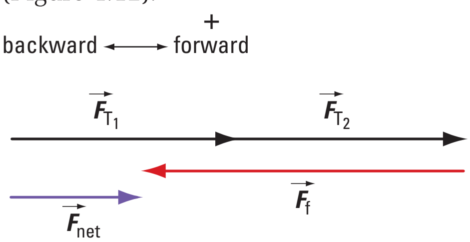

Figure 4.12

$$\vec{F}_{net} = \vec{F}_{T_1} + \vec{F}_{T_1} + \vec{F}_{f}$$
$$\vec{F}_{net} = 60.0 \text{ N} + 60.0 \text{ N} + (-85.0 \text{ N})$$
$$= 60.0 \text{ N} + 60.0 \text{ N} - 85.0 \text{ N}$$
$$= 35.0 \text{ N}$$
$$\vec{F}_{net} = 35.0 \text{ N [forward]}$$

Paraphrase

The net force on the canoe is 35.0 N [forward].

Practice Problems

1. Two dogs, A and B, are pulling a sled across a horizontal, snowy surface. Dog A exerts a force of 200 N [forward], and dog B exerts a force of 150 N [forward]. The force of friction exerted by the snow on the sled is 60 N [backward]. The driver attempts to slow down the sled by pulling on it with a force of 100 N [backward]. Starting with a free-body diagram, calculate the net force on the sled.
2. In a tractor pull, four tractors are connected by strong chains to a heavy load. The load is initially at rest. Tractors A and B pull with forces of 5000 N [E] and 4000 N [E] respectively. Tractors C and D pull with forces of 4500 N [W] and 3500 N [W] respectively. The magnitude of the force of friction exerted by the ground on the load is 1000 N.
   (a) Starting with a free-body diagram, calculate the net force on the load. (Hint: First calculate the net force without friction; then, decide the direction that the force of friction acts, and include it in the net force calculation.)
   (b) If the load is initially at rest, will it start moving? Explain.

Answers

1. 190 N [forward]
2. (a) 0 N
   (b) no

PHYSICS INSIGHT

A stationary object experiencing a net force of zero will not start to move. If the net force is not zero, the object will start to move in the same direction as the net force.

B1 Quick Lab

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Measuring Force Using a Spring Scale

Purpose

To determine how the amount of stretch of a calibrated spring is related to the magnitude of the force acting on an object.

Activity Overview

In this activity, you will use a spring scale to measure the force acting on an object. You will use a standard set of masses with hooks to attach them to the spring scale.

Your teacher will give you a copy of the full activity.

Prelab Questions

Consider the questions below before beginning this activity.

1. How is hanging a mass from a spring scale like pulling on the spring with your finger? How is it different?
2. Which do you think is the force the spring scale measures, the weight of a 100-g mass or the mass itself?

Figure 4.13 Possible spring scale setup

B2 Quick Lab

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Exploring Forces

Purpose

To explore the actions and effects of forces

Activity Overview

In this activity, you will try a number of simple experiments that demonstrate forces in action in different situations.

Prelab Questions

Consider the questions below before beginning this activity.

1. Before performing each experiment, predict what will happen, and why.
2. Share predictions with a classmate. How are they similar? Different?

Figure 4.14 Penny experiment

4.1 Check and Reflect

Key Concept Review

1. Draw a free-body diagram for each situation. The lengths of your arrows should represent the magnitudes of the forces.
   (a) A plane flying horizontally with its engine exerting a thrust of 1400 N [E] against some air resistance of 700 N [W].
   (b) A diver gently falling through water with a downward force of 800 N against the force of buoyancy of water of 650 N.
2. Explain what a force is, and state the SI unit of force.
3. Name the type of force responsible for each of the following scenarios:
   (a) An arrow falling toward Earth
   (b) A planet in orbit around the Sun
   (c) A match that is lit on a rough surface
4. Sketch a free-body diagram for
   (a) a bicycle moving west on a level road with decreasing speed
   (b) a ball experiencing forces of 45 N [up], 60 N [down], and 80 N [up] simultaneously
   (c) a rock falling through water at constant speed
5. (a) Describe the concept of net force, in terms of free-body diagrams.
   (b) Describe the concept of a normal force, in terms of free-body diagrams.
   (c) Explain why each of these concepts is important.

Connect Your Understanding

6. Why do you think it is important to assume that a rope under tension is taut and does not stretch?
7. Why must a direction be stated for a force?
8. Is it possible for a net force on an object to act in the opposite direction to the motion of an object? Explain.
9. Describe each of the four fundamental forces.
10. Explain how probes make use of a planet's gravitational field in order to gain speed.
11. Explain why the normal force is not present if an object is falling freely.
12. Describe a scenario where the normal force would not be equal to the force of gravity.
13. The total force of gravity acting on a biker and her motorbike is 1800 N [down]. With the engine engaged, the force of friction exerted by the road on the tires is 500 N [forward]. The air resistance acting on the biker and bike is 200 N [backward]. The normal force exerted by the road on the biker and bike is 1800 N [up].
    (a) Consider the biker and bike as a single object. Draw a free-body diagram for this object.
    (b) Calculate the net force in the vertical direction.
    (c) Calculate the net force in the horizontal direction.
14. The blanket toss is a centuries-old hunting technique that the Inuit used to find herds of caribou. During the toss, several people would hold a hide taut while the hunter would jump up and down, much like on a trampoline, increasing the jump height each time. At the top of the jump, the hunter would rotate through 360° looking for the herd. Draw a free-body diagram for a hunter experiencing a gravitational force of 700 N [down] while
    (a) standing at rest on the taut hide just before a jump
    (b) at the maximum jump height
15. List as many forces as you can that are acting on the surfer and his board shown below.

Question 15

Reflection

16. Describe three things about the nature of gravity that you did not know before working on this section.
17. How did your understanding of forces change after working with free-body diagrams?

For more questions, go to PHYSICS•SOURCE

4.2 Gravitational Forces Due to Earth

Section Summary

- Earth is surrounded by a gravitational field.
- Weight is the force of gravity acting on an object.
- Newton's law of universal gravitation describes the gravitational force between any two masses.

Describing Gravitational Force as a Field

One of Newton's great achievements was to identify the force that causes objects to fall near Earth's surface as the same force that causes the Moon to orbit Earth. He reasoned that this force of gravity is present throughout the universe. Previously, scientists had been unable to agree about whether different masses on Earth fall at the same rate, or how the Moon moves around Earth. Newton's model of gravity was able to accurately predict all these phenomena for the first time.

Gravitational force, $\vec{F}_g$, is the force that attracts any two objects together. You can feel its effect when you interact with an object of very large mass such as Earth. When you slide down a waterslide, you can feel the gravitational force exerted by Earth pulling you downward toward the bottom of the slide (Figure 4.15).

Figure 4.15 The attractive force between Earth and you is far greater than that between you and another person coming down the slide.

Gravitational force is an example of a force that acts on objects whether or not they actually touch each other, even if the objects are in a vacuum. These forces are referred to as action-at-a-distance forces.

In the 1800s, physicists introduced the concept of a field to explain action-at-a-distance forces. You encountered some fields in previous science courses when you worked with magnets.

Imagine you are moving the north pole of a magnet close to the north pole of another, fixed magnet. As you move the magnet closer to the fixed magnet, you can feel an increasing resistance. Somehow, the fixed magnet has created a region of influence in the space surrounding it. Physicists refer to an influence on a suitable object over a region of space, whether it is an attraction or a repulsion, as a **field**.

Since every object exerts a gravitational force in all directions, it influences the space around it. This region of influence of gravitational force due to an object is a **gravitational field**, and it is through this region that two or more objects interact (Figure 4.16).

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Explore More

How are real-life fields of force like science-fiction "force fields," and how are they different?

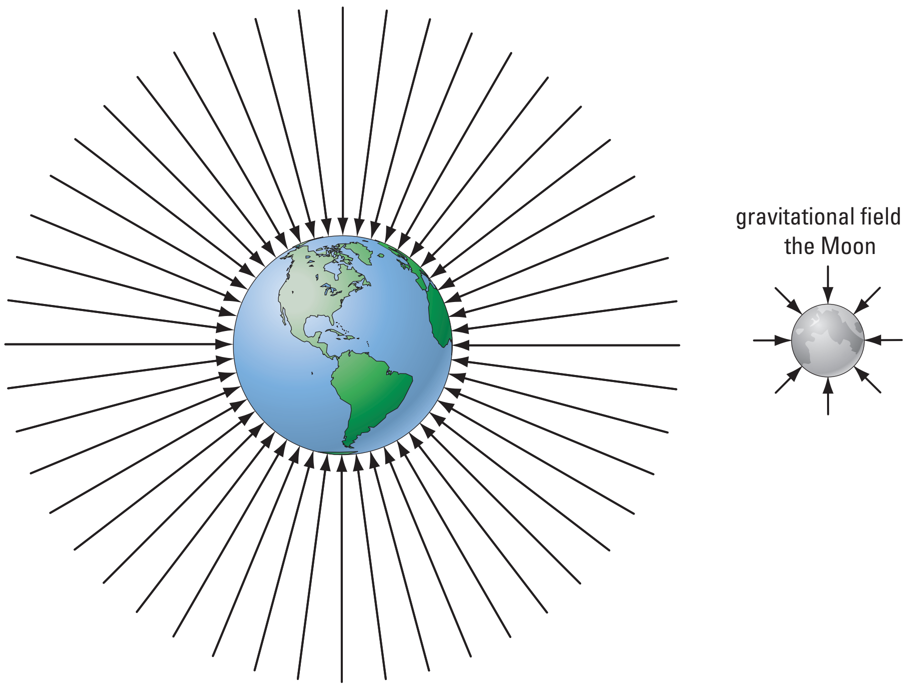

Figure 4.16 A two-dimensional representation of Earth's and the Moon's gravitational fields

To determine the magnitude and direction of a gravitational field created by an object, you could use a test mass m_{test}. The **test mass** is a mass too small to measurably affect the gravitational field. At different locations around the object, this test mass will experience a gravitational force that has a certain magnitude and direction. The direction of the gravitational force will be directed toward the centre of the object.

The **gravitational field strength** is defined as the gravitational force per unit mass:

$$\vec{g} = \frac{\vec{F}_g}{m_{\text{test}}}$$

If you release the test mass, it will accelerate toward the object with an acceleration equal to $\vec{g}$. Often, the scalar g is used to refer to the magnitude of the acceleration vector $\vec{g}$.

Measuring Force

The **weight** of an object is the force of gravity acting on the object. The symbol for weight is therefore also $\vec{F}_g$. Since weight is a force, it is measured in newtons (N). **Mass**, on the other hand, is a scalar that relates to the quantity of matter an object contains. It is measured in kilograms (kg).

Knowing the value of the gravitational field strength g, the equation above can be rearranged to solve for the gravitational force acting on the mass at that location: $\vec{F}_g = m\vec{g}$. One way you could measure forces involves using a calibrated spring scale (Figure 4.17). To measure the force of gravity acting on an object, attach the object to the end of the vertical spring on the scale, and observe the stretch of the spring.

When the spring stops stretching, the gravitational and elastic forces acting on the object balance each other. At this point, the elastic force is equal in magnitude to the weight of the object. So you can determine the magnitude of the weight of an object by reading the pointer position on a calibrated spring scale once the spring stops stretching.

Figure 4.18 shows how the magnitude of Earth's gravitational field strength changes as a test mass is moved farther away from Earth's centre. The farther the test mass is moved, the more significant is the decrease in g. In fact, the graph in Figure 4.18 shows an inverse square relationship:

$$g \propto \frac{1}{r^2}$$

The gravitational field strength is inversely proportional to the square of the distance.

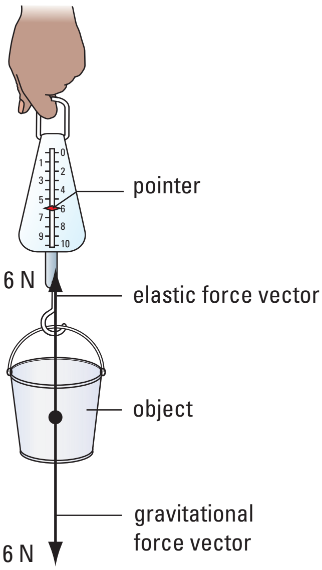

Figure 4.17 A spring scale is one type of instrument that can be used to measure forces.

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Explore More

Why does an inverse square relationship between gravitational field strength and distance make sense?

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Suggested Activity

- B3 Quick Lab Overview on page 113

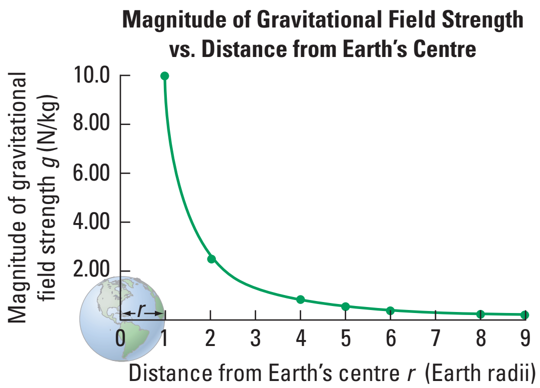

Figure 4.18 The magnitude of the gravitational field strength as a function of distance from Earth's centre

Since force is measured in newtons and mass in kilograms, the units of gravitational field strength are newtons per kilogram, or N/kg. Earth's gravitational field strength is 9.8049 N/kg in Toronto and 9.7647 N/kg at the top of Mount Everest. Usually, g is given as 9.81 N/kg. The variation in g near Earth's surface is usually negligible.

Example 4.3 demonstrates how weight is calculated using Earth's gravitational field strength g for simple cases.

Example 4.3

Calculate the weight of a physics student of mass 60 kg sitting in a classroom in Toronto.

Given
$m = 60$ kg
$g = 9.8049$ N/kg

Required
weight of student ($\vec{F}_g$)

Analysis and Solution
The weight of a student is equal to the gravitational force between the student and Earth. Since the student is on Earth's surface, $\vec{g}$ can be used.

$$\begin{aligned} F &= mg \\ &= (60 \text{ kg})\left(9.8049 \frac{\text{N}}{\text{kg}}\right) \\ &= 588 \text{ N} \end{aligned}$$

Paraphrase
The student's weight is 5.9×10^2 N [down].

Practice Problems

1. Calculate the weight of the 60 kg student in Example 4.3 if she is located on the top of Mount Everest, where $g = 9.7647$ N/kg.
2. Are the values for the student's weight from Question 1 and from Example 4.3 significantly different?
3. Calculate the mass of an object if its weight when located in Toronto is 735 N.

Answers

1. 586 N [down] or 5.9×10^2 N [down]
2. No, if accuracy and significant digits are taken into consideration
3. 75.0 kg

Concept Check

1. What happens to the gravitational field strength's magnitude if
   (a) r decreases by a factor of four?
   (b) r increases by a factor of two?
2. What happens to the gravitational field strength's magnitude if
   (a) m_{test} doubles?
   (b) m_{test} is halved?
3. What happens to the mass of an object if it is moved from Earth's surface to a high orbit? What happens to its weight?

Newton's Law of Universal Gravitation

Gravity affects all masses in the universe. No matter where you are on Earth or in outer space, you exert a gravitational force on an object and the object exerts a gravitational force, of equal magnitude but opposite direction, on you. Because gravitational force acts over any distance, the range of its effect is infinite.

Newton hypothesized that, given two objects A and B, the magnitude of the gravitational force exerted by one object on the other is directly proportional to the product of both masses:

$$F_g \propto m_A m_B$$

Figure 4.19 shows the magnitude of the gravitational force acting on an object at Earth's surface (r_{Earth}), one Earth radius above Earth ($2r_{\text{Earth}}$), and two Earth radii above Earth ($3r_{\text{Earth}}$). If the separation distance from Earth's centre to the centre of the object doubles, F_g decreases to $\frac{1}{4}$ of its original value. If the separation distance from Earth's centre to the centre of the object triples, F_g decreases to $\frac{1}{9}$ of its original value.

So, just as $g \propto \frac{1}{r^2}$, F_g is inversely proportional to the square of the separation distance (Figure 4.20):

$$F_g \propto \frac{1}{r^2}$$

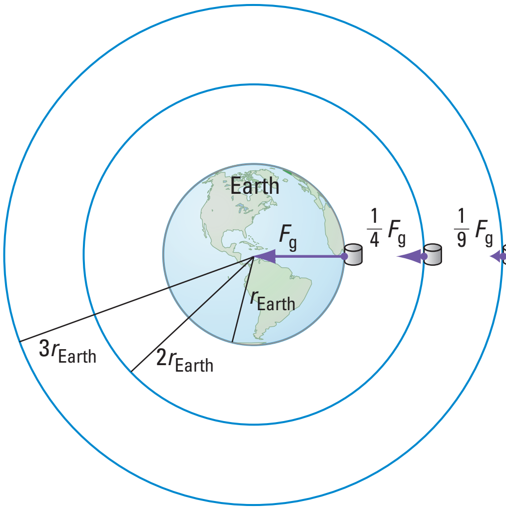

Figure 4.19 The magnitude of the gravitational force acting on an object some distance from Earth varies inversely with the square of the separation distance.

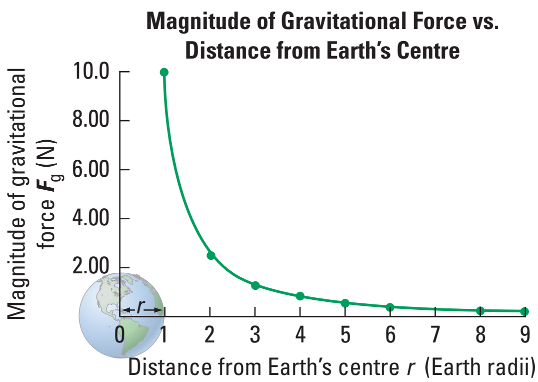

Figure 4.20 The magnitude of the gravitational force acting on a one-kilogram object as a function of distance from Earth's centre

If you combine both proportionalities into one statement, you get:

$$F_g \propto \frac{m_A m_B}{r^2} \text{ or } F_g = \frac{G m_A m_B}{r^2}$$

This mathematical relationship is Newton's law of universal gravitation. Figure 4.21 shows how the gravitational force varies as the masses and the separation distance change.

Any two objects, A and B, in the universe exert gravitational forces of equal magnitude but opposite direction on each other. The forces are directed along the line joining the approximate centres of both objects. The magnitude of the gravitational force is given by

$$F_g = \frac{G m_A m_B}{r^2},$$

where m_A and m_B are the masses of the two objects, r is the separation distance between the centres of both objects, and G is a constant called the **universal gravitational constant** that determines the strength of gravitational forces throughout the universe.

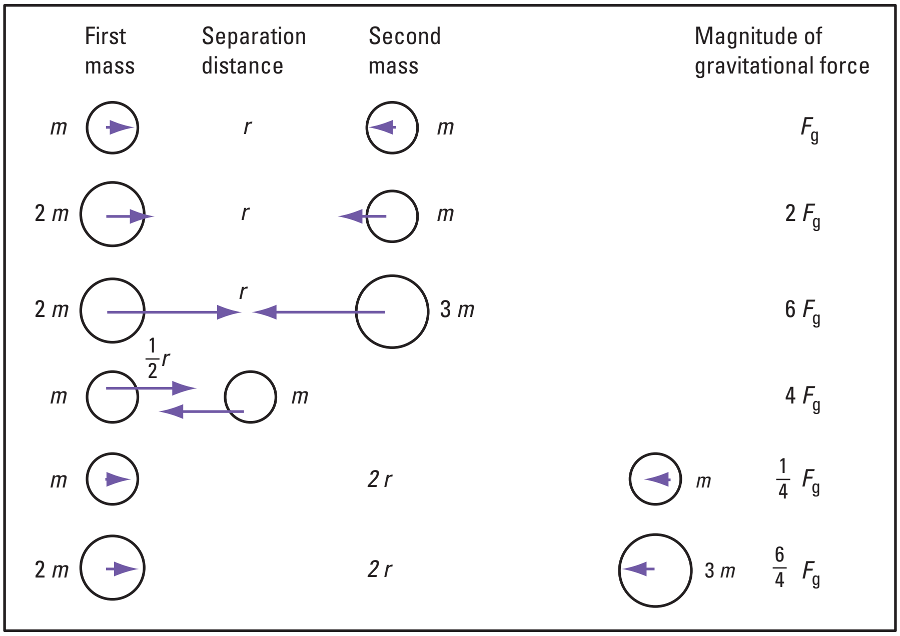

Figure 4.21 The magnitude of the gravitational force is directly proportional to the product of the two masses, and inversely proportional to the square of the separation distance.

Concept Check

Two identical stationary baseballs are separated by a distance *r*. Consider the tiny gravitational force which attracts each ball toward the other. What will happen to the magnitude of this gravitational force acting on either ball in each situation?

1. The mass of each ball doubles.
2. The distance of separation *r* is halved.
3. The mass of each ball is halved and *r* doubles.

Determining the Value of the Universal Gravitational Constant

Although Newton found a mathematical relationship for gravitational force, he was unable to determine the value of *G*. In 1798, scientist Henry Cavendish (1731–1810) used a torsion balance to confirm experimentally that Newton's law of gravitation is valid, and to determine the density of Earth. Cavendish's experimental setup was later used to determine the value of *G*.

A modern torsion balance is a device that uses a sensitive fibre and a beam of light to measure very minute forces due to gravity, magnetic fields, or electric charges (Figure 4.22). The currently accepted value of *G* to three significant digits, as measured by such a balance, is $6.67 \times 10^{-11}\ \text{N}\cdot\text{m}^2/\text{kg}^2$.

Example 4.4 on the next page uses Newton's law of universal gravitation to show that a person weighs slightly less at the top of a mountain than at its base. In other words, the force exerted by Earth on a person is less at the top of a mountain than at sea level.

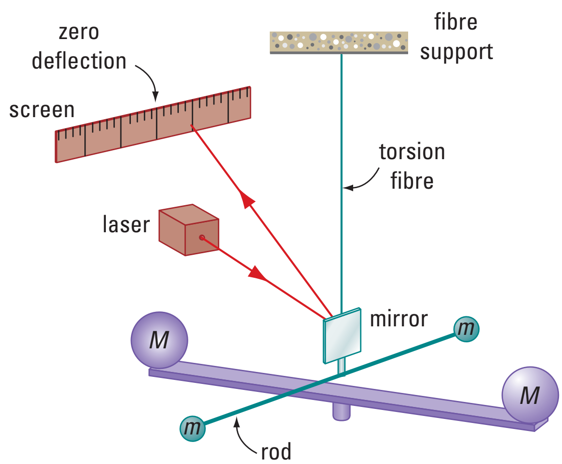

Figure 4.22 A modern torsion balance uses a laser beam to measure the amount of twist in the fibre.

Example 4.4

Mount Logan in the Yukon is 5959 m above sea level, and is the highest peak in Canada. Earth's mass is 5.97×10^{24} kg and Earth's equatorial radius is 6.38×10^{6} m. What would be the difference in the magnitudes of a 55.0-kg person's weight at the top of the mountain, and that person's weight at sea level (Figure 4.23)? Assume that Earth's equatorial radius is equal to the distance from Earth's centre to sea level.

Given

$m_p = 55.0$ kg
$h = 5959$ m
$m_{Earth} = 5.97 \times 10^{24}$ kg
$r_{Earth} = 6.38 \times 10^{6}$ m

Required

difference in magnitude of weight ($\Delta\vec{F}_g$)

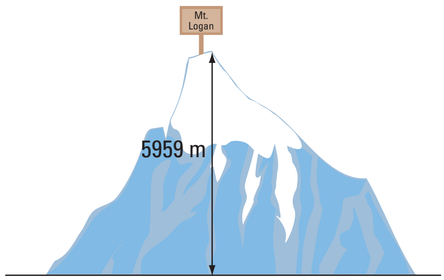

Figure 4.23

Analysis and Solution

Assume that the separation distance between the person at sea level and Earth's centre is equal to Earth's equatorial radius.

Sea level: $r_{SL} = r_{Earth} = 6.38 \times 10^{6}$ m
Top of mountain: $r_T = 6.38 \times 10^{6}$ m $+ 5959$ m

The person's weight is equal to the gravitational force exerted by Earth on the person, and is directed toward Earth's centre both at sea level and at the top of the mountain.

Calculate F_g at sea level using Newton's law of gravitation.

$$(F_g)_{SL} = \frac{Gm_p m_{Earth}}{(r_{SL})^2}$$
$$= \frac{\left(6.67 \times 10^{-11}\ \frac{\text{N}\cdot\cancel{\text{m}^2}}{\cancel{\text{kg}^2}}\right)(55.0\ \cancel{\text{kg}})(5.97 \times 10^{24}\ \cancel{\text{kg}})}{(6.38 \times 10^{6}\ \cancel{\text{m}})^2}$$
$$= 538.049 \text{ N}$$

Calculate F_g at the top of the mountain using Newton's law of gravitation.

$$(F_g)_T = \frac{Gm_p m_{Earth}}{(r_T)^2}$$
$$= \frac{\left(6.67 \times 10^{-11}\ \frac{\text{N}\cdot\text{m}^2}{\cancel{\text{kg}^2}}\right)(55.0\ \cancel{\text{kg}})(5.97 \times 10^{24}\ \cancel{\text{kg}})}{(6.38 \times 10^{6}\text{ m} + 5959\text{ m})^2}$$
$$= 537.045 \text{ N}$$

The difference in the magnitude of the weight is equal to the difference in magnitude of both gravitational forces.

$$\Delta F_g = (F_g)_{SL} - (F_g)_T$$
$$= 538.049 \text{ N} - 537.045 \text{ N}$$
$$= 1.00 \text{ N}$$

Paraphrase

The difference in the magnitudes of the person's weight is 1.00 N.

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Take It Further

How does the gravitational force on Earth's oceans due to the Moon create Earth's tides?

Practice Problems

1. Two people, A and B, are sitting on a bench. Their centres are 0.60 m apart. A has a mass of 55 kg and B a mass of 80 kg. Calculate the magnitude of the gravitational force exerted by B on A.
2. The mass of the *Titanic* was 4.6×10^{7} kg. Suppose the magnitude of the gravitational force exerted by the *Titanic* on the fatal iceberg was 61 N when the separation distance between their centres was 100 m. What was the mass of the iceberg?

Answers

1. 8.2×10^{-7} N
2. 2.0×10^{8} kg

Why is *G* Universal?

Why did Newton believe that his equation $F_g = \frac{Gm_A m_B}{r^2}$ would predict gravitational force anywhere in the universe, with the exact same value of G? He was building on the work of many previous scientists, including German astronomer Johannes Kepler (1571–1630), who worked out simple and accurate laws for the motion of bodies in our solar system. Newton realized that he could only explain Kepler's laws if G, the constant in his own law of gravitation, really was a constant with the same value everywhere. So thinking about planets moving in space allowed Newton to develop a law that also predicts how objects move due to Earth's gravity in everyday life. It works equally well for predicting how long a dive from the 10-m board takes or guiding spacecraft around the solar system.

B3 Quick Lab PHYSICS•SOURCE

How Mass and Weight are Related in Earth's Gravitational Field

Purpose

To determine the relationship between the mass of an object and the local value of the gravitational force exerted on that object

Activity Overview

In this activity, using a range of standard masses, you will measure the gravitational force on each mass — its weight — and determine a relationship between the masses and their weights.

Prelab Questions

Consider the questions below before beginning this activity.

1. Predict the type of relationship between mass and gravitational force you will discover in this activity.
2. How would you recognize this type of relationship?

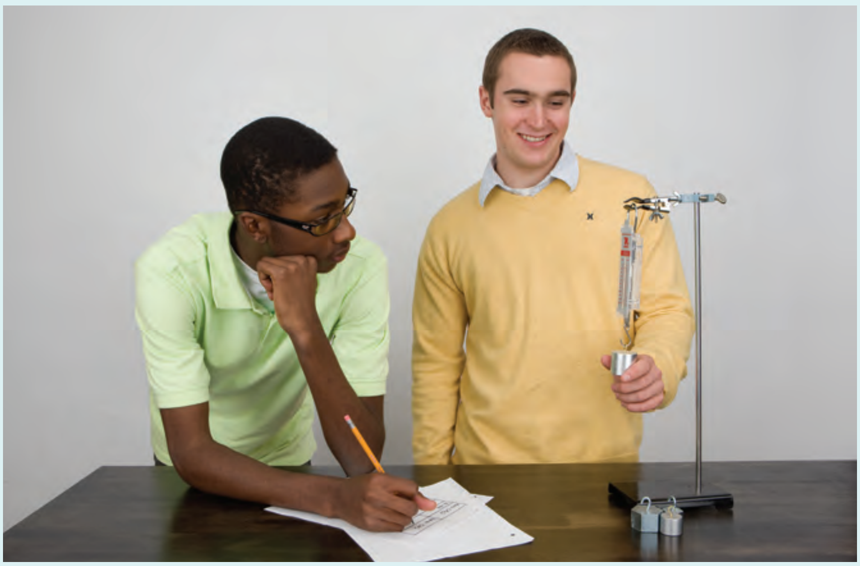

Figure 4.24 Lab setup

4.2 Check and Reflect

Key Concept Review

1. Calculate the weight of a 75-kg student sitting at a desk in a classroom.
2. Calculate the mass of a student if her weight is 5.3×10^2 N.
3. Why is G called a "universal" constant?
4. In your own words, define gravitational field strength.
5. In your own words, explain the concept of a gravitational field. Include an example of how a gravitational field affects another object.
6. Why do physicists use the concept of a field to describe gravity?
7. Distinguish between mass and weight. Explain using an example and a diagram.
8. Your weight changes slightly between the base of a mountain and its peak. Which variable is changing to cause this to happen?

Connect Your Understanding

9. The table below shows the magnitude of the gravitational force on objects of different mass in Ottawa.

Magnitude of Gravitational Force on Objects

Mass (kg)	0	1.50	3.00	4.50	6.00	7.50	10.0
Magnitude of Gravitational Force (N)	0	14.7	29.4	44.1	58.9	73.6	98.1

   (a) Graph the data with "Force" on the y-axis and "Mass" on the x-axis.
   (b) Calculate the slope of the line.
   (c) What does the slope represent?

10. Object A exerts a gravitational force of magnitude 8.2×10^{-10} N on object B. Determine the magnitude of the gravitational force if, simultaneously, the separation distance is tripled, m_A increases by 4 times, and m_B is halved. Explain your reasoning.

11. Suppose F_g is the magnitude of the gravitational force between two people with a separation distance between their centres of 1.0 m. How would F_g change if
   (a) the separation distance became 2.0 m?
   (b) one of the original two people was joined by a friend of equal mass while at this 2.0-m separation distance?

12. The Moon has a mass of 7.35×10^{22} kg and its equatorial radius is 1.74×10^6 m. Earth's mass is 5.97×10^{24} kg and its equatorial radius is 6.38×10^6 m.
   (a) Calculate the magnitude of the gravitational force exerted by
      i) the Moon on a fully suited 100-kg astronaut standing on the Moon's surface, and
      ii) Earth on a fully suited 100-kg astronaut standing on Earth's surface.
   (b) Explain why the values of F_g in part (a) are different.

13. Suppose the equatorial radius of Earth was the same as the Moon, but Earth's mass remained unchanged. The Moon has an equatorial radius of 1.74×10^6 m. Earth's mass is 5.97×10^{24} kg and its equatorial radius is 6.38×10^6 m.
   (a) Calculate the gravitational force that this hypothetical Earth would exert on a 1.00-kg object at its surface.
   (b) How does the answer in part (a) compare to the actual gravitational force exerted by Earth on this object?
   (c) How does the answer in part (a) compare to the actual gravitational force exerted by the Moon on this object, if it were are the Moon's surface?

Reflection

14. What was one thing you learned in this section that surprised you?
15. How did your understanding of mass and weight change after working on this section?

For more questions, go to PHYSICS•SOURCE

4.3 Gravitational Field Strength and Gravitational Acceleration

Section Summary

- Gravitational field strength and gravitational acceleration are closely related concepts.
- There are slightly different values of gravitational field strength on Earth.
- The variation in g on Earth can be applied in geology.
- Weightlessness is experienced during free fall, but the value of g is unchanged.

Determining Gravitational Field Strength

The acceleration due to gravity, $\vec{g}$, near or on Earth's surface is about 9.81 m/s² [down]. But where does the value of 9.81 m/s² come from?

Consider the forces acting on a test mass m_{test} some distance above Earth's surface, where Earth has a mass of m_{source}. The only force acting on m_{test} is the gravitational force exerted by Earth on the test mass (Figure 4.25).

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Suggested Activity

- B4 Inquiry Activity Overview on page 122

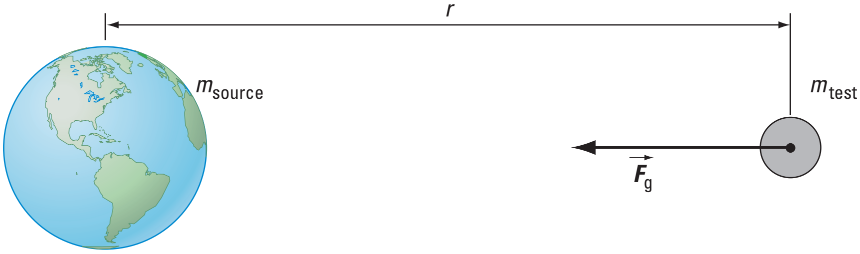

Figure 4.25 The gravitational force exerted by Earth on a test mass m_{test}.

The magnitude of $\vec{F}_g$ can be evaluated two ways: using the concept of weight or using Newton's law of gravitation.

Weight: $F_g = mg$

Newton's law of gravitation: $F_g = \dfrac{Gm_{test}m_{source}}{r^2}$

Since the value of F_g is the same no matter which equation you use, set both equations equal to each other.

$$\cancel{m_{test}}g = \frac{G\cancel{m_{test}}m_{source}}{r^2}$$

$$g = \frac{Gm_{source}}{r^2}$$

So no matter where the test mass is located in the universe, you can calculate the magnitude of the gravitational field strength (or gravitational acceleration) at any distance from a celestial body. To do this, you need to know the mass m_{source} of the celestial body and the separation distance r between the centres of the test mass and the celestial body.

Different Values of Gravitational Field Strength on Earth

For a long time, people thought that the magnitude of the gravitational field strength was constant at all locations on Earth's surface. However, scientists discovered that the value of *g* depends on both latitude and altitude. **Latitude** is the angular distance north or south of the equator. **Altitude** is the elevation of the ground above sea level. Figure 4.26 shows how the magnitude of *g* at sea level varies with latitude.

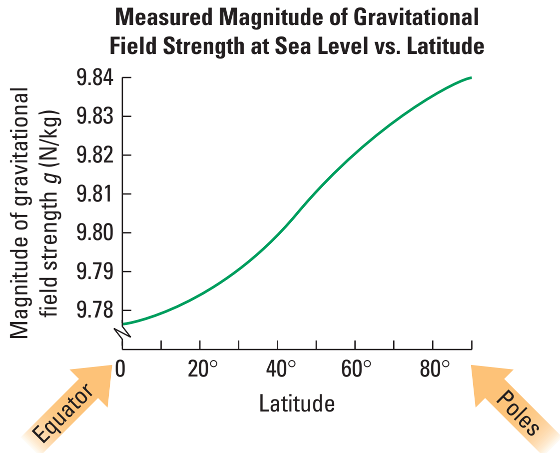

Figure 4.26 Gravitational field strength at sea level as a function of latitude

The value of *g* increases as you move toward either the North or South Pole, because Earth is not a perfect sphere. It is flatter at the poles and it bulges out slightly at the equator. In fact, Earth's radius is 21 km greater at the equator than at the poles. So an object at the equator is farther away from Earth's centre than if the object were at the North Pole. Since $g \propto \frac{1}{r^2}$, the farther an object is from Earth's centre, the smaller the value of *g* will be.

Other factors affect the gravitational field strength at Earth's surface. The materials that make up Earth's crust are not uniformly distributed. Some materials, such as gold, are denser than materials such as zinc. Earth's rotation about its axis also reduces the measured value of *g*, but the closer an object is to the North or South Pole, the less effect Earth's rotation has on *g*.

Applications of the Variation in *g* in Geology

The variation in the value of *g* on Earth is used to detect the presence of minerals and oil. Geophysicists and geologists use sensitive instruments called gravimeters to detect small variations in *g* when they search for new deposits of minerals or oil. Gold and silver deposits increase the value of *g*, while deposits of oil and natural gas decrease *g*. Figure 4.27 is an example of a map that shows different measured values of *g* as lines, where each line represents a specific value of *g*.

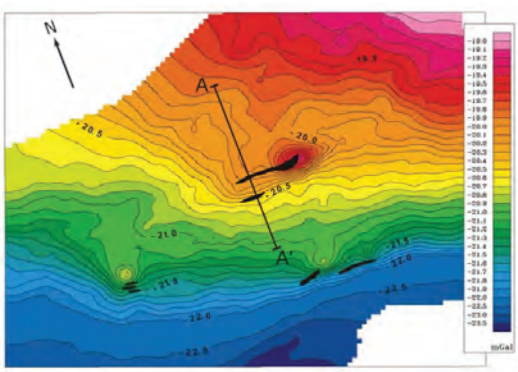

Figure 4.27 A map showing the location of sulphide deposits in northern New Brunswick (shown in black)

How Is Gravitational Field Strength Related to Gravitational Acceleration?

To see how gravitational field strength is related to gravitational acceleration, use the definition of a newton, 1 N = 1 kg·m/s². Then substitute kilogram-metres per second squared for newtons in the equation for gravitational field strength:

$$1\ \text{N/kg} = 1\,\frac{\cancel{\text{kg}}\cdot\dfrac{\text{m}}{\text{s}^2}}{\cancel{\text{kg}}}$$

$$\boxed{1\ \text{N/kg} = 1\,\frac{\text{m}}{\text{s}^2}}$$

Metres per second squared are the units of acceleration. So in terms of units, gravitational field strength and gravitational acceleration are equivalent.

Calculating the Gravitational Acceleration of an Object on Two Celestial Bodies

Example 4.5 demonstrates how to calculate the gravitational acceleration at the equator on Earth's surface and that on the surface of the Moon. These two values are then compared to find the ratio of g_{Earth} to g_{Moon}.

To solve Example 4.5 requires using data from Table 4.3, which shows the mass and equatorial radius of the Sun, the Moon, and each planet in the solar system.

Table 4.3 Masses and Radii for Celestial Bodies in the Solar System*

Celestial Body	Mass (kg)	Equatorial Radius (m)
Sun	1.99×10^{30}	6.96×10^{8}
Mercury	3.30×10^{23}	2.44×10^{6}
Venus	4.87×10^{24}	6.05×10^{6}
Earth	5.97×10^{24}	6.38×10^{6}
Earth's Moon	7.35×10^{22}	1.74×10^{6}
Mars	6.42×10^{23}	3.40×10^{6}
Jupiter	1.90×10^{27}	7.15×10^{7}
Saturn	5.69×10^{26}	6.03×10^{7}
Uranus	8.68×10^{25}	2.56×10^{7}
Neptune	1.02×10^{26}	2.48×10^{7}

*Source: Jet Propulsion Laboratory, California Institute of Technology

Example 4.5

(a) Calculate the magnitude of the gravitational acceleration of an object at the equator on the surface of Earth and the Moon (Figure 4.28). Refer to Table 4.3 above.

(b) Determine the ratio of g_{Earth} to g_{Moon}. How different (as a ratio) would your weight be on the Moon than on Earth?

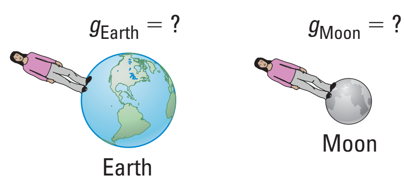

Figure 4.28

Given

$m_{Earth} = 5.97 \times 10^{24}$ kg $r_{Earth} = 6.38 \times 10^{6}$ m
$m_{Moon} = 7.35 \times 10^{22}$ kg $r_{Moon} = 1.74 \times 10^{6}$ m

Required

(a) magnitude of gravitational acceleration at equator on Earth and on the Moon (g_{Earth} and g_{Moon})
(b) ratio of g_{Earth} to g_{Moon}

Analysis and Solution

(a) Use the equation $g = \frac{Gm_{source}}{r^2}$ to calculate the magnitude of the gravitational field strength on each celestial body. The magnitude of the gravitational acceleration is numerically equal to the magnitude of the gravitational field strength.

Earth:

$$\begin{aligned} g_{Earth} &= \frac{Gm_{Earth}}{(r_{Earth})^2} \\ &= \frac{\left(6.67 \times 10^{-11}\ \frac{\text{N}\cdot\cancel{\text{m}^2}}{\cancel{\text{kg}^2}}\right)(5.97 \times 10^{24}\ \cancel{\text{kg}})}{(6.38 \times 10^{6}\ \cancel{\text{m}})^2} \\ &= 9.783\ \text{N/kg} \\ &= 9.783\ \text{m/s}^2 \end{aligned}$$

The Moon:

$$\begin{aligned} g_{Moon} &= \frac{Gm_{Moon}}{(r_{Moon})^2} \\ &= \frac{\left(6.67 \times 10^{-11}\ \frac{\text{N}\cdot\cancel{\text{m}^2}}{\cancel{\text{kg}^2}}\right)(7.35 \times 10^{22}\ \cancel{\text{kg}})}{(1.74 \times 10^{6}\ \cancel{\text{m}})^2} \\ &= 1.619\ \text{N/kg} \\ &= 1.619\ \text{m/s}^2 \end{aligned}$$

(b) Calculate the ratio of g_{Earth} to g_{Moon}.

$$\begin{aligned} \frac{g_{Earth}}{g_{Moon}} &= \frac{9.783\ \cancel{\text{m/s}^2}}{1.619\ \cancel{\text{m/s}^2}} \\ &= 6.04 \end{aligned}$$

Paraphrase

(a) The magnitudes of the gravitational accelerations at the equator on the surfaces of Earth and the Moon are 9.78 m/s² and 1.62 m/s², respectively.
(b) The ratio of g_{Earth} to g_{Moon} is 6.04. So your weight would be about 6 times less on the Moon than on Earth.

Practice Problems

1. A satellite orbits Earth at a distance of $3r_{Earth}$ above Earth's surface. Use the data from Table 4.3 on page 117.
   (a) How many Earth radii is the satellite from Earth's centre?
   (b) What is the magnitude of the gravitational acceleration of the satellite?
2. An 80.0-kg astronaut is in orbit 3.20×10^4 km from Earth's centre.
   (a) Calculate the magnitude of the gravitational field strength at the location of the astronaut.
   (b) What would be the magnitude of the gravitational field strength if the astronaut is orbiting the Moon with the same separation distance?
3. The highest satellites orbit Earth at a distance of about $6.6r_{Earth}$ from Earth's centre. What would be the gravitational force on a 70-kg astronaut at this location?

Answers

1. (a) $4r_{Earth}$
   (b) 6.11×10^{-1} m/s²
2. (a) 3.89×10^{-1} N/kg
   (b) 4.79×10^{-3} N/kg
3. 16 N [toward Earth's centre]

Concept Check

A student weighs 638 N [down] in Ottawa, Ontario.

1. The student says that he weighs 638 N [down] anywhere on Earth. Is he correct?
2. What property of matter would he be more accurate to state?
3. Why does this property of matter give a more accurate statement?

Free Fall

Suppose that a student is standing on a scale calibrated in newtons in an elevator. Suppose the elevator cable breaks (Figure 4.29). Assuming that frictional forces are negligible, the elevator, student, and scale all fall toward Earth with an acceleration of g. The student is now in **free fall**, the condition in which the only force acting on an object is $\vec{F}_g$. Italian scientist Galileo Galilei (1564–1642) made the first modern investigations into how objects in free fall behave.

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Suggested Activity

- B5 Quick Lab Overview on page 122

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Explore More

How did Galilieo's original free-fall experiment work?

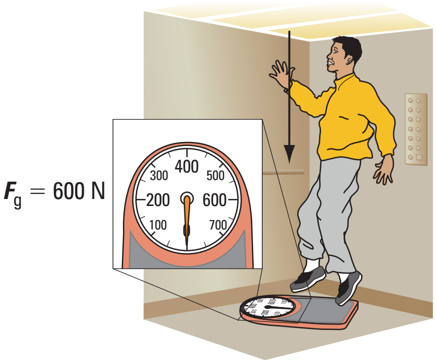

Figure 4.29 The elevator, student, and scale are in free fall.

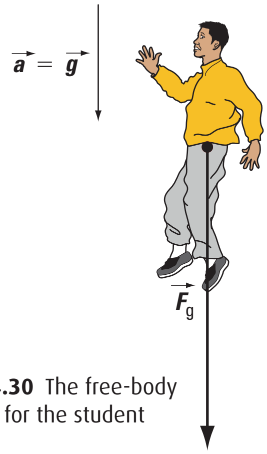

Figure 4.30 The free-body diagram for the student

To understand free fall, draw the free-body diagram for the student (Figure 4.30). In Figure 4.29, the scale reads zero because it no longer exerts a normal force on the student, so $\vec{F}_N = 0$. Since $\vec{F}_N = 0$, the student's apparent weight is also zero. Sometimes an object in free fall is described as being "weightless." However, this description is incorrect. In free fall, $\vec{F}_N = 0$ but $\vec{F}_g \neq 0$.

The gravitational acceleration can be used to calculate the time of fall for an object undergoing free fall. Example 4.6 shows how the acceleration due to gravity can be used to measure the time taken for an object to fall.

Example 4.6

Calculate the time needed for a 0.600 kg geology hammer to reach the surface if dropped from 10.0 m at the equator

(a) on Earth

(b) on the Moon

Given

$\vec{g}_{\text{Moon}} = 1.619\ \text{m/s}^2$ [down]

$\vec{g}_{\text{Earth}} = 9.783\ \text{m/s}^2$ [down]

$\vec{v}_1 = 0$ m/s

$\Delta\vec{d} = 10.0$ m [up]

$m = 0.600$ kg

Required

The time taken for the hammer to fall 10.0 m

Practice Problems

1. Calculate the time needed for a 25-cent coin of mass 4.4 g to fall if dropped from a height of 1.5 m at the equator
   (a) on Earth
   (b) on the Moon
2. It takes 1.03 s for an object to fall 8.10 m on Planet X.
   (a) Calculate $\vec{g}$ for Planet X.
   (b) Would you feel heavier on Planet X than you do on Earth? Explain.
3. How far will a mass fall in 5.3 s if dropped on Earth at the equator (assume air resistance has no effect)?

Answers

1. (a) 0.55 s
   (b) 1.4 s
2. (a) 15.3 m/s^2
   (b) Yes, because $\vec{g}$ is larger on Planet X than on Earth.
3. 1.4×10^2 m

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Explore More

Would a hammer and a feather, dropped on the Moon at the same time from the same height, hit the surface at the same instant?

Analysis and Solution

The mass of the hammer is not relevant.

Use the equation from Chapter 2, $\Delta\vec{d} = \vec{v}_1\Delta t + \frac{1}{2}\vec{a}(\Delta t)^2$ and substitute $\vec{v}_1 = 0$ m/s and each of g_{Earth} and g_{Moon} in turn for a, yielding $\Delta t = \sqrt{\frac{2\Delta d.}{g}}$

For simplicity, we will set the downward direction as positive.

(a) On Earth:

$$\begin{aligned}\Delta t &= \sqrt{\frac{2\Delta d}{g}}\\ &= \sqrt{\frac{2(10.0)\ \cancel{\text{m}}}{9.783\ \cancel{\text{m}}/\text{s}^2}}\\ &= \sqrt{2.044\ \text{s}^2}\\ \Delta t &= 1.430\ \text{s}\end{aligned}$$

(b) On the Moon:

$$\begin{aligned}\Delta t &= \sqrt{\frac{2\Delta d}{g}}\\ &= \sqrt{\frac{2(10.0)\ \cancel{\text{m}}}{1.619\ \cancel{\text{m}}/\text{s}^2}}\\ &= \sqrt{12.35\ \text{s}^2}\\ \Delta t &= 3.514\ \text{s}\end{aligned}$$

Paraphrase

It took 1.43 s for the hammer to fall 10.0 m on Earth and 3.51 s on the Moon (Figure 4.31).

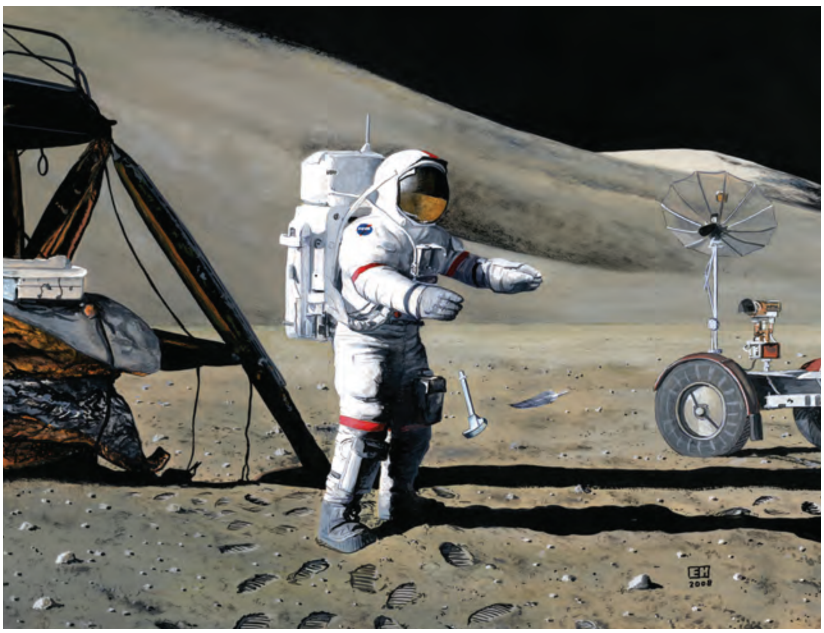

Figure 4.31 Astronaut David Scott drops a hammer and a feather on the surface of the Moon.

Weightlessness

Videos transmitted from the International Space Station (ISS) often show astronauts floating in their living area (Figure 4.32). Are the astronauts truly weightless in space? The answer is no. Then why do they appear to be weightless?

Figure 4.32 At the altitude of the International Space Station, the value of g is about 90% of its value at Earth's surface. However, the astronauts only experience microgravity in the range of about one millionth of this value.

Since the ISS is some distance above Earth, g is somewhat less than its value at Earth's surface, because $g \propto \frac{1}{r^2}$. However, this does not explain why astronauts feel weightless. While the ISS orbits Earth at high speed in an almost circular path, Earth exerts a gravitational force on the ISS and everything in it. So the ISS is able to remain in orbit. If an astronaut were standing on a scale in the ISS, the scale would read zero, because the ISS and everything in it are in free fall. The astronaut would feel "weightless" because the gravitational force exerted by Earth pulls the ISS and the astronaut toward Earth at the same acceleration.

Suppose an astronaut is in a rocket in deep space and the acceleration of the rocket is zero. The astronaut would experience no measurable gravitational forces from any celestial bodies, and the astronaut's acceleration would be zero. In this situation, the astronaut would have a true weight of zero as well as an apparent weight of zero, a condition called true weightlessness.

Astronauts experience free fall continuously for as long as they stay in orbit. But it takes a lot of energy to accelerate a spacecraft to orbital speed, which can be up to approximately 29 000 km/h. In the last few years, many aerospace companies have been researching or working on suborbital vehicles that reach significantly lower speeds to fly unpowered above Earth's atmosphere, but only for a few minutes. Imagine an elevator accelerating so rapidly that it bursts out of the top of the building and flies into the air. Until the elevator falls back to the top of the building, anyone inside will be in free fall. Suborbital flights work on the same principle.

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Explore More

What are the challenges of living in a microgravity environment for extended periods of time?

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Take It Further

How has gravity imaging helped scientists explain the extinction of the dinosaurs?

DI Key Activity

B4 Inquiry Activity

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REQUIRED SKILLS
- Measuring
- Recording and organizing data

Video

Determining the Acceleration Due to Earth's Gravity Using a Pendulum

Question

What is the acceleration due to gravity at Earth's surface?

Activity Overview

In this activity, you will calculate the value of g at Earth's surface by determining the period T of a pendulum of length ℓ — the time for the pendulum bob to go from one extreme position to the other and back again — and applying a formula that relates g to T and ℓ.

Figure 4.33 Using a pendulum to calculate acceleration due to Earth's gravity

Prelab Questions

Consider the questions below before beginning this activity.

1. What variables could affect the measurement of the period of a pendulum?
2. Look at the formula $T = 2\pi\sqrt{\frac{\ell}{g}}$, which you will use in this activity to try to determine g. The 2π term is constant. What variables do you think will affect the value of g? What variables do you think will not affect it?
3. What do you think will happen to the period T if you vary the mass of the pendulum bob, but keep all the other variables constant?

B5 Quick Lab

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Falling Coins

Purpose

To compare the rates of falling of objects of different shapes and sizes, dropped from the same height

Activity Overview

In this activity, you will investigate the rate at which different-sized coins fall in Earth's gravitational field. This is similar to the legendary experiment in which Galileo is said to have dropped different masses from the top of the Leaning Tower of Pisa in Italy.

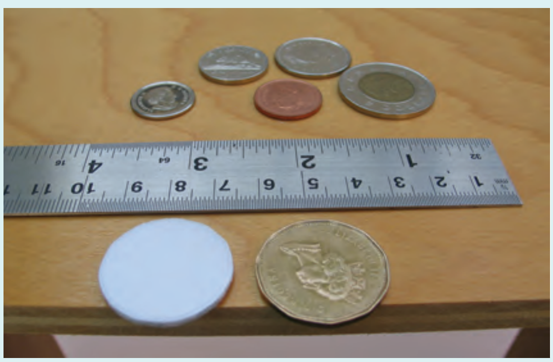


Figure 4.34 Comparing rates of falling objects

Prelab Questions

Consider the questions below before beginning this activity.

1. Predict whether a loonie will fall faster than a penny.
2. Predict whether a loonie will fall faster than a Styrofoam™ disk of the same size.
3. Justify your predictions in Questions 1 and 2.

4.3 Check and Reflect

Key Concept Review

1. Why is free fall different than simply letting yourself float under water?

2. Calculate the force of attraction between a 1.0×10^3-kg car and a 1.6×10^3-kg truck if their centres are separated by 2.6 m.

3. List two factors that affect the magnitude of the gravitational field strength at Earth's surface.

4. Explain why astronauts are never truly weightless while in orbit.

Connect Your Understanding

5. Where would you feel heavier, at the North Pole or at the equator? Explain.

6. Calculate the gravitational field strength at the location of a 70-kg astronaut $2.0r_{\text{Earth}}$ from Earth's centre. Use the data from Table 4.3 on page 117.

7. Is there a place in the universe where true weightlessness actually exists?

8. (a) Calculate the magnitude of the gravitational field strength at the surfaces of the celestial bodies listed in Table 4.3.
(b) Rank them from least to greatest.

9. Compared to Earth, how would your weight change on Uranus?

10. Graph the equation $g = \dfrac{Gm_{\text{Moon}}}{r^2}$ using technology. Plot g on the y-axis (range of 0 to 2.0 N/kg) and r on the x-axis (range of $1r_{\text{Moon}}$ to $5r_{\text{Moon}}$). Read values of g corresponding to specific values of r to answer these questions:
(a) Describe the graph of g vs. r. How is it similar to Figure 4.20 on page 110?
(b) What is the value of g
i) on the surface?
ii) at $0.5r_{\text{Moon}}$ above the surface?
iii) at r_{Moon} above the surface?
(c) At what distance is g one hundredth of the gravitational field strength on the surface of the Moon?

11. Explain why a 2.35-g penny and a 3.95-g nickel would hit the ground at the same time if dropped simultaneously from the same height.

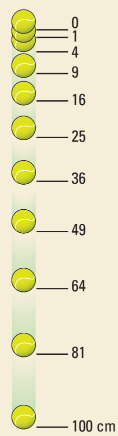
12. A 7.50-kg turkey standing at the top of Ishpatina Ridge, at 693 m the highest point in Ontario, weighs 73.5 N [down]. Calculate the magnitude of the gravitational field strength at this location.

13. Calculate the time required for an astronaut to free-fall 50 m on the Moon.

14. If an 85-kg astronaut has a weight of 314 N, which planet is she standing on?

15. A 50-kg astronaut experiences an acceleration of $5.0g$ [up] during liftoff.
(a) How many times greater than the astronaut's weight is the force she experiences due to the thrust of the spacecraft's engines?
(b) Draw a free-body diagram for the astronaut during liftoff.
(c) What is the astronaut's true weight?
(d) What is the astronaut's apparent weight?

16. The figure shows a ball falling in a vacuum (with no air resistance).
(a) What do you notice about the distance fallen after each frame?
(b) Why do you think this is so?
(c) What would be different if the ball were falling through air?



Question 16

Reflection

17. Describe three things about variations in Earth's gravitational field that you did not know before working on this section.

18. Describe an analogy that helps you understand the concept of free fall.

For more questions, go to PHYSICS•SOURCE

CHAPTER REVIEW

Key Concept Review

1. List the four fundamental forces in order of strength, from weakest to strongest. k
2. Name the fundamental force responsible for k
   (a) a leaf falling from a tree
   (b) holding the nucleus of a silver atom together
   (c) a spring returning to its original shape after being stretched
3. How can the net force acting on an object be determined? k
4. It is said that most forces that you would notice in everyday life are electromagnetic in origin. Why is this so? c
5. State how many forces must be present if an object such as a ball is deformed yet kept stationary. Draw a diagram to illustrate your answer. c
6. Draw a free-body diagram of k
   (a) a figure skater during a glide
   (b) a hammer falling on the Moon
   (c) an arrow in horizontal flight on a windy day
7. Why are free-body diagrams important tools in physics? k
8. Draw a free-body diagram for each object. k
   (a) A student applies a force of 50 N [right] to a mass while two other students each apply a force of 10 N [Left] on the same mass.
   (b) The engine of an airplane flying at constant velocity applies a thrust of 1.6×10^5 N.
   (c) A small model rocket exerts a thrust of 6.0 N in the opposite directon to a gravitational force of 0.39 N and negligible air resistance.
9. Describe how planetary gravitational forces can affect the path of a space probe. c
10. What is the significance of the term "universal" in Newton's law of universal gravitation? k
11. A brick placed on an equal arm balance requires 5.0 kg to just balance it. When the brick is hung from a spring scale, the scale reads 48 N. The balance, standard masses, spring scale, and brick are moved to a planet where the gravitational field strength is 2.0 times that on Earth. What will be the readings on the balance and on the spring scale in this new location? k
12. Why was the concept of a field introduced by physicists? k
13. Using your knowledge of gravitational fields, c
    (a) Draw an example of a gravitational field near a very massive object, such as a star, and another near a lighter object such as a comet.
    (b) How did you show the difference in the strengths of the fields?
14. How does gravitational field strength vary with the mass of a celestial body? Assume that the radius of the body is fixed. k
15. Calculate the gravitational force acting on a 9.6-kg mass k
    (a) 1.5×10^4 km above Earth's centre
    (b) At an altitude of 1.2×10^7 m above Earth's surface.
16. Given that the mass of Saturn is 5.69×10^{26} kg and its equatorial radius is 6.03×10^7 m, calculate the gravitational field strength at its surface. k
17. On which planets would you feel lighter than on Earth? k
18. Calculate the gravitational field strength experienced by an astronaut located at an altitude of 1.4×10^5 km above Earth's surface. k
19. Draw a concept map to identify and link the concepts needed to understand gravitational acceleration and gravitational field strength near a celestial body other than Earth. Create and solve a problem to demonstrate your understanding of these concepts. c

Connect Your Understanding

20. The gravitational field strength and the universal gravitational constant are both useful quantities.
    (a) How are they similar? t
    (b) How are they different? t
21. Astronauts who stay aboard the International Space Station must spend some time exercising their muscles. Discuss, in terms of physics, why it is important for them to exercise. a

22. The Moon exerts a gravitational force that is about $\frac{1}{6}$ that exerted by Earth. Explain why the mass of an object measured on the Moon using a mass balance is the same as if the object were on Earth's surface. a

23. Write a short paragraph summarizing Newton's law of gravitation. Include a numerical example that illustrates the law. t

24. Describe the effect a planet's gravitational field strength would have on future planetary settlers with regard to
    (a) Day-to-day life on that planet c
    (b) Future generations of settlers on that planet c

25. Why is it better to say that objects are massive as opposed to heavy? t

26. Calculate the gravitational force between two students of mass 55 kg and 75 kg sitting with their centres 65 cm apart. a

27. The gravitational field strength at Earth's surface is about 9.81 N/kg [down]. What is the gravitational field strength exactly 1.6 Earth radii from Earth's centre? a

28. Calculate the net forces for each situation in Question 8. a

29. Use the data from Table 4.3 on page 117. Calculate the true weight of a 60.0-kg astronaut on
    (a) the surface of Mars a
    (b) the surface of Saturn a

30. A 1.0-kg object, initially at rest, is dropped toward Earth's surface. It takes 2.26 s for the object to fall 25 m. Determine how long it takes a 2.0-kg object to fall this distance from rest at the surface of Jupiter. Use data from Table 4.3 on page 117. a

31. Object A experiences a gravitational force due to object B of magnitude 2.5×10^{-8} N. Determine the magnitude of the gravitational force if the separation distance is halved, m_A increases seven times, and m_B is reduced to one quarter of its original value. a

32. Show mathematically that the mass of an object has no effect on its acceleration while the object is in free fall in a vacuum. t

33. Describe the steps you would use to determine the distance from Earth's centre where the gravitational force exerted by Earth on a spacecraft is balanced by the gravitational force exerted by the Moon. Assume that you know the distance from Earth's centre to the centre of the Moon. Do not do the calculations. c

34. Would a student feel heavier on Mars or on Earth? Explain. c

35. Show that astronauts living on the International Space Station at an altitude of 3.5×10^2 km above Earth's surface still have about 90% of the gravitational force they felt while on the launching pad. a

36. Why can any mass found in the physics lab be a test mass when measuring Earth's gravitational field strength? t

Reflection

37. Identify three questions that you have about gravitational force and fields. c

38. What topics discussed in this chapter would you like to learn more about? Why? c

Unit Task Link

In this chapter, you learned about the force of gravity and its effects on various objects. You discovered that weight is measured in newtons and mass is measured in kilograms. The weight of an object is calculated using the equation $\vec{F}_g = m\vec{g}$.

You also discovered how to obtain a value for the gravitational field strength, g, in newtons per kilogram. Although this constant doesn't vary very much between locations, a careful measurement of this value for your particular location will be required for the Unit Task.

To prepare for this task, create a list of average masses for passenger cars, sport utility vehicles (SUVs), and light trucks. You will also be investigating the types of tires on various vehicles, so calculate the weight of an average passenger car tire as well as the weight of a tire from a typical SUV and a typical light truck.

For more questions, go to PHYSICS•SOURCE