4.1 Gravitational Force Near Earth

Some people try skydiving just for the thrill. Others may skydive as part of military training. Still others like the view and the feeling of weightlessness.

The only forces acting on a skydiver jumping out of a plane are gravity and air resistance. Since the force of gravity is so much greater in magnitude than the air resistance at the beginning of the dive, the skydiver accelerates downward, initially at 9.8 m/s^2 [down]. As the skydiver continues to fall, the acceleration decreases until the skydiver reaches a constant speed (**Figure 1**). At this speed, the skydiver is no longer accelerating. In this section, you will investigate the forces that act on a falling object and why that object eventually reaches a constant speed.

Figure 1 A skydiver is affected by the force of gravity and air resistance.

Air Resistance and Free Fall

Figure 2(a) shows a small, heavy ball falling from rest. The photograph was taken using a flash that goes on and off at equal time intervals. The image of the ball was then captured at different positions during its fall. Notice that the distance between the starting position and the position in the second image is small, while the images get farther and farther apart at later times. This uneven spacing means that the ball is accelerating while it is falling.

Now look at the falling object in **Figure 2(b)**. The photograph shows a light object, a maple key, with a large cross-sectional area. The cross-sectional area is the area you see if you look directly up at the falling object. Notice that the distance between successive images in this photograph is constant. This means that the object is not accelerating but is falling with constant velocity. So the net force acting on the object in the vertical direction is zero. In this situation, another force must be acting on the falling object other than gravity. The force that balances gravity is air resistance—friction caused by the air. In this chapter, we will often ignore air resistance when examining falling objects. When an object is falling under the influence of gravity only, the object is said to be in **free fall**.

free fall the motion of a falling object where the only force acting on the object is gravity

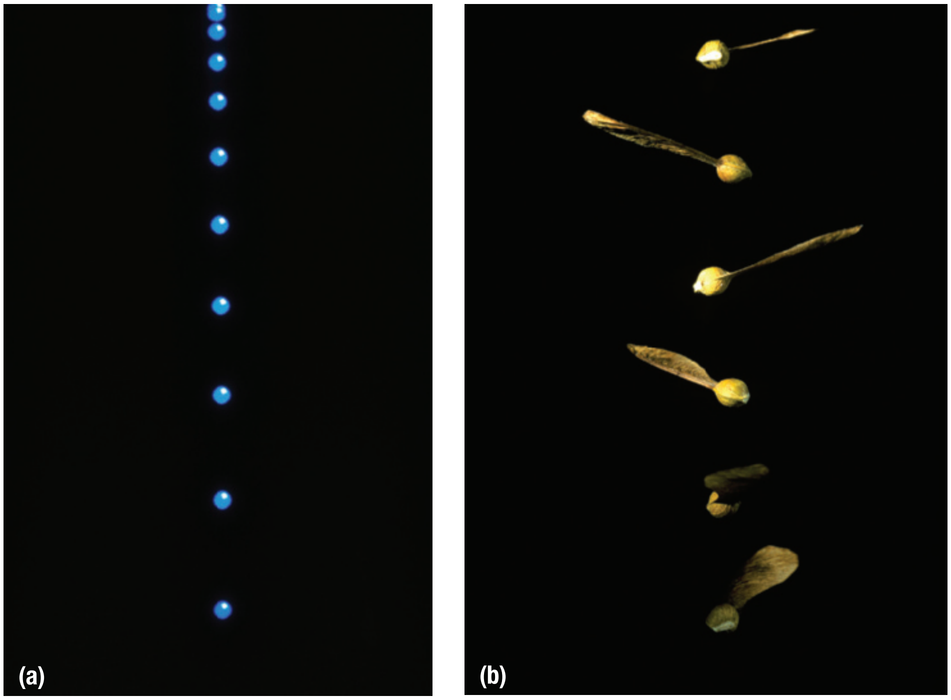

Figure 2 (a) Multi-flash photograph of a ball in free fall starting from rest (b) Multi-flash photograph of a light object with large surface area in free fall. Which object is accelerating? How can you tell?

The force of air resistance acting on an object depends on many factors. One factor is the cross-sectional area of the object. Larger cross-sectional areas experience more air resistance than smaller cross-sectional areas. To test this, hold a sheet of paper horizontally in one hand and an identical sheet of paper crumpled up into a ball in the other hand. Then drop both objects from the same height. You will notice that the crumpled paper falls much more quickly than the sheet of paper. Both objects have the same mass and experience the same force of gravity. However, the air resistance acting on each object is quite different. The horizontal sheet of paper has a larger cross-sectional area, so it experiences more air resistance. Another factor that affects the force of air resistance is the speed of the object. Faster-moving objects experience more air resistance. Air resistance acts opposite to the direction of motion of the object if there is no wind.

Now we return to the example of the skydiver. The skydiver jumps out of the plane and starts falling. The instant the skydiver leaves the plane, her initial velocity in the vertical direction is zero and she experiences very little air resistance (**Figure 3(a)**). As the skydiver continues to fall, her speed increases and she is now accelerating. As the speed of the skydiver increases, the magnitude of air resistance acting on her also increases (**Figure 3(b)**). During the time that the air resistance is increasing, the net force on the skydiver is decreasing. This means that the acceleration of the skydiver is decreasing. Eventually the magnitude of air resistance becomes great enough that it equals the magnitude of the force of gravity (**Figure 3(c)**). At this moment, the skydiver is moving at constant speed. The maximum constant speed reached by a falling object is called the **terminal speed**.

terminal speed the maximum constant speed of a falling object

To slow down, the skydiver must increase the force of air resistance acting on her body. To do this, the skydiver must increase her cross-sectional area moving through the air. So she opens her parachute. As soon as the parachute opens, the upward force of air resistance is much greater in magnitude than the downward force of gravity (**Figure 3(d)**). So the skydiver begins to slow down because the net force is directed upward while she is still falling downward. Since the speed of the skydiver is decreasing, the force of air resistance acting on the skydiver also decreases (**Figure 3(e)**). Eventually the air resistance decreases to the point where its magnitude again equals the force of gravity (**Figure 3(f)**). Now the skydiver is moving at a much slower terminal speed than before and she can land safely on the ground.

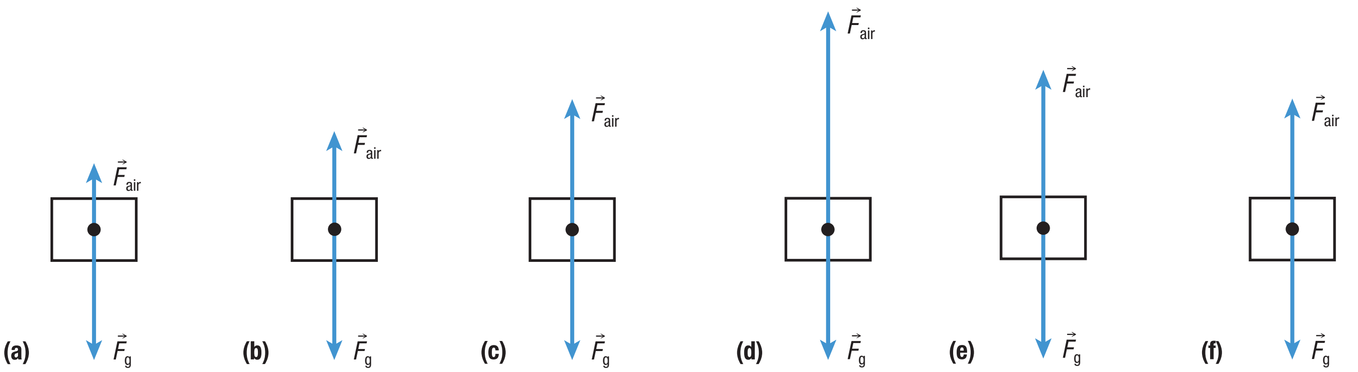

Figure 3 FBDs of a skydiver in free fall under various conditions. (a) The magnitude of air resistance is small at the beginning because the speed is small. (b) As the speed increases, so does the magnitude of air resistance. (c) Eventually the skydiver reaches a terminal speed. (d) The parachute opens and the magnitude of air resistance increases, and the skydiver slows down. (e) As the skydiver continues to slow down, the magnitude of air resistance decreases. (f) The terminal speed is lower with the parachute open.

Gravitational Field Strength

How can Earth pull on objects and make them fall toward its centre? Gravity is an action-at-a-distance force that pulls on objects without making any contact with them. This occurs because Earth is surrounded by a gravitational force field. A **force field** is a region of space surrounding an object that can exert a force on other objects; the field exerts a force only on objects placed within that region that are able to interact with that force. To represent the force field around Earth, we draw lines of force that point toward Earth's centre (**Figure 4**). No matter how large or small the mass of an object is, the object will always be attracted to Earth when it interacts with this force field.

force field a region of space surrounding an object that can exert a force on other objects that are placed within that region and are able to interact with that force

To determine the magnitude of Earth's gravitational force field at a particular location near its surface, physicists use a quantity called gravitational field strength. The **gravitational field strength** is the force, per kilogram of mass, acting on an object within a gravitational field. The gravitational field strength is a vector quantity because it has a direction. The gravitational field strength due to Earth always points toward Earth's centre. Gravitational field strength has units of newtons per kilogram. At Earth's surface, the gravitational field strength is 9.8 N/kg [down]. Notice that this has the same magnitude as the acceleration due to gravity at Earth's surface. In other words, the gravitational field strength at a location has the same magnitude as the acceleration due to gravity at that location. To determine the gravitational field strength at a particular location, you can measure the force of gravity acting on an object using a spring scale or force sensor and divide by the mass of the object. Then you can use the equation $\vec{F}_g = m\vec{g}$ to solve for $\vec{g}$:

gravitational field strength the force per unit mass acting on an object when placed in a gravitational field

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

Careful measurements of Earth's gravitational field strength show that its magnitude decreases as an object is moved farther away from Earth's surface. If the distance is large enough, Earth's gravitational field strength becomes very weak. For example, if the distance between an object and Earth's surface (at sea level) is equal to one Earth radius, the gravitational field strength is only 2.45 N/kg [down]. Of course, objects are not normally this far away from Earth's surface. Even at the top of Mount Everest at an altitude of 8848 m above sea level, the magnitude of the gravitational field strength is 9.7647 N/kg.

Figure 4 The gravitational force field surrounding Earth attracts all other objects placed within this field. The magnitude of Earth's gravitational field decreases as an object moves farther away from Earth's surface.

Since Earth is not a perfect sphere, the magnitude of the gravitational field strength at Earth's surface varies according to the geographic location of the object (**Figure 5**). Earth bulges out slightly at the equator due to the rotation of the planet. At the poles, an object at sea level is 21 km closer to Earth's centre than if it were at sea level at the equator. This means that the magnitude of the gravitational field strength is slightly greater at the poles than at the equator. For example, at the North Pole the magnitude of the gravitational field strength is 9.8322 N/kg, whereas at the equator it is 9.7805 N/kg. The magnitude of the gravitational field strength gradually increases with latitude as you travel from the equator toward either pole. On average, the gravitational field strength on Earth's surface is 9.8 N/kg [down], to two significant digits.

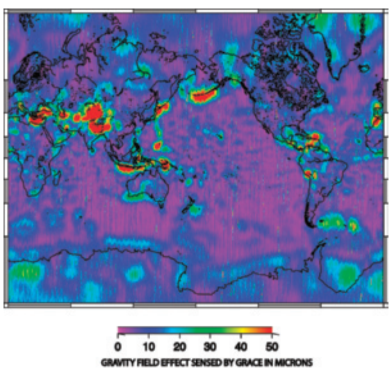

Figure 5 The magnitude of the gravitational field strength varies depending on the location on Earth's surface. On this map, red and yellow areas have a greater gravitational field strength.

The Difference between Mass and Weight

The terms "mass" and "weight" are used interchangeably in everyday language, but these two words have different meanings. Mass is the quantity of matter in an object. The only way to change the mass of an object is to either add or remove matter. The mass of an object does not change due to location or changes in gravitational field strength. The units of mass are kilograms, and mass is measured using a balance.

Weight is a measure of the force of gravity, $\vec{F}_g$, acting on an object. Since weight and the force of gravity are the same quantity, the weight of an object depends on location and the magnitude of Earth's gravitational field strength at that location. Weight is a vector, and its magnitude is measured in newtons with a spring scale or a force sensor. When measuring weight with a force sensor or a spring scale, the object must either be at rest or moving at a constant velocity while being supported by the scale or sensor.

On the Moon or a planet other than Earth, your weight is different but your mass is the same. For example, the magnitude of the gravitational field strength on the surface of the Moon is approximately one-sixth that on Earth's surface. This means that the force of gravity is weaker on the Moon and the magnitude of your weight is less. However, your body contains the same amount of matter at either location, so your mass is unchanged.

Astronauts aboard the International Space Station (ISS) appear to float within the station while they are performing tasks (**Figure 6**). This is often referred to as "weightlessness" or "microgravity." These terms are misleading because the force of gravity still acts on the astronauts—they are being pulled toward Earth's centre. In fact, gravity is the force that keeps the station and the astronauts in orbit. Without Earth's gravitational pull, the ISS would float off into space in a straight line at constant velocity. In reality, the astronauts and the ISS are in free fall.

You can experience a sensation of microgravity or apparent weight by travelling in an elevator. When the elevator is moving at a constant velocity, either up or down, everything appears normal. However, if the elevator accelerates upward, you feel heavier. If the elevator accelerates downward, you feel lighter. The following Tutorial will help to clarify how the vertical acceleration of an object such as an elevator affects how light or heavy you feel.

Figure 6 Canadian astronauts Julie Payette and Robert Thirsk on the ISS. Although these astronauts appear to be floating, they are actually in free fall.

CAREER **LINK**

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Investigation **4.1.1**

Acceleration Due to Gravity and Terminal Speed (p. 191)
You will explore factors that affect the acceleration due to gravity at your location and measure its value.

Tutorial 1 The Normal Force Is Not Always Equal in Magnitude to the Force of Gravity

The following Sample Problems demonstrate the relationship between the force of gravity and the normal force.

Sample Problem 1: Cart on an Incline

A cart rolls down an incline. Assume that friction is negligible. Draw an FBD for the cart. In which directions do the normal force and the force of gravity act on the cart?

Solution

First draw the FBD of the cart (**Figure 7**). The force of gravity on the cart is down since Earth attracts all masses toward its centre. However, the normal force is perpendicular to the surface. Since the surface of the ramp is tilted, the normal force is not directly up. This example clearly shows that the normal force and the force of gravity do not always act in opposite directions.

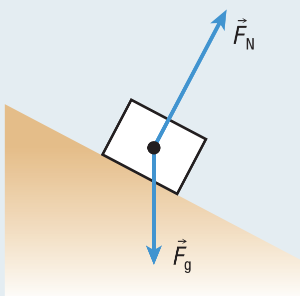

Figure 7

Sample Problem 2: Person Accelerating Up in an Elevator

A 50 kg person is standing on a bathroom scale inside an elevator. The scale is calibrated in newtons. What is the reading on the scale when the elevator is accelerating up at 2.2 m/s^2?

Solution

Step 1. Choose up as positive and down as negative.
Determine the force of gravity acting on the person.

$$\vec{F}_g = m\vec{g}$$
$$F_g = (50\ \text{kg})(-9.8\ \text{N/kg}) = -490\ \text{N}$$
$$F_g = 490\ \text{N}\ [\text{down}]$$

Step 2. Now draw the FBD of the person (**Figure 8**).

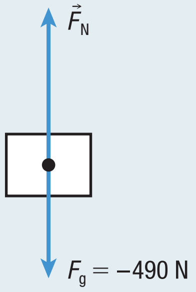

Figure 8

Step 3. Determine the normal force acting on the person. Since the elevator is accelerating up, the person is also accelerating up. The person's acceleration is equal to the elevator's acceleration.

$$\vec{F}_N + \vec{F}_g = m\vec{a}$$
$$F_N + (-490\ \text{N}) = ma$$
$$F_N - 490\ \text{N} = (50\ \text{kg})(2.2\ \text{m/s}^2)$$
$$F_N = 600\ \text{N}$$

The reading on the scale is equal to the normal force.
The reading on the scale is 600 N.

Sample Problem 3: Pushing on a Person Standing on a Bathroom Scale

A 60.0 kg person is standing on a bathroom scale calibrated in newtons. A friend pushes down on the person with a force of 72.0 N. What is the reading on the scale?

Solution

Step 1. Choose up as positive and down as negative.
Determine the force of gravity acting on the person.

$$\vec{F}_g = m\vec{g}$$
$$F_g = (60\ \text{kg})(-9.8\ \text{N/kg}) = -588\ \text{N}$$
$$F_g = 588\ \text{N}\ [\text{down}]$$

Step 2. Now draw the FBD of the person (**Figure 9**).

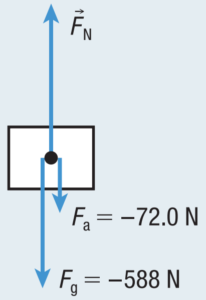

Figure 9

Step 3. Determine the normal force acting on the person. Since the person is at rest and not accelerating, the net force must be zero.

$$\vec{F}_N + \vec{F}_g + \vec{F}_a = 0$$
$$F_N + (-588\ \text{N}) + (-72.0\ \text{N}) = 0$$
$$F_N = 660\ \text{N}$$

The reading on the scale is equal to the normal force.
The reading on the scale is 660 N.

The last two examples show that the normal force is not always equal in magnitude to the force of gravity.

Practice

1. A 12 kg box sits on top of a 38 kg box. T/I C
   (a) Draw an FBD for each box.
   (b) Calculate the normal force acting on the 12 kg box. [ans: 120 N [up]]
   (c) Calculate the normal force acting on the 38 kg box due to the floor. [ans: 490 N [up]]
2. A child has a mass of 36 kg and is sitting on a seat on an amusement park ride. The ride makes the seat move up and down. Determine the normal force acting on the child when the child is
   (a) moving up at a constant velocity of 12 m/s [ans: 350 N [up]]
   (b) moving down at a constant velocity of 14 m/s [ans: 350 N [up]]
   (c) accelerating down at 1.8 m/s^2 T/I [ans: 290 N [up]]
3. A 72 kg person jumps up off a bathroom scale. Determine the acceleration of the person when the scale reads 840 N. T/I [ans: 1.9 m/s^2 [up]]
4. An electrician holds a 3.2 kg chandelier against a ceiling with a force of 53 N [up]. What is the normal force exerted by the ceiling on the chandelier? T/I [ans: 22 N [down]]

4.1 Summary

- Air resistance increases with the cross-sectional area and the speed of the object. Air resistance acts in a direction opposite to the velocity of the object.
- Force fields cause action-at-a-distance forces.
- The gravitational field strength is the force per unit mass acting on an object placed in a gravitational field. The gravitational field strength at Earth's surface is $\vec{g}$ = 9.8 N/kg [down]. This value decreases with distance from the surface of Earth. It is greater at the poles and less at the equator because Earth is not a perfect sphere.

4.1 Questions

1. Use Newton's second law and the force of gravity to explain why all objects fall with the same acceleration in the absence of air resistance. K/U
2. Explain why a person with an open parachute has a lower terminal speed than a person with a closed parachute. K/U
3. Why do light objects with large cross-sectional areas fall more slowly in air than heavy objects with small cross-sectional areas? K/U
4. In an action movie, a plane releases a heavy box while in flight. The box is attached to a parachute that opens as soon as it leaves the plane. Part of the way down to the ground, the parachute malfunctions and the box breaks free. Describe the forces acting on the box while it is falling and use them to describe the velocity and acceleration of the box. Use FBDs to explain your reasoning. K/U C
5. An astronaut with a mass of 74 kg goes up to the ISS on a mission. During his stay, the gravitational field strength on the station is 8.6 N/kg. T/I
   (a) What is the mass of the astronaut on the station?
   (b) What is the difference between the astronaut's weight on Earth's surface and his weight on the station?
   (c) Why does the weight of the astronaut change but not his mass when moving from the surface of Earth to the station?
   (d) Why does the astronaut appear weightless on the station?
6. Copy and complete **Table 1** by calculating the weight of an object of mass 20.000 kg at different latitudes on Earth. Use the results to answer the following questions. T/I

Table 1

Latitude (°)	Weight of object (N)	$\vec{g}$ (N/kg [down])	Distance from Earth's centre (km)
0 (equator)		9.7805	6378
30		9.7934	6373
60		9.8192	6362
90 (North Pole)		9.8322	6357

   (a) What is the difference in the weight of the object from the equator to the North Pole?
   (b) Why does the weight change at different latitudes?
   (c) Explain why the gravitational field strength increases with latitude.
7. A cargo box on a rocket has a mass of 32.00 kg. The rocket will travel from Earth to the Moon. K/U T/I
   (a) What will happen to the mass of the cargo box during the mission? Explain your reasoning.
   (b) Determine the weight of the box at the surface of Earth.
   (c) The weight of the box on the Moon is 52.06 N. Determine the gravitational field strength on the surface of the Moon.
8. Summarize the differences between mass and weight by copying and completing **Table 2**. K/U

Table 2

Quantity	Definition	Symbol	SI unit	Method of measuring	Variation with location
mass					
weight					

9. Copy **Table 3** and complete it for a 57 kg object on each planet. T/I

Table 3

Planet	Weight (N)	$\vec{g}$ (N/kg)
Mercury	188	
Venus	462	
Jupiter		26

10. A 24 kg object sits on top of a scale calibrated in newtons. Determine the reading on the scale if
    (a) the object is at rest and no one is pushing on it
    (b) the object is at rest and someone is pushing on it with a force of 52 N [down]
    (c) the object is at rest and someone is pulling on it with a force of 74 N [up] T/I