2.3 Gravity and Free Fall

Imagine dropping a baseball out of a second-floor window. What happens? Of course, the ball falls toward the ground. Is the speed constant or does the ball accelerate? If it accelerates, at what rate? Do all objects fall at the same rate? You will learn the answers to these questions in this section.

Vocabulary

free fall, acceleration due to gravity, velocity, weight, air resistance, terminal speed

Objectives

- ✓ Describe the motion of an object in free fall.
- ✓ Calculate speed and distance for an object in free fall.
- ✓ Distinguish between mass and weight.
- ✓ Explain how air resistance affects the motion of objects.

The acceleration due to gravity

The definition of free fall An object is in **free fall** if it is accelerating due to the force of gravity and no other forces are acting on it. A dropped baseball is in free fall from the instant it leaves your hand until it reaches the ground. A ball thrown upward is also in free fall after it leaves your hand. Although you might not describe the ball as "falling," it is still in free fall. Birds, helicopters, and airplanes are *not* normally in free fall because forces other than gravity act on them.

The acceleration of gravity Objects in free fall on Earth accelerate downward at 9.8 m/sec^2, the **acceleration due to gravity**. Because this acceleration is used so frequently in physics, the letter g is used to represent its value. When you see the letter *g* in a physics question, you can substitute the value 9.8 m/sec^2.

Speed in free fall If you know the acceleration of an object in free fall, you can predict its speed at any time after it is dropped. The speed of a dropped object will increase by 9.8 m/sec every second (Figure 2.11). If it starts at rest, it will be moving at 9.8 m/sec after one second, 19.6 m/sec after two seconds, 29.4 m/sec after three seconds, and so on. To calculate the object's speed, you multiply the time it falls by the value of g. Because the units of *g* are m/sec^2, the speed must be in m/sec and the time must be in seconds.

FREE FALL SPEED
(starting at rest)

$$v = gt$$

Speed (m/sec) → v; g ← *Acceleration due to gravity* (m/sec^2); t ← *Time* (sec)

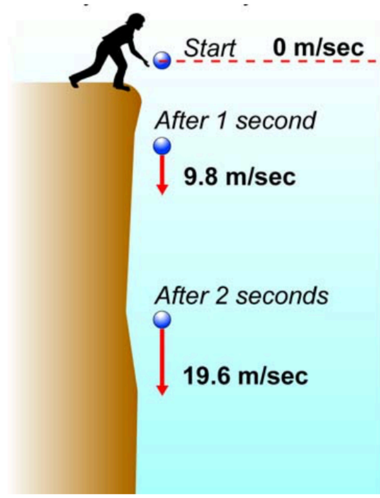


Figure 2.11: *The speed of a ball in free fall*

Upward launches

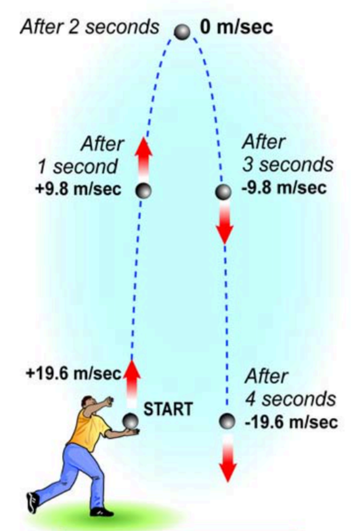
Throwing a ball upward When an object is in free fall, it accelerates *downward* at 9.8 m/sec^2. Gravity causes the acceleration by exerting a downward force. So what happens if you throw a ball *upward*? The ball will slow down as it moves upward, come to a stop for an instant, and then fall back down. As it moves upward, the speed *decreases* by 9.8 m/sec every second until it reaches zero. The ball then reverses direction and starts falling down. As it falls downward, the speed *increases* by 9.8 m/sec every second.

Velocity When an object's direction is important, we use the *velocity* instead of the speed. **Velocity** is speed with direction. In Figure 2.12, the ball's initial velocity is +19.6 m/sec and its velocity four seconds later is -19.6 m/sec. The positive sign means upward and the negative sign means downward.

Speed The acceleration of the ball is -9.8 m/sec^2 (-*g*). That means you subtract 9.8 m/sec from the speed every second. Figure 2.12 shows what happens to a ball launched upward at 19.6 m/sec. The speed decreases for two seconds, reaches zero, and then increases for two seconds. *The acceleration is the same all the time* (-9.8 m/sec^2) even though the ball is slowing down as it goes up and speeding up as it comes back down. The acceleration is the same because the change in speed is the same from one second to the next. The speed always changes by -9.8 m/sec every second.

Stopping for an instant Notice the ball's speed is 0 m/sec at the top of its path. If you watch this motion, the ball looks like it stops, because it is moving so slowly at the top of its path. To your eye it may look like it stops for a second, but a slow-motion camera would show the ball's speed immediately reverses at the top and does not stay zero for any measurable amount of time.

Acceleration You may want to say the acceleration is zero at the top, but only the *speed* is zero at the top. Speed and acceleration are not the same thing, remember — just like 60 miles and 60 miles per hour are not the same thing. The force of gravity causes the ball's acceleration. The force of gravity stays constant; therefore, the acceleration is also constant and cannot be zero while the ball is in the air.



Time (sec)	Velocity (m/sec)
0.0	19.60
1.0	9.80
2.0	0.00
3.0	-9.80
4.0	-19.60

Figure 2.12: *The motion of a ball launched upward at 19.6 m/sec.*

Gravity and weight

Gravity's force depends on mass

The force of gravity on an object is called **weight**. The symbol F_g stands for "force of gravity" and is used to represent weight. At Earth's surface, gravity exerts a force of 9.8 N on every kilogram of mass. That means a 1-kilogram mass has a weight of 9.8 N, a two-kilogram mass has a weight of 19.6 N, and so on. On Earth's surface, the weight of any object is its mass multiplied by 9.8 N/kg. Because weight is a force, it is measured in units of force such as newtons and pounds.

Weight and mass

We all tend to use the terms *weight* and *mass* interchangeably. Heavy objects have lots of mass and light objects have little mass. People and things such as food are "weighed" in both kilograms and pounds. If you look on the label of a bag of flour, it lists the "weight" in two units: 5 pounds in the English system and 2.3 kilograms in the metric system. As long as we are on Earth, where g = 9.8 N/kg a 2.3-kilogram object will weigh 5 pounds. But on the moon, g = 1.6 N/kg, so a 2.3 kilogram object will weigh only 0.8 pounds (Figure 2.14).

Weight and the second law

You should recognize that the value of 9.8 N/kg is the same as g (9.8 m/sec^2) but with different units. This is no coincidence. According to the second law, a force of 9.8 newtons acting on one kilogram produces an acceleration of 9.8 m/sec^2. For this reason the value of g can also be used as 9.8 N/kg. Which units you choose depends on whether you want to calculate acceleration or the weight force. Both units are actually identical: 9.8 N/kg = 9.8 m/sec^2.

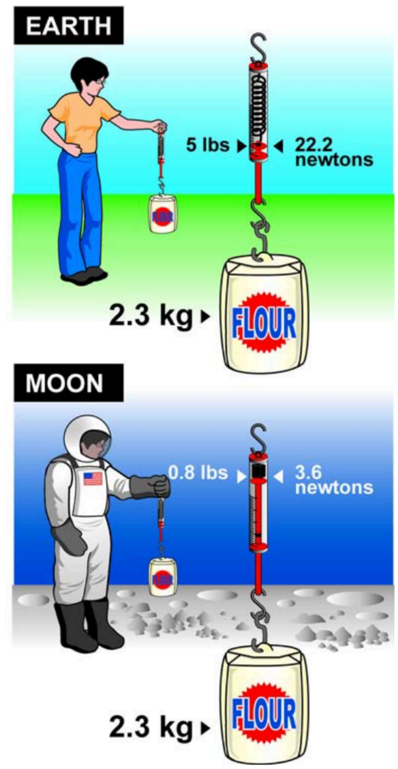


Figure 2.14: *An object that weighs 5 pounds on Earth weighs only 0.8 pounds on the moon. It has the same mass but different weights because gravity is stronger on Earth.*

WEIGHT

$$F_g = mg$$

Weight or force of gravity (N) → F_g; *Mass* (kg) → m; *Strength of gravity* (9.8 N/kg) → g

Mass is fundamental

Although mass and weight are related quantities, always remember the difference when doing physics. Mass is a fundamental property of an object measured in kilograms (kg). Weight is a *force* measured in *newtons (N)* that depends on mass and gravity. A 10-kilogram object has a mass of 10 kilograms no matter where it is in the universe. A 10-kilogram object's weight, however, can vary greatly depending on whether the object is on Earth, on the moon, or in outer space.

Weight and mass

Legend has it that around 1587 Galileo dropped two balls from the Leaning Tower of Pisa to see which would fall faster. Suppose the balls had masses of 1 kilogram and 10 kilograms.
a. Use the equation for weight to calculate the force of gravity on each ball.
b. Use your answers from (a) and Newton's second law to calculate each ball's acceleration.

1. Looking for: You are asked to find the force of gravity (weight) and the acceleration.

2. Given: You are given each ball's mass in kilograms.

3. Relationships: $W=mg$ $\quad a=F/m$

4. Solution: For the 1-kg ball:
a) W = (1 kg)(9.8 m/sec^2) $\quad W$ = 9.8 N
b) a = (9.8 N)/(1 kg) $\quad a$ = 9.8 m/sec^2

For the 10-kg ball:
a) W = (10 kg)(9.8 m/sec^2) $\quad W$ = 98 N
b) a = (98 N)/(10 kg) $\quad a$ = 9.8 m/sec^2 Both balls have the same acceleration.

Your turn...

a. Calculate the weight of a 60-kilogram person (in newtons) on Earth and on Mars (g = 3.7 m/sec^2). **Answer:** 588 N, 222 N
b. A 70-kg person travels to a planet where he weighs 1,750 N. What is the value of g on that planet? **Answer:** 25 m/sec^2

Why accelerations are the same

The example problem shows the weight of a 10-kilogram object is 10 times the weight of a 1-kilogram object. However, the heavier weight produces only one-tenth the acceleration because of the larger mass. The increase in force (weight) is exactly compensated by the increase in inertia (mass). As a result, the acceleration of all objects in free fall is the same.

Air resistance

Air resistance We just said the acceleration of all objects in free fall is the same. So why does a feather fall slower than a baseball? The answer is that objects on Earth are not truly in free fall because gravity is *not* the only force acting on falling objects. When something falls through air, the air exerts an additional force. This force, called **air resistance**, acts against the direction of the object's motion.

Factors affecting air resistance The size and shape of an object affect the force of air resistance. A feather has its weight spread out over a comparatively large area, so it must push a lot of air out of the way as it falls. The force of air resistance is large compared with the weight. According to the second law of motion of motion, acceleration is caused by the net force. The net force is the weight minus the force of air resistance. The feather accelerates at much less than 9.8 m/sec^2 because the net force is very small.

Why the baseball falls faster A baseball's shape allows it to move through the air more easily than a feather. The force of air resistance is much smaller relative to the baseball's weight. Since the net force is almost the same as its weight, the baseball accelerates at nearly 9.8 m/sec^2 and falls much more rapidly than the feather.

Terminal speed If you observe a falling feather it stops accelerating after a short distance and then falls at constant speed. That is because air resistance increases with speed. A feather only accelerates until the force of air resistance equals the force of gravity. The net force then becomes zero and the feather falls with a constant speed called the **terminal speed**. The terminal speed depends on the ratio of an object's weight to its air resistance. A tightly crumpled ball of paper has a faster terminal speed than a flat piece of paper because the flat sheet has more air resistance even though the papers' weights are the same.

Skydiving and terminal speed

Parachutes use air resistance to reduce the terminal speed of a skydiver. Without a parachute, the skydiver has a small area and can reach a speed of over 100 mph. The parachute increases the area dramatically and creates greater air resistance. The skydiver's terminal speed is then slow enough to allow for a safe landing.

1. What is happening to an object that is in free fall? Use the words acceleration, velocity, distance in your explanation.

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2. What is the acceleration due to gravity on earth?

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3. What letter do we use to describe the acceleration due to gravity, and what are the *units* for this acceleration?

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4. When a ball is thrown up in the air, what is its speed at the very top? What is its acceleration at the very top?

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5. What are two examples of units you could use for weight?

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6. What is the difference between mass and weight?

7. Look at the example for finding the weight of an object. Solve the other two questions here. If you get stuck use the ACE-M method shown in the example.

8. When something falls through the air, what are the two main forces pushing or pulling on it?

9. What is terminal speed?

10. Read this passage: *A feather only accelerates until the force of air resistance equals the force of gravity. The **net force** then becomes zero and the deather falls with a constant speed called the terminal speed.*
    Based on this passage, what do you think **net force** means?