


6 Newton's Second Law of Motion—Force and Acceleration PresentationEXPRESS Conceptual Physics

THE BIG IDEA An object accelerates when a net force acts on it.




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Recall the definition of acceleration:


$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time interval}}$$

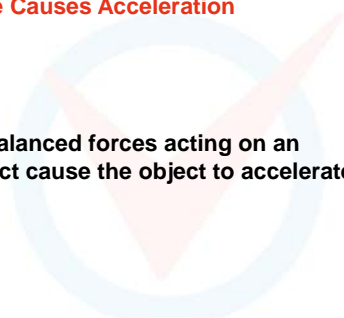
The *cause* of acceleration is *force*.



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6.1 Force Causes Acceleration

 **Unbalanced forces acting on an object cause the object to accelerate.**



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6.1 Force Causes Acceleration

When a hockey puck is at rest, the net force on it (gravity and the support force) is balanced, so the puck is in equilibrium.

Hit the puck (that is, apply an unbalanced force to it) and the puck experiences a change in motion—it accelerates.

Apply another force by striking the puck again, and the puck's motion changes again.

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6.1 Force Causes Acceleration

Recall from the previous chapter that the combination of forces acting on an object is the *net force*.

- Acceleration depends on the *net force*.
- To increase the acceleration of an object, you must increase the net force acting on it.
- An object's acceleration is directly proportional to the net force acting on it:

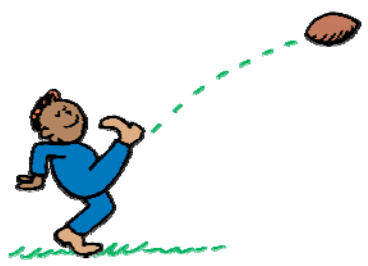
$$\text{acceleration} \sim \text{net force}$$

(The symbol \sim stands for "is directly proportional to.")

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6.1 Force Causes Acceleration

Kick a football and it neither remains at rest nor moves in a straight line.



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6.1 Force Causes Acceleration

CONCEPT CHECK: What causes an object to accelerate?

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6.2 Mass Resists Acceleration

CONCEPT CHECK: For a constant force, an increase in the mass will result in a decrease in the acceleration.

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6.2 Mass Resists Acceleration

Push on an empty shopping cart. Then push equally hard on a heavily loaded shopping cart. The loaded shopping cart will accelerate much less than the empty cart. Acceleration depends on the mass being pushed.

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6.2 Mass Resists Acceleration

The same force applied to twice as much mass results in only half the acceleration. The acceleration is *inversely proportional* to the mass.

$$\text{acceleration} \sim \frac{1}{\text{mass}}$$


Inversely means that the two values change in opposite directions. As the denominator increases, the whole quantity decreases by the same factor.

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6.2 Mass Resists Acceleration

The acceleration produced depends on the mass that is pushed.



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6.2 Mass Resists Acceleration

CONCEPT CHECK: How does an increase in mass affect acceleration?

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6.3 Newton's Second Law

Newton's second law states that the acceleration produced by a net force on an object is directly proportional to the magnitude of the net force, is in the same direction as the net force, and is inversely proportional to the mass of the object.

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6.3 Newton's Second Law

Newton's second law describes the relationship among an object's mass, an object's acceleration, and the net force on an object.

$$\text{acceleration} \sim \frac{\text{net force}}{\text{mass}}$$

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6.3 Newton's Second Law

By using consistent units, such as newtons (N) for force, kilograms (kg) for mass, and meters per second squared (m/s^2) for acceleration, we get the exact equation:

$$\text{acceleration} = \frac{\text{net force}}{\text{mass}}$$

If a is acceleration, F is net force, and m is mass,

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

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6.3 Newton's Second Law

The acceleration is equal to the net force divided by the mass.

- If the net force acting on an object doubles, its acceleration is doubled.
- If the mass is doubled, then acceleration will be halved.
- If both the net force and the mass are doubled, the acceleration will be unchanged.

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6.3 Newton's Second Law

think!

If a car can accelerate at 2 m/s^2 , what acceleration can it attain if it is towing another car of equal mass?

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6.3 Newton's Second Law

think!


If a car can accelerate at 2 m/s^2 , what acceleration can it attain if it is towing another car of equal mass?

Answer: The same force on twice the mass produces half the acceleration, or 1 m/s^2 .

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6.3 Newton's Second Law
do the math!

A car has a mass of 1000 kg. What is the acceleration produced by a force of 2000 N?




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6.3 Newton's Second Law
do the math!

A car has a mass of 1000 kg. What is the acceleration produced by a force of 2000 N?



$$a = \frac{F}{m} = \frac{2000 \text{ N}}{1000 \text{ kg}} = \frac{2000 \text{ kg}\cdot\text{m/s}^2}{1000 \text{ kg}} = 2 \text{ m/s}^2$$

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6.3 Newton's Second Law
do the math!

If the force is 4000 N, what is the acceleration?

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6.3 Newton's Second Law
do the math!

If the force is 4000 N, what is the acceleration?

$$a = \frac{F}{m} = \frac{4000 \text{ N}}{1000 \text{ kg}} = \frac{4000 \text{ kg}\cdot\text{m/s}^2}{1000 \text{ kg}} = 4 \text{ m/s}^2$$

Doubling the force on the same mass simply doubles the acceleration.

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6.3 Newton's Second Law
do the math!

How much force, or thrust, must a 30,000-kg jet plane develop to achieve an acceleration of 1.5 m/s²?

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6.3 Newton's Second Law
do the math!

How much force, or thrust, must a 30,000-kg jet plane develop to achieve an acceleration of 1.5 m/s²?

Arrange Newton's second law to read:

force = mass × acceleration

$$\begin{aligned}
 F &= ma \\
 &= (30,000 \text{ kg})(1.5 \text{ m/s}^2) \\
 &= 45,000 \text{ kg}\cdot\text{m/s}^2 \\
 &= 45,000 \text{ N}
 \end{aligned}$$

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6.3 Newton's Second Law

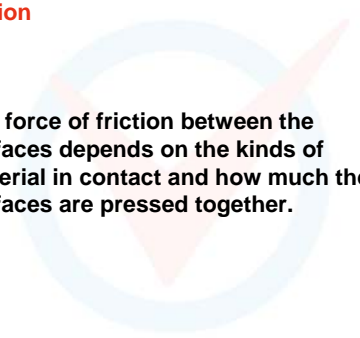
CONCEPT CHECK: What is the relationship among an object's mass, an object's acceleration, and the net force on an object?

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6.4 Friction

The force of friction between the surfaces depends on the kinds of material in contact and how much the surfaces are pressed together.



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6.4 Friction

Friction is a force and affects motion:

- Friction acts on materials that are in contact with each other.
- It always acts in a direction to oppose relative motion.
- When two solid objects come into contact, the friction is mainly due to irregularities in the two surfaces.

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6.4 Friction

Rubber against concrete produces more friction than steel against steel, so concrete road dividers have replaced steel rails.

The friction produced by a tire rubbing against the concrete is more effective in slowing the car than the friction produced by a steel car body sliding against a steel rail.

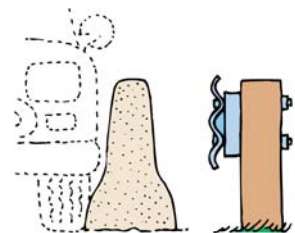
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6.4 Friction

A concrete road divider has a better design than a steel road divider for slowing an out-of-control, sideswiping car.

The concrete divider is wider at the bottom to ensure that the tire will make contact with the divider before the steel car body does.



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6.4 Friction

Both liquids and gases are called **fluids** because they flow.

- Fluid friction occurs as an object pushes aside the fluid it is moving through.
- The friction of liquids is appreciable, even at low speeds.
- **Air resistance** is the friction acting on something moving through air.

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6.4 Friction

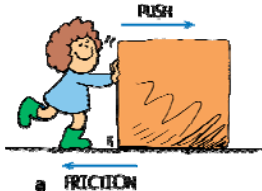
When friction is present, an object may move with a constant velocity even when an outside force is applied to it. In such a case, the friction force just balances the applied force. The net force is zero, so there is no acceleration. A diagram showing all the forces acting on an object is called a **free-body diagram**.

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6.4 Friction

The direction of the force of friction always opposes the direction of motion.

a. Push the crate to the right and friction acts toward the left.

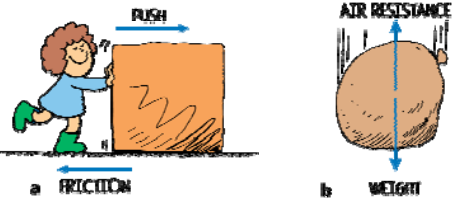


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6.4 Friction

The direction of the force of friction always opposes the direction of motion.

a. Push the crate to the right and friction acts toward the left.
b. The sack falls downward and air friction acts upward.



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6.4 Friction

think!

Two forces act on a book resting on a table: its weight and the support force from the table. Does a force of friction act as well?

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6.4 Friction

think!

Two forces act on a book resting on a table: its weight and the support force from the table. Does a force of friction act as well?

Answer: No, not unless the book tends to slide or does slide across the table. Friction forces occur only when an object tends to slide or is sliding.

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6.4 Friction

CONCEPT CHECK: What factors affect the force of friction between surfaces?

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6.5 Applying Force-Pressure

For a constant force, an increase in the area of contact will result in a decrease in the pressure.

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6.5 Applying Force-Pressure

The amount of force *per unit of area* is called **pressure**.
When the force is perpendicular to the surface area,

$$\text{pressure} = \frac{\text{force}}{\text{area of application}}$$

$$P = \frac{F}{A}$$

P is the pressure and A is the area over which the force acts. Pressure is measured in newtons per square meter, or **pascals** (Pa). One newton per square meter is equal to one pascal.

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6.5 Applying Force-Pressure

The force of the book on the table is the same.
The upright book exerts the same force, but greater pressure, against the supporting surface.

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6.5 Applying Force-Pressure

You exert more pressure against the ground when you stand on one foot than when you stand on both feet due to the decreased area of contact.
The smaller the area supporting a given force, the greater the pressure on that surface.

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6.5 Applying Force-Pressure

The driving force per nail is not enough to puncture the skin.
CAUTION: Do not attempt this on your own!

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6.5 Applying Force-Pressure

think!
In attempting to do the bed-of-nails demonstration, would it be wise to begin with a few nails and work upward to more nails?

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6.5 Applying Force-Pressure

think!

In attempting to do the bed-of-nails demonstration, would it be wise to begin with a few nails and work upward to more nails?

Answer: No, no, no! There would be one less physics teacher if the demonstration were performed with fewer nails. The resulting greater pressure would cause harm.

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6.5 Applying Force-Pressure

CONCEPT CHECK: How does the area of contact affect the pressure a force exerts on an object?

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6.6 Free Fall Explained

All freely falling objects fall with the same acceleration because the net force on an object is only its weight, and the ratio of weight to mass is the same for all objects.

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6.6 Free Fall Explained

Galileo showed that falling objects accelerate equally, regardless of their masses.

- This is *strictly* true if air resistance is negligible, that is, if the objects are in free fall.
- It is *approximately* true when air resistance is very small compared with the mass of the falling object.

Remember that only a single force acts on something in free fall—the force due to gravity.




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6.6 Free Fall Explained

In Galileo's famous demonstration, a 10-kg cannonball and a 1-kg stone strike the ground at practically the same time. This experiment demolished the Aristotelian idea that an object that weighs ten times as much as another should fall ten times faster than the lighter object.



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6.6 Free Fall Explained

Recall that mass (a quantity of matter) and weight (the force due to gravity) are proportional.

- A 10-kg cannonball experiences 10 times as much gravitational force (weight) as a 1-kg stone.
- Newton's second law tells us to consider the mass as well.
- Ten times as much force acting on ten times as much mass produces the same acceleration.

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6.6 Free Fall Explained

F stands for the force (weight) acting on the cannonball, and m stands for the correspondingly large mass of the cannonball. The small F and m stand for the weight and mass of the stone.

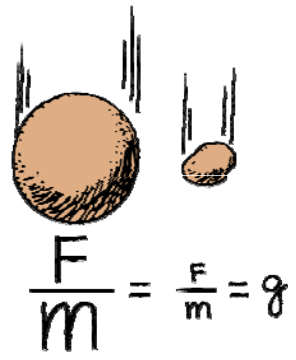
- The ratio of weight to mass is the same for these or any objects.
- All freely falling objects undergo the same acceleration at the same place on Earth.

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

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6.6 Free Fall Explained

The ratio of weight (F) to mass (m) is the same for the 10-kg cannonball and the 1-kg stone.



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

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6.6 Free Fall Explained



6 Newton's Second Law of Motion—Force and Acceleration Conceptual Physics

6.6 Free Fall Explained

The weight of a 1-kg stone is 10 N at Earth's surface. Using Newton's second law, the acceleration of the stone is

$$a = \frac{F}{m} = \frac{\text{weight}}{m} = \frac{10 \text{ N}}{1 \text{ kg}} = \frac{10 \text{ kg}\cdot\text{m/s}^2}{1 \text{ kg}} = 10 \text{ m/s}^2 = g$$

The weight of a 10-kg cannonball is 100 N at Earth's surface and the acceleration of the cannonball is

$$a = \frac{F}{m} = \frac{\text{weight}}{m} = \frac{100 \text{ N}}{10 \text{ kg}} = \frac{100 \text{ kg}\cdot\text{m/s}^2}{10 \text{ kg}} = 10 \text{ m/s}^2 = g$$

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6.6 Free Fall Explained

CONCEPT CHECK: Why do all freely falling objects fall with the same acceleration?

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6.7 Falling and Air Resistance


The air resistance force an object experiences depends on the object's speed and area.

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6.7 Falling and Air Resistance

A feather and a coin fall with equal accelerations in a vacuum, but very unequally in the presence of air. When falling in air, the coin falls quickly while the feather flutters to the ground. The force due to air resistance diminishes the net force acting on the falling objects.

When the forces of gravity and air resistance act on a falling object, it is not in free fall.



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6.7 Falling and Air Resistance

Speed and Area

You experience the force due to air resistance when you stick your hand out of the window of a moving car.

- If the car moves faster, the force on your hand increases.
- If instead of just your hand, you hold your physics book out the window with the large side facing forward, the air resistance force is much larger than on your hand at the same speed.

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6.7 Falling and Air Resistance

Air resistance force \sim speed \times frontal area

The expression shows that the air resistance force is directly proportional to the speed and frontal area of an object.

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6.7 Falling and Air Resistance

Terminal Speed

Terminal speed is the speed at which the acceleration of a falling object is zero because friction balances the weight.


Terminal velocity is terminal speed together with the direction of motion.

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6.7 Falling and Air Resistance

It's important to emphasize that zero acceleration does not mean zero velocity. Zero acceleration means that the object will maintain the velocity it happens to have, neither speeding up nor slowing down nor changing direction.




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6.7 Falling and Air Resistance

Sky divers reach terminal speed when air resistance equals weight.



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6.7 Falling and Air Resistance

A falling feather reaches its terminal speed quite quickly. Its area is large relative to its very small weight so air resistance has a large effect on the feather's motion.

A coin has a relatively small area compared to its weight, so the coin will have to fall faster to reach its terminal speed.

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6.7 Falling and Air Resistance

The terminal speed for a sky diver varies from about 150 to 200 km/h, depending on the weight and orientation of the body.


- A heavier person will attain a greater terminal speed than a lighter person.
- Body orientation also makes a difference. More air is encountered when the body is spread out and surface area is increased.

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6.7 Falling and Air Resistance

The flying squirrel increases its area by spreading out. This increases air resistance and decreases the speed of its fall.



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6.7 Falling and Air Resistance

Terminal speed can be controlled by variations in body orientation.

- A heavy sky diver and a light sky diver can remain in close proximity to each other if the heavy person spreads out like a flying squirrel while the light person falls head or feet first.
- A parachute greatly increases air resistance, and cuts the terminal speed down to 15 to 25 km/h, slow enough for a safe landing.

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6.7 Falling and Air Resistance

At low speeds, air resistance is often negligible, but at high speeds, it can make quite a difference.

If you hold a baseball and tennis ball at arm's length and release them at the same time, you'll see them strike the floor at the same time. But if you drop them from the top of a building, you'll notice the heavier baseball strikes the ground first.

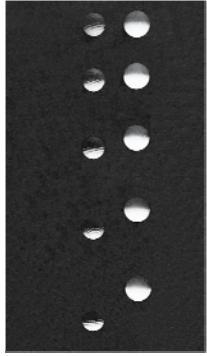
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6.7 Falling and Air Resistance

This stroboscopic photo shows a golf ball and a foam ball falling in air.

The heavier golf ball is more effective in overcoming air resistance, so its acceleration is greater.



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6.7 Falling and Air Resistance

think!

Which experiences a greater air resistance force, a falling piece of paper or a falling elephant?

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6.7 Falling and Air Resistance

think!

Which experiences a greater air resistance force, a falling piece of paper or a falling elephant?

Answer: The elephant! It has a greater frontal area and falls faster than a piece of paper—both of which mean the elephant pushes more air molecules out of the way. The effect of the air resistance force on each, however, is another story!

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6.7 Falling and Air Resistance

think!

If a heavy person and a light person open their parachutes together at the same altitude and each wears the same size parachute, who will reach the ground first?

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6.7 Falling and Air Resistance

think!

If a heavy person and a light person open their parachutes together at the same altitude and each wears the same size parachute, who will reach the ground first?

Answer: The heavy person will reach the ground first. Like a feather, the light person reaches terminal speed sooner, while the heavy person continues to accelerate until a greater terminal speed is reached.

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6.7 Falling and Air Resistance

CONCEPT CHECK: What factors determine the air resistance force on an object?

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Assessment Questions

1. An object will accelerate when
 - a. $\Sigma F = 0$.
 - b. it is unbalanced.
 - c. it is pushed or pulled with a net force.
 - d. its mass increases.

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Assessment Questions

1. An object will accelerate when
 - a. $SF = 0$.
 - b. it is unbalanced.
 - c. it is pushed or pulled with a net force.
 - d. its mass increases.

Answer: C

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Assessment Questions

2. When a net force acts on an object, its acceleration depends on the object's
 - a. initial speed.
 - b. mass.
 - c. volume.
 - d. weight.

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Assessment Questions

2. When a net force acts on an object, its acceleration depends on the object's
 - a. initial speed.
 - b. mass.
 - c. volume.
 - d. weight.

Answer: B

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Assessment Questions

3. A cart is pushed and undergoes a certain acceleration. Consider how the acceleration would compare if it were pushed with twice the net force while its mass increased by four. Then its acceleration would be
 - a. one quarter.
 - b. half.
 - c. twice.
 - d. the same.

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Assessment Questions

3. A cart is pushed and undergoes a certain acceleration. Consider how the acceleration would compare if it were pushed with twice the net force while its mass increased by four. Then its acceleration would be
 - a. one quarter.
 - b. half.
 - c. twice.
 - d. the same.

Answer: B

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Assessment Questions

4. Friction is a force like any other force and affects motion. Friction occurs in
 - a. solids sliding over one another.
 - b. fluids.
 - c. air.
 - d. all of these

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Assessment Questions

4. Friction is a force like any other force and affects motion. Friction occurs in

- solids sliding over one another.
- fluids.
- air.
- all of these

Answer: D

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Assessment Questions

5. When you stand on one foot instead of two, the pressure you exert on the ground is

- half.
- the same.
- twice.
- quadruple.

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Assessment Questions

5. When you stand on one foot instead of two, the pressure you exert on the ground is

- half.
- the same.
- twice.
- quadruple.

Answer: C

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Assessment Questions

6. The reason a 20-kg rock falls no faster than a 10-kg rock in free fall is that

- air resistance is negligible.
- the force of gravity on both is the same.
- their speeds are the same.
- the force/mass ratio is the same.

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Assessment Questions

6. The reason a 20-kg rock falls no faster than a 10-kg rock in free fall is that

- air resistance is negligible.
- the force of gravity on both is the same.
- their speeds are the same.
- the force/mass ratio is the same.

Answer: D

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Assessment Questions

7. Kevin and Suzanne go sky diving. Kevin is heavier than Suzanne, but both use the same size parachute. Kevin has a greater terminal speed compared with Suzanne because

- he has to fall faster for air resistance to match his weight.
- gravity acts on him more.
- he has greater air resistance.
- he has weaker terminal velocity.

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Assessment Questions

7. Kevin and Suzanne go sky diving. Kevin is heavier than Suzanne, but both use the same size parachute. Kevin has a greater terminal speed compared with Suzanne because
- a. he has to fall faster for air resistance to match his weight.
 - b. gravity acts on him more.
 - c. he has greater air resistance.
 - d. he has weaker terminal velocity.

Answer: A