3 Newton's First Law of Motion—Inertia

If you saw a boulder in the middle of a flat field suddenly begin moving across the ground, you'd look for the reason for its motion. You might look to see if somebody was pulling it with a rope, or pushing it with a stick or something. You'd reason that something was the cause of motion. Nowadays we don't believe that such things happen without cause. In general we would say the cause of the boulder's motion was a force of some kind. We know that something forces the boulder to move.

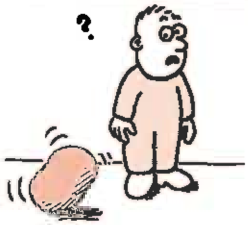


Fig. 3-1 Do boulders move without cause?

3.1 Aristotle on Motion

The idea that a force causes motion goes back to the fourth century B.C., when the Greeks were developing ideas of science. The foremost Greek scientist was Aristotle, who studied motion and divided it into two kinds: *natural motion* and *violent motion*.

Natural motion on earth was thought to be either straight up or straight down, such as the falling of a boulder toward the ground or the rising of a puff of smoke in air. Objects would seek their natural resting places: boulders on the ground, and smoke high in the air like the clouds. It was natural for heavy things to fall and very light things to rise. Aristotle proclaimed that, for the heavens, circular motion was natural, as it was without beginning or end. So the planets and stars moved in perfect circles about the earth. Since their motions were natural, they were not caused by forces.

Violent motion, on the other hand, was imposed motion. It was the result of forces which pushed or pulled. A cart moved because it was pulled by a horse; a tug-of-war was won by pulling on a rope; a ship was pushed by the force of the wind. The important thing about violent motion was that it had an external cause; violent motion was imparted to objects. Objects in their resting places could not move by themselves, but were pushed or pulled.

It was commonly thought for nearly 2000 years that if an object was moving "against its nature," then a force of some kind was responsible. Such motion was possible only because of an outside force; if there were no force, there would be no motion. So the proper state of objects was one of rest, if they were not pushed or pulled. Since it was evident to most thinkers up to the sixteenth century that the earth must be in its proper place, and that a force large enough to move it was unthinkable, it seemed clear that the earth did not move.

3.2 Copernicus and the Moving Earth

It was in this climate that the astronomer Nicolaus Copernicus (1473–1543) formulated his theory of the moving earth. Copernicus reasoned from his astronomical observations that the earth traveled around the sun. This idea was extremely controversial in his time, and he worked on his ideas secretly to escape persecution. In the last days of his life, at the urging of close friends, he sent his ideas to the printer. The first copy of his work, *De Revolutionibus*, reached him on the day he died, May 24, 1543.

3.3 Galileo on Motion

It was Galileo, the foremost scientist of the sixteenth century, who was the first to show that Copernicus's idea of a moving earth was reasonable. Galileo did this by demolishing the notion that a force was necessary to keep an object moving.

A **force** is any push or pull. **Friction** is the name given to the force that acts between materials that are moving past each other. Friction arises from the irregularities in the surfaces of sliding objects. Even very smooth surfaces have microscopic irregularities that act as obstructions to motion. If friction were absent, a moving object would need no force whatever for its continued motion.

Galileo showed that only when friction is present, as it usually is, is a force necessary to keep an object moving. He tested his idea with inclined planes—flat surfaces that are raised at one end. He noted that balls rolling down inclined planes pick up speed (Figure 3-2 left). They rolled to some degree in the direction of the earth's gravity. Balls rolling up inclined planes slowed down (Figure 3-2 center). They rolled in a direction that opposed gravity. What about balls rolling on a level surface, where they would neither roll with nor against gravity (Figure 3-2 right)? He found that for smooth horizontal planes, balls rolled without changing speed. He stated that if friction were entirely absent, a horizontally-moving ball would move forever. No push or pull would be required to keep it moving, once it was set in motion.

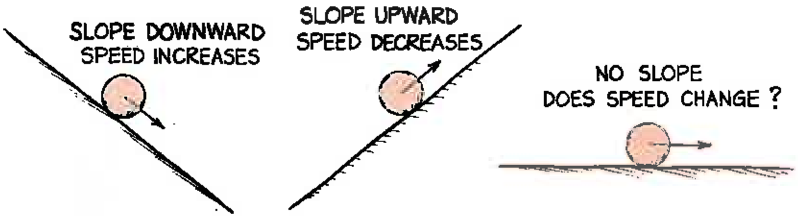


Fig. 3-2 (Left) When the ball rolls down, it moves with the earth's gravity and its speed increases. (Center) When it rolls up, it moves against gravity and loses speed. (Right) When it rolls on a level plane, it moves neither with nor against gravity. Does its speed change?

Galileo's conclusion was supported by another line of reasoning. He placed two of his inclined planes facing each other, as in Figure 3-3. He found that a ball rolling down one plane would roll up the other to nearly the same height. The smoother the planes, the more nearly equal were the initial and final heights. He found that the ball tended to attain the same height even when the second plane was longer and inclined at a smaller angle. In rolling to the same height, the ball had to roll farther. Additional reductions of angle for the upward plane gave the same results. Always the ball went farther as it tended to reach the same height.

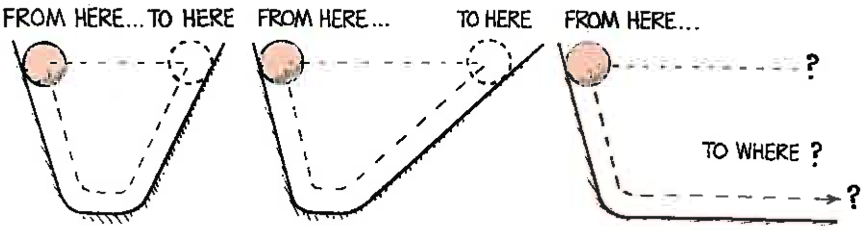


Fig. 3-3 (Left) A ball that rolls down an incline will roll up to its initial height. (Center) As the angle of the upward incline is reduced, the ball must roll a greater distance to reach its initial height. (Right) How far will it roll along the horizontal?

What if the angle of incline of the second plane was reduced to zero, so that the plane was perfectly horizontal? How far would the ball roll? He realized that only friction would keep it from rolling forever. It was not the nature of the ball to come to rest, as Aristotle had claimed. In the absence of friction, the moving ball would naturally keep moving. Galileo said that every material object has a resistance to change in its state of motion. He called this resistance **inertia**.

Galileo's concept of inertia discredited the Aristotelian theory of motion. It would be seen that although a force (gravity) is necessary to hold the earth in orbit around the sun, no force was required to keep the earth in motion. There is no friction in the empty space of the solar system, and the earth therefore coasts around and around the sun without loss in speed. The way was open for Isaac Newton (1642–1727) to synthesize a new vision of the universe.

▶ **Question**

A ball is rolled across the top of a pool table and slowly rolls to a stop. How would Aristotle interpret this behavior? How would Galileo interpret it? How would you interpret it?

3.4 Newton's Law of Inertia

Within a year of Galileo's death, Isaac Newton was born. In 1665, at the age of 23, Newton developed his famous laws of motion. They replaced the Aristotelian ideas that had dominated the thinking of the best minds for nearly 2000 years. This chapter covers the first of Newton's three laws of motion. The other two are covered in the next two chapters.

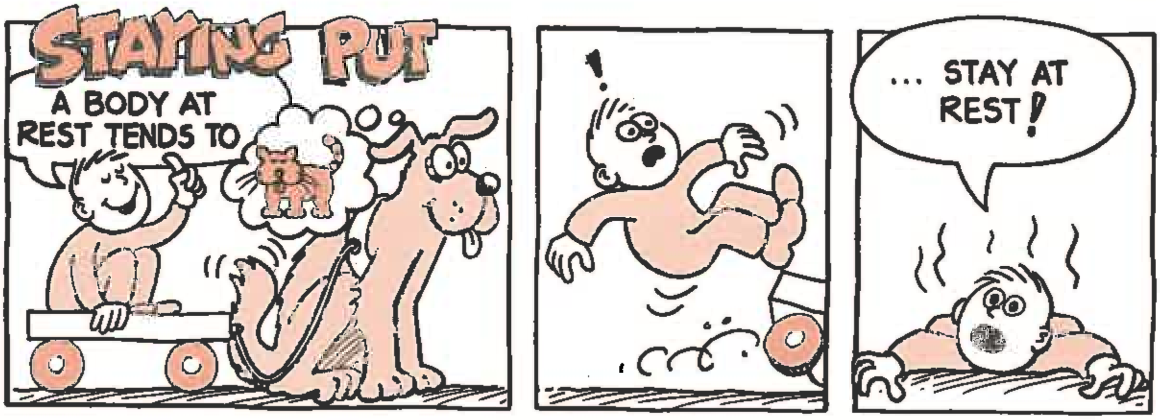
Fig. 3-4 Objects at rest tend to remain at rest.

Newton's first law, usually called the **law of inertia**, is a restatement of Galileo's idea.

> Every body continues in its state of rest, or of motion in a straight line at constant speed, unless it is compelled to change that state by forces exerted upon it.

▶ **Answer**

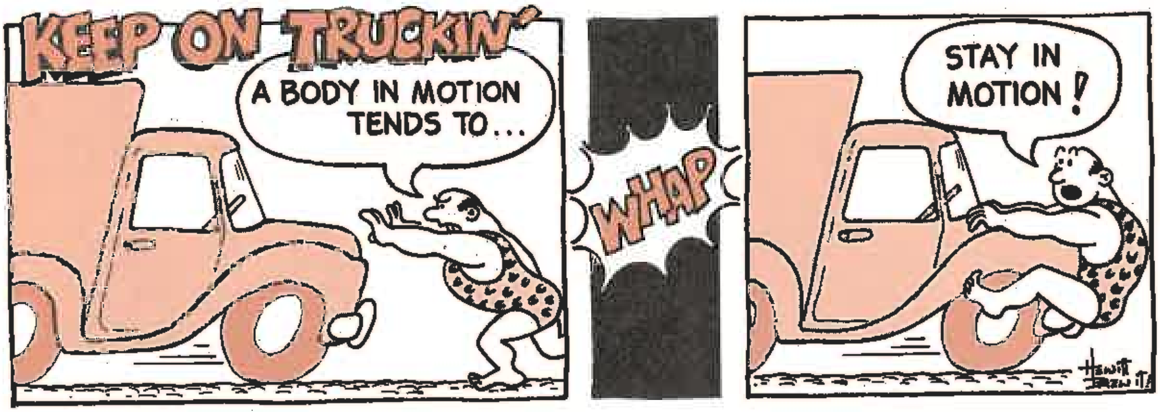
Aristotle would likely say that the ball comes to a stop because it seeks its proper state, one of rest. Galileo would likely say that once in motion the ball would continue in motion; what prevents continued motion is not its nature or its proper rest state, but the friction between the table and the ball. Only you can answer the last question!



Simply put, things tend to keep on doing what they're already doing. Dishes on a table top, for example, are in a state of rest. They tend to remain at rest, as is evidenced if you snap a table cloth from beneath them. (Try this at first with some unbreakable dishes! If you do it properly, you'll find the brief and small force of friction between the dishes and the fast-moving tablecloth is not significant enough to appreciably move the dishes.) If an object is in a state of rest, it tends to remain at rest. Only a force will change that state.

Now consider an object in motion. If you slide a hockey puck along the surface of a city street, the puck quite soon comes to rest. If you slide it along ice, it slides for a longer distance. This is because the friction force is very small. If you slide it along an air table where friction is practically absent, it slides with no ap-


Fig. 3-5 An air table. Blasts of air from many tiny holes provide a friction-free surface.



parent loss in speed. We see that in the absence of forces, a moving object tends to move in a straight line indefinitely. Toss an object from a space station located in the vacuum of outer space, and the object will move forever. It will move by virtue of its own inertia.

So we see the law of inertia provides a completely different way of viewing motion. Whereas the ancients thought forces were responsible for motion, we now know that objects will continue to move by themselves. Forces are needed to overcome any friction that may be present and to set objects in motion initially. Once an object is moving in a force-free environment, it will move in a straight line indefinitely. The next chapter will show that forces are needed to accelerate objects but not to maintain motion if there is no friction.

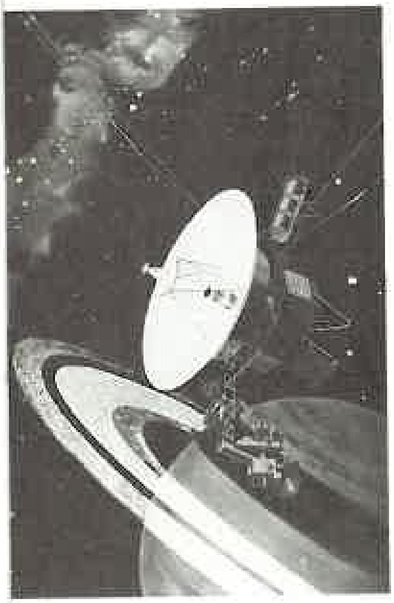


Fig. 3-6 The spacecraft launched in the late 1970s on the Pioneer and Voyager missions have gone past the orbit of Saturn (shown) and are still in motion. Except for the gravitational effects of stars and planets in the universe, their motion will continue without change.

▶ **Questions**

1. If suddenly the force of gravity of the sun stopped acting on the planets, in what kind of path would the planets move?
2. Would it be correct to say that the *reason* an object resists change and persists in its state of motion is because of inertia?

▶ **Answers**

1. The planets, like any objects, would move in a straight-line path if no forces acted upon them.
2. In a strict sense, no. Scientists don't know the reason that objects exhibit this property. Nevertheless, the property of behaving in this predictable way is called *inertia*. We understand many things and have labels and names for these things. There are also many things we do not understand, and we have labels and names for these things as well. Education consists not so much in acquiring new names and labels but in learning what is understood and what is not.

3.5 Mass—A Measure of Inertia

Kick an empty tin can and it moves. Kick a can filled with sand, and it doesn't move as much. Kick a tin can filled with solid lead, and you'll hurt your foot. The lead-filled can has more inertia than the sand-filled can, which in turn has more inertia than the empty can. The can with the most matter has the greatest inertia. The amount of inertia an object has depends on its **mass**—that is, on the amount of material present in the object. The more mass an object has, the more force it takes to change its state of motion. Mass is a measure of the inertia of an object.

Fig. 3-7 You can tell how much matter is in the can when you kick it.

Mass Is Not Volume

Many people confuse mass with volume. They think that if an object has a large mass, it must have a large volume. But volume is a measure of space and is measured in units such as cubic centimeters, cubic meters, or liters. Mass is measured in **kilograms**. (A liter of milk, juice, or soda—anything that is mainly water—has a mass of about one kilogram.) How many kilograms of matter are in an object, and how much space is taken up by that object, are two different things. Which has the greater mass—a feather pillow or a common automobile battery? Clearly the more difficult to set in motion is the battery. This is evidence of the battery's greater inertia and hence greater mass. The pillow may be bigger—that is, it may have a larger volume—but it has less mass. Mass is different from volume.

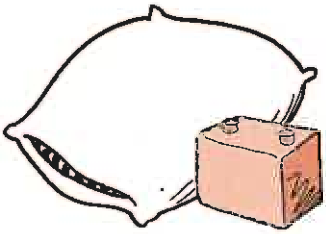


Fig. 3-8 The pillow has a larger size (volume) but a smaller mass than the battery.

Mass Is Not Weight

Mass is most often confused with weight. We say something has a lot of matter if it is heavy. That's because we are used to measuring the quantity of matter in an object by its gravitational attraction to the earth. But mass is more fundamental than weight; mass is a measure of the actual material in a body. It depends only on the number and kind of atoms that compose it. Weight is a measure of the gravitational force that acts on the material, and depends on where the object is located.

The amount of material in a particular stone is the same whether the stone is located on the earth, on the moon, or in outer space. Hence, its mass is the same in any of these locations. This could be shown by shaking the stone back and forth. The same force would be required to shake the stone with the same rhythm whether the stone was on earth, on the moon, or in a force-free region of outer space. That's because the inertia of the stone is solely a property of the stone and not its location.

But the weight of the stone would be very different on the earth

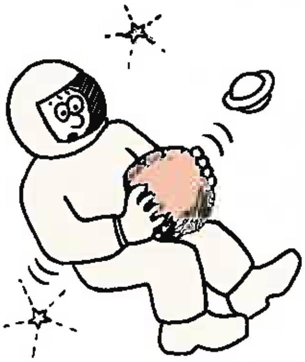


Fig. 3-9 The person in space finds it just as difficult to shake the stone in its weightless state as it is to shake it in its weighted state on earth.

and on the moon, and still different in outer space if the stone were away from strong sources of gravitation. On the surface of the moon the stone would have only one-sixth its weight on earth. This is because gravity is only one-sixth as strong on the moon as compared to on the earth. If the stone were in a gravity-free region of space, its weight would be zero. Its mass, on the other hand, would not be zero. Mass is different from weight.

We can define mass and weight as follows:

Mass: The quantity of matter in a body. More specifically, it is a measure of the inertia or "laziness" that a body exhibits in response to any effort made to start it, stop it, or change in any way its state of motion.

Weight: The force due to gravity upon a body.

Mass and weight are not the same thing, but they are proportional to each other. Objects with great masses have great weights. Objects with small masses have small weights. In the same location, twice as much mass weighs twice as much. Mass and weight are proportional to each other but not equal to each other. Mass has to do with the amount of matter in the object. Weight has to do with how strongly that matter is attracted by the earth's gravity.

▸ **Questions**

1. Does a 2-kilogram iron block have twice as much *inertia* as a 1-kilogram block of iron? Twice as much *mass*? Twice as much *volume*? Twice as much *weight* (when weighed in the same location)?

2. Does a 2-kilogram bunch of bananas have twice as much *inertia* as a 1-kilogram loaf of bread? Twice as much *mass*? Twice as much *volume*? Twice as much *weight* (when weighed in the same location)?

▸ **Answers**

1. The answer is yes to all questions. A 2-kilogram block of iron has twice as many iron atoms, and therefore twice the amount of matter, mass, and weight. The blocks are made of the same material, so the 2-kilogram block also has twice the volume.

2. Two kilograms of *anything* has twice the inertia and twice the mass of one kilogram of anything else. In the same location, two kilograms of anything will weigh twice as much as one kilogram of anything (mass and weight are proportional). So the answer to all questions is yes, except for volume. Volume and mass are proportional only when the materials are the same, or when they are equally compact for their mass—when they have the same *density*. Bananas are denser than bread—enough so that two kilograms of bananas have less volume than one kilogram of ordinary bread.

1 Kilogram Weighs 9.8 Newtons

In the United States it has been common to describe the amount of matter in an object by its gravitational pull to the earth—by its weight. The common, traditional unit of weight is the pound. In most parts of the world, however, the measure of matter is commonly expressed in mass units. The kilogram is the international, metric—SI*—unit of *mass*. The SI symbol for kilogram is kg. At the earth's surface, a 1-kg bag of nails has a weight of 2.2 pounds.

The SI unit of *force* is the **newton** (named after guess who?). One newton is equal to a little less than a quarter of a pound (like the weight of a quarter-pound burger *after* it is cooked). The SI symbol for newton is N (with a capital letter because it is named after a person). A 1-kg bag of nails has a weight in metric units of 9.8 N. Away from the earth's surface, where the force of gravity is less, it would weigh less.

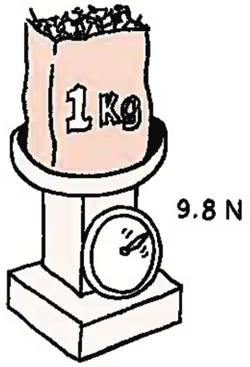


Fig. 3-10 One kilogram of nails weighs 2.2 pounds, which is the same as 9.8 newtons.

▸ **Question**

The text states that a 1-kg bag of nails weighs 9.8 N at the earth's surface. Does 1 kg of yogurt also weigh 9.8 N?

3.6 The Moving Earth Again

When Copernicus announced the idea of a moving earth in the sixteenth century, there was much arguing and debating of this controversial idea. One of the arguments against a moving earth was the following: Consider a bird sitting at rest at the top of a tall tree. On the ground below is a fat, juicy worm. The bird sees the worm and drops vertically below and catches it. This would not be possible, it was argued, if the earth moved as Copernicus suggested. If Copernicus were correct, the earth would have to travel at a speed of 107 000 km/h to circle the sun in one year. Convert this speed to kilometers per second and you'll get 30 km/s. Even if the bird could descend from its branch in one

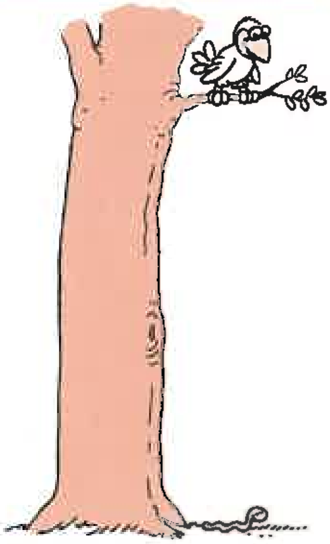


Fig. 3-11 Must the earth be at rest for the bird to catch the worm?

▸ **Answer**

Yes, at the earth's surface 1 kg of anything weighs 9.8 N. (We used nails in this example because most everybody identifies with nails—at least everybody who likes to build things. But not everybody likes yogurt.)

* SI stands for the French name, *Le Système International d'Unités*, for the international, metric system of measurement. The short forms of the SI units are called *symbols* rather than *abbreviations*.

second, the worm would have been swept by the moving earth a distance of 30 kilometers away. For the bird to catch the worm under this circumstance would be an impossible task. But birds in fact do catch worms from high tree branches, which seemed clear evidence that the earth must be at rest.

Can you refute this argument? You can if you invoke the idea of inertia. You see, not only is the earth moving at 30 km/s, but so are the tree, the branch of the tree, the bird that sits on it, the worm below, and even the air in between. All are moving at 30 km/s. A body in motion remains in motion if no unbalanced forces are acting on it. So when the bird drops from the branch, its initial sideways motion of 30 km/s remains unchanged. It catches the worm quite unaffected by the motion of its total environment.

Stand next to a wall. Jump up so that your feet are no longer in contact with the floor. Does the 30-km/s wall slam into you? Why not? Because you are also traveling at 30 km/s—before, during, and after your jump. The 30 km/s is the speed of the earth relative to the sun—not the speed of the wall relative to you.

People three hundred years ago had difficulty with ideas like these not only because they failed to acknowledge the concept of inertia, but because they were not accustomed to moving in high-speed vehicles. Slow, bumpy rides in horse-drawn carriages did not lend themselves to experiments that would reveal inertia. Today we flip a coin in a high-speed car, bus, or plane, and we catch the vertically-moving coin as we would if the vehicle were at rest. We see evidence for the law of inertia when the horizontal motion of the coin before, during, and after the catch is the same. The coin keeps up with us. The vertical force of gravity affects only the vertical motion of the coin.

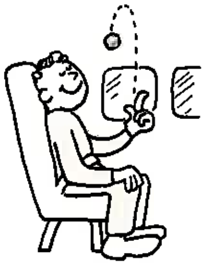


Fig. 3-12 Flip a coin in a high-speed airplane, and it behaves as if the plane were at rest. The coin keeps up with you: inertia in action.

Our notions of motion today are very different from those of our ancestors. Aristotle did not recognize the idea of inertia because he failed to imagine what motion would be like without friction. In his experience, all motion was subject to resistance, and he made this fact central to his theory of motion. We can only wonder how differently science might have progressed if Aristotle had recognized friction for what it is, namely a force like any other, which may or may not be present.

3 Chapter Review

Concept Summary

Galileo concluded that if it were not for friction an object in motion would keep moving forever.

According to Newton's first law of motion—the law of inertia—every body continues in its state of rest or of motion in a straight line at constant speed unless forces cause it to change its state.

Inertia is the resistance an object has to a change in its state of motion.

- Mass is a measure of inertia.
- Mass is not the same as volume.
- Mass is not the same as weight.
- The mass of an object depends on the amount and type of matter in it, but does not depend on the location of the object.
- The weight of an object is the gravitational force on it and depends on the location.

Important Terms

force (3.3)
friction (3.3)
inertia (3.3)
kilogram (3.5)
law of inertia (3.4)
mass (3.5)
newton (3.5)
Newton's first law (3.4)

Review Questions

1. What was the distinction that Aristotle made between *natural motion* and *violent motion*? (3.1)

2. Why was Copernicus reluctant to publish his ideas? (3.2)

3. What is the effect of friction on a moving object? How is an object able to maintain a constant speed when friction acts upon it? (3.3)

◇

4. The speed of a ball increases as it rolls down an incline, and the speed decreases as the ball rolls up an incline. What happens to the speed on a smooth horizontal surface? (3.3)

5. Galileo found that a ball rolling down one incline will pick up enough speed to roll up another. How high will it roll compared to its initial height? (3.3)

6. Does the law of inertia pertain to moving objects, objects at rest, or both? Support your answer with examples. (3.4)

7. The law of inertia states that no force is required to maintain motion. Why, then, do you have to keep peddling your bicycle to maintain motion? (3.4)

8. If you were in a spaceship and fired a cannonball into frictionless space, how much force would have to be exerted on the ball to keep it going? (3.4)

9. Does a 2-kilogram rock have twice the mass of a 1-kilogram rock? Twice the inertia? Twice the weight (when weighed in the same location)? (3.5)

10. Does a liter of molten lead have the same volume as a liter of apple juice? Does it have the same mass? (3.5)

11. Why do physics types say that mass is more fundamental than weight? (3.5)

12. An elephant and a mouse would both have the same weight—zero—in gravitation-free space. If they were moving toward you with the same speed, would they bump into you with the same effect? Explain. (3.5)

13. What is the weight of 2 kg of yogurt? (3.5)

14. If you hold a coin above your head while in a bus that is not moving, the coin will land at your feet when you drop it. Where will it land if the bus is moving in a straight line at constant speed? Explain. (3.6)

15. In the cabin of a jetliner that cruises at 600 km/h, a pillow drops from an overhead rack to your lap below. Since the jetliner is moving so fast, why doesn't the pillow slam into the rear of the compartment when it drops? (What is the horizontal speed of the pillow relative to the ground? Relative to you inside the jetliner?) (3.6)

Think and Explain

1. Many automobile passengers have suffered neck injuries when struck by cars from behind. How does Newton's law of inertia apply here? How do headrests help to guard against this type of injury?

2. Suppose you place a ball in the middle of a wagon, and then accelerate the wagon forward. Describe the motion of the ball relative to (a) the ground and (b) the wagon.

3. If an elephant were chasing you, its enormous mass would be most threatening. But if you zigzagged, its mass would be to your advantage. Why?

4. When you compress a sponge, which quantity changes: mass, inertia, volume, or weight?

5. a. A massive ball is suspended by a string from above, and slowly pulled by a string from below (Figure A). Is the string tension greater in the upper or the lower string? Which string is more likely to break? Which property—mass or weight—is important here?
   b. If the string is instead snapped downward, which string is more likely to break? Which property—mass or weight—is important this time?

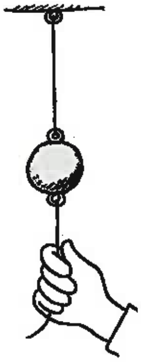


Fig. A

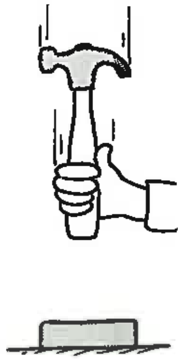


Fig. B

6. If the head of a hammer is loose, and you wish to tighten it by banging it against the top of a work bench, why is it best to hold it with the handle down (Figure B) rather than with the head down? Explain in terms of inertia.

7. Two closed containers look the same, but one is packed with lead and the other with a few feathers. How could you determine which had more mass if you and the containers were orbiting in a weightless condition in outer space?

8. What is your actual (or most desirable) weight in newtons?

9. If you are sitting in a bus that is traveling along a straight, level road at 100 km/h, you are traveling at 100 km/h too.
   a. If you hold an apple over your head, how fast is it moving relative to the road? Relative to you?
   b. If you drop the apple, does it still have the same horizontal motion?

10. As the earth rotates about its axis, it takes three hours for the United States to pass beneath a point above the earth that is stationary relative to the sun. What is wrong with this scheme: To travel from Washington D.C. to San Francisco using very little fuel, simply ascend in a helicopter high over Washington D.C. and wait three hours until San Francisco passes below?