5.1 Inertia and Newton's First Law

SECTION OUTCOMES

- Apply Newton's laws of motion to explain inertia.
- Evaluate appropriate processes for problem solving and decision making.

KEY TERMS

- classical/Newtonian mechanics
- quantum mechanics
- inertial frame of reference
- non-inertial frame of reference
- ficticious force

TRY THIS...

Place a coin on a card poised above an empty glass. Predict what will happen to the coin if you use your index finger to flick the card so that it flies off horizontally. Test your prediction and explain the results.

The understanding of force and motion progressed slowly from the time of Aristotle through to Galileo and then to Newton. In 1686, Sir Isaac Newton summarized in his book called *Principia Mathematica Philosophiae Naturalis* three laws of motion that are currently used to predict force and motion interactions for macroscopic objects. It was not until the 1900's that any significant additions were made to the field of mechanics.

The physics of force and motion is now divided into two very different categories, classical mechanics and quantum mechanics. This textbook deals almost entirely with **classical mechanics**, sometimes called **Newtonian mechanics**. Newtonian mechanics treats energy and matter as separate entities and uses Newton's laws of motion to predict the results of interactions between objects. The principles of Newtonian mechanics, although formulated 400 years ago, accurately predict and describe the behaviour of large-scale objects such as baseballs, cars, and buildings. Newtonian mechanics provides a connection between the acceleration of a body and the forces acting on it. It deals with objects that are large in comparison to the size of an atom, and with speeds that are much less than the speed of light ($c = 3.0 \times 10^8$ m/s). **Quantum mechanics**, on the other hand, attempts to explain the motion and energy of atoms and subatomic particles.

In the early part of the twentieth century, Einstein developed two ingenious theories of relativity, which, in part, deal with objects travelling close to the speed of light. Also included in his theories is the proposal that mass and energy are, in fact, different manifestations of the same entity. His famous equation, $E = mc^2$, describes how these two quantities are related. Einstein's theories predict everything that Newtonian mechanics is able to, plus much more. It is important to understand that Einstein's relativistic mechanics is an extension of Newtonian mechanics, not a replacement. Developing a conceptual framework to understand force and motion in terms of Newton's laws is necessary before attempting to grasp these more advanced theories of physics.

Newton's First Law

Newton originally considered Aristotle's ideas, but came to adopt Galileo's perspective that a body will tend to stay at rest or in uniform motion unless acted on by an external force. Clearly, many objects are at rest even though all objects on Earth are subjected to the force of gravity. So what is the precise meaning of "external force?" Consider the book on the desk in Figure 5.1. The book does not fall under the force of gravity because it is supported by the normal force of the desk pushing up on it. The key to understanding the meaning of "external force" is to consider all forces acting on an object. If the vector sum of all of the forces acting on an object is zero, then there is no *net force* acting on the object and its motion will not change. You would say that the forces are balanced and the object is in equilibrium.

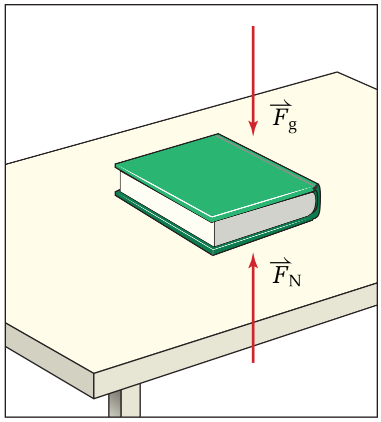


Figure 5.1 The forces on the book are balanced so the book remains at rest.

> **NEWTON'S FIRST LAW — THE LAW OF INERTIA**
>
> An object at rest or in uniform motion will remain at rest or in uniform motion unless acted on by an external force.

Hockey provides concrete examples of Newton's first law. A hockey puck at rest on the ice will not spontaneously start to move. Likewise, a puck given some velocity will continue to slide in a straight line at a constant speed. If the ice was truly frictionless and the ice surface was infinitely large, the puck would continue to slide forever.

You can apply Newton's laws to each dimension, independently. Consider the case in which a cart is pulled across a smooth tabletop with constant velocity. During the trip, a steel ball bearing is fired directly upward out of the cart. Magically, the ball will travel up and then back down, all the while remaining directly above the cart. In fact it is not magic, but Newton's first law, that is demonstrated here. The ball has the same horizontal velocity as the cart before it is launched. The ball maintains a horizontal velocity equal to that of the cart as it moves through the air. The forces that caused the ball to rise and fall were in the vertical dimension and had no effect on its horizontal motion.

Figure 5.2 Hockey provides a nearly frictionless surface for the puck to slide on and plenty of opportunity to observe how forces change the speed and direction of objects.

Figure 5.3 This performer's arm is resting on a bed of nails, yet he is able to break a brick over it without suffering any injury. Use Newton's law of inertia to explain how this is possible.

Frames of Reference and Inertia

In order to apply Newton's laws to predict the motion of an object, you must assign a reference frame and a coordinate system. However, in some reference frames, the law of inertia seems to be invalid. Recall the situation in which you chose the inside of a car as the reference frame.

An observer in the car's frame of reference might describe the motion of a person in the car by stating that "The passenger did not move during the entire trip." An observer who chose Earth's surface as a frame of reference, however, would describe the passenger's motion quite differently: "During the trip, the passenger moved 12.86 km." Clearly, descriptions of motion depend very much on the chosen frame of reference. Is there a right or wrong way to choose a frame of reference?

The answer to the above question is no, there is no right or wrong choice for a frame of reference. However, some frames of reference make calculations and predictions much easier than do others. Imagine that you are riding along a straight, smooth road at a constant velocity. You are almost unaware of any motion. Then the driver suddenly slams on the brakes and your upper body falls forward until the seat belt stops you. In the frame of reference of the car, you were initially at rest and then suddenly began to accelerate.

According to Newton's first law, a force is necessary to cause a mass — your body — to accelerate. However, in this situation you cannot attribute your acceleration to any observable force: No object has exerted a force on you. The seat belt stopped your motion relative to the car, but what started your motion? It would appear that your motion relative to the car did not conform to Newton's first law.

The two stages of motion during the ride in a car — moving with a constant velocity or accelerating — illustrate two classes of frames of reference. A frame of reference that is at rest or moving at a constant velocity is called an **inertial frame of reference**.

When you are riding in a car that is moving at a constant velocity, motion inside the car seems similar to motion inside a parked car or even in a room in a building. In fact, imagine that you are in a laboratory inside a truck's semitrailer and you cannot see what is happening outside. If the truck and trailer run perfectly smoothly, preventing you from feeling any bumps or vibrations, there are no experiments that you can conduct that will allow you to determine whether the truck and trailer are at rest or moving at a constant velocity. The law of inertia and Newton's second and third laws as well, apply in exactly the same way in all inertial frames of reference.

Now think about the point at which the driver of the car abruptly applied the brakes and the car began to slow. The velocity was changing, so the car was accelerating. An accelerating frame of

COURSE CHALLENGE: SPACE-BASED POWER

Reference Frames

A desire to know your location on Earth has made GPS receivers very popular. Discussion about location requires the use of frames of reference concepts. Ideas about frames of reference and this *Course Challenge* can be found in your e-book.

PHYSICS FILE

Albert Einstein used the equivalence of inertial and gravitational mass as a foundation of his general theory of relativity, published in 1916. According to Einstein's principle of equivalence, if you were in a laboratory from which you could not see outside, you could not make any measurements that would indicate whether the laboratory (your frame of reference) was stationary on Earth's surface or in space and accelerating at a value that was locally equal to *g*.

reference is called a **non-inertial frame of reference**. Newton's laws of motion do *not* apply to a non-inertial frame of reference. By observing the motion of the car and its occupant from outside the car (that is, from an inertial frame of reference, as shown in Figure 5.4), you can see why the law of inertia cannot apply.

Figure 5.4 The crosses on the car seat and the dots on the passenger's shoulder represent the changing locations of the car and the passenger at equal time intervals. In the first three frames, the distances are equal, indicating that the car and passenger are moving at the same velocity. In the last two frames, the crosses are closer together, indicating that the car is slowing. The passenger, however, continues to move at the same velocity until stopped by a seat belt.

In the first three frames, the passenger's body and the car are moving at the same velocity, as shown by the cross on the car seat and the dot on the passenger's shoulder. When the car first begins to slow, no force has yet acted on the passenger. Therefore, his body continues to move with the same constant velocity until a force, such as a seat belt, acts on him. When you are a passenger, you feel as though you are being thrown forward. In reality, the car has slowed down but, due to its own inertia, your body tries to continue to move with a constant velocity.

Since a change in direction is also an acceleration, the same situation occurs when a car turns. You feel as though you are being pushed to the side, but in reality, your body is attempting to continue in a straight line, while the car is changing its direction.

INERTIAL AND NON-INERTIAL FRAMES OF REFERENCE

An inertial frame of reference is one in which Newton's laws of motion are valid. Inertial frames of reference are at rest or in uniform motion, but they are not accelerating.

A non-inertial frame of reference is one in which Newton's laws of motion are not valid. Accelerating frames of reference are always non-inertial.

Clearly, in most cases, it is easier to work in an inertial frame of reference so that you can apply Newton's laws of motion with ease. However, if a physicist chooses to work in a non-inertial frame of reference and still apply Newton's laws of motion, it is necessary to invoke hypothetical quantities that are often called **fictitious forces:** inertial effects that are perceived as "forces" in non-inertial frames of reference, but do not exist in inertial frames of reference.

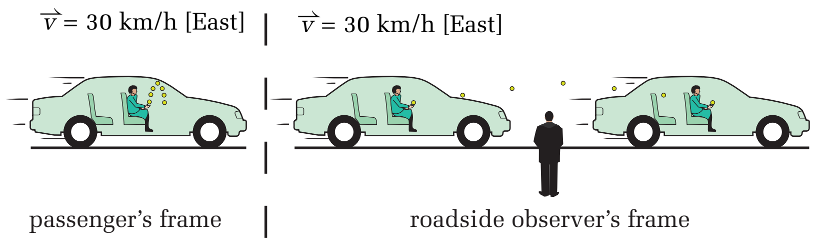
COURSE CHALLENGE: SPACE-BASED POWER

Staying in Orbit

Consider motion and the effect of perpendicular forces. Predict (a) the direction of the force on a geosynchronous satellite and (b) the source of the force.

Conceptual Problems

- Consider the example shown below. The passenger in a car travelling with constant velocity tosses and then catches a tennis ball. In the passenger's frame of reference, the ball goes straight up and comes straight back down under the influence of gravity. A roadside observer sees the tennis ball trace a different trajectory. Explain how different observers can see two different trajectories of the ball and yet both observers perceive that Newton's first law is validated by the observation.



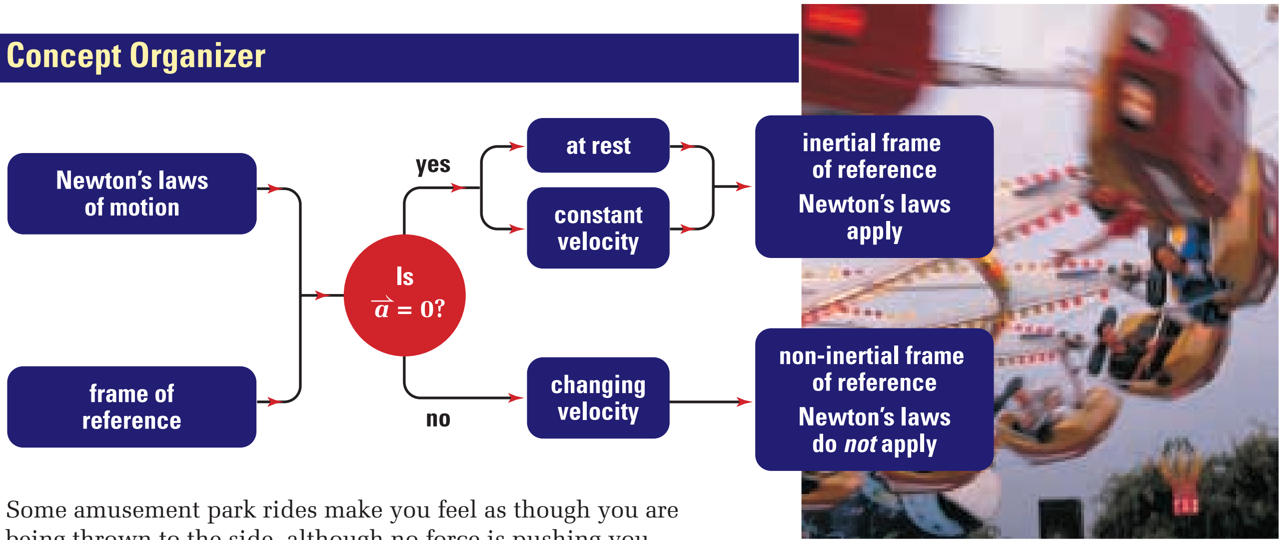
Both frames are inertial

- Passengers in a high-speed elevator feel as though they are being pressed heavily against the floor when the elevator starts moving up. After the elevator reaches its maximum speed, the feeling disappears.
  - **(a)** When do the elevator and passengers form an inertial frame of reference? A non-inertial frame of reference?
  - **(b)** Before the elevator starts moving, what forces are acting on the passengers? How large is the external (unbalanced) force? How do you know?
  - **(c)** Is a person standing outside the elevator in an inertial or non-inertial frame of reference?
  - **(d)** Suggest the cause of the pressure the passengers feel when the elevator starts to move upward. Sketch a free-body diagram to illustrate your answer.
  - **(e)** Is the pressure that the passengers feel in part (d) a fictitious force? Justify your answer.

PHYSICS FILE

Earth and everything on it are in continual circular motion. Earth is rotating on its axis, travelling around the Sun and circling the centre of the galaxy along with the rest of the solar system. The direction of motion is constantly changing, which means the motion is accelerated. Earth is a non-inertial frame of reference, and large-scale phenomena such as atmospheric circulation are greatly affected by Earth's continual acceleration. In laboratory experiments with moving objects, however, the effects of Earth's rotation are usually not detectable.

Concept Organizer



Some amusement park rides make you feel as though you are being thrown to the side, although no force is pushing you outward from the centre. Your frame of reference is moving rapidly along a curved path and therefore it is accelerating. You are in a non-inertial frame of reference, so it seems as though your motion is not following Newton's laws of motion.

Figure 5.5 You can determine the nature of a frame of reference by analyzing its acceleration.

5.1 Section Review

1. K/U State Newton's first law in two different ways.

2. C Identify the two basic situations that Newton's first law describes and explain how one statement can cover both situations.

3. MC A stage trick involves covering a table with a smooth cloth and then placing dinnerware on the cloth. When the cloth is suddenly pulled horizontally, the dishes "magically" stay in position and drop onto the table.
   (a) Identify all forces acting on the dishes during the trick.
   (b) Explain how inertia and frictional forces are involved in the trick.

4. K/U Give an example of an unusual frame of reference used in a movie or a television program. Suggest why this viewpoint was chosen.

5. K/U Identify the defining characteristic of inertial and non-inertial frames of reference. Give an example of each type of frame of reference.

6. C In what circumstances is it necessary to invoke ficticious forces in order to explain motion? Why is this term appropriate to describe these forces?