



Sir Isaac Newton (1642–1727)

forces, including gravity and the changing forces caused by air currents. If you could analyze the forces individually, you'd find that each force affects the paper's motion in a simple, predictable way. Sir Isaac Newton (1642–1727) discovered the remarkably simple laws that govern motion.

## • How did Newton change our view of the universe?

Newton was born in Lincolnshire, England, on Christmas Day in 1642. He had a difficult childhood and showed few signs of unusual talent. He attended Trinity College at Cambridge, where he earned his keep by performing menial labor, such as cleaning the boots and bathrooms of wealthier students and waiting on their tables.

The plague hit Cambridge shortly after Newton graduated, and he returned home. By his own account, he experienced a moment of inspiration in 1666 when he saw an apple fall to the ground. He suddenly realized that the gravity making the apple fall was the same force that held the Moon in orbit around Earth. In that moment, Newton shattered the remaining vestiges of the Aristotelian view of the world, which for centuries had been accepted as unquestioned truth.

Aristotle had made many claims about the physics of motion, using his ideas to support his belief in an Earth-centered cosmos. He had also maintained that the heavens were totally distinct from Earth, so that physical laws on Earth did not apply to heavenly motion. By the time Newton saw the apple fall, the Copernican revolution had displaced Earth from a central position, and Galileo's experiments had shown that the laws of physics were not what Aristotle had believed.

Newton showed that the same physical laws that operate on Earth also operate in the heavens.

Newton's sudden insight delivered the final blow to Aristotle's physics. When Newton realized that gravity operated in the heavens

as well as on Earth, he eliminated Aristotle's distinction between the two realms. For the first time in history, the heavens and Earth were brought together as one *universe*. Newton's insight also heralded the birth of the modern science of *astrophysics* (although the term wasn't coined until much later). Astrophysics applies physical laws discovered on Earth to phenomena throughout the cosmos.

Over the next 20 years, Newton's work completely revolutionized mathematics and science. He quantified the laws of motion and gravity, conducted crucial experiments regarding the nature of light, built the first reflecting telescopes, and invented the mathematics of calculus. We'll discuss his laws of motion in the rest of this section, and later in the chapter we'll turn our attention to Newton's discoveries about gravity.

## • What are Newton's three laws of motion?

Newton published the laws of motion and gravity in 1687, in his book *Philosophiae Naturalis Principia Mathematica* ("Mathematical Principles of Natural Philosophy"), usually called *Principia*. He enumerated three laws that apply to all motion, what we now call **Newton's laws of motion**. These laws govern the motion of everything from our daily movements here on Earth to the movements of planets, stars, and galaxies throughout the universe. Figure 4.5 summarizes the three laws.

**Newton's first law of motion:**

An object moves at constant velocity unless a net force acts to change its speed or direction.



**Example:** A spaceship needs no fuel to keep moving in space.

**Newton's second law of motion:**

Force = mass  $\times$  acceleration



**Example:** A baseball accelerates as the pitcher applies a force by moving his arm. (Once the ball is released, the force from the pitcher's arm ceases, and the ball's path changes only because of the forces of gravity and air resistance.)

**Newton's third law of motion:**

For any force, there is always an equal and opposite reaction force.



**Example:** A rocket is propelled upward by a force equal and opposite to the force with which gas is expelled out its back.

**Figure 4.5**

Newton's three laws of motion.

**Newton's First Law** Newton's first law of motion states that in the absence of a net force, an object will move with constant velocity. Objects at rest (velocity = 0) tend to remain at rest, and objects in motion tend to remain in motion with no change in either their speed or their direction.

**Newton's first law:** An object moves at constant velocity if there is no net force acting upon it.

The idea that an object at rest should remain at rest is rather obvious: A car parked on a flat street won't suddenly start moving

for no reason. But what if the car is traveling along a flat, straight road? Newton's first law says that the car should keep going at the same speed forever *unless* a force acts to slow it down. You know that the car eventually will come to a stop if you take your foot off the gas pedal, so one or more forces must be stopping the car—in this case, forces arising from friction and air resistance. If the car were in space, and therefore unaffected by friction or air, it would keep moving forever (though gravity would eventually alter its speed and direction). That is why interplanetary spacecraft need no fuel to keep going after they are launched into space, and why astronomical objects don't need fuel to travel through the universe.

Newton's first law also explains why you don't feel any sensation of motion when you're traveling in an airplane on a smooth flight. As long as the plane is traveling at constant velocity, no net force is acting on it or on you. Therefore, you feel no different from the way you would feel at rest. You can walk around the cabin, play catch with someone, or relax and go to sleep just as though you were "at rest" on the ground.

**Newton's Second Law** Newton's second law of motion tells us what happens to an object when a net force *is* present. We have already seen that a net force will change an object's momentum, accelerating it in the direction of the force. Newton's second law quantifies this relationship, telling us that the amount of the acceleration depends on the object's mass and the strength of the net force. We usually write this law as an equation: force = mass  $\times$  acceleration, or  $F = ma$  for short.

This law explains why you can throw a baseball farther than you can throw a shot in the shot put. The force your arm delivers to both the baseball and the shot equals the product of mass and acceleration. Because the mass of the shot is greater than that of the baseball, the same force from your arm gives the shot a smaller acceleration. Because of its smaller acceleration, the shot leaves your hand with less speed than the baseball and therefore travels a shorter distance before hitting the ground.

Newton's second law:

Force = mass  $\times$  acceleration ( $F = ma$ ).

Newton's second law also explains why large planets such as Jupiter have a greater effect on asteroids and comets than small planets such as Earth [Section 9.4]. Because Jupiter is much more massive than Earth, it exerts a stronger gravitational force on passing asteroids and therefore sends them scattering with a greater acceleration.

**Newton's Third Law** Think for a moment about standing still on the ground. Your weight exerts a downward force; if this force were acting alone, Newton's second law would demand that you accelerate downward. The fact that you are not falling means there must be no *net* force acting on you, which is possible only if the ground is exerting an upward force on you that precisely offsets the downward force you exert on the ground. The fact that the downward force you exert on the ground is offset by an equal and opposite force that pushes upward on you is one example of Newton's third law of motion, which tells us that every force is always paired with an equal and opposite reaction force.

Newton's third law: For any force, there is always an equal and opposite reaction force.

This law is very important in astronomy, because it tells us that objects always attract *each other* through gravity. For example, your

body always exerts a gravitational force on Earth identical to the force that Earth exerts on you, except that it acts in the opposite direction. Of course, the same force means a much greater acceleration for you than for Earth (because your mass is so much smaller than Earth's), which is why you fall toward Earth when you jump off a chair, rather than Earth falling toward you.

Newton's third law also explains how a rocket works: A rocket engine generates a force that drives hot gas out the back, which creates an equal and opposite force that propels the rocket forward.

## Common Misconceptions

### What Makes a Rocket Launch?

If you've ever watched a rocket launch, it's easy to see why many people believe that the rocket "pushes off" the ground. In fact, the ground has nothing to do with the rocket launch. The rocket's launch is explained by Newton's third law of motion. To balance the force driving gas out the back of the rocket, an equal and opposite force must propel the rocket forward. Rockets can be launched horizontally as well as vertically, and a rocket can be "launched" in space (for example, from a space station) with no need for a solid surface to push off from.

## 4.3 Conservation Laws in Astronomy

Newton's laws of motion are easy to state, but they may seem a bit arbitrary. Why, for example, should every force be opposed by an equal and opposite reaction force? In the centuries since Newton first stated his laws, we have learned that they are not arbitrary at all, but instead reflect deeper aspects of nature known as *conservation laws*.

Consider what happens when two objects collide. Newton's second law tells us that object 1 exerts a force that will change the momentum of object 2. At the same time, Newton's third law tells us that object 2 exerts an equal and opposite force on object 1—which means that object 1's momentum changes by precisely the same amount as object 2's momentum, but in the opposite direction. The total combined momentum of objects 1 and 2 remains the same both before and after the collision. We say that the total momentum of the colliding objects is conserved, reflecting a

ground. According to present understanding, the total energy content of the universe was determined in the Big Bang. It remains the same today and will stay the same in the future.

## 4.4 The Force of Gravity

Newton's laws of motion describe how objects in the universe move in response to forces. The laws of conservation of momentum, angular momentum, and energy offer an alternative and often simpler way of thinking about what happens when a force causes some change in the motion of one or more objects. However, we cannot fully understand motion unless we also understand the forces that lead to changes in motion. In astronomy, the most important force is gravity, which governs virtually all large-scale motion in the universe.

**MA** Motion and Gravity Tutorial, Lesson 2

### • What determines the strength of gravity?

Isaac Newton discovered the basic law that describes how gravity works. Newton expressed the force of gravity mathematically with his **universal law of gravitation**. Three simple statements summarize this law:

- Every mass attracts every other mass through the force called *gravity*.
- The strength of the gravitational force attracting any two objects is *directly proportional* to the product of their masses. For example, doubling the mass of *one* object doubles the force of gravity between the two objects.
- The strength of gravity between two objects decreases with the *square* of the distance between their centers. We therefore say that the gravitational force follows an **inverse square law**. For example, doubling the distance between two objects weakens the force of gravity by a factor of  $2^2$ , or 4.

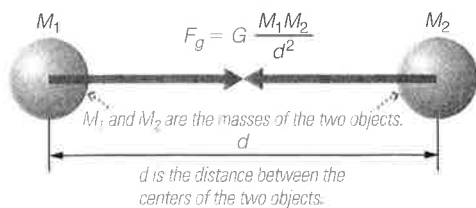
Doubling the distance between two objects weakens the force of gravity by a factor of  $2^2$ , or 4.

These three statements tell us everything we need to know about Newton's universal law of gravitation. Mathematically, all three statements can be combined into a single equation, usually written like this:

$$F_g = G \frac{M_1 M_2}{d^2}$$

where  $F_g$  is the force of gravitational attraction,  $M_1$  and  $M_2$  are the masses of the two objects, and  $d$  is the distance between their centers (Figure 4.14). The symbol  $G$  is a constant called the **gravitational constant**, and its numerical value has been measured to be  $G = 6.67 \times 10^{-11} \text{m}^3/(\text{kg} \times \text{s}^2)$ .

The **universal law of gravitation** tells us the strength of the gravitational attraction between the two objects.



**Figure 4.14**

The universal law of gravitation is an *inverse square law*, which means that the force of gravity declines with the *square* of the distance  $d$  between two objects.

#### think about it

How does the gravitational force between two objects change if the distance between them triples? If the distance between them drops by half?