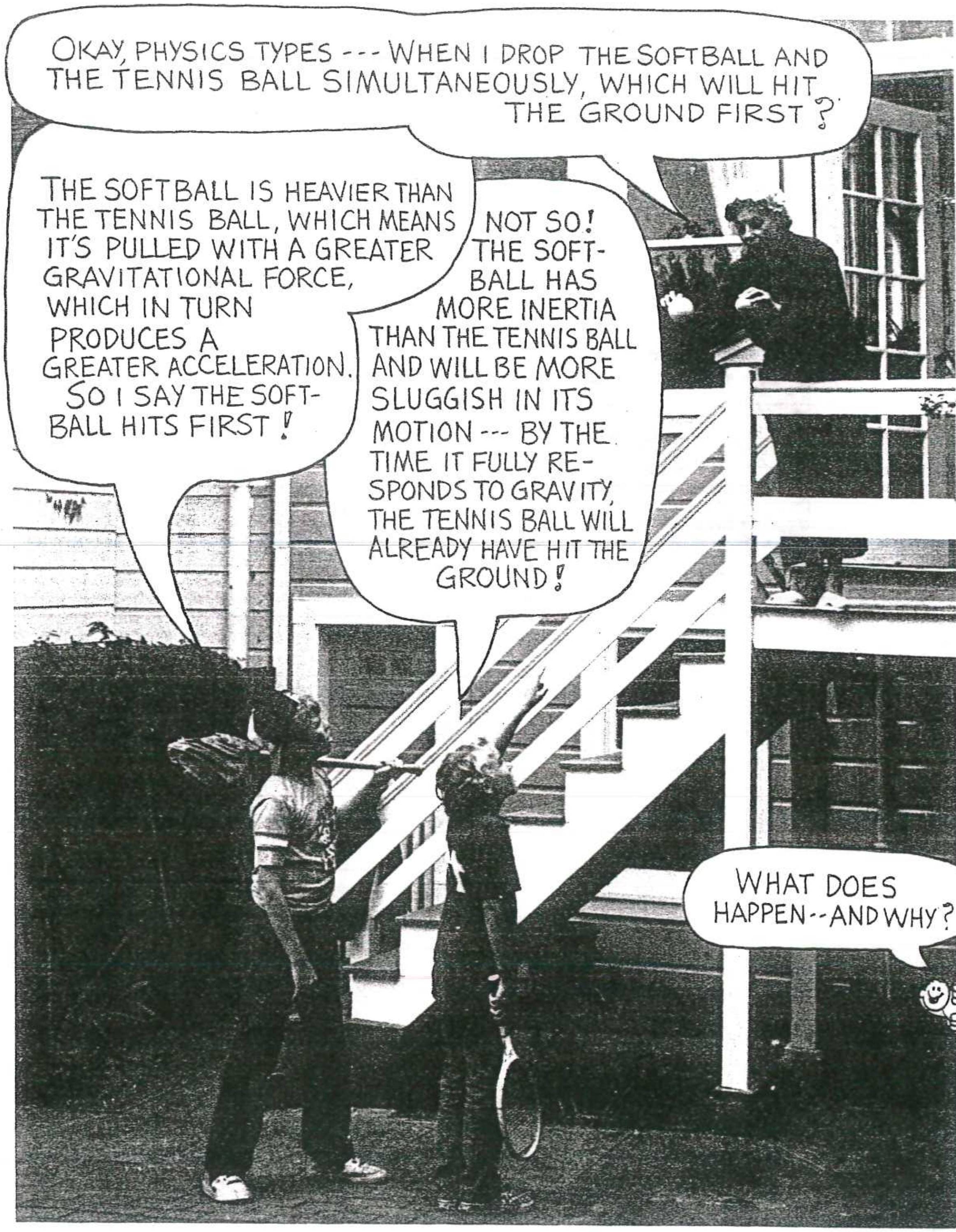

OKAY, PHYSICS TYPES --- WHEN I DROP THE SOFTBALL AND THE TENNIS BALL SIMULTANEOUSLY, WHICH WILL HIT THE GROUND FIRST?
THE SOFTBALL IS HEAVIER THAN THE TENNIS BALL, WHICH MEANS IT'S PULLED WITH A GREATER GRAVITATIONAL FORCE, WHICH IN TURN PRODUCES A GREATER ACCELERATION. SO I SAY THE SOFTBALL HITS FIRST!
NOT SO! THE SOFTBALL HAS MORE INERTIA THAN THE TENNIS BALL AND WILL BE MORE SLUGGISH IN ITS MOTION --- BY THE TIME IT FULLY RESPONDS TO GRAVITY, THE TENNIS BALL WILL ALREADY HAVE HIT THE GROUND!
WHAT DOES HAPPEN -- AND WHY?

4 Newton's Laws of Motion

Newton's First Law of Motion

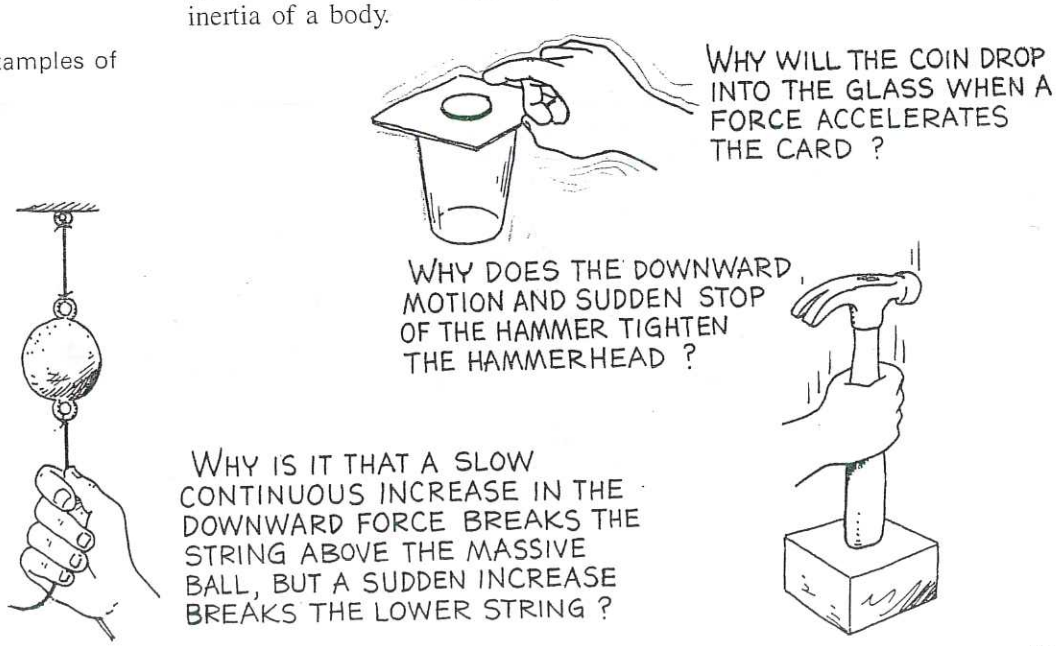
In 1642, the year that Galileo died, Isaac Newton was born. Twenty-three years later, Newton developed his famous laws of motion, which completed the overthrow of the Aristotelian ideas that had dominated the thinking of the best minds for 2000 years. We will consider these laws in order: the first, sometimes called the law of inertia, comes from Newton's *Principia*.

Law 1: ***Every body continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it.***

The key word in this law is *continues:* a body *continues* to do whatever it happens to be doing unless a force is exerted upon it. If it is at rest, it *continues* in a state of rest. If it is moving, it *continues* to move without turning or changing its speed. In short, the law says that a body does not accelerate of itself; acceleration must be imposed against the tendency of a body to retain its state of motion. This neatly summarizes our discussion of Chapter 2: recall that the tendency of a body to resist a change in motion was what Galileo called **inertia**.

Every body possesses inertia; how much depends on the amount of matter in the substance of a body—the more matter, the more inertia. In speaking of how much matter a body has, we use the term *mass*. The greater the mass of a body, the greater its inertia. **Mass** is a measure of the inertia of a body.

Fig. 4.1 Examples of inertia.



Mass corresponds to our intuitive notion of **weight**. We say something has a lot of matter if it is heavy. That's because we are accustomed to measuring the quantity of matter in a body by its gravitational attraction to the earth. But mass is more fundamental than weight; it is a fundamental quantity that completely escapes the notice of most people. There are times, however, when weight corresponds to our unconscious notion of inertia. For example, if you are trying to determine which of two small objects is the heavier, you might shake them back and forth in your hands or move them in some way instead of lifting them. In doing so, you are judging which of the two is more difficult to move, seeing which is the more resistant to a change in motion. You are really making a comparison of the inertias of the objects. It is easy to confuse the ideas of mass and weight, mainly because they are directly proportional to each other. If the mass of an object is doubled, its weight is also doubled; if the mass is halved, its weight is halved. But there is a distinction between the two. We can define each as follows:

Mass: *The quantity of matter in a body. More specifically, it is the measurement of the inertia or sluggishness 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 upon a body due to gravity.*

In the United States, the quantity of matter in an object has commonly been described by its gravitational pull to the earth, or its weight. This has usually been expressed in *pounds*. In most of the world, however, the measure of matter is commonly expressed in a mass unit, the **kilogram**. At the surface of the earth, the mass of a 1-kilogram brick weighs 2.2 pounds. In the metric system of units, the unit of force is the **newton**, which is equal to a little less than a quarter pound (like the weight of a quarter-pounder hamburger *after* it is cooked). A 1-kilogram brick weighs 9.8 newtons (9.8 N).[1] Away from the earth's surface, where the influence of gravity is less, a 1-kilogram brick weighs less. It would also weigh less on the surface of planets with less gravity than the earth. On the moon, for example, where the gravitational force on a body is only $\frac{1}{6}$ as strong as on earth, 1 kilogram weighs about 1.6 newtons (or 0.36 pound). On more

[1] So 2.2 lb equals 9.8 N, or 1 N is approximately equal to 0.2 lb—about the weight of an apple. In the metric system it is customary to specify quantities of matter in units of mass (in grams or kilograms) and rarely in units of weight (in newtons). In the United States and places that have been using the British system of units, however, quantities of matter have customarily been specified in units of weight (in pounds); and the unit of mass, called the *slug*, is not well known. See Appendix I for more about systems of measurement.

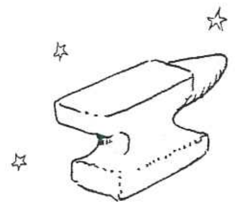


Fig. 4.2 An anvil in outer space, between the earth and moon, for example, may be weightless; but it is not massless.

massive planets it would weigh more. But the mass of the brick is the same everywhere. The brick offers the same resistance to speeding up regardless of whether the earth, moon, or anything at all is attracting it. In a space capsule located between the earth and the moon, where gravitational forces cancel one another, a brick still has mass. If placed on a scale, it wouldn't weigh anything, but its resistance to a change in motion is the same as on earth. Just as much force would have to be exerted by an astronaut in the space capsule to shake the brick back and forth as would be required to shake it back and forth while standing on earth. Except for friction effects, it would be just as hard to push a Cadillac limousine across a level surface on the moon as on earth. The difficulty of lifting it against gravity (weight) is something else. Mass and weight are different from one another (Figures 4.2 and 4.3).

It is also easy to confuse mass and size—or, more specifically, **volume**. Perhaps this is because when we think of a massive object, we think of a big object—that is, a voluminous object that occupies much space. But an object can be massive—a lead storage battery, for example—without occupying much space at all. This confusion might also occur because mass and volume are often proportional to each other, at least for the same material. For example, 2 kilograms of sugar will fill a bag of twice the volume as 1 kilogram of sugar. But this does not mean that mass *is* volume. Because 2 kilograms of sugar have twice the sweetening power of 1 kilogram, we don't say that mass *is* sweetening power. Two loaves of bread may have the same mass but quite unequal volumes. You can always compress a loaf of bread and change its volume, but the mass doesn't change; it contains the same amount of matter. So you see that mass is neither weight nor volume.

Fig. 4.3 The astronaut in space finds it is just as difficult to shake the "weightless" anvil as it would be on earth. If the anvil is more massive than the astronaut, which shakes more—the anvil or the astronaut?

Although Galileo introduced the idea of inertia, Newton grasped its significance. The law of inertia defines natural motion and tells us what kinds of motion are the result of impressed forces. Whereas Aristotle maintained that the forward motion of an arrow through the air required an impressed force, Newton's law of inertia instead tells us that the behavior of the arrow is natural; constant speed along a straight line (or, simply, constant velocity) requires no force. And whereas Aristotle and his followers held that the circular motions of heavenly bodies were natural and moving without impressed forces, the law of inertia clearly states that in the absence of forces of some kind the planets would not move in the divine circles of ancient and medieval astronomy but would move instead in straight-line paths off into space. Newton maintained that the curved motion of the planets was evidence of some kind of force. We shall see in the next two chapters that his search for this force led to the law of gravitation.

Question Would it be easier to lift a Cadillac limousine on the earth or to lift it on the moon?*

Newton's Second Law of Motion

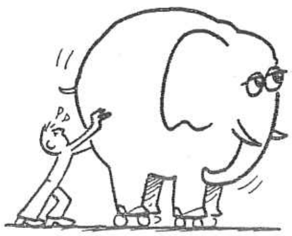


Fig. 4.4 The greater the mass, the greater the force must be for a given acceleration.

Every day we see bodies that do not continue in a constant state of motion: things initially at rest later may move; moving objects may follow paths that are not straight lines; objects in motion may stop. Most of the motion we observe is accelerated motion and is the result of one or more impressed forces. The overall net force, whether it be from a single source or a combination of sources, produces acceleration. The relationship of acceleration to force and inertia is given in Newton's second law.

Law 2: ***The acceleration of a body is directly proportional to the net force acting on the body and inversely proportional to the mass of the body and is in the direction of the net force.***

In summarized form, this is

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

In symbol notation, this is simply

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

We shall use the wiggly line $\sim$ as a symbol meaning "is proportional to." We say that acceleration a is directly proportional to the overall net force F and inversely proportional to the mass m. By this we mean that if F increases, a increases; but if m increases, a decreases. With appropriate units of F, m, and a, the proportionality may be expressed as an exact equation:

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

A body is accelerated in the direction of the force acting on it. Applied in the direction of the body's motion, a force will increase the body's speed. Applied in the opposite direction, it will decrease the speed of the

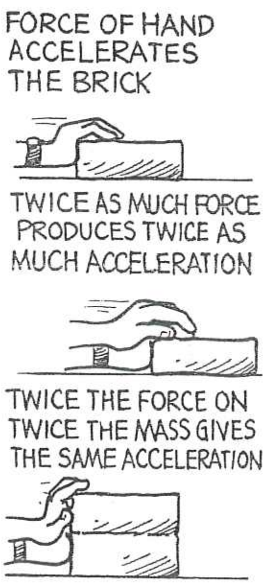


Fig. 4.5 Acceleration is directly proportional to force.

*__Answer__ A Cadillac limousine would be easier to lift on the moon because the force of gravity is less on the moon. When you *lift* an object, you are contending with the force of gravity (its weight) in addition to its inertia (its mass). Although its mass is the same on either the earth or the moon, its weight is only $\frac{1}{6}$ as much on the moon, and only $\frac{1}{6}$ as much effort is required to lift it there. To move it horizontally, however, you are not pushing against gravity. When mass is the only factor, equal forces will produce equal accelerations whether the object is on the earth or the moon.

body. Applied at right angles, it will deflect the body. Any other direction of application will result in a combination of speed change and deflection. *The acceleration of a body is always in the direction of the net force.*

A **force**, in the simplest sense, is a push or a pull. Its source may be gravitational, electrical, magnetic, or simply muscular effort. In the second law, Newton gives a more precise idea of force by relating it to the acceleration it produces. He says in effect that *force is anything that can accelerate a body*. Furthermore, he says that the larger the force, the more acceleration it produces. For a given body, twice the force results in twice the acceleration; three times the force, three times the acceleration; and so forth. Acceleration is directly proportional to force (Figure 4.5).

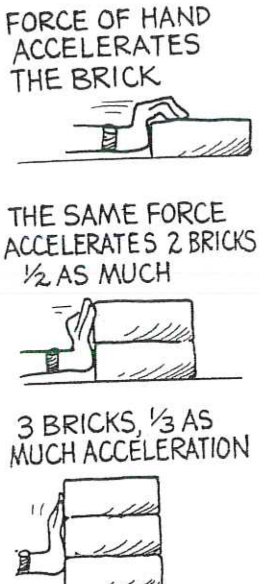


Fig. 4.6 Acceleration is inversely proportional to mass.

The body's mass has the opposite effect (Figure 4.6). The more massive the body, the less its acceleration. For the same force, twice the mass results in half the acceleration; three times the mass, one-third the acceleration. Increasing the mass decreases the acceleration. For example, if we put identical Ford engines in a Cadillac and a Volkswagen, we would expect quite different accelerations even though the driving force in each car is the same. The Cadillac with its greater mass has a greater resistance to a change in velocity than does the Volkswagen. Consequently, the Cadillac requires a more powerful engine to achieve comparable acceleration. To attain the same acceleration, a larger mass requires a correspondingly larger force. We say that acceleration is inversely proportional to mass.[2]

The acceleration of a body, then, depends *both* on the magnitude of the net force and on the mass of the body.

Question In Chapter 2 acceleration was defined to be the time rate of change of velocity; that is, a = (change in v)/time. Are we in this chapter saying that acceleration is instead the ratio of force to mass; that is, $a = F/m$? Which is it?*

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* **Answer** Acceleration *is* the time rate of change of velocity and is *produced by* a force. How much $\frac{\text{force}}{\text{mass}}$ (the cause) results in the rate $\frac{\text{change in } v}{\text{time}}$ (the effect).

[2] Mass is operationally defined as the proportionality constant between force and acceleration in Newton's second law, rearranged to read $m = \frac{F}{a}$. A 1-unit mass is that which requires 1 unit of force to produce 1 unit of acceleration. So 1 kg is the amount of matter that 1 N of force will accelerate 1 m/s^2. In British units, 1 slug is the amount of matter that 1 pound of force will accelerate 1 ft/s^2. We shall see later that mass is simply a form of concentrated energy.