INTERLUDE 2

Each Step Beyond

Newton, of course, did not create his laws of motion spontaneously while sitting under an apple tree. While in many ways his work was a revolutionary departure from previous ideas about motion, it owed an immense debt to Galileo's exhaustive study of motion. Newton and Galileo saw, as others had not, what motion would be like in a vacuum. To illustrate both the context from which Newton's ideas grew and the stumbling block posed by motion in a vacuum, we pause to consider the development of the laws of motion.

The first laws of motion were proposed by Aristotle (384–322 B.C.). In observing objects around him, Aristotle noticed that an object required a force in order to start moving. If that force was removed, the object eventually came to a stop. A large force resulted in a large velocity; a small force resulted in a small velocity. He concluded that force was related to velocity.

In some situations, however, force resulted in no velocity. We could push and push on a heavy boulder, but it would never budge. In order to explain these observations, Aristotle added the concept of resistance. Resistance to motion can arise from two sources. If the resistance is offered by the object we are trying to move, then resistance is a property of that object—like the later ideas of mass and inertia. If the resistance is offered by the material through which the object moves, then resistance is like friction—a force exerted by other materials. Aristotle chose the latter, calling resistance a property of the medium through which an object moves.

Combining the concept of resistance with the idea that force was related to velocity, Aristotle formulated his "second law:"

$$\text{Velocity} = \frac{\text{force}}{\text{resistance}}$$

It looks remarkably like Newton's second law, except that it relates force to velocity instead of acceleration, and it defines resistance as a property of the medium, not the object being moved. When Aristotle tried to imagine what would happen in a vacuum, he saw an absurdity. In a vacuum, the resistance would be zero and the object's velocity would increase to infinity. Aristotle concluded that vacuums did not exist.

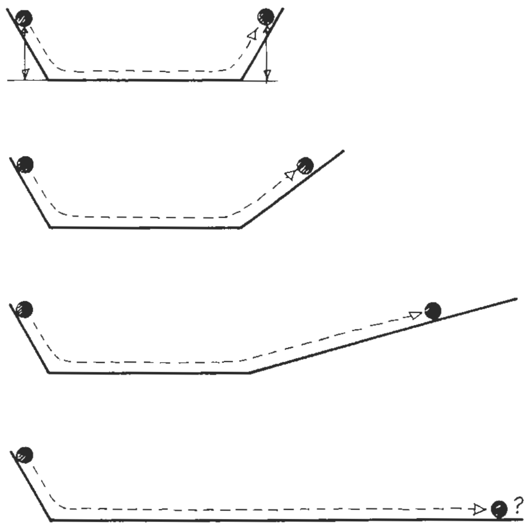
In the years from Aristotle to Galileo, Philoponus, Avicenna, and a number of other scientists grappled unsuccessfully with this problem of motion in a vacuum. Philoponus (ca. A.D. 500) attacked this problem of motion in a vacuum by suggesting that Aristotle's relationship be modified to

$$\text{Velocity} = \text{force} - \text{resistance}$$

If the resistance were zero, the object would move with a constant velocity directly proportional to the force. Consequently, motion in a vacuum would be possible. By suggesting that an object's motion depends on the difference between force and resistance, Philoponus' modification introduced what we have come to call the *net force.* However, Philoponus still related force to velocity, not acceleration.

Avicenna (A.D. 980-1037) proposed a different modification of Aristotle's relationship. Avicenna suggested that objects themselves have a property, which he called *mail,* that resists a change in motion. Objects moving in a vacuum would continue moving forever, not speed up forever as Aristotle had supposed. Avicenna's concept is in many ways a forerunner of Galileo's concept of inertia or Newton's concept of mass. However, since Avicenna had never seen objects that moved at a constant velocity forever, he, too, concluded that vacuums do not exist. Like Aristotle, Avicenna failed to pursue the question of what would happen if. For these scientists, what had not been observed simply was not possible.

Galileo (1564-1642) eventually made the mental jump from the observed to the hypothetical—from motion in everyday experience to motion without resistance. Going down an incline, he reasoned, a ball accelerates. If he placed a second incline facing the first, the ball would move up the second incline almost to the same height from which it had been released on the first incline. Mentally, Galileo removed friction and concluded that the ball would continue up the second incline until it reached exactly the same height from which it had been released. Next, Galileo decreased the angle of the second incline. Each time, the ball traveled until it almost reached the same height from which it had been released. At lower inclines, however,



the ball had to travel farther (Figure 1). If the angle of incline were reduced to zero, Galileo reasoned, the ball would continue moving forever. It is only the resistance offered by the surface and the air that keeps this from being so. Called the law of inertia, Galileo's conclusion paved the way for Newton's first law of motion.

Because of friction, Galileo was never able to actually observe an object moving along a level board with an unchanging velocity. But he could mentally remove friction and imagine what would happen. His guide in performing these imaginary experiments was the simplicity of the mathematical relationships he had discovered from actual measurements. A commitment to experimentation and simplicity allowed Galileo to see what others had not seen—motion in a frictionless world.

Newton built upon Galileo's work, adding the concepts of force and mass to Galileo's descriptions of motion. His second law,

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

relates net force to acceleration and identifies the mass of the object as the source of inertia. The second law incorporates Aristotle's concept of the resistance provided by the medium into the concept of net force. The net force acting on an object that you push or pull is the force you exert minus any frictional force provided by the medium. Resistance to motion is indeed a property of the medium. But resistance to a change in motion is a property of the object (called mass). Because they take both these properties into account, Newton's laws could predict motion in a vacuum as well as motion on earth.

If you had been asked to write your own laws of motion before reading about Newton's laws, you might well have written something like Aristotle's or Philoponus' laws. Most of us would. We are easily influenced by our everyday experiences. Sometimes these laws turn out to be wrong—like Aristotle's. Sometimes they turn out to be right, but only for a limited number of situations. Sometimes, they are broad enough to encompass a wide range of experiences, like Newton's laws, and they become part of the scientific heritage we hand down to future generations.

For over 200 years, Newton's laws were thought to describe all motion, observed and hypothetical. Once again, however, physicists had not considered a type of motion they had never seen—motion at speeds near that of light. Albert Einstein did. Wondering what he would see while riding along a beam of light, Einstein completely redefined our concepts of space and time. His work exposed the limitations of Newton's laws and presented an even broader model—the special theory of relativity. Like Newton, Einstein imagined something that he could not observe. Yet his ideas, like Newton's, have been borne out by actual experiments. By looking beyond our own experience—by taking that one step beyond—we find simpler and more powerful descriptions of nature.