# 13 Naive Theories of Motion

Michael McCloskey
*The Johns Hopkins University*

Everyday life provides people with countless opportunities for observing and interacting with objects in motion. For example, watching a baseball game, driving a car and even dropping a pencil involve encounters with moving objects. Thus, everyone presumably has some sort of knowledge about motion. However, it is by no means clear what form or forms this knowledge may take. Everyday experience may lead only to the acquisition of concrete facts about the behavior of specific objects in specific situations (e.g., when a moving billiard ball strikes a stationary ball head on, the moving ball often stops). Alternatively, experience may result in the induction of descriptive generalizations that summarize a variety of observations (e.g., moving objects eventually slow down and stop). Finally, experience might even lead to the development of implicit theories of motion that provide explanations for, as well as descriptions of, the behavior of moving objects (e.g., changes in the speed or direction of an object's motion are caused by external forces).

In this chapter we describe research aimed at determining what sorts of knowledge are in fact acquired through experience with moving objects. We first present some basic findings from experiments in which subjects solved simple problems concerning objects in motion. We then show that these and other findings imply that people develop on the basis of their everyday experience remarkably well-articulated naive theories of motion. Further, we argue that the assumptions of the naive theories are quite consistent across individuals. In fact, the theories developed by different individuals are best described as different forms of the same basic theory. Although this basic theory appears to be a reasonable outcome of experience with real-world motion, it is strikingly inconsistent with the fundamental principles of classical physics. In fact, the naive theory is remarkably similar to a pre-Newtonian physical theory popular in the 14th through 16th centuries.

In addition to considering the nature of the knowledge acquired through experience with moving objects, we briefly discuss the ways in which the experience-based knowledge interacts with knowledge acquired through classroom instruction in physics. Finally, we discuss the relationship of our work to other research concerning knowledge and reasoning about physics, and mention several important issues for future research.

## MISCONCEPTIONS ABOUT MOTION

We first attempted to probe people's knowledge about motion in a series of experiments employing simple, nonquantitative problems concerning the behavior of moving objects. Subjects were undergraduate students at the Johns Hopkins University. In each experiment three groups of subjects were employed: (1) students who had never taken a high school or college physics course; (2) students who had taken high school but not college physics; and (3) students who had completed at least one college physics course.

In one experiment we asked 48 subjects to solve thirteen simple problems. Each problem consisted of a diagram, with instructions that explained the diagram and asked the subject to make a qualitative prediction about the motion of an object. Two of the problems are shown in Fig. 13.1. For problem A the subjects were given the following instructions:

> The diagram shows a thin curved metal tube. In the diagram you are looking down on the tube. In other words, the tube is lying flat. A metal ball is put into the end of the tube indicated by the arrow and is shot out of the other end of the tube at high speed.

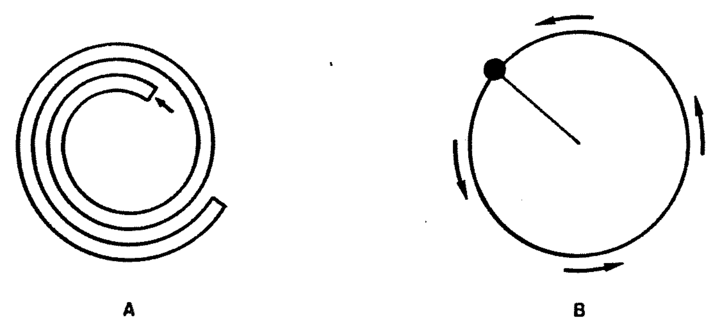


Fig. 13.1. Diagrams for the spiral tube problem (A) and the ball and string problem (B).



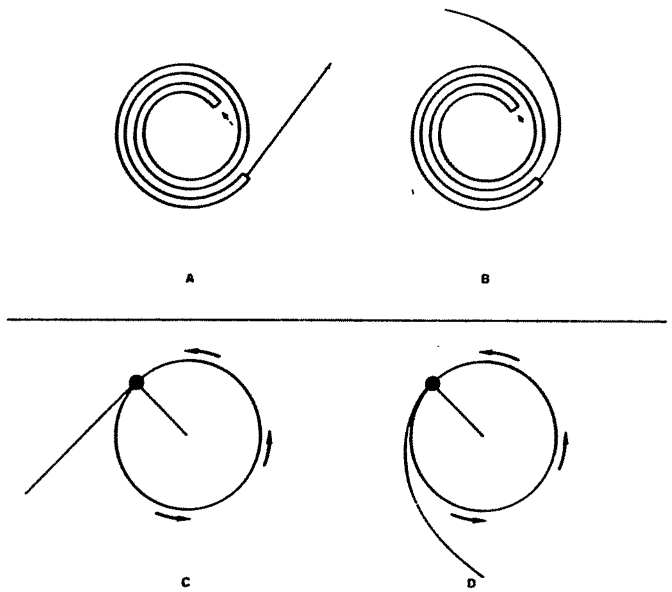


Fig. 13.2. Correct response and most common incorrect responses for the spiral tube problem and the ball and string problem. The correct responses appear in (A) and (C).

The subjects were then asked to draw the path the ball would follow after it emerged from the tube, ignoring air resistance and any spin the ball might have.

For problem B, the subjects were told:

> Imagine that someone has a metal ball attached to a string and is twirling it at high speed in a circle above his head. In the diagram you are looking down on the ball. The circle shows the path followed by the ball and the arrows show the direction in which it is moving. The line from the center of the circle to the ball is the string. Assume that when the ball is at the point shown in the diagram, the string breaks where it is attached to the ball. Draw the path the ball will follow after the string breaks. Ignore air resistance.

Newton's first law states that in the absence of a net applied force, an object in motion will travel in a straight line. Thus, the correct answer to the spiral tube problem is that after the ball leaves the tube it will move in a straight line in the direction of its instantaneous velocity at the moment it exits the tube (see Fig. 13.2A).

The correct answer to the ball and string problem is similar. As shown in Fig. 13.2C, the ball will fly off in a straight line along the tangent to the circle at the point where the ball was located when the string broke. In other words, the ball will travel in a straight line in the direction of its instantaneous velocity at the moment the string broke. (The force of gravity acts in a direction perpendicular to the horizontal plane, and so will not affect the speed or direction of the ball's horizontal motion.)

Somewhat surprisingly, a substantial proportion of the subjects gave incorrect answers to the problems (McCloskey, Caramazza & Green, 1980). For the spiral tube problem, 51% of the subjects thought that the ball would follow a curved path after emerging from the tube (see Fig. 13.2B). Similarly, for the ball and string problem 30% of the subjects believed that the ball would continue in curvilinear motion after the string broke (Fig. 13.2D). One other interesting aspect of the results is that most subjects who drew curved paths apparently believed that the ball's trajectory would gradually straighten out. This straightening of trajectories can be seen in the representative responses shown in Figs. 13.2B and 13.2D.

Figure 13.3 shows another problem we have used, the airplane problem. For this problem subjects were told that

> In the diagram, an airplane is flying along at a constant speed. The plane is also flying at a constant altitude, so that its flight path is parallel to the ground. The arrow shows the direction in which the plane is flying. When the plane is in the position shown in the diagram a large metal ball is dropped from the plane. The plane continues flying at the same speed in the same direction and at the same altitude. Draw the path the ball will follow from the time it is dropped until it hits the ground. Ignore wind or air resistance. Also, show as well as you can, the position of the plane at the moment the ball hits the ground.

The correct answer to the problem, which is shown in Fig. 13.4A, is that the ball will fall in a parabolic arc. The airplane will be directly above the ball when it hits the ground. This answer may be understood by noting that the total velocity of the ball may be decomposed into independent horizontal and vertical

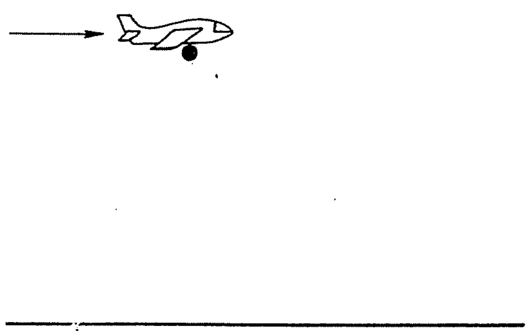


Fig. 13.3. Diagram for the airplane problem.



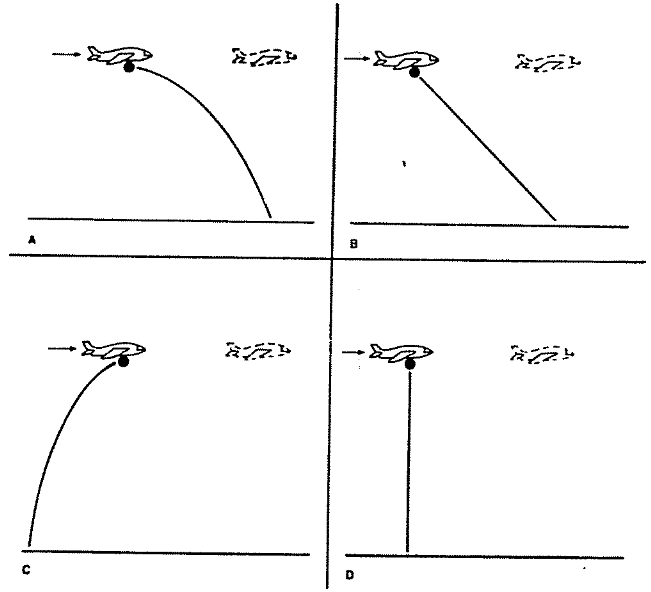


Fig. 13.4. Correct response (A) and incorrect responses (B-D) for the airplane problem.

components. Before the ball is dropped, it has a horizontal velocity equal to that of the plane, and a vertical velocity of zero. After the ball is released, it undergoes a constant vertical acceleration due to gravity, and thus acquires a constantly increasing vertical velocity. The ball's horizontal velocity, however, does not change. In other words, the ball continues to move horizontally at a speed equal to that of the plane. (The force of gravity acts in a direction perpendicular to that of the ball's horizontal motion, and consequently does not influence the ball's horizontal velocity. Further, no other forces are acting on the ball. Thus, according to the principle of inertia, the ball's horizontal velocity will remain constant.) The combination of the constant horizontal velocity and the continually increasing vertical velocity produces a parabolic arc. Finally, because the horizontal velocity of the ball is always the same as that of the plane, the plane will remain directly above the ball until the ball hits the ground.

When we presented the airplane problem to 48 subjects, we obtained a variety of responses (Green, McCloskey & Caramazza, 1980). Nineteen subjects, or 40%, drew forward arcs that looked more or less parabolic (see Fig. 13.4A). Fifteen of these 19 subjects indicated that the plane would be directly over the ball when the ball hit the ground. However, four subjects indicated that at the moment the ball hit the ground, the airplane would be well ahead of it horizontally.

Thirteen percent of the subjects thought that the ball would fall in a straight diagonal line (Fig. 13.4B), whereas another 11% indicated that the ball would move backwards when released (Fig. 13.4C). However, the most common incorrect response, which was made by 36% of the subjects, was that the ball would fall straight down (Fig. 13.4D). These results suggest that many people have little understanding of projectile motion.

Consider finally the very simple problem shown in Fig. 13.5, which we recently presented to 135 students in an introductory psychology class. The subjects were given the following instructions:

> The diagram shows a side view of a cliff. The top of the cliff is frictionless (in other words, perfectly smooth). A metal ball is sliding along the top of the cliff at a constant speed of 50 miles per hour. Draw the path the ball will follow after it goes over the edge of the cliff. Ignore air resistance.

The correct answer for the cliff problem is similar to that for the airplane problem. After the ball goes over the edge of the cliff, it will continue to travel horizontally at a constant speed of 50 mph. However, the ball will acquire a constantly increasing vertical velocity, and consequently will fall in a parabolic arc.

Seventy-four percent of the subjects drew trajectories that appeared more or less parabolic (see Fig. 13.6A). However, as shown in Figs. 13.6B and 13.6C the drawings of 22% of the subjects clearly showed the ball moving in an arc for some time and thereafter falling straight down. These subjects apparently believed that the ball's horizontal velocity, instead of remaining constant, would gradually decrease to zero. Several of the subjects who believed that the ball would eventually be falling straight down drew particularly interesting trajectories. In these trajectories, one of which is reproduced in Fig. 13.6C, the ball continues to travel in a straight horizontal line for some time after it goes over the edge of the cliff. The ball then turns rather abruptly and falls straight down.

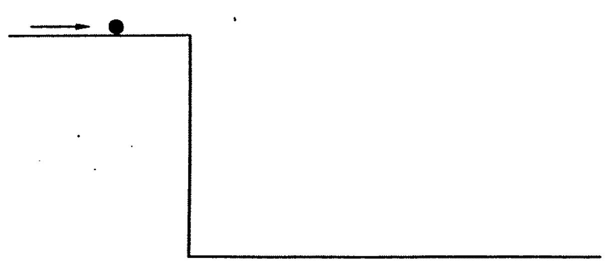


Fig. 13.5. Diagram for the cliff problem.



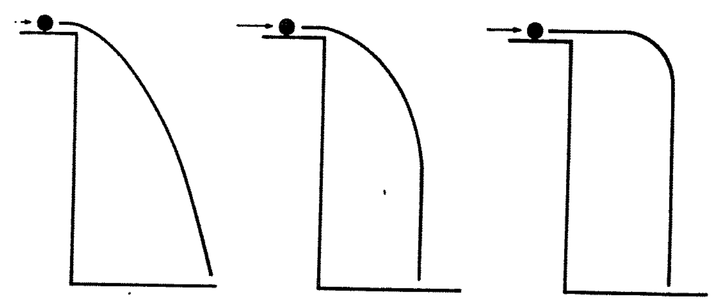


Fig. 13.6. Correct responses (A) and most common incorrect responses (B and C) for the cliff problem.

Other problems have produced results similar to those obtained for the four problems discussed here. In other words, although some subjects gave the correct answer, a large percentage made errors of various sorts.

For most of the problems we have employed, classroom physics instruction appears to affect the number but not the types of errors. In other words, subjects who have never taken a physics course make the most errors, subjects who have completed a high-school course do somewhat better, and subjects who have taken college physics make the fewest errors. However, the same sorts of errors are made by subjects in all three groups.

At first it appeared to us, as it must also appear to the reader, that the errors obtained for the various problems reflected a wide variety of separate and perhaps idiosyncratic misconceptions held by the subjects. However, as we show in the next section, additional research revealed that this was not the case.

## A NAIVE THEORY OF MOTION

In an attempt to uncover the bases for the errors observed on our simple problems, we conducted an experiment in which subjects were tested individually. The subjects first solved several problems, and were then interviewed at length about their answers. During the interviews, the subjects were asked to explain their answers to the problems presented initially. They were also asked to solve additional problems when there was need to clarify a point. The subjects were encouraged to talk about what they were thinking as they attempted to arrive at an answer to a question or problem. The interviews, which lasted 1.5 to 2.5 hours per subject, were tape recorded and later transcribed verbatim.

Subjects were 13 students at Johns Hopkins University. Four of the subjects had never taken a physics course, three had taken high school physics, and the remaining six had completed at least one year of college physics. The results for the problems presented prior to the interviews suggested that these 13 subjects were comparable to those from the earlier experiments. In particular, the subjects from the present experiment made the same sorts of errors as the subjects tested previously.

The interviews clearly indicated that at least 11 of the 13 subjects relied heavily upon a well-developed naive theory of motion in arriving at answers to the problems. Remarkably, all 11 subjects held the same basic theory. This theory, which we will refer to as a naive *impetus theory*, makes two fundamental assertions about motion. First, the theory asserts that the act of setting an object in motion imparts to the object an internal force or "impetus" that serves to maintain the motion. Second, the theory assumes that a moving object's impetus gradually dissipates (either spontaneously or as a result of external influences), and as a consequence the object gradually slows down and comes to a stop. For example, according to the impetus theory, a person who gives a push to a toy car to set it rolling across the floor imparts an impetus to the car, and it is this impetus that keeps the car moving after it is no longer in contact with the person's hand. However, the impetus is gradually expended, and as a result the toy car slows down and eventually stops.

In the following discussion we present evidence that our subjects do indeed hold a naive impetus theory. Further, we show that many of the errors observed for our problems follow from this basic theory and the specific elaborations of it developed by the subjects. However, before discussing these points we digress briefly to consider the differences between the impetus view and the principles of classical physics.

According to the impetus theory, an object set in motion acquires an internal force, and this internal force keeps the object in motion. This view, which draws a qualitative distinction between a state of rest (absence of impetus) and a state of motion (presence of impetus), is inconsistent with the principles of classical physics. Classical physics argues that in the absence of a net applied force, an object at rest remains at rest and an object in motion remains in motion in a straight line at a constant speed. Just as no force is required to keep an object at rest, no force is required to keep an object in motion. In fact, no qualitative distinction is made between a state of rest and a state of constant-velocity rectilinear motion. Any object that is not accelerating (i.e., not undergoing a change in speed and/or direction) can be described as at rest or as in constant-velocity motion, depending on the choice of a frame of reference. For example, a person riding in a car that is moving in a straight line at a constant speed may be described as at rest if the car is chosen as the frame of reference, or in motion if the ground is taken as the reference frame. According to classical physics, neither of these descriptions is any more valid than the other. Another way of saying this is that, within classical physics, states of absolute rest and absolute motion do not exist. Thus, it is not correct to say, as the impetus theory does, that moving objects have an internal force or impetus while objects at rest do not, because an object may be simultaneously described as at rest or in motion depending upon the choice of a frame of reference.



With this discussion in mind, let us now consider the results of the experiment in which subjects were interviewed about their answers to problems. Several aspects of these results provide strong support for the claim that many people espouse a naive impetus theory.

In the first place, several subjects stated the impetus view rather explicitly during the course of the interview. For example, one subject, who had completed one year of college physics, used the term *momentum* in explaining his answer to a problem involving the motion of a metal ball. When asked to explain what he meant by momentum, the subject stated:

> I mean the weight of the ball times the speed of the ball.... Momentum is...a force that has been exerted and put into the ball so this ball now that it's travelling has a certain amount of force....The moving object has the force of momentum and since there's no force to oppose that force it will continue on until it is opposed by something.

In a similar situation another subject, who had also taken college physics, defined momentum as

> a combination of the velocity and the mass of an object. It's something that carries it along after a force on it has stopped.... Let's call it the force of motion.... It's something that keeps a body moving.

The belief that motion is maintained by an impetus impressed on an object is quite clear in these statements.

The belief that moving objects slow down and stop due to the dissipation of impetus can also be seen in subjects' statements. For example, one subject, who had never taken a physics course, was asked to explain why a ball rolling along a floor would eventually come to a stop. The subject stated that friction and air resistance slow the ball down, and was then asked to explain how these factors affect the ball. He replied as follows:

> I understand that [friction and air resistance] adversely affect the speed of the ball, but now how. Whether they sort of absorb some of the force that's in the ball...I'm not sure. In other words, for the ball to plow through the air resistance or the friction if it has to sort of expend force and therefore lose it, I'm not sure.... That seems to be a logical explanation.

The subject's assumption that the ball slows down because friction and air resistance sap its impetus is clear, although the subject is unsure whether this assumption is correct.

The naive impetus theory was also used by subjects to explain the behavior of objects in more complex situations. One subject, who had completed both high school and college physics courses, was asked to draw the path followed by a ball thrown upward at a 45 degree angle. The subject drew a parabolic arc, which is correct, and was then asked to explain why the ball follows this sort of path. The subject responded by drawing force vectors at various points along the path of the ball (see Fig. 13.7), and explaining that

> The ball when it was first thrown was provided with a certain amount of force.... What's happening is that the force is basically being counterbalanced by gravity, and at this point [labeled 1 in Fig. 13.7] the upward force is still stronger than gravity, while here [point 2] they're both equal and here [point 3] gravity has become stronger.

In response to further questioning the subject stated that the upward force steadily decreased due to the constant force of gravity.

Two other subjects gave virtually identical explanations for the behavior of a projectile shot from a cannon. For example, one subject explained that the cannonball slows down as it moves from the cannon to the peak of the arc, and speeds up thereafter

> Because as it [the cannonball] comes up the force from the cannon is dissipating and the force of gravity is taking over. So it slows down.... As it makes the arc and begins to come down, gravity is overcoming the force from the cannon.

The subject further argued that the cannonball accelerates on the way down due to the continuing dissipation of the force from the cannon. Clement (1982) has obtained similar results with the same sort of problem.

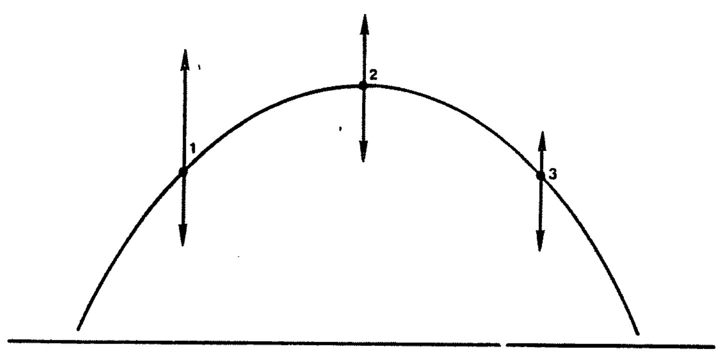


Fig. 13.7. Subject's drawing of the trajectory of a thrown ball, with vectors drawn by the subject to represent the "upward force" and the force of gravity at three points on the trajectory.



The view that many people espouse a naive impetus theory offers an interpretation for many of the errors made by subjects on the problems described in the preceding section. Consider, for example, the problem in which a moving ball goes over the edge of the cliff. As discussed earlier, many subjects indicated that the ball would move in an arc for some time and thereafter fall straight down (see Figs. 13.6B and 13.6C). This response seems to reflect a belief that the ball's impetus, which causes it to keep moving horizontally for some time after it goes over the edge of the cliff, gradually dissipates. When the original impetus is entirely gone, the ball has no forward motion and thus falls straight down. This interpretation is supported by statements made by several subjects in the interview experiment. One subject, who indicated that a ball going over a cliff would continue in a straight horizontal line for a short time and would then turn and fall straight down, said

> When it leaves the cliff the inertia force—the horizontal force—is greater than the downward motion force. When the horizontal force becomes less the ball would start falling...eventually the horizontal force would no longer have an effect, and it would be a straight downward motion.

Another subject who believed that the ball would eventually be falling straight down said that after the ball went over the cliff, its velocity would gradually be expended, so that

> It will come to a point.... where there's no longer any forward movement and the fall translates into a 90 degree fall, straight down.

The curved trajectories drawn for the spiral tube and ball and string problems (see Fig. 13.2) also stem from the impetus theory. The subjects who drew curved paths apparently believed that an object constrained to move in a curved path (e.g., by being shot through a curved tube) acquires a "curvilinear impetus" that causes the object to retain its curved motion for some time after it is no longer constrained. However, the curvilinear impetus gradually dissipates, causing the object's path to straighten out (see Figs. 13.2B and 13.2D). Support for this interpretation once again comes from statements by subjects during interviews. One subject, who had never taken a physics course, explained a curved trajectory drawn for a ball shot through a curved tube in the following way:

> The momentum from the curve [of the tube] gives it [the ball] the arc.... The force that the ball picks up from the curve eventually dissipates and it will follow a normal straight line.

Similarly, a subject explaining a curved trajectory for the ball and string problem stated that the ball would follow a curved path

> because of the directional momentum. You've got a force going around and [after the string breaks, the ball] will follow the curve that you've set it in until the ball runs out of the force within it that you've created by swinging.

It is interesting that the subjects argue that when curvilinear impetus dissipates, the ball will continue in rectilinear motion rather than stopping. This argument seems to imply that in addition to the rapidly-dissipated curvilinear impetus, the ball has a longer-lasting impetus for straight-line motion.

Consider finally the problem shown in Fig. 13.8A, the pendulum problem. The diagram represents a side view of a metal ball swinging back and forth at the end of a string. Subjects are told that when the ball is in the position shown and moving from left to right, the string is cut. They are then asked to draw the path the ball will follow as it falls to the ground, ignoring air resistance. The correct answer to the problem is shown in Fig. 13.8B.

Several manifestations of the naive impetus theory were observed in the context of the pendulum problem (Caramazza, McCloskey, & Green, 1981). First, a number of subjects used the impetus concept to explain the back and forth motion of the ball before the string was cut. One subject, for example, stated that "the gravity that pulls it (the ball) to the center gives it enough force to continue the swing to the other side." Another subject indicated that the ball stops at the ends of the pendulum's arc because "the force has been expended."

The impetus view was also evident in many subjects' ideas about how the ball would behave after the string was cut. Several subjects indicated that when the string was cut the ball would continue along the original arc of the pendulum for a short time, and would then either fall straight down, as in Fig. 13.8C, or would describe a more or less parabolic trajectory, as in Fig. 13.8D.

The interpretation of these responses in terms of a naive impetus theory is rather obvious. The response shown in Fig. 13.8C reflects a belief that the motion of the pendulum before the string is cut imparts a curvilinear impetus to the ball. When the string is cut, this impetus carries the ball along the original path for a short time. However, the impetus eventually dissipates, and the ball falls straight down. The response in Fig. 13.8D can be interpreted in a similar fashion. One subject who made this sort of response explained that when the string is cut, the ball has

> the momentum that is has achieved from swinging through this arc and should continue in a circular path for a little while.... then it no longer has the force holding it in the circular path, and it has the force of gravity downward upon it so it's going to start falling in that sort of arc motion because otherwise it would be going straight.

This subject apparently believes that when the curvilinear impetus has been expended, the ball will still have an impetus that in the absence of gravity would



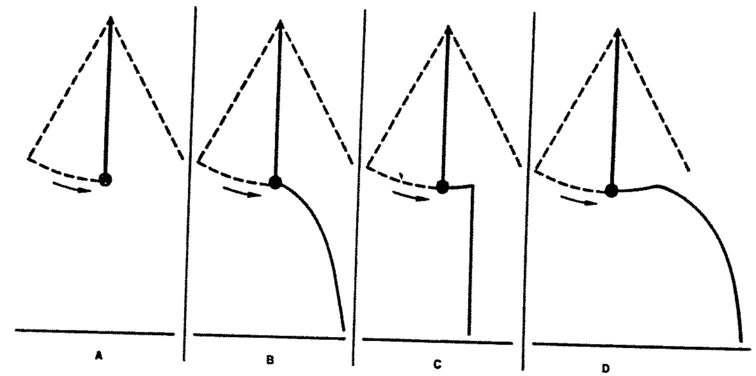


Fig. 13.8. Diagram for the pendulum problem (A) with the correct response (B) and two incorrect responses (C and D).

cause the ball to move in a straight line. Because of this additional impetus, the ball falls in an arc rather than straight down.

We have argued in this section that most of the subjects we have questioned in detail hold the same naive theory of motion, an impetus theory. However, several different forms of the impetus theory may be distinguished on the basis of the subjects' responses. In the next section we discuss these individual differences.

## INDIVIDUAL DIFFERENCES

The individual differences we have observed in the naive impetus theories represent differences among subjects in the position taken on four important issues. First, subjects differ on the issue of the existence of curvilinear impetus. As discussed earlier, many subjects believe that an object constrained to move in a curved path acquires a curvilinear impetus that causes it to follow a curved trajectory for some time after the constraints on its motion are removed. However, other subjects who hold the basic impetus theory do not postulate the existence of a curvilinear impetus.

The second important issue on which subjects differ concerns how impetus is dissipated. Some subjects believe that impetus is self-expending (i.e., dissipates spontaneously). These subjects argue that even in the absence of any external influences on a moving object, the object's impetus steadily decreases, causing it to slow down and stop (in the case of rectilinear impetus), or (in the case of curvilinear impetus) causing its path to become progressively straighter. A more common view, especially among students who have completed physics courses, is that impetus is sapped by external influences like friction and air resistance.

(We use the term *influences* rather than *forces* because students do not naturally view the external factors that decrease an object's impetus as forces in the classical physics sense.) Subjects who hold that impetus is decreased by external influences believe that in the absence of such influences the impetus does not dissipate. Thus, these subjects state that a ball moving on a frictionless plane in a vacuum, or a rocket moving through space, will continue to move at a constant speed indefinitely. Although this sort of statement is correct, the basis for it (i.e., the belief that motion is maintained by an impetus in the object) is, of course, not.

The view that impetus is sapped by external influences can be seen in the third quotation presented on p. 307. This view also manifests itself in the context of curvilinear impetus. Consider, for instance, the problem shown in Fig. 13.9, which involves a ball shot through a tube shaped like a circle with a 90 degree segment removed. One subject argued that in a vacuum, the ball would curve around and re-enter the tube, whereas in air the ball's path would be less curved and would eventually straighten out. This response suggests a belief that the curvilinear impetus dissipates in the presence of air resistance but not in a vacuum.

A third issue on which different subjects adopt different positions involves the interaction of impetus with gravity. Most subjects believe that gravity affects a moving object regardless of how much impetus it has. Thus, for example, most subjects state that a moving ball going over the edge of a cliff will immediately begin to fall. Some subjects, however, believe that gravity does not affect an object until its original impetus falls below some critical level. These subjects argue, for example, that a ball that goes over the edge of a cliff continues to

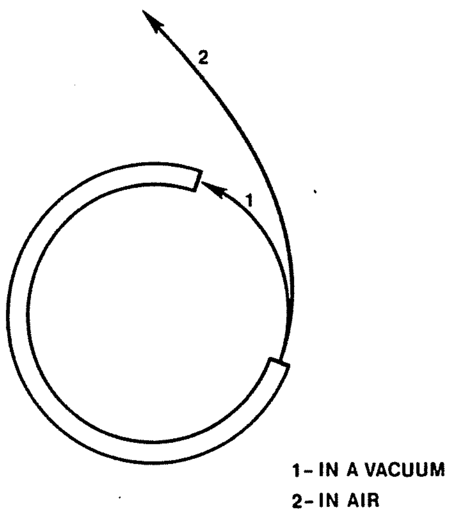


Fig. 13.9. Responses by one subject for a problem in which a ball is shot through a circular tube that is lying flat. The subject indicated that in a vacuum the ball would follow the trajectory labeled 1, while in air the ball would follow path 2.



travel in a straight horizontal line for some time before it begins to fall (see Fig. 13.6C). One subject, who gave this sort of response for a problem in which a ball launched by a spring-loaded piston goes over a cliff, explained that

> as it comes out at a certain force and speed it's going to eventually lose its horizontal momentum and as the momentum decreases it will begin to fall because gravity will begin to take over...your initial force—the spring—pushes it out, but it can't keep going at that speed indefinitely, sooner or later it's going to slow down. So as it slows down it begins to fall and somehow this line [the part of the trajectory where the ball begins to fall] is the relationship between the force of the spring and the force of gravity.

Subjects who believe that a moving object is immune to the effects of gravity until its impetus falls below a critical level differ in their views about just what this critical level is. Some of the subjects argue that gravity begins to affect the object when the object's internal force becomes weaker than the force of gravity. Thus, as we mentioned earlier, one subject who claimed that a ball going over a cliff would travel in a straight horizontal line for some time before starting to fall stated that

> when it leaves the cliff the inertia force—the horizontal force—is greater than the downward motion force[gravity]. When the horizontal force becomes less, the ball would start falling.

A few subjects, however, believed that gravity would not affect a moving object until its impetus had been entirely expended. For example, one subject, whose response to the cliff problem is shown in Fig. 13.10, stated that "gravity isn't going to affect it until it stops moving."

The last major issue on which subjects differ is perhaps the most interesting. This issue concerns how impetus is imparted to an object. Most subjects believe that any agent that sets an object in motion imparts to the object an impetus that will keep the object moving after the agent is no longer acting upon the object. However, some subjects believe that an object must be directly pushed or pulled to acquire impetus. According to these subjects, an object that is merely carried by another moving object does not acquire impetus.

Consider, for example, the airplane problem, in which a metal ball is dropped from a moving airplane. Many subjects indicate for this problem that the ball will fall straight down (see Fig. 13.4D). One subject explained this response by stating that the carrying of the ball by the airplane

> would give the ball no force in the $x$ [horizontal] direction...the only force acting on the ball would be in the $y$ direction, which is downward.

Consequently, the subject said, the ball would fall straight down.

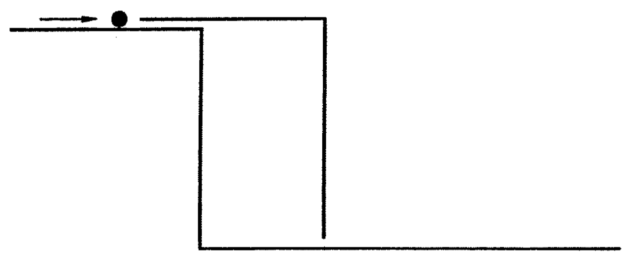


Fig. 13.10. One subject's response to the cliff problem.

The belief that impetus is acquired by a pushed but not by a carried object is revealed rather clearly by the problems shown in Fig. 13.11. For the problem shown in Fig. 13.11A, subjects are told that a ball is given a push to set it in motion, and that the ball slides along the top of the cliff at a constant high rate of speed. For the problem in Fig. 13.11B subjects are told that a ball is held by an electromagnet at the end of a metal rod, which is carried along by a conveyor belt at the same speed as the ball that was pushed. Subjects are further told that when

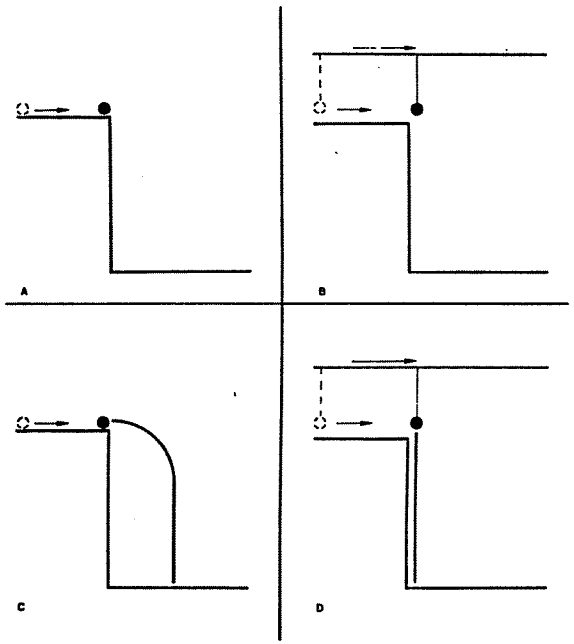


Fig. 13.11. Diagrams for the cliff problem (A) and the conveyor problem (B), with one common pattern of responses (C and D).



the ball reaches the position shown in the diagram, the electromagnet is turned off, releasing the ball. The conveyor belt continues to move. For both problems subjects are asked to draw the path the ball follows as it falls.

These two problems were presented to 7 of the 13 subjects in the experiment in which subjects were interviewed about their answers. Three of the subjects indicated that while the pushed ball would fall in some sort of arc (as shown in Fig. 13.11C), the carried ball would fall straight down (Fig. 13.11D). One of these subjects explained that with the pushed ball

> You've got a lot of force behind it, which would give it some motion straight out.

However, she continued, the carried ball, although it is moving at the same speed as the pushed ball, does not have any force behind it. She concluded that

> speed is not what controls the fall—it's the force behind it....To me speed and force are two different things, so it [the carried ball] is going to fall straight down.

Another subject who gave the same response explained that the carried ball would fall straight down "because the ball *itself* isn't moving, it's just moving because it's attached to that [the conveyor]." A person with whom we have discussed these problems informally expressed a similar view by saying that the pushed ball has its own motion and therefore will continue to move after it goes over the cliff. However, she said, the ball on the conveyor is being carried and therefore does not have its own motion. Thus, it will fall straight down.

## HISTORICAL PARALLELS: THE MEDIEVAL IMPETUS THEORY

The naive theory held by our subjects is strikingly similar to the theory of impressed force or impetus discussed by Philoponus in the 6th century and developed in detail by John Buridan and others in the 14th century. (For detailed discussion of this theory, see Butterfield, 1965; Clagett, 1959; Dijksterhuis, 1961; and Franklin, 1976.) Like our subjects' naive theory, the medieval impetus theory assumes that the act of setting an object in motion impresses in the object a force, or impetus, that serves to keep the object in motion. Buridan (Clagett, 1959) for example, states that a mover

> in moving a moving body impresses in it a certain impetus or a certain force...[which impetus acts] in the direction toward which the mover was moving the body, either up or down, or laterally, or circularly...It is by that impetus that the stone is moved after the projector [i.e., mover] ceases to move [it]. But that impetus is continually decreased by the resisting air and by the gravity of the stone [pp. 534–535].

The parallels between the medieval impetus theory and our subjects' conception of motion extend far beyond the basic claim that motion is maintained by an impressed force. First, as the quotation from Buridan suggests, many impetus theorists postulated a circular impetus that served such purposes as maintaining the motion of a wheel or sustaining the rotation of the celestial spheres. This circular impetus is clearly very similar to our subjects' curvilinear impetus.

Further, just as our subjects differed on the question of whether impetus dissipates spontaneously or as the result of external forces, so did the earlier proponents of the impetus theory (Clagett, 1959; Dijksterhuis, 1961). Buridan, for instance, argued that impetus is not self-expending. However, others, including Franciscus de Marchia, Oresme and, much earlier, Avicenna, asserted that while an object's impetus could be depleted by air and other factors, the impetus would dissipate even in the absence of these factors.

The impetus theorists also resemble our subjects in their views on the interaction of impetus and gravity. Some theorists, like some of our subjects, believed that gravity would affect an object's motion regardless of how much impetus the object had. Other proponents of the impetus theory, however, held different views. Avicenna, for example, argued that only a single impetus could reside in an object an any one time. According to this view, a stone thrown upward at a 45 degree angle would acquire an impetus that would cause it to travel along a straight line at a 45 degree elevation until the impetus was exhausted and the stone came momentarily to rest. The stone's natural gravity would then impart a natural impetus to the stone, causing it to fall straight down (Clagett, 1959). This view is similar to that of the subjects who believed that gravity would not affect an object until its impetus had been entirely expended. As we have seen, for example, one subject, in discussing a ball going over the edge of a cliff, said that "gravity isn't going to affect it until it stops moving."

Several of our subjects held the less extreme view that gravity will not affect an object until its impetus falls below some critical (nonzero) level, but will thereafter cause the object to begin to fall. This viewpoint echoes the argument made centuries earlier by Albert of Saxony, who asserted that a projectile's impetus initially overpowers its natural gravity (Crombie, 1952). Thus, for example, a projectile fired horizontally will for some time follow a straight horizontal trajectory. However, the projectile's impetus gradually weakens and at some point the projectile, while still moving forward, will begin to fall.

One can also find some hint in the writings of Buridan and others of the belief held by several of our subjects that an object carried by another moving object will not acquire impetus. Buridan, for example, offers several arguments in favor of the view that the earth, rather than the heavens, rotates (Clagett, 1959; Franklin, 1976). However, he ultimately rejects this viewpoint on grounds that if the earth turned, an arrow shot straight upward should hit the ground some distance away from the point at which it was launched, rather than returning directly to the launch point (which is, to a close approximation, what it actually does). The



implicit assumption is that the arrow would not acquire any impetus by virtue of being carried along by the moving earth. Thus, when shot upward it would not continue moving laterally in the direction of the earth's rotation. Rather it would travel straight up and down, while the original launch point moved out from under it.

The close correspondence between the medieval impetus theory and the naive theory held by our subjects can also be seen in the remarkable similarity between medieval explanations for certain phenomena, and the explanations given by our subjects. Galileo (Galilei, 1632/1967) who in his early writings endorsed the impetus theory, provides one simple example:

> I have put forth the observation of the pendulum so that you would understand that the impetus acquired in the descending arc...is able by itself to drive the same ball upward by a forced motion...in the ascending arc. [p. 227].

This explanation is virtually identical to that given by the subject who stated that "the gravity that pulls it [the ball] to the center gives it enough force to continue the swing to the other side."

The correspondence between the explanation for projectile motion given by some of our subjects and that given by several impetus theorists is even clearer. Recall that two of our subjects explained the behavior of a projectile fired from a cannon by saying that the impetus from the cannon is initially stronger than the force of gravity, and consequently the cannonball moves upward. However, the impetus progressively weakens and the cannonball slows down. At the peak of the trajectory the impetus and the force of gravity are equal. Thereafter, the impetus from the cannon continues to weaken, so that gravity is now the stronger force. Consequently, the projectile begins to fall, accelerating as it does so because the original impetus is still being dissipated.

Compare this explanation with that given in Simplicius's description of a theory proposed by Hipparchus (Clagett, 1959):

> Hipparchus...declares that in the case of earth [i.e., an object] thrown upward it is the projecting force that is the cause of the upward motion...then as this force is diminished, (1) the upward motion proceeds but no longer at the same rate, (2) the body moves downward under the influence of its own internal impulse [i.e., gravity], even though the original projectory force lingers in some measure, and (3) as this force continues to diminish the object moves downward more swiftly [p. 543].

Galileo, in *De Motu* (ca. 1590/1960) offers a similar explanation:

> the body moves upward, provided the impressed motive force is greater than the resisting weight. But since that force....is continually weakened, it will finally become so diminished that it will no longer overcome the weight of the body and

> will not impel the body beyond that point...as the impressed force characteristically continues to decrease, the weight of the body begins to be predominant, and consequently the body begins to fall...there still remains...a considerable force that impels the body upward...[that] force continues to be weakened...and the body moves faster and faster [p. 89].

Clement (1982) has also pointed out the resemblance between students' explanations of projectile motion and that of Galileo.

These strong parallels between our subjects and the earlier impetus theorists suggest that the impetus theory is a very natural outcome of experience with moving objects in the real world.

In this context it is worthwhile to comment briefly on the claim made recently by several researchers that students' beliefs about motion are Aristotelian (e.g., Champagne, Klopfer & Anderson, 1980). These researchers have pointed out that many students, like Aristotle, believe that a force is required to keep an object in motion. There is, however, an important difference between the Aristotelian view and that of modern students. Specifically, Aristotle held that an object remains in motion only so long as it is direct contact with an *external* mover. Thus, for example, in the Aristotelian view a projectile is kept in motion by air pushing on it from behind. In contrast, modern students, as we have shown in this paper, believe that motion is maintained by a force impressed in the object itself. In other words, students believe that objects are kept in motion by internal and not external forces. Thus, the students' naive conception of motion is most similar not to the Aristotelian theory, but to the later impetus theory, which was developed in reaction to the Aristotelian view.

## NAIVE THEORIES AND PHYSICS INSTRUCTION

It is beyond the scope of this paper to consider in detail the interaction of students' naive theories with information presented in a physics course. However, we should note briefly that the naive theories seem to create a number of difficulties for students taking physics. In particular, information presented in the classroom may frequently be misinterpreted or distorted to fit the naive impetus view, with the result that many students emerge from physics courses with their impetus theories largely intact. Indeed, we found in the experiment in which subjects were questioned in detail that most of the subjects who had taken physics courses still held some form of impetus theory.

An example of the distortion of information to make it fit the naive impetus theory is provided by the definitions of momentum given by two subjects who had taken college physics (see p. 307). Both subjects knew that an object's momentum is defined as the product of its mass and its velocity. However, the



subjects also believed that "momentum is...a force that has been exerted and put into the ball" and "it's something that keeps a body moving."

The concepts of energy and inertia seem also to lend themselves to misinterpretation. For example, one subject, who had completed a college physics course, defined inertia in the following way:

> when you throw something that's what keeps it going...you put a little force behind it and it'll just keep going...inertia is...just the force that's on it when you let it go—sort of a residual force on it.

Distortion may occur even for very explicit information about the behavior of a moving object. For example, a subject presented with the ball and string problem (see Fig. 13.1B) stated that he knew the ball would fly off in a straight line tangent to the circle at the point where the string broke, because this situation had been discussed in his college physics course. However, he further stated that when the string broke, the ball would curve along its original path for a very short time, and would then turn rather abruptly and follow a path parallel to the tangent to the circle at the point where the string broke.

These examples make it very clear that the naive impetus theory is very strongly held and is not easily changed by classroom physics instruction. Thus, it may be useful, as several researchers have suggested (e.g., Champagne et al., 1980; Clement, 1982; Minstrell, 1982), for physics instructors to discuss with students their naive beliefs, carefully pointing out what is wrong with these beliefs, and how they differ from the views of classical physics. In this way students may be induced to give up the impetus theory and accept the Newtonian perspective.

## A BRIEF REVIEW OF RELATED RESEARCH

The studies described in this paper contribute to a growing body of recent research concerning knowledge and reasoning in physics and related domains. In this section we mention briefly a few of the studies that are relevant to the issues we have discussed.

Several research groups have investigated the difficulties that students have with basic principles of mechanics (e.g., Champagne et al., 1980; Champagne, Klopfer, Solomon & Cahn, 1980; Clement, 1979, 1982; diSessa, 1979; Minstrell, 1982). Champagne et al., (1980) have reported that on problems involving free fall, many college students indicate that objects fall at a constant speed. Clement (1982) and Viennot (1979) have noted impetus-like beliefs in students attempting to describe the forces acting on objects in simple situations (e.g. a coin thrown straight up). Minstrell (1982) has also discussed difficulties that students have in understanding forces. Further, he has described an intensive demonstration-discussion method which appears to be successful in overcoming these difficulties.

Other researchers have attempted to characterize people's knowledge of mechanics concepts (e.g., mass, acceleration). Piaget (1970) studied children's understanding of movement and speed, reporting that these seemingly simple concepts are actually quite complex, and are poorly understood by young children. More recently, Trowbridge and McDermott (1980, 1981) have argued that the concepts of velocity and acceleration pose some difficulty even for adults. Finally, several studies have used proximity analysis methods (e.g., multidimensional scaling) to reveal the subjective organization of mechanics concepts (see Preece, 1978, for a review).

A number of interesting results have been obtained in studies of physics problem-solving by experts and novices (e.g., Chi, Feltovich & Glaser, 1981; Bhaskar & Simon, 1977; Larkin & Reif, 1979; Larkin, McDermott, Simon & Simon, 1980a; Novak & Araya, 1980). For example, Larkin et al. (1980) have reported that beginning physics students solving textbook problems use a strategy quite different from that employed by experts. Specifically, experts work forward from the quantities given in the problems to the desired unknown quantity, while novices work backward from the unknown to the givens.

The research on problem-solving has stimulated a number of attempts to develop explicit models of knowledge representation and processing in mechanics (e.g., Larkin, McDermott, Simon & Simon, 1980b; Novak, 1976, 1977; de Kleer, 1975, 1977). Novak, for example, has developed a program that diagrams and solves statics problems stated in English.

Other research has examined knowledge and reasoning in areas of physics other than mechanics, as well as in other branches of science. Fredette and Lochhead (1980), for example, have discussed students' misconceptions about electric circuits, and Nussbaum and Novak (1976) have described children's conceptions of the earth. In addition, Collins, Stevens and Goldin (1979; Stevens & Collins, 1980) have examined students' misconceptions about the complex physical systems involved in climate and rainfall.

More general aspects of scientific thinking have also been examined (e.g., Inhelder & Piaget, 1958; Gentner, 1980, in press; Kuhn, 1977; Siegler, 1978). Gentner (1980, in press) for example, has discussed the role of analogies (e.g., atoms are like miniature solar systems) in scientific thinking, and Kuhn (1977) has considered the function of thought experiments in scientific development. In addition, Carey (this volume) and her colleagues are examining the processes by which scientific concepts such as heat and temperature come to be differentiated.

The recent research on scientific knowledge and reasoning has produced many important insights, and should provide a firm foundation for the development of more complete and detailed descriptions of the scientifically naive individual, the expert, and the process by which the former is transformed into the latter.



## CONCLUDING REMARKS

We nave argued in this paper that people develop on the basis of their everyday experience remarkably well-articulated naive theories of motion. These theories provide not only descriptions of, but also causal explanations for, the behavior of moving objects. In particular, many people believe that the act of setting an object in motion impresses in the object an internal force or impetus. This impetus is assumed to keep the object in motion after it is no longer in contact with the original mover. According to this view, moving objects eventually slow down and stop because their impetus gradually dissipates. This naive theory is, as we pointed out, strikingly similar to the medieval theory of impetus.

Although we have focused in this paper on naive theories of motion, we should note that people reasoning about the behavior of moving objects use, in addition to naive theories, several other sorts of knowledge. For example, some subjects in solving our simple problems made use of analogies, memories for specific experiences (e.g., throwing a rock with a sling), isolated facts about mechanics (e.g., Galileo found that heavy and light objects fall at the same rate) and knowledge acquired through formal instruction in physics (e.g., a projectile's motion can be analyzed into independent horizontal and vertical components). However, for most subjects a naive impetus theory played a prominent role in attempts to solve problems.

The findings of the present study suggest a number of interesting directions for subsequent research. First, there is need to characterize in greater detail people's naive theories in mechanics and in other scientific domains. Second, future research should seek to determine how the naive theories develop. Addressing this issue may involve exploring in children as well as in adults, what sorts of information people glean from observing and interacting with moving objects, and how they generate from this information a theoretical framework for explaining the behavior of moving objects. For example, the assumption that carried objects do not acquire impetus may stem from a frame of reference confusion in the observation of moving objects. Consider, for instance, a person who has seen a film taken from an airplane of bombs dropped from the plane. From the frame of reference of the plane, the bombs will drop nearly straight down. The person observing this may confuse frames of reference and consequently may believe that the bombs hit the ground at the point that was directly beneath the airplane when the bombs were released. From this faulty datum the person may conclude that a carried object does not acquire impetus. Other assumptions of the naive impetus theory may perhaps represent deductions made from observations that focused on salient aspects of an event (e.g., a push given to an object) and ignored less salient factors (e.g., air resistance). Additional research will be required to determine whether these speculations are reasonable.

Finally, future research should seek to determine what role, if any, naive theories of motion play in everyday life. An acquaintance of ours was recently stepping onto a ladder from a roof 20 feet above the ground. Unfortunately, the ladder slipped out from under him. As he began to fall he pushed himself out from the edge of the roof in an attempt to land in a bush about three feet out from the base of the house (in the hope that the bush would break his fall). However, he overshot the bush, landing about 12 feet from the base of the house and breaking his arm. Was this just a random miscalculation, or did our acquaintance push off too hard because of a naive belief that he would move outward for a short time and then fall straight down (rather than continuing to move outward throughout the fall)? Research in which people interact with actual moving objects may shed some light on the question.

In research currently in progress, we are attempting to address these other issues. It is to be hoped that this research will enable us to acheive a better understanding of naive conceptualizations of motion.

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