A LIVELY ELECTRONIC COMPENDIUM OF RESEARCH, NEWS, RESOURCES, AND OPINION

Astronomy Education Review

Volume 5, Sep 2006 - May 2007
Issue 2

# Learning about Gravity II. Trajectories and Orbits: A Guide for Teachers and Curriculum Developers

by **Claudine Kavanagh**
Tufts University
**Cary Sneider**
Museum of Science, Boston

Received: 10/20/06, Revised: 01/02/07, Posted: 03/15/07

The Astronomy Education Review, Issue 2, Volume 5:53-102, 2007

## Abstract

This is the second and final part of a review of educational research on children’s ideas about gravity. The first part concerned students’ understanding of how and why things fall. This article picks up the trail of research studies that address students’ understanding of the more complex ideas of projectile motion and orbits and examines how the recommendations of national education standards fare in light of this body of research. The article begins with a brief historical sketch of how these ideas developed in human history and a summary of the relevant *Benchmarks* and *Standards*. The review then summarizes the results of studies of children’s and adults’ ideas about projectiles and orbits. When viewed together, these studies revealed a number of common misconceptions about gravity: that gravity needs air; that there is no gravity in space; that objects in orbit are weightless, so gravity does not affect them; that the force of gravity diminishes rapidly with increasing altitude; that force is needed to keep an object in orbit; that planets closer to the Sun or that spin faster have more gravity; and that gravitational forces between objects are not equal and opposite. These misconceptions are surprisingly widespread, even among university students and teachers. The second part of the review concerns teachers and teaching. Included are studies about teachers’ awareness of their students’ misconceptions, the effectiveness of typical physics instruction, teaching interventions with students, and professional development of teachers. These studies illustrate a number of effective methods for teaching students and teachers about projectiles and orbital motion. The article ends with conclusions drawn from the research and recommendations for curriculum development and teaching. So as to avoid redundancy, this article will assume that readers have read Part I of this review, which appears in the same issue of the *Astronomy Education Review*.

# 1. INTRODUCTION

Until 1979, there was no reason to doubt that students who graduated from high school and college physics classes with good grades had a fairly good understanding of Newtonian theory. That confidence was shaken by a short article written by a professor at the University of Paris and published in the *European Journal of Science Education* (Viennot 1979). Paper-and-pencil tests of several hundred university students revealed that many held misconceptions about forces and motion even though they were capable of solving challenging quantitative problems involving the same concepts typically found in most physics textbooks. For example, Viennot gave his students a diagram showing six balls tossed into the air by a juggler. Although some balls were moving upward, some were at the top of their trajectory, and others were moving downward, they were all at the same height above ground. The students were asked to ignore the effects of air resistance and to draw arrows showing the forces on each of the balls. The students were expected to draw only a downward arrow on each ball showing the force of gravity, but many students drew an arrow in the direction of motion instead. Viennot noted that this intuitive theory was similar to the theory of impetus that had been taught by John Buridan at the same university—600 years before! Viennot indicated that further studies of university students in Belgium and England confirmed that this misconception was widespread. Furthermore, formal physics instruction was ineffective in convincing most students to abandon the idea that motion implies force. The challenge of confirming these results and uncovering other misconceptions about force and motion has since been taken up by dozens of researchers all over the world, so we now have a very good understanding of the nature and extent of the difficulties that students encounter in learning fundamental physics.

Viennot (1979) succeeded in learning about his students' misconceptions by asking them to explain everyday situations regarding how objects move under the influence of gravity. Virtually all the subsequent research on this topic has taken a similar approach, whether through pencil-and-paper tests, individual interviews, or recorded class discussions. The result is a remarkably rich description of students' conceptions and misconceptions about the paths taken by projectiles and what keeps satellites and planets in their orbits. The article will start with a brief history of how these ideas developed in the history of science and an overview of what students are expected to learn at various age levels according to the *Benchmarks for Science Literacy* (American Association for the Advancement of Science [AAAS] 1993) and the *National Science Education Standards* (National Research Council [NRC] 1996). It concludes with answers to the following questions and recommendations for teachers and curriculum developers.

- What misconceptions do students hold about projectile motion and orbits?
- To what extent do these misconceptions reflect the history of gravitational theory?
- Are national standards documents reasonable concerning age-level recommendations?
- What teaching methods are most promising?
- What research remains to be done?

# 2. HISTORY OF GRAVITATIONAL THEORY

The following summary of the history of gravitational theory is based primarily on the work of Toulmin and Goodfield (1961), Lloyd (1970, 1973), Grant (1971), Crombie (1952), and Kuhn (1957). A question to keep in mind is whether a revolutionary model, as proposed by Thomas Kuhn, or an evolutionary model, favored by Toulmin and Goodfield, more adequately describes the development of gravitational theory in human history.

## 2.1 The Origin of Gravitational Theory in Ancient Greece

Aristotle, founder of the school known as the Lyceum and teacher of Alexander the Great, developed the first comprehensive theory of motion that we know about in the fourth century BC. Aristotle’s ideas about projectile motion and the orbiting bodies that he observed were set within a larger theoretical framework that encompassed his understanding of the cosmos as a whole.

**Projectile Motion:** A falling object was considered by Aristotle to be in "natural" motion, whereas a projectile, such as an arrow shot from a bow, was thought to be in "violent" or "forced" motion. He believed that forced motion could only come from a living agent and that a constant force is needed to keep a projectile moving after it leaves the thrower. He thought that this continuous force was due to air that was pushed out of the way by the projectile and swirled around behind the projectile to fill the vacuum. Because Aristotle did not believe that an object could have two different motions at a time, in his view, the trajectory of a projectile consisted of two phases: violent motion in the direction of the force that gradually disappeared, followed by natural motion toward the center of the Earth.

**Orbits in Space:** Aristotle proposed that the Sun, moon, planets, and stars consisted of a fifth elemental substance whose natural motion was to follow perfect and eternally moving circles. He proposed that the planets were located on transparent spheres, nested one inside the other, from the sphere that carried the "fixed stars" to the innermost sphere that carried the Moon. The motive force behind all planetary motion was the Primum Mobile, the outermost sphere, which was continuously powered by a divine force. Revising this theory by adding and adjusting spheres set the agenda for successive generations of astronomers for nearly 2,000 years.

## 2.2 Developments in the Middle East and the Mediterranean

**Projectile Motion:** John Philoponus, a Christian philosopher, scientist, and theologian who lived in Alexandria, Egypt, during the sixth century AD, challenged Aristotle’s idea that air could rush around behind an arrow and push it forward. Instead, Philoponus proposed that the medium just provided a resisting force. To explain how the projectile continued to move, he proposed that some sort of motive force is imparted to the projectile itself so that it continues to move of its own accord. The less resistance it encounters, the less it will be slowed. For the next few centuries, Arab scholars, such as Ibn Bajja of Saragossa, Spain, continued to think and write about the force that keeps a projectile moving. Some thought that the motive force would eventually die away and disappear, while others thought it would last indefinitely unless it encountered resistance.

**Orbits in Space:** Aristotle believed that the speed of the Sun, Moon, and planets in their orbits around the Earth was proportional to the ratio of force to resistance. If resistance were zero, then speed would be infinite, which is obviously impossible. Therefore, he thought that there must be some kind of rarified substance that filled the cosmos. In contrast, Philoponus suggested that the relevant relationship was the difference between force and resistance. From that point of view, motion through a vacuum was perfectly reasonable. Speed would simply be proportional to the force that started it in motion. Infinite speeds were not involved at all, so it was possible to think about how something might actually move in a vacuum, which later became important for considering how the Sun, Moon, and planets might move.

## 2.3 Further Developments in Medieval Europe

**Projectile Motion:** Expanding on the ideas of Philoponus, Francis of Marchia, and John Buridan, teachers at the University of Paris in the 14th century proposed the term "impetus" for a motive force acquired by a projectile that is proportional to the speed of an object and its quantity of matter.

The concept of impetus is similar to what we would call *momentum* (mv). However, whereas today we consider momentum to be a measure of motion, impetus was thought to be the cause of motion. Albert of Saxony, another scholar of this period, proposed that projectiles follow a path that has three phases: (1) an initial period dominated by impetus, in which the object moves in a straight line in the direction it was thrown; (2) an intermediate period in which impetus declines and natural motion begins to take over; and (3) a final period in which impetus completely disappears and the object falls straight down.

The idea that a trajectory consisted mainly of three simple stages remained unchanged over the next two centuries, as indicated by Paulus Puchner's (1577) illustrated instructions to cannoneers (Figure 1).

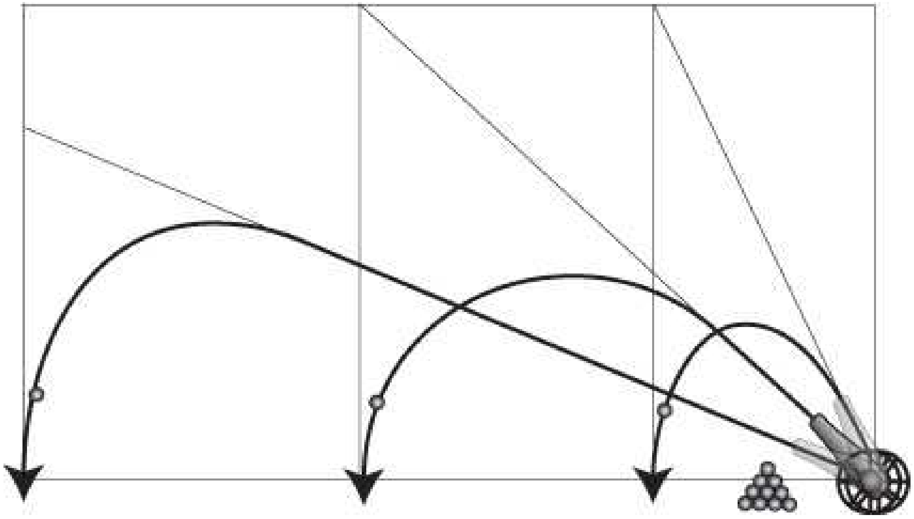


**Figure 1.** Illustration of the trajectories of cannonballs fired at different elevations, based on an illustration from Paulus Puchner's 1577 instructions to cannoneers

The medieval philosophers took one more important step concerning bodies in free fall that would later turn out to be important in understanding projectile motion and orbits. In the 14th century, one of the best-known Merton scholars, Oresme, wrote a treatise showing how a graphical method can be used to represent the relationships among time, distance, and velocity under uniform acceleration, thus paving the way for a quantitative representation of motion that we later see in the works of Galileo (Galilei 1638) and Newton (1687, 1728).

**Orbits in Space:** Buridan applied the idea of impetus to explain the acceleration of falling bodies, the arc of a projectile, and even celestial orbits that moved with a kind of circular impetus. The model for circular impetus was a spinning wheel or any object that, when forcefully spun, would continue spinning on its own. Buridan proposed that when God created the world, each of the celestial objects was given a certain amount of circular impetus. With virtually no resistance in the celestial realm, the objects continued to move in the same way forever, with no need for additional intervention to keep them going—and therefore no need of a Primum Mobile.

Keep in mind that these ideas were not quite the same as the modern concepts of linear and angular momentum, but they certainly were suggestive of those later ideas. An even more important contribution of the Merton scholars was the first effort to apply mathematical formulae and graphs to express ideas about motion, and the realization that the same underlying theory might explain both Earthly and celestial motion. Still, it would take another two or three centuries for the modern theory of gravity to finally emerge.

## 2.4 Galileo’s and Newton’s Theories of Gravity

**Projectiles:** Galileo is credited with being the first person to describe the shape of a projectile’s path as a parabolic curve, which results from its tendency to move horizontally at a constant speed while also falling with a constant acceleration. Galileo had heard of a recent discovery by Niccolo Tartaglia that gravity starts acting the instant it loses contact with the thrower. In explaining horizontal motion, Galileo described experiments in which he rolled a ball down one side of a U-shaped ramp and watched it roll up to very nearly the same height on the other side of the U. As he lowered and extended the "down" side of the U, he found that the ball traveled farther and farther horizontally. He reasoned that if the slope was lowered all the way to the horizontal, and if he could make the ramp smooth enough to eliminate friction completely, the ball would continue to move forever, *without a constant force to keep it going*. This idea was very close to Newton’s first law of inertia, except that Galileo thought that the ball would follow the curve of the Earth rather than go in a straight line forever.

**Orbits in Space:** In the 16th century, several forces came together that fundamentally changed people’s understanding of the universe. A "new star" (nova) that appeared in the sky 1572 shook the popular belief that the stars are fixed and unchanging. And a popular description of the Copernican theory by the Englishman Thomas Diggs, published in 1576, depicted the stars as distributed in space, which stretched without limit in all directions. The idea of an unbounded universe greatly appealed to Giordano Bruno, who envisioned that the distant stars might in fact be suns, around which might be other worlds like ours. Bruno’s ideas were profoundly disturbing to officers of the Church, who had him burned at the stake for his ideas in the year 1600. It was against this background of ideas that Galileo saw for himself, through his telescope, that there were untold numbers of stars beyond those that we can see. So the idea of an unbounded universe, in which an object set in motion might continue to move in a straight line, was not impossible. Nonetheless, Galileo never abandoned the idea of perpetual circular motion. The idea that an object would continue to move in a straight line without the need of continuous propulsion was developed in the 17th century by Borelli, Descartes, and Huygens, and finally codified as Newton’s first law of motion. Although Newton was not the first to claim that an object will move forever at uniform velocity in a straight line unless acted on by an outside force, he was the first to integrate this idea into a complete system of motion in which the same set of rules applied on Earth and in the heavens. Following is an illustration (Figure 2) and corresponding description for how projectile motion is related to orbital motion, taken from a popular article that Newton wrote. It was published in 1728, the year after his death.

> That by means of centripetal forces the planets may be retained in certain orbits, we may easily understand, if we consider the motions of projectiles; for a stone that is projected by the pressure of its own weight forced out of the rectilinear path, which by the initial projection alone it should have pursued, and made to describe a curved line in the air; and through that crooked way is at last brought

> down to the ground; and the greater the velocity is with which it is projected, the farther it goes before it falls to the Earth. We may therefore suppose the velocity to be so increased, that it would describe an arc of 1, 2, 5, 10, 100, 1000 miles before it arrived at the Earth, till at last, exceeding the limits of the Earth, it should pass into space without touching it . . . and go on revolving through the heavens in those orbits just as the planets do in their orbits.

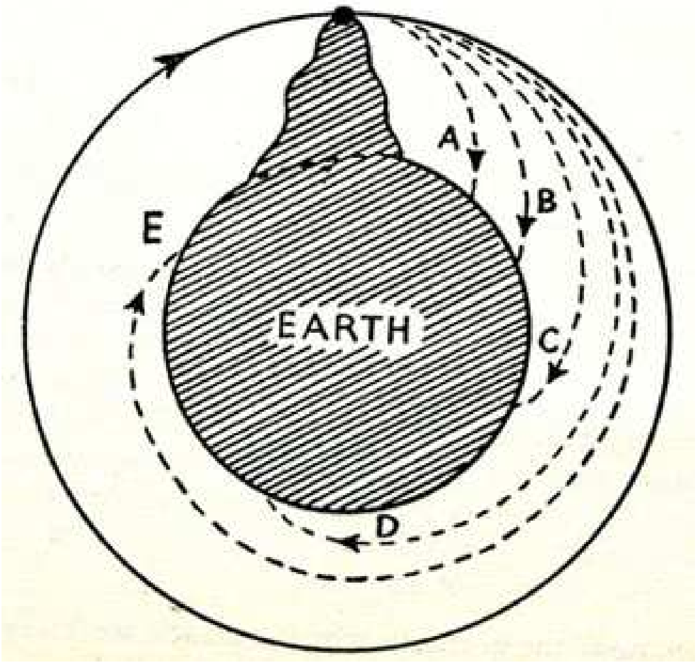


**Figure 2.** Isaac Newton's theory of orbital motion, from *The System of the World*, 1728

Newton's theory of projectiles and orbits involved his laws of motion: the law of inertia, which describes objects moving with uniform velocity; the second law, F=ma, which describes how objects accelerate when subjected to a force; and the third law, which states that the gravitational attraction between two bodies is equal and opposite. Newton worked out the quantitative details of his theory of gravity with the help of Kepler's discoveries about the motion of the planets, Galileo's work on kinematics, and Copernicus's theory of a Sun-centered Solar System. Equally important was the concept of the universe as a vast, nearly empty space extending without limit in all directions, as had been proposed by Thomas Diggs in England and Giordano Bruno in Italy during the previous century. Newton's detailed and comprehensive theory of motion and of gravity was published in his major work, *Philosophiae Naturalis Principia Mathematica* (1687), usually referred to as *The Principia*. Newton's comprehensive theory made it possible to determine the orbits of all the planets and known moons of the Solar System, to predict when comets would return, to explain the tides, and even to start thinking about launching artificial satellites as indicated by his drawing and description (Figure 2) of how a projectile may achieve a stable orbit.

## 2.5 Einstein’s Theory of Gravity

This brief sketch of the development of gravitational theory would be incomplete without a reference to the profoundly different conception of orbits and projectiles in Einstein’s general theory of relativity. Imagine for a moment a piece of rocky debris that escaped some distant planetary system. For eons, it travels in a straight line through space until it comes close enough to be influenced by Earth’s gravitational field. Its path begins to curve toward Earth’s center, and it may go into orbit or fall toward Earth, creating a fiery parabolic trail as it burns up in the atmosphere. That’s the Newtonian view. According to Einstein’s theory of general relativity, which he published in 1915, the meteor never deviates from a straight line. It is space itself that is curved by the presence of a massive body: our planet Earth. Even light rays follow the curve of spacetime, which is why a cluster of galaxies can serve as a "gravitational lens," bending the light from galaxies even more distant, just as a curved glass lens bends light to form an image.

Over the centuries, as philosophers, scholars, and scientists built upon their colleagues’ ideas to explain motion, their theories about the world emerged and changed. Both evolutionary and revolutionary metaphors of this process offer insights. Looking back over two millennia, we can see original ideas emerge, flourish, or falter as a result of the intellectual climate, and broader theories gradually evolve. On the other hand, each insight and change in worldview was undoubtedly a revolution in thinking for the individuals who moved this process forward. These two metaphors—evolution and revolution—may prove helpful to teachers and curriculum developers in designing experiences to help students develop their own useful theories about gravity. We return to these ideas in our concluding remarks.

The historical development of gravitational theory up through the time of Newton is very briefly summarized in Table 1. Portions of this table appear again in Section 5, Conclusions, to illustrate similarities and contrasts with students’ common misconceptions. Einstein’s general theory of relativity is not included in the table because we have found no studies on students’ misconceptions that would make a comparison worthwhile.

**Table 1.** Historical development of the theory of gravity

| **Aristotle** | **Medieval Scholars** | **Galileo & Newton** |
|---|---|---|
| **Projectile Motion** | | |
| A thrown object keeps moving because air that is forced to the side moves around to push the object forward.<br>The medium provides force to keep the object moving and resistance to slow it down.<br>Force can only be applied by a living agent.<br>Speed is proportional to the propulsive force and inversely proportional to size [mass] and resistance of the medium.<br>Objects are subject to only one simple motion at a time. | A thrown object keeps moving because a temporary force, or "impetus," is impressed on the object.<br>Impetus is proportional to the speed of the object times its quantity of matter [mass].<br>The medium through which the projectile moves only provides resistance.<br>Impetus may slowly wear out or be overcome by gravity.<br>Gravity could begin to act while impetus declines. | A thrown object keeps moving because uniform motion does not require a constant force.<br>The medium through which the projectile moves only provides resistance.<br>A projectile follows a parabolic curve because of its tendency to travel horizontally at constant velocity, while simultaneously accelerating downward because of the pull of gravity.<br>If air resistance is ignored, the only force on a projectile during its entire flight is the downward force of gravity. |
| **Orbits** | | |
| Celestial objects consist of a substance for which circular motion is natural.<br>Space is filled with a rarefied element because a vacuum is impossible.<br>Celestial objects ride on transparent spheres, which are continuously turned by the outermost sphere and driven by divine intervention.<br>Gravity [heaviness] applies only on Earth. | When God created the world, He impressed a circular impetus on all celestial objects.<br>Space is filled with a rarefied element that provides no resistance to celestial objects moving through it.<br>The same explanation for earthly motion might explain celestial motion, although Earth is still the center of the universe. | Earth is a planet orbiting the Sun, within an infinite space.<br>Gravity is the mutual attraction between any two bodies.<br>Orbital motion is a special case of projectile motion. The elliptical path of a satellite is due to its tendency to travel horizontally (tangent to a point in its orbit) at constant velocity while being pulled toward the center of gravity between it and a more massive body. |

Next we turn to the recommendations of the *National Standards* and *Benchmarks* regarding how and when students are expected to explain projectile motion, and the orbits of planets, moons, and artificial satellites.

# 3. NATIONAL STANDARDS AND BENCHMARKS

The *National Science Education Standards* (NRC 1996) and *Benchmarks for Science Literacy* (AAAS 1993) agree that phenomena involving gravity are too abstract to present at the elementary level. Although these two documents differ in wording, detail, and emphasis, they are in very close agreement concerning what students can be expected to learn about projectile motion and orbits at the middle and high school levels. These expectations are briefly summarized below, illustrated by a few of the many references to gravity that appear in the *National Standards* and *Benchmarks*.

## 3.1 Middle School Standards

**Projectile Motion:** Although full understanding of projectile motion is not expected until high school, middle school students are expected to observe relevant phenomena so that they can begin to understand how these forces act. According to the *National Standards,*

> The study of motions and the forces causing motion provide concrete experiences on which a more comprehensive understanding of force can be based in grades 9–12. By using simple objects, such as rolling balls and mechanical toys, students can move from qualitative to quantitative descriptions of moving objects and begin to describe the forces acting on the objects. Students' everyday experience is that friction causes all motion to stop. Through experiences in which friction is reduced, students can begin to see that a moving object with no friction would continue to move indefinitely, but most students believe that the force is still acting if the object is moving or that it is "used up" if the motion stop. (NS grades 5–8, 154)

**Orbits in Space:** Students at the middle school level are expected to develop a qualitative understanding of orbital motion as an extension of projectile motion. If a projectile is launched with sufficient power at just the right angle, it will go into orbit because its curving path will match the curve of Earth. In other words, an object in orbit is always falling, but it always "misses" hitting the ground. Students are also expected to know that planets and moons are kept in their orbits in a similar manner, as we see from these statements in the *Benchmarks* and *National Standards*:

> An unbalanced force acting on an object changes its speed or direction of motion, or both. If the force acts toward a single center, the object's path may curve into an orbit around the center. (BM, grades 6–8, 90)
>
> From activities with trajectories and orbits and using the Earth-Sun-Moon as an example, students can develop the understanding that gravity is a ubiquitous force that holds all parts of the solar system together. (NS, grades 5–8, 159)

## 3.2 High School Standards

**Projectile Motion:** At the high school level, students are expected to understand that the trajectory of a projectile is the result of applying Newton’s first and second laws and the law of universal gravitation, as indicated by the following general statement in the *Benchmarks*:

> Newton’s system was based on the concepts of mass, force, and acceleration, his three laws of motion relating them, and a physical law stating that the force of gravity between any two objects in the universe depends only upon their masses and the distance between them. (BM grades 9–12, 243)

**Orbits in Space:** Newton’s laws lead to the conclusion that the path followed by a projectile that is launched into orbit follows a mathematical path called an *ellipse*. As indicated by the following statement in the *Benchmarks*, students are expected to understand that such mathematical precision is possible as a result of Newton’s laws:

> Isaac Newton created a unified view of force and motion in which motion everywhere in the universe can be explained by the same few rules. His mathematical analysis of gravitational force and motion showed that planetary orbits had to be the very ellipses that Kepler had proposed two generations earlier. (BM grades 9–12, 243)

Nonetheless, *Benchmarks* also makes it clear that although students are expected to know that such mathematical precision is possible, not all high school students should be expected to solve quantitative problems involving trajectories and orbits.

**Gravitational Theory:** In addition to the challenges described earlier in this article, students in grades 9–12 are also expected to understand the following theoretical issues concerning gravity.

> **Universal gravitation:** The same natural laws that apply on Earth operate throughout the universe.
>
> **Large-scale structure:** Massive structures seen in the universe today, including planets, stars, galaxies, and clusters of galaxies, have resulted from the effects of gravity acting between atoms and subatomic particles when the universe was young.
>
> **Einstein’s general theory of relativity:** This theory explains orbital motion as being the result of distortions in space and time around massive bodies.

Against this background (which summarizes the historical development of the theory of gravity) and standards for what students can be expected to learn at various grade levels, we offer a reasonably thorough review of the research literature concerning what today’s students know about trajectories and orbits and what instructional techniques are likely to be fruitful at various age levels.

# 4. LITERATURE REVIEW

When we set out to identify, analyze, and report on the major research studies concerning students’ understanding of gravity, we began with a computer search for articles with the word "gravity" in the title. These studies referenced articles about "force and motion," which further expanded our literature search. Because most researchers situate their studies within a larger context, often to gather data that bear on a theoretical issue, our search led to papers about the nature of students’ naïve concepts of the physical world and the mechanisms of conceptual change. Consequently, this review will encompass a similarly broad swath of studies and touch on the theoretical issues that they raise. However, for the sake of coherency and usefulness to teachers and curriculum developers, the discussion will always be rooted in learners' understanding of gravity.

The literature review is organized in three parts: (1) Projectile Motion, (2) Orbits, and (3) Teachers and Teaching. The first two sections include primarily status studies, while the third includes studies of teachers' knowledge and experimental studies on the effectiveness of instruction. Although most of the studies reported several misconceptions, we limited our review of each study to just one or two central findings. A list of all studies included in this review appears in Table 2, at the end of this section.

## 4.1 Projectile Motion

The following studies concerned how students responded to questions about projectile motion. Questions about projectiles can be based on three general scenarios: (1) an object moves horizontally for a time and is then allowed to fall (such as a ball rolling off a table or a box dropped from an airplane); (2) an object is thrown directly upward; or (3) an object is thrown or launched at an angle between 0° and 90° (such as an arrow shot from a bow).

As with free fall, researchers have found a number of misconceptions about projectile motion that are remarkably resistant to change. These include:

1. Motion implies a force in the direction of motion.
2. Objects fall straight down if not supported.
3. Impetus may wear out or be overcome.
4. Only living or active things can impart impetus.
5. Projectiles continue to accelerate after they are released.

After reviewing the evidence for these misconceptions about projectile motion, we will touch on a theoretical issue that was addressed by many of the researchers who studied students' concepts of projectile motion: Do commonsense theories for projectile motion exist?

### *4.1.1 Motion Implies a Force in the Direction of Motion*

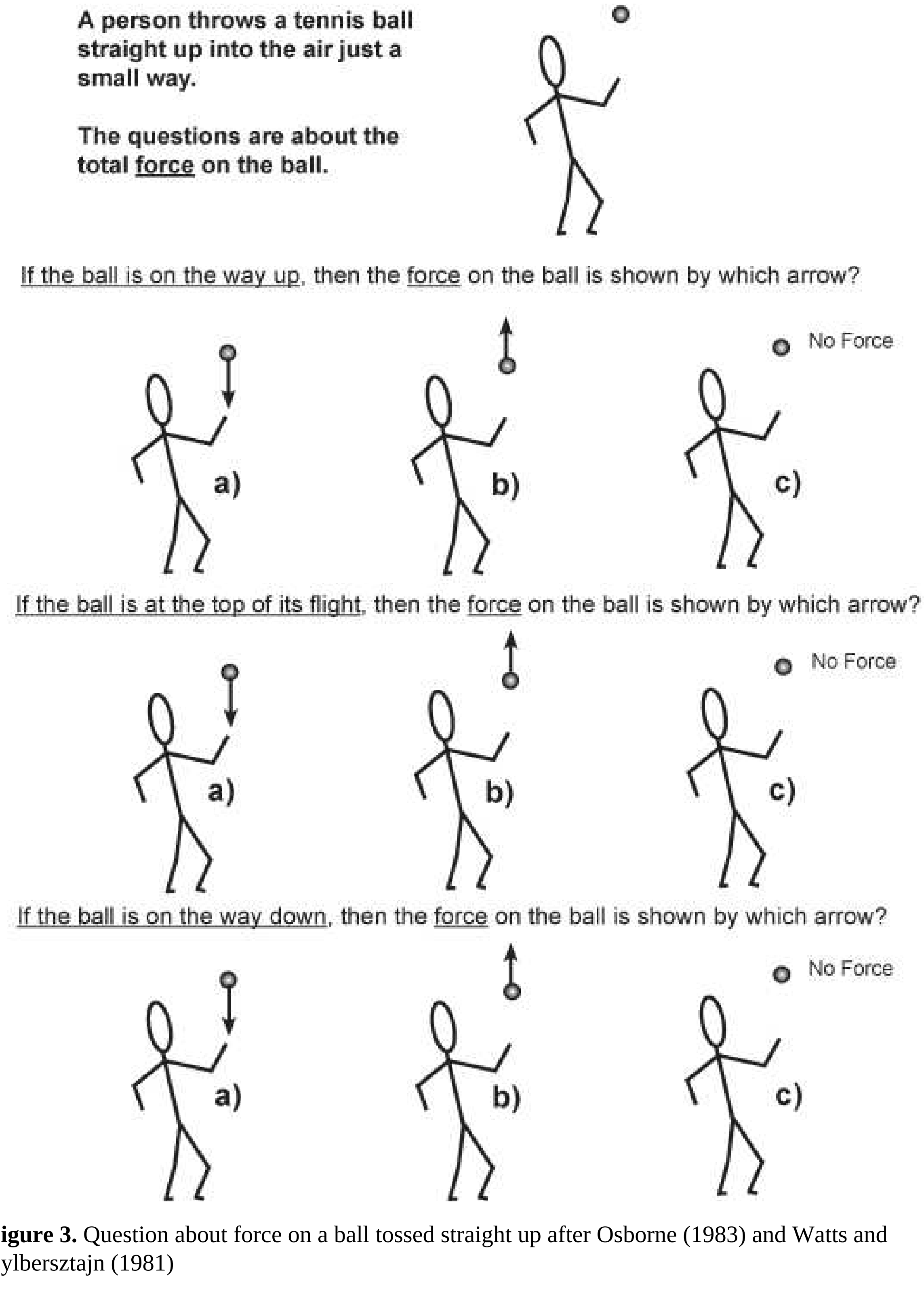
Clement (1982) was one of the first researchers to confirm Viennot's (1979) finding that large numbers of university students believe that motion implies force and that this misconception is resistant to change. He administered a questionnaire about projectile motion to 150 American engineering freshmen before they took an introductory physics course. The students were asked to show the forces acting on a coin that was tossed directly upward by drawing arrows showing the direction and strength of forces acting on the coin. A large majority of the students showed arrows in the direction of motion rather than (or in addition to) the downward force of gravity. He then administered the same questionnaire to a sample of students after they had taken the physics course. He found that 75% of the postinstruction group also provided an arrow indicting a force in the direction of motion for the first half of a coin's trajectory. He concluded:

> The "motion implies a force" preconception is not likely to disappear simply because students have been exposed to the standard view in their physics course. More likely, Newtonian ideas are simply misperceived or distorted by students so as to fit their existing preconceptions; or they may be

> memorized separately as formulas with little or no connection to fundamental qualitative concepts. (Clement, 70)

Clement also agreed with Viennot that the students’ intuitive notions about force and motion were similar to the idea of impetus that was conceived and formalized in the 14th century.

Osborne (1983) adapted a questionnaire from Watts and Zylbersztajn (1981) that easily distinguished between students who believed that motion implies a force in the direction of motion from those who held the Newtonian view that gravity is the only force acting on a thrown ball once it leaves the thrower’s hand, if air resistance is ignored (see Figure 3). The multiple-choice question shows a stick figure throwing a ball straight up. Students are asked to circle the sketch showing the force on the ball on the way up, at the top of its flight, and on the way down. Those who understand that gravity acts downward at all stages of the trajectory will choose sketches a,a,a, whereas those who believe that there is a force in the direction of motion will circle sketches b,c,a. The researchers found that the number of students who held the incorrect view that motion implies a force in the direction of motion *increased* from age 13 (46%) to 14 (53%) to 15 (66%) and was about 53% for the 16- and 17-year-olds who were studying physics. To explain these results, the author speculated that a student who believes that impetus explains projectile motion might naturally assume that the term "force," which is taught in school, is the name of the intuitive idea of impetus. In other words, the response pattern b,c,a, makes perfect sense to such a student if the word "force" has the same meaning as "impetus."



A person throws a tennis ball straight up into the air just a small way.

The questions are about the total force on the ball.

If the ball is on the way up, then the force on the ball is shown by which arrow?

If the ball is at the top of its flight, then the force on the ball is shown by which arrow?

If the ball is on the way down, then the force on the ball is shown by which arrow?

**Figure 3.** Question about force on a ball tossed straight up after Osborne (1983) and Watts and Zylbersztajn (1981)

Other researchers also noted that students seemed to be applying the impetus concept but used other words to describe what they meant. Halloun and Hestenes (1985b), for example, noted that various students expressed the idea of an impressed impetus that caused continuing movement but used terms such as "force," "energy," "inertia," "speed," "velocity," "acceleration," or "power" to express the idea.

### *4.1.2 Objects Fall Straight Down If Not Supported*

Readers of this review are probably familiar with the cartoon in which an animated character runs off a cliff and continues running horizontally until realizing that he/she/it is no longer supported, then plunges straight down. Presumably adults (or at least university physics students) laugh because they realize that the cartoon character would instead follow a parabolic trajectory that combines the continuing horizontal motion of the character with the force of gravity. However, McCloskey and his colleagues conducted a series of studies showing that although university students may laugh at the idea that awareness controls gravity, most believe that the subsequent "straight-down" motion accurately describes how projectiles move. These studies are briefly described next.

Caramazza, McCloskey, and Green (1981) questioned 44 university students, most of whom had studied physics, about what would happen to a swinging pendulum ball if the connecting string was cut at each of four locations (see Figure 4). Cutting the string when the pendulum ball is at its lowest point is dynamically the same as a ball rolling off a cliff: it would fall along a parabolic trajectory because of its horizontal motion combined with the force of gravity. However, 64% of the university students indicated that the ball would fall straight down when the string is cut, and another 11% assumed that it would continue in its present curving path for a short time and then fall straight down. Only 25% gave scientifically correct answers.

McCloskey (1983) administered questionnaires to 48 university students with various levels of experience with formal physics education. One question showed a ball rolling over the edge of a precipice and asked students to draw the path of the ball. Many students drew an inverted capital L, in which the ball continues for a short distance in the same direction after it rolls off the cliff and then abruptly falls straight down to the ground. In another question, students were asked to draw the trajectory of a metal ball dropped by an airplane in flight. The most common incorrect answer, given by 36% of the respondents, was a vertical line for the ball’s path leading straight down to the ground from the point where it was released. Other incorrect answers included a diagonal line forward (13%) and a line indicating that the ball would fall backward (11%). Only 40% drew forward arcs that looked more or less parabolic. Comparing students with different levels of physics education, the authors concluded,

> 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. (McCloskey, 305)

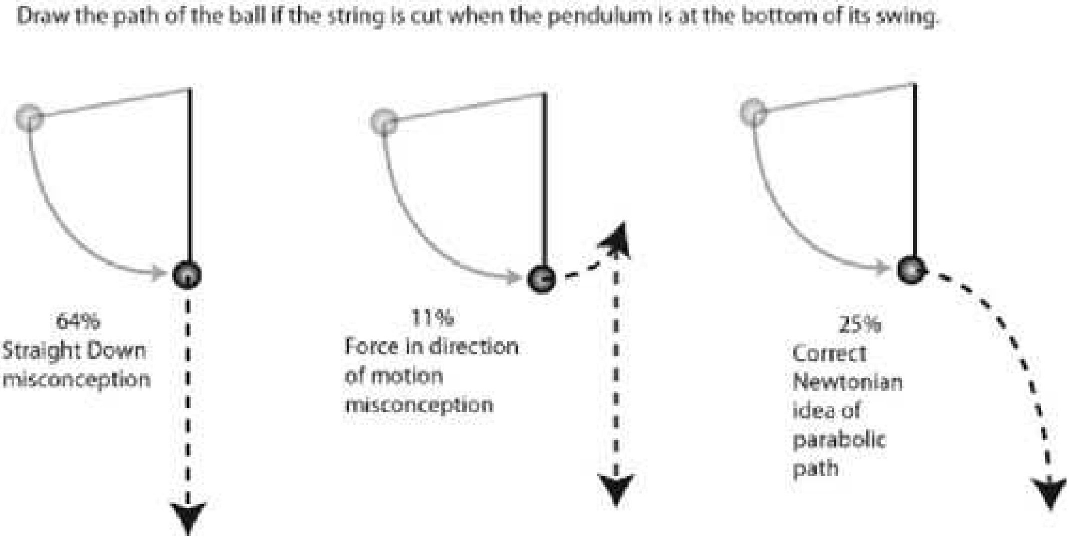


**Figure 4.** What would happen to a pendulum bob if the string is cut when it is at its lowest point? Percentages indicate the proportion of 44 college students who gave that answer. (From Caramazza, McCloskey, & Green 1981)

McCloskey, Washburn, and Felch (1983) conducted a series of experiments to investigate the origin of the straight-down belief using both paper-and-pencil diagnostics, participatory experiments, and interviews. In one experiment, students were given a steel ball bearing and asked to say where they would drop the ball to hit a target as they walked at a constant velocity. Thirty-eight percent said that they would release the ball before getting over the target, 51% said that they would drop it when they are right over the target (the straight-down belief), and 11% said that they would release it after passing the target (backward belief.) Based on these and other experiments, the authors speculated that the straight-down belief originates in a common experience in which we drop something from within a moving vehicle. Because we observe the object falling within the reference frame of the moving vehicle, it appears to drop straight down.

Whitaker’s (1983) questionnaire given to 100 American undergraduates was mentioned previously in the first gravity article (Kavanagh & Sneider 2007) in relation to the "heavier objects fall faster" misconception. The questionnaire also asked what would happen to a ball dropped by a rider on horseback. Almost half the students with physics experience (19 of 40) responded correctly, while only 14 of 60 students with no physics exposure were able to answer the question correctly. Among the rationales they gave were: "Gravity pulls down, that is all that is acting on the ball" and "it has only vertical acceleration, no horizontal velocity or acceleration or force exerted on the ball" (Whitaker, 354). These statements might be explained by the conclusion of the previous study—that students visualize the ball in the horse and rider frame of reference, so they do not recognize the horizontal motion given to the ball to be relevant to the problem at hand.

### *4.1.3 Impetus May Wear Out or Be Overcome*

In the "straight-down" response indicated above, a projectile does not follow a curving path; the object simply continues in the same horizontal direction for a short distance, then abruptly heads downward. The idea that impetus would gradually wear out or fade as gravity takes over suggests a path midway between the inverted L and a parabolic path. McCloskey (1983) described in-depth interviews, lasting 1 1/2 to 2 1/2 hours, with 13 undergraduates from a university in the United States. Although most of the subjects had taken high school or college physics, 11 of the 13 subjects expressed ideas consistent with a naïve impetus theory of projectile motion. When asked why projectiles tend to follow an arcing path, they generally expressed the idea that the impetus is dissipated or overcome by other forces: "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." In another situation, a student explained what happens to a ball that rolls off a cliff: "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 down motion" (McCloskey, 308-09). The trajectories that these students are describing are like that shown in Figure 1, which were believed to accurately describe projectiles during the centuries leading up to the work of Galileo.

### *4.1.4 Only Living or Active Things Can Impart Impetus*

In their interviews with 22 university students concerning the trajectory of objects that are projected horizontally and released, Halloun and Hestenes (1985b) noticed a pattern in what at first seemed inconsistent responses to similar problems. Some students predicted that an object thrown horizontally by hand would follow a parabolic trajectory, but the same object dropped from an airplane moving at the same horizontal speed would drop straight down. When the interviewer asked the students to explain why they gave different answers to those two questions, they realized that some students expressed a belief similar Aristotle’s: that only a living agent can exert an external force on an object. For example, one student said that when throwing the ball, "You are giving the ball a speed in a straight direction . . . the harder you throw it, the more it will go straight." But when the ball is dropped from a plane, "the plane was just carrying it . . . the plane does not give it a power to go straight." Similar comments were made by other students to justify the same apparently inconsistent responses.

### *4.1.5 Projectiles Continue to Accelerate after They Are Released*

One study shows that many students believe that before impetus wears out or is overcome, it may actually increase. Hecht and Bertamini (2000) administered written questionnaires to several groups of undergraduates in Virginia and England. In the first experiment, 176 undergraduates in a psychology class were given a questionnaire asking where a ball thrown to a catcher reaches its maximum speed. They were also asked to respond to a multiple-choice question describing how the speed of the ball varies. Approximately half of the subjects indicated that the ball would speed up after leaving the thrower’s hand. The researchers conducted three additional experiments to rule out possible misunderstandings of the question. However, the findings turned out to be robust, even among undergraduates who frequently played sports.

### *4.1.6 Do Commonsense Theories for Projectile Motion Exist?*

Most of the early researchers in this field were struck by what seemed to be commonsense theories, which led students to make the same pattern of mistakes on many different problems. That is, students’ novice ideas regarding motion appeared to be sufficiently well organized and internally consistent to merit the term "theory," albeit prescientific and somewhat idiosyncratic. Champagne, Klopfer, and Anderson (1980) summed up the key elements of a commonsense belief system about motion that they observed in many of the subjects they studied:

1. A force, when applied to an object, will produce motion.
2. Under the influence of a constant force, objects move with constant velocity.
3. The magnitude of the velocity is proportional to the magnitude of the force; any acceleration is due to increasing forces.
4. In the absence of forces, objects are either at rest or, if they are moving (because they stored up momentum while previous forces were acting), they are slowing down (and consuming their stored momentum). (1077)

As the number of studies grew, researchers tended to become more aware of inconsistencies in students' responses to what the researchers considered similar problem situations. Examples like that cited above, in which Halloun and Hestenes (1985b) uncovered a deep-seated belief that explained an apparent inconsistency, were rare. More frequent were reports about inconsistent patterns of responses that were used to refute the idea that students held consistent sets of beliefs that could be called "theories." Following are three examples of such studies.

Maloney (1988) presented 64 undergraduates who were not studying physics with 12 tasks, six involving spheres thrown off cliffs, and six involving a horizontal stream of liquid. Based on the students' responses, Maloney inferred the rules that the students were applying in the context of each task. The subjects applied different rules to the spheres than to the streams of water, but there was also a great deal of variation within each set of tasks. Maloney concluded,

> These subjects' rule usage was quite flexible with essentially no consideration of the fact that all of the situations involved the same type of motion. That is, the subjects seemed to treat each situation as unique with no need to correlate a rule on one task set with the rules on related task sets. . . . Since our job as science teachers is essentially to get our students to apply the proper rules consistently, it is important to know if anything is going to interfere with students learning the proper rules and the procedures for applying them. Clearly, any rules which the students bring with them could interfere with their use of the proper rules. (511–12)

Finegold and Gorsky (1991) devised a study to determine the extent to which students' responses to questions about projectiles were guided by an underlying commonsense theory. Their subjects were 333 university students and 201 high school pupils, divided into groups according to the amount of physics training that they had received. All the subjects responded to a written questionnaire about projectiles, and 35 were interviewed. The researchers found that students who had stronger physics backgrounds did better and were more consistent in their responses. Not one of the students lacking a physics background answered all questions correctly. Twenty-nine percent of the students who had taken an "ordinary" physics course and 46% of those who had taken a university physics course answered all questions correctly. Among students who did poorly on the questionnaire, there was no evidence that they applied commonsense laws such as "motion implies a net force" consistently across tasks.

Cooke and Breedin (1994) used a variety of performance tasks, rather than interviews or questionnaires, to determine the extent to which subjects spontaneously applied impetus theory. They found that impetus explanations made up only 15%–16% of all explanation errors. It seemed to them that subjects offered ideas about motion with very little forethought and that this activity was done "on the fly."

The above studies lend support to diSessa's (1993) proposal that students' knowledge structures are better described as fragmentary rather than theory based. He proposed that when learners encounter problems, they apply knowledge structures that he termed *phenomenological primitives* (or *p-prims*). These are tiny statements of useful ideas that may be applied properly in some situations but that lead to erroneous conclusions if overgeneralized. According to diSessa's proposal, learners fashion together any number of independent p-prims to interpret real-world situations. In his view, impetus is not a systematic and coherent theory. Rather, it is a loose collection of notions about specific situations that only give consistent answers in a few specific situations, such as a ball tossed upward.

Liu and MacIsaac (2005) completed a study that could be interpreted as forming a bridge between researchers who claim that students hold theories about projectile motion and those who believe that knowledge is fragmentary. They administered a well-known diagnostic tool, the Force Concept Inventory developed by Helloun and Hestenes (1985a), to a group of 614 university students enrolled in a calculus-based physics course. They found that students used impetus theory significantly more often in familiar problem contexts and when a question called for explanation rather than prediction of how a projectile would move. Students' academic achievement had no bearing on whether they chose to use naïve impetus theory. The researchers concluded, "We perceive a continuous trajectory of student conceptual development in science concepts starting with pieces of ideas and ending up with scientific theories as consensus models. If we can map out such a trajectory for each of the major concepts learned in the science curricula, we will be in a much stronger position to develop instruction and assessment that are much more appropriate and relevant to student learning" (Liu & MacIsaac, 112).

### *4.1.7 Summary*

There is broad agreement that the majority of students who take introductory physics courses in high school or college have a poor conceptual understanding of Newton's laws. Even students with good grades and who can solve mathematical problems related to projectile motion tend to fall back on intuitive, nonscientific notions when asked to draw the path of a projectile. Those intuitive ideas about motion are highly resistant to change. Several researchers cited examples in which students distorted physics concepts and even observations to fit their intuitive ideas about motion.

The concept of impetus, a kind of inner force impressed on an object to keep it moving after it is no longer in contact with the thrower, plays the same role for projectile motion as "support theory" does for falling objects. Both are ideas about how objects move that are formulated by people on their own, without the benefit of instruction. As we've seen in this section, although there is considerable variation among students' concepts of impetus, common attributes include:

- Whenever there is movement, there must be a force in the direction of motion.
- An object projected horizontally (such as a ball rolling off a cliff) will fall straight down.
- Impetus will either "wear out" after a while or be overcome by gravity.
- Living things can impart impetus.
- Projectiles continue to accelerate after they have left the hand of the thrower.

We also addressed the question of whether the impetus concept is a unified theory or better described as a loose collection of concepts about motion, each of which applies in only a limited number of situations. We did not find any studies that presented conclusive evidence on one side or the other, and as suggested by Liu and MacIsaac (2005), both perspectives may be true to some extent.

## 4.2 Orbits

Researchers have found several common misconceptions about gravity related to orbital motion:

1. Gravity needs air.
2. There is no gravity in space.
3. Objects in orbit are weightless, so gravity does not affect them.
4. The force of gravity diminishes rapidly with increasing altitude.
5. Force is needed to keep an object in orbit.
6. Planets closer to the Sun or that spin faster have more gravity.
7. Gravitational forces between objects are not equal and opposite.

### *4.2.1 Gravity Needs Air*

A widely reported finding is that many students believe that gravity needs air, either as a means of transmitting the gravitational force from one body to another, or as a causative factor, as in the statement, "Gravity is caused by air pressure which holds us down." Following are some of the many studies that have reported this misconception.

Watts (1982) found the idea that gravity needs air to be common among his sample of 20 British secondary students 12–17 years old. Many of the students believed that gravity required a medium through which its force could be transmitted, and that the absence of air would result in the absence of gravity. Following are Watts's thoughts about the origin of this misconception:

> Gravity is seen as ending at the upper limit of the atmosphere. . . . These are very commonly held opinions and must be the result from attempts to interpret popular coverage of news items concerning space exploration. They are examples of people using a framework to interpret a situation outside of common experience. (118)

Noce, Torosantucci, and Vincentini (1988) conducted a large scale, cross-age study in Italy. Subjects were given a questionnaire that pictured an astronaut on the Moon who loses a tool. They were asked what will happen to the tool and to justify the answer. Their sample of 362 subjects included high school students, first-year university students, adults, and elementary teachers. Although the percentage of subjects who gave the Newtonian answer, that the object would fall, increased from 4% at the middle school level to 35% of the adults and 50% of students at a scientific high school, at all age levels, the majority of subjects believed that objects on the Moon would float because air is necessary for gravity to act, and there is no gravity on the Moon.

Sequira and Leite (1991) interviewed 27 fourth-year physics students at a university in Portugal concerning falling objects in air and in a vacuum. Fifteen percent of the students claimed that there is no gravity in a vacuum. One student, who predicted that the heaviest of three objects would hit bottom first, gave the following explanation when the three objects fell at the same rate in an evacuated cylinder: "There is no gravity in a vacuum and therefore the weight no longer interferes with the falling velocity and this explains the same falling velocity for the three objects." (47)

Gunstone and White (1980) found that a small percentage of first-year college students (12 out of 458 students) at a university in Australia believed that gravity decreases at higher elevations because the air is thinner.

Finally, in their review of research on force and motion, Gunstone and Watts (1985) shared the following transcript of a physics graduate student (Abe) who was completing his training to become a teacher. He was asked what would happen to a balloon partially inflated with air in a bell jar when all the air had been removed.

> Abe: The balloon will float.
> Interviewer: Why?
> Abe: Because gravity will be reduced. (86)

### *4.2.2 There Is No Gravity in Space*

For students to make sense of how objects stay in orbit—whether around Earth, the Sun, or another planet—they need to understand that gravitational forces extend beyond our own atmosphere, into the space between the planets. Two different misconceptions lead students to believe that there is no gravity in space: (1) the idea, indicated above, that gravity needs air, so there can be no gravity in space where there is no air, and (2) the idea that Earth is a special place.

Ruggiero et al. (1985) interviewed 22 Italian middle school students, aged 12 to 13 years, concerning their ideas about weight and gravity. Although none of the questions explicitly mentioned air, several of the students indicated that air is needed for gravity to operate: "Weight exists only on the Earth, because there is air . . . and gets smaller higher up because air is rarefied" (187-88). When asked to describe the motion of objects on the Moon, some students in this sample maintained that objects there float because of the absence of gravity. Some students believed that the lack of air on the Moon means that there is no gravity there. Others viewed gravity as something that is both Earth centered and Earth specific. The Moon was considered to be too far from the Earth to experience gravity.

In addition to the large-scale cross-age study in Italy reported by Noce et al. (1988), the researchers also administered to 88 Italian fifth graders the questionnaire about an astronaut who loses a tool. Only eight of the children said that the tool would fall, and of those, only three gave the Newtonian answer that it fell because it was attracted by gravity. The vast majority of the students' answers concerned gravity as a force that only applies on Earth. For example, "The force of gravity is our atmosphere"; "It is a kind of air that pulls downwards"; "[It is a] force of the universe that pushes people down"; and "[It is the] force that keeps people, animals and things in air."

In 1993, Reynoso, Fierro, and Torres conducted a large-scale study involving both questionnaires and interviews with 302 students from preschool through preuniversity, and 20 teachers. Respondents were asked about their beliefs regarding the motion of objects falling on Earth and on the Moon. They found that students largely maintained the belief that objects would fall on Earth and would float if released on the Moon. These researchers found that older students in this sample also tended to use more sophisticated language to explain their reasoning, regardless of whether their conceptual understanding was correct.

Bar and Zinn (1998), whose study of 472 Israeli students aged 9–18 is referenced above, found that

> the belief that Earth is unique with regard to gravitation and magnetism was found to be common among younger participants and appeared to be retained by many older ones up to the age of 18. The pupils thought of gravitation as a phenomenon relevant to the Earth alone. They defined gravitation as a force that holds us to the Earth, causes us to fall on Earth, prevents us from flying and so on. None of the views recorded related gravitation to the force that acts between any two masses in space. (479)

### *4.2.3 Objects in Orbit Are Weightless, So Gravity Does Not Affect Them*

Sharma et al. (2004) evaluated a single regular final exam question from a group of 200 undergraduates. Half of the sample had completed a "fundamentals" physics course for students with little or no prior physics background. The other half had completed a "regular" physics course. The question asked how an astronaut might explain his new weight as "zero" despite knowing that his mass had not changed since blasting off from Earth’s surface. The great majority of students chose to represent gravity—and therefore weight—as being equal to zero, or nearly so. Students from both courses chose "zero-gravity" language to describe both the spaceship and its inhabitants. The researchers found little substantive difference between the two groups concerning their conceptual understanding of weight inside an orbiting spacecraft. However, the exam’s grader gave widely variant marks for the answers of the two groups. A significant portion of the "fundamentals" students used common language and received no marks for their description of the spaceship in orbit. Students in the more advanced physics course used more scientific terminology and consistently received more credit for their answers.

Galili (1995) administered questionnaires to 175 Israeli students, from ninth grade (age 14) to university level. All the students had been taught the "weight = force of gravity" definition. One of the questions showed an astronaut in the cabin of a satellite coasting around Earth, and asked whether gravitational force acts on the astronaut and whether the astronaut has weight. Only 40% of students with minimal physics backgrounds and 50% who had a stronger physics education correctly noted that gravity would act on the astronaut and the astronaut would have weight. The most common error was made by 20%–30% of all groups, who said that the astronaut was "weightless" and therefore did not have weight or gravity. Most students attributed the weightless/gravityless condition to either the lack of air or the presumed great distance from Earth. One student wrote in explanation, "There is no weight inside the satellite according to Newton’s law of gravitation" (Galili, 59). One student who responded that there is gravity but no weight explained, "There is no gravitational force inside the satellite revolving around the Earth because there is no weight there, and if there is no weight, so there is no gravitation. In spite of this there is the gravitational force on the satellite as a body, but there is no gravitation inside" (60). In a subsequent question, students were asked about what a person in an elevator would feel if the cable is cut. Although 60% of the students in both categories correctly noted that gravity would be the only force acting inside the elevator, only a small percentage of students predicted that the person in the elevator would feel as though he were weightless, and not a single student mentioned that the "free-fall" condition in the elevator would be similar to the conditions inside an orbiting satellite. Galili concluded, "Weightlessness seems to be understood by students as a phenomenon with a functional dependence on location (big distance from the Earth) and/or medium (empty interstellar space), but not the state of motion (free fall). This understanding is not in accord with the Newtonian mechanics paradigm" (64).

In subsequent papers, Galili and Kaplan (1996) and Galili (2001) argued that textbooks confuse students by defining weight as the force of gravity on an object, and then showing them illustrations of astronauts floating "weightless" in orbit. Although it is possible to resolve the conflict by defining "apparent weight" and "true weight," he recommended instead that weight be operationally defined as the contact force that an object exerts on a scale. He noted several advantages of using the operational definition of weight, including: (1) that it would be consistent with students' intuitive understanding of "heaviness"; (2) that operational definitions are generally preferred in the sciences; and (3) that presentations of "weightless" conditions in orbit would no longer contribute to students' misconceptions about whether gravity exists in space. Galili is not alone in making this argument. Morrison (1999) reviewed prominent physics textbooks and NASA publicity materials, and he concluded that science educators should use more precise language when distinguishing weight from gravity. Chandler (1991) noted that the term "microgravity" reinforces students' belief that gravity extends only to the top of the planet's atmosphere.

Gürel and Acar (2003) conducted a study of 86 high school students and 50 college students regarding their beliefs about weightless environments. They asked students what would happen to a person in an elevator if the steel cable is cut. Only 2% of their student sample provided both the correct answer paired with the correct rationale. "One high school student said that while the elevator is falling, it would get closer to the ground and therefore the Earth's gravity would increase" (6). The researchers concluded, "The problem seems to be that the students have difficulty in realizing that a spacecraft orbiting the Earth is in a state of continuous free-fall" (1). They also reported that most students in their sample lacked a sufficient sense of the magnitude of gravitational force and were unable to bridge the gap between their school experience and everyday experience.

### *4.2.4 The Force of Gravity Changes Rapidly with Increasing Altitude*

Although Gürel and Acar (2003) undertook their study to learn about students' conceptions of weightless environments, they also learned that many students have an unrealistic understanding of how gravity varies with altitude. Other researchers have reported similar results. Gunstone and White (1981), whose research was reported earlier, noted that most of the 468 first-year physics students in their study were aware that gravity decreases with altitude, but most made large errors of scale. For example, in judging how the weight of a bag of sand would change when taken to the top of Mount Everest, many thought that it would decrease significantly, some indicating that it was due to the rarified air.

Watts (1982) reported that several of the 20 British high school students he interviewed believed that gravity *increases* with height, possibly expressing an idea like gravitational potential energy. One student gave an example that if a rubber ball is dropped from a great height, it bounces higher than if it was dropped from a distance closer to the ground.

Two of the questions in the questionnaire that Galili (1995) administered to 175 students from high school through college (described earlier) were intended to explore students' understanding of how gravity varies with altitude. In one question, students were shown a diagram of two spacecraft in orbit, one at 100 km altitude and the other at 200 km altitude. In each spacecraft, an astronaut tries to weigh a 1 kg weight with a spring scale. Students are asked about the results of the weighing and what inferences the astronaut would make regarding the weight. Although there would only be an insignificant difference (2%) in the gravitational force at these two altitudes, many of the students thought that there would be a big difference. Forty percent of the students who had weaker physics backgrounds thought that gravity and weight would be significantly decreased at the higher altitude, and 55% of the students with stronger backgrounds made the same mistake. In other words, students who knew more about physics and who had in fact learned that gravity decreases with altitude were more likely to reply that the distance mattered a lot. The most frequent reason given was ". . . because of the distance."

Except for occasional anomalous results, such as the finding by Watts (1982) that a few students thought that gravity would *increase* with altitude, nearly all others reported that many students understood gravity would *decrease* with altitude, but at a far greater rate than it actually does. Reasons given included that the air is thinner at high altitudes, that there is no air in space, and that gravity decreases with distance. It is possible that students exaggerate the difference that altitude makes because they are thinking about height above the ground rather than distance from the center of the Earth.

### *4.2.5 A Force Is Needed to Keep an Object in Orbit*

Berg and Brouwer (1991) studied high school students' ideas about gravity and orbits in Canada. One of the items on their questionnaire showed a small capsule in orbit around Earth. The students were asked, "If the astronaut were to leave and remain just outside the capsule, what would happen?" Some students maintained that there is no gravity in space and that the propulsive power of the capsule would drive it further along the orbital path while the astronaut stays in place, where he or she let go of the capsule. These students also indicated that the astronaut would "float downward" toward Earth because he or she had no propulsive power to maintain an independent orbit.

### *4.2.6 Planets That Are Closer to the Sun or That Spin Faster Have More Gravity*

Treagust and Smith (1989) and Smith and Treagust (1988) surveyed Australian 10th graders after instruction in astronomy. Twenty-four students were interviewed in half-hour sessions using diagrammed scenarios on cards, and 113 students were surveyed using a paper-and-pencil diagnostic tool. The authors found widespread enthusiasm for astronomical topics. Furthermore, students had retained some knowledge: the names of heavenly objects and our location in the universe. However, the students were unable to convey fundamental conceptual knowledge about how gravity works and how the orbit of a planet is affected by its location in the Solar System. One of the questions showed a drawing of three planets: one with no rotation, one with slow rotation, and one with fast rotation. Students were asked, "Which planet will be easiest to 'take off' from?" Forty-seven percent of the students responded that the planet with no rotation would be easiest to take off from "since lack of rotation makes the rocket leaving the planet easier." Sixteen percent chose the planet with slow rotation, "since Planet B's rotations are not too fast and does not hold things down." In the same study, many of the students also expressed the idea that planets closer to the sun had stronger gravity. "Even some of the more able students expressed these misunderstandings and misconceptions" (Treagust & Smith, 390).

Piburn (1988) gave interviews and written questionnaires to 40 Australian university students who were non–science majors. Piburn found that many of the ideas expressed by high school students persisted at the university level, but that the 15 students who performed better on a test of propositional logic tended to have fewer misconceptions than the 25 students who had lower scores on the logic test. Twenty-seven percent of the students who performed well on the logic test and 60% of those who performed poorly on the test agreed with the statement, "The gravity of a planet depends on its distance from the Sun."

### *4.2.7 Gravitational Forces between Objects Are Not Equal and Opposite*

Newton’s third law, that two interacting bodies exert equal and opposite forces on each other, is not intuitively obvious for most students. One example, which will be discussed in the context of Section 4.3 (Teachers and Teaching), is that the force exerted by a table on an object equals the force that the object exerts on the table. Another is that two objects in space exert equal and opposite forces on each other, whether they have the same mass or widely different masses.

Dostal’s 2005 dissertation involved more than 2,000 students enrolled in physics courses at Iowa State University. Test instruments included multiple-choice and free-response versions of a questionnaire about gravity. These instruments were administered to students before and after they had taken an algebra-based or more advanced calculus-based course in mechanics. Some students were also interviewed. In agreement with many previous researchers, Dostal found that even after learning about Newton’s laws in college physics classes, most students—including many of the most academically talented—believed that a more massive body exerts a stronger force on a less massive body than the less massive body exerts on the stronger. This was found to be true whether the two bodies were Earth and an asteroid or two asteroids of the same size but different mass. One of the questions from Dostal’s survey considered the relative attraction between two asteroids in space, with no other objects in the vicinity. His diagram stipulated that although the two objects were both the same size, one was three times as massive as the other. More than 80% of first-year physics students drew arrows indicating unequal forces between the two objects, and 69% of second-year physics students indicated that there were unequal forces between the two objects.

### *4.2.8 Einstein’s Relativity*

There are a few studies regarding commonly held beliefs about the temporal elements of Einstein’s special theory of relativity, but we have been unable to find research on teachers’ and/or learners’ conceptions of Einstein’s general theory of relativity, which concerns gravity.

### *4.2.9 Summary*

To understand orbital motion, students first need to understand free fall and projectile motion. As we’ve seen in the previous sections, even "A" students have a poor grasp of these more elementary concepts. A further barrier to a good conceptual understanding of orbital motion, described in this section, is the finding that many students believe that air is needed for gravity to act. This misconception leads to the further misunderstanding that gravitational attraction rapidly diminishes with an increase in altitude until there is none at all in space. That set of misconceptions is strengthened by reports of astronauts "floating weightless in orbit." As to what keeps an object in orbit, some students believe that a constant force is needed, which is provided by the spacecraft itself, and without constant thrust, it would fall out of orbit. Finally, students have misconceptions about the nature of gravity itself, with some believing that it is caused by the spinning of a planet on its axis.

Although discouraging, these findings do not in themselves demonstrate that it is impossible for most students to learn about orbital motion—only that most physics instruction is ineffectual when students are questioned about their qualitative understanding of orbital motion. As we’ll see in Section 4.3 (Teachers and Teaching), some promising approaches have been examined.

## 4.3 Teachers and Teaching

Research in this area is divided into four sorts of studies:

1. Teachers’ Awareness of Common Misconceptions
2. The Effects of Physics Instruction
3. Teaching Interventions with Students
4. Professional Development of Teachers

### *4.3.1 Teachers’ Awareness of Common Misconceptions*

Berg and Brouwer (1991) surveyed 315 Canadian ninth-grade students and interviewed 20 teachers regarding several aspects of gravity. Their purpose was to determine the extent of students’ misconceptions prior to taking high school physics, and teachers’ awareness of the misconceptions that their next group of students were likely to hold. The researchers adapted diagnostic tools from researchers who published their studies of students’ conceptions about projectile motion and orbits. Prevalence of students’ misconceptions was found to be similar to that found in other studies. However, most of the teachers were relatively unaware of the magnitude of students’ misconceptions and even held some of these mistaken ideas themselves. For example, six of the teachers thought that there must be a force in the direction of motion. More than half of the students expressed the idea that there is no gravity in space, but none of the teachers was aware of this misconception. Regarding a question about what would happen to an object dropped by an astronaut on the Moon, the average prediction of the teachers was that 73.5% of the students would correctly indicate that the object would fall to the surface. However, most of the students believed that there is no gravity on the Moon because there is no air on the Moon, yet only one teacher was aware of this misconception. Seventeen of the 20 teachers were unaware of the research in teaching strategies to promote conceptual change. The researchers reported that since the study was carried out, they scheduled a number of in-service and preservice activities for teachers to acquaint them with this important area of research. (Other studies of teachers’ awareness of students’ common misconceptions related to free fall were reported in Part I of this review, Kavanagh & Sneider 2007.)

### *4.3.2 Effect of Physics Instruction*

Several researchers compared groups of students who had taken physics classes with those who had not in order to determine whether their understanding of gravity improved as a result of instruction. Although other studies reported in previous sections compared students with various levels of education, the following were undertaken primarily to determine the effectiveness of existing physics instruction. As shown below, most studies showed that physics courses reduced the number of students who held misconceptions, but a surprisingly large number of students still held non-Newtonian beliefs.

Eckstein and Shemesh (1993) conducted three studies of Israeli students in grades 2–12. The students were asked to draw the path of two balls rolling off a table, with the second ball rolling faster than the first. The researchers categorized the drawings and the explanations given by the students. They developed categories (and relevant subcategories) to classify responses:

- Level 1: Novices drew both balls falling straight down after reaching the end of the table.
- Level 2: Intermediates drew the first ball falling straight down and the faster ball moving to the right. (seven subcategories)
- Level 3: Experts drew parabolic paths in which both balls move forward, but the second ball reaches a greater horizontal distance before reaching the floor. (six subcategories)

The researchers found that students' abilities to correctly predict what will happen to the projectiles improved as a result of both maturation and instruction. Regarding maturation, they found a decline in novices from grades 2–4 to 5–8 to 9–12 (51%, 30%, 11%) and an increase in experts (8%, 25%, 42%). Regarding the effects of instruction, the researchers found that 47% of the grade 11–12 students who had not taken physics still drew the slowest ball falling straight down after reaching the end of the table, whereas all the grade 11–12 students who had taken physics were in the "expert category." In the highest category, a subset of the "expert" category, students drew both balls following a curved path. The authors compared this sample with the nonphysics students in grades 11–12 of the previous study and concluded that "appropriate teaching methods can change misconceptions."

Fischbein, Stavy, and Ma-Naim (1989) conducted a study that compared 44 Israeli 10th graders who had not studied physics with 45 11th graders who had studied physics. The researchers used written questionnaires and interviews to determine whether students used the concept of impetus or the Newtonian concept of inertia to predict what would happen in two "active" scenarios (a ball rolling down hill and then over a precipice, and a spring that pushes a box across a smooth surface) and two "passive" scenarios (an object towed and released by an airplane, and an object towed and released by a car). Objects used in the questions included a heavy box, a ball, and a glider. As expected from previous research, most 10th graders used the anticipated impetus concept to explain what would happen, with predictions that depended on the object and on whether the object is given forward motion passively or actively. The effect of instruction was to greatly improve the students' abilities to predict the path of a projectile, regardless of the object, or whether it is released passively or actively. However, when the 11th graders were asked to explain their predictions, nearly all attributed the forward motion to "energy" that was imparted to the object, suggesting that the students still relied on an interpretation of projectile motion similar to the impetus theory. The researchers concluded that "these students can give a correct statement of the law of inertia, but they have no real understanding of its meaning" (77).

### *4.3.3 Teaching Interventions with Students*

We have found several studies that describe the results of specific interventions to help students correct their misconceptions about gravity.

Dharmadasa and Silvern (2000) found that third graders made larger conceptual gains as a result of a constructivist unit on force and motion than did those in a traditional demonstration and lecture classroom. Their study included 67 third-grade students in the United States; 32 received the experimental unit, and 35 served as controls. The experimental treatment was presented 45 minutes per day, five days a week for six weeks. The assessment instrument was an interview about a task in which a student is given a pendulum and asked to play a game, the goal of which is to hit a small target with the bob and explain his or her thinking at each step. The researchers' questions were designed to reveal the students' thinking about force and motion while playing the game. The research team developed a coding scheme based on the work of Piaget to classify students' ideas about force. The researchers concluded, "The results were statistically significant, indicating that constructivist instruction had positive effects on children's conceptualization of force . . . the number of children in the experimental group who moved to higher levels of reasoning are more than twice the number of children who moved forward in the control group" (100).

Palmer and Flanagan (1997) compared 63 Australian students aged 11 and 12 with 66 students aged 15 and 16. They wanted to find out if younger students have an easier time rejecting the misconception that "motion implies force," as compared with older students, who may be less willing to change their ideas. All students were given a pretest that consisted of an audiotaped interview in which they were shown drawings of various everyday situations involving projectiles. The teaching intervention consisted of a refutational text—a short written passage that directly refuted the idea that motion implies force. The text consisted of handwritten responses to the same questions asked during pretesting. The text did not present information as the only correct way to answer the questions. Rather, these elements were an option that the students could consider applying, such as in the case of a basketball being thrown: "The ball hasn’t got an engine! So there is no force pushing it upwards after it has left the person’s hand. Just the force of gravity pulls it, so it will soon head downwards" (321). All students who indicated that they believed that "motion implies force" were interviewed after they read the text, and students who indicated that they had changed their understanding were asked to come back for an additional interview one to two weeks later for a delayed posttest. On the pretest, 66% of the younger students and 75% of the older students expressed the idea that motion implies force. On the posttest, 43% of the younger students and 57% of the older students had revised their conceptions. On the delayed posttest, 37% of the younger students and 44% of the older students had revised their conceptions, indicating that some of the students had reverted to their earlier conceptions. Nearly all the students who successfully changed their understanding said that the text was influential, yet there was no statistical difference between genders or age levels in either group of students.

Bar, Sneider, and Martimbeau’s 1997 classroom intervention was developed to correct the misconception that there is no gravity in space and to help students develop a qualitative understanding of how natural and artificial satellites stay in orbit. The subjects were 48 sixth graders in two classes. The students had studied the Solar System earlier in the year and had not expressed confusion about how planets stay in their orbits. But when the researchers interviewed 10 of the students, they found that 8 of the 10 believed that gravity needed air to act, and these students did not understand the role of gravity in keeping planets in their orbits. Additionally, the researchers interviewed the same students after the intervention and gave all students a written pretest and posttest. The intervention consisted of a series of classroom activities and thought experiments presented during two 45-minute class periods. In the first activity, the students were asked to draw what they think will happen to a ball after it rolls off a table. The students discussed their predictions and then worked in groups of three or four to perform the experiment and draw what they saw. The students then shared and discussed their observations of a curved trajectory. The teacher explained that the curved trajectory was due to the object’s horizontal motion when it left the table, and the downward attraction of gravity. The students could see that if the ball was rolled off the table faster, it went farther from the edge of the table before hitting the ground. The instructor then showed a series of slides of what would happen as a ball is hit faster and farther–first by a baseball bat and then shot from a cannon—so that it eventually goes into orbit around Earth. The teacher then encouraged the students to discuss answers to these questions: What would happen to the Space Shuttle if someone turned off Earth’s gravity? The teacher reinforced the idea that even in space, where there is no air, the gravitational attraction keeps the Space Shuttle, satellites, and our Moon in orbit. Finally, the students looked at images of Jupiter and its moons to discuss how those moons were kept from flying off into space. On the pretest, 27% of the students believed that gravity acted in space, where there is no air. On the posttest, conducted a week later, 48% believed that there is gravity in space, and another 8% believed that there is gravity "near planets." However, 21% of these students still clung to the idea that there is no gravity in space.

Dostal’s (2005) research on college students’ difficulties in applying Newton’s laws to everyday situations (summarized earlier) led him to develop a series of worksheets to help students reverse some of their misconceptions about gravity. The worksheets were written in a format similar to *Tutorials in Introductory Physics* produced by the Physics Education Group at the University of Washington (McDermott, Shaffer, & the Physics Education Group at the University of Washington 2002). The worksheets were designed to help students think further about topics that had proved to be a stumbling block in Dostal’s prior research. The worksheets were just a few pages in length and intended for use in just one class period, led by a graduate teaching assistant. The first three pages gave students a working definition of force. The remainder of the packet addressed Newton’s third law in the context of gravity, the dependence of gravitational force on mass and separation distance, and how gravity affected an orbiting space shuttle. Discussion of the worksheets required approximately 30 minutes of a 50-minute class session. Students’ responses to the worksheets were overwhelmingly positive. The students who used the worksheets also performed significantly better on exam questions related to gravity than did students in a control group that did not use the worksheets.

### *4.3.4 Professional Development of Teachers*

Following are interventions designed to help teachers understand how Newton’s laws apply to motion under gravity.

Hynd, Alvermann, and Qian (1997) used a variety of experimental conditions to help preservice teachers learn about projectile motion. Some received a refutational text paired with a demonstration, while others were asked to merely read a refutational text. Randomly selected groups were told that they would be expected to provide an original lesson about projectile motion, which would be videotaped. The researchers also noted the number of previously completed science courses and the respondents’ interests in science. Evidence for concept change at the end of the data collection period was sparse, regardless of experimental treatment. Of the 73 participants, all began with some sort of alternative framework. At the end, only two participants answered questions about projectiles correctly. This finding suggests that the majority of students merely developed new nonscientific ideas during their lessons on force and motion and that authentic concept change is very difficult to achieve despite a variety of pedagogical techniques employed to assist with this process. For those who did improve their understanding, personal motivation and a tendency to view scientific knowledge as a useful analytical tool were cited as influencing factors.

Prescott (2004) engaged four teachers and 47 high school students in two girls’ schools in Sydney, Australia, in a study that combined the professional development of teachers and an evaluation of a constructivist unit on projectile motion. Two of the teachers (one from each of the schools) participated in a training program concerning students’ misconceptions about projectiles, and consequently learned to correct some of their own misconceptions. These two teachers then taught their students using an approach that engaged the students in a variety of activities involving projectile motion in different contexts. They urged the students to recognize similarities in the motions that they observed. Once the students understood projectile motion qualitatively, they introduced equations so that the students could expand their understanding to solve quantitative problems. The other two teachers did not participate in the training and presented projectile motion with the usual approach, which involved deriving the equations of motion horizontally and vertically, and then solving as many questions from the text as could fit into the allocated time. Overall, the students who participated in the constructivist-based teaching program did better than those who took the traditional classes. Prescott concluded,

> While the teaching program was successful in helping students deal with their misconceptions about objects dropped from a moving carrier, it was less successful in dealing with the impetus misconception. The most significant factor determining whether student misconceptions were eliminated was found to be the teachers' ability to deal with their own misconceptions. (xiv)

### *4.3.5 Summary*

As with studies of teachers' understanding of free fall reported in Part I of this review (Kavanagh & Sneider 2007), whenever researchers have taken a close look at teachers' understanding of gravity, they have found the same misconceptions as among university students and younger students. Even teachers who can correctly apply Newton's laws to projectiles and orbits are unlikely to be aware that many of their students harbor misconceptions that are very difficult to extinguish. However, research studies in the other three sections are encouraging. In the second section, we found that some portion of the students who enroll in physics classes in high school or college do shed some of their misconceptions. The biggest changes appear to be in better predicting the results of phenomena (such as the shape of a trajectory) rather than the explanations for phenomena. The studies reported in Sections 4.3.3 and 4.3.4 (Teaching Interventions with Students, and Professional Development of Teachers) are especially encouraging because they report on specific interventions that work for many students and teachers. A remarkable feature of these studies is that some of the successful interventions don't require a great deal of class time. The implication is that students' engagement and interaction with the subject matter are key to teaching for deep understanding. These experiments provide promising models for the next generation of learning studies. All the research studies reviewed in this article are listed in Table 2.

**Table 2.** Articles reviewed in this article, listed alphabetically

| Author & Title | Subjects & Methods | Findings |
|---|---|---|
| Bar, Sneider, & Martimbeau (1997)<br>What Research Says: Is There Gravity in Space? | –48 middle school students<br>–Intervention strategy, with pretest and posttest data. | **Orbits:** Followed student progress through prescribed activities meant to teach gravity in space and the orbit concept and to specifically question students' reliance on the concept of air being necessary for gravitational action. Data one-week postinstruction indicated that initial beliefs are difficult to overcome, because reported student gains were modest. |

| | | |
|---|---|---|
| Bar & Zinn (1998)<br>Similar Frameworks of Action-at-a-Distance: Early Scientists’ and Pupils’ Ideas | –300 students, 9–18 years old<br>–Interviews with demonstrations | **Orbits:** Personal misconceptions follow a similar development to historical development, indicating stage theory. Found that students believe that air is required for "action-at-a-distance" forces, such as gravity. Suggested that teachers can use historical analysis to assist students with these concepts. |
| Berg & Brouwer (1991)<br>Teacher Awareness of Student Alternative Conceptions about Rotational Motion and Gravity | –315 high school students and 20 teachers<br>–Questionnaire<br>(Canada) | **Projectile motion:** Found that teachers underestimated the "motion implies a force" conception among students.<br>**Orbits:** Misconceptions about basic ideas in physics were common and widespread. Teachers were relatively unaware of these ideas among their students and did not have teaching strategies to help students rethink their own ideas about physical science. Students thought that there is no gravity in space without air. Students thought that an astronaut in orbit without propulsion would fall slowly downward toward Earth. |
| Caramazza, McCloskey, & Green (1981)<br>Naïve Beliefs in "Sophisticated" Subjects: Misconceptions about Trajectories of Objects | –44 undergraduates<br>–Questionnaire | **Projectile Motion:** Found that 75% of respondents demonstrated gross misconceptions when trying to predict the path of a simple pendulum trajectory. Included three suggestions for future research: more details about naïve motion beliefs, their origin, and the effect of formal instruction on these naïve beliefs. |
| Clement (1982)<br>Students’ Preconceptions in Introductory Mechanics | –150 undergraduates<br>–150 preinstruction questionnaires<br>–43 postinstruction questionnaires | **Projectile Motion:** Described students’ ideas as being similar to pre-Newtonian thinking. Found evidence for "motion implies a force" misconception and "impetus"-type thinking. |

| | | |
|---|---|---|
| Champagne, Klopfer, & Anderson (1980)<br>Factors Influencing the Learning of Classical Mechanics | ~ 375 undergraduates<br>–Questionnaires, tests of math, and logical reasoning skills, and survey of previous physics education. | **Projectile Motion:** Students' ability to adopt Newtonian explanatory frameworks was compared with their scores on math and reasoning skills. Found that even students who had previously studied physics used commonsense conceptions. |
| Cooke & Breedin (1994)<br>Constructing Naïve Theories of Motion on the Fly | –Experiment 1: 60 individuals (40 undergraduates and 20 working adults)<br>–Experiment 2: 148 individuals (undergraduates, academic faculty, and engineers) | **Projectile Motion:** Respondents with formal physics training made fewer errors in estimating shape of trajectory. Researchers' experimental design separated trajectory path prediction and rationale. Researchers found naïve impetus theory in only 15% of respondents and that strategies for problem solving were highly contextualized. Results disputed by Ranney (1994). |
| Dharmadasa & Silvern (2000)<br>Children's Conceptualization of Force: Experimenting and Problem Solving | Experiment conducted in four third-grade classrooms: 35 children in the experimental group and 32 children in the control condition | **Projectile Motion:** Found that third graders who had constructivist environments made greater conceptual gains than students who were given traditional demonstrations of projectile motion. |
| diSessa (1993)<br>Toward an Epistemology of Physics | Theory of cognition | Students apply phenomenological primitives ("p-prims") as an interpretation scheme when learning classical mechanics. diSessa encouraged instructors to help students refine their p-prims rather than work to extinguish them. |
| Dostal (2005)<br>Student Concepts of Gravity | ~ 2,000 undergraduates<br>–Coursework and worksheets evaluated<br>–28 follow-up interviews | **Orbits:** Found that the majority of students maintained that the force of gravity is unequal between two objects of different mass in space. Students did not understand the relative magnitude of the force of gravity in space. Students also demonstrated difficulties with applying Newton's third law to gravitational attraction between objects in space. |

| | | |
|---|---|---|
| Eckstein & Shemesh (1993)<br>Development of Children's Ideas on Motion: Impetus, the Straight-Down Belief and the Law of Support | –139 students (grades 4, 5, 7, 8, 9) and 631 students (grades 2–12, inclusive)<br>–Questionnaire | **Projectile Motion:** Found naïve beliefs, such as the "straight-down" belief, prevalent among younger students. As students mature, they gradually adopt Newtonian rationales for the motion of objects. |
| Finegold & Gorsky (1991)<br>Students' Concepts of Force as Applied to Related Physical Systems: A Search for Consistency | –534 high school students and undergraduates<br>–Questionnaire | **Projectile Motion:** Responses were coded according to level of physics education and consistency of answers. Research found that 79% of university and advanced high school students' answers remained consistent, regardless of whether those answers/ideas were correct. Those with less physics education were less consistent in identifying forces at work in their answers. 46% of university students answered all six items correctly, as did 29% of the advanced high school students and 0% of the ordinary-level high school students with no physics education. |
| Fischbein, Stavy, & Ma-Naim (1989)<br>The Psychological Structure of Naïve Impetus Conceptions | –45 grade 10 students and 44 grade 11 students<br>–Questionnaire and interviews | **Projectile Motion:** Found some evidence of Newtonian thinking among 11th graders, otherwise ideas from "impetus theory" held sway. |
| Galili (1993)<br>Weight and Gravity: Teachers' Ambiguity and Students' Confusion about the Concepts | –198 high school students and undergraduates<br>–Questionnaire | **Orbits:** Found that textbooks often associate weight too closely with gravity, allowing students to rationally (but wrongly) conclude that no weight must equal no gravity. Concluded that "apparent weight" terminology was of no help to students. Student rationales not directly tested, but inferred from coded responses. Promoted a definition for weight as "a result of weighing." |

| | | |
|---|---|---|
| Galili (1995)<br>Interpretation of Students' Understanding of the Concept of Weightlessness | –175 high school students and undergraduates<br>–Questionnaire | **Orbits:** Found that students attributed weightlessness in an orbiting satellite to either lack of air or presumed "large" distance from Earth, but not free fall. Student rationales directly measured. |
| Galili & Kaplan (1996)<br>Students' Operations with the Weight Concept | –128 high school students and undergraduates<br>–Questionnaire | **Orbits:** Found that students were unable to use "apparent weight" terminology in testing situation. Promoted differentiating weight with gravity as a pedagogical concern. |
| Gunstone & Watts (1985)<br>Force and Motion<br>(in Driver, Guesne, & Tiberghien, Eds.) | –Summary report from several studies in intuitive physics<br>–Interviews | **Projectile Motion:** Found that students identified as academically gifted also report that gravity needs air. |
| Gunstone & White (1980)<br>A Matter of Gravity | –Large-sample undergraduates<br>–2,650 total observations collected using eight (prediction/demonstration/observation/explanation) examples | **Projectile Motion:** Study concluded that although students were generally aware of physics knowledge, they were unable to relate this to real-world situations presented in the testing scenarios. Inertia relatively rarely invoked as explanation. Researchers concluded that more focus must be made on integrating physics knowledge into general knowledge. |
| Gürel & Acar (2003)<br>Research into Students' Views about Basic Physics Principles in a Weightless Environment | –85 high school students and 50 undergraduates<br>–Questionnaire | **Orbits:** Found that students have little sense of the scale of magnitude of gravity, in relation to other forces. |
| Halloun & Hestenes (1985b)<br>Common Sense Concepts about Motion | –478 undergraduates (survey data)<br>–22 undergraduates (interview data)<br>–Questionnaire and follow-up interview | **Projectile Motion:** Found support for the "motion implies a force" conception. |

| | | |
|---|---|---|
| Hecht & Bertamini (2000)<br>Understanding Projectile Acceleration | –424 undergraduates<br>–Multiple experiments | **Projectile Motion:** Results inconsistent with naïve impetus theory. Results suggested that elements of motion, velocity, and position are processed separately in the brain. |
| Hynd, Alvermann, & Qian (1997)<br>Preservice Elementary School Teachers' Concpetual Change about Projectile Motion: Refutation Text, Demonstration, Affective Factors, and Relevance | –73 preservice teachers<br>–Experimental and observational data, questionnaire, pretest and posttest, and videotaped lesson | **Projectile Motion:** All participants held alternative frameworks to explain projectile motion at the beginning of the experiment. Only 2 respondents answered questions correctly at the end of the data collection period. Researchers suggested that other participants merely compartmentalized their (memorized) correct answers without integrating a Newtonian mental model to explain projectile motion. |
| Liu & MacIsaac (2005)<br>An Investigation of Factors Affecting the Degree of Naïve Impetus Theory Application | –614 undergraduates<br>–Force Concept Inventory and questionnaire | **Projectile Motion:** Results indicated:<br>1. Students used impetus thinking with explanations of motion, rather than predictions of parabolic motion.<br>2. Familiar situations elicited impetus theory.<br>3. Students' academic achievement had no effect on use of impetus theory.<br>4. A call for explanations and familiarity were positively correlated with impetus thinking. Course grade had no effect. |

| | | |
|---|---|---|
| Maloney (1988)<br>Novice Rules for Projectile Motion | –64 undergraduates<br>–Questionnaire | **Projectile Motion:** Studied rule usage patterns in male and female students with no prior college physics education. Found that female students were more likely to use nonrelevant information when constructing physics problem solutions for motion. Found that respondents used rules to answer question about projectile motion but in a flexible manner. Prior physics education had a modest positive effect on outcomes. |
| McCloskey (1983)<br>Naïve Theories of Motion (in Gentner & Stevens, Eds.) | –48 undergraduates<br>–Questionnaire and interviews | **Projectile Motion:** Student results were coded according to their level of formal physics education. Study concluded that formal physics training decreased errors but that all groups made errors of the same kind. Respondents who provided data through the semistructured interviews gave rationales for their predictions based on naïve physics, or "impetus theory" of motion. Researchers concluded that naïve physics is systemic, well developed, and internally coherent. Also found evidence that students thought that horizontal motion dissipates instantaneously, then gravity takes over in falling projectiles. This makes objects turn an apparent 90-degree angle in the air and then move "straight down." |
| McCloskey, Washburn, & Felch (1983)<br>Intuitive Physics: The Straight-Down Belief and its Origin | ~ 175 undergraduates<br>–Multiple direct experimental methods presented | **Projectile Motion:** Although unable to directly confirm the presence of deeply seated perceptual error, the findings explain the origin of the "straight-down" belief. |

| | | |
|---|---|---|
| Noce, Torosantucci, & Vincentini (1988)<br>The Floating of Objects on the Moon: Prediction from a Theory or Experimental Facts? | –Cross-age study (224 secondary students, 64 university students, and 74 adults, none a physics expert)<br>–Questionnaire and interviews with 10 students | **Orbits:** Found that students associated gravity with Earth, as an object dropped on the Moon was believed to fall toward Earth (essentially, to float). Found misconceptions about gravity to be common and widespread among all ages in response groups. Found that most respondents believed that gravity is a special property of Earth. |
| Osborne (1983)<br>Building on Children's Intuitive Ideas (in Osborne & Freyberg, Eds.) | –Meta-analysis with middle school, high school and university students<br>–Semistructured interviews | **Projectile Motion:** Found that Buridan's physics (force in the direction of motion) was common thinking among 12-17-year-olds. Findings suggested that it is easier to teach 10-year-olds than 17-year-olds. |
| Palmer & Flanagan (1997)<br>Readiness to Change the Conception That "Motion-Implies-Force": A Comparison of 12-Year-Old and 16-Year-Old Students | –63 year 6 students and 66 year 10 students<br>–Questionnaire and interviews | **Projectile Motion:** Found evidence of impetus-based misconceptions among both younger and older students, but no evidence of increased difficulty with concept change among older students. Motivation and positive attitude toward science may be influential factors for assisting authentic conceptual change. |
| Piburn (1988)<br>Misconceptions about Gravity Held by College Students | –40 college students<br>Questionnaire and interviews | **Orbits:** College students in this sample shared many of the same misconceptions about gravity and orbits as high school students. |
| Prescott (2004)<br>Student Understanding and Learning About Projectile Motion in Senior High School | –4 high school teachers and 47 high school students<br>–Evaluation of professional development and classroom instruction | **Projectile Motion:** Found that students' ability to correctly apply Newtonian analysis to projectile motion was correlated with teachers' ability to understand their own misconceptions. |

| | | |
|---|---|---|
| Reynoso, Fierro, & Torres (1993)<br>The Alternative Frameworks Presented by Mexican Students and Teachers Concerning the Free Fall of Bodies | –302 students (preschool through preuniversity)<br>–20 teachers<br>Questionnaire and interviews | **Orbits:** Students widely reported that objects would fall on Earth but would float on the Moon. |
| Ruggerio, Cartelli, Dupre, & Vincentini-Missoni (1985)<br>Weight, Gravity, and Air Pressure: Mental Representations by Italian Middle School Pupils | –40 middle school students<br>–Semistructured interviews | **Orbits:** Found that students believed that airless environments on the Earth are radically different from one in space. Therefore, gravity does not exist in space. |
| Sequira & Leite (1991)<br>Alternative Conceptions and History of Science in Physics Teacher Education | –Multiple studies with high school students and undergraduates<br>–Questionnaire | **Falling Motion:** 52% of students maintained that the heavier object would fall faster "because it is the heaviest." Some of the students who held this belief used equations to justify their responses. Also found that students used seemingly sophisticated terms (and equations) to convey non-Newtonian ideas about falling motion. Found that at least one student thought that objects in a vacuum would be unaffected by external forces, thus, gravity needs a medium through which it is transmitted.<br>**Projectile Motion:** "Motion requires a force in that direction" concept was found to be common among respondents. |

|  |  |  |
|---|---|---|
| Sharma, Millar, Smith, & Sefton (2004)<br>Students' Understandings of Gravity in an Orbiting Space-Ship | –200 undergraduates<br>–Coursework extracted from final exam for analysis | **Orbits:** Researchers identified no qualitative difference between advanced and ordinary-level physics students, although the course instructor marked exam questions differently. Findings suggested that students wrongly adapted the "zero gravity" language to describe orbits. Students who used more scientific-sounding language were rewarded with more points regardless of whether their answer was correct. |
| Smith & Treagust (1988)<br>Not Understanding Gravity Limits Students' Comprehension of Astronomy Concepts | –113 high school students<br>–Questionnaire and interviews | **Orbits:** Documented four misconceptions among high school students<br>1. A planet's gravity is related to its distance from the Sun.<br>2. The Sun's gravity influences not only the planets to orbit around the Sun but also the gravity on the planet.<br>3. A planet's rotation (or lack thereof) affects its gravity.<br>4. A planet's distance from the Sun determines its rotational rate. |
| Treagust & Smith (1989)<br>Secondary Students' Understanding of Gravity and the Motion of Planets | –113 high school students<br>–Questionnaires and 24 follow-up interviews | **Orbits:** Found that although students had enthusiastically learned their location in the galaxy and were very interested in astronomy, their underlying ideas about gravity contained deeply flawed assumptions. Misconceptions about gravity and orbital motion were widespread and common. Interest in astronomy did not correspond to better comprehension of gravitation in the universe. |
| Viennot (1979)<br>Spontaneous Reasoning in Elementary Dynamics | ~ 350 high school students and undergraduates<br>–Questionnaire | **Projectile Motion:** Found that students commonly used impetus notions to predict the motion of objects. Students commonly used intuitive ideas about physics. |

| | | |
|---|---|---|
| Watts (1982)<br>Gravity—Don’t Take It for Granted! | –20 students 12–17 years old<br>–Semistructured interviews | **Projectile motion:** Found that the "impetus" conception was common in their sample of respondents.<br>**Orbits:** Overall, this sample did not believe that gravity exists in space. |
| Whitaker (1983)<br>Aristotle Is Not Dead: Student Understanding of Trajectory Motion | –100 undergraduates<br>–Questionnaire | **Projectile Motion:** Found that students believed in naïve physics for trajectories and had impetus-based conceptions for motion. |

# 5. CONCLUSIONS

In this section, we discuss the implications of the preceding research summary in light of the questions that motivated this review:

1. What common misconceptions do students hold about gravity?
2. To what extent do these misconceptions reflect the history of gravitational theory?
3. Are national standards documents reasonable concerning age-level recommendations?
4. What teaching methods are most promising?
5. What research remains to be done?

## 5.1 What Common Misconceptions Do Students Hold about Projectiles and Orbits?

As reported in Part I of this review (Kavanagh & Sneider 2007), even students who do well in solving quantitative problems of the type typically encountered in textbooks may still hold misconceptions about gravity when asked qualitative questions. These findings are briefly summarized below.

### *5.1.1 Misconceptions about Projectiles*

*Motion implies a force in the direction of motion.* This is a very strong misconception held by a great many students at all age levels and even by teachers.

*Objects fall straight down if not supported.* Though not as widespread as the first idea, quite a few high school students and even college students expressed the idea that if a ball rolls off a cliff, it will not follow a curving path, but fall straight down.

*Impetus may wear out or be overcome.* A great many students and adults believe that a thrower imparts a force to a projectile that stays with it and is the cause of continuing motion. Although they may use a term such as "energy," "force," or "acceleration," the concept is very similar to the medieval idea of impetus. The curving shape of a trajectory is then explained as gravity "takes over" and impetus dies away or is overcome by the gravitational force.

*Only living or active things can impart impetus.* Among those who hold the impetus idea, some tend to believe that greater impetus is imparted by an active agent, such as a person, bow, or gun, than by a passive agent, such as being dropped from an airplane.

*Projectiles continue to accelerate after they are released.* A surprisingly large number of college students believe that after a projectile is released (in this case, by a person who threw a ball), it will accelerate to a greater speed.

### *5.1.2 Misconceptions about Orbital Motion*

*Gravity needs air.* This is a very widespread notion among large numbers of elementary and high school students, and even many university students and teachers.

*There is no gravity in space.* This is a logical conclusion for people who believe that gravity needs air ("Because there is no air in space, there is no gravity there either").

*Objects in orbit are weightless, so gravity does not affect them.* Teachers and textbooks inform students, "Weight is the force of gravity on an object." They are also told that astronauts float "weightless" in space. This information leads to the logical conclusion that gravity does not act on astronauts, or anything else in space.

*The force of gravity diminishes rapidly with increasing altitude.* If students believe that gravity needs air, then at high altitudes where the air is thin, gravity must also decrease. Some believe that an object speeds up as it falls because the force of gravity increases rapidly as the object gets closer to the Earth.

*Force is needed to keep an object in orbit.* Students who believe that there is no gravity in space do not understand how a satellite can stay in Earth orbit. Some students have reported that a spacecraft stays in orbit as a result of its propulsion ("If an astronaut were to step outside and his rope were to break, he’d fall to Earth because he has no propulsion").

*Planets closer to the Sun or that spin faster have more gravity.* Students who understand that there is indeed gravity in space hold various ideas about where it is strongest. Quite a few high school students thought that planets closer to the Sun have stronger gravity; others thought that the speed of a planet’s daily motion (rotation) determines the strength of its gravitational field.

*Gravitational forces between objects are not equal and opposite.* It is common even for college students to believe that a massive object exerts a greater force on a less massive object than the less massive object exerts on the object with greater mass.

## 5.2 To What Extent Do These Misconceptions Reflect the History of Gravitational Theory?

The mistaken idea that heavier objects fall more quickly than light objects is widely known, but the realization that a great many modern people of all ages express ideas similar to the impetus theory developed by medieval scholars is an important contribution of this body of research.

A disagreement among researchers has been whether students’ misconceptions are more closely related to the ideas of Aristotle or to the medieval scholars, such as Oresme, Buridan, and Albert of Saxony. To resolve this issue, we have prepared Table 3, which compares students’ common misconceptions with the gravitational theories of Aristotle and the medieval scholars. (This is similar to Table 1, except that the ideas of Galileo and Newton are replaced by the students’ common misconceptions.) Our interpretation of this side-by-side comparison is that when students are asked about projectiles, their ideas are more similar to those of the medieval scholars. However, when asked about orbital motion, their ideas are unique to our modern age. Although the idea that "gravity needs air" can easily be matched to the ideas of both Aristotle and the medieval scholars, other misconceptions are entirely the product of seeing images of "weightlessness" inside the Space Shuttle, or of astronauts bounding across the lunar surface in slow motion.

**Table 3.** Comparison of students’ misconceptions with early gravitational theories

| **Aristotle** | **Medieval Scholars** | **Common Misconceptions** |
|---|---|---|
| **Projectile Motion** | | |
| A thrown object keeps moving because air that is forced to the side moves around behind to push the object forward.<br>The medium provides force to keep the object moving, and resistance to slow it down. Force can only be applied by a living agent.<br>Speed is proportional to the propulsive force and inversely proportional to size [mass] and resistance of the medium.<br>Objects are subject to only one simple motion at a time. | A thrown object keeps moving because a temporary force, or "impetus," is impressed on the object.<br>Impetus is proportional to the speed of the object times its quantity of matter [mass].<br>The medium through which the projectile moves only provides resistance.<br>Impetus may slowly wear out or be overcome by gravity.<br>Gravity could begin to act while impetus declines. | Motion implies a force in the direction of motion.<br>Objects fall straight down if not supported.<br>Impetus may wear out or be overcome.<br>Only living things can impart impetus.<br>Projectiles continue to accelerate after they are released. |
| **Orbits** | | |
| Celestial objects consist of a substance for which circular motion is natural.<br>Space is filled with a rarefied element because a vacuum is impossible.<br>Celestial objects ride on transparent spheres, which are continuously turned by the outermost sphere and driven by divine intervention.<br>Gravity [heaviness] applies only on Earth. | When God created the world, He impressed a circular impetus on all celestial objects.<br>Space is filled with a rarefied element that provides no resistance to celestial objects moving through it.<br>The same explanation for earthly motion might explain celestial motion, although Earth is still the center of the universe. | Gravity needs air, so the force of gravity diminishes rapidly with increasing altitude, and there is no gravity in space.<br>Objects in orbit are weightless, so gravity doesn’t affect them.<br>Force is needed to keep an object in orbit.<br>Planets closer to the Sun or that spin faster have more gravity.<br>Gravitational forces between objects are not equal and opposite. |

## 5.3 Are National Standards Documents Reasonable Concerning Age-Level Recommendations?

***Middle School Level.*** Regarding projectile and orbital motion, the standards recommend that middle school students experiment with rolling balls and other moving objects to "begin to describe" the forces acting on objects and "begin to see" how an object would move in a frictionless environment. In other words, students should be exposed to these ideas through activities, but mastery should not be expected. That recommendation is consistent with the learning studies involving middle school students.

According to this research, the most challenging standard for middle school students is to "develop the understanding that gravity is a ubiquitous force that holds all parts of the solar system together" (NSES, grades 5-8, 159). To accomplish this, students will need to first understand that gravity exists beyond Earth’s atmosphere, that it doesn’t need air to act, and that the strength of a planet’s gravitational field depends only on its mass. Overcoming these and related misconceptions is very difficult for many students. Nonetheless, some helpful ideas for tackling this have been suggested by the learning studies reported in this review and will be summarized in the recommendations to follow.

***High School Level.*** Although it was written prior to some of the research reported in this review, *Benchmarks for Science Literacy* (AAAS 1993) still provides what is perhaps the best summary of the difficulties that high school students encounter in learning to apply the theory of gravity to the phenomena of projectile motion and free fall:

> Newton’s laws of motion are simple to state, and sometimes teachers mistake the ability of students to recite the three laws correctly as evidence that they understand them. The fact that it took such a long time, historically, to codify the laws of motion suggests that they are not self-evident truths, no matter how obvious they may seem to us once we understand them well. Much research in recent years has documented that students typically have trouble relating formal ideas of motion and force to their personal view of how the world works. These are three of the obstacles:
>
> 1. A basic problem is the ancient perception that sustained motion requires sustained force. The contrary notion that it takes force to change an object’s motion, that something in motion will move in a straight line forever without slowing down unless a force acts on it, runs counter to what we can see happening with our eyes.
> 2. Limitations in describing motion may keep students from learning about the effects of forces. Students of all ages tend to think in terms of motion or no motion. So the first task may be to help students divide the category of motion into steady motion, speeding up, and slowing down. For example, falling objects should be described as falling faster and faster rather than just falling down. As indicated earlier, the basic idea expressed in Newton’s second law of motion is not difficult to grasp, but vocabulary may get in the way if students have to struggle over the meaning of force and acceleration. Both terms have many meanings in common language that confound their specialized use in science. Like inertia, the action-equals-reaction principle is counterintuitive. To say that a book presses down on the table is sensible enough, but then to say that the table pushes back up with exactly the same force (which disappears the instant you pick up the book) seems false on the face of it. (*Benchmarks*, all grade levels, 87)

In addition to those concerns mentioned in *Benchmarks*, high school students have other difficulties to overcome. For example, we now know that there is a lot of confusion around the terms "weight" and "weightlessness" and that many students aren't even aware that gravity exists in space, on other planets, or in the spaces between the planets.

## 5.4 What Teaching Methods Are Most Promising?

Research studies that compared students who had not taken physics with those who have generally found that the physics students had a higher percentage of correct (Newtonian) answers to questions about gravity, although results were still well below teachers' expectations. Although such studies are useful, they do not reveal which teaching methods are effective or even promising, such as those reported in Sections 4.3.3 and 4.3.4. All the learning studies involved activities with materials and discussions except for Palmer and Flanagan (1997), whose treatment consisted of a short text reading that refuted common misconceptions about motion.

As reported in Part I (Kavanagh & Sneider 2007), researchers who used constructivist teaching tended to be successful. The term "constructivist" refers to an overall approach in which students articulate their initial thinking about a subject and then work to "reconstruct" their thinking so as to better match the modern scientific view.

The cornerstone of the constructivist teaching technique is to bring about conceptual conflict in the minds of learners. The conflict can occur between a learner's misconception and another's viewpoint, in contrast to new and compelling data, in light of historical arguments, or even between two conflicting ideas expressed simultaneously by the learner. Specific ideas for how to do this are discussed in Section 6, Recommendations.

## 5.5 What Research Remains to Be Done?

Although a great deal has already been learned about how students learn (or fail to learn) to apply gravitational theory to projectile motion and orbits, much remains to be done. Because researchers have generally planned their studies to build on the work of previous researchers in order to test the earlier work while expanding the topics to be explored or the theoretical issues to be addressed, or to diversify the pool of subjects, the research to date has maintained a very narrow a focus. We have not identified a single study in which the researchers selected topics for study by first creating a list of national or state standards on which we have little or no data. For example, we were unable to find any studies on students'

- recognition that the same natural laws that can be observed on Earth apply throughout the universe;
- understanding of the idea that the massive structures seen in the universe today have resulted from the effects of gravity acting between atoms and subatomic particles when the universe was young;
- understanding of Kepler's discovery that planets—and all orbiting bodies—follow elliptical orbits; and
- understanding of gravity in Einstein's general theory of relativity that explains orbital motion as the result of distortions in space and time around massive bodies.

From the perspective of teachers and curriculum developers, the most important area for future research should be learning studies to answer questions about the effectiveness of alternative teaching methods. The studies in Sections 4.3.3 and 4.3.4 provide excellent models for this kind of research.

One example of a research question that begs to be answered was discussed in Section 4.2, in which Galili and his colleagues argued that students would better understand orbital motion and acquire fewer misconceptions if weight was defined operationally as the reading on a scale rather than the force of gravity on an object. Physics educators have debated this proposal for many years. Teachers and curriculum developers would be very interested in the results of a definitive study that compared the two approaches.

Another question worthy of research is the value of teaching students about the history of science. *Science for All Americans* ((Rutherford & Ahlgren 1989) makes the case that scientifically literate individuals should be conversant with a few key episodes that shaped modern science, including the Newtonian synthesis. Several of the studies in this review recommend historical lessons on gravitational theory as a means for students to recognize their own misconceptions. Sequira and Leite (1991), and more recently, Bar and Zinn (1998), suggested that learning how early conceptions of gravity (such as impetus theory) were overturned may help students critically examine their own beliefs.

Finally, there are theoretical issues to resolve, such as the question of whether students' misconceptions about gravity form a coherent framework akin to a personal scientific theory, as McCloskey (1983) suggested, or whether common misconceptions are a loose collection of fragmentary ideas, as proposed by diSessa (1993). Although such questions do indeed have ramifications for teaching, and cognitive scientists place a high premium on studies that have theoretical implications, it may be one of those issues that depends more on the interpretation of data than on the design of a definitive study.

# 6. RECOMMENDATIONS

Recommendations reported in Part I of this review (Kavanagh & Sneider 2007) are quite broad and apply to the teaching of gravitational theory, regardless of specific phenomena. We therefore conclude this article with a restatement of those recommendations with examples drawn from projectile motion and orbits.

**1. Curriculum development should focus on major transitions and key concepts at appropriate grade levels.** Projectile motion can only be understood as a superposition of two fundamental kinds of motion: (1) an object with no forces—or perfectly balanced forces acting on it—that moves at constant velocity in a straight line, and (2) an object accelerating in free fall. Students need to fully understand these two concepts separately before they can combine them in analyzing the motion of a projectile. Understanding orbital motion requires prior understanding of projectile motion (because it is a special case) in which the free-fall component is perfectly synchronized with the motion of the projectile around a spherical Earth. In other words, an object in orbit continues to fall, but it keeps "missing" the Earth. Like any other object in free fall, a body in orbit is continually accelerated, but in this case, acceleration is defined as a constant change in direction rather than a change in speed. Understanding each of these key concepts involves a transition from thinking about the world in one way, and beginning to think about the world differently. For example, students initially have difficulty separating the concept of "velocity" from "speed," but such a distinction is essential if they are to recognize that acceleration can occur if an object changes its direction while continuing to move at the same speed. Curriculum development should focus on these major transitions.

**2. Instruction should begin by checking understanding of prior learning.** Not all topics in physics are as hierarchically structured as projectile and orbital motion. As described in the previous paragraph, each concept builds on prior understanding. If students have misconceptions about Newton's first law, they will not be able to grasp projectile motion. If students don't understand projectile motion, they should not begin to study orbits. Therefore, instruction on these topics should have diagnostic questions and activities built into them so that the teacher can continually monitor students' understanding and make midcourse corrections whenever necessary.

**3. Sufficient time should be allowed for learning.** Millennia were needed to develop the set of ideas codified in Newton's three laws, and centuries for scientists to explore their full range of application. The studies reported in this review illustrate that very few students fully understand these ideas right away, or after a single exposure. Curriculum developers and teachers should work together to plan when interventions should occur so that enough time can be devoted to learning and applying these ideas in many different situations.

**4. Engage students in applying the theory of gravity to real-world contexts.** Baseballs, footballs, basketballs, and swimmers jumping off a diving board are all real-world examples of projectile motion. Teachers can use software packages that allow students to analyze these real-world examples to see how closely they match the theoretical models. Although it is more difficult to personally analyze orbital motion, students can analyze orbital motion on a NASA video or Star Trek program. The point is that students are more likely to retain their learning if they have several opportunities to apply what they learn in real-world settings.

**5. Help teachers build confidence while increasing their understanding of gravity.** Prescott (2004) set out to compare the value of teaching for qualitative understanding of projectile motion before introducing quantitative problems, in contrast to the usual method of having students solve as many quantitative problems as possible. Although Prescott found that the qualitative-first approach was better, an unexpected finding was that the more deep-seated misconceptions (impetus theory) were more difficult to address in the classroom and that "the most significant factor determining whether student misconceptions were eliminated was found to be the teachers' ability to deal with their own misconceptions." Both preservice and in-service teacher educators might keep in mind that it takes confidence and hard intellectual work for adults to "deal with their own misconceptions" but that such work is essential if we are eventually to succeed with students.

**6. Provide teachers with the means to assess their own students' understanding of gravity.** The wide variety of studies reported in both parts of this review—the current article and Kavanagh & Sneider 2007—indicate a great many scenarios and questions that curriculum developers and teachers can use to stimulate students' thinking about free fall, projectile motion, and orbits. Curriculum developers and teachers will find these studies to be a gold mine of ideas, not only for monitoring students' progress in unraveling their misconceptions but also for sowing the seeds of doubt and discord that enable learners to rethink their current understanding and to unravel deep-seated misconceptions so that they can develop a fully Newtonian view of the cosmos.

## Acknowledgments

This review project was carried out as an activity of the New England Space Science Initiative in Education (NESSIE), which is charged with assisting NASA's educational product developers in creating appropriate instructional materials. NESSIE is a collaborative project of the Museum of Science, Boston, the Smithsonian Astrophysical Observatory, and Tufts University, with support from NASA's Science Mission Directorate. Any opinions, findings, conclusions, or recommendations expressed in this study are those of the authors and do not necessarily reflect the views of the sponsor.

## References

American Association for the Advancement of Science. 1993, *Benchmarks for Science Literacy*, New York: Oxford University Press.

Bar, V., & Zinn, B. 1998, "Similar Frameworks of Action-at-a-Distance: Early Scientists' and Pupils' Ideas," *Science Education*, 7(5), 471.

Bar, V., Sneider, C., & Martimbeau, N. 1997, "What Research Says: Is There Gravity in Space?," *Science & Children*, 34(7), 38.

Berg, T., & Brouwer, W. 1991, "Teacher Awareness of Student Alternate Conceptions About Rotational Motion and Gravity," *Journal of Research in Science Teaching*, 28(1), 3.

Caramazza, A., McCloskey, M., & Green, B. 1981, "Naïve Beliefs in 'Sophisticated' Subjects: Misconceptions about Trajectories of Objects," *Cognition*, 9(2), 117.

Champagne, A., Klopfer, L., & Anderson, J. 1980, "Factors Influencing the Learning of Classical Mechanics," *American Journal of Physics*, 48(12), 1074.

Chandler, D. 1991, "Weightlessness and Microgravity," *The Physics Teacher*, 29(5), 312.

Clement, J. 1982, "Students' Preconceptions in Introductory Mechanics," *American Journal of Physics*, 50(1), 66.

Cooke, N., & Breedin, S. 1994, "Constructing Nnaïve Theories of Motion on the Fly," *Memory & Cognition*, 22(4), 474.

Crombie, A. 1952, *Augustine to Galileo: The History of Science A.D. 400–1650*, London: Falcon Educational Books.

Dharmadasa, I., & Silvern, S. 2000, "Children's Conceptualization of Force: Experimenting and Problem Solving," *Journal of Research in Childhood Education*, 15(1), 88.

diSessa, A. 1993, "Toward an Epistemology of Physics," *Cognition & Instruction*, 10(2&3), 105.

Dostal, J. 2005, "Student Concepts of Gravity," Master's thesis, Iowa State University, Ames, Iowa, http://www.physics.iastate.edu/per/members/Dostal_Thesis.pdf.

Eckstein, S., & Shemesh, M. 1993, "Development of Children’s Ideas on Motion: Impetus, the Straight-Down Belief and the Law of Support," *School Science & Mathematics*, 93(6), 299.

Finegold, M., & Gorsky, P. 1991, "Students’ Concepts of Force as Applied to Related Physical Systems: A Search for Consistency," *International Journal of Science Education*, 13(1), 97.

Fischbein, E., Stavy, R., & Ma-Naim, H. 1989, "The Psychological Structure of Naïve Impetus Conceptions," *International Journal of Science Education*, 11(1), 71.

Galilei, G. 1638, *Dialogue Concerning the Two Chief World Systems*, S. Drake (Trans.), Berkeley: University of California Press, 1974.

Galili, I. 1993, "Weight and Gravity: Teachers’ Ambiguity and Students Confusion about the Concepts," *International Journal of Science Education*, 15(2), 149.

Galili, I. 1995, "Interpretation of Students’ Understanding of the Concept of Weightlessness," *Research in Science Education*, 25(1), 51.

Galili, I. 2001, "Weight versus Gravitational Force: Historical and Educational Perspectives," *International Journal of Science Education*, 23(10), 1073.

Galili, I., & Kaplan, D. 1996, "Students’ Operations with the Weight Concept," *Science Education*, 80(4), 457.

Grant, E. 1971, *Physical Science in the Middle Ages*, Cambridge: Cambridge University Press.

Gunstone, R., & Watts, M. 1985, "Force and Motion," in *Children’s Ideas in Science*, R. Driver, E. Guesne, & A. Tiberghien (Editors), Milton Keynes, UK: Open University Press.

Gunstone, R., & White, R. 1980, "A Matter of Gravity," *Research in Science Education*, 10, 35.

Gunstone, R., & White, R. 1981, "Understanding of Gravity," *Science Education*, 65(3), 291.

Gürel, Z., & Acar, H. 2003, "Research into Students’ Views about Basic Physics Principles in a Weightless Environment," *Astronomy Education Review*, 2(1), 65. http://aer.noao.edu/cgi-bin/article.pl?id=45.

Halloun, I., & Hestenes, D. 1985a, "The Initial Knowledge State of College Physics Students," *American Journal of Physics*, 53(11), 1043.

Halloun, I., & Hestenes, D. 1985b, "Common Sense Concepts about Motion," *American Journal of Physics*, 53(11), 1056.

Hecht, H., & Bertamini, M. 2000, "Understanding Projectile Acceleration," *Journal of Experimental Psychology: Human Perception and Performance*, 26(2), 730.

Hynd, C., Alvermann, D., & Qian, G. 1997, "Preservice Elementary School Teachers’ Conceptual Change about Projectile Motion: Refutation Text, Demonstration, Affective Factors, and Relevance," *Science Education*, 81(1), 1.

Kavanagh, C., & Sneider, C. 2007, "Learning about Gravity I. Free Fall: A Guide for Teachers and Curriculum Developers," *Astronomy Education Review*, 5(2), http://aer.noao.edu/cgi-bin/article.pl?id=220.

Kuhn, T. 1957, *The Copernican Revolution*, Cambridge, MA: Harvard University Press.

Liu, X., & MacIsaac, D. 2005, "An Investigation of Factors Affecting the Degree of Naïve Impetus Theory Application," *Journal of Science Education & Technology*, 14(1), 101.

Lloyd, G. 1970, *Early Greek Science: Thales to Aristotle*, New York: Norton.

Lloyd, G. 1973, *Greek Science after Aristotle*, New York: Norton.

Maloney, D. 1988, "Novice Rules for Projectile Motion," *Science Education*, 72(4), 501.

McCloskey, M. 1983, "Naïve Theories of Motion," in *Mental Models*, D. Gentner & A. Stevens (Editors), Hillsdale, NJ: Erlbaum, 299.

McCloskey, M., Washburn, A., & Felch, L. 1983, "Intuitive Physics: The Straight-Down Belief and Its Origin," *Journal of Experimental Psychology: Learning, Memory & Cognition*, 9(4), 636.

McDermott, L., Shaffer, P., & The Physics Education Group at the University of Washington. 2002, *Tutorials in Introductory Physics*, Upper Saddle River, NJ: Prentice-Hall.

Morrison, R. 1999, "Weight and Gravity: The Need for Consistent Definitions," *The Physics Teacher*, 37(1), 51.

National Research Council. 1996, *National Science Education Standards*, Washington, DC: National Academy Press.

Newton, I. 1687, *Principa, Volume II: The System of the World*, Berkeley: University of California Press, 1966.

Newton, I. 1728, *The System of the World*, Amherst, NY: Prometheus Books, 1995.

Noce, G., Torosantucci, G., & Vincentini, M. 1988, "The Floating of Objects on the Moon: Prediction from a Theory or Experimental Facts?," *International Journal of Science Education*, 10(1), 61.

Osborne, R. 1983, "Building on Children's Intuitive Ideas," in R. Osborne & P. Freyberg (Editors), *Learning in Science: The Implications of Children's Science*, Portsmouth, NH: Heinemann, 41.

Palmer, D., & Flanagan, R. 1997, "Readiness to Change the Conception That 'Motion-Implies-Force': A Comparison of 12-Year-Old and 16-Year-Old Students," *Science Education*., 81(3), 317.

Piburn, M. 1988, "Misconceptions about Gravity Held by College Students," conference proceedings, NARST Annual Meeting, Lake of the Ozarks, Missouri. April 10-13, 1988. (ERIC Document Reproduction Service No. ED 292616).

Prescott, A. 2004, "Student Understanding and Learning About Projectile Motion in Senior High School," PhD diss., School of Education, Australian Centre for Educational Studies, Macquarie University.

Ranney, M. 1994, "Relative Consistency and Subjects' 'Theories' in Domains Such as Naïve Physics: Common Research Difficulties Illustrated by Cooke and Breedin," *Memory Cognition*, 22(4), 503.

Reynoso, E., Fierro, E., & Torres, G. 1993, "The Alternative Frameworks Presented by Mexican Students and Teachers Concerning the Free Fall of Bodies," *International Journal of Science Education*, 15(2), 127.

Ruggiero, S. Cartelli, A., Dupre, F., & Vincentini-Missoni, M. 1985, "Weight, Gravity, and Air Pressure: Mental Representations by Italian Middle School Pupils," *European Journal of Science Education*, 7(12), 181.

Rutherford, F., & Ahlgren, A. . 1989, *Science for All Americans*, New York: Oxford University Press.

Sequira, M., & Leite, L. 1991, "Alternative Conceptions and History of Science in Physics Teacher Education," *Science Education*, 75(1), 45.

Sharma, M., Millar, R., Smith, A., & Sefton, I. 2004, "Students' Understandings of Gravity in an Orbiting Space-Ship," *Research in Science Education*, 34(3), 267.

Toulmin, S., & Goodfield, J. 1961, *The Fabric of the Heavens*, New York: Harper.

Treagust, D., & Smith, C. 1986, "Secondary Students' Understanding of the Solar System: Implications for Curricular Revision," annual conference, International Group for the Advancement of Physics Teaching, Copenhagen, Denmark.

Treagust, D., & Smith, C. 1989, "Secondary Students' Understanding of Gravity and the Motion of Planets," *School Science and Mathematics*, 89(5), 380.

Viennot, L. 1979, "Spontaneous Reasoning in Elementary Dynamics," *European Journal of Science Education*, 1(2), 205.

Watts, D. 1982, "Gravity–Don't Take It for Granted!," *Physics Education*, 17(4), 116.

Watts, D., & Zylbersztajn, A. 1981, "A Survey of Some Children's Ideas of Force," *Physics Education*, 16(6), 360.

Whitaker, R. 1983, "Aristotle Is Not Dead: Student Understanding of Trajectory Motion," *American Journal of Physics*, 51(4), 352.