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Learning about Gravity I. Free Fall: A Guide for Teachers and Curriculum Developers

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

This article is the first of a two-part review of research on children's and adults understanding of gravity and on how best to teach gravity concepts to students and teachers. This first article concerns free fall—how and why objects fall when they are dropped. The review begins with a brief historical sketch of how these ideas were developed in human history, followed by a summary of the relevant standards and benchmarks. The body of research is organized by the nature of the findings, beginning with studies of the youngest children, followed by older students, adults, and teachers. Although a diversity of misconceptions are found at all age levels, in general children, between the ages of 7 and 9 progress from the idea that things fall because they're not supported to things fall because they're "heavy." Between the ages of 9 and 13, students begin to use the term "gravity," an unseen force, to explain falling, such as "gravity acts just on heavy objects," or "things fall because air is pushing them down." Surprisingly, many high school and college students who can successfully solve numerical problems involving gravity hold qualitative misconceptions similar to those held by much younger students. The finding that even college physics students have significant misconceptions about free fall underscores the importance of effective teaching at the middle and high school levels. Some studies have found that few teachers are aware of their students' misconceptions or know what to do about them. A few studies have reported success in helping students shed their misconceptions, leading to promising recommendations for curriculum development and teaching.

1. INTRODUCTION

A previous review of educational research concerned children's ideas about gravity as it relates to Earth as a spherical body (Agan & Sneider 2004). At issue in that review was how children's understanding of gravity matures from the notion that "things fall down" to the more sophisticated idea that "things fall toward the center of Earth." However, the concept of gravity that is taught in middle school, high school, and college goes well beyond those initial ideas. Students are expected to learn how objects accelerate in free fall, why objects with different masses hit the ground at the same time, that gravity is a force that acts at a distance, that objects exert an equal and opposite force on each other, and Einstein's theory that gravity and acceleration are equivalent.

The modern scientific explanations for these phenomena are more than isolated facts. Understanding these concepts and how they are related requires that students learn to apply the three laws of motion and the law of universal gravitation, formulated by Isaac Newton more than 300 years ago. This system of ideas predicts and explains such a wide variety of physical phenomena that it is often cited as *the* model scientific theory (see, for example, Feynman 1965, Chapter 1). Although Newton's theory of gravity has been modified in some important respects by Einstein's theory of general relativity, it still forms a central pillar of the science of physics, and it will continue to form an essential part of the school science curriculum for the foreseeable future.

Given the scope of this research and its potential value to teachers and curriculum developers, we felt that we could contribute to the field of science education by compiling a reasonably comprehensive review of research on students' understanding of gravity. Although this compilation is not exhaustive—we continue to find additional studies every now and then—it represents our best effort to locate all relevant studies. We invite readers to send us additional references.

Our initial attempts to summarize this research resulted in an unusually long article for the *Astronomy Education Review*. Consequently, on the advice of reviewers, we have split the review into two shorter articles. In this first article, we discuss the research on students' understanding of how and why objects fall when they are dropped—the phenomenon of free fall. In a companion article (Kavanagh & Sneider 2007), we discuss students' understanding of projectile motion and orbits.

Before summarizing the relevant research, we will set the context by describing the historical developments that led to the modern theory of gravity, and what the *National Science Education Standards* (National Research Council [NRC] 1996) and *Benchmarks for Science Literacy* (American Association for the Advancement of Science [AAAS] 1993) have to say about what students of various ages should learn about free fall. The article will conclude with answers to the following questions, and recommendations for teachers and curriculum developers that are firmly rooted in educational research.

- What misconceptions do students hold about free fall?
- To what extent do these misconceptions (Note 1) 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

Several educational researchers have noted that children's understanding of gravity develops in ways that are strikingly similar to how the gravity concept evolved in human history (e.g., Viennot 1979; Caramazza, McCloskey, & Green 1983; Halloun & Hestenes 1985b; Piaget & Garcia 1989; Sequeira & Leite 1991; Bar & Zinn 1998; Galili 2001). Although such comparisons are common in science education literature, the parallels are especially striking with respect to gravity. By drawing such parallels, we do not intend to imply that students spontaneously develop the broad and sophisticated theories about the world like those formulated by Aristotle. Instead, we suggest that parallels between historical ideas and students' thinking, such as "heavier objects fall faster," provide valuable insights into the origin of certain misconceptions, and we suggest learning experiences that might help them develop more fruitful models of the world.

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

Perhaps the most fundamental question that underpins all of science to this day is, Why do things change? Biologists study the origin of species, chemists study the processes that cause substances to change, and physicists study changes in matter and energy. One of the first recorded debates about change may be traced to a dispute between Parmenides and Heraclitus in the fifth century B.C. Heraclitus argued that change is constant, while Parmenides argued that change is impossible. Both viewpoints are reflected in the modern scientific worldview, which encompasses incessant movement at the atomic and subatomic levels, as well as constancy embodied in various conservation laws.

From the viewpoint of physics, a key question related to change concerns change in position over time. Parmenides's student Zeno devised a famous paradox about motion to support his master's claim that change is impossible. One version of this paradox asserts that an arrow could never reach its target because to get there, it would first have to go half the distance, then it would need to travel half of the remaining distance, then half of that distance, and so on. It wasn't until Newton and Leibnitz invented the calculus more than 2,000 years later that it was possible to account for such an infinite series of diminishing numbers in a reasonably satisfying way.

In the fourth century B.C., Aristotle, founder of a school named the Lyceum and teacher of Alexander the Great, took a more practical approach to the question of motion. Aristotle was very good at synthesizing the ideas of his predecessors into grand schemes. Most of what we know about the ancient Greek concept of gravity comes from his written works. Like modern scientists, Aristotle frequently cited his predecessors, if only to show that that their ideas were only partially correct. Like today's scientists, Aristotle's ideas about motion were set within a larger theoretical framework that encompassed his understanding of the cosmos as a whole.

Aristotle’s theory about falling objects rested on two fundamental beliefs about the cosmos. One was that the Earth is shaped like a ball. The other was that all things consist of four elemental substances: earth, water, air, and fire. Aristotle asserted that "heavy" things, which were made primarily of earth, sought their natural resting place at the center of the universe, which he took to be the center of a spherical Earth. Things that were twice as heavy fell twice as fast. Falling objects moved increasingly quickly as they fell because they were getting closer to their natural resting place in the center of the universe. Water was not as heavy as Earth, so it formed a layer on top. "Light" things, composed of air and fire, tended to rise away from the center, according to their natures. The relative abundance of these four elemental substances in any given object determined its natural tendency to rise or fall.

The words "gravity" and "levity" in English are derived from the Latin words *gravitas* and *levitas*, used in translations of Aristotle’s original works to describe the qualities of heaviness and lightness. These qualities characterized the nature of substances that determined their movement. So it was that the term "gravity" came to be associated with the earliest theory of falling objects.

2.2 Development of the Gravity Concept in the Middle East

Although science continued to advance for a time after Aristotle, various social, political, and religious forces intervened to derail a very promising start. Luckily, Middle Eastern scholars retained and promoted these Greek ideas through centuries of teaching and learning. Cultural centers in Armenia, Egypt, Syria, Persia, and India, among others, translated the works of Aristotle and others from Greek into local languages, and eventually into Latin.

John Philoponus, a Christian philosopher, scientist, and theologian who lived in Alexandria, Egypt, during the sixth century A.D., challenged Aristotle’s assertion that the speed of a falling body is proportional to its weight. Several hundred years before Galileo’s famous experiment at the Tower of Pisa, Philoponus claimed to have dropped a heavy and light object, and found the difference in falling time to be negligible.

2.3 Further Developments in Medieval Europe

The ancient Greek learning, doubly translated and annotated, re-entered Europe in the 11th and 12th centuries A.D. Many of these works eventually found their way to the first universities that were being established in Europe, including the University of Paris in France and Merton College in England.

An important step in understanding falling objects was taken when scholars at Merton College defined acceleration as occurring when a body covered the same additional distance in successive periods of time (Grant 2004). 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 these and other relationships that we later see in the works of Galileo and Newton.

2.4 Galileo’s and Newton’s Theories of Gravity

Two centuries after the scholars at Merton College defined acceleration, Galileo completed the work by describing the accelerated movement of falling objects. The problem that earlier researchers faced was that falling objects move too quickly to accurately measure their motion with the available tools. Galileo’s approach was to slow down the motion by observing the journey of a ball rolling down a very smooth, perfectly straight grooved ramp. Using a water clock, he found that the ball traveled one quarter of the way down the ramp in half the time it took for the ball to travel all the way down the ramp. Doing the experiment many times with different distances and different slopes, he found that for any given slope, the distances traversed were proportional to the square of the time. He inferred that an object falling vertically would follow the same relationship.

The Merton scholars defined uniform acceleration, but they did not make measurements to determine whether their ideas about motion applied to real objects. Their definitions of uniform velocity and acceleration were mathematical abstractions. Galileo's measurements showed that the distances traveled by bodies falling under the force of gravity were proportional to the square of the time, so that their motion did indeed fit the definition of uniform acceleration as he had anticipated. And because he wrote in Italian rather than Latin, this important result became widely known. Galileo did not, however, explain *why* two objects of vastly different weights would fall with approximately the same acceleration, other than to show that Aristotle's views were contrary to experience. He discussed these ideas in his famous book on physics, *Dialogue Concerning the Two Chief World Systems* (1638/1974). The Inquisition of the Catholic Church found this text to be objectionable, and Galileo was forced to recant much of its content.

It was not until Newton (1687/1966, 1728/1995) developed his laws of motion and universal gravitation that a more satisfactory answer could be given. The first law of motion, also called the law of inertia, describes objects moving with uniform velocity. The second law concerns objects that are accelerating. The equation $F = ma$ defines force as the mass of an object times its acceleration, and in another form, $a = F/m$, states that acceleration is *inversely proportional* to mass. The third law states that the gravitational attraction between two bodies is equal and opposite. Newton's law of universal gravitation states that the mutual gravitational force between two bodies is *directly proportional* to the product of the masses of the objects and *inversely proportional* to the square of the distance between them.

An important consequence of Newton's three laws is an explanation for why objects of different masses fall with the same acceleration. In brief, more massive objects experience a greater downward pull, in precisely the amount needed to accelerate them at the same rate as a less massive object. This relationship can be shown mathematically by solving two equations simultaneously for the acceleration due to gravity and noting that the result only includes the mass of Earth, and not the mass of the object that is falling. In these equations, m_O is the mass of the falling object, F_g is the force of gravity on the object, a_g is the acceleration of the object due to gravity, m_E is the mass of Earth, and G is the gravitational constant.

Step 1. Write the equations for Newton's second law of motion and the universal law of gravitation.

$$F_g = m_o\, a_g \quad \text{(second law of motion)}$$

$$F_g = G\, \frac{m_o\, m_E}{R^2} \quad \text{(law of universal gravitation)}$$

Step 2. Combine these two equations.

$$m_o\, a_g = G\, \frac{m_o\, m_E}{R^2}$$

Step 3. Solve for a_g and note that the result does not include m_o.

$$a_g = G\, \frac{m_E}{R^2}$$

2.5 Einstein's Theory of Gravity

An important concept in Einstein's theory of general relativity is the Principle of Equivalence, in which a force produced by a gravitational field cannot be distinguished from a force of the same magnitude produced by acceleration, so that if a person in a room with no communication with the outside experiences a downward force, it is impossible to tell if the room is on the surface of a planet or within an accelerating spacecraft.

2.6 Summary

Over the centuries, philosophers, scholars, and scientists have built upon ideas of the past to make progress in understanding how and why objects fall. Both evolutionary and revolutionary metaphors of this process offer insights. From the evolutionary perspective, we can look back over more than two millennia and see original ideas emerge, flourish, or falter as a result of changes in the intellectual environment. From the revolutionary perspective, we can see profound changes in worldview that are required by the individuals who have made the breakthroughs. These two metaphors—evolution and revolution—may be helpful to teachers and curriculum developers. The evolutionary view recognizes that several small steps may be involved as an individual student gradually develops a better understanding of gravity from elementary school, to middle school, to high school, and that the intellectual environment of the classroom may determine whether new ideas can be thoughtfully considered. The revolutionary metaphor reminds us that even a small step may involve a profound change in how a student thinks about the world, so it could be too much to expect all students to make these transitions on cue. 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. 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**
	Falling Objects	
Heavy things fall because they seek their natural resting place in the center of the universe. Speed of fall is proportional to the weight of an object. Speed increases during fall as an object gets closer to the center of the universe.	Objects accelerate as they fall. Uniform acceleration is defined as covering the same additional distance in successive periods of time.	The concept of uniform acceleration is found to apply to actual objects in free fall. Objects of different weights fall with the same acceleration because gravitational force is directly proportional to mass, while acceleration is inversely proportional to mass.

Next we turn to the recommendations of the *National Standards* and *Benchmarks* regarding what students should learn about falling objects.

3. NATIONAL STANDARDS AND BENCHMARKS

The concept of gravity is prominent in both the *National Science Education Standards* (NRC 1996) and *Benchmarks for Science Literacy* (AAAS 1993). In both documents, the term is used frequently in several contexts to describe what students should know about the physical sciences, the Earth and space sciences, and the nature and history of science. Although the *National Standards* and *Benchmarks* differ in wording, detail, and emphasis, they are in very close agreement concerning the aspects of gravity and depth of understanding to be expected at the elementary, 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 Elementary Level Standards

Neither the *Benchmarks for Science Literacy* (BM) nor the *National Science Education Standards* (NS) propose that students in elementary school be taught that gravity is the force that makes things fall. As summarized in the *Benchmarks*,

> The main notion to convey in the elementary years is that forces can act at a distance. Students should carry out investigations to become familiar with the pushes and pulls of magnets and static electricity. The term *gravity* may interfere with students' understanding because it is often used as an empty label for the common (and ancient) notion of "natural motion" toward the Earth. The important point is that the Earth *pulls* on objects. (BM, grades 3–5; 94)

3.2 Middle School Standards

At the middle school level, students are expected to leave behind their previous perception that "things just naturally fall" and to recognize that gravity is a force that pulls things toward Earth's center and acts throughout the universe. Students at this level are also expected to learn that gravity is a force that acts between *all* objects in the universe and that the strength of this force depends on the mass of the objects and how far apart they are.

3.3 High School Standards

Falling Objects: In addition to the middle school level of understanding, students at the high school level are expected to know how to calculate the magnitude of the gravitational force. "Gravitation is a universal force that each mass exerts on any other mass. The strength of the gravitational attractive force between two masses is proportional to the masses and inversely proportional to the square of the distance between them" (NS, grades 9–12; 180).

Gravitational Theory: In addition to the challenges described above that students encounter as they struggle to understand how Newton's laws provide a basis for understanding falling objects, 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. Students should learn how well the principle of universal gravitation explains the architecture of the universe and much that happens on Earth. The principle will become familiar from many different examples (star formation, tides, comet orbits, etc.) and from the study of the history leading to this unification of the Earth and sky. The "inversely proportional to the square" aspect is not a high priority for literacy. Much more important is escaping the common adult misconceptions that the Earth's gravity does not extend beyond the atmosphere or that it is caused by the atmosphere (BM grades 9–12; 96)

> **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. Early in the history of the universe, matter, primarily the light atoms hydrogen and helium, clumped together by gravitational attraction to form countless trillions of stars. Billions of galaxies, each of which is a gravitationally bound cluster of stars, now form most of the visible mass in the universe. (NS grades 9–12; 190)

> **Einstein's general theory of relativity:** Relativity is not a topic to be taken up in the elementary and middle school years as either history or science. To be sure, a full understanding of relativity theory is far beyond the capacity of most 17 year-olds, but it is far too important to be ignored. By treating relativity historically in high school, it is possible to avoid falling into the trap of trying to teach its technical and mathematical details. The main goals should be for students to see that Einstein went beyond Newton's worldview by including it as a limiting case in a more complete theory. (BM grades 9–12; 245)

Against this background, we offer a reasonably thorough review of the research literature concerning what today's students know about free fall, and what instructional techniques are likely to be fruitful at various age levels.

4. LITERATURE REVIEW

This body of research is exceptionally diverse with respect to student characteristics, research methods, and geographical locations. Included are studies of young children, adolescents, college students, and teachers in North America, Europe, Australia, the Middle East, and Africa. Methods range from paper-and-pencil questionnaires to interviews about everyday phenomena, humorous cartoons that violate physical laws, and taped dialogues about falling objects. The variety of responses from all this research reveals a breathtaking diversity of ideas and beliefs about free fall in a gravitational field. Yet out of this diversity emerges a core of common gravity misconceptions that is robust across studies.

Our initial attempt to summarize the research by age level was unsatisfactory because there were many cross-age studies. A clearer picture emerged when we sorted the results according to whether the purpose was to understand student's current conceptions of falling objects, or studies of teacher knowledge and teaching methods. Consequently, the literature review consists of two sections: 4.1 Understanding Free Fall, and 4.2 Teachers and Teaching. A list of all studies included in this article appears in Table 2.

4.1 Understanding Free Fall

We have identified a number of studies that provide insight into students' reasoning about how things fall, and how their ideas change (or fail to change) with increasing maturity and educational attainment. We've organized the studies by the following conceptions about gravity:

1. Things fall if they're not supported.
2. Strength and effort prevent falling.
3. Gravity is not a force.
4. Heavier objects fall faster.
5. Gravity attracts only heavy, slow, or inactive objects.
6. Gravity acts upward.

To keep this review manageable in length and readability, we have not listed every finding of every study. Instead, we highlight the findings of one or two studies that best illustrate each misconception.

4.1.1 Things Fall if They're Not Supported

Selman et al. (1982) interviewed 105 children (15 preschoolers, 30 kindergartners, and 60 first graders) in the Boston, Massachusetts, area to learn about the emergence of the idea of invisible forces. When shown falling objects, the youngest children explained falling in terms of tangible actions and objects but did not refer to any unseen forces. For example, "You let them go. They were too close to the edge" (Selman et al., 189). Many of the older (first-grade) children, on the other hand, explained the demonstrations by referring to unseen forces such as, "The heaviness pulls them down" and "The Earth pulls them." Working within the Piagetian paradigm, the researchers were more interested in correlations between tasks than in percentages of students who gave various responses, but the implication was that by the end of first grade, many (if not most) students could conceive of unseen forces. This work clarified the importance of an early stage in development of the concept of gravity—that forces exist that we cannot see—a capability that could be cultivated at the elementary level by having children engage with phenomena such as magnetism, in which unseen forces can be felt and their effects directly observed.

To investigate when students abandon the "support" explanation for free fall in favor of unseen forces, Bar et al. (1994) reported the results of interviews with 400 Israeli children between the ages of 5 and 13 (Pre-K through grade 7). None of the children had been taught about gravity, weight, or free fall. Questions included why objects fall when dropped but the Sun, clouds, and airplanes do not fall, and why some things sink and others float when placed in water. In coding students' responses, the researchers divided responses into three categories: (1) things fall if not supported; (2) things fall if they are heavy; and (3) "the Earth" or "gravity" pulls them down. At age five, they found that most children (80%) answered that things fall because they aren't supported: "Objects fall because they are not held" and "The clouds do not fall because they are glued to the sky." By eight years old (second grade), the percentage giving this answer was down to about 40%, and by age 13 (seventh grade), responses in the three categories were: (1) things aren't supported (5%); (2) objects are heavy (20%), and (3) "the Earth" or "gravity" pulls them down (75%).

4.1.2 Strength and Effort Prevent Falling

A series of studies (Bliss & Ogborn 1993; Bliss, Ogborn, & Whitelock 1989; Whitelock 1991) were undertaken to test an earlier prediction that students' misconceptions about falling objects stemmed from a "commonsense theory of motion" (Hayes 1979; Ogborn 1985). If students come to class with such mental models, it's important for science teachers to know about it because these intuitive but incorrect ideas would make it difficult for students to accept some of the counterintuitive ideas about physics that they are taught in school. A tenet of the theory is that

> Everything needs support except the ground that gives support but is not itself supported. Air and water can also support things but this is often only partial. To support something needs "strength" or "effort" or both. If the strength of a support is not enough it may break or yield. Thus a shelf supports heavy objects by being 'strong' whereas a bird supports itself by its own effort of flying. People support things when carrying them through their own strength and effort. . . . The [commonsense] law of falling is that, having started to fall, things fall more rapidly the higher up they start and the heavier they are. (Bliss et al., 262)

The researchers interviewed students in England using representations of nonsensical situations taken from comic books. "Comics proved to be a very fruitful medium for eliciting tacit knowledge because not only did children enjoy the task but they also talked easily and at length about why events could or could not happen" (Bliss et al., 271). Further, the comic book images were intended to evoke situations outside of school so as not to bias students by answering with language and ideas learned in science classes. The series of studies included children at all grade levels, from elementary through high school. The results confirmed the commonsense theory of motion in that subjects responded to each comic book illustration by explaining what occurred in terms of support or effort. Mentions of gravity were rare, even by the older students, and the use of the term did not indicate any fundamental change in the nature of their explanations. Further, as the theory predicted, the responses given were not correlated with the age of the respondents.

The study by Bar et al. (1994) mentioned above also found ample evidence that many students see effort and strength as relevant to the free-fall situation. Some students expressed the idea that an object can support itself; for example, "Boats do not sink because people row them"; "Clouds do not fall because they make wind"; and "Clouds are heavy and strong, thus they can hold themselves up." Over the entire age range, students' explanations shifted to an unseen force, with most students in the age 9–13 range saying that objects fall because of "the Earth's attractive force."

It is not clear why Bar et al. (1994) found that older students tended to mention unseen forces, whereas the subjects whom Bliss et al. (1989) interviewed did not, except to note that interviews about the comic book situations may have been more likely to elicit responses about lack of support than about unseen forces.

4.1.3 Gravity Is Not a Force

A major task of high school science is to help students refine the concept of an "unseen force" into the modern concept of gravity. However, Halloun and Hestenes (1985b) found that some students come to college still believing that falling is a "natural motion" that does not require a force, despite having been taught about gravity in high school. For example, the following is an excerpt from one interview in which an undergraduate is questioned about the forces acting on a ball held in the hand and resting on a table: "There was a force when you were holding [a ball] in your hand . . . [but when the ball is sitting on a table] there is not a force on the ball . . . this is different. The ball wants to go down, but the table is only holding it . . . keeping it from moving" (1059).

To sum up these first three interrelated sets of misconceptions, the idea that things fall because they are not supported is mostly given by young children and takes many different forms. In the simplest case, things fall because their support is removed. The idea that strength and effort determine whether something falls is somewhat more complex and can refer to an external agent or the object itself. The statement by a college student above is similar to Aristotle's ideas about free fall, in that an object's natural tendency is to fall down, and inanimate objects cannot exert forces by themselves.

It could be argued that explaining free fall in terms of support is not, strictly speaking, a misconception because it is true that if support is removed, an object will indeed fall. And perhaps some of the students who gave answers related to support understood gravity perfectly well but chose to refer to lack of support instead. However, this next set of ideas is quite clearly wrong from a Newtonian point of view.

4.1.4 Heavier Objects Fall Faster

Galileo's famous experiment at Pisa and his thought experiment in which a heavy and light object are tied together and then dropped are compelling stories that teachers typically use before introducing the mathematical argument showing that objects with different masses will accelerate at the same rate. (This is shown in section 2.4 Galileo's and Newton's Theories of Gravity.) Consequently, much of the research in this area has been undertaken to determine whether students who have taken high school and college physics courses have learned this lesson.

Champagne, Klopfer, and Anderson (1980) administered a Demonstration, Observation, and Explanation of Motion test (D.O.E.) to 110 students enrolled in an introductory physics course at a major U.S. university. In this test, the instructor carries out demonstrations and asks students to observe (and sometimes predict) the motion of objects and answer questions about what they see. Although 70% of the subjects had studied high school physics, some for two years, the D.O.E. test revealed that four out of five students believed that, all other things being equal, heavier objects fall faster than lighter ones (Note 2). They also reported that many students believed that objects fall at constant speed, arguing that speed depends only on weight (mass), which also remains constant. Students who had learned that objects accelerate in free fall reconciled their inconsistent beliefs by saying that acceleration must be due to an increasing force of gravity as the object gets closer to the ground, and they further supported this idea by claiming that there is no gravity in space (1078). The authors note that these ideas closely resemble Aristotle's explanations for how and why things fall.

Even some students who have been acknowledged as academically gifted share this fundamental misconception. Gunstone and Watts (1985) indicated that a student who had been identified by his school as academically talented claimed to have witnessed heavier objects hitting the ground first in the past. "When the two cubes were dropped there and then, [the student] claimed to see the aluminum cube hit the ground first. Most people present saw the two cubes hit the ground together. [The student's] belief that the aluminum would fall faster was apparently so strong that it influenced his observation" (87).

Sequeira and Leite (1991) conducted several studies of high school and college students in Portugal. They reported interviews with 27 fourth-year university physics students who were asked to answer questions about free fall. Fifty-two percent of the students stated that of the objects, the heaviest one would take the shortest time to fall "because it is the heaviest." Although these students had studied free fall and more advanced gravity topics, the idea that heavier objects fall faster persisted among most of the students, as it did among 10th-grade high school students who had not yet been formally taught about free fall. The researchers gave an example of a student who incorrectly used a mathematical equation to support his belief that heavier objects fall faster: "According to the law of universal attraction $F_g = G\, m_O\, m_E/R^2$ the force that attracts the objects to the Earth is proportional to the mass of the objects. For equal distances, the sphere, the object having greater mass, is the object more rapidly attracted" (46).

Whitaker (1983) documented this conception by using questionnaires among his sample of 100 undergraduates, which he attributed to students' commonsense conceptions of motion. These students attributed greater acceleration to objects with greater mass. Halloun and Hestenes (1985b) administered questionnaires to 478 American undergraduates and found that many college students believed heavy objects to fall faster than light objects despite direct instruction to the contrary. Through interviews with 22 of the students, the researchers found that some students thought that gravity and weight were two different forces:

> Heavier objects fall faster because I know this. . . . Because we have two kids . . . and when we go down a water slide which is reasonably frictionless . . . I go faster when I have a kid on my shoulders than when I go down alone. . . . Gravity is the same for all objects. . . . It’s the same pull all the way around for different objects. . . . But besides gravity there is weight. (1062)

Galili (1993, 1995, 2001) has suggested that some misconceptions about weight could be avoided if we define it operationally as the force exerted by an object on a spring scale rather than the gravitational force on an object. If so, it would not be wrong to indicate "besides gravity there is weight." We’ll return to this point in Part II of our review of educational research on gravity, in the context of students’ understanding of "weightlessness."

4.1.5 Gravity Attracts Only Heavy, Slow, or Inactive Objects

Watts (1982) interviewed 20 British secondary students, 12–17 years old, by asking them questions about drawings of six situations: a golfer, a person holding a balloon, an astronaut on the Moon, two flashlights (one on and one off), a book on a table, and a diver perched on a diving board. The researcher reported that many students indicated that gravity acted selectively on objects that were heavy, slow, or inactive. For example, most students saw the flashlight that was turned on as more "active" and therefore more likely to "counteract" gravity than the flashlight that was turned off. Other examples:

> Louis, age 12, in response to the drawing of the astronaut on the moon: "No . . . he wouldn’t float off into space because most of those astronauts have . . . they’ve got those sort of heavy boots haven’t they?"
>
> Jonathan, age 15, in response to the golf ball, "And as it is going slower . . . the gravitational effect is more push on it ’cause it’s going slower."
>
> Cushlar, age 17, "The slower the thing goes the more gravity has an effect on it." (120)

Similar ideas were evident in Ameh’s 1987 study of Nigerian high school students, where one student responded: "No gravity on the moon, unless he is wearing the Apollo thing that they wear to go to the moon. If he is wearing them, at least I will say that there is gravity. If not wearing anything, no gravity" (213).

Palmer (2001) interviewed 56 students in grade 6 (11–12 years old) and 56 students in grade 10 (15–16 years old). Students were asked to identify which objects were acted on by gravity in nine different scenarios and later to justify those choices in the context of follow-up interviews. Only 11% of the students in grade 6 and 29% of the students in grade 10 correctly indicated that gravity acted on all the objects, and so were classified as group one. The students who indicated that gravity did not act in some of the situations gave a variety of answers. The most common of these were that gravity only acts on falling objects but not on objects moving upward (40% in grade 6 and 45% in grade 10, of those who did not indicate that gravity acted in all nine scenarios); that gravity does not act on stationary objects (34% in grade 6 and 28% in grade 10); and that gravity does not act on objects buried underground (74% in grade 6 and 60% in grade 10). The author proposed that rather than focus exclusively on misconceptions, teachers might help students who have some correct scientific understandings about gravity to expand the variety of contexts to which their scientific understanding applies.

4.1.6 Gravity Acts Upward

Palmer (2001) found that a fairly large number of the 112 students he interviewed (32% of grade 6 students and 30% of grade 10 students) indicated that gravity acted on things that were moving upward to force them up. For example, a grade 6 student said, "Because they're moving, [gravity is] making it go upwards." A 10th-grade student said, "Because they are actually moving, gravity is taking it up." A small number of students in this group indicated their belief that gravity was *only* an upward force.

Stead and Osborne (1980) interviewed 42 English students ranging in age from Form 1 to Form 7 (middle and high school). Students were asked, "What is gravity? Tell me about it." Most of the students said that gravity is a force that "pushes you down" or "holds you down on Earth." But a few indicated that they understood gravity to be a force that pushes upward. For example, "Well, humans can't fly so birds have got something—they're naturally lighter—there must be some kind of gravity keeping them up there." Similarly, some students confused gravity with buoyancy and supposed that gravity was the force that pushes an underwater diver up to the surface.

Dostal's (2005) dissertation from Iowa State University suggests that the idea of gravity as an upward force persists into the university level for a few students. His research involved asking university physics students to draw an arrow indicating the force of gravity on a falling ball. Ninety-two percent of the undergraduate students correctly supplied a downward arrow to represent the force of gravity, but a small minority (7%) drew an upward arrow, as if the force of gravity were reaching up to the ball.

4.1.7 Gravity, Air, and Magnetism

Bar and Zinn (1998) undertook two studies to determine if difficulties that students encounter when they learn about gravity and magnetism reflect similar difficulties because both forces act at a distance. Their first study involved 300 Israeli students, aged 9–17, using a written questionnaire and follow-up interviews with 20 of the students. They found that 40% of the students connected magnetic attraction and gravity, assuming that if there is no gravity, a magnet will not function. Many of the students also assumed that if there is no air to conduct these forces, neither gravity nor magnetism could act. In the second study, with 172 Israeli pupils aged 14–18, 50% said that gravity would not operate in the absence of air. The percentage of students giving this answer was not significantly different across the 14–18-year-old age range. The researchers noted that like scientists of past generations, a large proportion of the students thought of the Earth as a unique environment beyond which the rules of physics do not apply. This finding confirms Bar et al.'s (1994) study of 400 Israeli children, aged 9–13, in which many children maintained that celestial objects are not subject to gravity because they are beyond the Earth's atmosphere, where there is no gravity.

4.1.8 Summary

The above findings may at first seem daunting to teachers and curriculum developers. Many of the cross-age studies find little change in misconceptions over the years. Even many university students, including those who have taken physics, still have significant misconceptions about free fall. However, some age-related trends are apparent. Bar et al. (1994) noted that a profound change occurs in most children between the ages of 7 and 9 (second and third grade). At the beginning of this age range, most children express the idea that things fall because they aren't supported, whereas at the end of this period, children tend to see "heaviness" as a reason for falling, and "heaviness" takes on the connotation of amount of matter, similar to the scientists' definition of mass. Although the idea of support continues to be important, it is now connected to the idea that heavy things fall if not supported. Then, between the ages of 9 and 13 (fourth to eighth grade), students begin to use the term "gravity"—an unseen force—more frequently. Bar and her coauthors summarized this progression as follows: "The children's reasoning becomes gradually more abstract: tangible connection at ages 5–7 years, heaviness as a property of the object at ages 7–9 years, and the attractive force of the Earth at ages 9–13" (194).

The above research indicates that even then, many students expect that gravity acts just on heavy objects or in special circumstances, or that it is somehow linked to air or magnetism. The suggestion is that students are mentally equipped to articulate and possibly modify their concept of gravity if they have the opportunity to do so. Students will not readily give up their misconceptions without effective instruction.

This research is consistent with the recommendation of national standards that formal explanations of phenomena involving gravity be postponed until middle school, when students are able to envision unseen forces. However, upper elementary students may benefit from experiences with magnets so that the idea of "unseen forces" is not entirely new when they encounter presentations about gravity in middle school.

4.2 Teachers and Teaching

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

1. Teachers' knowledge and awareness of common misconceptions
2. Teaching interventions with students
3. Professional development of teachers

4.2.1 Teachers' Knowledge and Awareness of Common Misconceptions

Watts and Zylbersztajn (1981) interviewed 125 British 14-year-olds and their five teachers to determine the teachers' abilities to anticipate learning difficulties of incoming students. "Our supposition was that a 'gulf of understanding' exists between teachers and pupils and we wanted to judge the extent of that gap" (360). Students completed a multiple-choice test booklet containing 12 questions regarding the nature of force and motion. Afterward, students were interviewed to explain their responses further. "For some children, gravity is present all the time. Others think that it will only act when a stone that is thrown upwards is on the way down. A minority subscribed wholly to the ancient view that the Earth seems to be the natural place for things to fall, no force being needed in the process" (363). The teachers answered the same 12 questions and were asked to predict the misconceptions that incoming students were likely to have. The researchers concluded that their sample of science teachers had a difficult time predicting the degree to which their students used misconceptions when answering questions related to gravity and free fall, although they were hesitant to generalize from this small sample of five teachers.

Kruger, Summers, and Palacio (1990) interviewed 20 English elementary school teachers and found that they generally held many of the same mistaken beliefs about gravity as their students. In one instance, teachers attributed an astronaut's ability to stand on the Moon to the heaviness of his boots and other equipment. When asked what would happen to the astronaut if the boots were removed, one teacher responded, "He'll float off because there isn't any gravity. So he needs to be dressed in such a way so that he has a sufficient weight force to hold him down" (390). The researchers also reported that the use of apparently scientific language by the teachers was not associated with a corresponding ability to explain the actions of gravity, particularly in their use of the terms "force" and "energy" within a Newtonian framework. Further, some of the teachers invented scientific-sounding terms such as "movement force" or "inanimate force" to express their misconceptions (394).

Ameh (1987) interviewed 40 students from Forms 3, 4, and 5 (ages 14, 15, and 16) and their teachers in Nigeria. Her qualitative study found naïve conceptions of gravity by both students and teachers:

> Interviewer: Is there gravity on a man falling from a plane?
>
> Teacher 1: No there is no gravity because the higher you go the less the frictional force on you. If a man is on the air, although there is a tendency for him to come down because the pressure there is less due to the reduced air in the atmosphere, reduction in the gravitational pull as you go higher. (214)

4.2.2 Teaching Interventions with Students

Minstrell (1982) developed an effective method to help students in two physics classes understand the "at-rest" condition of an object resting on a table. Prior to these lessons, most students were aware that there was a force holding the book on the table (about 15% believed the force to be air pressure), but few agreed that there was an equal and opposite force exerted by the table on the book. Some of the students indicated that "gravity" held the book down; however, they did not understand gravity to be a force, but rather a tendency of an object to fall. The idea that the table exerted an upward force made sense to only about 50% of the students. For most students, the table was considered to be just "in the way." The intervention consisted of a series of discussions and demonstrations. The instructor introduced the use of arrows to show the direction and magnitude of forces, and used these to clarify two different views: gravity acting downward only versus gravity plus an equal force exerted upward by the table. In the first demonstration, a student was asked to hold the book on an outstretched arm and to say if it is necessary to exert an upward force to counter gravity. More books were added to clarify the necessity of an upward force. In the next demonstration, the teacher reflected a beam of light off the tabletop and then stood on the table so that the slight deflection of the table caused the light beam to shift its position. Finally, a ruler was hung from a spring so that the students could see the spring exert a force. Students were polled at several points during the demonstrations and discussions. Whereas in the beginning, only half the students believed that the table exerted an upward force, at the end, all but one student agreed that there was an upward force equal to the downward force of gravity. The researcher concluded that the following conditions are necessary for conceptual change to occur: (1) an engaging, free-thinking, free-speaking social context in which students are encouraged to articulate their beliefs, (2) a juxtaposition of a variety of firsthand experiences with static objects, and (3) encouragement to search for the simplest consistent, rational argument that will explain the similarity of effects in an apparent diversity of experiences.

4.2.3 Professional Development of Teachers

Smith and Peacock (1992) described the methods and results of a teacher education program in England designed to help elementary and middle school teachers learn the concepts that they were expected to teach their students under the new national curriculum. Using diagrams and scenarios from previous research studies, the researchers developed a questionnaire for all 14 teachers in the study and interviewed two of the teachers. With regard to dropping objects of different masses, only three of the teachers expressed the idea that the gravitational force on the two objects was different. When asked which of the two masses would fall quickest, four of the teachers said that the heavier would fall first, two said the lighter would fall first (because of air resistance), and the other seven gave the accepted view that the two masses would fall at the same speed.

The instructional treatment, which lasted two hours, involved the teachers in discussions designed to provoke their awareness of two internal contradictions:

1. Heavy objects are more strongly attracted by gravity than lighter objects, yet they fall at the same rate. Resolving this apparent contradiction requires the concept of inertia (that the heavier object requires a stronger force to make it move).
2. An object that is light for its size, such as a feather, falls at a constant rate because the force of air resistance equals the force of gravity.

But most people believe that if two opposing forces are equal, there should be no motion. This can be resolved by understanding that an object moving at a steady speed in a constant direction has balanced forces acting on it. After the two-hour lesson, the teachers were asked to write about what they found most helpful and what was difficult to understand. Although some of the teachers started out with very low confidence in their ability to teach this subject, their comments at the end of the lesson were very positive. For example (Smith & Peacock 1992, 124):

- "Once you’ve got all the ideas out, you can clear all the blocks and see the contradictions. All the talk has helped."
- "I think talking about the contradictions is an enlightening approach. You’ve got to get people to admit they were wrong. It’s okay. It’s the best approach."
- "You teach things better when you’ve really worked on it. You skate over things you find easy."
- "I didn’t know what I didn’t know."

McDermott (1984, 1993; McDermott, Shaffer, & The Physics Education Group at the University of Washington 2002) has led a research and teaching group at the University of Washington for the past three decades. She and her team have developed a program for university students in a teacher preparation program that incorporates many of the findings and insights described in this article. The philosophy that underlies their approach is succinctly stated as follows:

> Teaching by telling is an ineffective mode of instruction for most students. Students must be intellectually active to develop a functional understanding. . . . A coherent conceptual framework is not typically an outcome of traditional instruction. Students need to participate in the process of constructing qualitative models that can help them understand relationships and differences among concepts. (McDermott 1993)

The applicability of this statement to the teaching and learning of gravity is obvious in the light of studies reported by Minstrell (1982) and Smith and Peacock (1992), as well as the learning studies that will be reported in Part II of this review.

4.2.4 Summary

Researchers who have taken a close look at teachers' understanding of gravity have found the same misconceptions as among university students and even younger students. Even teachers who can correctly apply Newton's laws are often unaware that many of their students are likely to harbor misconceptions that are very difficult to extinguish. However, the learning studies are encouraging. A common finding is that students' engagement and interaction with the subject matter is 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
Ameh (1987) An Analysis of Teachers' and Their Students' Views on the Concept "Gravity"	–40 Form 3, 4, & 5 students and their 4 teachers –Transcript from dialogue	Neither students nor teachers are using scientific knowledge to answer science inquiry questions about gravity. Students and teachers thought that gravity required air for transmission of force.
–Bar & Zinn (1998) –Similar Frameworks of Action-at-a-Distance: Early Scientists' and Pupils' Ideas.	–300 students, 9-18 years old –Interviews with demonstrations	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.
Bar, Zinn, Goldmuntz, & Sneider (1994) Children's Concepts about Weight and Free Fall	–400 students (4-13 years old) –Questionnaire & interviews	Youngest students in this sample thought all objects fall at the same rate. Older students thought heavier objects accelerate faster.
Bliss, Ogborn, & Whitelock (1989) Secondary School Pupils' Commonsense Theories of Motion	–26 elementary & middle school children –Semistructured interviews	Used ideas from comic strip scenarios to investigate children's ideas about motion. Found that support theory was likely to be used by the oldest and the youngest students sampled. Found that students rarely referred to gravity as the source of action or motion.

Champagne, Klopfer, & Anderson (1980) Factors Influencing the Learning of Classical Mechanics	–110 undergraduates –Demonstration, Observation, Explanation (DOE) test	Found that students believed that heavier objects fall faster, even among those students who had previously studied physics.
Dostal (2005) Student Concepts of Gravity	–~ 2000 undergraduates –Coursework & worksheets evaluated –28 follow-up interviews	Documented students' ideas that gravity acts upward on an object.
Galili (1993) Weight and Gravity: Teachers' Ambiguity and Students' Confusion about the Concepts	–Diagnostic test results from 33 10th-grade students, 60 11th-grade students, 36 12th-grade students, 27 adult learners (age 23+), & 42 preservice teachers	Found evidence that students (and their textbooks) commonly apply the definition of weight as being equal to the force of gravity. This leads students to mistakenly conclude that weightlessness (such as in the orbit) must also mean no gravity.
Galili (1995) Interpretation of Students' Understanding of the Concept of Weightlessness	–34 students, grade 9 & 10 –86 students, grade 11 & 12 –55 preservice teachers –Two different questionnaires, both administered to all sample subjects	Documented students' and teachers' ideas about the relationship between weight and gravity. Recommended an operational definition of weight.
Gunstone & Watts (1985) Force and Motion (from Driver, Guesne & Tiberghien, eds.)	–Cross-age study –Multiple methods	Found that students identified as "academically gifted" promoted the concept that heavier things fall faster. Found that even physics graduates think gravity doesn't act in a vacuum.

Halloun & Hestenes (1985a) The Initial Knowledge State of College Physics Students	–Diagnostic test results from 980 undergraduates and 49 high school students	Authors developed and validated a diagnostic test for high school and secondary math and physics knowledge. Items were chosen to highlight the differences between "commonsense" physics and a Newtonian framework. Found that mathematical proficiency did not predict achievement in physics. Students' initial knowledge of physics was highly correlated with achievement. Traditional instruction methods did not improve scores.
Halloun & Hestenes (1985b) Common Sense Concepts about Motion	–478 undergraduates (survey data) –22 undergraduates (interview data) –Questionnaire and follow-up interview	Found at least one student who maintained that gravity was not a force. Students were shown to have multiple ideas about motion that were context driven. Found evidence for both "heavier things fall faster" and "support theory" ideas.
Kruger, Summers, & Palacio (1990) An Investigation of Some English Primary School Teachers' Understanding of the Concepts of Force and Gravity	–20 elementary school teachers –Interview	Found that the ideas held by most of this small sample of teachers corresponded with those held by elementary students. Teachers used scientific-sounding language to describe nonscientific explanations for force and motion. Found that teachers thought that gravity was an atmospheric effect.
Minstrell (1982) Explaining the "At Rest" Condition of an Object	–2 high school physics classes –Classroom-based discourse –56 grade 6 students & 56 grade 10 students –Interviews	Found that approximately 15% of the students initially thought "air pressure" was responsible for holding a book on a table. Fifty percent of students conceptualized an upwards force from the table holding up the book.
Palmer (2001) Students' Alternative Conceptions and Scientifically Acceptable Conceptions about Gravity	–56 grade 6 students & 56 grade 10 students –Interviews	Found misconceptions about gravity to be common regardless of science education experience.

Selman, Krupa, Stone, & Jaquette (1982) Concrete Operational Thought and the Emergence of the Concept of Unseen Force in Children's Theories of Electromagnetism and Gravity	–60 students total (10 each from grades 1, 3, 5, 7, and 9, and 10 additional high school students) –Interviews	Identified four levels in responses: –Level 1: conceptions based on overt correlated events –Level 2: conceptions based on unilateral unseen forces –Level 3: conceptions based on multiple or interactive unseen forces –Level 4: conceptions based on balanced or transformative systems
Sequira & Leite (1991) Alternative Conceptions and History of Science in Physics Teacher Education	–Multiple studies with high school students and undergraduates –Questionnaire	Fifty-two percent 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 objects in a vacuum would be unaffected by external forces, thus, gravity needs a medium through which it is transmitted.
Smith & Peacock (1992) Tackling Contradictions in Teachers' Understanding of Gravity and Air Resistance	–14 teachers –Questionnaires and follow-up interviews	Found that at least one teacher had difficulty accepting that gravity accelerates all objects equally.
Stead & Osborne (1980) Gravity: A Working Paper of the Learning in Science Project	–42 students (middle and high school) –Semistructured interviews	Although most students acknowledged that gravity pushes one down on Earth, others indicated that gravity acts upward on objects. Students also confused gravity and buoyancy.

<table>
<tr><td>Watts (1982)
Gravity—Don’t Take It for Granted!</td><td>–20 students (12–17 years old)
–Semistructured interviews</td><td>Students couldn’t realistically apply their knowledge of gravity to situations outside the classroom. Students maintained that gravity operates only on heavy objects. Found that students maintain:
1. Gravity requires a medium through which to act.
2. Gravity requires air.
3. Gravity increases with height.
4. Moving objects fail to overcome gravity.
5. Gravity begins to act once things fall and continues only until the object is at rest on the ground.
6. Gravity is a large force.
7. Gravity is a selective force and acts only on certain things.
8. Gravity is not weight.</td></tr>
<tr><td>Watts & Zylbersztajn (1981)
A Survey of Some Children’s Ideas about Force</td><td>–125 students (14 years old)
–5 teachers
–Interviews</td><td>Some students presented Aristotelian notions about falling objects. Students maintained that a motion implies a force in that direction. Found that the 5 teachers in this study were not able to predict students’ use of alternative theories and were likely to share the same misunderstandings as their students.</td></tr>
<tr><td>Whitaker (1983)
Aristotle Is Not Dead: Student Understanding of Projectile Motion</td><td>–100 undergraduates
–Questionnaire</td><td>Found that students widely believed that heavier objects fall faster.</td></tr>
<tr><td>Whitelock (1991)
Investigating a Model of Commonsense Thinking about Causes of Motion with 7–16 Year Old Pupils</td><td>–224 students (7–16 years old)
–Questionnaire</td><td>Findings suggest a conceptual relationship between effort (required to move) and support (to keep things from falling). Researcher graphed relationship between actual responses and predicted responses.</td></tr>
</table>

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 free fall?
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 Free Fall?

The research studies reviewed in this article clearly indicate that misconceptions about free fall abound across the age and educational spectrum. Elementary, middle, high school, and university students, as well as primary and secondary school teachers, hold ideas about falling objects that depart significantly from the Newtonian worldview. Furthermore, although students with formal science backgrounds tend to use more sophisticated vocabulary, the kinds of reasoning errors they make are strikingly similar to the errors made by their younger and less educated peers.

It is important to note that the research studies reported here do not address students' abilities to solve quantitative problems of the type typically encountered in textbooks. Students' abilities to solve those problems are typically tested through problem sets and exams. Instead, these research studies focus on students' abilities to answer questions about how and why things fall. It is by asking questions such as these that researchers have found that few people who graduate from our school systems—including those who received top grades in physics—understand the foundational ideas of the classical (Newtonian) theory of gravity.

Although different reviewers of the same material may classify misconceptions somewhat differently, it seemed to us that the findings fell into the following categories:

- *Things fall if they're not supported.* When asked why things fall when dropped, children just entering school will say that things fall because they're not held up. By second grade, more than half of the students instead refer to the heaviness of objects, or some unseen force, and by seventh grade, very few students fall back on this sort of explanation.
- *Strength and effort prevent falling.* When young children are asked what keeps something from falling, they will usually refer to some sort of effort or strength that prevents it from falling, and they even use this reasoning for the Sun, Moon, and clouds.
- *Gravity is not a force.* For students who believe that things just naturally fall, no force is necessary. A few older students and even adults hold this misconception.
- *Heavier objects fall faster.* This is a very deep-seated misconception held by a great many people at all ages. Most adults who have not taken physics, and even some successful physics students, hold this idea.
- *Gravity attracts only heavy, slow, or inactive objects.* This is a loose collection of misconceptions expressed by various high school students in different contexts and in various studies.
- *Gravity acts upward.* Quite a few high school students and even some college students indicated a

belief that gravity pushes upward rather than acting to pull things down to Earth's surface.

The above list is a very brief summary of the major misconceptions that students have expressed concerning free fall. A much richer description with illustrative examples is described in Section 4, Literature Review. Now we turn to the next question, which concerns the extent to which these ideas reflect the historical development of the theory of gravity.

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

As indicated in the introduction, a great many researchers have remarked on the striking similarity of students' misconceptions to ideas that were strongly held for centuries by the natural philosophers whose ideas led to modern science. Specifically, the idea that heavier objects fall more quickly than light objects is attributed to Aristotle, whose ideas about the physical world were held to be true by educated people for nearly two millennia. Table 3 illustrates that students' misconceptions are indeed similar to many of Aristotle's ideas, though we have no evidence that students share Aristotle's worldview of a spherical Earth at the center of the universe. Consequently, it may be helpful, as recommended by Bar and Zinn (1998), for students to learn about how Aristotle's ideas were eventually rejected so that they can better recognize and overcome their own misconceptions.

Table 3. Comparison of students' misconceptions about free fall with early gravitational theories

Aristotle	Medieval Scholars	Students' Misconceptions
Heavy things fall because they seek their natural resting place in the center of the universe. Speed of fall is proportional to the weight of an object. Speed increases during fall as an object gets closer to the center of the universe. Light objects rise upward, away from the center of the universe.	Objects accelerate as they fall. Uniform acceleration is defined as covering the same additional distance in successive periods of time.	Heavier objects fall faster. Gravity attracts only heavy, slow, or inactive objects. Gravity is not a force. Things fall if they're not supported. Strength and effort prevent falling. Gravity acts upward.

One more useful lesson from history is that science is a social enterprise, yet textbooks tend to emphasize the role of the individual. For example, many textbooks describe Galileo's arguments showing that Aristotle's ideas about falling objects were absurd. However, few textbooks attend to the minor players, or the intellectual climate that allowed ideas to survive and for critical conversations to take place, in a way that reflects the different (even opposing) perspectives. It is difficult to imagine how the theory of gravity could have been developed if the major players did not have the opportunity to listen to alternative ideas and thereby engage in heated conversations about the nature of the world. The idea that classroom environments should reflect this aspect of the scientific community is supported by a recent review of the much larger body of research on learning. Bransford, Brown, and Cocking (1999) found that

> these studies also emphasize the importance of class discussions for developing a language for talking about scientific ideas, for making students' thinking explicit to the teacher and to the rest of the class, and for learning to develop a line of argumentation that uses what one has learned to solve problems and explain phenomena and observations. (171)

Teaching in this way requires considerable skill to facilitate discussions so that students can clarify their own ideas and compare their thinking with other students' ideas about falling objects.

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

Elementary level. Although neither *Benchmarks for Science Literacy* (AAAS 1993) nor the *National Science Education Standards* (NRC 1996) recommend that students be taught about gravity before middle school, they do recommend that students have opportunities to work with magnets. As indicated by several of the studies, students make an important transition in early elementary school in which they begin to think about forces that they cannot see. Therefore, this recommendation seems reasonable in light of the research.

Middle school level. Bar et al. (1994) indicated that students in the middle school grades were uniquely ready for questioning their assumptions about the nature of gravity. "By the time [students] reach age 13, they understand that gravity acts on heavy objects to pull them down, and that a heavy object will fall unless supported" (167). Indeed, without effective teaching and learning opportunities, many adults' ideas about gravity remain indistinguishable from preinstructional ideas. Middle school-age students can begin to differentiate the concepts of gravity, weight, and free fall. These ideas, the researchers concluded, can be consolidated with a general enthusiasm for space-related topics and general astronomy.

Osborne (1983) reported,

> In some respects we have had more success teaching Newtonian ideas to 11-year-olds than to 14-year-olds. The older children are sometimes less interested and/or more inflexible in their ideas than the young children. While we may frequently attempt to teach ideas too early in terms of the intellectual development of our pupils, we must also consider the possibility that we may at present be introducing new ideas at a stage when children are no longer interested or do not want to be interested. (49)

We conclude from these and other findings that middle school is a good time to engage students in learning to apply Newton's laws of motion to falling objects, although it is difficult to predict the extent to which any given group will be motivated and capable of learning these challenging ideas. Much will, of course, depend on the chosen teaching methods, as we discuss in the next section.

With respect to the content of the middle school physics curriculum, the research supports some of the ideas but not others in the national standards documents. For example, at the middle school level, students are expected to leave behind their previous perception that "things just naturally fall" and to recognize that gravity is a force that pulls things toward Earth’s center. Leaving behind the idea that "things just naturally fall" in favor of an unseen force is feasible because studies indicate that many students do make this transition, even in the absence of instruction. However, many students envision that falling motions are directed toward Earth’s surface, not Earth’s center.

High school level. According to national standards, high school students are expected to learn to apply Newton’s laws of motion and universal gravitation in situations on Earth and in space, both qualitatively and quantitatively. The suggestion is that once students learn to apply these laws qualitatively, the next step will be for them to learn to apply the laws of motion quantitatively. Starting with a qualitative understanding of gravity is supported by the research, but the standards documents do not emphasize strongly enough that a qualitative understanding is the greater challenge by far. Consequently, curricula and teaching should be designed to engage students in a variety of challenges involving the qualitative use of gravity concepts before they are expected to solve quantitative problems.

5.4 What Teaching Methods Are Most Promising?

Keeping in mind that misconceptions about gravity are deep seated and difficult to change, even in light of apparently contradictory evidence, most of the learning studies tested constructivist methods of teaching. The term "constructivist" does not refer to a rigid method, but 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. Constructivist methods are thought to be especially helpful in cases in which people hold strong but erroneous views that must be changed before they can understand a new concept. That is certainly the case with gravity.

Here are some common elements of successful learning studies:

1. The teacher prepares an intriguing phenomenon for students to observe and think about. It might be a game, lab activity, stimulating reading, or picture of a situation. The most important element is that it serves as the basis for students to make a prediction, offer an explanation, or explain their thinking in a way that reveals their beliefs about gravity.
2. Students are urged to articulate their various beliefs about the phenomenon. Even when a student gives the correct Newtonian explanation, other students are invited to share their ideas as well. The teacher further clarifies these different ideas for the class, without indicating which is right or wrong. Presenting multiple viewpoints like this allows students a "safe distance" from which to observe their own ideas and see how they compare with other students’ ideas.
3. The teacher engages the students in a social situation in which the students are encouraged to share their thinking and explain why they think their viewpoint is correct.
4. The students take part in various activities to explore the phenomenon further, but this time with various preliminary ideas (in addition to their own) and predictions to test.
5. The teacher leads the students individually, in small groups, or as a class to resolve which explanations or ways of thinking about the phenomenon are consistent with observations, make the most sense, and are close to the modern (Newtonian) view of science.

Another constructivist approach is to encourage students to discover misconceptions by finding conflicts in their own thinking patterns. For example, Smith and Peacock (1992) noted that several of the teachers in their program thought that heavy and light objects fall at the same speed because the force of gravity on all objects is a constant. The researchers then asked these teachers to consider the following statement: "The force of gravity on heavy objects is the same as the force of gravity on light objects. Since weight is defined as the force of gravity on an object, heavy and light objects must weigh the same."

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.

5.5 What Research Remains to Be Done?

In several respects, the science of education concerning students' understanding of free fall is quite mature. Research studies have been conducted on many continents and the findings have been similar, so we know that the misconceptions that have been identified are robust and widespread geographically. Further, most studies have used similar methods: written questionnaires buttressed by interviews. The interview results have been especially revealing because they provide the researchers with quotes from students that illuminate their thinking and sometimes prompt investigations that the researchers had not initially anticipated. The questionnaire results have also been valuable in identifying misconceptions that are especially widespread and deep seated. And because the research studies cite not only the few seminal papers from the late 1970s and early 1980s but more recent studies as well, it is clear that the more recent studies are interlinked, building on recent and early accomplishments. Because the content of introductory physics courses is relatively stable, nearly always covering Newton's laws as applied to falling objects, there are excellent opportunities to apply the results of the research—not only to better understand how people learn but also to improve the effectiveness of instruction.

Nonetheless, 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. For example, many learning studies have used variants of constructivist teaching methods. However, constructivist methods are not well defined. Therefore, studies that tease apart various elements of constructivist teaching to determine which methods are most effective in facilitating learning would be extremely helpful.

6. RECOMMENDATIONS

The conclusions in the previous section represent our interpretation of the research on students' understanding of gravity and motion. In addition to these conclusions, our study of the research literature has led us to offer the following recommendations for curriculum development and teacher education.

1. Curriculum development should focus on major transitions and key concepts at appropriate grade levels. The research reviewed in this article indicates important transitions in students' understanding of gravitational theory. For example, the youngest students gradually transition from thinking of falling as a "natural motion of objects" to the idea of "unseen force." Science curricula for the middle school level should help students differentiate the concepts of gravity, weight, and free fall and help students distinguish between falling at a constant velocity and acceleration. The high school curriculum should engage students in applying Newton’s laws qualitatively before asking them to compute answers to quantitative questions. Developers of instructional materials in science should target such challenging transitions and concepts.

2. Instruction should begin by checking understanding of prior learning. The finding that many students have misconceptions about gravity suggests that teachers at all grade levels should start every instructional unit on gravity by checking their students’ understanding of concepts that were taught at prior grade levels. This can be done, as mentioned earlier, by asking students to predict what would happen in various physical situations and to justify their predictions. These activities should be built into curricula on gravity at all levels. This can be thought of as a "spiral curriculum," with extraordinary efforts to be certain that students have reached preceding levels before setting them on the course to the next level.

3. Sufficient time should be allowed for learning. It is important to recognize that learning the basic concepts of classical mechanics takes time. Although some relatively short treatments have been shown to be effective, in most cases, teachers will need to budget extra time to ensure that the entire class actually learns the lessons appropriate for that grade level, and that the most advanced students have opportunities to expand the range of application. It is therefore better to focus extensive teaching efforts at a few target grade levels than to teach a little bit of gravity every year.

4. Engage students in applying the theory of gravity to real-world contexts. If there is one lesson that we hope readers come away with after reading this article, it is that students do not have enough opportunities to think about how Newton’s laws apply in real-world contexts. The mathematically rich problems in textbooks sometimes mask students’ misconceptions because they can find the right equation and plug in numbers to get the right answer. Unless instructors can encourage their students to transport science learning across the boundaries of the classroom into the real world, the entire value of science education will be called into question. To put it differently, science educators succeed when their students carry with them the insights of science into their own world of everyday lived experience. Designing problems that engage students in applying their growing understanding of motion to real-world contexts is challenging but essential if students are to become scientifically literate. Luckily, there are several examples in the research studies reported in this article, and the field of engineering offers many more.

5. Help teachers build confidence while increasing their understanding of gravity. The research studies reported above indicate that some teachers have many of the same misconceptions as their students. That was even the case with some of the high school physics teachers who were interviewed. A further problem is that many teachers, especially at the elementary and middle school levels, have low self-confidence in physical science. Recognizing this problem, Smith and Peacock (1992) cautioned,

> There is a danger of disabling teachers by exposing contradictions and their misconceptions. This could simply reinforce their awareness of gaps in their knowledge and their view that physics is hard. Whatever support is provided should be designed to give them some success and confidence and enhance their ability to apply knowledge in teaching situations. (125)

6. Provide teachers with the means to assess their own students’ understanding of gravity. It is now widely seen as self-evident in the field of science education that students’ ideas prior to instruction play a major role in their ability to acquire and internalize new information about the world (Bransford et al. 1999). Although it is valuable for teachers to learn about the results of research on common misconceptions, it is far more valuable if a survey of their own students’ ideas is built into the start of every unit. Although teachers do not have the time to interview students individually, a well-constructed written questionnaire followed by a class discussion can be very effective at eliciting students' ideas. The studies reviewed here provide an excellent bank of questions that curriculum developers can use for this purpose.

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Notes

Note 1: The authors acknowledge proposals to replace the term "misconception" with other terms such as "alternative framework" so as to recognize and respect students' intellectual efforts to make sense of the world. In this case, we prefer the older term to emphasize the gap between what science teachers are charged with teaching and their students' current understanding.

Note 2: As Galileo pointed out in his writings, the heavier object will generally outstrip the lighter object by a small amount due to air resistance, but the difference is very small compared with Aristotle's prediction that an object that is twice as heavy will fall twice as fast. The researchers generally take this into account either by asking the students to ignore air resistance or by selecting two objects that are obviously different in weight but are shaped so that air resistance will have a negligible effect when the experiment is demonstrated.

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