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Weight, Mass, and Gravity: Threshold Concepts in Learning Science

Abstract

Threshold concepts are essential ideas about the natural world that present either a barrier or a gateway to a deep understanding of science. Weight, mass, and gravity are threshold concepts that underpin students' abilities to understand important ideas in all fields of science, embodied in the performance expectations in the *Next Generation Science Standards* (NGSS). This study begins with a review of research on students' difficulties in understanding these concepts individually and in relation to each other, based on individual interviews and surveys of several hundred children that illustrate how students' understanding of weight, mass, and gravity develops over the lifespan, from age five through adult. New data from an additional 451 subjects in the critical age range of 10 to 14 years old support and extend the prior findings. The purpose of the current study is to provide teachers and curriculum developers with actionable and up-to-date information that educators can use to help children at the upper elementary, middle, and high school levels achieve Next Generation Science Standards.

Introduction

Large parts of our nations' science education systems are broken, and we have known about some of the problems through educational research for decades (U.S. National Commission on Excellence in Education, 1983; Fleishman, 2010; Martin et. al, 2012). It's time to bring these findings to a broader audience so that practitioners can use the information to fix some of the most glaring problems. A recent step in the right direction has been development *of Next Generation Science Standards* (NGSS Lead States, 2013) in the United States, but it is just that—a step. The new standards provide clear targets for assessment, but do not provide a pathway for reaching them.

In this paper, we argue that to meet the new standards curriculum developers and teachers must focus on helping students develop deep, flexible, and useful **threshold concepts** that provide the intellectual underpinnings of the standards. To illustrate this instructional strategy we have chosen the concepts of weight, mass, and gravity, since they are essential for grasping a number of performance expectations in all disciplinary areas. While we understand and support the new vision for three-dimensional instruction (i.e., combining practices, crosscutting concepts, and core ideas) implicit in the NGSS, we claim that the need to help children grasp fundamental concepts continues to be important.

The difficulties posed by students' inability to understand and differentiate the **concepts** of *weight* and *mass* are well known in physics. Klopfer, Champagne, and Chaiklin (1992) noted that children enter school with initial ideas about certain essential "ubiquitous quantities" (e.g., weight, mass, volume and density), and that a goal of science instruction is to develop the spontaneous concepts into a scientific understanding of these quantities—a goal that the authors acknowledged was only rarely achieved, even by the time students reach college.

In a compelling video, entitled "Lessons from Thin Air" (Schneps & Sadler, 1997), a bright seventh grader is interviewed before and after a class on photosynthesis. Prior to the class he is asked what a tree is mostly made from. His response is that it is made from soil and water. After a six-day unit on photosynthesis, during which he experienced a lab activity coordinated with lectures on how plants extract carbon from carbon dioxide in the air, and learns about the chemistry of photosynthesis, he was again asked the same question. Despite instruction from a knowledgeable teacher, he again gives the same answer—that the material in a tree comes from soil and water. Although he correctly stated the chemical equation for photosynthesis, when asked if the wood, bark, and leaves come mostly from carbon dioxide in the air, he replies that is impossible because air doesn't weigh anything, stating "If it did we wouldn't be able to breathe." Although it may not be surprising that seventh grade students have difficulty understanding that gases have weight, the same video shows that graduates from Harvard and MIT give the same answer as the high school student—that the considerable mass of a tree could not possibly have come from carbon in the air. Like the seventh grader, the college graduates had no difficulty memorizing the chemical formula for photosynthesis, but when they really thought about it, even that classic example of conservation of mass seemed like they were getting something (wood, bark, and leaves) from nothing (the air.)

The third threshold concept that we will describe in this paper is the meaning of *gravity*, which also seems to be poorly learned at the middle school level (Kavanagh and Sneider, 2007a, 2007b), with misconceptions continuing into adulthood. Recognizing that understanding

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of basic physics concepts are important for the study of geology, college professors Ashghar and Libarkin (2010) surveyed 197 students enrolled in geology courses at a mid-western university concerning their understanding of gravity. They found that only 21% had the correct scientific idea that gravity is a force of attraction, and that very few students incorporated the concepts of attraction, mass, and force into their explanations of gravity. Various students expressed the ideas that Earth's "spin," "magnetism," and "atmosphere" caused the force of attraction between Earth and other objects. The researchers identified gravity as one of a small group of important *threshold concepts* that can act as barriers to learning, or provide a gateway to deep understanding of many related concepts.

In this paper, we have chosen to focus on weight, mass and gravity since these terms are interrelated threshold concepts for several of the performance expectations in the *Next Generation Science Standards (*NGSS Lead States, 2013). As the NGSS becomes widely adopted, students will be expected to have a robust scientific understanding of these concepts in order to achieve a number of performance expectations. Following is a list of performance expectations that require understanding of weight, mass, and/or gravity.

> *5-LS1-1.*[1] *Support an argument that plants get the materials they need for growth chiefly from air and water.*

If it were not for the compelling illustration on the video, it might not be obvious that students' understanding that gases have weight is essential to achieve this performance expectation. The concept is also central to ideas related to weather, climate and the interaction of Earth systems.

> *5-PS1-2. Measure and graph quantities to provide evidence that regardless of the type of change that occurs when heating, cooling, or mixing substances, the total weight of matter is conserved.*

The concept underpinning this performance expectation is conservation of weight under phase transformations, which can be very challenging for fifth grade students (Galili & Bar, 1997), as we will discuss in our literature review.

> *MS-PS2-2. Plan an investigation to provide evidence that the change in an object's motion depends on the sum of the forces on the object and the mass of the object.*

Concepts underlying this performance expectation include mass, as embodied in Newton's Laws of Motion, and also the relationship between force and motion which is subject to the common misconception that gravity does not act on all objects, however they may be moving. For example, many students believe that gravity does not act on an object that has been thrown upward, until it reverses direction and starts to fall (Palmer, 2001).

> *MS - ESS2 - 4. Develop a model to describe the cycling of water through Earth's systems driven by energy from the sun and the force of gravity.*

Traditionally the water cycle has been taught at the elementary level. Moving it to the middle school will make it more accessible, but still challenging as it requires students to conserve matter under phase change from liquid to gas, and to understand how solar energy and gravity act together to drive convection currents that make the water cycle possible.

> *5-PS2-1. Support an argument that the gravitational force exerted by Earth on objects is directed down.*

The idea that Earth is a ball in space has implications for such fundamental concepts as "up" and "down" and how gravity acts on objects that are at rest, falling, or being thrown upwards. This is also an area that has been widely studied, but for which some questions still remain (Agan & Sneider, 2004).

The present investigation has been undertaken to provide a finer-grained analysis of students' schemas during the critical period ages 10 to 14, when students are expected to develop an initial scientific understanding of gravity, weight, and mass and their interconnections. Although there is an extensive literature on students' understanding of these threshold concepts, most of the studies were done decades ago, so the findings may not be true of today's students. By conducting a systematic study of children's ideas across a broad age range we hope to provide teachers and curriculum developers with the actionable and up-to-date information that they need to help students at the upper elementary, middle, and high school levels achieve Next Generation Science Standards.

Historical Background

In many cases the trajectory of a child's understanding of a concept may parallel the development of a concept in the history of science. Consequently, a brief historical review can provide useful insights for researchers by suggesting the possible causes of learners' difficulties, as well as for teachers to be aware of possible misconceptions that their students may hold. Children can also benefit from accounts of scientists of the distant past who may have shared some of their own ideas about the world, and how the scientists eventually changed their ideas as a result of new data, or new ways of thinking (Bar and Zinn, 1998).

In the history of science, the weight concept developed prior to any understanding of mass or gravity. Conceptions of weight known from antiquity are: Plato (428-327 BC), who proposed that weight is a tendency of bodies to move towards similar bodies, so that a rock falls because it is attracted to other rocks. Aristotle (384-322 BC, 1952) included weight in his system of the world in which all heavy objects tended toward the center of the universe, which he took to be the center of the Earth. Both

[1] Each performance expectation in the NGSS is given a code. The code "5-LS" refers to fifth grade life science. LS1 refers to the first core idea "From Molecules to Organisms: Structures and Processes." The final numeral ("1") is the first performance expectation for that core idea in fifth grade.

Aristotle and Plato included the idea of levity or lightness, in their descriptions. In Aristotle's system, light objects, such as fire, tended to move upwards, away from the center of the universe. A generation later Euclid (325-265 BC) defined weight by the process of weighing, using a balance scale. The same idea was repeated by Archimedes (287-212 BC).

In renaissance times, Galileo (1564-1642 AD) discounted Aristotle's idea of levity by pointing out that it led to the absurd idea that if you tied a one-pound object to a two-pound object, the result would be an object weighing 1-1/2 pounds, rather than three pounds. Although Galileo supported Copernicus' (1543) idea that Earth revolved around the sun, Newton's idea of gravity had not yet been proposed, so Galileo had no good explanation for how the Earth kept circling the sun, or why the moon didn't fall to Earth. So even as late as Galileo's time, the modern concepts of mass and gravity had not been determined. The greatest change in the weight concept took place as part of the Newtonian revolution. In the *Principia*, Newton (1687) defined the force of attraction among all material objects as gravitation. He defined weight (W) as the force of gravitation (F_g) on a body and made a clear distinction between mass (m) and weight that can be expressed in a simple equation relating these two quantities to the free acceleration (g) towards the Earth:

$$W = F_g = mg$$

The concept of weight as defined by Newton was not a property of a single object, but rather a force between two objects (Wolf, 1968). Developing the formal concepts of mass and gravity was a struggle for Isaac Newton and his contemporaries. So it should not be surprising that it is a struggle for our students.

Prior Research

Developing an appropriate research review for this paper has been challenging because the concepts of weight and gravity are deeply embedded in an extensive conceptual ecology (Posner et al., 1982) that includes such concepts as gravity, force, and motion, each of which have been extensively studied. A review of research on children's and adults' understanding of gravity alone summarized the findings of 62 studies on this topic (Kavanagh & Sneider, 2007a, 2007b). A fully comprehensive review of research related to weight and mass would fill the pages of a hefty book. We have, therefore, selected studies that bear on the particular aspects of weight and mass that are likely to impede children's understanding of performance expectations in the NGSS, such as those listed in the introduction.

Weight

The classic work on children's understanding of weight began with Piaget (1929, 1972). He recognized that young children associate the weight of an object with the effort to hold, lift, or move the object. Piaget also studied students' understanding of conservation of weight—that is, their recognition of whether the weight of an object changes if the object is deformed or cut into pieces (Piaget, 1929, 1972). Expanding on the earlier work, Galili and Bar (1997) conducted a cross age study by interviewing 280 children, ages 5 to 16, and compiling written questionnaires for an additional 225 participants, ages 10 to 16. Like Piaget, they found that the youngest children ages 5-6 (Kindergarten, 1st grade) thought that an object was heaviest when it was in the form of a ball, and it weighed less when it was cut into pieces or spread out. The children expressed their understanding of weight in tactile terms—the ball-shaped object *felt* heavier when they held it in their hand, so they believed that it actually *was* heavier than when it was reshaped or divided. It was not until they reached age 7-9 (second to fourth grade) that about 80% of children were able to conserve weight despite changes in appearance.

Although most children in the age range 7-9 could conserve weight when the shape of an object was changed, Galili and Bar (1997) found that only about 50% recognized that the weight of a sample stayed the same when a solid became a liquid, as when ice or a wax candle melted. It was not until children reached age 10 that a majority of the children (about 75%) understood that weight was conserved during a phase change.

In addition to the usual conservation questions the researchers asked the children which objects have weight and which do not. Very few of the 5-6 year-olds attributed any weight at all to light objects, such as a feather, a cotton ball, a hair, or dust. By age 10 more of the children attributed weight to light objects, but still only 40% attributed any weight at all to a hair, and only 10% to dust. It wasn't until age 15-16 when more than 90% of the subjects recognized that even very light objects, such as a hair or dust, have weight. However, even among 16 year-olds 17% of the students did not think that air has weight.

Mass

At the middle school level the concept of mass is introduced by the ambiguous phrase "amount of matter." Mass is also operationally defined and distinguished from weight by comparing the masses of two objects by use of a balance scale. Students are given the example that an object transported to the moon would weigh less than on Earth, as measured by a spring scale, since the moon has only one sixth the amount of gravity as Earth, but the mass of the object, measured on a balance, would not change.

Cheeseman and McDonough (2013) in Australia found that when shown pictures of objects being compared using a balance, the youngest children, ages 6-7, did not "trust the scale," (p. 13) while the older children in the study, ages 8-9, saw the balance as providing evidence of the relative heaviness of different objects, which can be taken as a rough idea of mass, a conserved property of the object.

Gravity

Gravity is usually introduced to children as an explanation for why things fall to the ground. Bar, Zinn, and Goldmuntz (1994) conducted individual interviews with 400 children, ages 4-13, and asked them why things fall. Nearly all of their responses could be summarized in three categories: a) the object was not held; b) the object was heavy; and c) the object was pulled by the attractive force of the Earth (i.e., gravitation). As shown in Figure 1, at the youngest ages the great majority of children responded that objects fall because they are not held up by something. Between ages 7 and 10 all three explanations were common. By the time they reached age 13, the great majority of children say that objects fall because they are pulled by the attractive force of the Earth (or by gravity).

Palmer (2001) conducted individual interviews of 112 students: including 56 in grade 6 (11-12 years-old) and 56 in grade 10 (15-16 years old) in Australia. Students were asked to identify which objects were acted on by gravity in nine different scenarios and to justify their choices. 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. A common misconception was that gravity only acts on falling objects (where force is in the direction of motion), but not on stationary objects "since they are not moving." This finding is consistent with Gunstone and Watts (1985), who found that a common misconception that force implies motion, and the direction of the force is parallel to the direction of the motion. Palmer also found that many students believe that gravity does not act on objects buried under the Earth, an idea consistent with a comment from a college instructor (personal communication) that some of his students thought a satellite cannot fall into the ocean because water does not have gravity—just earth.

Weight and Gravity on the Moon

Given the common instructional method of helping students distinguish between weight and mass by asking students to imagine transporting objects to the moon, where they are weighed with a spring scale and compared on a balance, it is important to know how students think about such scenarios, and a number of researchers have conducted such studies (Watts, 1982; Ruggiero, et al., 1985; Ameh, 1987; Noce, Torosantucci, & Vincentini, 1988; Kruger, Summers, & Palacio, 1990). Typical answers to questions about what would happen to an astronaut on the moon were that they would float away since there is *no gravity on the moon*, unless they were sufficiently heavy to stay down—even without gravity. For example, Watts (1982) quoted Louis, age 12, who said, "No, he wouldn't float off into space because most of the astronauts have… they've got those sorts of heavy boots, haven't they?" Kruger, Summers, and Palacio (1990) reported similar findings with English elementary teachers and quoted one who said, "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." Stein (2010) found beliefs that in order not to float an astronaut should stand on the moon or hold the ladder connected to the space ship. One explanation given is that gravity needs air and the moon is airless (Bar & Zinn, 1998).

Noce, Torosantucci, and Vincentini (1988) conducted a large-scale, cross-age study in Italy. Their sample of 362 subjects included high school students, first-year university students, adults, and elementary teachers. The percentage of subjects who gave the Newtonian answer, that the object would fall to the moon, increased from 4% at the middle school level to 35% of the adults and 50% of students at a scientific high school. Most of those who indicated that objects on the moon would float said that air is necessary for gravity to act, and, since there is no air on the moon, there is no gravity either. This finding was confirmed by Bar, Zinn, and Goldmuntz (1994) who found that even children who can successfully explain that weight is the force of gravity on an object, and that mass does not change when an object is transported to the moon, nonetheless believe that gravity only acts on "heavy" objects.

Investigations of the ideas of high school students and adults (including college students and teachers) about weight, mass, and gravity found that adults have many of the same misconceptions as younger children (Tural, Akdeniz, & Alev, 2010; Gonen, 2008; Galili & Lehavi, 2003, 2006). Ashgar and Librakin's study (2010), for example, found very little difference between their college students' ideas and those reported in the literature for young children, despite the fact that many of their subjects were geology majors.

Weight, Mass, Gravity, as Threshold Concepts

The video mentioned previously, showing that not even graduates of Harvard

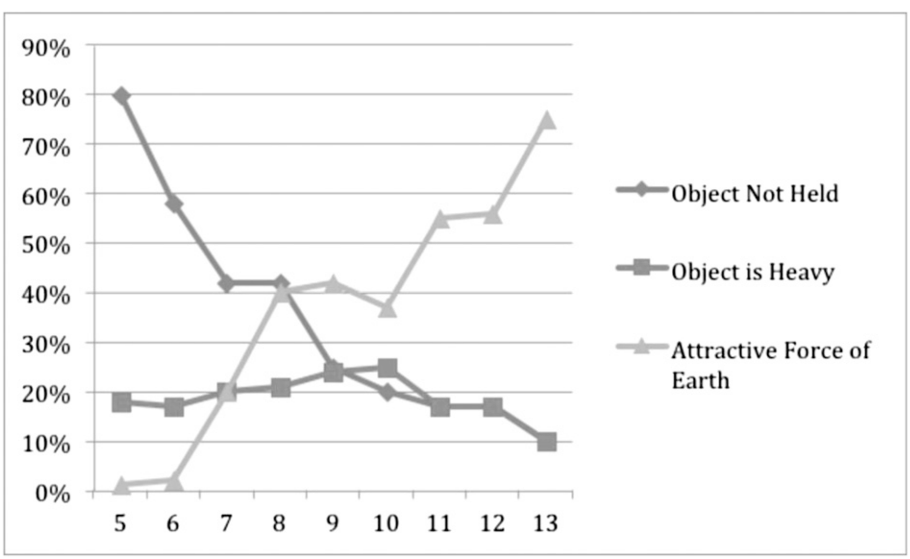

Figure 1. The reasons for free fall given by children from age 5 to age 13. (from Bar, Zinn, & Goldmuntz, 1994)

and MIT understood that plants draw most of their mass from carbon in the air, illustrates how failure to understand certain concepts in physical science can act as a barrier to understanding concepts in chemistry and biology. But it is not the only example. Driver (1985) noted that children's difficulty in conserving weight acted as a barrier to understanding what occurs when a nail rusts or a candle burns. In a study of children's understanding of the water cycle, Bar (1989) found that it was not until age 13 that children had a sufficient grasp of conservation of mass during a phase change to fully understand the water cycle.

Results of Instruction

Despite the difficulties mentioned above, there have been some successful efforts to teach these threshold concepts. Bar, Sneider, and Martimbeau (1987) developed a 90-minute instructional unit about orbits for sixth graders (12 years old) by borrowing ideas directly from the history of science. Subjects were 48 students in two classes who had previously studied the solar system and expressed no confusion about how the planets stayed in their orbits. Interviews with ten of the students at the start of the unit showed that 8 of the 10 believed that gravity needed air to act, so there was no gravity in space. The unit followed Newton's famous illustration of a cannon firing cannonballs from a mountaintop, as illustrated in figure 2. Each successive shot went further and faster until one cannonball finally achieved orbit. The students began by observing the trajectory of balls rolling off a table, then did the thought experiment of successively faster balls going further and faster until one goes into orbit. The researchers helped them extend their reasoning to the Space Shuttle and finally the orbit of the moon. The teacher then explained that that if there were no gravity in space, the moon would not stay in its orbit. Therefore, gravity cannot depend on air.

A written pre-test of all of the students showed that prior to instruction only 27% of the students believed that gravity acted in space. After instruction 48% believed that there is gravity in space, and an additional 8% believed that there is gravity "near the planets." Interviews with the same ten students after the class showed that eight of the ten had considerably advanced their understanding of gravity.

Sneider and Ohadi (1998) conducted a learning study involving 539 students in grades four through eight from 18 classrooms in 10 states, aimed at helping children unravel their misconceptions about the Earth's shape and gravity. Instruction involved several sessions using a constructivist-historical teaching strategy in which students learned about how ancient philosophers thought about patterns they observed in the sky, such as the daily motion of the sun, moon, and stars, as well as phases and eclipses, and discussed alternative models of the Earth in space to explain these phenomena. They also discussed various thought experiments, such as what would happen to a rock that fell through a hole dug all the way through the Earth from pole to pole. The findings showed significant gains for all students on the Earth's shape concept and a basic gravity concept (down is towards the center of the Earth.)

Galili (1995) and Galili and Kaplan (1996) reported the results of a written assessment about weight and gravity presented to 34 high school students (ages 14-15), who had just studied weight and gravity in elementary and middle school, and 141 high school and college students (ages 16-22) who had taken high school physics where they learned two definitions of weight: an object's *true weight*, which is the gravitational force acting on the object, and *apparent weight* to account for situations such as an astronaut in orbit who appears to be "weightless," even though the astronaut is subject to Earth's gravitational field. Questions that students were asked included:

An astronaut is inside a cabin of a satellite coasting around the earth.

a. Does the gravitational force act on the astronaut?

b. Does the astronaut have weight? Explain your answers.

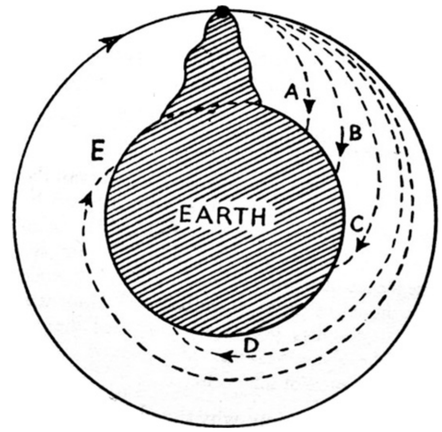

Figure 2. Illustration *from Isaac Newton's The System of the World* (1728)

Only 40% of the less advanced students and 50% of the more advanced students responded "yes" to both questions. Many of the students explained that weight and gravity were considerably reduced due to the great distance from earth. (In fact, gravity would only be reduced by about 2% at the altitude of an orbiting space shuttle.) The second most common answer explained a "no" response to both questions because gravity would be far less at that distance, while others said there would be no gravity in space. None of the students, including the college students, applied the two weight concepts (true and apparent) that are taught in high school physics to explain the situation of the astronaut in orbit.

In a recent learning study, Stein and Galili (2014) taught concepts of weight and gravitation to 141 ninth grade students (age 14) in an Israeli middle school. The instructional method was to define weight operationally as the force exerted by a body on a spring scale. The majority of students not only improved their understanding of the nature of gravitation, and recognized that there is gravitation in space, but also succeeded in explaining the phenomenon of free fall, including what happens to astronauts inside an orbiting space station. The middle school students provided more accurate qualitative responses to questions about weight than high school students who were taught using the traditional method, that weight is the force due to gravitation.

Taken together, these studies show that some progress can be made in helping students develop a consistent model of how and where gravity acts by engaging them in observations and discussions about what happens to objects that fall into holes in the Earth, or that are launched into orbit. A teacher can rely on the human capacity to develop consistent modes of thinking in helping students develop an intuitive understanding of how gravity acts. However, attempting to persuade students to give up the idea of weight as the property of an object and instead conceptualize it as a force between two objects is not only difficult, it is counterproductive since the vision of an astronaut floating in a space cabin reinforces the misconception that since the astronaut is weightless there is no gravity in space.

Table 1. Schemas about gravity, weight, and mass

Schema taught by science teachers	Common and persistent schemas
Gravity	**Gravity**
There is gravity in space.	*Gravity only exists on or near Earth.*
Gravity acts on bodies whether they are stationery or in motion, going up or free falling.	*Gravity needs air, thus it is missing on the moon or in space.*
Gravity acts at a distance and does not need air.	*Gravity acts on falling bodies. Gravity does not act on bodies thrown upwards or resting bodies.*
The force of gravity diminishes gradually with increases in altitude.	*The strength of gravity diminishes rapidly with distance from Earth..*
Weight	**Weight**
Weight is the force of gravity exerted on a body.	*Weight is heaviness.*
A body has weight if it is at rest or if it is moving, as long as it is affected by gravity.	*Weight is the property of a body.*
For a falling body its true weight is not the same as its apparent weight.	*A body does not have weight if it is falling.*
	A body in space is weightless.
	A body does not have weight if it is at rest.
	On the moon, an object will "float" if it is not heavy.
	Light matter, like gasses, have no weight.
Mass	**Mass**
Mass is the amount of matter in an object, measured by comparing the object with a known mass using a balance scale.	*Mass is the same as weight.*

Common Schemas that Persist over Time

Piaget's original work continues to be a useful way to summarize a large body of work concerning children's ideas about the physical world. By interviewing children he identified common ideas, which he called "schemas." The research literature described above can be summarized by listing the schemas that researchers have found to be common among children and adults. Table 1 compares the schemas about gravity, weight, and mass that science teachers attempt to teach middle students, with the schemas that are found to be common and persist despite instruction. We have found this table to be helpful in summarizing the findings described above, and in interpreting the results of the present study.

Despite the best efforts of educators to teach students about the important concepts of weight and mass, few are able to overcome their initial idea that weight is a property of an object, not a force that may change as an object is transported to the moon or placed in orbit. Because students tend to maintain their misconceptions even after instruction, science teachers—not just in physics, but in all fields of science—are faced with the challenge of building a deeper understanding of mechanics on shaky ground.

Purpose of the Current Study

In order to be effective it is important for teachers to have a clear understanding of their students' pre-instructional ideas (Bybee et. al, 2006). Consequently, they need to know what their students' ideas might be and what questions to ask. Curriculum developers must have a deeper knowledge of how students' ideas typically develop over time, since students sometimes revert to earlier ideas when confronted with novel situations (National Research Council, 2007). The purpose of this study is to provide that background.

Method

Following a well-established tradition of educational researchers (e.g., Piaget, 1929, 1972), our method is to infer children's understanding of a concept by asking them questions about what might occur in a given situation, ranging from common everyday examples, such as an object resting on a table, to hypothetical situations, such as an object transported to the moon.

In the 1980s, we interviewed a group of 40 ten-year-old pupils about whether or not an astronaut in a satellite (Space Shuttle) is affected by gravity and if the astronaut has weight. Approximately 90% said the astronaut is *not* affected by gravity but that the astronaut *does* have weight. The main justification given by the students was that there is no gravity in space, but that astronauts (everybody) always have weight. That is, the students indicated their belief that weight is the property of an object and is not defined by the force of gravity.

In reviewing the large body of research on this topic (Kavanagh & Sneider, 2007a, 2007b), it has occurred to us that this pair of questions ("Is it affected by gravity? Does it have weight?") could provide a means for probing students' changing schemas for weight and gravity over a considerable age range, and that the same question could be varied to provide information on how those schemas changed when students were asked to consider what would happen in different locations (e.g., on a table, in a falling elevator, in space, or on the moon) and in different conditions (i.e., falling or stationary).

Participants

Subjects in the current study were 491 students in Isareli schools, from age 10 to age 14, organized in three groups.

Group 1. We will consider the group of forty 10 year-olds interviewed in the

1980s to be Group 1. We will not analyze their comments in detail here, since it was a small sample. We mention this group primarily because they gave intriguing responses, which led to the current study.

Group 2. 265 pupils in Israeli schools participated: 29 5th graders (age 10) and 24 6th graders (age 11) in elementary school; and 66 seventh graders (age 12), 73 eighth graders (age 13), and 73 ninth graders (age 14) in middle school. Students were tested at the beginning of the school year, before any additional instruction about the concepts of weight and gravity. Students were asked to complete a written questionnaire. This group was included to determine how students' understanding develops over a broad age range.

Group 3. 186 pupils, of age 14 (ninth grade) learning in Israeli schools, completed a questionnaire with the same questions as group 2, and with extra questions to check the significance of the answers of group 2 (of the same age), and to expand our understanding of the concepts.

Instrument

The questionnaire for Group 2 included three multiple-choice questions derived from earlier studies in which students were interviewed about their understanding of weight and gravity. The researcher asked the students to mark their answers on the questionnaire and to explain their reasoning in writing. After the students completed the questionnaire and their papers were collected, the researcher led a class discussion so that students could hear how others answered the questions. By asking students at each grade level these questions we were able to determine how students' ideas about weight and gravity typically change over time.

The questionnaire for Group 3 included the same three questions, as a check on reliability. Students in Group 3 were asked additional questions to develop a finer-grained understanding of their ideas about weight and gravity in various situations.

The questions, selected response options, and data from groups 2 and 3 are shown in Tables 2 and 3.

Findings

Given the nature of the data, and our goal of confirming and refining the results of prior research, we use a descriptive approach, rather than computing inferential statistics. We rely primarily on percentages of students at various ages so that it is easy to compare with the findings of previous researchers.

Concepts of Weight, Mass, and Gravity Across Ages 10-14

Findings for questions 1, 2, and 3, are shown in Table 2. Notice that the percentage of responses for the 14 year-olds in Group 2 are very similar to the responses of 14 year-olds in group 3. Thus, group 3 provides a check of reliability—that these questions are likely to elicit similar responses from students of the same age, who have been exposed to the same curriculum.

Q1. What is the meaning of weight? At all age levels the most common answer to the first question, by a large margin, was: b. "If the object is heavy or light" (average 56%). During the class discussion that followed administration of the questionnaire students in all of the classes gave examples of heavy objects and said that they are hard to hold and lift, in order to illustrate the meaning that they attached to the word "weight." Thus, their ideas of weight included both the *idea* of "heaviness" related to tactile

Table 2. Distribution of responses to the first three questions by Groups 2 and 3*

Q1 What is the meaning of weight?	10 years	11 years	12 years	13 years	14 years	14 years**
Group	**2**	**2**	**2**	**2**	**2**	**3**
N =	29	24	66	73	73	186
a. Object is big or small	0%	0%	0%	0%	0%	0%
b. Object is heavy or light	72%	54%	65%	40%	49%	46%
c. Force of gravity exerted on the body	10%	21%	3%	25%	29%	26%
d. Quantity of matter the body contains	7%	13%	15%	16%	4%	4%
e. Force exerted on the support	10%	13%	15%	19%	18%	23%
Q2 If a 5 kg object is taken to the moon:	**10 years**	**11 years**	**12 years**	**13 years**	**14 years**	**14 years**
a. Both weight and mass will increase	0%	3%	3%	0%	2%	1%
b. Mass will not change, weight will increase	3%	3%	15%	0%	2%	2%
c. Mass will not change, weight will decrease	35%	25%	46%	62%	77%	72%
d. Mass and weight will decrease	62%	70%	38%	33%	19%	17%
Q3. An astronaut is in a space shuttle revolving around the Earth.	**10 years**	**11 years**	**12 years**	**13 years**	**14 years**	**14 years**
a. The astronaut IS influenced by gravity and DOES have weight.	21%	17%	24%	14%	12%	12%
b. The astronaut IS influenced by gravity and does NOT have weight.	7%	4%	15%	21%	27%	23%
c. The astronaut is NOT influenced by gravity and DOES have weight.	64%	48%	32%	49%	40%	41%
d. The astronaut is NOT influenced by gravity and does NOT have weight.	0%	0%	2%	0%	2%	0%

* The table does not include students who did not answer the questions.
** Data reported in the last column is from Group 3.

forces—the *feeling* of a heavy or light object.

We note that the most common response b. "If the object is heavy or light" is ambiguous. That is, "heaviness" could be considered a naïve notion of weight as a property of a body, somewhat similar to the more formal concept of mass, or as a force exerted on a support, such as the felt weight of an object when held in the hand. This answer is consistent with the response of a substantial minority of students who explain that things fall "because they are heavy" (Bar, Zinn, and Goldmuntz,1994). It is also consistent with the commonly expressed idea that astronauts are able to walk on the moon where there is no gravity because they wear heavy shoes (Watts 1982). Without interviewing students it is difficult to tell which of these schemas are guiding their responses.

Q2. If a 5kg object is taken to the moon. . . The scenario is aimed at finding out whether or not the participants recognize that weight can change but mass does not change in a world with weaker gravity. The great majority of pupils in grades five and six (ages 10 and 11) indicated that both mass and weight will decrease, showing that they do not distinguish between these two terms in the particular context. However, some students in each of these groups (35% and 25%) responded correctly that mass would stay constant while weight would decrease. These children may have learned the definition of mass at school, since it is included in the school curriculum. They may also have learned it from television or other informal sources. Students in grade seven and older (ages 12, 13, 14, 14) were more likely to answer this question correctly (46%, 62%, and 77% and 72% respectively). This finding is consistent with DePierro and Grafalo (2003), who used the students' knowledge of this distinction in Socratic dialog as a means for advancing their understanding. The conservation of mass is based on the operational definition that compares the two masses on the balance scale. For these age levels, students have learned the formal distinction between mass and weight.

Q3. An astronaut is in a space shuttle revolving around the Earth… First consider the students who answer a. or b., indicating their understanding that there IS gravity in space (acting on the astronaut). Only a minority of students believe that is the case. At 10 years old, 28% of students believe that the astronaut IS influenced by gravity. Even among the two groups of 14 year olds, only a minority believe there is gravity at the altitude of the space shuttle (39% and 35%). Regarding weight, the findings are reversed. Among students who answer a. or c., that the astronaut DOES have weight, 85% of 10 year-olds believe that the astronaut has weight, in agreement with our findings from Group 1. That percentage declines somewhat among older students, so that by age 14, only half of the students believe that the astronaut has weight (52% and 53%).

This is a remarkable finding. The idea that a body has weight even in space is popular among 10 year-olds, from which we can infer the schema "*Weight is the property of a body,*" which does not change when it goes into space. However, over the next few years students learn that astronauts are "weightless" in space. That is likely the reason why relatively few 14 year-olds believe that astronauts have weight.

Further information from this question can be gathered by looking at the specific responses, which combine the students' understanding of weight and gravity. Of the four choices, the most common across all ages is choice c. that the astronaut is NOT influenced by gravity, but DOES have weight. This was the response given also by approximately 90% of 10 year-olds in the 1980s. In this study it was given by 64% of 10 year-olds and 40% of 14 year-olds in Group 2 and 41% of the 14 year-olds in Group 3. In terms of schemas, we can infer that the students who made this selection hold the following schema:

Gravity only exists on or near Earth. It does not exist on a satellite, or in space.

Weight is the property of a body.

The second most common choice among 14 year-olds, selected by 27% in Group 2 and 23% in Group 3, is b. that the astronaut IS influenced by gravity, but does NOT have weight. Students who made this selection very likely hold the following schemas:

There is gravity in space (Or may be near the earth).

A body in space is weightless.

Notice that very few of the youngest children choose this option (7% of 10 year-olds and 4% of 11 year-olds). It is quite possible that over time the students have additional opportunities to see astronauts apparently weightless in the Space Shuttle. The more informed older students may also have heard that gravity keeps the shuttle in orbit, which would explain this response. We doubt if this answer relates to an operational definition of weight. The third most common response by the 14 year-olds is choice a. that the astronaut IS influenced by gravity and DOES have weight. Schemas that we can attribute to these children are:

Gravity exists in space.

Weight is the property of a body.

OR Weight is the force of gravity exerted on a body.

A science teacher who wanted students to understand that there is gravity in space and that weight has the Newtonian meaning of the force of gravity on an object would probably be pleased with this answer. However, it is important that such answers be interpreted cautiously since it is likely that at least some of the students take the first meaning—that weight is the property of a body rather than the force of gravity on a body—since whether an object is "heavy or light" is the most common definition given by students at all ages.

Almost no students gave choice d. as their answer that gravity does NOT act in space and weight is NOT influenced by gravity. The frequency of responses a., b., and c., are shown in Figure 3.

The similarity in responses between the 10 year-olds in the 1980s to the

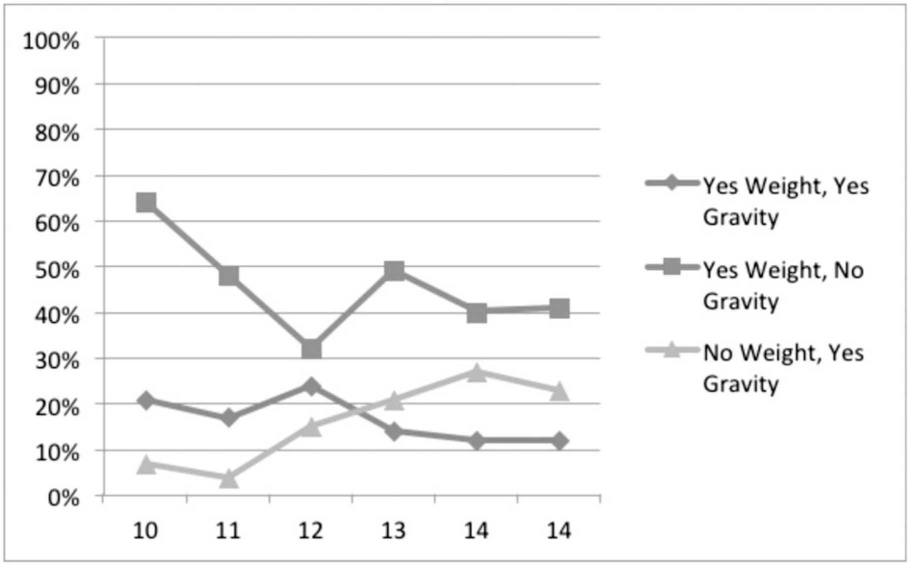

Figure 3. Frequency of responses from Groups 2 and 3 to the question: "An astronaut is in a space shuttle revolving around the Earth. Does the astronaut have weight? Is the astronaut influenced by gravity?" (Data are from Table 2.)

10 year-olds in the current study, and the similarity in responses between the 14 year-olds in Groups 2 and 3 give us confidence that these findings are consistent across grades and over time.

Where does gravity act? Further information about how students envision weight and gravity can be gathered from the written responses to the other questions presented to Group 3 that consists of 186 students, all approximately 14 years old. The questions and frequency of responses are shown in Table 3 and Figure 4. Notice that the first row of data is also displayed in Table 1. It is repeated here so it can be compared with the other answers from this group. The first four questions involve falling bodies; the last two involve stationary objects. Q8 is about an object on the moon.

Combing the data from the first two columns for falling objects (Q3, Q4, Q5, and Q6) reveals a major difference in where students believe such objects are acted on by gravity. This is shown in Figure 4.

This finding is not surprising in light of the many studies that have shown most students believe there is no gravity in space. However, it does show more detail than prior studies. Although the great majority of students (91%) understand that objects falling near Earth's surface are affected by gravity, fewer believe that gravity acts inside a falling elevator (68%), and even fewer expect gravity to act on an object falling to the moon's surface (50%) or in orbit (35%).

These findings suggest that the schemas "*Gravity only exists on or near Earth*" and "*Earth is unique*" are too simplistic to describe the great majority of students' ideas. Some students may hold the schema: "*Gravity exists near all large bodies in space* (also the moon)" but, "*Gravity does not affect bodies in orbit.*" Other students may hold the schema, noted by Stein (2010) that: *The moon has gravity, but it acts only on bodies that are in contact with it*.

In contrast, we do not find the same relationship between location and weight for falling objects or objects at rest on a table. Combining the data in columns a. and c., we observe the pattern shown in Figure 5.

There is very little difference in students' responses to whether or not an object has weight, wherever it may be. The percentage of students who said that the object has weight was 53% in orbit, 71% on the moon, 67% in a falling elevator, and 86% on Earth's surface. These findings suggest that nearly all 14 year-olds hold the schema: "*Weight is a property of a body.*" This idea, which is similar to the more formal concept of mass, and applies to objects in various locations and states of motion, seems to persist from about age of 8 or 9 years old, when students first learn that a scale can be used to compare the weights (or masses) of different objects, and persists through years of schooling during which they are told that the "real" definition of weight is the gravitational force on a body.

We asked the last two questions, to test Palmer's (2001) finding that 34% of

Table 3. Distribution of answers to questions 3-8 by students in Group 3 (N = 186, age 14 years old)

	a. Yes Gravity Yes Weight	b. Yes Gravity No Weight	c. No Gravity Yes Weight	d. No Gravity No Weight
Q3. An astronaut is in a space shuttle revolving around the Earth.	12%	23%	41%	0%
Q4. An object is falling to the moon's surface.	38%	12%	23%	22%
Q5. An object is in a free falling elevator.	49%	19%	18%	5%
Q6. An object is falling from a table.	63%	28%	2%	2%
Q7 An object is resting on a table.	70%	5%	16%	5%
Q8. An object is resting on the moon's surface.	45%	5%	26%	17%

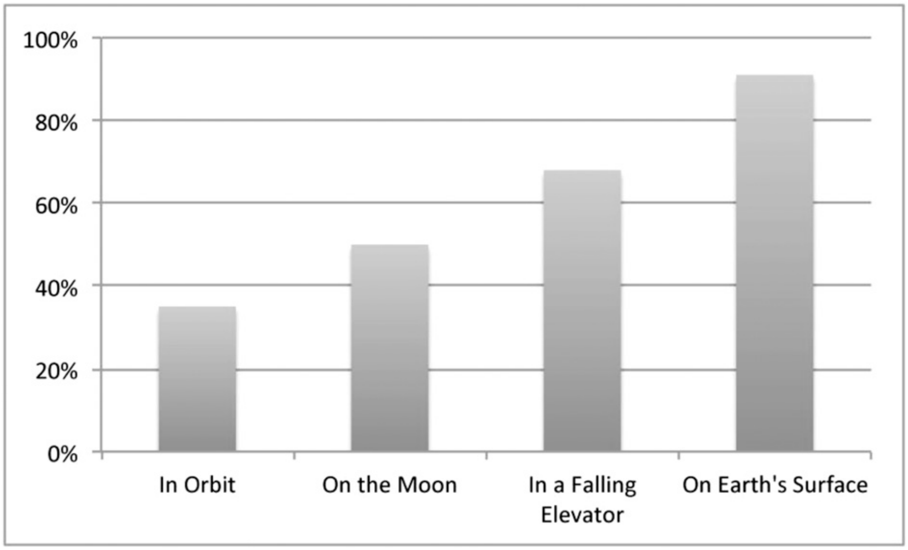

Figure 4. Where does gravity exist? Responses from Group 3 (age 14, N = 186)

students in grade 6 and 28% of students in grade 10 believed that gravity did not act on stationary objects. Our findings were consistent, in that 21% of the 14 year-olds in our sample (9th grade) did not believe that gravity acted on an object resting on a table, while only 4% thought that gravity did not act on an object falling from a table. However, we did not see such a difference when asking students about objects on the moon—45% percent believed that an object falling on the moon would not be acted on by gravity, while 43% believed that an object resting on the moon's surface would not be acted on by gravity.

To sum up these findings: Misconceptions about gravity are widespread, and most students enter high school with the pre-Newtonian idea that gravity is a special property of planet Earth (and in some cases only to its soil, not water). And, at least on Earth, whether or not gravity influences the motion of a body depends on how that body is moving. Very few students succeed in learning that weight is the force of gravity on an object. Instead, the idea of weight as "heaviness" of a body remains for most students the central idea of weight. Separating the concepts of mass and weight is also challenging, especially since both terms are closely bound to the idea of gravity, about which most students have deeply seated misconceptions.

Discussion

The educational community in the United States is now faced with a new set of standards that require students to think deeply about scientific issues, and to be able to apply learned concepts to new situations, and in many cases, to solve engineering challenges. That means it will no longer be sufficient for students to parrot back learned definitions, such as "weight is the force of gravity on an object." They must develop a conceptually deep understanding of core ideas.

In this paper we have summarized a considerable body of research, including the findings of many researchers and our own recent additions, about student's ideas concerning three threshold concepts—weight, mass, and gravity. These three concepts provide the intellectual underpinning of many of the performance expectations in the Next Generation Science Standards. Failure to understand these concepts is likely to impede students' abilities to achieve performance expectations. As we have shown, very few students have developed a deep conceptual understanding of these concepts.

The first step in determining what to do about the situation is to understand the problem. That has been the primary purpose of this paper. We did not make new discoveries about students' understanding of these three concepts. We have shown that the problems identified by previous researchers persist. We now need to turn to the question of what to do about it.

The Concept of Weight

As we mentioned in the introduction to this paper, the history of science can offer insight. It is not difficult to see a parallel with the development of the concept of weight in children and the development of the weight concept in history. The first ideas about weight concern how heavy something feels. For children age 5-6, a ball feels heavier than the same object pushed into a different shape because they perceive it to be heavier on the hand. Children who are a little more mature can learn to conserve weight by experimenting with a balance, finding that two lumps of clay on a balance have the same weight, no matter how their shapes may be changed. This is the concept of "heaviness" that is measureable and represents an early notion of mass. Developing the formal concepts of mass and gravity was a struggle for Isaac Newton and his contemporaries. So it should not be surprising that it is a struggle for our students.

Objects that appear to weigh nothing. The question of what objects have weight and which do not is exceptionally important in understanding many other ideas in science, as suggested in the introduction concerning a bright seventh grader who did not believe that the mass of a tree could come from carbon in the air, since air "doesn't weigh anything." Although children do not typically mention lightness in the sense of levity as described by Plato and Aristotle, they do have an idea that a light object has little or no weight at all, an idea that persists into high school and for many adults regarding certain objects (hair, dust) and substances (water vapor, air). There are many different activities, videos, and other instructional resources that have been developed to help students learn that even air has weight, and it is

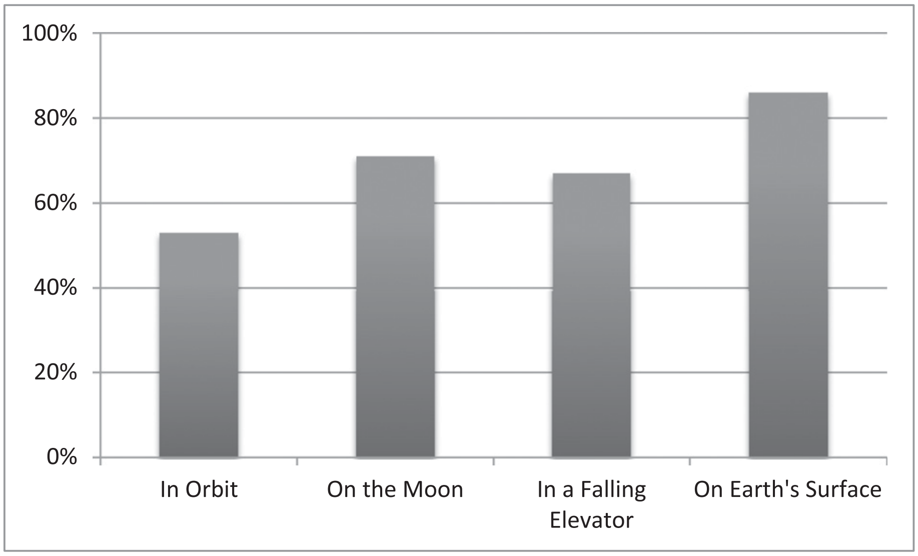

Figure 5. Does an object have weight? Responses from Group 3 (age 14, N = 186)

essential that some collection of these become part of the curriculum at the upper elementary level, once students have a solid grasp of weight as the property of an object that can be weighed with a scale.

A proposed definition of weight. Given the widespread finding that across the age spectrum it is extremely difficult to change people's perception that weight is anything but felt "heaviness," we support the recommendation by others that science curricula no longer try to convince students that weight is not a property of an object, but rather a force due to gravity. Instead, we believe that weight should be defined operationally, as the result of weighing with a spring scale (Galili, 1995; Galili & Kaplan, 1996; Galili, 2012; Morrison, 1999). This recommendation is consistent with children's earlier conception of weight as felt "heaviness." With this definition students will have no difficulty understanding the "weightless" condition of astronauts in orbit, while still being acted on by gravitation. Since objects in orbit cannot be weighed—that is, they cannot be weighed by a spring scale—they are indeed weightless. Thus there is no need for the distinction between true and apparent weight, which is currently taught in advanced high school physics courses, and is poorly understood by students, even at the college level.

Although we advocate defining weight operationally, we caution that this alone will not solve the problem that many students have difficulty believing that air has weight, since it is impossible to weigh air with a spring scale. However, certain demonstrations may help students grasp this idea. For example, the teacher can "pour" carbon dioxide gas onto a burning candle to extinguish the flame. Students can blow bubbles and watch them float on a layer of carbon dioxide gas in a bowl. Definitions alone do not substitute for a variety of experiences with phenomena and conversations in which students develop a rich and nuanced understanding of these threshold concepts.

Weight and Newton's Third Law. This concept of weight can also help students better understand Newton's third law—that pairs of interacting objects exert equal and opposite forces on each other. An object on a spring scale is an excellent example of such a reaction pair. In a classical example of good physics teaching, Minstrell (1982) devised a means for demonstrating that a table exerts a force on an object that rests on it. He bounced a beam of light off the surface of a lab table so that it shone on a wall. When he jumped on the table the students could see the light move, confirming that the table acted like a spring, to oppose the force of the object. Similarly when students weigh an object with a spring scale they observe the effect of the object on the spring.

Mass. Regarding the concept of mass, the findings reported here do support the distinction between weight and mass as typically presented in middle school. We found that the percentage of students who correctly separate the two concepts when considering what happens when an object is transported to the moon, increases from 35% at age 10 to 77% at age 14. Keeping in mind common misconceptions about gravity, it is important that when presenting the idea of mass, it is essential to also address the gravity concept at the same time. We do not claim that students will fully understand the distinction between the two concepts by age 14, but it's a start, and it's a distinction worth making for learning of additional concepts at a later time, such as the idea of density.

Gravity. Regarding instruction in gravity, recall the instructional unit cited in the literature review about a 90-minute instructional unit concerning orbits. Based on Newton's description of how a cannon could fire a cannonball into orbit, the unit succeeded in at least doubling the number of sixth grade children who understood that there is gravity in space. Such historical examples can be especially rich in suggesting instructional methods.

In the long term it will be important to conduct further learning studies in order to determine how best to help students learn that Earth's gravity extends to the Moon and beyond, and that the Moon and planets exert their own gravitational pull on other bodies. Students should be able to envision weighing an object on different planets, noting how the weight is proportional to the mass of the planet, and comparing the mass of two objects on different planets using a balance, finding that mass does not change, but weight does. Understanding these foundational concepts is necessary if students are to eventually build a deep and consistent understanding of free fall, trajectories, and orbits— concepts that are important for all citizens to understand in the modern age.

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