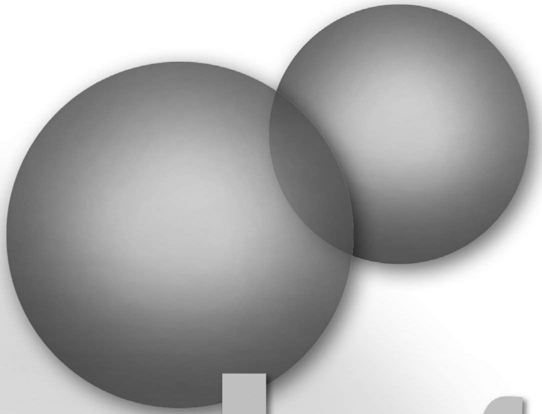
VOL. 1

# Uncovering Student Ideas in Physical Science

## 45 NEW Force and Motion Assessment Probes



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# Uncovering Student Ideas in Physical Science

## 45 NEW Force and Motion Assessment Probes

By Page Keeley and
Rand Harrington

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# Dedication

*This book is dedicated to Rand's parents, Bev and Don Harrington, and to Bev Cox, an extraordinary science specialist retired from the Orange County School District in Orlando, Florida. Through Bev's leadership, formative assessment has impacted hundreds of teachers and thousands of students in one of the largest school districts in the nation.*

# Foreword

Formative assessment—or assessment for learning—has become an increasingly common focus for teachers and schools since the late 1990s. Touted by research as the single most effective strategy for advancing learning for all students, formative assessment has been incorporated by more and more teachers into their classroom practices. As they do so, they are discovering that the process is far more complex than simply administering a probe or checking in occasionally to see if students are "getting it." Teachers are finding that to effectively use assessment results to further learning, the strategies they employ have to be carefully linked to specific learning goals. Formative assessment provides them with rich information that allows them to understand not only *what* students have learned but *how* they are learning. Teachers see the importance of asking students two critical questions: *What do you know?* and *How do you know that?* Getting answers to these questions are especially important in assessing conceptual learning (as opposed to assessing skill mastery) in science and mathematics.

To really attend to students' ideas in the classroom requires a change in perspective for teachers and students. Many of the teachers with whom we have worked describe it as a move from a focus on teacher performance to a focus on student learning—a shift from teacher- or lesson-based learning to learning-based lessons. A focus on student learning also means using probes, elicitations, and lessons that will help teachers answer a question they must pose to themselves: *What and how are my students learning in relation to the learning goal?* This focus also entails reflecting on the information collected and interpreting it to answer two additional questions: *What are the strengths and problematic aspects of the students' thinking?* and *What do these students need next to deepen their learning?* Finally, a focus on student learning means that subsequent instruction addresses the question *What learning experience or feedback will address the identified needs as well as the learning goal?* This cycle of collection, interpretation, and action is an ongoing process in which the art and science of instruction meet. In addition, it requires teachers to draw more heavily than they have before on their science content and pedagogical content knowledge (knowledge of how students learn a particular science concept) in order to make the cycle effective. As many teachers have observed, formative assessment initially appears to be easy to carry out. In fact, that impression is deceptive. Formal assessment takes time, tenacity, and resources if it is to be done well.

*Uncovering Student Ideas in Physical Science* is the latest addition to an important series of resources that support teachers who are building and refining their use of formative assessment in science. The re-organization of resources around important "big ideas" in science not only emphasizes the targeted nature of the formative assessment process but also is likely to help teachers address their own learning needs more systematically. As in the earlier, four-volume *Uncovering Student Ideas in Science* series by Page Keeley and her colleagues, she and Rand Harrington in this volume provide information and references in the Teacher Notes accompanying each probe to help teachers scaffold their own learning as well as that of their students. The Purpose description, for example, provides important information about what a specific probe is expected to elicit and how this might be related to larger learning goals. This discussion of the purpose, together with the Related Ideas in the National Standards sections, will help teachers be more purposeful in collecting information about student learning and in selecting assessment tools and strategies that are closely tied to a specific learning goal.

The suggestions provided in Administering the Probe can be used by teachers to anticipate and eventually interpret their students' responses. This section and the Related Concepts section will support teachers in their efforts to become more flexible in their assessments and to hone in on student understanding of a particular idea. These sections also underscore the ongoing, targeted nature of formative assessment. For example, the half-dozen probes in the book that are related to Newton's first law could be used at various points in a unit to explore students' developing conceptual understanding. One or two probes could be used early in the unit when focusing on straight-line motion. Another probe could be used midway by relating the first law to relative motion. Finally, three other probes could be used when instruction focuses on the topics of changing direction and circular motion. Alternatively, the same six probes could be used by a school or district to articulate its curriculum regarding motion. As noted in the probes themselves, some would be appropriate at the intermediate or middle school level, while others could be used for review and extension at the high school level.

Both the Explanation and Related Research sections offer resources to support teachers' knowledge needs. The brief scientific explanation provided with each probe not only helps teachers to better interpret their students' responses but also could alert them to their own content-related learning needs before they engage their students. Meanwhile, the descriptions of findings from related research give teachers additional information about the intention of each probe and about why the student thinking it elicits matters in the overall progression of learning. Teachers can use this information to develop the pedagogical content knowledge that is so important to effective formative assessment. In turn, they will be able to better understand how students learn the subject of force and motion.

Although no written resource will provide teachers with a "silver bullet" solution to every challenge, this new *Uncovering Student Ideas in Physical Science* series promises to do more than any other resource I know of to give support to teachers who are trying to engage in effective formative assessment in science. This book and the four volumes to follow in the series on physical science, together with earlier works such as *Science Curriculum Topic Study* and *Science Formative Assessment*, are essential additions to the library of any professional science educator or organization. This growing set of tools provides teachers with greater opportunities to explore their students' thinking, challenge their own, and have fun in the process.

**Jim Minstrell**
***FACET Innovations***

# Preface

## Background

Since the late 1990s, K–12 science educators have acknowledged the critical importance of using diagnostic tools and formative assessments to improve teaching and learning. Significant research-based publications such as *How People Learn: Brain, Mind, Experience, and School* (Bransford, Brown, and Cocking 2000) raised teachers' awareness of the need to identify the preconceptions that students bring to the science classroom and use these preconceptions as springboards for learning. However, student- and teacher-friendly questions that make K–12 students' thinking visible to themselves and their teachers were not readily available. Thus, the four-volume *Uncovering Student Ideas in Science* series was born.

In October 2005, the first book in the series rolled off the press, making its debut at the NSTA Area Conference in Hartford, Connecticut. The book was the first of its kind. It gave K–12 educators a set of probing science questions to use with students on life, Earth, space, and physical science. The "probes" link key ideas in the K–12 content standards (AAAS 1993 and NRC 1996) to research on students' commonly held ideas. Each probe is accompanied by detailed teacher background notes on science content and suggestions for use in the classroom. Although the physics education community had developed diagnostic assessments for many years for high school and undergraduate physics students, such as the Force and Motion Conceptual Evaluation (Thornton and Sokoloff 1998), no similar assessment that probed K–12 students' science preconceptions existed until Volume 1 in the *Uncovering Student Ideas in Science* series was published.

Three additional volumes later—with a total of 100 K–12 formative assessment probes now published—the *Uncovering Student Ideas in Science* series has soared in popularity. The four books are used by thousands of K–12 classroom teachers, university professors, professional developers, instructional coaches and mentors, and even parents. The series has become a valuable resource for improving student learning and deepening teachers' science content knowledge.

Each volume's introduction contains vital information about the use of the probes and formative assessment:

- Introduction to Vol. 1: Presents an overview of formative assessment: what it is and how it differs from summative assessment. Background on probes as specific types of formative assessments and how they are developed is provided.
- Introduction to Vol. 2: Describes the link between formative assessment and instruction and suggests ways to embed the probes into your teaching.
- Introduction to Vol. 3: Describes how to use the probes and student work—either individually or through professional learning communities—to (a) deepen your understanding of students' ideas and the implications of those ideas for instruction, (b) learn new science content, or (c) even uncover a deeply rooted misconception you might have.
- Introduction to Vol. 4: Describes the link between formative and summative assessment. Gives reasons why an investment in formative assessment before and throughout instruction can improve students' performance on the summative end.

# Preface

Collectively, these four introductions will expand your assessment and instructional repertoires and will deepen your understanding of students' thinking and effective science teaching.

## The New Series: *Uncovering Student Ideas in Physical Science*

In 2009, after the publication of Volume 4, Page Keeley, principal author and probe developer of the *Uncovering Student Ideas in Science* series, decided to begin a new set of books that would focus on specific topics in physical science. The new series is called *Uncovering Student Ideas in Physical Science.* This book—on force and motion—is the first in that anticipated five-volume series. The topics of the four volumes to come will be electricity and magnetism, energy, sound and light, and matter.

## Format of This Book

This book contains 45 probes on force and motion for a variety of grade levels, from elementary grades up through high school. It is made up of three sections: Section 1, Describing Motion and Position; Section 2, Forces and Newton's Laws; and Section 3, Mass, Weight, Gravity, and Other Topics. The format is similar to that of the earlier four volumes, with a few changes due to the topic-focused nature of this series. For example, the book's introduction (starting on p. 1) focuses specifically on why force and motion ideas are challenging to teach and learn. As in the earlier series, each probe is followed by a Teacher Notes section, which is made up of these eight elements.

### 1. Purpose

This section describes the purpose of the probe—that is, why you would want to use it with your students. It also states the general science concept or topic targeted by the probe and the specific ideas the probe is trying to elicit from students. Before using a probe, you should be clear about what the probe can reveal. Taking time to read the purpose will help you decide if the probe fits your intended use.

### 2. Related Concepts

Each probe is designed to target one or more related concepts that often cut across grade spans. These concepts are also included on the concept matrix charts on pages 12, 67, and 140. A single concept may be addressed by multiple probes as indicated on the concept matrix. You may find it useful to use a cluster of probes to target a concept or specific ideas within a concept. For example, there are six probes that relate to Newton's first law of motion.

### 3. Explanation

A brief scientific explanation accompanies each probe and clarifies the scientific content that underlies the probe. The explanations are designed to help you identify what the "best" or most scientifically acceptable answers are (sometimes there is an "it depends" answer) as well as clarify any misunderstandings you might have about the content.

The explanations are not intended to provide detailed background knowledge about the content nor are they written for an audience of physicists. In writing these explanations, we were careful to keep in mind that our audience will include teachers who have little or no physics background. We tried not to oversimplify the science but at the same time we wanted to provide the science content a novice teacher would need. If you need additional background information on the content, refer to the NSTA resources listed at the beginning of each section (pp. 13, 69–70, and 141–142), such as *Force and Motion: Stop Faking It! Finally Understanding Science So You Can Teach It* (Robertson 2002) or a Science Object from the NSTA Learning Center.

### 4. Administering the Probe

In this section, we suggest ways to administer the probe to students, including appropriate grade spans and, in some cases, modifications to make a probe that is intended for one grade span useful for another. A modification might be to eliminate certain choices from the list of possible answers for younger students, who may not be familiar with particular words or examples. In other probes, we might recommend using the word *weight* instead of *mass* as a "stepping-stone" concept with younger elementary students, who frequently confuse the word *mass* with the phonetically similar word *massive*. (See a description of stepping-stone ideas on p. 5 in the introduction.) The Administering the Probe section also tells teachers when it is a good idea to establish the context for the probe by showing students the various items that are referred to in the probe (e.g., a ramp, a ball). Also, although the probes were designed to be used by individual students, this section occasionally recommends that a probe be used in small groups.

The suggested grade levels, which appear in the concept matrixes that precede each section, are intended to be suggestions only. Your decision about whether or not to use a probe depends on why you are using the probe and on your students' readiness. Do you want to know about the ideas your students are expected to learn in your grade-level standards? Are you interested in how preconceived ideas develop and change across multiple grade levels in your school whether or not they are formally taught? Are you interested in whether students achieved a scientific understanding of previous grade-level ideas before you introduce higher-level concepts? Do you have students who are ready for advanced concepts? We recommend that you weigh the suggested grade levels against the knowledge you have of your own students, your school's curriculum, and your state's standards.

### 5. Related Ideas in the National Standards

This section lists the learning goals stated in the two national documents generally considered the national science standards: *Benchmarks for Science Literacy* (AAAS 1993) and the *National Science Education Standards* (NRC 1996). The learning goals from these two documents are quoted here because almost all state standards are based on them. Also, because the probes are not designed as summative assessments, the learning goals in this section are not intended to be considered alignments but rather ideas that are related in some way to the probe.

Some targeted probe ideas, such as the simple machines–related ideas in Section 3, are not explicitly stated as learning goals in the standards, but they are clearly related to concepts in the standards that address specific ideas about forces and energy. The national science standards do not include simple machines for the purpose of learning the types and names of simple machines; instead, simple machines are used as a context in the standards for important learning goals. However, because ideas such as simple machines often appear in state standards and are commonly used in curriculum materials, we have included them here as "Other Topics" (probes #39–#45). When the ideas elicited by a probe appear to be a strong match (aligned) with a national standard's learning goal, these matches are indicated by a star symbol (★). You may find these "matches" helpful when you are using probes with lessons and instructional materials that are strongly aligned to your state and local standards and specific grade level.

Sometimes you will notice that an elementary learning goal from the national standards is included in middle school and high school probes. This is because it is useful to see the related idea that the probe may build on from a previous grade span. Likewise, sometimes a high school learning goal from the national standards is included even though the probe is designated for grades K–8. This is because it is useful to consider the next level of sophistication that students will encounter in their spiraled learning.

### 6. Related Research

Each probe is informed by research regarding students' typical preconceptions about force and motion. The authors primarily drew on two comprehensive research summaries commonly available to educators: Chapter 15 in *Benchmarks for Science Literacy* (AAAS 1993) and Driver's *Making Sense of Secondary Science: Research Into Children's Ideas* (Driver et al. 1994). We also examined physics education research. The research findings will help you better understand the intent of the probes and the kinds of thinking your students are likely to reveal when they respond to them. We encourage you to seek new and additional published research. The Curriculum Topic Study (Keeley 2005) website at *www.curriculumtopicstudy.org* has a searchable database to access additional current research articles on learning.

It should be noted that although many of the research studies we cite were conducted in past decades and involved children in other countries as well as the United States, most of the results of these studies are considered timeless and universal. Whether students develop their ideas in the United States or in other countries, research indicates that many of their ideas about force and motion are pervasive, regardless of geographic boundaries and societal and cultural influences.

### 7. Suggestions for Instruction and Assessment

A probe remains simply diagnostic, not formative, unless you use the information acquired from your students to inform your instruction. After analyzing your students' responses, the most important step is to decide on the student interventions and instructional paths that would work best for you, based on your students' thinking. We have included suggestions gathered from the wisdom of teachers, the knowledge base on effective science teaching, research, and our own collective experiences working with students and teachers. In the "Suggestions for Instruction and Assessment" section, you will not find extensive lists of detailed instructional strategies but rather brief suggestions for planning or modifying your curriculum or instruction to help students learn ideas that they may be struggling with. After administering a probe, you may find that you need to provide an effective context for certain topics or that using a bridging analogy would work for you and your students. Effective contexts and bridging analogies are among the suggestions in this section.

Learning is a very complex process and no single suggestion will help all students learn. But formative assessment encourages you to think carefully about the variety of instructional strategies and experiences needed to help students learn scientific ideas. As you become more familiar with the ideas your students have and the many factors that may have contributed to their misunderstandings, you will identify additional strategies to teach for conceptual change.

### 8. References

References are provided for the standards, research findings, and some of the suggestions cited in the Teacher Notes. You might want to read the full research summary or access a copy of the research paper or resource cited in the Related Research section.

## Introductory Elements of Each Section

Each of this book's three sections begins with three elements.

1. **Concept Matrix** (pp. 12, 68, and 140).

The matrix allows the user to see at a glance what science concepts are related to each probe and what the most appropriate grade level is for using the probe.

2. **Related Curriculum Topic Study (CTS) Guides.** This is a list of four or five topics that are covered in the book *Science Curriculum Topic Study: Bridging the Gap Between Standards and Practice* (Keeley 2005) and are related to the probes in that section. The guides in *Science Curriculum Topic Study* were used to inform the development of the probes in this book. For more information on how the guides themselves were developed, and an example of a guide and how it was used to develop a probe, see the Appendix on pages xix–xxi.
3. **Related NSTA Press Books, NSTA Journal Articles, and NSTA Learning Center Resources.** NSTA's journals and books are increasingly targeting the ideas that students bring to their learning. We have provided a few suggestions for additional readings and online resources that complement or extend the use of the individual probes and the background information that accompanies each probe. These resources can be used to improve teachers' content knowledge, pedagogical content knowledge, and instructional repertoire. Searching the Learning Center on the NSTA website at *http://learningcenter.nsta.org/?lid=hp* will provide additional resources.

## Using the Probes: Curricular and Instructional Considerations

Unlike most summative assessments, the probes in this book are not limited to one grade level. What makes them interesting and useful is that they provide insights into the knowledge and thinking students may acquire as they progress from one grade span to the next. Sometimes the same idea comes up at different grade levels in a different context. Teachers in the middle school or high school grades might ask teachers in the elementary grades to give a probe to younger students, who may already have ideas about a particular concept before they formally encounter the concept in later grades. Elementary teachers can share the results with middle school or high school teachers so those teachers learn the kinds of ideas younger students have already formed that may affect their learning of more sophisticated concepts in later grades. Some probes can be used across elementary, middle school, and high school grades; others may cross over just a few grade levels; and a few are designed specifically for high school physics students or for elementary students. Teachers from different grade spans (e.g., in middle school and high school) with a spiraling curriculum could administer the same probe and come together and discuss their findings. To do this, it is helpful to know what students typically experience at a given grade span about force and motion. The instructional and curricular considerations described in the essays about force and motion in *Benchmarks for Science Literacy* (AAAS 1993) and the *National Science Education Standards* (NRC 1996) are summarized below.

### Elementary Grades

During the early grades—from preschool and kindergarten through grade 2—children should have many varied opportunities to observe and describe all kinds of moving things. They should be encouraged to ask questions such as, Does it [an object] move in a straight line? Does it move fast or slow? How far will it move? What direction will it move in? Where does its motion start? Where does its motion end? How can I make it move (including using magnets to make things move without touching)? How can I change the way it moves? Teachers should encourage the children to investigate their questions by recording and drawing what they see.

This is also the time when young children should be developing the descriptive language needed to describe motion and position, using terms such as *straight, zigzag, round and round, back and forth, fast and slow, up, down, in front,* and *behind.* They should also have opportunities to use simple measurement devices, including ones they create, and be introduced to techniques to measure distance and time.

During the intermediate grades (grades 3–5), students should continue describing motion. They should also sharpen their measurement skills, becoming more quantitative in their measurements. Their descriptions and drawings will become much richer and more detailed than in their early days in school. They should become increasingly familiar with techniques and units for measuring distance, time, and speed. Varied opportunities should be provided to manipulate objects by pushing, pulling, throwing, dropping, sliding, and rolling. Students in grades 3–5 should also become increasingly facile with measurement tools such as rulers, tape measures, clocks, and stopwatches. Recording motion data and looking for patterns on simple grids and graphs should be integral parts of the curriculum. By the end of fifth grade, students should be able to describe speed as the distance traveled in a given unit of time.

This idea that forces can move things at a distance without objects touching is further developed in grades 3–5 as students investigate pushes and pulls using magnets and electrically charged objects. Through these experiences, they begin to work out some of the general relationships between force and a change in motion. They should investigate and experience a variety of forces. During this grade span, most students internalize a force as a push or pull of one thing on another, a prerequisite to the notion of interactions.

Early notions about gravity develop before students are ever introduced to the word. In the early years, they observe that things fall downward if there is nothing to hold them up. In grades 3–5, they develop the notion that things fall or remain on the ground because the Earth *pulls* on them. During these years, students have many experiences balancing objects and begin to recognize quantitative aspects of balancing.

### Middle School

Students continue describing motion, with increasing attention to appropriate scientific terminology. Using simple objects, such as rolling balls and mechanical toys, students move from qualitative to quantitative descriptions of motion and describe the forces acting on the moving objects. Given opportunities to see the effect of reducing friction, they can begin to imagine a frictionless situation when describing motion. At this level, students move from thinking about motion in terms of motion-or-no-motion to categorizing motion as steady motion (e.g., constant speed, uniform motion), speeding up, and slowing down. They perform basic calculations to determine speed and recognize the difference between speed in a single moment of time versus average speed.

This is a time to connect students' learning in mathematics to applications in science because a conceptual and procedural understanding of ratio and proportion is important to quantitatively describing motion. In middle school, students transition from thinking about just speed, to speed and direction, using the term *velocity.* (*Note:* Acceleration is a difficult concept at this level and is not emphasized in the grade-level standards.) Students become more skilled and precise in their use of measurement tools and techniques, including the use of computer probeware to analyze motion. Representations such as motion diagrams and graphs should be used to encourage students to analyze and communicate motion data.

The relationship between force and motion is further developed at this grade level. Students become familiar with the concept of inertia and seem to have little problem with believing an object at rest tends to stay at rest unless acted upon by an outside force. They can relate everyday phenomena to this idea. However, they have a difficult time accepting the idea that an object in motion will keep moving unless a force is applied to it. The more experiences students have seeing the effect of reducing friction and discussing it, the easier it may be to get them to accept the idea that a moving object will keep moving in a frictionless environment.

Students should now develop the notion of balanced and unbalanced forces and should have ample opportunity to describe the forces acting on objects. Instruction should include opportunities to think about both active and passive forces because students at this age tend to equate force with motion and may think there is no force acting on an object that is not moving, such as a book on a table.

The notion of gravitational force is introduced at this level. Students move beyond terrestrial gravity to realizing that gravity applies to all matter everywhere in the universe. They also move beyond thinking about the Earth *pulling* to the idea of gravity as a force directed from Earth's center. They also begin to learn qualitatively that gravitational force depends on the size of the masses and the distance between them.

Overall, the concrete experiences students have in middle school with identifying forces and describing motion provide the foundation on which a more comprehensive and detailed understanding of force and motion will be developed in high school.

### High School

In high school, students learn to use more sophisticated mathematics to represent various motions, a field of study within physics called "kinematics." However, students need explicit help to maintain a connection between these representations and the actual motion. Position, velocity, and acceleration graphs are an integral part of their learning, and students spend time thinking deeply about the differences between a quantity and a change in that quantity. At this level, students realize the power of mathematics in describing and representing real-world phenomena and are expected to be able to calculate and then interpret the slope of a graph. Motion detectors are frequently used to help students learn these concepts. These detectors provide real-time graphs of the motion of an object (such as a walking student) and can be a significant benefit to those who struggle to understand the connection between a graph and the motion.

In addition to graphs, students are also introduced to vectors (arrows) as a way to represent position, velocity, and acceleration. Although this representation can be very useful, vectors can also be difficult to understand because the length of each vector (an arrow) can represent different quantities (such as the speed or the acceleration of the object). At a basic level, students can learn how to add and subtract vectors graphically, while students with the prerequisite mathematics skills and conceptual understanding can learn to use trigonometry to analyze vector components.

An understanding of vectors and motion graphs is then typically applied to objects that are moving in two dimensions, such as projectile or circular motions. One increasingly popular method of collecting data of objects moving in two dimensions is to use video cameras. The short film clips can be imported into a computer and used to measure the position of the object as a function of time and to generate motion graphs.

After students have a firm understanding of kinematics, the topics of dynamics are typically introduced. Dynamics includes the study of forces (Newton's three laws), momentum, energy, and rotations. Students learn how to use their understanding of motion to infer the presence of a net force (when there is a change in the velocity of an object) and to infer changes in mechanical energy. Mechanical energy is the combination of kinetic energy (energy of motion) and gravitational potential energy (energy related to the location of the object near other masses like the Earth). Forces that are applied to an object and result in the object moving can cause a change in these energies.

One of the primary problem-solving tools introduced in high school physics courses is the free-body diagram. The purpose of this diagram is to indicate all the forces acting on a single object. Each force on the diagram is represented by an arrow (or vector) that shows the size of the force (by the length of the arrow) and the direction in which the force is acting. Adding the forces (to determine the net force) requires that students take the directions of each force into account. Mathematically, this requires students to add or subtract vectors, which is different than adding or subtracting numbers.

After developing an understanding of forces, students learn to apply these ideas in increasingly more difficult contexts. A context would include systems with multiple objects that interact, including the analysis of collisions, and systems that rotate. The analysis of collisions requires an understanding of Newton's third law, which lies at the foundation of the principle of the conservation of momentum. Objects that rotate provide a context for students to revisit kinematics and dynamics using angular quantities, such as angular velocity, angular acceleration, and torque. In addition, many physics courses contain a separate unit on gravity. This unit typically includes the introduction to the universal law of gravity and the study of planetary motions using Kepler's laws.

Students need these multiple contexts to gain a deeper understanding of the fundamental principles of force and motion. Many physics teachers encourage or require students to pursue research projects or to conduct independent experiments. One such area that is rich in possibilities is the study of simple machines. Studying simple machines gives students practice in identifying forces and analyzing motions in situations that include levers, pulleys, and gears; they also explore the conditions required for static equilibrium (balancing).

It should be noted that although the sequence of ideas we describe is very common to most high school physics courses, variability does exist. One variation is to introduce the concept of energy prior to the concept of force. Another variation is the "physics first" program, with physics being taught in ninth grade, followed by chemistry and biology. If this sequence is adopted, it is generally recommended that the physics course focus more on concept development and experimental methods than on traditional problem solving that requires a more sophisticated understanding of mathematics.

## Formative Assessment Reminder

Now that you have the background on this new series and this book, let's not forget the formative purpose of these probes. Remember—a probe is not formative unless you use the information from the probe to modify, adapt, or change your instruction so that students have increased opportunities to learn the important ideas related to force and motion. As a companion to this book, NSTA has co-published the book *Science Formative Assessment: 75 Practical Strategies for Linking Assessment, Instruction, and Learning* (Keeley 2008). In this book you will find strategies to use with the probes to facilitate elicitation of student thinking, support metacognition, spark inquiry, encourage discussion, monitor progress toward conceptual change, encourage feedback, and promote self-assessment and reflection. We hope these probes and the techniques you can use along with them will stimulate new ways of assessing your students, create conducive environments for learning, promote richer discussions, and help you discover and use new knowledge about teaching and learning.

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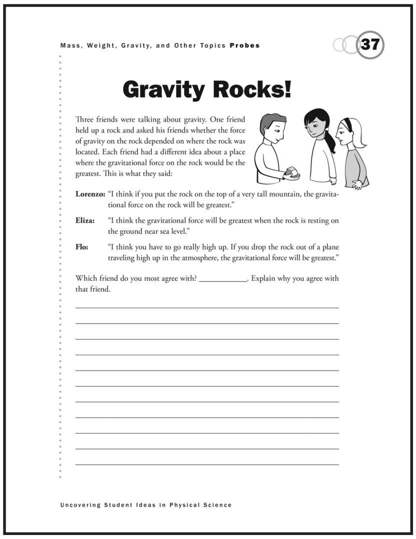
## Appendix

The book *Science Curriculum Topic Study: Bridging the Gap Between Standards and Practice* (Keeley 2005) describes the process for creating a standards-based and research-informed assessment probe. The book is made up of 147 single-page curriculum topic study (CTS) guides intended for science educators to use to

- learn more about a science topic's content,
- examine instructional implications,
- identify specific learning goals and scientific ideas,
- examine the research on student learning,
- consider connections to other topics,
- examine the coherency of ideas that build over time, and
- link understandings to state and district standards.

The CTS guides use national standards (*Benchmarks for Science Literacy* [AAAS 1993] and the *National Science Education Standards* [NRC 1996]) and research (Driver et al. 1994 and others) in a systematic study process that deepens teachers' understanding of particular science topics. For example, Figure 1 (p. xx) shows a CTS guide that was used to study the topic of *gravitational force.* Then, as shown in Figure 2 (p. xxi), the resources in that guide were used to create a probe on *gravity.*

In Figure 2, the ideas from the standards in the left-hand column in bold type were matched with commonly held student ideas as cited in the research. These ideas are in the right-hand column, also in bold type. Then, based on the infor-



Mass, Weight, Gravity, and Other Topics **Probes** 37

**Gravity Rocks!**

Three friends were talking about gravity. One friend held up a rock and asked his friends whether the force of gravity on the rock depended on where the rock was located. Each friend had a different idea about a place where the gravitational force on the rock would be the greatest. This is what they said:

**Lorenzo:** "I think if you put the rock on the top of a very tall mountain, the gravitational force on the rock will be greatest."

**Eliza:** "I think the gravitational force will be greatest when the rock is resting on the ground near sea level."

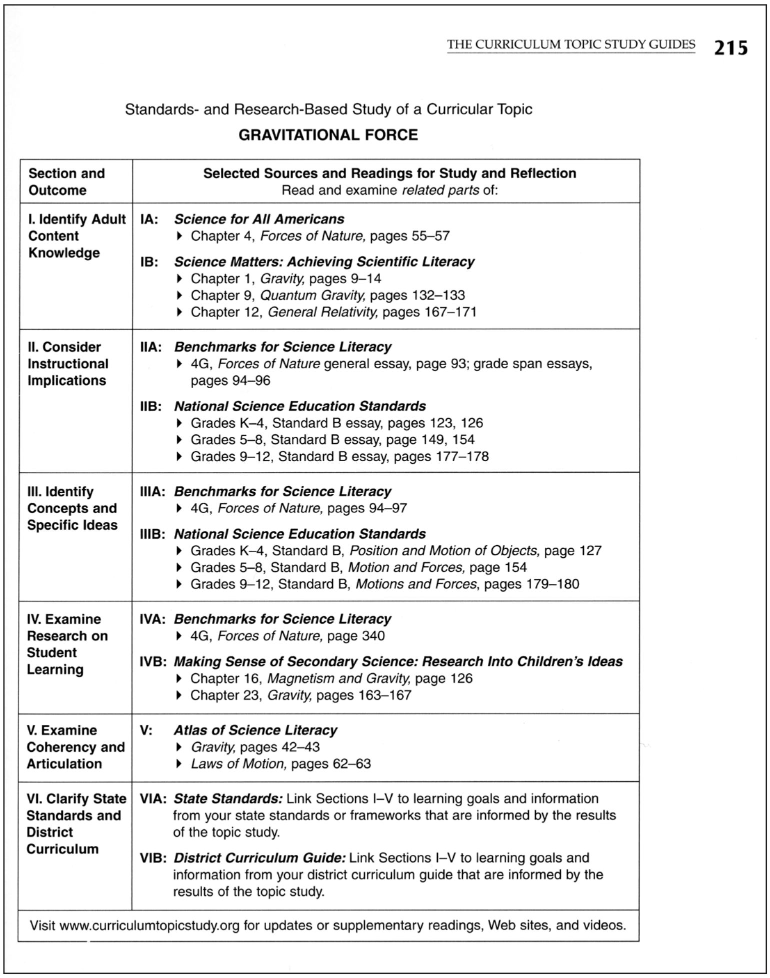
**Flo:** "I think you have to go really high up. If you drop the rock out of a plane traveling high up in the atmosphere, the gravitational force will be greatest."

Which friend do you most agree with? ____________. Explain why you agree with that friend.

Uncovering Student Ideas in Physical Science

# Preface

**Figure 1. Curriculum Topic Study (CTS) Guide: Gravitational Force**



THE CURRICULUM TOPIC STUDY GUIDES 215

Standards- and Research-Based Study of a Curricular Topic

**GRAVITATIONAL FORCE**

| **Section and Outcome** | **Selected Sources and Readings for Study and Reflection** Read and examine *related parts* of: |
|---|---|
| **I. Identify Adult Content Knowledge** | **IA:** ***Science for All Americans***<br>▸ Chapter 4, *Forces of Nature,* pages 55–57<br>**IB:** ***Science Matters: Achieving Scientific Literacy***<br>▸ Chapter 1, *Gravity,* pages 9–14<br>▸ Chapter 9, *Quantum Gravity,* pages 132–133<br>▸ Chapter 12, *General Relativity,* pages 167–171 |
| **II. Consider Instructional Implications** | **IIA:** ***Benchmarks for Science Literacy***<br>▸ 4G, *Forces of Nature* general essay, page 93; grade span essays, pages 94–96<br>**IIB:** ***National Science Education Standards***<br>▸ Grades K–4, Standard B essay, pages 123, 126<br>▸ Grades 5–8, Standard B essay, page 149, 154<br>▸ Grades 9–12, Standard B essay, pages 177–178 |
| **III. Identify Concepts and Specific Ideas** | **IIIA:** ***Benchmarks for Science Literacy***<br>▸ 4G, *Forces of Nature,* pages 94–97<br>**IIIB:** ***National Science Education Standards***<br>▸ Grades K–4, Standard B, *Position and Motion of Objects,* page 127<br>▸ Grades 5–8, Standard B, *Motion and Forces,* page 154<br>▸ Grades 9–12, Standard B, *Motions and Forces*, pages 179–180 |
| **IV. Examine Research on Student Learning** | **IVA:** ***Benchmarks for Science Literacy***<br>▸ 4G, *Forces of Nature,* page 340<br>**IVB:** ***Making Sense of Secondary Science: Research Into Children's Ideas***<br>▸ Chapter 16, *Magnetism and Gravity,* page 126<br>▸ Chapter 23, *Gravity,* pages 163–167 |
| **V. Examine Coherency and Articulation** | **V:** ***Atlas of Science Literacy***<br>▸ *Gravity,* pages 42–43<br>▸ *Laws of Motion,* pages 62–63 |
| **VI. Clarify State Standards and District Curriculum** | **VIA:** ***State Standards:*** Link Sections I–V to learning goals and information from your state standards or frameworks that are informed by the results of the topic study.<br>**VIB:** ***District Curriculum Guide:*** Link Sections I–V to learning goals and information from your district curriculum guide that are informed by the results of the topic study. |
| Visit www.curriculumtopicstudy.org for updates or supplementary readings, Web sites, and videos. | |

*Source:* Keeley, P. 2005. *Science curriculum topic study: Bridging the gap between standards and practice.* Thousand Oaks, CA: Corwin Press and Arlington, VA: NSTA Press.

mation in this chart, the probe "Gravity Rocks!" on page 171, for example, was developed to see whether students recognize that gravitational force decreases with distance from the Earth's surface and whether students confuse gravitational potential energy with gravitational force. This process was generally used throughout this volume, with additional research derived from physics education research.

*Science Curriculum Topic Study* was developed as a professional development resource for teachers with funding from the National Science Foundation's Teacher Professional Continuum Program. The book is accompanied by *A Leader's Guide to Science Curriculum Topic Study* (Mundry, Keeley, and Landel 2009). The leader's guide includes a workshop model and a CD-ROM of resources, templates, tools, and PowerPoint slides for leading a professional development session on how to create a probe. After using the probes in the present book, you might like to try to create your own probe using the curriculum topic study (CTS) guides/topics on at the beginning of each section in this book (pp. 12, 68, and 140).

**Figure 2. Curriculum Topic Study (CTS) Chart for Developing a Probe on Gravity***

| CTS Section III<br>(K–12 Concepts and Specific Ideas) | CTS Section IV<br>(K–12 Research on Learning) |
|---|---|
| **Gravity**<br>• Things near the earth fall to the ground unless something holds them up. BSL K–2<br>• The earth's gravity pulls any object on or near the earth toward it without touching it. BSL 3–5<br>• **Every object exerts gravitational force on every other object. The force depends on how much mass the objects have and on how far apart they are.** The force is hard to detect unless at least one of the objects has a lot of mass. BSL 6–8<br>• The sun's gravitational pull holds the earth and other planets in their orbits, just as the planets' gravitational pull keeps their moons in orbit around them. BSL 6–8<br>• Gravity is the force that keeps planets in orbit around the sun and governs the rest of the motion in the solar system. Gravity alone holds us to the earth's surface and explains the phenomena of the tides. NSES 5–8<br>• **Gravitational force is an attraction between masses. The strength of the force is proportional to the masses and weakens rapidly with increasing distance between them.** BSL 9–12<br>• **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.** NSES 9–12 | **Gravity**<br>• Elementary students typically do not see gravity as a force. They see the phenomenon of falling as 'natural' with no need to attribute it to force. BSL<br>• **Some high school students believe gravity increases with height above earth's surface** or are not sure whether the force of gravity would be greater on a wooden ball or lead ball of the same size. BSL<br>• High school students have difficulty conceptualizing gravitational forces as interactions and that the magnitudes of the gravitational forces that two objects of different mass exert on each other are equal. BSL<br>• Children's ideas about Earth's gravity depend on their conception of a spherical earth and how 'down' is interpreted. MSSS<br>• Holding, rather than pulling, seems to be a common perception of gravity bound up with the idea of gravity being associated with air pushing down and an atmosphere of air that prevents things from floating away. MSSS<br>• Only some objects exert gravitational force and gravity only affects heavy things. MSSS<br>• Earth's magnetism and spin are associated with gravity. MSSS<br>• **Some students confuse gravity with potential energy in assuming a higher force of gravity at higher heights.** MSSS<br>• …There is no force of gravity in water which is why things float, there is less gravity in water, there is gravity in water but it acts upward, or gravity only acts on the parts of the body above the surface of the water. MSSS<br>• Some students think gravity only applies to objects on earth. MSSS<br>• Gravity as 'molecules of gravity' in air. MSSS |

*The ideas from the standards in the left-hand column in bold type were matched with commonly held student ideas as cited in the research. These ideas are in the right-hand column, also in bold type.

BSL= *Benchmarks for Science Literacy* (AAAS 1993)
NSES= *National Science Education Standards* (NRC 1996)
MSSS= *Making Sense of Secondary Science* (Driver et al. 1994)

# Acknowledgments

We would like to thank the teachers and science coordinators we have worked with for their willingness to field-test probes, share student data, and contribute ideas for additional assessment probe development. We would also like to thank our colleagues at the Maine Mathematics and Science Alliance (MMSA) (*www.mmsa.org*) and the Blake School in Minneapolis who support us in this work. In addition, we thank the Math-Science Partnership directors, our professional development colleagues, and our university partners throughout the United States whom we have had the pleasure of sharing the *Uncovering Student Ideas in Science* work with in various projects.

We would also like to thank our reviewers for providing useful feedback to improve the original manuscript of this book: Marilyn Decker, former director of science with the Boston Public Schools; Dr. Arthur Eisenkraft, University of Massachusetts; Dr. Pam Kraus, FACET Innovations; Dr. Stamatis Vokos, Seattle Pacific University; Dr. Gerald Wheeler, former executive director of the National Science Teachers Association; and John Whitsett, coordinator of curriculum and instruction for the Fond du Lac (Wisconsin) School District and former physics teacher. We especially thank Dr. Jim Minstrell at FACET Innovations for taking the time to write a foreword for this first volume in the new series of *Uncovering Student Ideas* books. Jim has certainly set the gold standard for us in terms of what it really means to attend to student thinking when planning for instruction and teaching for understanding.

# About the Authors

**Page Keeley** is the senior science program director at the Maine Mathematics and Science Alliance (MMSA) where she has worked since 1996. She directs projects in the areas of leadership, professional development, linking standards and research on learning, formative assessment, and mentoring and coaching, and she consults with school districts and organizations nationally. She was the principal investigator on three National Science Foundation grants: the Northern New England Co-Mentoring Network; Curriculum Topic Study: A Systematic Approach to Utilizing National Standards and Cognitive Research; and PRISMS: Phenomena and Representations for Instruction of Science in Middle School. She is the author of 10 books (including this one): four books in the *Curriculum Topic Study* series (Corwin Press); four volumes in the *Uncovering Student Ideas in Science: 25 Formative Assessment Probes* series (NSTA Press); and *Science Formative Assessment: 75 Practical Strategies for Linking Assessment, Instruction, and Learning* (Corwin Press and NSTA Press).

Most recently she has been consulting with school districts, Math-Science Partnership projects, and organizations throughout the United States on building teachers' capacity to use diagnostic and formative assessment. She is frequently invited to speak at national conferences, including the annual conference of the National Science Teachers Association. She led the People to People Citizen Ambassador Program's Science Education delegation to South Africa in 2009 and to China in 2010.

Page taught middle and high school science for 15 years; in her classroom she used formative assessment strategies and probes long before there was a name attached to them. Many of the strategies in her books come from her experiences as a science teacher. During her time as a classroom teacher, Page was an active teacher leader at the state and national level. She received the Presidential Award for Excellence in Secondary Science Teaching in 1992 and a Milken National Distinguished Educator Award in 1993. She was the AT&T Maine Governor's Fellow for Technology in 1994, has served as an adjunct instructor at the University of Maine, is a Cohort 1 Fellow in the National Academy for Science and Mathematics Education Leadership, and serves on several national advisory boards.

Prior to teaching, she was a research assistant in immunology at the Jackson Laboratory of Mammalian Genetics in Bar Harbor, Maine. She received her BS in life sciences from the University of New Hampshire and her MEd in secondary science education from the University of Maine. Page was elected the 63rd president of the National Science Teachers Association for the 2008–2009 term. In 2009 she received the National Staff Development Council's Susan Loucks-Horsley Award for her contributions to science education leadership and professional development.

# About the Authors

**Dr. Rand Harrington** is the preK–12 science department chair and science curriculum coordinator for The Blake School in Minneapolis. He began his teaching career in 1980 as a middle school science teacher in California after receiving a degree in environmental science at Western Washington University. In 1985, after teaching and traveling throughout the world, he returned to school and received a second bachelor's degree in physics and then completed both his master's degree and PhD in physics at the University of Washington.

As a science teacher, Rand had long been interested in understanding how people learn, and he soon joined the Physics Education Research Group at the University of Washington under the leadership of Lillian McDermott. While working with this group, he taught and helped develop curriculum materials for *Physics by Inquiry*, a curriculum for preservice teachers, as well as *Tutorials in Introductory Physics*, which is used in many introductory physics courses. Rand was able to pursue his own interests in electricity and magnetism and eventually wrote his PhD thesis on identifying and addressing the difficulties students have with understanding electric phenomena.

After graduation from the University of Washington, Rand accepted an assistant professor appointment at the University of Maine, where he founded the Physics Education Research Group (originally called LRPE) and collaborated with the Maine Mathematics and Science Alliance (MMSA). In 1998 he was awarded a Higher Education SEED Foundation grant from MMSA and the Maine Department of Education to work with preservice teachers and to reform the introductory physics courses for nonscience majors at the University of Maine. In addition he received a National Science Foundation grant to examine best practices in science teaching. He has served on the ETS Physics SAT II test construction committee and on the American Association of Physics Teachers committee on research in physics education.

In 1999, he left Maine to help start a "Physics First" high school science program at the Harker School in San Jose, California. During that time, he adapted materials for a high school curriculum based on modeling, *Tutorials in Introductory Physics*, and *Physics by Inquiry*. He also became interested in computer-based tutorials and the effectiveness of online homework such as WebAssign and Mastering Physics. In 2005, Rand assumed his present position at The Blake School in Minneapolis.

He has served as a consultant for several independent schools, is a reviewer for the *American Journal of Physics*, teaches a summer course for undergraduate science and engineering majors at the University of Minnesota, received the Juliet Nelson Award for Excellence in Teaching, and has taught physics to Tibetan monks as part of the Science for Monks program in Dharamsala, India. His most recent interests are finding effective methods to "extend the thinking" of students at all grade levels and to use the computer as a tool for effective learning.

# Introduction

## Force and Motion: Research, Teaching, and Student Ideas

> We are convinced that the more probes that teachers use, the sounder their appreciation of their students' understanding, the more interesting they and their students will find their teaching, and the better will be the learning that follows.
>
> —Richard White and Richard Gunstone
> *Probing Understanding*

There is little doubt that the topics of force and motion present difficult challenges for both students and their teachers. Students have had more direct, personal experience with the ideas of force and motion than they have had with perhaps any other topics in the science curriculum; thus, they often come to class with fully formed and strongly held beliefs. Not all of these beliefs are consistent with a scientific view, however. When teachers take deliberate actions to understand what students believe, and why, they are taking an important first step toward improving their teaching practices.

## Historical Background

Swiss child psychologist Jean Piaget identified some of these difficulties with the concepts of force and motion in interviews with children over a half century ago (Inhelder and Piaget 1958). During interviews on a task identified as "Conservation of Motion in a Horizontal Plane," he found that "the subject provides contradictory explanations: Light balls go farther because they are easier to set in motion. Larger ones go father because they are stronger. There is an absence of laws." In the late 1950s and early 1960s, curriculum developers and researchers such as Robert Karplus, Arnold Arons, and others made use of the work of Piaget and developed science curricula using various conceptual change models borrowed from cognitive psychologists. Even as curricula have evolved over the decades since the 1960s, however, student difficulties persist and teachers who listen carefully will still hear the echoes of Piaget's young research subjects (Arons 1977; Karplus and Thier 1967).

In addition to numerous mathematical difficulties that students experience in describing motion (a field of study called kinematics), deep conceptual difficulties also exist. Extensive interviews with students and experiences in the classroom have helped teachers and researchers develop a better understanding of these conceptual difficulties. The results from this work have been used to create various diagnostic tests, primarily for secondary students and undergraduates, including the commonly used Force Concept Inventory (Hestenes, Wells, and Swackhamer 1992) and the Mechanics Baseline Test (Hestenes and Wells 1992) as well as parts of the physics Diagnoser project (FACET Innovations 2008) and the Force and Motion Conceptual Evaluation (Thornton and Sokoloff 1998).

## Why Students Have Difficulties With Force and Motion Concepts

What is the source of these difficulties and why are they so persistent? One area that seems to underlie many of the problems is related to a person's ability to differentiate between a quantity and a change in that quantity. For example, understanding the difference between height (a quantity) and rate of growth (a change in that quantity) is similar to understanding the difference between position (a quantity) and speed (a change in that quantity). Perhaps the most difficult ratio for students to understand in the study of motion is the ratio we call acceleration (the change in velocity in one unit of time). Acceleration involves a rate of change of a quantity that is itself a rate (i.e., the rate of a rate). The fact that a child's growth rate can be decreasing while the child continues to grow taller is as difficult for students to grasp as the idea that acceleration can be decreasing even as the object continues to speed up (Arons 1983, 1984a, 1984b).

In addition to the difficulties students have with ratios and proportional reasoning, many students hold deeply ingrained beliefs about the nature of force. Their difficulties may be semantic and inadvertently reinforced by commonly used phrases such as, "I will force you to…," "may the force be with you," or "the force of gravity." The use of the word *force* in these statements implies that force is an object or a property of that object rather than *an interaction between objects* (the scientific definition). Teachers can help even our youngest students by making sure they use the word *force* as a description of an interaction, rather than as a property of a single object (Touger 1991).

Many students are also deeply committed to the idea that motion does not happen without a cause. However, in nature, it is only the change in motion that demands a causal interaction and not motion itself. This is highly counterintuitive because in our everyday experiences we rarely experience the absence of interactions (forces). The change in motion of an object is a result of ***unbalanced*** forces, and constant motion is the result of ***balanced*** forces or the absence of interactions altogether (no forces acting). In the case of constant motion, one of the forces is often "hidden" in the interaction that we call friction. This misleads us to think that the active force (such as a push from the hand acting on the object) is the only force acting. If an object is sliding on a surface, when the hand stops pushing, then the object slows down and stops. This slowing is a result of the friction interaction by the surface acting on the object. However, students rarely, if ever, experience what happens when the hand is removed and *there are no other forces acting.* In this case, the object would continue moving in a straight line, neither speeding up nor slowing down indefinitely (or until the object interacts with another object).

One of our goals should be to move students from what is called Aristotelian thinking (motion implies force) to Newtonian thinking (change in motion implies an unbalanced force). Researchers have found that less than 25% of our high school or college physics students typically come to our classrooms with a Newtonian view of forces (Hake 1998). After instruction, this number typically does not exceed 50% even though many of these same students can excel in applying the mathematics necessary to solve traditional problems. This evidence suggests that it is important to help even our youngest students develop an understanding of force as an *interaction* between two objects—in place of their *mis*understanding that it is a property of, or an action caused by, a single object.

## Common Instructional Difficulties Related to Teaching About Gravitational Interactions

The subtleties related to understanding gravitational interactions also can present challenges to both teachers and their students. These difficulties can be categorized into three major areas: (1) understanding the nature or cause of gravity, (2) understanding the difference between weight and mass, and (3) understanding the motion of falling objects.

### The Nature or Cause of Gravity

One of the best examples of how to elicit student ideas related to the cause of gravity comes from the research of a former high school physics teacher and current senior research scientist and co-founder of FACET Innovations, Jim Minstrell (Minstrell and Kraus 2005). Minstrel showed his students a small weight hanging from a spring scale. He then placed the scale with the weight inside a bell jar. A bell jar is a large glass dome that is sealed at the bottom. A pump is then used to remove the air from the inside of the jar. Minstrell asked his students to predict what would happen to the scale reading as air was removed from inside the jar. The results were striking: A large number of students believed that the scale reading either would be reduced or would go to zero as the air was removed! Children's books, such as one of the books in the popular Magic School Bus series (Cole and Degen 1990) show astronauts who appear "weightless" when they leave their space ship. These images inadvertently reinforce incorrect ideas about the relationship between gravity and atmosphere. It also does not help when terms such as *weightless* and *zero gravity* are used in common (nonscientific) speech. It can be difficult to help students understand that "gravity" is the name we give to a universal interaction between any two masses and that this interaction happens "at a distance"—meaning the objects do not have to touch.

### Understanding the Difference Between Weight and Mass

Perhaps the most difficult (and contentious) idea for students to understand is the difference between *weight* and *mass.* To further complicate matters, even scientists do not always agree on how to define these words. For example, in Europe, scientists define *weight* as the force needed to hold you up (such as the reading on a bathroom scale). Using this definition, an object that is not being held up (e.g., when an object is in free fall) would be called weightless. Astronauts circling the Earth would be described as weightless using this definition.

However, in the United States, scientists define *weight* as the gravitational force. A bathroom scale can indicate your weight but only if the scale itself is not accelerating. For example, if you weigh yourself on a scale inside an elevator that is speeding up (while the elevator is going upward), the scale would read more than your actual weight, but less than your actual weight when the elevator slows down. In the United States, this reading would be called your "apparent weight." Defining weight as the gravitational force also means that a person is never "weightless" because gravity is a long-range force that does not require contact. Astronauts in the Space Shuttle may feel weightless, but there is still gravitational force acting on them by the Earth. This gravitational force (called their "weight" by those in the United States) is why the astronauts move in a circular orbit around the Earth. You can see why these ideas can easily confuse students!

To avoid these difficulties, we can introduce students to a different concept called mass, which is a property of matter. (Don't worry, this definition is agreed upon by all scientists!) This property is the same regardless if you are in an elevator, on the Moon, or in orbit.

One way to help students understand the difference between these concepts is to use a spring scale to find the weight of an object and to use a balance to find the mass of an object. A spring scale will have a smaller reading on the Moon than on the Earth (the object will weigh less on the Moon). However, if an object can balance 10 g of mass on the Earth, then it will also balance the same 10 g on the Moon.

Scientists try to keep these ideas separate by using different units for mass and weight. In the metric system, mass is measured in grams or kilograms and weight is measured in newtons. In the English system of measurement, weight is measured in pounds and mass is measured in "slugs." To further complicate matters, the word *slug* is so uncommon that food packagers prefer to mix the units, often equating weight units (like pounds or ounces) to mass units (like grams or kilograms). If you look at a scale in the produce section of a supermarket, you will see that both pounds and ounces *and* grams and kilograms are used. If your students struggle with these ideas, tell them they are not alone. Several years ago NASA lost a very expensive satellite that did not go where NASA wanted the satellite to go. After a lot of troubleshooting, NASA identified the problem: Software engineers had used units of pounds (the gravitational force acting on a mass of one slug) while scientists had used units of newtons (the gravitational force acting on a mass of one kilogram)! In other words, one NASA team had used metric units and another had used English units in their calculations and no one noticed until it was too late.

### Understanding the Motion of Falling Objects

Galileo discovered a very important physical principle: Gravitational force is directly proportional to the mass of an object. This means that an object with twice the mass of another object will also weigh twice as much as that object. According to some accounts, Galileo discovered this by dropping cannonballs with different masses off the Tower of Pisa. He noticed that the more massive ball reached the ground at about the same time as a less massive ball; therefore, the force on the more massive ball must be more than the force on the less massive ball. (If the forces were the same, then the less massive ball would reach the ground first!)

Why is this idea difficult for our students to accept? Because when our students drop objects, the objects will likely NOT reach the ground at the same time—the more massive object will reach the ground first. Skydivers, skiers, and bikers are all aware of this fact—that is, the heavier you are, the faster you go. So who is correct? You can see why students start to think that the science we teach them is not only irrelevant, but also incorrect. The answer is that objects only fall with the same acceleration in the absence of air resistance or friction. Experienced physics teachers learn to minimize the effect of air resistance by using small heavy objects and dropping them only a short distance. It is not clear if this strategy is successful for all students because many will walk away wondering why experiments in science class conflict with their everyday experiences.

## Stepping-Stones: Emerging Concepts and Language

There are many challenges to teaching science, but one of the most difficult choices we face as teachers is to know when to accept a child's emerging concept, called a stepping-stone, in place of a scientific idea that most scientists would agree is important and correct from a scientific point of view. Stepping-stone concepts are actually central to effective learning, yet they are not always what come to the minds of physicists when they are asked about important ideas in physics. In a recent symposium at the National Academies of Science, at which a reorganization of K–12 science education around core science ideas was being considered, it was proposed that candidates for core ideas include both stepping-stone ideas as well as scientific ideas (Wiser and Smith 2009).

When looked at through the eyes of more advanced students, some of young children's emerging ideas could be judged as being incorrect or downright wrong. For example, when is $F_{net} = ma$ a correct statement of Newton's law of motion? We know that this is true only when several assumptions are made, such as when applied to a system whose mass is not changing or a system that is not moving too fast (relative to the speed of light). However it would be misleading to claim that $F_{net} = ma$ is wrong. At some point we should teach our students that all of the relationships we use to describe nature are in fact models that provide only an approximation of what we can observe directly.

Teachers are often unsure about when to use the word *weight* and when to use the word *mass* with their students. For older students, this distinction is important and we often attempt to correct students who misuse these terms. However, the use of the word *weight* in younger grades should be considered a stepping-stone concept (matter has weight) preceding the core scientific idea that matter has mass. Younger students often mistake the word *mass* with the phonetically similar word *massive* and further confuse their understanding of mass with the concept of volume.

Other stepping-stone concepts are related to the use of the word *distance* in place of *position* or *displacement* and the use of the word *time* when we really mean *time interval.* Both of these concepts merge when we choose zero time and zero position as our starting points (as is common in math textbooks). Older students often confuse these concepts, so it is tempting to differentiate these ideas at a young age. However, it is our experience that it is best to wait to differentiate between these concepts until early middle school.

Several learning progressions are currently being investigated in the physical sciences. Learning progressions are defined as "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" (NRC 2007, p. 214). Because learning progressions are empirically tested, they will provide the much-needed research to help teachers decide when to use a stepping-stone in lieu of a core scientific idea.

In constructing the probes in this book, we have tried to follow this guide: We generally use the words *weight, distance,* and *time* in probes designed for younger students while we use *mass, position, displacement,* and *time interval* in probes for older students. However, we encourage teachers to use those terms that best match their own learning goals regardless of the wording that was chosen for any individual probe.

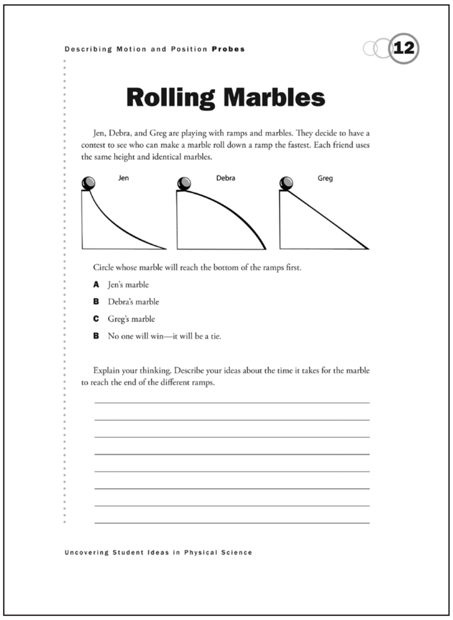
## Implementing the Force and Motion Probes

The probes in this book can be used as windows into student thinking before, during, or after instruction. It should be noted that if a probe is used before instruction, teachers must carefully plan their curricula so that, after completing the probe, students have an opportunity to develop the relevant ideas. If a probe is administered before instruction, and there is no immediate follow-up, students may feel frustrated at not knowing the "correct answer" and teachers may feel compelled to provide students with direct answers without the necessary background or experiences. If the probes are used during instruction, the teacher must be sure to present other activities that reinforce the science concept on which the probe is based. If the probes are used after instruction, the teacher uses the information gained from the probes to plan for further learning opportunities that will help students who are still struggling with the concept. The advantage of using the probes after instruction—still formatively and not as summative assessments—is that students are better prepared to participate in classroom discussion. Students must feel comfortable sharing their ideas in the discussions, and the teacher must carefully manage the discussions so that all ideas are valued.

Classroom discussions are also wonderful opportunities to reinforce the necessary components of a scientific explanation when the teacher requires students to state their claims, the evidence in support of those claims, and the explanations that connect the claims to the evidence (Krajcik et al. 2006). If discussions are conducted during or after instruction, then students will have better access to direct evidence to support their claims.

Below are examples of how two probes in the book could be used as formative assessments both before and after instruction:

### (Before Instruction)
### Scenario 1: Fifth-Grade Unit on Motion Using the "Rolling Marbles" Probe (p. 59)



Describing Motion and Position **Probes**

12

Rolling Marbles

Jen, Debra, and Greg are playing with ramps and marbles. They decide to have a contest to see who can make a marble roll down a ramp the fastest. Each friend uses the same height and identical marbles.

Jen
Debra
Greg

Circle whose marble will reach the bottom of the ramps first.

**A** Jen's marble
**B** Debra's marble
**C** Greg's marble
**B** No one will win—it will be a tie.

Explain your thinking. Describe your ideas about the time it takes for the marble to reach the end of the different ramps.

Uncovering Student Ideas in Physical Science

**Teacher:** Today we are going to be scientists! We are going to study the motion of a marble rolling down hills. Let us look at three different shapes of a hill. Which hill do you think the marble will get to the bottom of first? Draw a circle around that hill. Now let's share with each other.

**Alisha:** I think the hill that is a straight line will be the fastest. This is because the marble has the shortest distance to travel.

**Michael:** I don't know, but I think maybe the hill that is steep at the end. This is because the ball will be moving the fastest at the finish line.

**Georgia:** I think it might be the hill that is steep at the beginning because the marble will start rolling really fast and get ahead of the other marbles.

**Teacher:** To be good scientists, we need to test our ideas, but we have to make sure our tests are fair. What do we need to do to make sure our tests are "fair"?

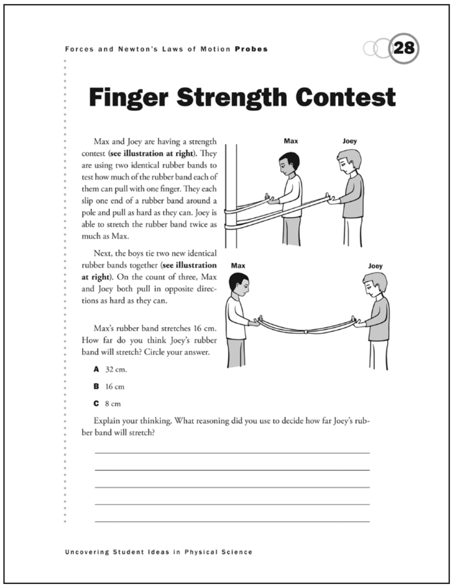
**Jimmy:** I think they must use the same size marble.

**Lorenzo:** And the marbles must start at the same height!

**Mayumi:** The hills should be made out of the same material.

**Teacher:** Here are three flexible tubes. Work with your partners and see if you can find out what shape track will help the marble get to the bottom first.

### (After Instruction)
### Scenario 2: Eighth-Grade Physical Science Class Using the "Finger Strength Contest" Probe (p. 127)



Forces and Newton's Laws of Motion **Probes** 28

## Finger Strength Contest

Max and Joey are having a strength contest (**see illustration at right**). They are using two identical rubber bands to test how much of the rubber band each of them can pull with one finger. They each slip one end of a rubber band around a pole and pull as hard as they can. Joey is able to stretch the rubber band twice as much as Max.

Next, the boys tie two new identical rubber bands together (**see illustration at right**). On the count of three, Max and Joey both pull in opposite directions as hard as they can.

Max's rubber band stretches 16 cm. How far do you think Joey's rubber band will stretch? Circle your answer.

**A** 32 cm.

**B** 16 cm

**C** 8 cm

Explain your thinking. What reasoning did you use to decide how far Joey's rubber band will stretch?

Uncovering Student Ideas in Physical Science

*The students have just completed a unit on Newton's three laws of motion.*

**Teacher:** What would the length of a stretched rubber band tell us about the forces acting on the rubber band?

**Willie:** If the rubber band is longer, I think that means there is a greater force.

**Teacher:** Can you give me an example to support this idea?

**Shirley:** Yes. If I pull harder, the rubber band gets longer … just like this! [She demonstrates this to the class with a rubber band between her fingers.]

**Teacher:** Because of what Shirley and Willie described, a rubber band can be used as a "force meter."

*Teacher hands out the probe called "Finger Strength Contest."*

**Teacher:** Please answer the questions as you can on your own. Try to write an explanation that cites evidence to support your answer.

*When the students have completed the probe, the teacher collects the results and quickly scans each paper. She keeps a tally to see how many students say the change in the length of the rubber bands will be the same and how many think the change in the length of each rubber band will be different. She notices that more than half the students believe the change in the lengths of the rubber bands will be different, a violation of Newton's third law.*

**Teacher:** The results show us that about half of you believe that the rubber bands will have a different length and the other half believes the rubber bands will have the same length. I want you to work in groups of three or four to come up with an explanation for either of these answers and to find evidence to support that answer—but don't actually perform the experiment. On your individual whiteboards, please write your claim at the top, the evidence to support that claim, and an explanation (connect the evidence to your explanation). If you cannot agree as a group, then you may complete two different whiteboards.

***After students complete the task, the teacher collects the whiteboards and displays them in front of the room. She arranges the whiteboards so that they are grouped according to the explanations and the claims.***

**Teacher:** Let's look at the evidence that was used to support your claims. Do I have a volunteer from each group to describe the evidence that the groups used in their explanations?

**Michelle:** At first we thought the rubber bands would be different lengths because they pull with different forces. But then we remembered the lab we did last week where we attached two force probes together and pulled on them. No matter how we pulled, the forces were equal! So they must be the same.

**Dillon:** But this just doesn't make sense to us. Our evidence is that if you pull twice as much, the rubber band will stretch twice as much. So if one person is stronger, then that person's rubber band should also stretch twice as much!

**Shemar:** Yes, we thought the same thing. But now we agree with Michelle's group. This is also like the spring we put between two bathroom scales. No matter how much we pushed on one scale, the other scale would always have the same reading. So the spring is kind of like a force equalizer. Even if we try to pull differently, the forces always equal out.

## A Final Caveat: Teachers Beware!

In choosing the probes in this book, we have attempted to find examples that connect basic principles to real-life experiences. However, there are a few probes that ask students to imagine an experience that they have never had—such as living in a world without friction or one in which there were no other forces acting on an object. In these cases, we have tried to be clear by not mixing real-life situations with these "ideal" frictionless or massless experiences found in a typical physics textbook. To avoid some difficulties, we recommend that you be ready to listen to all of your students' answers and their explanations before being too judgmental about what is right or wrong. Even in the Teacher Notes that follow each probe, we give a standard scientific response based on a few simple assumptions. There may be times when a student may not make the same assumptions, and although his or her answer may be different from ours, it could still be quite correct based on that student's own interpretation of the problem.

We leave you now with the words of the well-known cognitive psychologist David Ausubel: "The most important single factor influencing learning is what the learner knows. Ascertain this and teach accordingly" (Ausubel, Novak, and Hanesian 1978). While it is interesting in and of itself to discover what your students are really thinking, remember that assessment is not formative unless you use the information you have uncovered in the assessment to guide your instruction and promote learning.

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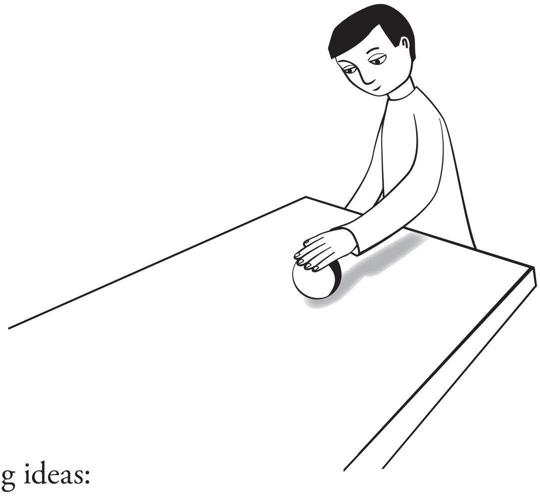
# Just Rolling Along



Jerome rolled a rubber ball across a very long table by giving the ball a very light push and then letting it roll across the table on its own. Six of his classmates observed the ball as it rolled.

Jerome wondered what happened to the speed of the ball after it left his hand. He asked the other students if they think it is possible to make the ball roll at a constant speed (*constant speed* means the ball is neither slowing down nor speeding up).

The students in Jerome's group shared the following ideas:

**Anna:** "It is not possible to make the ball roll at a constant speed."

**Dev:** "It is possible for the ball to roll at a constant speed if you tilt the table slightly downward."

**Tad:** "It is possible for the ball to roll at a constant speed if you tilt the table slightly upward."

**Jack:** "It is possible for the ball to roll at a constant speed if you make the table perfectly flat."

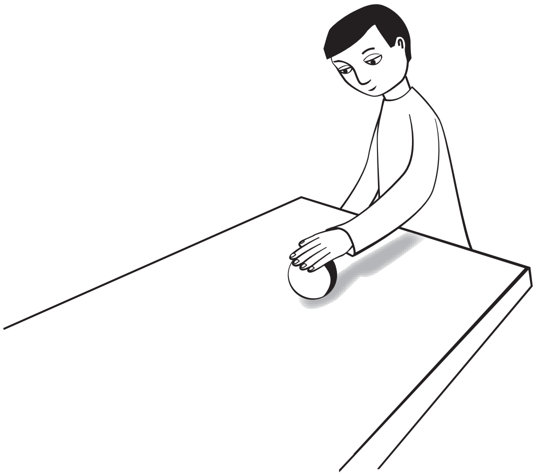
**Byron:** "It is possible for the ball to roll at a constant speed if you roll the ball really fast."

**Talia:** "It is possible for the ball to roll at a constant speed if you roll the ball really slow."

Circle the name of the student you think has the best idea. Explain why you think that is the best idea.

# Just Rolling Along

## Teacher Notes



### Purpose

The purpose of this assessment probe is to elicit ideas about uniform motion. The probe is designed as a starting point to encourage students to use evidence and observations to support their ideas. The goal is for students to eventually develop and then test an operational understanding of the concept of speed.

### Related Concepts

constant speed, displacement, speed, time intervals, uniform motion

### Explanation

The best answer is Dev's: "It is possible for the ball to roll at a constant speed if you tilt the table slightly downward [at a very small angle])". When level, the ball slows down and when at a steep angle, the ball speeds up. One can then reason (and then verify experimentally) that there must be an angle at which the ball neither speeds up nor slows down.

The correct answer can also be found by analyzing forces. There is an angle at which the frictional force is balanced by the component of the gravitational force along the direction of the ball's motion. When the table is level, the ball will slow down because the friction force by the table is acting on the ball. This force acts opposite the direction of motion. In addition, when the table is level, there is no gravitational force acting in the direction of motion.

### Administering the Probe

This probe is appropriate for middle school and high school students. Make sure that students, particularly middle school students, understand what the term *constant speed* means even though it is defined in the probe. Have props (rubber ball and long table) available to illustrate the context of the probe. This probe can be used with the P-E-O strategy: *predict, explain* the reason for your prediction, and *observe*; if students' observations do not fit their predictions, students revise their predictions and explanations (Keeley 2008). To observe this motion, students will need to roll the ball slowly. If the table is tilted too much, then the ball will continuously speed up. With just a small tilt, they should be able to find the place where part of the gravitational force that pulls the ball down the incline is offset by the rolling friction acting on the ball by the table.

This probe can be answered and tested from a purely kinematics point of view, without requiring an explanation of forces on the part of the teacher or students. It can also be used as a probe in Section 2, "Forces and Newton's Laws," if you are interested in probing further for students' explanations of the forces involved.

## Related Ideas in *National Science Education Standards* (NRC 1996)

### 5–8 Motions and Forces

★ The motion of an object can be described by its position, direction of motion, and speed.

## Related Ideas in *Benchmarks for Science Literacy* (AAAS 1993, 2009)

### 6–8 Motion

- An unbalanced force acting on an object changes its speed or direction of motion, or both

### 9–12 Motion

★ Any object maintains a constant speed and direction of motion unless an unbalanced outside force acts on it.

## Related Research

- Many researchers have found that substantial numbers of students are strongly committed to the idea that constant speed implies that a constant force is being applied to a moving object (Driver et al. 1994, p. 158).
- This probe addresses a particular "problematic facet" (Minstrell 1992) that objects—even objects rolling on horizontal surfaces—slow down because of gravity. Students do not see the need to have the force that is changing the motion be related to the direction of motion.

## Suggestions for Instruction and Assessment

- This probe can be used at the start of a unit on kinematics—the branch of physics that deals with the motion of a body or system without reference to force and mass—as a way to elicit ideas that students have prior to instruction. If used in this way, it should be immediately followed up with a hands-on experiment in which students test their predictions and provide supporting evidence for their ideas.
- Students will develop a wide variety of reasons to support their prediction (even if it is not correct). Understanding that there must be a point where the ball neither speeds up nor slows down is similar to understanding a "point of inflection" in mathematics and can be quite difficult for some students. These students would benefit from taking measurements, such as comparing the time it takes the ball to move across the first half of the table with the time it takes the ball to travel across the second half of the table. They should then be led to adjust the tilt of the table until these two times are the same.
- It is important for teachers to listen carefully to how students use key words such as *force, momentum,* and *energy*. How students use these words can provide a window into student thinking about ideas not yet introduced in the unit. Rather

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★ Indicates a strong match between the ideas elicited by the probe and a national standard's learning goal.

than correcting any inaccurate uses, ask students what they mean by these terms and then redirect them to use more direct descriptions of the motion (such as speeding up, slowing down, or moving at constant speed).

- Be aware that many students will try to bring the concept of force into their explanations and therefore may have a difficult time observing the motion without a bias.
- This probe can be used in postinstruction to see if students have developed an operational definition of speed and if they understand how to design an experiment to test an idea.
- Be careful when using this probe that you do not imply that objects—even objects rolling on horizontal surfaces—slow down because of gravity, As described by some of the "facets of student knowledge" (see Minstrell 1992), some students do not see the need to have the force that is changing the motion be related to the direction of the motion.

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Note: Page numbers in *italics* refer to charts.

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