VOL. 2

Uncovering Student Ideas in Science

25 More Formative Assessment Probes

By Page Keeley,
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and Joyce Tugel

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Foreword

While writing this foreword, I found myself revisiting the 50-odd years of my involvement in science education. I recalled the many ideas, techniques, concepts, and research findings that have passed through my experience and flowed into my teaching repertoire like so much effluent through the filtering rushes in a stream. Some remain vital today and others still cling to the stalks, tried, tested, and found wanting.

I remember so vividly the night of October 4, 1957, when as a nation we were alerted to the beeping of Sputnik as it circled our planet, totally unaware of the influence its presence would have on science education over the next decade. It marked not only the beginning of the space race but the beginning of the rapid and frantic attempts of our nation to "beef up" the science, math, and engineering skills of our students. Science finally had a real place in the school curriculum. The Russians had beaten us to space and we were worried about our future as a nation! The United States responded swiftly with the National Defense Education Act, which allowed teachers like myself to update our content at summer institutes and provided for the development of a different kind of curriculum for school science.

Since then there have been many innovations in our field, including the famed "alphabet soup" curriculum projects of the 1950s and 1960s (e.g., SCIS, SAPA, COPES, Harvard Project Physics) and subsequent curriculum projects such as Insights, GEMS, AIMS, STC, and FOSS.

Then came the advent of the standards decade with Project 2061 and the *Benchmarks for Science Literacy* (AAAS 1993) and the *National Science Education Standards* (NRC 1996). We finally had a guide to what content should be taught and how it should be presented. Many of the states then developed their own versions of the standards, but there was uncertainty about how to use standards on the local level.

In 2005, Page Keeley authored *Science Curriculum Topic Study: Bridging the Gap Between Standards and Practice,* which was the first comprehensive guide to help us bridge the gap between the two sets of national standards, research on student learning, and teaching practice. This was a timely, much-needed book.

Following the development of state standards, each state instituted ways to hold schools accountable for teaching to the standards. For

Foreword

many states, this resulted in "high-stakes" tests, which were enshrined in legislation. Schools gave these tests to students in the spring and received the results sometime during the next school year. The accountability factor was there, but it did little for the teachers who wanted to improve current learning for their students. Many school districts implemented a teaching unit for selected grades entitled "Review for the Test." I thought to myself, "Maybe this really is a good time to retire!"

Many of us believed that teachers needed a way to find out what their students knew, what kind of preconceptions students brought to the classroom, and what teachers could do with this information to improve instruction. Again, Page Keeley and her team from the Maine Mathematics and Science Alliance entered the picture, along with the National Science Teachers Association, with the first volume of *Uncovering Student Ideas in Science: 25 Formative Assessment Probes,* published in 2005. This book focused on helping teachers discern their students' thinking about different science topics. It also helped teachers figure out what to do with this information and where to find help in moving their students to a new and deeper understanding of science concepts.

A workable strategy for formative assessment was now available to the busy teacher. The probes published in the first volume of *Uncovering Student Ideas in Science* were a success, and teachers from all over the country began to find that formative assessment can help them become better teachers. This may indeed have been an example of the "tipping point" that Malcolm Gladwell (2000) talks about in his book *The Tipping Point: How Little Things Can Make a Big Difference.* I knew it was mine. Finding this kind of innovation is exciting to me because teachers once again can be in charge of classroom instruction. The arrival of a truly inquiry-based focus on science education, coupled with assessment, is what I and so many others have been waiting for.

Well, doesn't a successful book deserve a sequel? Here it is, with 25 new probes and accompanying teacher guides. This is the kind of innovation that is enough to keep an old dog like me barking out there in the field for a few more years. Woof!

Dr. Richard Konicek-Moran
Professor Emeritus
University of Massachusetts, Amherst

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Preface

Overview

Since the release of the first volume of *Uncovering Student Ideas in Science: 25 Formative Assessment Probes* (Keeley, Eberle, and Farrin 2005), science educators have shown widespread interest in using formative assessment probes to identify the variety of ideas students bring to their learning and to design instruction based on these preconceptions. This shift from an overemphasis on summative assessment at the end of instruction to a balanced system of formative and summative assessment that happens before, throughout, and at the end of instruction has occurred at the practitioner, researcher, and even policy levels. To understand the reasons for this shift, it will help to briefly review the evolution of formative assessment.

As with the acceptance of new science knowledge and theories, so the emergence and building of new ideas can result in new understandings. Typically a new idea in science is not discovered without previous study and research that has collected a body of evidence in support of the new idea. As the evidence begins to mount and become overwhelming, a point is reached in which the idea becomes accepted and "discovered," often resulting in a new paradigm (Kuhn 1962). The recent research and discoveries that support formative assessment have come about in a similar fashion, causing a paradigm shift in assessment beliefs and practices. While we cannot list everyone who has contributed to the recent "revolution" in accepting formative assessment as a powerful classroom strategy, we would like to acknowledge several of the researchers, assessment specialists, science educators, and practitioners who have sparked our interest, expanded our knowledge base, and helped shape the ideas we include in this book.

Some of the early pioneers in examining students' ideas in science during the 1980s were Rosalind Driver, Edith Guesne, Andrée Tiberghien, Wynne Harlen, Roger Osborne, and Peter Freyberg. They were instrumental in raising science educators' awareness of the use of students' ideas in science as a starting point for effective instruction. In the 1990s Audrey Champagne, Bonnie Shapiro, Lillian McDermott, and Jim Minstrel further articulated the different purposes and kinds of diagnostic, formative, and summative information that science teachers can gain through assessment. Philip Sadler and Matthew Schneps brought us video examples through the *Private Universe Project* (Harvard-Smithsonian Center for Astrophysics 1995), which showed the wide range of ideas students and adults hold, even after instruction. In the same video series, Dick Konicek helped us understand the power of constructivist teaching that takes into account students' ideas. The seminal work of the American Association for the Advancement of Science (AAAS) Project 2061 made explicit links between student ideas and K–12 student learning goals. The summaries of the cognitive research on students' learning of particular concepts and ideas in science appeared in Chapter 15 of the *Benchmarks for Science Literacy* (AAAS 1993), tying research to a clear set of K–12 learning goals. The standards or benchmarks for K–12 student learning in science were now supported by a body of research.

In the late 1990s and continuing to the present, many books and articles about assessment by researchers and practitioners reached educators. Often, however, these publications failed to spell out how formative assessment can be used to improve science instruction and learning. These books were written for a broad audience of practitioners across content areas and lacked connections to the specific nuances of science as a discipline. Research from the cognitive sciences that raised the profile of formative assessment in the science classroom began to reach practitioners with the publication of *How People Learn: Brain, Mind, Experience, and School* (Bransford, Brown, and Cocking 1999) and *How Students Learn: Science in the Classroom* (Donovan and Bransford 2005). These publications helped us understand how to create and use an assessment-centered environment that acknowledged the importance of starting with students' preconceptions, teaching for transfer, and the role of metacognition.

While new ideas about assessment were emerging in the United States, significant findings in regard to formative assessment were being implemented and disseminated in the United Kingdom. There, researchers and practitioners published resources for teachers that included a variety of science assessment strategies designed to elicit students' ideas and spark inquiries; these ideas and inquiries could lead students to construct new understandings that resolve the dissonance between their preconceptions and scientific explanations (Naylor and Keogh 2000).

The metastudy of formative assessment by Black and Wiliam (1998) crystallized the purposes and effectiveness of formative assessment in instruction as "assessment for learning" rather than "assessment of learning." Black and Wiliam provided evidence for educators that formative assessment is a powerful instructional strategy and includes a variety of forms and purposes. They described how assessment is purposefully used to guide and inform instruction, not to just note in some formal or informal fashion what students are thinking. They further articulated how formative assessment plays out in the science classroom (Black and Harrison 2004).

Preface

In 2003 the Maine Mathematics and Science Alliance received a National Science Foundation grant to develop a set of materials to help K–16 educators link national standards and research on student learning to classroom practice. The resulting publication, *Science Curriculum Topic Study: Bridging the Gap Between Standards and Practice* (Keeley 2005), describes the process used to develop the probes in this book. This process links the concepts and ideas from national and state standards to the research on student misconceptions. The information is then used to develop formative assessment probes that reveal the range of ideas noted in the research as well as unique ideas some individual students may hold. The process was applied to develop the first set of 25 probes in Volume 1 of *Uncovering Student Ideas in Science* (Keeley, Eberle, and Farrin 2005) and has been used extensively in professional development to help teachers develop their own probes. Together, these two publications and this new book comprise a powerful set of tools to enhance and extend K–12 science teachers' use of formative assessment.

Collectively, these evolving contributions by researchers, assessment specialists, science education specialists, and practitioners have informed our development of the assessment probes for the *Uncovering Student Ideas in Science* series. It is our hope that the books in this series will support an idea-centered classroom in which teachers use the probes in conjunction with a variety of instructional techniques and questioning strategies. Such instructional practice can make students' thinking and learning visible for the purpose of guiding both students and teachers through the learning process.

Formative assessment is a key feature of classrooms where successful teaching and learning are taking place. The environment of an assessment- and idea-centered classroom is one in which students feel safe to express their ideas, know their ideas are important regardless of whether they are right or wrong, engage in deep thinking and reflection, and have opportunities to test their ideas to revise and improve their thinking. We hope this book can support such an environment.

Next Steps

Uncovering Student Ideas in Science is planned as a series of formative assessment probe books, each volume describing a new application and providing 25 new probes. Volume 1 provided an overview of formative assessment and formative assessment probes. This volume (Volume 2) focuses on ways to use formative assessment to teach for conceptual change. In the third volume of *Uncovering Student Ideas in Science,* we will describe ways teachers can individually use the probes for their professional development as well as ways to develop professional learning communities that engage teachers in examining student work and thinking.

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Acknowledgments

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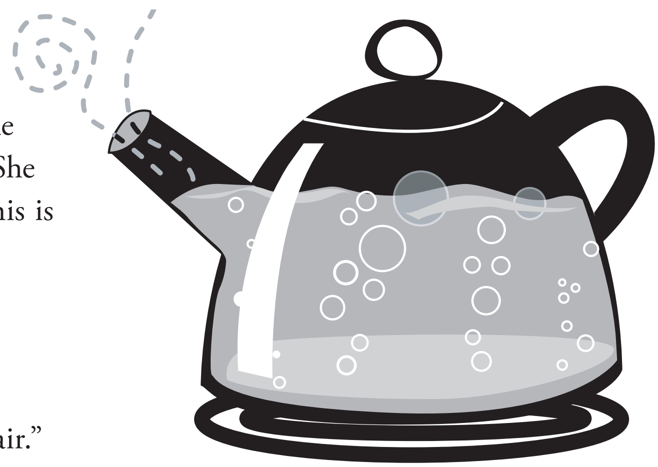
What's in the Bubbles?

Hannah is boiling water in a glass tea kettle. She notices bubbles forming on the bottom of the kettle that rise to the top and wonders what is in the bubbles. She asks her family what they think, and this is what they say:



Dad: "They are bubbles of heat."

Calvin: "The bubbles are filled with air."

Grandma: "The bubbles are an invisible form of water."

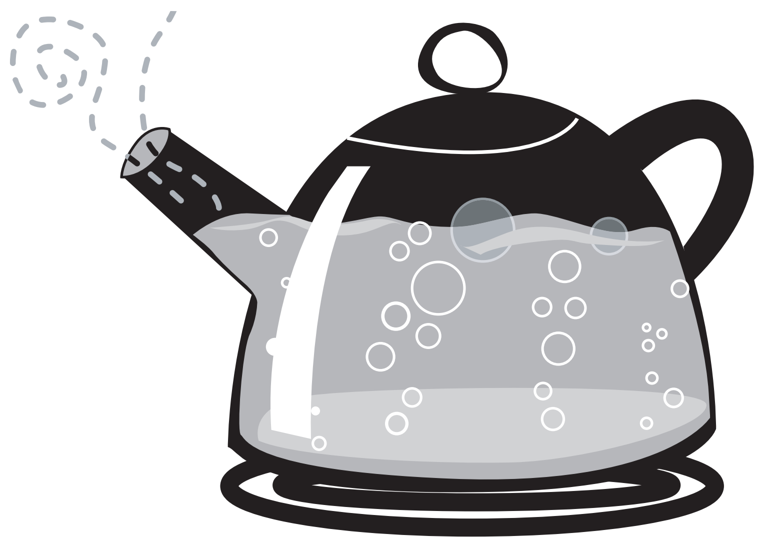
Mom: "The bubbles are empty—there is nothing inside them."

Lucy: "The bubbles contain oxygen and hydrogen that separated from the water."

Which person do you most agree with and why? Explain your thinking.

What's in the Bubbles?

Teacher Notes



Purpose

The purpose of this assessment probe is to elicit students' ideas about particles during a change in state. The probe is designed to find out if students recognize that the bubbles formed when water boils are the result of liquid water changing into water vapor.

Related Concepts

atoms or molecules, boiling and boiling point, change in state, energy

Explanation

The best response is Grandma's: The bubbles are an invisible form of water. This invisible water is called water vapor, a gaseous form of water that is not visible; it is unlike steam, which contains some condensed liquid water. When water is heated, the energy supplied to the system results in an increase in molecular motion. If enough heat is supplied, the molecules have so much energy that they can no longer remain loosely connected, sliding past one another as they do in a liquid. The energy now allows the attractive forces between water molecules to be overcome, and they form an "invisible" gas in the form of water vapor. Since the molecules in the gas phase are so much farther apart than in the liquid phase, they have a much lower density, are more buoyant (causing them to "bubble up"), and escape into the air. The bubble is the invisible water vapor.

Curricular and Instructional Considerations

Elementary Students

At the elementary level, students have experiences observing changes in state. The idea of change is connected to physical properties of materials by subjecting materials to heating and freezing. Water is often used as a familiar material for observing phase changes. Elementary students know change in states of water from the solid to liquid to gas phase, although the change from liquid to gas phase is a more abstract idea developed more fully in upper elementary grades.

In early elementary grades, students' experience with bubbles that result when water boils is primarily observational and is often linked to experiences at home boiling water on a stove. It is too early to introduce the abstract idea of invisible water molecules that make up water vapor. However, students can develop the precursor idea that water, in the form of invisible water vapor, escapes from the surface of an uncovered liquid. It may be too soon to introduce the idea that bubbles of boiling water contain water vapor, although students can observe steam going into the air from water that boils, even though steam contains some tiny droplets of water. Students must understand the simpler idea that water goes into the air in a form we cannot see before the idea of kinetic molecular theory, which helps explain why bubbles form and what they are, is introduced in middle school. The notion that water vapor is a gas is a grade-level expectation in the national standards. Children develop conceptions about bubbles early on through their everyday experiences, so it is not too early to ask students their ideas about boiling and bubbles. However, it is best to hold off on expecting a scientific explanation until students are ready.

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Middle School Students

In middle school, students have opportunities to examine the characteristics of different states of matter, and they begin to conceptualize the particle movements associated with phase changes from solid to liquid to gas. Students observe and measure characteristic properties such as boiling point and melting point. Students have had varied experiences with boiling water. They compare evaporation of a liquid under ordinary ambient conditions as well as in situations where increased application of heat is involved, such as boiling water. This probe is useful in determining students' preconceptions related to the common phenomenon of bubbles forming in boiling water.

High School Students

During high school, instructional opportunities connect the macroscopic properties of substances studied in middle school to a microscopic level. An understanding of kinetic molecular theory is a grade-level expectation in the standards that can be used to explain what the bubbles in boiling water are. This probe may be useful in determining if students revert to their earlier preconceptions about bubbles or if they can explain what is happening at a molecular level.

Administering the Probe

You may wish to use visual props for this probe. Bring a beaker of water or some other clear glass, boiling-safe container to a full boil so that students can see the bubbles forming and rising to the surface. Be sure students are wearing safety goggles and are not too close to the heat source if they are observing the boiling up close. Continue to heat the boiling water as students respond to the probe and explain their thinking. Teachers may want to continue to probe students' ideas about boiling by combining this probe with the "Turning the Dial" (p. 47) and "Boiling Time and Temperature" (p. 53) probes.

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

K–4 Properties of Objects and Materials

- Materials can exist in different states—solid, liquid, and gas. Some common materials, such as water, can be changed from one state to another by heating or cooling.

5–8 Properties and Changes in Properties of Matter

- A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the sample. A mixture of substances often can be separated into the original substances using one or more of the characteristic properties.

9–12 Structure and Properties of Matter

★ Solids, liquids, and gases differ in the distances and angles between molecules or atoms and therefore the energy that binds them together. In solids the structure is nearly rigid; in liquids molecules or atoms move around each other but do not move apart; and in gases molecules or atoms move almost independently of each other and are mostly far apart.

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

3–5 Structure of Matter

- Heating and cooling cause changes in the properties of materials. Many kinds of changes occur faster under hotter conditions.

3–5 The Earth

★ When liquid water disappears, it turns into a gas (vapor) in the air and can reappear as a liquid when cooled, or as a solid if cooled below the freezing point of water. Clouds and fog are made up of tiny droplets of water.

6–8 Structure of Matter

★ Atoms and molecules are perpetually in motion. Increased temperature means greater average energy of motion, so most substances

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

expand when heated. In solids, the atoms are closely locked in position and can only vibrate. In liquids, the atoms or molecules have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas. In gases, the atoms or molecules have still more energy and are free of one another except during occasional collisions.

Related Research

- In a study by Barker (2004), many students ages 8–17 thought that the bubbles seen in boiling water are made of heat, air, oxygen, or hydrogen. Another conception was a change in state model that involved molecules breaking up on boiling and reforming on condensing. Barker also discovered that students find it hard to appreciate the reversibility of phase changes, thinking of each process as a separate event.
- Students' understanding of boiling precedes their understanding of evaporation from surfaces such as dishes and roads. In a sample of students ages 6–8, 70% understood that when water boils vapor comes from it and that the vapor is made of water. However, the same students did not recognize that when a wet surface dries, the water turns to water vapor (Driver et al. 1994).

Suggestions for Instruction and Assessment

- Use the phenomenon of bubbles to explain what happens to water molecules during a change in state from boiling liquid to gas.
- Encourage students to draw the stages of what they think is happening to the water as it is heated. Continue drawing right up to the stage where bubbles are formed and rising to the top and bursting. Carefully note how students get to the bubble stage—do the bubbles appear spontaneously in their drawings, or does the act of drawing help them make sense of what is happening to the water to form bubbles?
- Students may have trouble accepting that water vapor is in the bubbles if they do not understand the idea that water vapor is invisible. Help students contrast the concept of invisible water vapor with visible water in the air such as clouds and fog, which are made of tiny suspended droplets rather than water molecules spread far apart.
- Ask students to observe and describe what happens to the water level as the water boils. Encourage them to explain where the water went. How was it able to leave the glass container? Probe students to consider how the bubbles were involved in decreasing the water level. Challenge students who had the idea that the bubbles were air or nothing to explain how their model could account for the decreased water level.
- Consider how to present phase changes as reversible. Allow students to see heating and cooling cycles for themselves, so they can realize that phase changes do not result in a new substance being formed. This cycle may help them see that the water escapes as a gas in the bubbles and can be recovered again through cooling.

- By upper elementary grades, students should begin using terminology such as *water vapor*. Using the correct terminology and developing an understanding that water is in the air may help them overcome the idea that water changes into air rather than remaining the same substance but in a form that you cannot see.
- Be cautious when using the term *steam* with students to describe the gas or vapor form of water. What students are actually seeing over the boiling water when they refer to steam is a wispy mist—it is visible because it is water in a gaseous state that also contains tiny water droplets. Those tiny droplets scatter light at their surfaces, allowing us to "see" the "steam" in much the same way that we can see fog or clouds. The common use of the word steam is different from the way scientists or engineers use the word *steam*. To them, steam and vapor are both invisible forms of water in the gaseous state. However, when students (and often teachers) use the word *steam* in the context of this probe, they are usually calling the visible substance that forms above the boiling water a gas. Technically this common use of the word *steam* is incorrect since a gas is invisible. The Standards use the term *vapor* (not steam) to describe the invisible, gaseous form of water and explicitly point out that clouds and fog are made up of tiny droplets of water in order to distinguish forms of water in the air that we can see from forms we cannot see. Older students may be introduced to the scientific use of the word *steam* and compare it to how it is commonly used in our everyday language, once they have grasped the idea that substances in the gaseous state are not visible.

Related NSTA Science Store Publications and NSTA Journal Articles

See articles and publications listed on page 58.

Related Curriculum Topic Study Guides
(Keeley 2005)
"Physical Properties and Change"
"States of Matter"

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