VOL. 3

Uncovering Student Ideas in Science

Another 25 Formative Assessment Probes

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Contents

Preface

Introduction

Physical Science and Nature of Science Assessment Probes

Life, Earth, and Space Science Assessment Probes

Dedication

This book is dedicated to Dr. Gerry Wheeler, upon his retirement as executive director of the National Science Teachers Association. His leadership, vision, creativity, respect for science teachers, and commitment to all students will live on for many years.

Preface

Overview

This book is the third in the highly successful *Uncovering Student Ideas in Science* series. The addition of 25 more formative assessment probes has now expanded the collection to a total of 75 probes into student thinking in science—thinking that is rarely revealed through standard assessment questions. A new addition to the collection of Earth, space, physical, and life science probes is the inclusion of three probes that target the nature of science and science as inquiry. Together, the probes focus on important fundamental ideas in science that cut across multiple grade spans.

Regardless of whether you teach elementary, middle, or high school science, misconceptions are tenacious and often follow students from one grade to the next. Taking the time to elicit and examine student thinking is one of the most effective ways to support instruction that leads to conceptual change and enduring understanding. It is also the starting point for differentiating instruction to meet the content needs of all students.

Since Volume 1 was released in October 2005, thousands of teachers and hundreds of thousands of K–12 and university students have used the probes. The response has been very encouraging. Teachers have said that students actually ask for and look forward to the opportunity to use an assessment probe. Students eagerly ask teachers for "one of those probe things"—certainly not the typical student reaction when it comes to assessment!

Not only are teachers using probes to elicit students' ideas and inform instructional practices, but they have become a tool for transformative teacher learning. In our work at the Maine Mathematics and Science Alliance, we provide professional development to many school districts, math-science partnership projects, and other teacher enhancement initiatives throughout the United States that have embedded the use of these probes in their teacher professional development programs. Working with teachers has shown us that formative assessment is a powerful catalyst for engaging teachers in examining student learning and teacher practice. As a result of the growing interest in using these probes for teacher professional development, we decided to focus Volume 3 on considerations for using probes in a professional learning context.

While you are probably most interested in using the 25 probes in this book, don't overlook the Introduction (pp. 1–13) or the Introductions in Volumes 1 and 2. Each Introduction will expand your understanding of formative assessment and its inextricable link to instruction and learning. Volume 1 provides an overview of formative assessment, including what it is and how it differs from summative assessment. It also provides background on probes as specific types of formative assessments and

how they are developed. Volume 2 describes the link between formative assessment and instruction and suggests ways to embed the probes in your teaching. This volume (Volume 3) describes how you can use the probes and student work to deepen your understanding of teaching and learning.

Each probe is accompanied by an extensive Teacher Notes section that clarifies the probe and can be used to improve teachers' content knowledge of fundamental ideas in science as well as increase their knowledge of appropriate curricular emphasis and pedagogical implications. The Teacher Notes are made up of the following elements:

Purpose

This section describes the general concept or topic targeted by the probe and the specific idea being elicited by the probe. It is important to be clear about what the probe is going to reveal. Being clear will help you decide if the probe fits your intended target.

Related Concepts

Each probe is designed to target one or more related concepts that cut across grade spans. These concepts are described in the Teacher Notes and are also included on the matrix charts on pages 16 and 110. A single concept may be addressed by multiple probes. You may find it helpful to use a cluster of probes to target a concept or specific ideas within a concept. For example, there are three probes that target kinetic molecular theory.

Explanation

A brief scientific explanation, reviewed by scientists and content specialists, accompanies each probe and provides clarification of 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 not a "right" answer) as well as clarify any misunderstandings you might have about the content. The explanations are not intended to provide detailed background knowledge on the concept, but enough to connect the idea in the probe with the scientific knowledge it is based on. If you have a need for further explanation of the content, several of the probe notes list NSTA resources, such as the series *Stop Faking It! Finally Understanding Science So You Can Teach It,* that will enhance and extend your understanding of the content.

Curricular and Instructional Considerations

The probes in this book are not limited to one grade level as summative assessments are. Rather, they provide insights into the knowledge and thinking that your students may have related to a topic as they progress from one grade span to the next. Some of the probes can be used for grades K–12, while others may cross over just a few grade levels. Teachers from two grade spans (e.g., middle school and high school) might decide to use the same probe and come together and discuss their findings. To do this, it is helpful to have insight into what students typically experience at a given grade span

as it relates to the ideas elicited by the probe. Because the probes do not prescribe a specific grade level for use, you are encouraged to read the curricular and instructional considerations and decide if your students have had sufficient experience to make the probe useful.

The Teacher Notes also describe how the information gleaned from the probe is useful at a given grade span. For example, it might be useful for planning instruction when an idea in the probe is a grade-level expectation or it might be useful at a later grade to find out whether students have sufficient prior knowledge to move on to the next level. Sometimes the student learning data gained through use of the probe indicates that you have to back up several grade levels to teach ideas that are not really clear to students.

We deliberately chose not to suggest a grade level for each probe. If these were intended to be used for summative purposes, a grade level, aligned with a standard, would be suggested. However, these probes have a different purpose. Do you want to know about the ideas your students are expected to learn in your grade-level standards? Are you interested in how ideas develop and change across multiple grade levels in your school even when they are not formally taught? Are you interested in whether students have achieved a scientific understanding of previous grade level ideas before you introduce higher-level concepts? The descriptions of grade-level considerations in this section can be coupled with the section that lists related ideas in the national standards in order to make the best judgment about grade-level use.

Administering the Probe

In this section, we suggest ways to administer the probe, including a variety of modifications that may make the probe more useful at certain grade spans. For example, the Teacher Notes might recommend eliminating certain examples from a justified list for younger students who may not be familiar with particular words or examples, or using the word *weight* instead of *mass* with younger elementary students who might confuse the word *mass* with *massive*. The notes also include suggestions for demonstrating the probe context with artifacts and eliciting the probe responses while students interact within a group.

Related Ideas in the National Standards

This section lists the learning goals stated in the two national documents generally considered the "national standards": *Benchmarks for Science Literacy* (AAAS 1993) and *National Science Education Standards* (NRC 1996). Since the probes are not designed as summative assessments, the learning goals from those two documents are not intended to be considered alignments but rather as related ideas connected to the probe. Some targeted ideas, such as a student's conception of a life cycle on page 111, are not explicitly stated as learning goals in the standards but are clearly related to national standards concepts that address specific ideas about life cycles. When the ideas elicited by a probe appear to be a strong match with a national standard's learning goal, these matches are indicated by a star symbol (★).

Preface

Related Research

Each probe is informed by related research when it is available. Because the probes were not designed primarily for research purposes, an exhaustive literature search was not conducted as part of the development process. We drew primarily from two comprehensive research summaries commonly available to educators: Chapter 15 in *Benchmarks for Science Literacy* (AAAS 1993) and *Making Sense of Secondary Science: Research Into Children's Ideas* (Driver et al. 1994). Although both of these resources describe studies that have been conducted in past decades, and involved children not only in the United States but in other countries as well, many of the results of these studies are considered timeless and universal. Many of the ideas students held that were uncovered in the research during the 1980s and 1990s still apply today. It is important to recognize that cultural and societal contexts can influence students' thinking, but research also indicates that many of these ideas are pervasive regardless of geographic boundaries. Hence the descriptions from the research can help you better understand the intent of the probe and the variety of responses your students are likely to have. As you use the probes, you are encouraged to seek new and additional research findings. One source of updated research can be found on the Curriculum Topic Study (CTS) website at *www.curriculumtopicstudy.org.* A searchable database on this site links each of the CTS topics to additional research articles and resources.

Suggestions for Instruction and Assessment

After analyzing your students' responses, it is up to you to decide on appropriate student interventions and instructional planning. We have included suggestions gathered from the wisdom of teachers, the knowledge base on effective science teaching, and our own collective experience as former teachers and specialists involved in science education. These are not exhaustive or prescribed lists but rather suggestions that may help you modify your curriculum or instruction in order to help students learn ideas that they may be struggling with. It may be as simple as realizing that you need to provide a variety of contexts or that a specific strategy or activity might work with your students. Learning is a very complex process and most likely no single suggestion will help all students learn the science ideas. But that is part of what formative assessment encourages: thinking carefully about the variety of instructional strategies and experiences needed to help students learn scientific ideas.

Related NSTA Bookstore Publications and Journal Articles

NSTA's journals and books are increasingly targeting the ideas that students bring to their learning. We have provided suggestions for additional readings that complement or extend the use of the individual probes and the background information that accompanies them. For example, Bill Robertson's *Stop Faking It!* series may be helpful in clarifying content that teachers struggle with. A journal article from

one of NSTA's elementary, middle school, or high school journals may provide additional insight into students' misconceptions or provide an example of an effective instructional strategy or activity that can be used to develop understanding of the ideas targeted by a probe. Other resources listed in this section provide a more comprehensive overview of the topic addressed by the probe.

Related Curriculum Topic Study Guides

NSTA is a copublisher of the book *Science Curriculum Topic Study: Bridging the Gap Between Standards and Practice* (Keeley 2005). This book was developed as a professional development resource for teachers with funding from the National Science Foundation's Teacher Professional Continuum Program. It provides a set of 147 curriculum topic study (CTS) guides that can be used 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 and research in a systematic process that deepens teachers' understanding of the topics they teach.

The probes in this book were developed using the CTS guides and the assessment tools and processes described in Chapter 4 of the CTS book. The CTS guides that were used to inform the development of each of the probes are listed. Teachers who wish to delve deeper into the standards and research-based findings that informed the development of the probe and are linked to its use in curriculum and instruction may wish to use the CTS guides for further information.

References

References are provided for the standards and research findings cited in the Teacher Notes.

As a companion to this book and the other two volumes, NSTA has copublished *Science Formative Assessment: 75 Practical Strategies for Linking Assessment, Instruction, and Learning* (Keeley 2008). In this book you will find a variety of strategies to use with the probes to facilitate elicitation, support metacognition, spark inquiry, encourage discussion, monitor progress toward conceptual change, encourage feedback, and promote self-assessment and reflection.

We hope this volume of probes will be as useful to you as the other two volumes. As the popular saying goes, "Build it and they will come," and indeed, you came. In concluding this third volume, we turn the cliché around to say, "Come and we will build it." In other words, we sincerely hope the demand for quality formative assessment continues—and, if it keeps coming, we will keep "building"!

Acknowledgments

The assessment probes in this book have been extensively field-tested by several teachers and hundreds of students in Maine, New Hampshire, Iowa, Missouri, Florida, and California by the Maine Mathematics and Science Alliance (MMSA). 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. In particular we would like to acknowledge the following people for their contributions to this volume: Dick Beer, Kennebunk, ME; Margaret Collins, Hooksett, NH; Bev Cox, Orlando, FL; Linda D'apolito, Falmouth, ME; Michelle DeBlois, Livermore Falls, ME; Kevin Fleury, Hooksett, NH; David Gerlach, Cedar Rapids, IA; Susan German, Hallsville, MO; Rita Harvey, Cathedral City, CA; Mark Koenig, Gardiner, ME; Kelle Kolkmeier, Cedar Rapids, IA; Elizabeth Lynch, Dover, NH; Anne MacDonald, Falmouth, ME; Molly Malloy, Orlando, FL; Kellie Martino, Hooksett, NH; Rainey Miller, Cedar Rapids, IA; Bonnie Mizzell, Orlando, FL; Margo Murphy, Thomaston, ME; Lisa Nash, Dover, NH; Betsy O'Day, Hallsville, MO; Michael Praschak, Lewiston, ME; Nicole Rodway, Hooksett, NH; Terri Schott, Cedar Rapids, IA; Amy Troiano, Poland, ME; Jane Voth-Palisi, Concord, NH; Joan Walker, Orlando, FL; Andy Weatherhead, Kittery, ME; Katherine Wheeler, Hillsboro, NH. We sincerely apologize if we overlooked anyone.

We would also like to thank our colleagues at the Maine Mathematics and Science Alliance *(www.mmsa.org),* who continue to support us in this work, as well as our professional development colleagues, Math-Science Partnership Directors, and university partners throughout the United States, with whom we have had the pleasure of sharing this work. In addition, special thanks goes to Dr. Herman Weller at the University of Maine whose graduate seminar, attended by one of the authors, sparked an interest in the nature of science that subsequently went into developing the nature of science probes for this volume. And certainly, we are deeply appreciative of the efforts of the National Science Teachers Association (NSTA) in supporting formative assessment and the outstanding staff that make up the NSTA Press.

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In addition, Page Keeley is the 2008–2009 president of NSTA.

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Introduction

> When data are used by teachers to make decisions about next steps for a student or group of students, to plan instruction, and to improve their own practice, they help *inform* as well as *form* practice; this is *formative assessment*.
>
> —Maura O'Brien Carlson, Gregg E. Humphrey, and Karen S. Reinhardt, *Weaving Science Learning and Continuous Assessment* (2003, p. 4.)

Imagine a team of fourth-grade teachers meeting after school with their district science coordinator to plan for implementation of a new curriculum unit, called "Silkworm." The unit, developed at a summer institute with the support of an entomologist university partner, addresses culminating learning goals related to the characteristics and needs of organisms, life cycles, and behaviors. The teachers are excited about using silkworms as a new context for learning about life cycles. The unit is designed to help students understand that the life cycles of different organisms differ in their details, but all include a cycle of birth, growth and development, reproduction, and death.

The district science coordinator relates that in previous grades students investigated the life cycles of painted lady butterflies using one of the kit-based science programs: The students hatched frog eggs from the local pond, observed the development from

Introduction

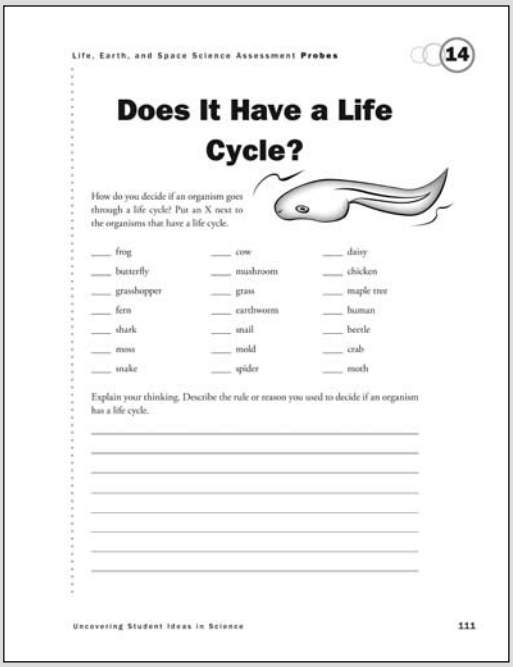
tadpole to frog, and planted bean seeds to observe their development from seed to flowering plants. The teachers conclude that their fourth-grade students have sufficient prior knowledge of life cycles to begin the silkworm investigation without the need to review basic life-cycle concepts.

During the meeting, the district science coordinator alerts the teachers to a new book in their district resource library, *Uncovering Student Ideas in Science, Volume 3: Another 25 Formative Assessment Probes* (this book). One of the probes, shown in Figure 1, is titled, "Does It Have a Life Cycle?" The science coordinator shows the teachers the probe, along with the accompanying Teacher Notes. The notes indicate that some students tend to associate life cycles only with the examples they have encountered in school, such as certain types of plant, butterfly, frog, or mealworm life cycles or organisms that are similar to those they studied.

The teachers' curiosity is piqued by this finding. They wonder if their own students' understanding of life cycles might be limited by the examples and activities they have experienced in school. Are students able to make generalizations about life cycles beyond the individual organism they have studied? The teachers agree to give the probe to their students the next day and meet after school to look at the results.

The next day the teachers meet again and bring samples of their students' work.

Figure 1. "Does It Have a Life Cycle?" Probe



Life, Earth, and Space Science Assessment Probes 14

Does It Have a Life Cycle?

How do you decide if an organism goes through a life cycle? Put an X next to the organisms that have a life cycle.

___ frog	___ cow	___ daisy
___ butterfly	___ mushroom	___ chicken
___ grasshopper	___ grass	___ maple tree
___ fern	___ earthworm	___ human
___ shark	___ snail	___ beetle
___ moss	___ mold	___ crab
___ snake	___ spider	___ moth

Explain your thinking. Describe the rule or reason you used to decide if an organism has a life cycle.

Uncovering Student Ideas in Science 111

Their assumption that the students are ready to begin the unit with a firm foundation of basic life cycle ideas has been shattered: They noticed that the majority of students had little difficulty choosing "butterfly," "frog," and "chicken," and several chose "bean plant," yet they failed to check off other plants and animals. Few students checked off "human." The teachers think that the problem may be that their students have never explicitly encountered the bigger idea that every living plant and animal has a life cycle, even though that cycle may vary depending on the type of organism. Analyzing the students' reasoning, the teachers notice that several students hold similar

context-bound ideas such as "it has to look very different at one time in its life," "it has to go through metamorphosis," and "it has to lay eggs." They even notice that a few students from each class correctly explained what a life cycle is yet failed to check off all the living things on the list.

As the teachers examine and discuss the data, pointing out similar misconceptions held by groups of students as well as a few idiosyncratic ideas, they realize how much they are learning about their students that they would not have known without using the probe. The district science coordinator asks the teachers to think about how they can use the data to modify the silkworm life cycle lessons so that their students can move past their context-bound ideas. The teachers discuss ways to challenge students' preconceptions, to explicitly connect the silkworm's life cycle to other organisms' life cycles, and to help students develop the broader generalization that all plants and animals go through a life cycle. The teachers develop a set of probing discussion questions for small groups that will challenge students' pre-formed ideas and lead to a whole-class discussion. They also decide to share their fourth-grade data with the first-, second-, and third-grade teachers.

The above example illustrates how formative assessment probes can uncover valuable information for teachers that often goes unnoticed in the science classroom and passes on from one grade to the next. The "Silkworm" unit is content rich and inquiry based, designed to develop students' understanding of life science concepts. It was designed to build on students' previous experiences with plant and animal life cycles, but it lacked a component that would uncover students' prior ideas about the basic concept of a life cycle. Students were asked to recall the details of the life cycles of the organisms they studied in previous years, yet they were not called upon to develop the fundamental idea that every plant and animal goes through a life cycle. It is likely that these students would have simply added the silkworm to their collection of "conceptions of life cycles by individual organisms"—rather than use a generalization that applies to all multicellular organisms they encounter in school and in everyday life—if their teachers had not taken the time to uncover their organism-specific concept of a life cycle. It is also likely that these teachers would not have uncovered this conception if they had not had formative assessment probes whose purpose was to reveal commonly held ideas.

Formative Assessment Probes

This book, as well as the two volumes that precede it, is designed to probe for commonly held ideas about fundamental concepts that

can develop early in a student's education and persist all the way through high school if not identified and targeted for conceptual change instruction. This third collection of K–12 formative assessment probes continues to provide assessment examples that teachers can use to ask interesting questions, provoke lively discussions, encourage argumentation in small groups about differing ideas, orchestrate classroom discourse that promotes the public sharing of ideas, and examine students' ideas and reasoning through their written science explanations. These probes support students in being more metacognitive—that is, in becoming more aware of how and why they think about ideas in science—and also help teachers to aid individual students and the class progress toward developing scientific understanding (Keeley 2008).

Each assessment probe in this book, as well as those in Volumes 1 and 2, is a carefully designed question based on a formative assessment development process used in *Science Curriculum Topic Study* (Keeley 2005) that gives information to teachers about students' factual and conceptual understandings in science and the connections students make between and across ideas. Students respond to probes in writing as well as through small-group or class discussion, generating a range of ideas that help the teacher diagnose and address potential learning difficulties. Typically, teachers use the probes to identify potential misconceptions that can be barriers as well as springboards for learning, gather information on student thinking and learning in order to make informed decisions to plan for or adjust instructional activities, monitor the pace of instruction, and spend more time on ideas that students struggle with. In addition to informing instruction and promoting student learning—purposes that are described extensively in Volumes 1 and 2 and in the complementary publication, *Science Formative Assessment: 75 Practical Strategies for Linking Assessment, Instruction, and Learning* (Keeley 2008)—assessment probes are powerful tools to enhance teacher learning.

Using Probes to Examine Teaching and Learning

Probes provide an entry point for teachers at all levels, from preservice to experienced teacher leaders, to examine and discuss the teaching and learning process, including the effective use of formative assessment. Some teachers think they are using formative assessment when they use probes to gather evidence of misconceptions but then proceed with their lesson plans despite their students' responses to the probes. There is little point in gathering data from formative assessment if the data are not used to fashion what comes next—"only when such refashioning occurs does the assessment become formative assessment" (Atkin and Coffey 2003, p. 6). Furthermore, the use of probes can extend beyond "refashioning" instruction. It can update the teachers' science content and pedagogical content knowledge and result in transformative teacher learning. Unlike additive learning, in which teachers acquire a new activity or strategy to add to their

instructional repertoire, transformative learning results in changes in deeply held beliefs, knowledge, and habits of practice (Thompson and Zueli 1999).

Probes and Transformative Learning for Teachers

Using the probes as a transformative teacher learning experience fits with Thompson and Zueli's five requirements for transformative learning (Loucks-Horsley et al. 2003). A transformative learning experience should

1. *Create a high level of cognitive dissonance.* That is, new information, whether it is the content of the probe or the students' ideas as seen in students' written work or probe discussions, should reveal a "disconnect" between what the teacher thought he or she knew about the content (or about his or her students' ideas) and what is actually revealed through the probe. For example, a teacher might take the probe before using it with students and find that he or she has the same misconception that was revealed in the research. Or a high school teacher might believe that her chemistry students understand very basic matter concepts and be surprised to learn that her students have misconceptions about fundamental ideas.

2. *Provide sufficient time, structure, and support for teachers to think through the dissonance they experience.* Study groups, mentoring, coaching sessions, and professional learning communities give teachers a vehicle to make sense of the probe content, of the curricular and instructional implications of students' responses, and of their students' ways of reasoning.

3. *Embed the dissonance-creating and dissonance-resolving activities in teachers' actual situations.* For example, it is wise to use probes that relate to a learning goal in the teacher's curriculum and use his or her students' work to examine students' ideas and consider adjustments to instruction.

4. *Enable teachers to develop new ways of teaching that fit with their new understanding.* It is not enough for teachers to improve their own understanding of the content of a probe or to become aware of the misconceptions their students have. Teachers must consider how they will make the content accessible to their students and how they will change their teaching practices or lessons to help students develop conceptual understanding.

5. *Engage teachers in a continuous process of improvement.* Regular examination of student work from the probes (as well as the Teacher Notes that follow each probe) brings to light new problems related to teaching and learning, develops new understandings about content and pedagogy, and encourages teachers to make modifications to their lessons or try new instructional strategies.

Introduction

Nine Suggestions for Using Probes as Assessment for Teacher Learning

Volume 2 in this series addressed ways to use probes as assessment *for* learning to *promote* student learning and *inform* instruction. It also provided a variety of suggestions for embedding probes in instruction. Here, we offer suggestions for ways to use the probes in this book and in Volumes 1 and 2 as assessments *for teacher learning*.

1. **Always do the probe yourself.** Before giving the probe to your students, take it yourself and think about your prior experiences in school and in everyday situations that may be contributing to your response. Think about when and how you learned the content of the probe and whether you once had misconceptions or still have them. Note any difficulties you had responding to the probe. Being metacognitive about your own knowledge and experiences can help you understand what your students or other teachers might have thought or have experienced while taking the probe. It also points out areas of conceptual difficulty in which you may be helped by further professional development, university courses, or the support of a knowledgeable colleague or university partner.

2. **Use the Teacher Notes.** The Teacher Notes section that follows each probe contains a wealth of information that can deepen your understanding of the content of the probe and its curricular and instructional implications. Examine the Teacher Notes *before* looking at the student work to sharpen your analytical lens and to anticipate what you might find when you examine students' thinking. Use the Teacher Notes as references in your discussion of student work with other teachers in order to move beyond opinion and speak from a common knowledge base.

3. **Examine student work in collaborative structures.** Collaborative learning environments are good settings in which to examine the student work from the probes and to discuss the accompanying Teacher Notes. Structures that promote collegial learning include professional learning communities (PLCs), study groups, mentoring, instructional coaching, teacher research teams, and inquiry and reflective practice groups. The ongoing nature of these structures allows teachers to reconvene after making modifications or trying out new strategies and receive feedback from their colleagues on the formative decisions they made.

4. **Embed the probes into existing professional development.** Using the probes for teacher learning does not have to be a stand-alone professional learning experience. The probes can be used to examine student thinking within a

variety of content-focused workshops and institutes as well as within embedded professional development strategies, such as lesson study (Lewis 2002), teacher research (Roberts, Bove, and Van Zee 2007), curriculum topic study (Keeley 2005), study groups (Murphy and Lick 2001), and curriculum implementation, content immersion, and demonstration lessons (Loucks-Horsley et al. 2003).

5. **Select specific areas to focus on.** Looking at student work from the probes can initially be daunting. The responses to the probes provide such a treasure trove of data that it is sometimes hard to know what to focus on. Table 1 shows some of the things you might look for.

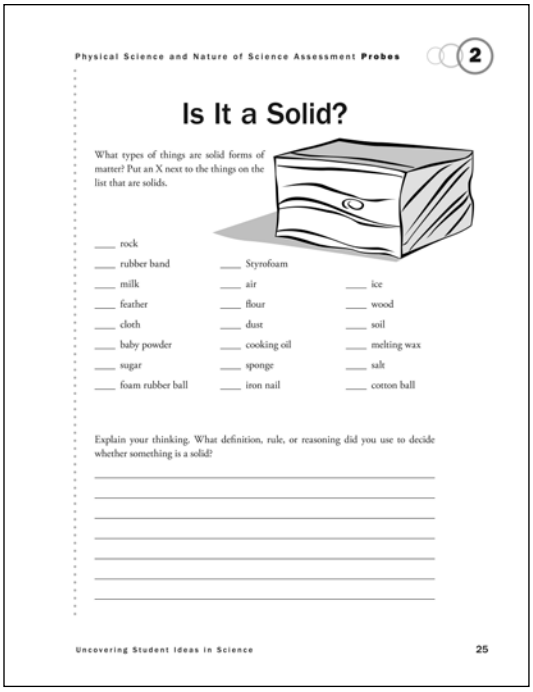
6. **Examine student thinking across grade spans.** An aspect of these probes that distinguishes them from summative assessments is that they are designed to be used across multiple grade levels. Sometimes, a single probe can be used at all levels—elementary, middle, and high school. For example, the "Is It a Solid?" probe shown in Figure 2 (p. 8) may elicit misconceptions about solids that may develop as early as first grade in a unit on solids and liquids and continue through high school if not addressed. Sometimes, the ideas do not change much from one grade span to the next; students just get a lot more "scientific" and their ideas become more muddled with other concepts they are learning as they move up through the grades.

Table 1. What to Look For in Students' Responses to Probes

Areas for Analysis	What to Look For
Concepts and ideas	Number of students choosing a selected response (use tallies); groups of students using similar explanations
Use of terminology	Confusion of everyday words with their scientific meaning; appropriate use of scientific terminology
Transfer of learning	Ability to apply ideas across contexts or in new situations
Prior knowledge or experience	Ideas that students bring to their learning; experiences students may have had that impact their ideas
Sophistication level	Grade levels at which the students' ideas are typically developed
Reasoning	Types of rules or justifications students use to support their ideas
Ability to explain	Students' ability to write or verbalize an explanation

Introduction

Figure 2. "Is It a Solid?" Probe



Physical Science and Nature of Science Assessment **Probes** 2

Is It a Solid?

What types of things are solid forms of matter? Put an X next to the things on the list that are solids.

___ rock
___ rubber band
___ milk
___ feather
___ cloth
___ baby powder
___ sugar
___ foam rubber ball
___ Styrofoam
___ air
___ flour
___ dust
___ cooking oil
___ sponge
___ iron nail
___ ice
___ wood
___ soil
___ melting wax
___ salt
___ cotton ball

Explain your thinking. What definition, rule, or reasoning did you use to decide whether something is a solid?

Uncovering Student Ideas in Science 25

There is tremendous value in analyzing students' responses to the same probe with colleagues from other grade levels. Because learning goals become more complex as students progress in school, it is important to take into account the targeted concept and learning goal for the particular grade you teach, including its level of sophistication. Here are some questions to ask yourself before and after you examine student work at various grade levels and read the Teacher Notes:

- How do my district's curricular learning goals at my grade level match the national learning goals described in the Teacher Notes?
- Which parts of my district's learning goals does the probe address?
- How well do my students know the learning goals related to a probe that come before my grade level? Are there learning goals that come after my grade level that they have had opportunities to achieve?
- To what extent does the Curricular and Instructional Considerations section described in the Teacher Notes match my classroom or district context? To what extent are my students familiar with the context of the probe, the correct response, and the distracters (wrong choices)? Should I tell students to ignore some of the distracters?
- Do any of the age-related research findings match the ages of students in my classes?
- When I look at the student work, do I find that any of my students' ideas are among the research findings in the Teacher Notes?
- What seems to be most problematic for students? Is this indicative of one grade span or is it seen across grades? What patterns do I notice?
- If students hold similar ideas, how do their explanations differ or remain the same across grade spans?
- Taking into account the types of ideas my students have and their reasoning, which points in the Suggestions for Instruction and

Assessment section in the Teacher Notes might be appropriate for me to use?

- What other curricular or instructional actions might I need to take?

7. **Categorize types of ideas.** Researchers and science educators have categorized students' science ideas in various ways. As you examine your students' ideas, try matching them to the following categories of ideas adapted from *Science Teaching Reconsidered* (NRC 1997):
   - **Scientific ideas.** These are the accurate conceptions that a scientifically literate person would have. Scientifically accurate ideas can range from basic, precursor understandings to sophisticated, complex ideas, depending on the developmental level of the student.
   - **Preconceptions.** These are popular conceptions based on everyday experiences. Often, they take root even before students have been taught scientific ideas. For example, students think the phases of the Moon are caused by the shadow of the Earth on the Moon. This conception is often rooted in students' everyday experience of seeing how part of an object is shaded when something blocks the light shining on the object.
   - **Conceptual misunderstandings.** These misunderstandings arise when students are taught scientific concepts in a way that does not challenge them to confront their beliefs or in a way that fails to connect disparate pieces of knowledge. For example, even though students have been taught the idea of the water cycle, they may believe that evaporated water moves immediately upward to a cloud. In their minds, they see the water going up to the clouds rather than existing in the air around them. They may correctly use terms like *evaporation* and *condensation* and know that water can exist as water vapor, yet fail to understand that water vapor is in the air around us. Another example is recanting an incorrect definition of matter but not accepting the idea that air is matter. Misrepresentations also lead to conceptual misunderstandings, such as the exaggerated elliptical orbit of the Earth around the Sun that leads to misconceptions about seasons. Overgeneralizations and undergeneralizations—for example, all animals have fur and legs and only shiny or smooth objects reflect light—are also categorized as conceptual misunderstandings.
   - **Nonscientific beliefs.** These are views learned by students from nonscientific sources, such as religious or mythical teachings, and

pseudosciences, such as astrology. For example, in religious instruction, some students learn through literal interpretation of the Bible about the short time in which the Earth and the organisms that inhabit it were created. Scientific evidence, however, shows that the Earth was created about 5 billion years ago and life began with simple, one-celled organisms. The result has been considerable controversy in teaching certain aspects of science, such as the origins of the Earth or life and the Earth's and life's evolution.

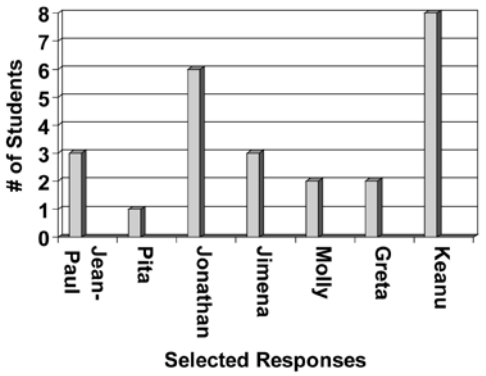
- **Vernacular misconceptions.** These arise from the use of scientific words and phrases that mean one thing in everyday life and another in a scientific context. An example is the word *theory,* which means a "hunch" to some people but to scientists means a well-established, thoroughly tested idea. Sometimes the way words are used implies something other than what was intended; for example, "heat rises" and "the Sun moves across the sky" may imply that heat is the physical entity that rises rather than the air or that the Sun is actually the object that is moving around the Earth. Sometimes a scientific word is misused, as in the phrase "a hard candy melts in your mouth." Melting is a physical process. The candy does not melt, it dissolves. As a result of the misuse of the word *melt* students have a hard time distinguishing between melting and dissolving. Likewise, misuse of the term *zero gravity*—rather than the correct term, *microgravity*—has led students to think there are instances where there is no gravity acting on an object in space.
- **Factual misconceptions.** These are inaccuracies that may be taught and learned in school or home and are retained unchallenged throughout adulthood. For example, the notions that lightning never strikes twice in the same place, that water in a bathtub drain swirls in the opposite direction in the Southern Hemisphere than it does in the Northern Hemisphere, or that the blood in your veins is blue are all incorrect. Such ideas may remain part of many students' and adults' beliefs because they have been (incorrectly) taught them.

8. **Crunch the data and create classroom profiles and graphs.** Classroom profiles provide a written record of students' misconceptions for the teacher to analyze, share with other teachers, and refer to in monitoring conceptual change over time (Shapiro 1994). The classroom profile breaks each distracter down into the

Figure 3. Classroom Profile for "Thermometer" Probe (Grade 7)

Response Choices	Students' Supporting Explanations for Their Choices	# of Students
1. (Jean-Paul) "The hot water pushed it up."	• "The hot water creates a force that pushes the liquid up." • Repeats the answer choice with no further explanation.	2 1 **Total:** 3
2. (Pita) "The mass of the red liquid increased."	• "When the liquid gets hot from the water, it gets heavier and expands."	1 **Total:** 1
3. (Jonathan) "The heat inside the thermometer rises."	• "The red liquid is in the form of heat and it rises." • Explains how heat rises when it's warm but doesn't mention the red liquid. • Repeats the answer choice with no further explanation.	2 3 1 **Total:** 6
4. (Jimena) "The air inside the thermometer pulls it up."	• "Air pressure makes it go up." • "The air gets warm and creates a vacuum, which sucks the liquid up." • "The warm air creates a force that pulls up on the liquid."	1 1 1 **Total:** 3
5. (Molly) "The molecules of the red liquid are further apart."	• "As the liquid warms up, the space between the molecules increases." • "The liquid is turning to a gas so the molecules are further apart."	1 1 **Total:** 2
6. (Greta) "The number of molecules in the red liquid increased."	• "The molecules break apart when the liquid gets hot, making more molecules." • "There is more liquid so there are more molecules."	1 1 **Total:** 2
7. (Keanu) "The molecules of the red liquid are getting bigger."	• "The heat makes the molecules expand [also includes 'grow' and 'stretch.']" • "Things expand or get bigger when they warm up [but doesn't mention molecules]." • Gave no explanation—just "that's how thermometers work." • Gave no further explanation—left blank.	4 2 1 1 **Total:** 8

Figure 4. Graph of Class Responses to "Thermometer" Probe



kinds of reasoning students use and the number of students who used similar reasoning for that response. The exercise in grouping similar responses is an excellent professional development exercise for teachers that models similar ways that researchers code responses. Teachers can also include an additional column with the names of students who shared each idea. Classroom profiles can be shared with students (with names removed); most students show great interest in knowing what other students think and how the other students' thinking compares to their own. Creating graphs and charts to visually show the tallies of students' responses is another way of sharing data with students; the visual tallies are also useful in teacher collaborative groups. Figure 3 (p. 11) shows a classroom profile for a seventh-grade class's response to the probe "Thermometer" (on p. 33 of this book). Figure 4 shows a graph of the student responses from the probe.

9. **Read and discuss professional literature.** Further your understanding of the content related to the probe, students' ideas, and effective strategies and activities to use to teach for conceptual change by selecting and reading professional literature from the related NSTA publications list provided for each probe. In addition, you may want to read the references cited, including the full research papers. Also, search *www.curriculumtopicstudy.org.* This database regularly posts new research articles on students' misconceptions and other resources for teacher professional development related to the topic of each probe.

Whatever probe or probes you decide to use in your classroom, remember the outcomes will be threefold. First, you will learn a lot about your students; this new information will lead to modifications in how and what you teach. Second, you will learn a lot about standards and research-based teaching and learning that applies to all students. And third, you will learn the value in sharing the probes, your student data, your inquiries into practice, and your new learning with other teachers.

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Physical Science and Nature of Science Assessment Probes

Physical Science and Nature of Science Assessment Probes
Concept Matrix

Related Science Concepts	Physical Science										Nature of Science		
	Pennies	Is It a Solid?	Thermometer	Floating Balloon	Hot and Cold Balloons	Mirror on the Wall	Batteries, Bulbs, and Wires	Apple on a Desk	Rolling Marbles	Dropping Balls	Is It a Theory?	Doing Sciencce	What Is a Hypothesis?
Acceleration										✓			
Atom	✓												
Balanced Forces								✓					
Circular Motion									✓				
Complete Circuit							✓						
Conservation of Matter					✓								
Density				✓									
Electric Circuit							✓						
Electricity							✓						
Experiment												✓	
Force								✓	✓	✓			
Gas				✓	✓								
Gravity								✓		✓			
Hypothesis											✓		✓
Inertia									✓				
Kinetic Molecular Theory			✓	✓	✓								
Liquid		✓											
Mass				✓	✓					✓			
Mirrors						✓							
Nature of Science											✓	✓	✓
Newton's First Law									✓	✓			
Properties of Matter	✓	✓		✓	✓								
Reflection						✓							
Scientific Inquiry												✓	✓
Scientific Law											✓		
Scientific Method												✓	✓
Solid		✓											
Theory											✓		
Thermal Expansion			✓										
Thermometer			✓										
Weight				✓	✓					✓			

Pennies

A shiny new penny is made up of atoms. Put an X next to all the things on the list that describe the atoms that make up the shiny new penny.

___ hard ___ soft

___ solid ___ copper-colored

___ very small ___ has mass

___ always moving ___ do not move ___ cold

___ warm ___ shiny ___ dull

___ made of smaller particles

___ contains mostly empty space

Describe your thinking about the atoms that make up the penny. Explain why you selected the things on the list as ways to describe atoms.

_____

_____

_____

_____

_____

_____

_____

_____

_____

_____

Pennies

Teacher Notes

Purpose

The purpose of this assessment probe is to elicit students' ideas about the properties of atoms. The probe is designed to determine whether students can distinguish between the microscopic properties of an atom and the macroscopic properties of a substance or object made up of atoms.

Related Concepts

atom, properties of matter

Explanation

Five items on the list make up the best response: very small, has mass, always moving, made of smaller particles, and contains mostly empty space. Atoms are the smallest particles of matter that make up the substances zinc and copper (elements) in the penny. Most pennies circulating today are made up of 97.5% zinc and 2.5% copper. If a penny were made of pure copper, it would contain about 2.4×10^{24} copper atoms. This indicates that the size of an individual atom is very small. A penny weighs only about 2 g. With over 10^{24} atoms in a penny, this shows that the mass of an individual atom is extremely small, yet it still has mass. Atoms and molecules are always in motion and reach a minimum of motion in very extreme, cold conditions. Since the penny is a solid, the atoms that make up the penny are in a fixed position and can only move by vibrating. An atom is mostly empty space. Even though the zinc and copper atoms make up the solid substance of the penny, the atoms themselves are mostly empty space. They consist of a small, dense nucleus surrounded by electrons that move in an area of space about a trillion

times larger in volume than the nucleus, making the total atom mostly empty space. The atom is made up of even smaller particles—protons and neutrons in the nucleus and electrons found outside the nucleus. Scientists have discovered even smaller particles that make up the protons and neutrons. Properties such as hard, solid, copper-colored, shiny, cold (or warm) describe the macroscopic properties of the substances (zinc and copper) or object (penny) and are not the properties of the individual atoms.

Curricular and Instructional Considerations

Elementary Students

At the elementary school level, students describe the properties of materials, objects, and familiar substances, like water. The focus is on observable and measurable properties of macroscopic matter.

Middle School Students

At the middle school level, students transition from focusing on the properties of objects and materials to the properties of substances. They develop an understanding of the atom as the smallest unit of matter that has mass and takes up space. They begin to distinguish between states of matter by using the idea of position and movement of atoms and molecules. However, the idea of empty space within an atom and between atoms is difficult for students at this age because they still tend to view matter as a continuous substance.

High School Students

At the high school level, students learn about the physical and chemical properties of atoms. They learn to distinguish between the macroscopic properties of elements and the microscopic properties of the atoms that make up elements. At this level, they learn about subatomic particles and the architecture of an atom. Their deepening understanding of kinetic molecular theory, introduced in middle school, helps them recognize that atoms and molecules are constantly moving and reach a minimum of motion in temperatures approaching absolute zero (0° Kelvin).

Administering the Probe

Because this probe targets ideas related to the properties of atoms, it is most suitable for middle school and high school grades. Consider showing students a shiny new penny and, although they do not need to know the composition of new pennies for this probe, you can explain that pennies today are not made entirely of copper.

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

K–4 Properties of Objects and Materials

- Objects have many observable properties, including size, weight, shape, color, temperature, and the ability to react with other substances. Those properties can be measured using tools, such as rulers, balances, and thermometers.

9–12 Structure of Atoms

★ Matter is made of minute particles called *atoms,* and atoms are composed of even smaller components. These components have measurable properties, such as mass and electric charge. Each atom has a positively charged nucleus surrounded by negatively charged electrons.

9–12 Structure and Properties of Matter

- Atoms interact with one another by transferring or sharing electrons that are farthest from the nucleus. These outer electrons govern the chemical properties of the element.
- 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)

K–2 Structure of Matter

- Objects can be described in terms of the materials they are made of (clay, cloth, paper, etc.) and their physical properties (color, size, shape, weight, texture, flexibility, etc.).

3–5 Structure of Matter

- Materials may be composed of parts that are too small to be seen without magnification.

6–8 Structure of Matter

- All matter is made up of atoms, which are far too small to see directly through a microscope. The atoms of any element are alike but are different from atoms of other elements. Atoms may stick together in well-defined molecules or may be packed together in large arrays. Different arrangements of atoms into groups compose all substances.

★ Atoms and molecules are perpetually in motion. In solids, the atoms are closely locked in position and can only vibrate.

9–12 Structure of Matter

★ Atoms are made of a positive nucleus surrounded by negative electrons.

★ The nucleus, a tiny fraction of the volume of an atom, is composed of protons and neutrons, each almost 2,000 times heavier than an electron. The number of positive protons in the nucleus determines what an atom's electron configuration can be and so defines the element.

- Scientists continue to investigate atoms and have discovered even smaller constituents of which neutrons and protons are made.

Related Research

- Middle school and high school students are deeply committed to a theory of continuous matter. Although some students may think

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

that substances can be divided up into small particles, they do not recognize the particles as building blocks, but as formed of basically continuous substances under certain conditions (AAAS 1993, p. 336).

- Students of all ages show a wide range of beliefs about the nature and behavior of particles, including a lack of appreciation of the very small size of particles (AAAS 1993).
- Some students, when recognizing the minute size of atoms, reason that because atoms are so small they have zero or negligible mass (Driver et al. 1994).
- Although some students can depict the orderly arrangement of atoms or molecules in a solid, they have difficulty recognizing the vibration of the particles (Driver et al. 1994).
- Several studies of students' initial conception of an atom show that they perceive it either as "a small piece of material" or the "ultimate bit of material obtained when a portion of material is progressively subdivided." Such "bits" are thought to vary in size and shape and possess properties similar to the properties of the parent material. For example, some students consider atoms of a solid to have all or most of the macro properties that they associate with the solid, such as hardness, hotness/coldness, color, and state of matter (Driver et al. 1994, p. 74).
- Children's naive view of particulate matter is based on a "seeing is believing" principle in which they tend to use sensory reasoning. Being able to accommodate a scientific particle model involves overcoming cognitive difficulties of both a conceptual and perceptive nature (Kind 2004).

Suggestions for Instruction and Assessment

- Be explicit in developing the idea that any property of a material is a result of the arrangement of the particles, not a result of the individual particles having that property.
- Ask students to draw what they think an atom and a group of atoms look like. Their representations will vary and can be used as starting points for discussions about the properties of things we cannot see.
- Do not assume students will recognize the difference between properties of atoms and properties of substances. After teaching about properties of atoms and molecules, provide an opportunity for students to use a graphic organizer to compare and contrast microscopic and macroscopic properties at a substance and atomic/molecular level. Repeat this using an example of a solid, liquid, and gaseous substance.
- Be up-front with students about the difficulty in conceptualizing small particles like atoms and molecules. Explain how scientists have been trying to understand atoms for the last 2,000 years, and it was not until the early 19th century that the idea of atoms was accepted. It took more than a century after that to understand the structure of atoms, which is still being studied by scientists today. If it took scientists this long to understand the particulate nature of matter, then do not expect

students to change their models overnight (Kind 2004).

- Have students imagine they are wearing "atomic spectacles" that allow them to "see" atoms. Show them a shiny penny, nickel, or dime and ask them what the atoms look like. Encourage them to draw the atoms. Have them discuss the differences and similarities between their ideas and drawings, further probing for ideas about color or continuous matter.
- Use analogies to depict the very small size of atoms in relation to the total volume of an atom.
- Demonstrate how something that is non-continuous can look continuous depending on the magnitude of our view. For example, show students a sponge and have them examine the many holes. Stand far enough away so that students cannot see the individual holes. The sponge will look like a continuous block of matter, even though it is full of holes. Relate this to looking at the penny without powers of magnification that would allow one to see at the atomic level.
- Representations of atoms often lead to students' misconceptions. Use the PRISMS (Phenomena and Representations for Instruction of Science in Middle School) website at *http://prisms.mmsa.org* to find examples of atomic representations, along with their likely instructional effectiveness, that can be used in teaching about atoms.

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Related Curriculum Topic Study Guide

(Keeley 2005)

"Particulate Nature of Matter (Atoms and Molecules)"

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Index