Teaching Science for Motivation and Understanding

Andy Anderson, August, 2003

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What does it mean to teach science well?

You are probably reading this because you plan to become a science teacher. You probably have already spent a lot of time learning things that will be useful in your science teaching, including time in science classrooms. Let's take a minute to consider your experience as a science student and some things you might learn from it.

- Estimate how many science teachers or instructors you have had in middle school, high school, and college. You will probably come out with a pretty big number—20 or more.
- List the science teachers you would consider as excellent role models—the ones you would really like to be like? How many are there?
- Which teachers are satisfactory role models—ones you could be satisfied with being like? How many are there?
- Figure out where you want to rank among this sample of science teachers that you know well. What are the odds of becoming a teacher like the ones you look to as role models?
- Try to describe some of the knowledge and practices that made your best teachers special. What did they know and what did they do that helped you understand and appreciate science? How did their students respond?

This paper is basically a very long answer to the questions above, especially the last one. Although it is written mostly by one author, it is in many ways a collective effort. It is based on the experiences of those of us who have worked in teacher education at Michigan State University, as science learners, as science teachers, and as science teacher educators.[1] We expect that although our answers to the questions above differ from yours in detail, we share with you a couple of basic goals for your science teaching. One of the goals is *motivation to learn:* Good science teachers convince their students to put effort into learning and understanding science. A second goal is *understanding for all:* Good science teachers help all their students make progress toward scientific understanding.

We assume you share the same goals, but don't expect it to be easy. Think about all the teachers who did NOT make your list of role models. In a lot of ways they are like you—college graduates, knowledgeable about science (some have Ph.D.'s). Like you, most of them *want* to be good science teachers, but some of them are living proof that knowing science and wanting to teach well are not enough. What will it take for you to beat the odds?

Perhaps we should start with a recognition that "beating the odds" is never an all-or-nothing proposition in science teaching. You know enough now to motivate some of your students and help them learn with understanding, while not even the best teachers succeed in reaching all their students all of the time. Your can improve your success rate, though. We hope that by the end of your intern year you will be able to help many more students learn with understanding than you do now.

This paper includes our best ideas about how you can become a successful science teacher. We begin with some basic thoughts about the meanings of the goals that most science teachers share—motivation and understanding. This leads to a discussion of the *problems of practice* that all science teachers face.

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[1] People at Michigan State who have contributed to the ideas in this paper include in particular Gail Richmond and Joyce Parker, as well as Ed Smith, Jim Gallagher, Shinho Jang, Ajay Sharma, Kelly Grindstaff, In-Young Cho, Mark Olson, and Mark Enfield.

Motivation and Understanding in Science Learning

There usually isn't a lot of argument about the idea that student motivation and student understanding are important goals for science teachers. The appearance of consensus is deceptive, though, because motivation and understanding can mean different things to different people. In this section we explain our definitions of motivation and understanding.

Motivation: Expectancy times value for sustained effort

The kind of motivation that we care about involves sustained effort, not just temporary excitement. Getting students interested or enthusiastic about science is a good start, but motivation to learn entails a sustained commitment to developing scientific knowledge and using it to make sense of the material world. (Newmann, et al., 1992; Brophy, 1998). Your students' enthusiasm will pay off only if it translates into a willingness to come to class, day after day, and put sustained effort into the work of learning science.

Motivation to learn in this sense is a response of students to your science teaching. You will find that almost all your students are motivated to learn *something*—music or basketball or video games if not science. So they will *decide* (perhaps subconsciously) whether science is something that they are motivated to learn. We know something about how people decide whether something is worth their sustained effort. Students' willingness to put effort into learning depends on both *expectancy* (their perceived chances of success) and the *value* that they attach to success in the goal they are pursuing (Brophy, 1998, page 14).

Motivation to learndepends on the *product* of expectancy and value. If either expectancy or value is zero, then students will not be motivated to learn. Thus students who are convinced that they cannot learn something (zero expectancy) will not put much effort into learning, no matter how valuable the knowledge might be to them. What's the point if they are going to fail anyway? Similarly, students who don't value what they are being taught will not put much effort into learning, no matter how easy it is. Why should they bother? So at least moderate levels of both expectancy and value are essential for students to be motivated to learn.

As a science teacher, you will find that a few of your students are *intrinsically motivated* to learn science. They come to your class liking science or believing that science is important (high value) and that they are capable of learning science (high expectancy). These are easy and rewarding students to teach. Other students are *extrinsically motivated.* They believe that they are capable of learning science (high expectancy) and will do whatever it takes to get a good grade (so they attach value to the grade rather than the science that they learn). While you might wish for purer motives, you can still help these students to learn with understanding. For these students it is your responsibility as a science teacher to make sure that the work they do to get their grades really helps them to acquire valuable knowledge. We will discuss how you can fulfill your responsibilities to these students in the section on science content and learning goals, below.

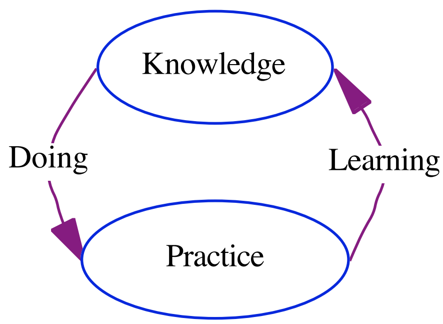
As a student, you are probably motivated to learn science, either intrinsically or extrinsically (or most likely, a combination of the two). As a teacher, you will work with students who are not motivated to learn science, either because they don't care (low value) or because they don't believe that they can succeed (low expectancy). These problems often go together, and it isn't always easy to tell which is the more important. Many students , for example, would rather be seen by their peers as lazy or rebellious than as stupid, so they will pretend not to care, even if the underlying problem is their fear of failure. You will probably worry a lot about unmotivated students. We discuss them in more detail in the section on students and assessment below.

Understanding: Connected knowledge and practice

How well do you understand understanding? When you say that you *understand* something—a scientific concept or how your car works or another person—what does that mean? There is no single correct answer to this question, but we will try one that should be useful to you as a science teacher.

Our answer centers on the relationship between *knowledge* and *practices*. These words have specific meanings for us. *Knowledge* refers to all of the ideas, beliefs, facts, attitudes and skills that people have in their heads (or even their bodies, in the case of physical skills). *Practices* are activities that people engage in repeatedly, often in a slightly different way each time. Your life is organized around practices, each of which at one time was new to you and required hours of learning. Think of tying shoes as an example. You could list many other examples, such as ordering in a restaurant, studying for a test, driving to work, or talking about the weather. Practices include not just physical activities but also verbal activities such as reading, writing, explaining, describing, and predicting.

We tend to think of some things as mostly knowledge (e.g., science) and other things as mostly practice (e.g., science teaching), but that is never really the case. Knowledge and practice are always linked. All knowledge is acquired through practices and used in practices. All practices require and use knowledge. The figure below illustrates the relationship



As the arrows in the graphic on left show, knowledge and practice are related to learning as well as doing. We engage in practices (learning activities) to acquire new knowledge, then we use our knowledge to engage in practices (applications of what we have learned). These processes go on constantly, and usually subconsciously. We don't think about what knowledge we are using when engage in a practice, but it is always there. Similarly, we are constantly learning from the practices that we engage in, whether we consciously intend to or not. People who play a lot of basketball or dance a lot or read a lot, even if they do them just for fun. We don't have to "practice" with the intention of learning in order to gain knowledge and get better at a practice.

Learning always involves gaining knowledge by engaging in some practice. There are many different kinds of practices that lead to learning, though. Some practices lead to *learning from others*. When people participate in a social group or listen to a lecture in a classroom, they are learning from the people around them, especially people who have knowledge that they lack. Other practices lead to *learning from experience*. When people practice alone or try something and see how it turns out or do a scientific experiment, they are learning from experience—they interact with the world and reflecting on their experiences. Learning science and learning to teach science involve both kinds of learning.

It is easy to lose track of the connections between knowledge and practice when you are planning and teaching. If you think about "covering content," then you may be thinking of knowledge but not practice. If you think about "teaching skills", then you may be thinking of practice but not knowledge. If you want to teach for understanding, though, you always have to keep in mind the connections between what you want your students to know and what you want them to do. The relationships between scientific knowledge and scientific practices are discussed further in the section on science content and learning goals, below.

Here's one way to express a basic principle that sums up what we have said about understanding, knowledge, and practice: *What you do is what you learn.* This is an important principle, so let's give it an acronym: WYDIWYL,

This is a principle that people accept as pretty obvious in everyday life, but somehow we seem to forget it when we teach. For example, students who listen to a lecture in which the teacher explains a scientific concept clearly are learning to listen, but the *teacher* is the one who is getting practice in explaining the concept. If you are a good student, you may take advantage of the lecture by practicing explanations on your own as you study. As a teacher, though, you can't expect to have all good students. It will be your obligation to engage your students in the practices that are important for scientific understanding, and to help them acquire the knowledge they need for those practices.

Knowledge and practice in science teaching: The teaching cycle and problems of practice

Most of the difficult and important things that we do involve complex sets of interrelated practices—practices that require a lot of knowledge. People who are good or excellent at anything are people who have put a lot of time and energy into mastering the practices that go with that activity. Try this:

- Pick something you are good at (a sport, dancing, art, cooking, knitting, biology research, etc.)
- Make a list of practices you need to have mastered to be good at this.
- Estimate how many years and how many hours you have spent learning and engaging in those practices.

Getting good at any complicated set of practices, including science requires both a lot of years and a lot of hours. Two more years may seem like a long time to spend in a teacher education program, and it is. If you compare the time you will have with the amount of time, either in years or hours, that you have spent learning other important and complex practices, though, you can appreciate that it isn't much time compared with the amount of learning ahead. Good teaching requires an exceptionally complex set of practices—sometimes we will talk about *building a pattern of practice*. Furthermore, the practices required for good teaching can't be done in isolation. So we organize these practices into cycles.

One of those cycles is the *teaching cycle*. Most of the work of teaching for understanding takes place *outside* the classroom. One of our major goals this year is to introduce you to those hidden parts of teaching that you rarely see as a student. You can think of many of the practices of teaching as fitting together in a teaching cycle based on the ideas of Wilson, Shulman, and Richert (1987). Our version of the teaching cycle includes three parts or stages. Though we discuss them sequentially in this paper, you will find that they are all mixed up in your actual teaching practice. The order is not important, but the three stages are. These stages are as follows:

- *Clarifying goals: Students' knowledge and practices*. As a teacher, you have to decide what you want your students to learn and what you want them to do in the classroom. (Remember the close relationship between learning and doing—WYDIWYL.) That is, you have to choose knowledge and practices that are developmentally appropriate and meaningful for your students. In order to clarify your goals well, you need a deep understanding of both your students and the science content you are teaching.
- *Classroom community and teaching strategies*. Deciding what you *want* your students to do is not the same as making it happen in the classroom. As a teacher, you have to manage your classroom so that students are motivated to learn and engaged in the practices that you value. You also have to plan strategies—sequences of teaching activities—that will help them develop the knowledge they need to engage in those practices.
- *Assessment, reflection, and revision*. As a teacher, you have to give your students grades. You also have to decide whether your teaching strategies are working—whether your students are really acquiring the knowledge and practices that you think are important. Both of these obligations require careful assessment of your students' learning. When your assessment reveals that your students didn't learn exactly what you had hoped (which is almost always), you need to change your goals or your teaching strategies in response. This is how you learn from experience as a teacher.

Each stage of a teaching cycle involves a lot of interrelated practices. The rest of this paper is devoted mostly to a discussion of those practices. The discussion is organized around four *problems of practice* that you will encounter, in more or less complex forms, during every teaching cycle. These problems of practice are as follows:

- *Science content and learning goals*. There is a sense in which you already know a lot of science. You will find, however, that teaching requires a different kind of understanding of science. The challenges that teaching poses for your scientific understanding are particularly apparent when you decide on goals for your students' learning, when you plan lessons, and when you conduct class discussions.

- *Students and assessment*. You will see how diverse your students are, and how often students respond to your teaching in ways that you might not expect. You will want to motivate these diverse students to learn and to help all of them learn with understanding. Furthermore, you will need to monitor your students' progress and grade their performance in fair and reasonable ways.
- *Classroom environments andteaching strategies*. It seems reasonable that you should be able to find teaching activities to teach the topics in your curriculum. But collecting activities is not enough. You will need to think strategically about how each activity might contribute to your students' motivation and learning. You will also need to manage your classroom efficiently and to create learning communities for the diverse students in your classes.
- *Professional resources and relationships*. Teaching involves working with adults as well as students. You will need to find resources for their teaching and to cope with poorly written textbooks and ineffective teaching tools. You will also need to use the social support systems associated with the program, including course instructors, field instructors, mentor teachers, and school administrators. You will have to work collaboratively with colleagues, to communicate with parents, and to learn from parents about your students.

As teacher educators, we feel that there are lots of parallels between learning science (what you want to help your students do) and learning to teach science (what we want to help you do). So this section is the first stage of *our* teaching cycle. In broad strokes, we have clarified our goals for your learning. We want to help you learn to teach science for motivation and understanding. The stages of the teaching cycle give you an overview of the practices you will need to engage in as a teacher. Each stage of every teaching cycle includes many individual practices, and each individual practice requires a lot of knowledge. The four problems of practice above are our framework for discussing the knowledge and practices that you will need to master; the remainder of this paper is organized around those four problems of practice.

Our program is also organized around the teaching cycle and these problems of practice, and around the principle of WYDIWYL—what you learn is what you do. You will engage in several teaching cycles each semester during this program. They will grow in length and complexity, starting with ten-minute lessons to your peers in the teaching lab this semester, leading up to ten weeks of teaching 100 or so students during the second semester of your internship. As you do each teaching cycle you will encounter the problems of practice above, and you will be learning from experience and learning from others, including your peers, course instructors, field instructors, and mentor teachers.

Science Content and Learning Goals: What Are You Teaching?

Teaching science in schools does not require a detailed understanding of advanced science. You probably will not teach your students about the molecular structures of the enzymes in the Krebs cycle or about Maxwell's equations. Yet teaching for motivation and understanding puts great demands on a teacher's scientific knowledge. To come up with appropriate stories and examples or to develop activities that engage your students in scientific thinking, you will need *a deep understanding of fundamental science*. There will be times when you lack that understanding, or when you have trouble using your understanding as a basis for deciding what your students should be learning.

This section has two parts. The first part explains what we mean by "a deep understanding of fundamental science," in part by contrasting stereotypical school science with the sense-making knowledge and practices of scientists. The second part is about what to do—how to make sure that you understand the science that you teach and how to use your understanding to decide on goals and activities for your students.

Scientists' Science and School Science

We use the same word—science—to describe both what scientists do and what students do in schools. "Science," though, doesn't always mean the same thing. Scientists' science is an ongoing discussion within communities of people who are trying to make sense of the material world; scientists have developed a deep and detailed understanding of advanced science. School science is for young people who lack scientists' understanding and experience, so it cannot be as deep or as detailed as scientists' science. Too often, though, school science "throws out the baby with the bath water." In trying to simplify scientists' science, we lose track of its basic purpose—making sense of the material world—and concentrate instead on getting students to perform meaningless tasks in exchange for grades.

In this part we look first at school science with an eye to understanding why it is the way it is. We then contrast stereotypical school science with the sense-making knowledge and practices of scientists' science. Finally, we come back to the implications for your teaching: How can an understanding of this contrast help you focus on developing a deep understanding of fundamental science for your students.

School Science: Procedural Display of Separated Knowledge and Practices

Here's a basic fact about school science that we would sometimes like to forget: It's about grades. Students perform tasks that teachers tell them to do, and teachers give them grades in return. Walter Doyle (1984) calls this "the performance for grade exchange," and we will discuss it in more detail in the section on grading, below. It is important to bring grades up here, though, because the need to give grades has important effects on how textbooks are written and how science teachers (and professors) teach. What do you do when you are supposed to teach science—a detailed, complex way of making sense of the world that even the most experienced scientists have not fully mastered—to students who don't have much knowledge or experience, AND you have to give them grades for how well they learn it?

Here are some sensible but problematic things that lots of science textbooks and teachers do:

- Treat scientific knowledge as authoritative and correct; don't confuse the students with too much discussion of alternate hypotheses or reasons for doubt.
- Break scientific knowledge and practice down into simple, separate, manageable pieces. This generally requires separating the pieces of knowledge, including facts, definitions, diagrams,

sequences of events, laboratory and problem-solving skills. Table 1, below, lists some typical kinds of knowledge and skills for different subjects.

- Keep the students' practices simple and easy to grade. Be very clear and explicit about how you will expect students to display their knowledge and skills in order to get good grades.

Table 1: School Science as Separate Knowledge and Skills

Subject	*Facts and Definitions*	*Diagrams and Sequences of Events*	*Laboratory and Problem-solving Skills*
Geology	Age of earth Geologic periods Types of rocks	Rock cycle Structure of the earth	Scientific method Classifying rocks
Chemistry	Names of elements Types of chemical reactions	Synthesis of organic compounds Molecular structures	Scientific method Balancing equations Gas laws
Biology	Five kingdoms Parts of cell Names of parts, stages, organisms	Stages in mitosis Canonical stories of evolution Food webs	Scientific method Punnett squares Taxonomic classification
Physics	Newton's laws Conservation of mass and energy Force, inertia, mass, weight, momentum, etc.	Radioactive decay sequences Force vectors	Scientific method Physics word problems

These are sensible responses to a difficult problem. They work well to clarify teachers' and students' roles in the performance for grade exchange; teacher and students know what is expected of them and how they can perform their roles correctly. Unfortunately, there are some bad side effects for many students. Rather than treating knowledge and practices as connected, this approach separates bits of knowledge(facts, definitions, etc.) from bits of practice (laboratory and problem solving skills). Rather than helping students to make sense of the world around them, this approach rewards *procedural display*—doing what the teacher says in order to get a grade.

An Example of Procedural Display: The Montillation of Traxoline

It is very important that you learn about traxoline. Traxoline is a new form of zionter. It is montilled in Ceristanna. The Ceristannians gristerlate large amounts of fevon and then bracter it to quasel traxoline. Traxoline may well be one of our most lukizes snezlaus in the future because of our zionter lescelidge.

Answer the following questions in complete sentences.

1. What is traxoline?
2. Where is traxoline montilled?
3. How is traxoline quaselled?
4. Why is it important to know about traxoline

Some questions to consider:

- What was your strategy for answering the questions? Did it require you to understand what you were writing?
- How do you think you learned this strategy?

School science and procedural display manage the performance for grade exchange very efficiently. Students know what they have to do, and the standards for assigning grades are unambiguous. However, remember the principle of WYDIWYL: What students learn from doing procedural display is how to do procedural display. If you are interested in the goals for science teaching that we discussed above—motivation to learn and understanding—then there is a big problem with this kind of school science: It doesn't give most students with a deep understanding of fundamental science. Instead they end up with something more like a "shallow understanding of fragmented facts and skills."

Many educators are aware of these problems with school science, and one commonly proposed solution is "discovery" or "inquiry" learning. Advocates of discovery learning suggest that rather than forcing students to memorize bits of knowledge and practice routinized skills, we should be helping students to develop their own knowledge and skills. Give the students access to rich experiences with the material world, these advocates suggest, and with guidance they can develop real understanding rather than engaging in procedural display.

Though it sounds attractive, we are NOT advocates of discovery learning. Like stereotypical school science, discovery learning is proposed as a simple solution to a complex problem, and unfortunately there are no simple solutions. Teaching for motivation to learn and understanding will require you to delve more deeply into how scientists make sense of the world and use their knowledge. This is the issue that we address below.

Scientists' Science: Making Sense of the Material World

Scientists' science is too complicated to teach in schools, but the typical school science approach to simplifying scientists' science leaves many students with shallow and fragmented knowledge. In this part we look more closely at scientists' science, paying special attention to the qualities that make it potentially important and valuable for all students, even if some of the detail and complexity have to be left out. The great physicist Niels Bohr wrote something that helps us to consider this question:

> The task of science is both to extend our experience and reduce it to order, and this task represents various aspects, inseparably connected with each other. Only by experience itself do we come to recognize those laws which grant us a comprehensive view of the diversity of phenomena. As our knowledge becomes wider we must always be prepared, therefore, to expect alterations in the points of view best suited for the ordering of our experience. (quoted in Hawkins, 1991, p. 100)

Scientific knowledge. In contrast with the separated facts, definitions, sequences, and diagrams of school science, scientists make sense of the world by finding connections among *experiences, patterns,* and *explanations*. Our understanding of the nature of scientific knowledge is represented in Figure1, below.

Experiences, patterns, and explanations are our words for describing scientific knowledge. Scientists themselves usually use different words, such as *observations, data, generalizations, laws, hypotheses, models,* and *theories*. Let's start from the bottom of Figure 1, considering our words and scientists' words for each part.

- *Experience in the material world (observations or data).* We can know the systems and phenomena of the world only through our interactions with them--through our experience in the material world. Scientists choose to concentrate on experiences that thy can verify, reproduce, describe or measure precisely, record, and share; these are the experiences that they call observations or *data*. Thus scientists are constantly seeking to create new experiences and to select and refine them into data suitable for pattern finding. Descriptions of individual plants or animals, individual measurements denoted by points on a graph, weather reports, and readings from particle detectors in cyclotrons are all experiences that scientists would consider data. Scientists work hard to make sure that their observations are tied as closely as possible to the *phenomena*(events) and *systems* of the material world. The broad base of Figure 1 indicates that scientific knowledge is based on *lots* of experience; most scientists spend a large part of their professional lives accumulating experience (i.e., collecting data) in some small portion of the material world and sharing their data with other scientists.
- *Patterns in experience (laws and generalizations).* Scientific laws and generalizations are statements about patterns that scientists see in their data. The gas laws, for example, present patterns of relationships among the temperature, pressure, and volume of gases that encompass millions of individual measurements (experiences) that scientists have made over the years. Thus

pattern finding is an essential scientific practice, a key step in Bohr's "reducing our experience to order." Graphs and data tables are ways of presenting data (i.e., organizing experience) so that readers can see the patterns. These patterns in experience are the essential links between data and theories.

- *Explanations of patterns in experience (models and theories).* Scientific models and theories are designed to explain patterns in experience. For example, biologists accept the theory of evolution because it explains many different patterns that scientists have observed in different ways—in the fossil record, in changes in populations observed by humans, in the biochemical makeup of different organisms, and so forth. The great scientific theories are beautiful in the elegant and parsimonious way that they explain a "diversity of phenomena." Scientific models are simpler versions of theories that explain a smaller set of patterns. For example, a "billiard ball model" of a gas explains the patterns summarized in the gas laws pretty well, but not why gases sometimes condense into liquids. The small tip of Figure 1 indicates that the power of scientific theories and models lies in their parsimony—a few theories can explain many different patterns, each of which is based on thousands of observations.

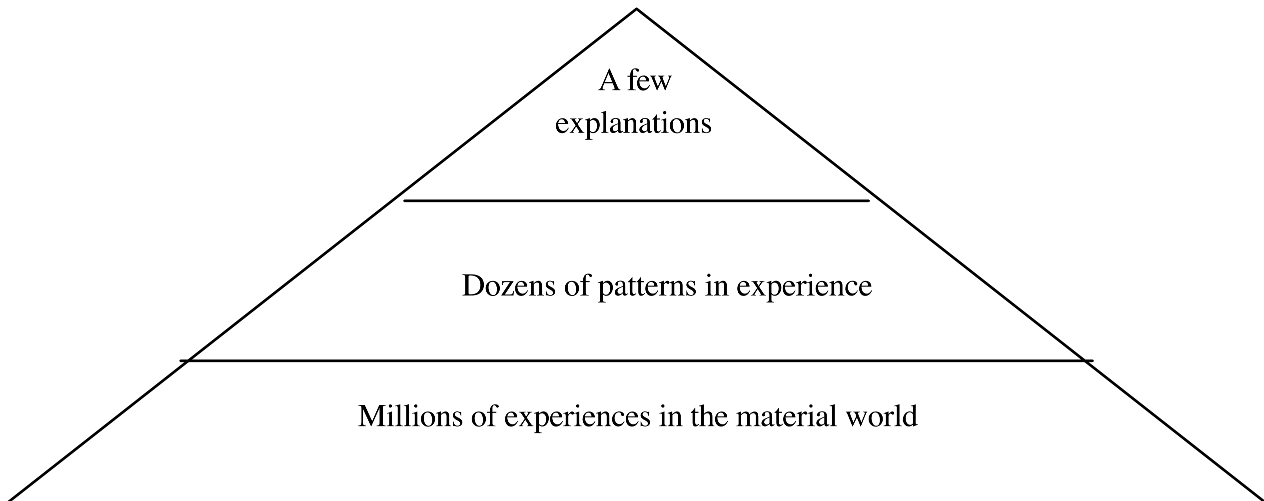


Figure1: Scientific knowledge

Notice that there is no mention of "facts" in the account above. There is a reason for that. When scientists are speaking quickly they may use the word "fact" to indicate any sort of knowledge claim (observations, patterns, or theories) that is generally accepted by the scientific community. When they are being careful, though, as when they are writing research reports, they generally use more precise terms for the kinds of knowledge claims they are making. It is also important to remember that "scientific facts" aren't always true. Sometimes a law or theory that is accepted by one generation of scientists is rejected by the next. As Bohr says, "As our knowledge becomes wider we must always be prepared, therefore, to expect alterations in the points of view best suited for the ordering of our experience."

Table 2, below, is designed as a contrast to Table 1. Table 1 presented examples of scientific knowledge and skills organized into "school science" categories—facts, definitions, diagrams, sequences of events, laboratory and problem-solving skills. Table 2 presents examples of knowledge in the same subjects organized into the categories we used to describe scientists' science. You will probably find the categories of Table 1 more familiar and comfortable; after all, you have a lot more experience with school science than with scientists' science. You will also find that most science textbooks are organized around the categories in Table 1.

So teaching science is a lot easier if you just go with the categories of Table 1. This isn't surprising; those categories were developed to make teaching easier. You have to remember, though, that easier isn't always better. The categories of Table 1 are designed to support procedural display and the performance for grade exchange. If you aspire to help your students participate in

Bohr's dialogue with nature, you will need to learn a way of thinking about science content that uses the less familiar categories of Table 2.

Table 2: Scientists' Science as Experiences, Patterns, and Explanations

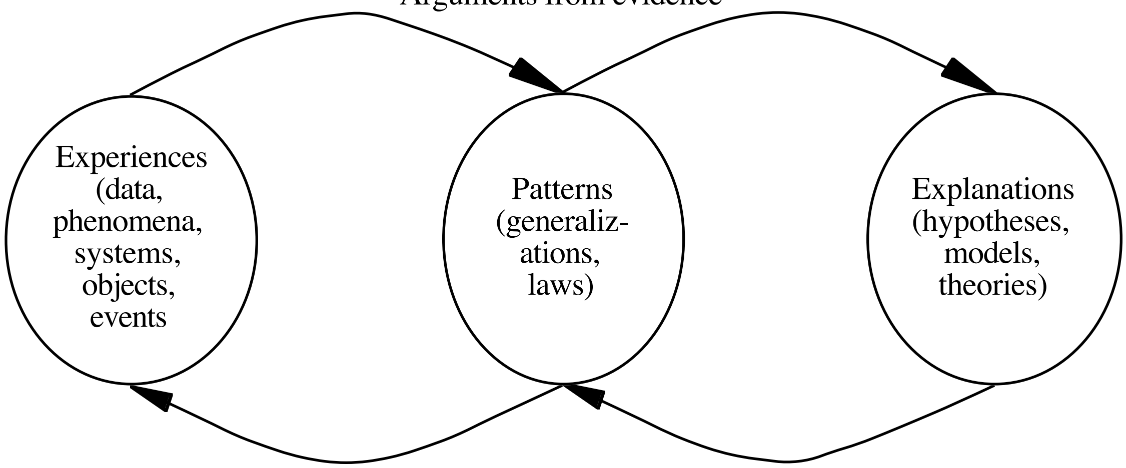
Subject	*Experiences (observations, phenomena, data, systems in real world)*	*Patterns (laws, generalizations, data displays or representations)*	*Explanations (models, hypotheses theories)*
Geology	Types and location of rocks, fossils, landforms Individual events and processes: Earthquakes, volcanoes, erosion, deposition	Patterns in location of events and landforms: stratigraphic layers, "ring of fire, locations of moraines and lakes Continental jigsaw	Plate tectonics Ice age theory
Chemistry	Attempts to create, separate, purify substances Heating, compressing, mixing, substances Physical and chemical properties of substances	Gas laws Periodic table Types of chemical reactions	Quantum theory Atomic molecular theory Kinetic molecular theory
Biology	Anatomy and physiology of individual organisms Life, growth, death of individual organisms Microscopic observations of cells Chemical analyses of substances in organisms	Systematics: comparative anatomy and physiology Pedigrees and patterns of inheritance Population interactions Patterns of biochemical similarity	Evolution Biochemical processes Ecological matter flow and energy cycling
Physics	Motions of objects Changes in motion Motions of planets	Kepler's laws Newton's laws Law of universal gravitation	General relativity Quantum theory

Scientific understanding requires *connected knowledge of experience, patterns, and explanations* (or in scientific terms of data, generalizations, and theories). You will find that sometimes you have been able to pass tests on a topic without developing that kind of connected knowledge, so you will need to reconstruct your own understanding before you are ready to teach the topic. How do people make and use those connections? To answer this question, we shift our focus to scientific practices.

Practices of scientific understanding. In thinking about scientific knowledge, we considered it essential for candidates to understand the key experiences, patterns, and explanations relevant to the topics that they taught, and to distinguish among them. In thinking about scientific practices, we considered it essential for candidates to understand scientific *inquiry* and *application,* as represented in Figure 2, below.

Bohr's quote above focuses on scientific *inquiry:* "to extend our experience and reduce it to order." Our present scientific knowledge is the product of generations of scientific inquiry. Scientific inquiry is worthwhile, though, only because the knowledge it produces is valuable. Thus the practices of *application*—using scientific knowledge to describe, explain, predict, or design phenomena and systems in the material world—are as important as the practices of inquiry. We have made science a school subject because of the benefits that society derives from scientific inquiry and application. We want students to share in those benefits.

Inquiry (constructing explanations from patterns in experience)
Arguments from evidence



Application (Using scientific patterns and theories to describe, explain, predict, design)
Model-based reasoning

Figure 2: Scientific practices (inquiry and application)

We consider scientific application and inquiry to be the most fundamental and important kinds of scientific practices; they will get most of our attention as we discuss planning and teaching science classes. We will also discuss a couple of other kinds of practices that play important roles in scientific sense making. *Telling the story* involves organizing and explaining scientific knowledge in a coherent way. *Reflection* involves understanding the nature and limits of science—for example, constructing scientific arguments and critiquing others' arguments, explaining the limits and the tentative nature of scientific knowledge, explaining roles that science and technology play in our society, and relating science to other ways of knowing about the world.

Persuasive arguments and habits of mind: Curiosity and rigor. Scientific application and inquiry have been extraordinarily successful; scientists have built up a large and powerful array of experiences, patterns, and explanations. This success can be attributed in part to the approach to application and inquiry that is encouraged by scientific subcultures. In some ways scientists are like very rigorous 4-year-olds

- They are curious, asking why and how things work. Every time they figure out an answer to one question, there's always another "why."
- They want to make sure their observations are as complete and detailed as possible, and that their explanations account completely for every detail of the processes that they study.

This combination of curiosity and rigor sets scientific reasoning apart from other approaches to reasoning that prevail in our everyday lives. In scientific inquiry, for example, scientists exhibit curiosity by constantly seeking out new experiences, looking for patterns, and trying to explain those patterns. They exhibit rigor by trying to be as accurate and precise as possible in the data they create and record, by following research designs and using special equipment that eliminate possible sources of error, and by developing arguments for why their explanations are better than all reasonable alternative hypotheses.

Scientists also exhibit curiosity and rigor in the ways that they approach application. They show curiosity by constantly being on the lookout for new examples—systems or phenomena that they can describe or explain using their models or theories, interesting predictions that they can make and test, or interesting new designs that make use of scientific theories. They exhibit rigor in application by engaging in *model-based reasoning*—careful and precise use of models to predict and explain phenomena. The box below focuses on one common application practice—scientific explanation--contrasting model-based reasoning with other common, but less rigorous, approaches to explanation.

Approaches to Explaining Experiences with the Material World

1. Procedural display: This isn't really an explanation at all. The explainer produces words, facts, or diagrams that are not personally meaningful to him or her, but that are what the audience wants (e.g., answering test questions for a grade). We will inevitably see some of this if we are studying school learning. Procedural display can sometimes be rigorous, as when students learn procedures for solving complex problems in chemistry or physics. When students engage in procedural display, however, they are following rules rather than satisfying their curiosity about the material world, so students who engage in procedural display are not exhibiting the scientific habits of mind of curiosity combined with rigor.
2. Practical knowledge. This isn't really an explanation in the scientific sense, either. Sometimes students focus on figuring out how they can make things happen rather than trying to explain how the world operates independently of their actions. For example, one way of understanding how a kite flies is to know the steps you can follow to get the kite up in the air. This is a different kind of understanding from an explanation of the physics of interaction between the kite and the wind, but it is a kind of understanding that we all need and value.
3. Narrative/metatphorical: The phenomena to be explained are incorporated into a story that explains their place in some meaningful account of how the world is. The story lays out a sequence of events, but does not require the kind of rigorous causation that model-based reasoning requires. For example, students studying the light and dark reactions in photosynthesis would appreciate that each step in the process is important, but not necessarily worry about whether they could account for every atom in the molecules or whether each step obeyed the first and second laws of thermodynamics.

   Narratives are often associated with analogies or metaphors, in which the phenomena to be explained are compared with something familiar and "experientially real" to the explainer. For example, students trying to understand photosynthesis might be satisfied with the idea that chloroplasts are like little factories that make sugar from the raw materials of water and carbon dioxide, using sunlight for energy. Since metaphors typically break down at some point, they cannot be used to account systematically for all details of a process.
4. Model-based: The explainer develops an account which systematically relates observed characteristics of the phenomena to a theoretical model. Models are recognized to be limited with respect to precision and domain of applicability, but within those limits they are expected to work unerringly, without requiring ad hoc additional premises or "fudge factors."

   For example, consider the "billiard ball model" of a gas. This could be taken as a metaphor: molecules of gases are like little round hard balls bouncing around. It isn't such a great metaphor, since we don't think of molecules as either round or hard. It works much better as a model, though, saying that we can make accurate predictions about the behavior of gases if we base our calculations on the assumption that molecules of gases have some of the same essential characteristics as billiard balls—mass, volume, and elastic collisions. This model works well within an understood range of temperatures and pressures.

   Conservation laws (matter, energy, molecules in physical changes, atoms in chemical changes, charge, momentum, etc.) often play a critical role in model-based reasoning. They provide "accounting systems" that must be satisfied before scientists can accept an explanation of what is happening in systems or events.

Except for procedural display, all of the approaches to explanation described above are important and legitimate ways of making sense of the world. Indeed, model-based reasoning is a fairly recent invention in the history of science, going back only to the time of Galileo and Newton. Before that, we had accumulated extensive knowledge of the world in the form of practical knowledge, stories, and metaphors. For many fields, including science teaching, these are still the main forms of knowledge that we have to work with. Model-based reasoning has proved to be exceptionally precise and powerful, though, an approach to the practices of inquiry and application that exemplifies the scientific habits of mind of curiosity combined with rigor. Helping students to appreciate and master the power of model-based reasoning is therefore an important goal for science teachers.

Scientists have developed a variety of specialized intellectual and technological tools that support rigorous model-based reasoning, including the following:

- Technological tools such as laboratory equipment, measuring devices, or instruments that extend the range of our senses such as microscopes and telescopes.
- Mathematical tools that enable measurement (a precise form of description) and precise predictions of future observations. Word problems in chemistry and physics typically involve using mathematical tools to make predictions.
- Technical vocabulary that enables precise description and explanation. Sometimes scientists create technical vocabulary by attaching specialized meanings to pre-existing words (e.g., force, energy, power, plate, cell, respiration). At other times scientists invent new words to express specialized meanings (e.g., photosynthesis, propane, ecosystem, tectonics).

A lot of time in science classes is appropriately devoted to helping students master the use of these tools. Note, though, what school science often does to scientific tools. Laboratory equipment, mathematical techniques, and technical vocabulary are *tools* that scientists use in their application and inquiry. In school science, these tools can become "content" that students use to get grades through procedural display rather than tools for application and inquiry.

Scientists exhibit curiosity and rigor in their practices because these habits of mind are practically useful in scientific work. In particular, scientists are constantly confronted with the need to develop *persuasive arguments*—they must convince their colleagues that the observations, patterns, and explanations they develop should be included in the growing body of scientific knowledge.

Again, there is a real contrast between scientists' science and school science. Scientists normally work with uncertain, contested knowledge, on the cutting edge of their disciplines, so they must develop rigorous, persuasive arguments. Students are like scientists in that they are seeking to expand their knowledge of the material world, but argument and persuasion rarely play a role in their learning process. Instead, they are given books full of authoritative knowledge to be learned and reproduced.

Summary: Scientists' science vs. school science

Scientists' science is immensely valuable to our society, so valuable that we have made it into a required school subject. All students are expected to learn some science. Scientists' science, though, is too detailed and complex for children to learn. Thus school science arises out of a reasonable attempt to simplify scientists' science and organize it so that we can measure students' progress and assign grades. Unfortunately, something often goes wrong along the way. We would like our science classes to be full of students who are motivated to learn science because it helps them understand the world. Instead, many science classes are filled with students who engage listlessly in procedural display, reproducing facts and definitions in order to get grades.

Our hypothesis is that the problem lies partly in how scientists' science gets translated into school science—something essential is lost in the translation. (For a more complete account of how scientists' science is transformed into school science, see Appendix A.) We have therefore taken a detailed look at adult scientific reasoning, paying special attention to those qualities that you might want to preserve in the science content that you teach—qualities of adult scientific reasoning that could also occur in the reasoning of twelve-year-old students who are studying evaporation and condensations. We have focused on three qualities:

- The *organization of knowledge* into connected sets of experiences (also known as observations, examples, phenomena, or data), patterns (also known as laws, generalizations, or data displays such as graphs and charts) and explanations (also known and theories or models). This is very different from the compilations of facts, definitions, diagrams, sequences of events, laboratory techniques, and problem-solving procedures found in many science textbooks.
- The close connection between scientific knowledge and scientific practices (especially *application and inquiry*). This is very different from school science, where scientific knowledge is typically taught separately from scientific practice, and the most important classroom practice may be the performance for grade exchange.
- Scientists' need to develop persuasive arguments that convince their colleagues of the quality of their observations, patterns, and explanations. Curiosity and rigor are *habits of mind* that enable scientists to develop persuasive arguments and to apply their knowledge through *model-based reasoning*. This is also very different from typical school science, where students rarely need to develop persuasive arguments or engage in model-based reasoning, so curiosity and rigor are not as important as following directions correctly.

At the beginning of this section we suggested that teaching science for motivation and understanding required a *deep understanding of fundamental science,* but we did not define what that meant. We believe that the qualities suggested above provide the basis for a definition. You, or your students, have a deep understanding of fundamental science for a school science topic if your understanding has the qualities discussed above: You have developed connected sets of experiences, patterns, and explanations; you can use your knowledge for application and inquiry, and you can exhibit curiosity and rigor in developing persuasive arguments or engaging in model-based reasoning.

Developing a deep understanding of fundamental science is a lifelong project. We think you will find that the best science teachers—the ones you look to a role models—have spent hundreds of hours learning science *after* they graduated from college. We also think you will find that the best science teachers exhibit scientific habits of mind—curiosity and rigor—in the ways that they approach the lifelong process of learning to teach. They exhibit curiosity by seeking out opportunities to learn science, finding resources and activities, finding interesting examples and stories, and learning more about their students. They exhibit rigor by checking their own model-based reasoning, skeptical assessment of student learning, skeptical assessment of teaching activities, and careful application of teaching techniques such a learning and inquiry cycles (described below). We hope that you aspire to be one of those teachers.

Deciding on Goals and Activities for Your Students

So here's a typical situation: You have just learned that you are going to have to teach some new topic that you haven't taught before. (At the beginning of your teaching career, just about every topic is a new topic that you haven't taught before.) You want to motivate your students to learn and help them understand this topic, but you have a lot of questions: Do you have a deep understanding of the fundamental knowledge and practices that go with this topic? What is it important for your students to understand about this topic? How can you engage them in scientific sense-making activities, and not just procedural display in exchange for grades?

A starting place for thinking about this problem is the principle of WYDIWYL: What your students learn will be what they do. So if you want them to be motivated to learn and to develop a deep understanding of fundamental science, you will need to engage them in activities that have the qualities of scientific understanding discussed above: making connections among experiences, patterns, and explanations; engaging in application and/or inquiry; and developing scientific habits of mind—curiosity and inquiry as exhibited in model-based reasoning.

Typically, you will have *resources*—textbooks, worksheets, laboratory manuals, websites—available to support your teaching. You will need these resources, but you often will find that they present a problem: You will often find yourself working with resources designed to support school science. That is, they organize knowledge into facts, definitions, and skills; separate knowledge from practice; and support procedural display and efficient grading. To teach for motivation and understanding, you will need to reconstruct the scientific knowledge and practices that constitute a deep understanding of fundamental science for this topic, AND do it at a developmentally appropriate level for your students.

In this part we describe a set of planning practices that can help you decide on appropriate scientific knowledge and practices for your students. We focus in particular on procedures for the first part of the teaching cycle—clarifying your goals. But as we focus on clarifying your goals we really have the whole teaching cycle in mind. The knowledge you identify in your goals is the basis for your classroom discussions. The practices that you identify in your goals are also the activities that students will engage in while you are teaching and the practices that you will assess in your tests and assignments. If these are important and interesting practices, then you have made a critical step in teaching for understanding.

Our procedures for clarifying your goals are more detailed and elaborate than the practices of most experienced teachers, including the teachers you would think of as role models. We are convinced, though, that these procedures are especially useful to people who are learning to teach. They will provide you with a technical language for making your goals for your students' learning explicit and connected with your teaching and assessment. This will enhance both your learning from experience (because it is easier to decide how successful you have been when you are clear about your purposes in teaching) and your learning from others (because you have made your thinking explicit in a form that allows you to communicate with us and with your colleagues).

When you have a good understanding of these procedures, you will find that you can clarify your goals for a unit that you are teaching fairly quickly and easily. That will not be the case at first, though. You will find the process of clarifying your goals time consuming, difficult, and sometimes frustrating. This is partly because you are learning the procedures and technical language you need for this course. Even more, the process of clarifying goals will be time consuming at first because you will be working out your own understanding of the content you teach, developing the deep understanding of fundamental science that you need to teach science well.

So one challenge that you face as you clarify your goals is to *clarify your own understanding* of the topic that you have to teach, making sure that you can identify the key observations, patterns, and explanations for this topic, and that you can connect them through application and inquiry. But that isn't enough. You probably know some professors who had a deep understanding of the content they were teaching, but still could not help their students understand it.

A second major challenge in clarifying your goals is to *describe knowledge and practices at the students' level*, using vocabulary, observations, patterns, and explanations that are appropriate for their age and experience. The principle of WYDIWYL is important here. If you can be clear and precise in your descriptions of the knowledge and practices you want your students to engage in, then you have gone a long way toward deciding what activities you need to plan for your classroom teaching.

A third major challenge that you face in clarifying your goals is to *describe your purposes in terms of students' learning*, rather than just your teaching activities. Students go to school in order to prepare them for life outside of school, so you need to describe knowledge and practices that will be meaningful after your class is over, not just what they will do during your class.

Teaching a topic for understanding requires you to think about:

- *Big ideas:* A storyline that connects the key patterns and explanations in ways that make sense to your students, using vocabulary and concepts that you expect them to understand.

- *Experiences, patterns, and explanations:* The list of experiences, patterns, and explanations that your students should be able to connect through application and inquiry.
- *Practices or objectives:* The practices of scientific understanding that your want your students to be able to engage in as a result of your lesson (possibly including telling the story, using scientific knowledge to describe, explain, predict, or design, developing skills for constructing new scientific knowledge, and reflecting on scientific knowledge).

Each of these is important, but their order is arbitrary. You may find it useful to think about objectives, first, then write big ideas. Or you may find it useful to start with another part of the teaching cycle, such as classroom activities or assessment, before you clarify your goals. Before you teach, though, it is important to have clearly written goals that include all three parts. These three parts are discussed below.

Defining Student Knowledge: Big Ideas

Writing *big ideas* is one approach to correcting some key deficiencies of school science. A "school science" treatment of a topic (including the treatment in many textbooks) includes a lot of content—facts, definitions, diagrams, formulas, and so forth—presented in a way that does not help students identify the most important points or make connections between one lesson or chapter and another. Writing big ideas will help you prepare to do these things yourself.

Your statement of big ideas should describe briefly, in language you expect your students to use, the key patterns in observations and the theories or models we use to explain those patterns. You might think of Big Ideas as a summary of the key ideas in your lesson or unit that you would like an excellent student to give after it is over. Here are some things to think about in writing big ideas.

- Big ideas don't include every vocabulary word in the unit (though they should include the most important ones), and they don't have many specific examples.
- Big ideas are rarely confined to an individual lesson. If you are writing plans for a single lesson, you may need to include ideas from other lessons to write a coherent statement of the big ideas you want your students to understand.
- Big ideas should express the key patterns and explanations, not just name them. In the examples below, for example, the statements do not just name photosynthesis or heat transfer as ideas to understand. They explain those theories in student language.
- The word "students" does NOT belong in your statement of big ideas. Think of big ideas as what you would like your students to be able to tell you after the unit or lesson is over.
- The language you use in your summary of big ideas should be the language you would like your students to use. For example, look at the differences between the middle school and high school big ideas for photosynthesis below.

In addition to textbooks and other resources that your mentor may have available, there are other important resources that you can use as you are writing big ideas. Perhaps the most important are the national standards documents: *Benchmarks for Science Literacy* (on the web at http://project2061.aaas.org/tools/) and the *National Science Education Standards* (http://www.nap.edu/readingroom/books/nses/html). If you are teaching middle school or basic high school courses, the standards documents are written as statements of big ideas in age-appropriate language; you may be able to copy your big ideas directly from them. College preparatory classes at the high school level commonly go beyond the expectations in the standards documents. We will introduce you to additional resources available on the course web site.

Example for explaining how plants get their food (middle school level). Plants are different from animals because they do not eat or digest food. Instead, they make their own food through a process called photosynthesis. Photosynthesis takes place in the leaves of most green plants. The plants take raw materials that are not food—water and carbon dioxide—and use energy from sunlight to make sugar. The sugar travels from the leaves to all parts of the plant. The plants combine the sugar with minerals from the soil to make all the different substances that they need to grow and to use and store energy. All animals depend on food that plants make through photosynthesis.

Example for explaining how plants get their food (high school level). Plants are autotrophs; they make their own food from raw materials in the air and soil. (Animals and fungi are heterotrophs; they depend on plants for food.) Plant leaf cells contain chloroplasts, organelles where the pigment chlorophyll captures energy from sunlight and uses that energy to combine carbon dioxide and water to make the monosaccharide glucose. Oxygen is released as a waste material. All of the other substances in plants—polysaccharides such as starch and cellulose, fats, proteins, nucleic acids, etc.—are made by the plants as they combine glucose with minerals from the soil. Plants (and ultimately animals) use these substances for energy and growth.

Example for explaining how substances change temperature through heat transfer processes (middle school level). When substances get hotter they are gaining heat energy; when substances get colder they are losing heat energy. That energy has to come from (or go to) somewhere. Sometimes heat energy is produced or absorbed by physical, chemical, or nuclear changes in matter. Substances can also gain or lose energy through heat transfer. Heat transfer occurs in three different ways. Heat transfer through conduction occurs when faster moving molecules bump into slower moving molecules and transfer some of their energy. Heat transfer through convection occurs when there are moving currents in fluids (liquids or gases). Heat transfer through radiation occurs when substances emit visible or invisible (infrared) light rays and other substances absorb those rays.

Defining Knowledge: Experiences, Patterns, and Explanations

Scientific big ideas (patterns and explanations) are always grounded in data—observations or experiences that scientists have selected and recorded. As we discussed above (see pages 7-9), the power of scientific theories lies in their parsimony—the ability of a few theories to account for thousands of different observations. Students will appreciate the power of science—and master the objectives—only if they have the opportunity to practice using the big ideas on many different examples. Unfortunately, school science is often deficient in specific observations or examples, so as a teacher you will have to think of examples that you can connect with the big ideas that you are teaching.

You can display connected experiences, patterns, and explanations in a three-column table like those below. Your big ideas should give you a good start on the Patterns and Explanations, columns. You will need to pick out the key patterns and explanations and list them in your table. Each pattern or explanation that you list should be connected with several specific observations in the Observations column. Here are some criteria that you should try to meet as you fill out the table:

- Your observations, patterns, and explanations should be connected to your big ideas. The key models, laws, and theories in the big ideas statement should be listed in summary form in your table.
- Your observations, patterns, and explanations should be connected to one another. For example, each model or theory that you list should have observations and patterns to go with it.
- Observations focus on specific real-world objects, systems, or phenomena, *not* the concepts we use to explain them. For example, “light-dependent reactions” and “light independent reactions” are not good real-world examples for photosynthesis. Similarly, “temperature,” and “convection” are not good real world examples for heat transfer.
- Observations are specific, individual data points. You may find it useful to describe groups of related observations, with a few illustrative examples. (See the examples for photosynthesis and heat transfer below.)
- The best observations are *experientially real* to your students. They should be either systems or phenomena that your students have already experienced or that you could help

them experience, first hand or vicariously. (This does *not* imply that your list should consist only of examples actually included in your class activities.)

Example: Observations, Patterns, Explanations Table for High School Photosynthesis

Observations or experiences (examples, phenomena, data)	**Patterns (laws, generalizations, graphs, tables, categories)**	**Explanations (models, theories)**
Mass changes in growing plants (e.g., bean plants growing, bean plants making beans, oak trees growing, spirogyra (an alga) growing Von Helmont's experiment Responses of potted plants to directional light sources (e.g., bean plants, spider plants, ferns by windows) Carbon dioxide and oxygen production by plants (e.g., bean plants, algae, radish sprouts) in light and dark Plants (e.g., bean plants, radishes, grass) growing in light and dark	Plants grow with light and die in the dark Plants turn their leaves toward light sources Plants gain more mass when they grow than the soil they are planted in loses Plants are net emitters of carbon dioxide in the dark and absorbers of carbon dioxide in the light	Plants use energy from sunlight to make glucose from water and carbon dioxide Plants grow by synthesizing all of the organic substances (polysaccharides, proteins, fats, nucleic acids, etc.) of which they are made out of glucose and soil minerals
⇐ **Application: Model-based Reasoning**		
Inquiry: Finding and Explaining Patterns in Experience ⇒		

Example: Observations, Patterns, Explanations Table for Middle School Heat Transfer

Observations or experiences (examples, phenomena, data)	**Patterns (laws, generalizations, graphs, tables, categories)**	**Explanations (models, theories)**
Temperature changes due to heat transfer by radiation (e.g., sun warming the earth, sitting in front of a fire, warming by a heat lamp, infrared camera, earth cooling at night) Temperature changes due to heat transfer by conduction (e.g, metal spoon in hot water, wooden spoon in hot water, ice in aluminum foil, ice in Styrofoam)	In systems with substances of different temperatures, the warmer substances cool down and the cooler substances warm up. This can happen even if the substances are separated by empty space. Solid substances change temperatures at different speeds, depending on the temperature of the objects they are in contact with and the	Heat energy[2] is the total energy of motion of all the molecules of a substance. Temperature is the average energy of motion of the individual molecules Heat can be transferred by radiation: Moving molecules emit visible or infrared light, which can be absorbed by other molecules. Heat can be transferred by

[2] Physicists distinguish between heat--energy being transferred from one substance to another--and thermal or internal energy—the energy of molecular motion stored in a substance. We feel that this distinction is too complex for middle school students, who have a great deal of difficulty distinguishing heat—an extensive variable denoting the total amount of energy—from temperature—an intensive variable denoting the concentration of thermal energy. See, for example, Linn and (ref).

Temperature changes due to heat transfer by convection (e.g., wind blowing on earth, pot of water heating on a stove, piece of ice melting in a cup, person in shorts vs. person in winter clothes, lava lamp)	nature of the substances (thermal conductors or insulators) Warm fluids rise in cooler fluids of the same type (convection currents)	conduction: Moving molecules transfer energy to other molecules that they bump into Heat can be transferred by convection: Moving fluids carry heat with them from one place to another.
⇐ **Application: Model-based Reasoning**		
Inquiry: Finding and Explaining Patterns in Experience ⇒		

Defining Practices: Objectives for Student Learning

Big ideas and real-world examples both concern the *knowledge* that students need to understand a topic—the experiences, patterns, and explanations. Objectives concern the other dimension of scientific understanding, the *practices* that students will be able to engage in after they have completed the unit. As we discussed above (see pages 9-10) school science tends to separate knowledge from practice, making both less meaningful. By writing good objectives that are connected with your big ideas and experiences-patterns-explanations tables, you can reconnect knowledge and practice for your students.

Our treatment of objectives is based on the Michigan Curriculum Framework (http://www.michigan.gov/mde). The Michigan Curriculum Framework includes three kinds of objectives, as described in Appendix B: Constructing scientific knowledge, reflecting on scientific knowledge, and using scientific knowledge. All of these objectives emphasize preparing students for active, social practices that they will engage in as workers and citizens. We also recognize that sometimes it is valuable for students to be able to "tell the story," summarizing what they know about a topic in an accurate and coherent way.

These practices are discussed in detail in Appendix B.

- *Telling the story*. People who understand science can tell others about what they know, providing coherent, parsimonious accounts of the world around them.
- *Constructing scientific knowledge*. People who understand science have "learned how to learn." They can learn things they don't already know either by consulting sources of information or by investigating the world themselves. Bohr's "extending our experience and reducing it to order" describes a way of constructing scientific knowledge. We often refer to the process of constructing scientific knowledge as *scientific inquiry*. Thus constructing objectives are "learning how to learn" objectives, focusing on the practices of learning from experience or from others.
- *Using scientific knowledge*. People who understand science can use their knowledge to describe the world around them in precise detail; they can use theories and models to explain phenomena; they can make accurate predictions about future observations; and they can design systems that give us control over the material world. These are all applications of scientific knowledge—ways of using it in real-world contexts. Thus *scientific application* is as important as scientific inquiry.
- *Reflecting on scientific knowledge*. People who understand science also understand scientific culture and the scientific enterprise. They can construct scientific arguments and critique others' arguments; they can explain the limits and the tentative nature of scientific knowledge; they can explain roles that science and technology play in our society; and they can relate science to other ways of knowing about the world.

As a science teacher in Michigan, you are responsible for helping your students to master the Michigan objectives, so we will ask you to identify relevant objectives whenever you teach. You will generally find that the Michigan objectives are much broader and more inclusive than the topic of your lesson, so you may find it useful to also write your own, more specific objectives. Much of our work this year will focus on Using objectives. When you write Using objectives, you should follow the standard form used in the Michigan Curriculum Framework. Students will:

Knowledge (optional)]	*Verb*	*Real-world context*
[Use (some kind of scientific knowledge or skill)]	to (some form of description, explanation, predication, or design)	(some set of real-world examples).

Other objectives follow slightly different rules, which we will discuss during the course of the year. All objectives, though, describe social practices that you want students to be good at after you are finished teaching the topic. For example, here are some possible objectives for a unit on plants and photosynthesis.

Objective	***Type***
1. Explain the steps in the process of photosynthesis.	Telling the story
2. Explain how plants get their food.	Using
3. Predict the effects of different environmental conditions on plant growth and survival.	Using
4. Design experiments to investigate the effects of different environmental conditions on plant growth and survival.	Constructing
5. Critique arguments made by politicians and economists about the effects of global warming on plant growth.	Reflecting

As another example, here are some possible objectives for a unit on heat transfer

Objective	***Type***
1. Compare and contrast heat transfer by conduction, convection, and radiation.	Telling the story
2. Classify examples of heat transfer according to the kind of heat transfer that is taking place.	Using
3. Explain examples of heat transfer in terms of energy and molecular motion.	Using
4. Design systems that use thermal conductors or insulators to control rates of heat transfer	Using
5. Design experiments to compare substances with respect to their properties as thermal conductors or insulators.	Constructing

Here are some important things to consider when you are writing objectives:

- Objectives should describe student learning—something that your students will be able to do after the class is over—not just classroom learning activities. For example, “Conduct an experiment on plant growth under different environmental conditions” is a good learning activity, but not a good objective. It doesn’t say what students will learn to do as a result of conducting the experiments.
- Do not write too many small objectives. Even a unit that is several weeks long should be organized around a small number of significant objectives.
- The Michigan Curriculum Framework does not include any “Telling the Story” objectives. This is because while telling the story is sometimes important, it is never enough. At least some of your objectives for every topic need to be Using, Constructing, or Reflecting.

- Whenever students learn something they are constructing new knowledge. This does not mean, though, that they are mastering Constructing objectives. Constructing objectives concern *learning how to learn,* not just learning. Students are accomplishing Constructing objectives when they develop skills in constructing new knowledge through inquiry.
- Objectives should describe practices that connect the observations, patterns, and explanations in your table.
- Objectives should relate to classes of examples, not just individual examples. For example, "Explain how plants get their food" is a better objective than "Explain how an oak tree gets its food."
- It will generally take several lessons for your students to master a single objective, so you should not expect to finish teaching an objective in a single lesson (see the discussion of learning cycles, below).

Why Is Clarifying Your Goals Important?

Clarifying your goals can seem like a lot of extra work when you are short on time and have to come up with classroom activities. If you want to teach for motivation and understanding, though, you need a strong sense of what your goals are before you can create or select good teaching activities. In particular, we feel that by clarifying your goals carefully, you can meet the three challenges described in the beginning of this part:

- You will *clarify your own understanding* of the topic that you have to teach, making sure that you can identify the key observations, patterns, and explanations for this topic, and that you can connect them through application and inquiry. As you try to write big ideas, experiences, patterns, and explanations, and objectives, you will confront limitations in your own understanding and have a chance to resolve them before you are in front of a class.
- Figuring out (with the help of state and national standards) the appropriate *depth and level of detail for your students' knowledge and practice*. A careful job of clarifying your goals will prepare you to apply the principle of WYDIWYL to your teaching. Your big ideas are the ways you want students to tell the story of their understanding. Your objectives are the practices (especially application and inquiry) that you want your students to engage in. As they engage in these practices, you want them to connect the experiences, patterns, and explanations that you have listed in your table.
- Making sure you are clear about your *purposes in terms of student learning*. When you are busy planning and carrying out activities, it is easy to lose track of the learning that is supposed to result. A careful job of clarifying your goals will help you to connect your students activities in school to their preparation for life outside of schools, since you will have defined knowledge and practices that are relevant and useful outside of school.

If you do a good job of clarifying goals for your students, you have taken a substantial step toward our shared goal of teaching science for motivation and understanding. You have described knowledge that is important and potentially meaningful and interesting for your students. You have also described meaningful and important practices that your students can find interesting and useful. Helping your students to achieve these goals, though, requires a deep understanding of your students and of teaching strategies. These are the topics we address in the next sections.

Students and Assessment: Who Are You Teaching?

So now here's a situation. Between your knowledge of science and resources such as textbooks, research, and state and national standards, you have written some pretty good goals for your students. You have described knowledge and practices that are developmentally appropriate, useful to your students outside of school, and exhibit the key qualities of scientific sense-making (connected experiences, patterns, and explanations, connected knowledge and practice, scientific habits of mind). You know from the principle of WYDIWYL that if you can just get your students engaged in these practices, there's a pretty good chance that they will learn them. You're ready to teach, right?

Not exactly. You are likely to find that no matter how carefully you explain the knowledge and practices in your goals, there are problems when it is time for the students to engage in them. Some of your students will be fine, but others will be reluctant if not surly and uncomprehending. If you really want to teach for motivation and understanding, you will need to understand your students, socially, emotionally, culturally, and intellectually.

Think about how you understood your fellow students when you were in high school. You saw a lot of them—probably over 100 every day. Some were your friends, and you knew quite a bit about them: who they liked and who they disliked, how they were likely to behave in class, what subjects they found difficult, what kind of grades they made, what sports they played, and so forth. Many of the students you saw each day were mere acquaintances, and you didn't really know much about them. You might know generally how well they behaved in class, how well they did in school, and who their friends were, but not much more.

Now think of yourself as a secondary science teacher. Again you will see a lot of students, probably over 100 every day. Now, however, you will be responsible for their learning. If you want to teach for understanding, you can't afford for your students to be mere acquaintances. You will have to know all of them well enough, both academically and socially, to help them learn.

In particular, you must understand your students in order to motivate them to learn. Remember that we discussed motivation as the product of expectancy (students' assessment of their chances for success) times value (students' assessment of the worth of the outcome). You can increase students' expectancy by understanding how they think about the topics that you study—the intellectual resources and the misconceptions that they bring with them to a topic. This is the subject of the first part of this section. You can increase the value students give to learning science by understanding their social and cultural interests and values. This is the subject of the second part of this section. Finally, you can increase the motivation of all students, especially externally motivated students, by grading their work in a fair and reasonable way. This is the subject of the final part of this section.

Understanding and Responding to Your Students' Thinking: Expectancy

As a student, you may not have known very much academically about even your close friends. You knew something about their academic interests and how well they did in class, but unless you actually studied with them or worked with them on group projects, you probably didn't know much about how they *thought* about science—how they understood models and theories, what pattern in experience they saw, or how they went about solving problems, for example.

As a teacher, it will be your job to understand your students in this deeper and more complex way. Recent research on science and mathematics learning shows that all students have a rich repertoire of ways of understanding, calculating, and finding patterns in the world. Students' ways of understanding are often "unscientific," but functional within the limits of their own experience.

Consider Jeremiah, for example. A sixth-grade student who is below average in academic achievement, he seems to have been unaffected by a unit on plants that emphasized photosynthesis as the process by which plants make their own food in their leaves. He confidently describes how plants take in food from the soil and transport it up to their leaves, which "use it." The only function that he suggests for leaves is "to help plants keep cool." When he is asked directly about photosynthesis, he says, "I don't pay much attention to that stuff. Me and my brother, we know enough about plants." What Jeremiah and his brother know about plants turns out to include extensive and detailed knowledge about how to grow vegetable gardens, based in part on detailed observations of growing garden plants and the insects that live on them. (For a transcript of an interview with Jeremiah, see Appendix E.)

Thus Jeremiah is not simply ignorant about plants. Rather, his failure to recognize and value the knowledge he encounters in school is in part a reaction to the school's failure to recognize and value his knowledge. His observations of plants are more extensive and detailed , and he sees important patterns in plants' growth and development. Even Jeremiah's unscientific explanation of how plants get their food is not simply wrong. Rather, it is a sensible way of understanding plants that is consistent with his experience and functional for his purposes.

Jeremiah is like many students in that when he starts to study a new topic, he brings with him a combination of *intellectual resources* and *misconceptions*. Intellectual resources include the experiences that students have had with the parts of the material world that they are studying and the patterns that they have seen in those experiences. Misconceptions are incomplete patterns and explanations—ways of thinking that are consistent with students' limited set of experiences but not with the larger data sets that scientific communities have developed. Teaching science is hard partly because we can't really separate misconceptions from intellectual resources—they are two different sides of the same coin. Teachers who understand their students' intellectual resources and misconceptions, though, can use this knowledge to teach more effectively.

Recognizing students' intellectual resources and incorporating them into your teaching can also be difficult because they are usually embedded in non-model-based ways of thinking about the world. As we discussed in the box on pages 11-2, practical knowledge, stories, and metaphors are important and legitimate ways of making sense of our experience, while model-based reasoning is a relatively recent invention, a way of thinking that seems obscure, technical, and difficult to many students.

So teaching science requires you to maintain a difficult balance. On one hand, you want to help students appreciate the power of model-based reasoning and master its practices. On the other hand, you want to recognize and use the intellectual resources that students bring with them to class, even though they are embedded in other approaches to making sense of the world. Thus part of your role as a science teacher is to search for what Warren, et al. (2001) describe as *generative continuities* between students' intellectual resources and your goals for their learning. You will find that this is easiest for students who are most like you, and much more difficult for students with whom you have less in common, intellectually, socially, and culturally.

So effective teachers must recognize the reality and the importance of their students' ways of understanding and help them find new ways of "extending their experience and reducing it to order." One resource that you can use as you confront this challenge is research on students' scientific and mathematical thinking. Much of this research treats students learning as a process of *conceptual change,* in which students extend their experience, overcome their misconceptions, and achieve Bohr's "alterations in the points of view best suited for the ordering of our experience." You will have access to that research as you plan and teach (e.g., Driver, et al, 1994).

Reading the research, though, is not the same as understanding the thinking of your own students. You will need to learn about their experiences with the material world, the patterns they see, and how they explain those patterns, and you will need to use that knowledge in your teaching. How teachers can develop and use that knowledge is discussed in the section on the assessment cycle, below.

Purposes of Classroom Assessment

In a well-taught class assessment is not really a separate activity from instruction. The class proceeds like a dialogue between the teacher and the students: the students learn from the teacher as the teacher learns from the students. The characteristics of the activity that help the teacher learn from the students are what we call assessment.

We often associate assessment with testing and grading. Assigning grades is one important purpose for assessment, but it is not the only one. Classroom assessment is also important because it can help students to assess their own understanding and decide what they need to concentrate on in order to learn effectively. Classroom assessment is also a way to improve your teaching, giving you the information about your students' understanding that will help you adapt your plans to your students' needs. Each purpose of assessment requires different qualities, as summarized in the table below.

Purposes of Classroom Assessment

Purpose	***Essential Qualities***	***Ways to Be Efficient***
Grading	• Connection to goals • Appropriate difficulty (reasonable risk) • Transparency (e.g., clear rubrics) and reliability (consistent scores for same student)	Avoid too many essays
Helping students assess their own understanding	• Connection to goals • Promoting student thinking about big ideas • Quick personal feedback	Students checking their own or each other's work
Improving instruction	• Connection to goals • Exploring the nature and limits of students' understanding, not just how well they did • Providing opportunities for *interesting wrong answers* that reveal students' thinking	Sample students with clinical interviews or complex questions

Each of these three purposes is discussed in this paper. Grading is discussed in the part on grading fairly, below. Helping students to assess their own understanding is addressed in the discussion of learning cycles in the next section. In this part, we address the third purpose: Understanding students' thinking in order to improve your instruction.

Developing Assessment Tasks

When you assess students to improve instruction, your purpose is to understand *how they make sense of the patterns in their experience*—their intellectual resources and misconceptions. Some misconceptions (including Jeremy's ideas about plants) are very common among people learning science. There is an extensive research literature on these student conceptions. Chapter 15 of *Benchmarks for Science Literacy* or *Making Sense of Secondary Science* (Driver, et al., 1994) are resources that give you access to that literature. We will also make more of that literature accessible over the class web site. This research literature can be very valuable to you, both as a source of assessment tasks to try and as a source of ideas to help you understand your students' reasoning.

You can use assessment tasks to help you understand your students' reasoning before you begin teaching a topic—*preassessment*—while you are teaching a topic—*embedded assessment*—or at the end of your teaching about a topic—*postassessment*. These tasks can take many forms, including: (a) normal classroom tasks such as worksheets, journal questions, or lab reports, (b) clinical interviews in which you talk with an individual student or a pair of students, or (c) formal assessments such as test questions. For a detailed discussion of clinical interviews, see Appendix D; for transcripts of actual clinical interviews, see Appendix E.

Perhaps the most important characteristic of a good assessment task for improving instruction is that it is designed to help you *learn from incorrect answers*. If you want to teach for understanding, it's not enough to know whether students "get" a certain concept or not, or even "how well" they understand the scientific concept. You want to know how *they* make sense of the topic—what their experiences are, what patterns they see in their experiences, and what models they use to explain those patterns. For these purposes you need to design tasks that students can respond to in interesting ways regardless of their scientific understanding.

In the interview with Jeremiah described above, for example, questions about a plant that was sitting in front of him or about the plants in his garden were much more useful than a question about the definition of photosynthesis. The question about photosynthesis merely showed what he didn't know. The questions about plants and his garden showed what he did know and how he made sense of it. In general, the best questions draw on situations that are experientially real to the students and avoid the use of specialized vocabulary.

Here are some issues to consider as you develop assessment tasks:

- The *research literature* is not a substitute for understanding your own students, but it can be a valuable source for ideas about tasks and about likely misconceptions.
- The work you have done on *clarifying your goals* is also a valuable resource for designing assessment tasks. Can you ask about real-world examples from your list that will be familiar to your students? Can you engage them in practices like those in your objectives?
- The best tasks are often ones that a scientist would answer with the patterns and theories you intend to teach. If you are going to be teaching about heat transfer, for example, try to think of questions that scientists would answer with ideas about heat transfer—if heat transfer is the answer, then what is the question?
- You need to consider ways in which your questions are vague or might be misinterpreted by the students. You want to allow for a variety of student responses, but responses that miss the point of your question won't help you very much.
- It is often more useful to *ask about specific examples* than to try to get students to explain their models and theories. Thus for Jeremiah the questions about the plant in front of him (specific example) were more useful than the question about photosynthesis (theory).
- What your students know about a topic will often take the form of *practical knowledge or stories and metaphors* (see the discussion of habits of mind, above). Look for questions that call for these kinds of knowledge rather than theories or procedural display.

Making Sense of Students' Responses: Learning from Incorrect Answers

At the end of Appendix E you will find three different descriptions of what Jeremiah understands about plants. Read them, then think about how each might be useful to you as a teacher. The first description is primarily evaluative. It asserts, correctly, that Jeremiah did not learn some key points in the content covered in the plant unit. If your primary purpose is grading, this kind of description is probably sufficient. The second description goes beyond evaluation to a detailed assessment of which parts of the plant unit Jeremiah understands and which he does not. If your primary purpose is to decide which points you need to emphasize in a chapter review. The third description tries to capture Jeremiah's interests and thinking about plants in his own terms, focusing on what he DOES know and how he expresses his knowledge, even if what he knows doesn't quite fit in the school curriculum. If you want a true dialogue with students like Jeremiah, the kind of dialogue that might motivate them to learn and help them understand, then this is the kind of insight into students' thinking that you need to strive for. It isn't easy.

A good assessment task often produces a confusing variety of responses from students. How can you find patterns in all of the different things that they say? How can you explain those patterns and use them to improve your teaching? There are no absolute rules for this process, but here are some practices that are often useful. There is no set order for these practices. For example, you might develop a preliminary version of a rubric, then use it to look for patterns in students responses, then come back to rewrite the rubric. You might think of these practices as four things that you need to get done before you are finished making sense or students' responses; the order is up to you.

Writing your own expected response. Try answering the question yourself in terms that you would like your students to use. Your own response can provide a useful comparison with the answers that students actually give.

Looking for patterns in student responses. Try putting the responses in piles that are similar in some way, or ordering them from the best to the worst, or looking for different parts of the response that you can use to analyze them. Try whatever you can do that helps you see order in the whole set of responses. You are especially interested in patterns that (a) are connected with students' ways of thinking and (b) are connected with the Big Ideas for your topic.

Making sense of the patterns you find. It is especially useful if you can develop theories about the kind of thinking that is responsible for the patterns that you see? What experiences are the responses based on? How did they make sense to the students? What kinds of naïve conceptions are they revealing? You may find the research literature very helpful for explaining the patterns you find in student responses. Are there ways in which your students are similar to the students described in the research?

Developing a rubric for analyzing or classifying student responses. A rubric is a checklist or a set of criteria that you can use to classify or analyze student responses. Rubrics may do several things:

- *Help you to put responses in order or judge their quality*. For example, your assignments for this course include checklists that we will use to assess the quality of your work.
- *Identify parts, aspects or qualities in student responses* that enable a more fine-grained analysis, making it possible for you to say that a response was good in some respects but lacking in others. You can often use the patterns and models in your Big Ideas or your Observations-patterns-explanations table as a basis for identifying important aspects of student responses for your analysis.
- *Classify individual student responses according to a theory* about different ways that students have of understanding the topic. A good theory with an accompanying rubric will show how students' responses differ from those of scientists, but also how they are reasonable from the students' perspectives.

The most useful rubrics do all of these things at once. For example, one of the questions that Jeremiah responded to asked him to explain the parts of a plant that was on the table in front of him and their functions. Our rubric for analyzing the responses of Jeremiah and other students to this task looked at five aspects of their answers:

- *Which parts of plants did they name?* Most of the students we talked to named at least roots, stems, and leaves, and that was sufficient for our purposes.
- *What did they say about the functions of the leaves?* Some students said that leaves made food for the plant or engaged in photosynthesis. Many students had completely different answers. Jeremiah, for example, said that leaves help keep plants cool.
- *How did they say that the plant gets its food?* If the students didn't mention how plants get their food, then we asked a probing question about how the plant gets its food. It was particularly interesting to hear how they said that food travels inside the plant. Some students described food as traveling *down* the stem after it is made in the leaves. Other students described food as traveling *up* the stem after the plant absorbs it from the soil. Joy changed her answer from up to down during the interview, indicating that she was successfully using her theories to reason about specific examples.
- *What did they say was the food for the plant?* Some students (including Joy) said that food was something that plants make. A few (including Ed) mentioned sugar or glucose. Other students mentioned things that plants bring in from outside, such as "plant food," minerals, water, or sunlight.

- *Did they mention photosynthesis?* Interestingly, some students who provided scientifically correct accounts of how plants make their own food could not define photosynthesis. Ed, for example, provided the most complete explanation of how plants get their food, but could not remember the definition of photosynthesis. Other students who mentioned photosynthesis could not use the concept to explain how plants get their food. We interpret that as procedural display—learning to produce vocabulary words on demand without understanding them in a personally meaningful way.

Adjusting Your Teaching and Assessment

Good assessments that produce interesting wrong answers and reveal your students' thinking can make your teaching both fascinating and frustrating. Good assessments can make your teaching more interesting because they open the door to teaching that is a real dialogue based on students' intellectual resources and misconceptions, rather than "school science" monologues—covering content and procedural display. Good assessments can also be frustrating because they increase the risk and ambiguity of teaching. Once students have revealed their misconceptions, you can't just ignore them.

There are three basic ways that you can respond to what you learn about your students' intellectual resources and misconceptions. You can adjust your teaching; you can rethink your goals; and/or you can revise your plans for the next time you teach the topic.

Adjusting your teaching. Teaching based on good assessment is a dialogue rather than a monologue. Your students respond to you, and you respond to them, too. You can, for example, incorporate students' experiences into your teaching. You can respond directly to students' misconceptions, showing your students that you understand and respect their reasoning at the same time as you help them to see the power of scientific concepts. You can alter your learning cycles (see below), adding more modeling or coaching that addresses the difficulties your students are having.

When you adjust your teaching, you need to include plans for additional assessment activities. Your next assessment tasks will not be exactly the same as the ones you just used, but will still emphasize the same knowledge and practices. Your students will continue to learn from you as you continue to learn from them.

These kinds of adjustments enable you to improve both your students' understanding and their motivation to learn: By being more responsive to your students' thinking you improve both their expectancy of success and the value or interest they have in being successful. We see the best teachers constantly learning from and responding to their students. Learning to do this well is a career-long project.

Rethinking your goals. Sometimes you will find that there just is not enough time for your students to achieve all the goals you had in mind. You have to choose between covering content and teaching for understanding. This is sometimes called the *breadth vs. depth* problem. School science in the United States has traditionally "solved" this problem by opting for breadth—covering lots of content in a superficial way.[3] This is easier, but it doesn't work if your goal is to teach for motivation and understanding. Sometimes you will have to give up on some goals in order to help your students achieve others with understanding.

It is important, but difficult, to be strategic in choosing which goals you will emphasize. You will probably find during your intern year, for example, that the units you teach keep taking longer than you expected. The temptation is strong in this situation to keep working on the current

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[3] Recent international studies of science learning have shown that this is especially an American problem. Compared with other nations whose students do better on science achievement tests (and there are many of them), American science curricula cover more topics and more vocabulary each hear. So more content coverage leads to less learning, even though the US spends more on education than any of the countries that do better in international comparisons. See, for example, Schmidt, et al., 2001.

unit until you are satisfied that most of your students have achieved your goals. When you do this, you are, in effect, choosing not to teach some other unit that is scheduled for later in the year. This may be the right decision, but you should make it consciously. Decide which goals really are the most important, and perhaps drop some objectives from your current unit in order to save time for important objectives later on.

Revising your plans for the next time you teach the topic. No matter how carefully you prepare, it is almost impossible to teach a topic really well the first time. Careful assessment helps you understand your students better than you could possibly have understood them before you taught. The students you teach the next time will be different, of course, but they will also come to you with many of the same experiences and misconceptions as this year's students.

Learning more about your students often helps you revise your understanding of content and pedagogy as well as students. You know better what Big Ideas and practices are appropriate for your students, what real-world examples are familiar to them, and which ideas need the most emphasis when you teach. You also learn which teaching strategies and materials really work for your students, enabling them to move on to the next stage in the learning cycle, and which need to be revised. Because you have a better idea of what you are looking for, you will be better able to evaluate teaching strategies and materials that you come across, finding the ones that really work for your students. Thus what you learn from teaching can help you revise all parts of your plans for your future teaching.

Learning to Teach from Experience

Like learning science, learning to teach science involves both learning from experience and learning from others. Just having experience, though, does not necessarily mean that you will learn to teach for motivation and understanding. (Think about the experienced teachers you know who you do not think of as role models.)

Learning to teach from experience, like learning science from experience, requires active inquiry on your part. You must make sure you have the data you need, find patterns in those data, explain those patterns, and change your teaching in response. For some problems of practice, such as discipline and classroom management, the data are easy to find. You usually know it when students are misbehaving. If you are interested in teaching for understanding, though, the data are harder to get. After all, students know that their grades will be better if they can appear to understand when they really don't. This is why careful assessment of your students' understanding is both important and difficult.

Learning from experience is also difficult because it is hard to find time to do it. When you are teaching full time, you always have another topic to teach which is taking up your time and energy. Then by the time you are ready to teach the topic the next year you have forgotten a lot of what you learned the first time you taught the topic. This is why it is important to develop ways of taking a few notes immediately about changes that you want to make the next time you teach the topic. You will have to develop a system that works for you. One advantage of developing your plans and materials electronically is that it is easy to copy and change them without destroying the originals.

Understanding Students Socially and Culturally: Value

We have suggested that students' motivation to learn is proportional to the product of expectancy times value. If you do a good job of assessing your students' thinking and responding to their ideas in your teaching, you can increase their expectancy of learning successfully. But what about value? How can teachers affect the value that students attach to their academic work? Like expectancy, value is both individually and socially determined. The national standards documents identify knowledge and practices that scientists and science educators consider to be of value, but what students find personally interesting or worthwhile may be different.

The craft of science teaching involves, in part, finding tasks or activities that students see as interesting while teaching content that our society considers valuable. It would be nice if there were a close relation between the knowledge that society values and the knowledge that students value. It would be nice if students were thoughtful about how their learning will contribute to their career goals or their future duties as citizens , but for most students, most of the time, these are adult worries. They place the greatest value on knowledge or practices that they find personally interesting.

Making science interesting to students is a challenge on multiple fronts. In this part we focus on the part of this problem that has to do with understanding your students. First we discuss the nature of students' interests in science and how you can learn about them and respond to them. Second, we discuss ways in which social and cultural norms affect students' responses to school and to science classes in school.

Understanding and Responding to Your Students' Interests

Although we have not been explicit about it, in fact we have already discussed students' interests and values in several ways above. The box on habits of mind on pages 11-2 provides a useful frame for our discussion. Interesting teaching takes advantage of students' intellectual resources and habits of mind. In particular, good science teachers find ways to connect with and encourage sense-making strategies other than model-based reasoning. Here are some general points about what students find interesting:

- Students are interested in teachers who are interested in them. If you understand and respond to students' ideas, incorporate their experiences into your teaching, or look for ways to enjoy the company of your students while you are teaching science, they will find the content you are teaching more interesting.
- It's easier to make science interesting to students if you're interested in it yourself. If you can choose your topics, pick ones that you are enthusiastic about. If the topics you have to teach are set by a curriculum that you are given, look for the examples and experiences that interest you and build your teaching around them.
- Procedural display is boring, since it doesn't really involve making sense of science content. This means that school science is boring for most students.
- Model-based reasoning is interesting, but only AFTER students have learned how to do it. Even then, model-based reasoning is an acquired taste for many students; it is an austere, technical, demanding way to make sense of the world whose elegance becomes slowly apparent over time. In the physical science, *discrepant events* can be a useful way of engaging students in model-based reasoning. When students see something happen that contradicts their personal theories of how the world works, the need for cognitive consistency will lead many into, in Bohr's words, "expect alterations in the points of view best suited for the ordering of our experience."
- Like Jeremiah, many students enjoy developing and using practical knowledge—making things happen by growing plants, nurturing animals, building boats, designing bridges, protecting dropped eggs, etc. This practical knowledge is often useful in itself, though it gets short shrift in the standards documents. It also provides students with experiences that they can connect with patterns and explanations with your help and guidance.
- Metaphors and analogies can make science more interesting for students, even if they are "unscientific." It sometimes helps, for example, to ask students what and electron "wants to do," or to imagine themselves as a plant, or a carbon atom, or some other part of a system that they are studying. Warren, et al. (2001) refer to this as *imaginative embodiment*.
- There are many ways to make science more interesting embedding the content you are studying in narrative contexts. During this term we will study how one biology teacher has organized her class around *cases* that embody the experiences, patterns, and explanations in the curriculum (Richmond & Neureither, 1998). Disasters and diseases often make for

interesting cases, as do extremes of any kind—the hottest day, largest insect, most powerful earthquake, smallest mammal, etc. Otherwise dull patterns can be more interesting to students if they are given a narrative structure—telling the story of a carbon atom going through the carbon cycle, or a sugar molecule in your digestive system, or an algal cell going through its life cycle, for example.

We conclude with a couple of general ideas about student interests.[4] First, the work of making science interesting is never done. Students and their interests change from year to year, so what was interesting to your last group of students may not be interesting to other students in the future. Second, student interest is as much a product of the general culture of your classroom as it is of particular activities. Students will lose interest quickly in even the most spectacular activities if they don't see them leading to valuable results. On the other hand, students will stick with apparently boring activities if they have reason to believe that they are heading toward an interesting conclusion. For you as a teacher, sustaining student interest is partly a matter of building classroom norms and values—the topic of the next part of this paper.

Social and Cultural Norms and Values

Motivating students to learn science is hard because many of your students did not come to class to learn science. They are in your class because they have to be in a required course, or because their parents want them to be there, or because they are taking what their friends are taking. In addition to learning science, your students are always pursuing social goals and purposes—making friends, gaining status, or resisting authority. As a teacher, you inevitably find yourself playing a role in your students' social lives.

For the students who are most like you, you will find it fairly easy to understand your students' social goals and appeal to their personal values. For other students, though, this will be much more difficult. This is particularly true when you encounter resistance and alienation. You may find yourself wondering, "what did I ever do to him to make him treat me like that?" Sometimes it's personally about you, but often you and your students are stuck in a set of institutional and power relationships that inevitably puts you at odds. You have studied and discussed these relationships in TE 250 and TE 301, but they become much more real when you personally become the target—and the cause—of students' resistance and alienation. These are the students that may be most difficult for you to connect with personally, and they are the students who may give you the most discipline problems. Our starting point for discussions of these students will be *Cooperative Discipline,* by Linda Alford, a text for TE 402.

The factors that affect students' science learning are cultural as well as personal. There is a rich body of sociocultural research on how culture, gender, and language affect students' ways of understanding science[5]. This research documents the many ways in which students differ from one another—and from the expectations of school science—in their ways of talking, reading, and writing and in their approaches to describing and explaining the world around them. The expectations in the science standards are not simple truths about the material world. They are products of a particular culture, which happened to be dominated by European men.

So science teachers who aspire to help all their students achieve scientific understanding need to be aware of the diverse cultural resources that their students bring to school with them and learn how to take advantage of those cultural resources, finding what Warren, et al. (2001) describe as "generative continuities" between the scientific knowledge and practices that they are teaching and the students' approaches to making sense of the world around them.

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[4] Chapter 8 of Weinstein's textbook also contains many good ideas about capturing students' interests.

[5] For general discussions of this literature, see Gee (1991) or Heath (1983). Discussions of this research specific to science education can be found in Anderson, Holland, and Palincsar (1997), Brickhouse (1993), Lee & Fradd (1998), and Warren, Ballenger, Ogonowski, Rosebery & Hudicourt-Barnes (2001).

Finding these generative continuities is especially important for students who come to your class believing that *school is not meant to help them.* They sometimes have good reasons for these beliefs. Competition and group work can exacerbate status hierarchies in classrooms, which may enhance the efforts of high-status students while discouraging lower-status students (Cohen, 1994a, b; Richmond & Striley, 1995). African American students and other members of what Ogbu (1992) labels "caste-like minorities" face additional challenges resulting both from cultural traditions of resistance to historically hostile dominant cultures and from unconsciously prejudicial treatment by teachers and their fellow students (Kurth, Anderson, & Palincsar, 2002; Steele, 1992,1999). We will discuss some of these ideas in depth in TE 402.

So science teachers who care about the learning of their low-status students face a special set of challenges. They must engender classroom social norms that accept and reward effort by all students. Teachers must also work to overcome historical patterns of prejudice that alienate and marginalize some of their students. We hope you will be one of those teachers, and we will return to these challenges in the next section on teaching strategies.

Grading Fairly

The previous parts of this section have focused primarily on factors that affect students' intrinsic motivation to learn science—factors that affect their expectancy of learning with understanding and the value they place on that outcome. As you know, though, intrinsic motivation is hardly the whole story. Almost all students care about grades (as they should. For some extrinsically motivated students, grades are the only academic outcome that they really value.

As we suggested in our introduction to ideas about motivation, extrinsic motivation doesn't have to be a bad thing. What you would like to do as a teacher is make sure that their pursuit of grades engages them in learning knowledge and practices that will be valuable to them later in life. What makes this complicated is a potential conflict between your interests and your students' interests that we will explore in this part.

Doyle (1983) points out that grading is in fact a socially complex practice that serves multiple purposes. What Doyle terms the *performance for grade exchange* is the key accountability system through which teachers and students negotiate about the nature and purposes of academic work. While it might seem that students would prefer meaningful work that engages them in scientific application and inquiry, Doyle points out that this not always the case. Meaningful and challenging work exposes students to *risk* (the likelihood of failure) and *ambiguity* (lack of clarity about what it takes to succeed). Students respond to work that is too risky or ambiguous with complaints and resistance or with downright rejection—some students will not even attempt work that seems too risky and ambiguous to them.

Students generally don't like risk or ambiguity--for good reasons—so it might seem that teachers need to make risk and ambiguity as low as possible. To some extent, this is right. The adult world is a risky, ambiguous, potentially dangerous place. One of the purposes of schools is to protect students from those risks while they are still acquiring the knowledge and skills they need to be successful in adult life.

As the table below indicates, however, some risk and ambiguity are inherent in meaningful work. Thus as a teacher you need to avoid unnecessary risk and ambiguity (about standards and procedures for behavior or academic work) while helping students to understand and accept risk and ambiguity that are important or necessary. There aren't any clear guidelines, though, about when risk and ambiguity are unnecessary and when they are important for meaningful learning.

These ideas about risk and ambiguity help to explain why school science and procedural display are so common even though we all like to complain about them. Because they make the rules of the performance for grade exchange very clear, they minimize ambiguity. For some extrinsically motivated students (and their parents) this virtue maybe much more important than any ideas you might have about the value of scientific understanding and habits of mind.

	Low Risk	***High risk***
Low Ambiguity	Easy class (Easy school science) *McDonald's*	Traditional hard class (Difficult school science) *Professional sports*
High Ambiguity	"Joke" class (Discovery science) *Unemployment*	Bad class (Scientists' science) *Professional work*

While you cannot remove all risk and ambiguity from your class and still teach for understanding, there is a lot you can do to eliminate *unnecessary* risk and ambiguity. For example, you can make your goals clear to your students, then make sure that your teaching activities and your assessment standards are aligned with those goals. This consistency reduces risk and ambiguity for your students, but it can be hard to achieve. When you create a test, for example, you need to be sure that the questions are consistent with your objectives and classroom activities, and that your most important objectives get the most points. This is not a time when students like surprises!

There are also many ways you can reduce risk and ambiguity through the way you manage your courses.[6] You can make sure that students know what is expected of them and when it is due through public unit plans or schedules that are handed out, posted in the room, and/or posted on a class website. You can have consistent ways for students to turn in work, get it back, and find out about work that they missed when they were absent. Class websites are one good way to accomplish these and other course management goals; we will help you begin construction of a class website this term.

How you assign grades to student work also makes a difference in the levels of risk and ambiguity that students experience. In the section on understanding students' thinking above we suggested that deliberately vague questions could sometimes help you understand students' ideas, habits of mind, and intellectual resources. This is true, but the unit test is NOT the place to ask a vague question. For important tests, projects, and assignments, your standards should be clear and public, perhaps in the form of scoring rubrics that students can apply to their own work. It often pays to listen to students' complaints, too, and change grades if they make good arguments. Students need to know that you expect your standards to make sense, and you will change if they don't.

So managing risk and ambiguity in the performance for grade exchange is an important part of your work as a teacher. Teachers who are successful in teaching for motivation and understanding do all they can to reduce unnecessary risk and ambiguity while helping their students to see that some risk and ambiguity play a necessary role in the pursuit of scientific understanding.

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[6] Chapters 9 and 10 of the Weinstein text have many good suggestions about ways to manage student work that reduce risk and ambiguity.

Teaching Strategies: How Are You Teaching?

Suppose you are getting ready to teach a science unit. You have made sure you understand the science content yourself. You have goals, activities, and assessment procedures that are consistent with one another and that focus on important scientific understanding. You have worked hard to understand your students socially and culturally, and you have some understanding of the interests, misconceptions, and intellectual resources that your students bring to the unit. All of these are necessary, but still not sufficient if you want to teach for motivation and understanding. In addition, you will have to manage all the students in your classes, getting them to work together to create a learning community whose norms and values support engagement and understanding. You will also have to develop strategies to help students learn from others (learning cycles) or from experience (inquiry cycles). This section focuses on these important teaching practices.

Creating and Managing a Classroom Learning Community: Management, Safety, Participation, and Communication

Think about having a party for 30 of your friends. When you have that many people around, you can't just "hang out." You need to think about where they will all fit, what they will eat and drink, what they will be doing, how long they will stay, and who will clean up afterward. It's a lot of work in addition to being fun.

As a teacher, you will be responsible for 30 or so students about 5 times a day, 5 days a week. You will need to have them under control, but that's not enough. You will need to develop them into learning communities with rules and routines that get classroom work done efficiently, and with norms and standards that encourage rigorous scientific thinking and helping one another. The practical knowledge that you will need to accomplish this includes knowledge of *management, safety, participation,* and *communication.* Let's consider each of these in turn.

Classroom management and discipline. Discipline and management are not a primary focus for this paper. This is not because we consider them to be unimportant. In fact we will spend substantial amounts of time working you on management and discipline problems, including reading in Albert's (1996) book on cooperative discipline and case studies of challenging students. We will also use Weinstein's (1996) book on secondary classroom management and organization. In addition, discipline and classroom management are primary foci for other courses in the program (especially TE 801 and 803), so in this paper we focus primarily on teaching practices more specifically associated with students' success in learning science.

Safety. As a science teacher you are responsible for the physical safety of your students. In addition to managing your classroom effectively and maintaining discipline, this requires you to think about safety in science laboratories, which are potentially dangerous places, and not just for obvious reasons. All students are aware that acids and flames are dangerous, but the closest I came to having a student seriously injured came when one student accidentally poked another student in the eye with a meter stick. Labeling, storage, and disposal of chemicals can also be important safety issues. One good source of information and resources for laboratory safety is the Flinn catalog and web site (http://www.flinnsci.com).

If you want to teach science for motivation and understanding, students psychological safety is as important as their physical safety. All classrooms develop explicit standards and implicit social norms that affect students' speech, behavior, and social relationships. In some classrooms, these norms enable students to feel safe as they raise questions, admit confusion, or express their ideas about difficult questions. In other classrooms, students feel threatened and unwilling to risk being wrong. The best science teachers manage to create environments were academic press—a continuing drive for content understanding—is combined with norms that encourage raising questions and taking risks.

Creating this kind of environment is not easy because most adolescents are very sensitive about looking stupid in front of their friends, and for most adolescents, being publicly wrong about something is the same thing as looking stupid. This is another respect in which school science (where the right answers are spelled out by the teacher before students have to speak) can seem safer to a lot of students than the kind of dialogue based on students' ideas that we envision as part of teaching for understanding. Rewarding students for expressing their ideas and building classroom social norms that recognize how questions and wrong answers can help the class is an important challenge you will face as you try do develop a classroom that is both psychologically and physically safe (cf. Cobb, Yackel, & Wood, 1989).

Participation and communication. Both in class discussions and when students are working in small groups, their learning depends on their ability to participate actively and to communicate with one another. This is a social, organizational, and intellectual challenge.

It is a social challenge because people tend to sort themselves into status hierarchies that give different social roles to different members of a group. The high-status members, of course get the best roles, which is usually good for them but bad for the low-status members of the group. As a teacher, you cannot stop students from forming status hierarchies, but you can work to ensure that even the low-status members of your class have roles that enable them to participate actively and learn successfully. We will discuss and read about this problem extensively in TE 402 (Weinstein, Chapters 10 and 11; Cohen, 1994; Herrenkohl, Palincsar, & De Water, 1997,;Richmond& Striley, 1996).

It is an organizational challenge because students' ability to participate and communicate depends on your ability to create a well-ordered environment where tasks, expectations, and the rules governing participation are clear. Thus good management, discipline, and learning tasks are necessary prerequisites for student participation and communication.

Finally, participation and communication present you with an intellectual challenge because, even if they are all speaking English, not all your students "speak the same language" in terms of their interests, ideas, and habits of mind. Students who express themselves differently can easily talk past one another—and you—leaving everyone frustrated with your attempts to communicate about science. When this happens, school science can once again seem like an attractive alternative.

Teachers can try to sustain communication among students by creating a 'congruent third space' in which different ways of talking and acting can meet and interact (Moje, Collazo, Carrillo and Marx, 2000). This is, of course, far easier said than done. You have to look for generative continuities between the official scientific ideas and habits of mind and the ones that students bring with them to the classroom.(Warren, Ballenger, Ogonowski, Rosebery, and Hudicourt-Barnes, 2000). This is one of the hardest things that any science teacher has do do; even the most accomplished teachers find it a constant struggle.

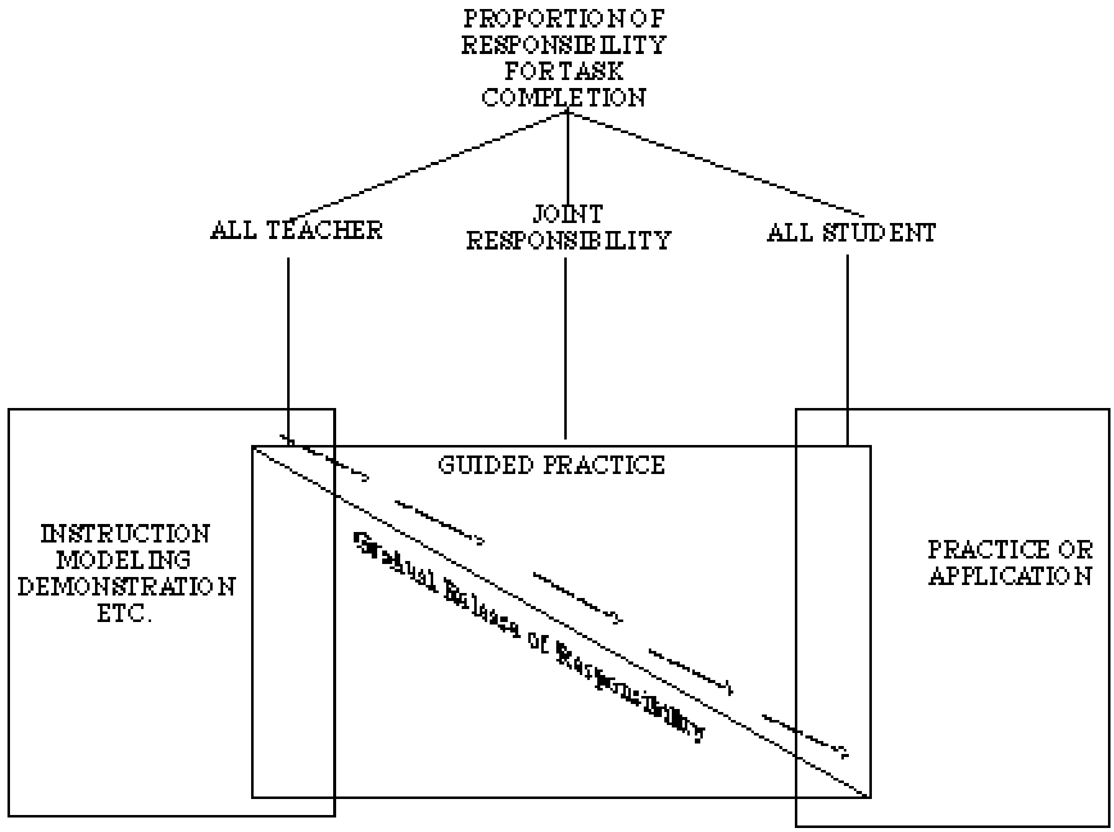
Learning Cycles: Helping Students Learn from Others

If your classroom is a well-managed learning community where students participate actively and communicate with you and one another, you have "set the stage" for successful science learning. If you have clear goals and assessment plans, you also know what kind of action you want to see taking place on that stage. You still have a fundamental problem though: Your students can't do what you want them to do. How do you get them from where they are to where you want them to be?

There are two basic approaches to this problem. Most commonly, you will have to teach them or help them teach each other. In this case, your students will be learning from others. We discuss *learning cycles* as a way to help students learn from others in this part. The other basic approach involves students in scientific inquiry as a way of learning from experience. We discuss *inquiry cycles* as a way of learning from experience in the next section.

If an objective is pretty simple for your students, you may not need a learning cycle. You can show them what to do, have them practice a bit, and be done with it. For more difficult objectives, though, your students may need to go through a process of *scaffolded learning*. Students can master difficult practices if they want to learn them and they have the opportunity to work on them repeatedly under different conditions.

Collins, Brown, and Newman (1989) suggest that meaningful learning of difficult practices often involves creating situations where (a) students are put in situations where they can observe other people engaging in the activity—*modeling*, (b) the students engage in the practice with scaffolding or support from others—*coaching,* and (c) the support is gradually withdrawn until the students are independently engaged in the practice—*fading*. These are the key middle steps of a *learning cycle*.[7], depicted in Figure 3, below.



Modeling Coaching Fading

Figure 2.4: Transfer of responsibility in the learning cycle

Stages of the Learning Cycle

In addition to modeling, coaching, and fading, our version of the learning cycle has two other stages. In order for modeling, coaching, and fading to be effective, students need to understand what they need to learn and to be motivated to learn—a stage that we label *establishing the problem.* Finally, students will forget even the best-taught knowledge and practices if they do not get a chance to encounter and use them again later, after the main teaching of the learning cycle is over. This stage we call *maintenance*. All five stages of the learning cycle are described in the table below.

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[7] Other science educators such as Lawson (1994) or Karplus (**ref**) describe learning cycles with different meanings and emphases. For other discussions of learning cycles in school and out see also Lave and Wenger (1991) and Resnick (1987).

Stages of the Learning Cycle

Stage	*Goals for Students*	*Common Strategies*
Establishing the problem	• discuss relevant personal experiences and ideas • understand learning goals • expectancy: believe that they are capable of understanding • value: establish interest and relevance of learning goals	• building on questions raised by students or problems that they are curious about • eliciting students' ideas about discrepant events or familiar situations • encouraging discussion and debate among students • discuss connections to previous units or learning cycles
Modeling	• see and understand how an expert accomplishes the objective • understand what they know and what they still have to learn	• "think aloud" problem solving • presenting scientific ideas in the context of real world problems • explicit contrasts between scientific and naive thinking
Coaching	• practice using scientific ideas to accomplish the objective with support and feedback	• scaffolding (providing support and structure that will gradually be withdrawn) • special problems that focus on student misconceptions or learning difficulties • systematic feedback and reinforcement • cooperative group work • working with multiple examples of related meaningful tasks
Fading	• learn to do the task independently	• gradually reduce scaffolding and other forms of assistance • evaluation methods that maintain the integrity of the task • test questions that focus on key student difficulties
Maintenance	• apply knowledge in other contexts	• providing opportunities to use the knowledge in other units or courses • connecting key ideas and practices for this objective with other important ideas and practices

Here are a couple of examples of learning cycles.

Example learning cycle for explaining how plants get their food

Stage	*Brief Description of Classroom Activities*
Establishing the problem	A class discussion asking students to go talk about: --how they think a particular plant gets its food --what they think the food is --what direction the food travels in the stem.
Modeling	Explanation from teacher of how a bean plant gets its food, with special emphasis on definition of food, role of sunlight
Coaching	Students work on activities that use other plant growth examples above: --working in groups to explain how oak trees get their food, using worksheets that emphasize the key points to be included in the explanation. --a class discussion of where the food in beans comes from, with emphasis on how sugars travel through the plant and are transformed into other kinds of food.

	--explaining why grass growing in the sunlight looks greener and healthier than grass growing in the shade.
Fading	Students work individually on other examples: --explaining how spirogyra (algae) are able to grow and multiply, --predicting and explaining what would happen to seeds that are dropped by bats into rich moist soil on the floor of a cave.
Maintenance	Students continue to use idea of photosynthesis in other contexts, for example: --the ecological carbon cycle, --food chains and food webs (which start with photosynthesis), --energy flow in ecosystems, --the relationship between photosynthesis and cellular respiration.

Example learning cycle for explaining temperature change through heat transfer

Stage	***Brief Description of Classroom Activities***
Establishing the problem	Students predict and explain how fast ice will melt in different situations: --sitting in a cool metal cup, --sitting in a styrofoam cup, --sitting inside a warm winter mitten, --sitting under a heat lamp.
Modeling	Teacher explains the results of a demonstration above, with special emphasis on contrasts between the students' predictions and explanations and scientists' predictions and explanations. These will probably include clarifying the difference between temperature change and heat flow, and thinking about the nature and direction of heat flow.
Coaching	Students engage in several activities that use other examples of heat transfer: --working as a whole class to explain examples of heat transfer by conduction (e.g., a spoon in hot coffee), convection (e.g., explaining how water at the top of a beaker on a hot plate gets hot), and radiation (e.g., explaining why you feel warmer on the side of you that is facing a fire). --working in groups on scaffolded worksheets with other examples of heat transfer by conduction, convection, and radiation. --comparing and discussing group explanations --discussing interesting examples of heat transfer that students bring from home or ask about.
Fading	Students engage in other activities that require them to explain heat transfer with less support: --designing systems for cooling off hot water quickly or slowly and explaining how they work --individually answering questions about other examples of heat transfer (e.g. How does the sun heat the earth? Why does the wind blow? How could you decide which metal conducts heat best?)
Maintenance	Students continue to use idea of heat transfer in other contexts, for example: --energy use in our homes, --energy changes associated with physical, chemical, or nuclear changes in matter, --daily and seasonal variations in temperature, --plate tectonics and volcanoes.

Here are some important things to notice about learning cycles as described in this section:

- *Assessing student thinking*. Understanding your students is just as important as understanding the scientific ideas and practices that you are teaching. Every stage in the learning cycle needs to include embedded assessment that will help you and your students understand their ideas and practices—both correct and incorrect.

- *Keeping the objective whole*. Students work through several examples where they use the big ideas in combination to accomplish the objective for a specific "piece of the real world." This is different from studying facts or concepts separately from one another or from their application to real-world examples.
- *Parallel examples that follow a common pattern*. There needs to be a common pattern in the real-world examples that you use for the different stages of the learning cycle and in the approach that students can take to solve the problems. It is often good to make that pattern explicit by giving students a sequence of steps or a set of key questions. For example, all the explanations of heat transfer should include the following:
  --identify the objects or substances between which the heat transfer occurs,
  --identify the mechanism of heat transfer: Conduction, convection, or radiation, and
  --explain the mechanism: Collisions of molecules, currents in fluids, or emission and absorption of visible or infrared light.
  Similarly, all explanations of plant growth should:
  --locate where in the plant food is being made,
  --distinguish between food (sugar or glucose) and raw materials from which food in made (water and carbon dioxide),
  --explain that the plant combines the raw materials to make sugar or glucose, and
  --if appropriate, explain how sugars move to other parts of the plant or are used for energy and growth.
  If you are explicit about the pattern that you want students to follow, you will find that it is very useful. It provides a basis for scaffolding during the coaching phase of the cycle, and for a rubric that you can use to evaluate students' work.
- *Learning as transfer of responsibility*. Progress within a learning cycle comes when students take more responsibility for accomplishing the objective or when they improve the quality of their performance. This is different from moving from one skill or concept to the next one.
- *Scaffolding is temporary*. Learning cycles require careful modeling and coaching that make difficult tasks easier for students to manage. The learning cycle is not complete, though, until students can accomplish the objective on their own—for a new example—without special support from you or from one another.
- *Connecting learning cycles*. In a good curriculum, learning cycles are carefully connected to one another. The fading for one learning cycle helps to establish the problem for others. Maintenance means that ideas and skills from one learning cycle are built into others.

Lesson Planning: Objectives, Materials, Activities, and Post-lesson Notes

Most learning cycles include several lessons. When you are planning an individual lesson, it is important to consider how the activities of the lesson will fit into the overall plan for your learning cycle. It is also important to prepare the materials and activities of the lesson carefully. Appendix C contains a sample lesson plan on heat transfer to which you can refer as you read this section.

Objectives. In standards-based teaching the lessons are "wrapped around" your objectives for student learning. Learning cycles also vary in length and intensity. Some learning cycles (for example, a learning cycle on scientific inquiry) may extend across the entire year, with establishing the problem and modeling in the fall and coaching whenever students to an activity involving inquiry. Therefore, you might be working on more than one objective during a single lesson, but a single lesson rarely contains an entire learning cycle.

In planning your lesson, therefore, it is important to think both about *what objectives you will be working on* and *what stages in the learning cycle your students will be on for each* *objective*. For example, the lesson in Appendix C establishes the problem and begins modeling for objectives about predicting and explaining temperature changes.

Here are some important things to consider in developing objectives for your lesson.

- Your objectives should come from the objectives you listed in Clarifying your Goals, above.
- Your objectives should meet the criteria for good objectives discussed in Clarifying your Goals, above.
- The activities of your lesson should focus in the objectives you have chosen
- The activities of the lesson should accomplish the goals for students appropriate for the stage(s) in the learning cycle that you are working on for each objective.

Materials. The most time-consuming part of lesson planning often involves developing the materials that you will use and developing lists that you can check before you start teaching. A good list is important. You are often interrupted or distracted just before class begins, so you need a quick way to check just before class begins. Your materials list should include the following:

- *Presentation materials*. These are materials you will use for lectures, class discussions, or demonstrations that you will use for the whole class. They may include overhead transparencies, PowerPoint presentations, and demonstration set-ups. If you are using technology or doing a demonstration, you should *always* check your equipment and set-up to make sure everything is working before class begins.
- *Copied materials*. These includes handouts, worksheets, etc. It is always dangerous to count on the copy machine being available and in working order 15 minutes before class starts. You should have your copied materials stacked and ready to go before class starts. It is safer to have a few extra copies. You also need a way of keeping track of copied materials from previous lessons for students who were absent.
- *Textbooks*. If you will be using textbooks, you need a routine for making sure all your students have their textbooks to use, and you know what pages they should turn to.
- *Class laboratory materials*. If you are doing a laboratory, there may be some materials that are available in stations and used by the class as a whole. (For example, shared equipment or containers of expendable supplies. You need to have those materials listed on your plan and ready before class.
- *Materials for laboratory stations*. Laboratory or field activities also commonly have materials that are distributed to individuals or small groups. You need to be sure you know what materials each group will have and how many groups there will be in each class. If you are doing a laboratory for several classes in a row, then you will need to have clean-up and checking procedures to make sure the students in one period get their stations ready for the next period class.
- *Other materials*. You may sometimes have special activities that require other materials.

Activities. Planning the activities of a lesson is a complex process in which you are juggling multiple concerns—the learning cycles you are working on, classroom management, developing norms and standards, maintaining your rules and routines, etc. You can never write down everything you have to remember while doing your lesson. On the other hand, it's very difficult to remember your plans if you don't have some written notes. It is important to remember that when you plan a lesson you are planning your *students'* activities, not just your own. It may be useful to think of your lesson as consisting of three segments:

- *Introduction*. This part of the lesson includes a beginning-of-class routine that should help your students use their time productively while you are taking care of obligations such as role check, talking to students who have been absent, etc. Beyond that, you want to make sure that you get your students into the substance of the lesson, reminding them of the learning cycle they have been working on and connecting the ideas of the previous lesson with the activities of the current lesson.

- *Main lesson activities*. The bulk of the lesson consists of learning activities that take your students through the parts of the learning cycle that you have planned for them. These activities need to bring together the work you have done on clarifying your goals, planning learning cycles, and embedded assessment. Thus they may include:
  - Key examples, patterns, models or theories
  - Key questions that you will use to start discussions
  - What the students AND the teacher will be doing
  - Embedded assessment activities that will indicate students' understanding
  - References to materials you or the students are using during this activity
  - Procedural details , including transitions, materials management, etc.
- *Conclusion*. You probably will also want a concluding routine at the end of class. Your substantive conclusion should help your students remember the most important points of the lesson and anticipate the lesson to come. You also need to make sure that the room is clean and ready for the next class, that students have their papers in, etc.

Time management is an important part of lesson planning, and a difficult one when you are a beginning teacher. You should always have contingency plans—what you will do if the activities of the lesson take more or less time than you had anticipated. Five minutes with a class full of students and nothing to do can seem like a very long time!

Post-lesson notes. Lessons hardly ever go exactly the way you had planned. It's a good idea to save a space on your lesson plan for jotting down how the lesson went and what you might want to change about it in the future. You will often be too busy to make the changes in your activities and materials right away, but you will need some notes to help you remember what needs to be changed when you do get around to revising the lesson.

Inquiry Cycles: Helping Students Learn from Experience in the Material World

While scientific inquiry requires mastery of skills that students can learn through learning cycles, it also involves another dimension. People engaged in inquiry use evidence to develop new ideas about how the world works. In Bohr's words, they "extend their experience and reduce it to order." Thus, as depicted in Figure 2 above, there is a reciprocal relationship between application and inquiry. Application involves using models and theories to make sense of experience; inquiry involves finding patterns in experience and developing models and theories. Thus inquiry is how students learn from experience about science.

We often associate inquiry with laboratory or field experiences for students. However, not all laboratory experiences involve inquiry, and not all inquiry involves laboratories. Here are some kinds of laboratory activities that are NOT inquiry:

Laboratory Activities That Are Not Inquiry
1. Confirmation labs: students follow directions. Purposes:
• Practicing lab techniques
• Confirming accuracy of laws and theories
2. "Consumer reports" labs: students compare products or practices to find the best one. Purposes:
• Reasoning about and developing experimental techniques
• Practicing evidence-based argumentation and decision making
3. Explanation labs: students observe phenomena, then use models and theories to explain what they saw. Purposes:
• Connecting representations at different levels of abstraction
• Practicing detailed explanations of real-world examples

4. Design labs (engineering inquiry): students use scientific principles to design systems that accomplish specific purposes (e.g., egg drop lab, building bridges, maximizing crop yield). Purposes:
- Applying scientific theories to practical design problem.
- Building engineering skills

There are also some common misconceptions about inquiry. One is that inquiry involves following certain steps in a fixed order, the "scientific method." In fact, studies of scientists at work show that they rarely follow the steps of the scientific method, [8]so it probably doesn't make sense to require students to follow those steps either. The "scientific method" in a lot of science classes can be another artifact of school science—a way of standardizing and simplifying the complex process of scientific inquiry.

Science teachers can engage their students in inquiry in a variety of ways, including experiments in laboratories or other settings, field investigations, analyses of data available on the Internet or from other sources, and simulations. A list of common types of classroom inquiry includes the following:

Types of Inquiry Activities

1. Naturalistic or field inquiry: students look for patterns in observations that they make. Examples:
- Geological or ecological field work
- Astronomical observations, such as sun and moon

2. Experimental inquiry: students create new experience in the lab, often with planned variation. Examples:
- Systematically observing products of different reactions
- Comparing plant growth under different conditions

3. Data analysis: students look for and explain patterns in "experientially real" data sets that are given to them.[9] Examples:
- Looking for patterns in weather or geographic data
- Explaining reported results of dangerous experiments

4. Simulations: students look for patterns and explain results in "virtual worlds" that imitate reality. Examples:
- Models of moving objects or electrical circuits
- Ecosystem models

A final misconception about student inquiry is that it necessarily involves putting students in control or giving them freedom to explore. In fact, students often need a lot of scaffolding in order to do productive inquiry, so inquiry cycles can have substantial variations in the amount of teacher control, ranging from exercises in which students try to figure out answers to problems posed by the teacher to project-based learning in which students design their own investigations. All of these

[8] See, for example, Latour and Woolgar (1979) or Bazerman (1988). There is one context in which scientists DO follow a fixed set of steps like those of the scientific method. This comes when they report their work to other scientists. Thus in scientific communities the scientific method is a form of argument or a means of persuasion. A journal article that includes background, questions, methods, results, and conclusions is more likely persuasive to other scientists. Thus even though your students may not follow the steps of the scientific method when they are doing inquiry, it may be useful for you to require those steps in their reports on their work. They can provide a useful kind of scaffolding for student reports.

[9] See Haury (2001) for a good list of data sets available on the Internet.

approaches share some essential features. Our list of these features is adapted from *Inquiry and the National Science Education Standards* (National Research Council, 2000, page 27):

Essential Features of Classroom Inquiry

Essential Feature	Variations			
1. *Questions.* Students engage in scientifically oriented questions.	Learner poses a question	Learner selects among questions, poses new questions	Learner sharpens or clarifies question provided by teacher, materials, or other source	Learner engages in question provided by teacher, materials, or other source
2. *Evidence: Data and patterns.* Students respond to questions by looking for patterns in data—their own experiences and/or data supplied by the teacher.	Learner determines what constitutes evidence and collects it	Learner directed to collect certain data	Learner given data and asked to analyze	Learner given data and told how to analyze
3. *Students' explanations.* Students formulate explanations from evidence	Learner formulates explanation after summarizing evidence	Learner guided in process of formulating explanations from evidence	Learner given possible ways to use evidence to formulate explanation	Learner provided with evidence
4. *Scientific theories or models.* Students compare their explanations to explanations based on canonical scientific models or theories	Learner independently examines other resources and forms the links to explanations	Learner directed toward areas and sources of scientific knowledge	Learner given possible connections	
5. *Communication: Argumentation and justification.* Students explain and justify their methods, results, and conclusions.	Learner forms reasonable and logical argument to communicate explanations	Learner coached in development of communication	Learner provided broad guidelines to use sharpen communication	Learner given steps and procedures for communication
	Learner directed ←——→ Teacher directed			

You could think of the table above as suggesting the stages of a learning cycle on inquiry cycles. All the inquiry cycles you do with your students should have these features, though not necessarily in the order listed. At the beginning of the year you will probably need to provide your students with a lot of scaffolding, to your inquiry cycles will be more like those suggested by the right-hand column of the table. As your students become more adept at inquiry, though, your support can fade, and your inquiry cycles will move toward the middle or left-hand columns of the table.

The best science teachers that we know organize almost all their science teaching around learning and inquiry cycles (though they may not use those terms). They often interweave learning and inquiry cycles in complex ways, and they usually have more learning cycles than inquiry cycles. Though it is important for students to understand and experience scientific inquiry, it is not an efficient way to learn all the patterns, models, and theories that we would like students to know. Inquiry is important, but application is why we consider scientific knowledge valuable.

Professional Resources and Relationships: Using Resources and Learning from Mentors and Colleagues

In the previous three sections we discussed the teaching cycle and the process of using assessment to learn from experience. In this section we discuss aspects of your teaching practice that do not involve direct contact with students. First we consider ways that you can use and learn from the many teaching resources that are available. Second, we consider your learning to teach from others, including your course instructors, mentor teachers, and colleagues. Finally, we consider the ways in which you can explain your teaching practice to others, helping them to understand what you are doing and why.

Finding, Using, and Adapting Resources

The Internet has dramatically changed the availability of resources for classroom teachers. Teachers who are dissatisfied with the textbooks and other resources supplied by their schools can now quickly find a variety of free alternatives. At best, though, these alternatives are raw materials for the painstaking process of building effective learning cycles and inquiry cycles. At worst, they are distractions, "patent medicines" that provide activities to keep students busy without supporting learning with understanding.[10] Thus teachers who wish to teach for motivation and understanding must be expert evaluators and adaptors, finding appropriate resources and adapting those resources to support their practices.

In this course and TE 402 we will introduce you to a variety of resources and to standards for evaluating them, including the standards developed by Project 2061. Perhaps the most important thing to remember is that as a teacher, it is your job to develop effective learning cycles and inquiry cycles. These provide the framework into which you can insert the resources that you find. When those resources don't fit your needs, you should modify them. When they don't provide for all the essential parts of a learning or inquiry cycle, you should fill in the gaps yourself.

Learning from Mentors and Colleagues and Participating in Professional Communities

Learning to teach is hard. Being an instructor or a mentor for beginning teachers is hard, too. Mentors are supposed to be good role models AND be sensitive, caring people who understand the process of learning to teach and can create or design learning cycles for you focusing on the practices of teaching. Most of us know how to do some of that, but no one does all of it well. You will find that most of the people you work with—course instructors, mentor teachers, and field instructors—are better at some aspects of science teaching than others, understand you in some ways but not others, and can help you with some of the problems you encounter in learning to teach but not others. This can be frustrating, but it is also an important part of becoming a professional, and ultimately a leader.

You are still in your teaching apprenticeship, but being a good apprentice is an active process that involves thought and judgment on your part. Your instructors and mentors are all imperfect people; you can't expect consistent wisdom from any of us, so to be a successful apprentice you will need to figure out and take advantage of what each of us has to offer while recognizing our limitations.

Becoming skillful at learning from others is important because teaching science for understanding is more than any individual teacher can handle alone. Good teaching practice requires the support of professional communities that give teachers intellectual support and that

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[10] Project 2061 has pioneered an extensive effort to develop standards for evaluating teaching materials and to evaluate representative materials. See Kesidou & Roseman, 2002 and the Project 2061 website: http://www.aaas.org/project2061/.

encourage professional norms in teaching and learning to teach..[11] Successful teachers find or help to create those communities within their schools or larger organizations such as university-based graduate programs, professional development or curriculum projects, or professional associations.

Successful participation in professional communities demands specific commitments and skills of teachers. They must be able to win the respect of their colleagues by expressing their commitment to teaching for understanding and by sharing ideas and resources. They must be willing and able to listen and learn from others. They must care about their colleagues and support them personally and professionally. They must exemplify, in other words, norms of both leadership and collegiality. We hope that your participation in this program will give you a chance to help create such a community and benefit from being a member.

Explaining Your Practice and Job Searches

One final practice that is important to good teaching is explaining your teaching practices to others, starting with your students, but including parents, colleagues, course instructors, administrators, and job search selection committees. This will be a major focus of TE 801-3 during your intern year, but we will share a few ideas about explaining yourself.

First, most of the people you are working during your teacher preparation program know how difficult science teaching is. We know that classes hardly ever go as well as you would like; there is always something wrong with your teaching practice. It sometimes takes courage to admit what is wrong because teaching is very personal as well as being very hard. Identifying and talking about both the good parts and the bad parts of your teaching, though, is ultimately the best way to learn to teach—people can't help you with your problems if you don't tell about them. This kind of balanced approach will also make your accounts of your teaching more credible—most knowledgeable listeners are skeptical of someone talking about teaching and saying that everything is going well.

Finally, we have a few observations about what we hear that selection committees look for when they are interviewing candidates. The qualities that selection committees look for include the following (more or less in order of importance):

- The ability to teach science for motivation and understanding. Their first concern is what kind of classroom teacher you will be.
- The ability to work with colleagues. This includes both the hope that you will "fit" with other members of the department and the hope that you will bring in new ideas, especially in the areas of standards, current research, and technology.
- A match between your qualifications and experience and the position the school has available.
- Personal style, originality, creativity. These qualities are sometimes essential for teaching for motivation and understanding, but selection committees generally consider them less important in and of themselves. They are looking for professionals, not artists.

When you are teaching, effectiveness counts for more than originality. It will generally be OK to copy from one another and from the resources you find as you plan, teach, assess, and reflect. Good teachers are people who have good judgment about what to copy and how to modify what they copy for their own students, as well as when they need to develop their own materials and activities because nothing they have really matches their needs. During the next two years—and for

[11] Those professional norms include the characteristics identified by Newmann and associates (1996) as critical to supporting teaching for understanding: Shared norms and values, collective focus on student learning, collaboration, reflective dialogue, and deprivatization of practice. Such professional communities contrast with typical school communities dominated by what Little (1982, 1993) describes as norms of isolation and egalitarianism. For more about school professional communities, see Gamoran, Anderson, Quiroz, Secada, Williams, and Ashmann (2003). See also Elmore (2002), Newmann and Associates (1996), and Spillane, Halverson & Diamond (2001). See also Lehrer and Schauble (2002) for an example of work done by a productive professional community.

the rest of your teaching career—you will be finding and sharing the resources that you need to teach science for understanding.

Conclusion

A truly excellent pattern of practice in science teaching is a daunting accomplishment. Though we fall short ourselves, we know a few teachers who come close to exhibiting all of the qualities described in this paper. These teachers' knowledge includes a deep understanding of fundamental science; they understand key experiences, patterns, and explanations for every topic that they teach. They use their understanding to engage students in the practices of scientific inquiry and application. They understand their students, conceptually, socially, and culturally. They create classroom learning communities whose norms and standards encourage all students to expend effort toward meaningful science learning, and they are able to plan and carry out learning cycles and inquiry cycles that make meaningful learning an attainable goal for all their students. They continue learning and helping others to learn through their participation in professional communities. For most teachers and all our candidates, though, this chapter presents an unattainable vision of excellence.

In our current educational system, though, this vision makes almost impossible demands on the knowledge, skill, and dedication of science teachers. Asking teachers to enact this vision in today's schools is somewhat like asking doctors to perform twenty-first-century medicine in nineteenth-century hospitals.[12] Excellent science teaching today is a virtuoso accomplishment, attained only by a few teachers of exceptional talent and dedication.

Furthermore, our vision is not the only one that counts. You and your mentors have your own ideas about excellent science teaching, ideas that were as deeply rooted in your practice and experience as our ideas are in ours. We do not expect you to accept our ideas without question. One of our goals for the program is to graduate teachers who are "bilingual," familiar with the theory and practice of reform science teaching while being prepared to work successfully in schools as they are today.

We wrote above about curiosity and rigor as habits of mind that good scientists bring to their work and that you should seek to engender in your students. We hope that you will also bring those habits of mind to your science teaching. You can exhibit curiosity by seeking out opportunities to learn science, by finding new and interesting resources and activities, by searching for good examples that go with the patterns and explanations in your texts, and by being genuinely interested in your students and their thinking. You can exhibit rigor by developing a deep understanding of fundamental science, by skeptically assessing your students' learning and your own teaching activities, and by making careful use of learning and inquiry cycles to organize your teaching. If you show these habits of mind in your teaching practice, then we are confident that your students benefit from having you as a science teacher.

[12] A recent pair of publications from the National Research Council explores the systemic demands of science education reform and the available evidence about the nature and limited extent of the system's response to those demands: Weiss, Knapp, Hollweg, and Burrill (2001), and Hollweg & Hill, in press.

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Index

Appendix A: Transforming Scientists' Practices into School Knowledge

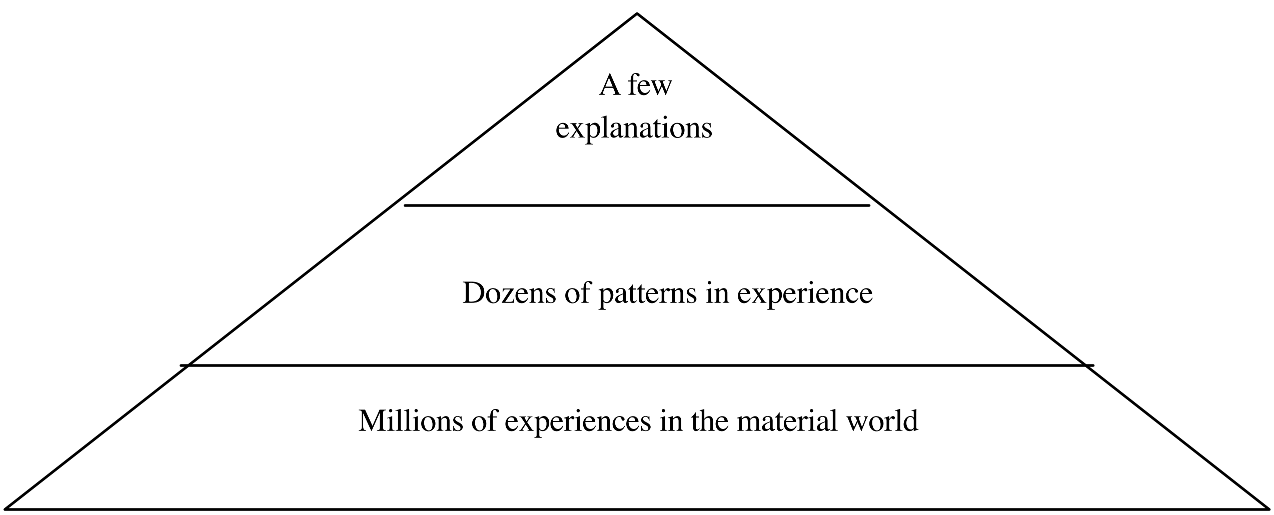
> The task of science is both to extend our experience and reduce it to order, and this task represents various aspects, inseparably connected with each other. Only by experience itself do we come to recognize those laws which grant us a comprehensive view of the diversity of phenomena. As our knowledge becomes wider we must always be prepared, therefore, to expect alterations in the points of view best suited for the ordering of our experience.
>
> --Niels Bohr

In the quote above Niels Bohr addresses both the *knowledge* and the *practice* of science. Scientific knowledge, as he described it, includes "experience itself," "laws which grant us a comprehensive view of the diversity of phenomena," and "points of view best suited for the ordering of our experience." His description of scientific practices suggest that scientists "extend our experience and reduce it to order, "recognize … laws," and "alter… points of view."

Many scientists would accept this as a reasonable, if incomplete, description of what they know and do. Bohr does not, however, describe school science as it is experienced by most students. In this essay I hope to explore how scientists' knowledge and practices are transformed into school science, the distortions that occur during this process. I also wish to suggest ways that school science might retain some of the most valuable aspects of scientists' knowledge and practice.

Scientists' Knowledge and Practices

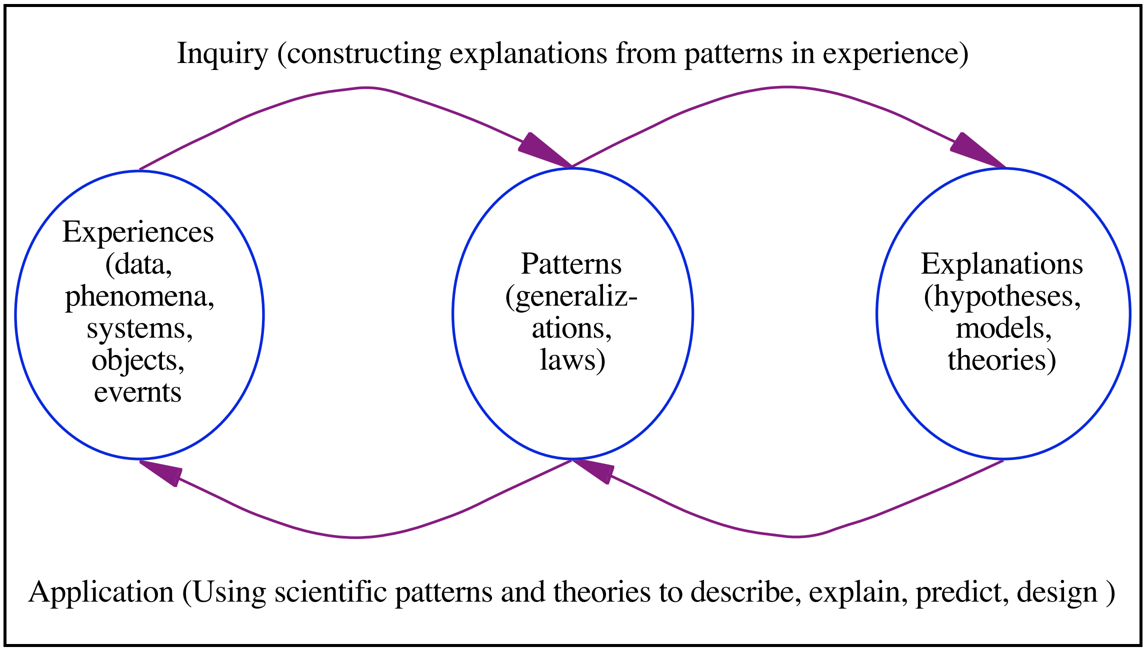
Scientists' Knowledge: Experiences, patterns, and explanations



Most practicing scientists spend a majority of their research time immersed in *experiences* with the material world. They develop new instruments or techniques for data collection, they plan and carry out data collection, often spending many tedious hours doing multiple observations or trials. They publish their data and share it with other scientists, thus enhancing their personal experiences with those of their colleagues and predecessors.

Patterns in experience (e.g., laws, generalizations) and *explanations* of those patterns (e.g., theories, models) play a critical role in guiding scientists' data collection efforts and giving them purpose. Scientific communities accumulate experiences for the purposes of finding patterns in those experiences, developing explanations of those patterns, and testing the validity of their patterns and explanations against new experiences. *Scientific understanding* is achieved when scientists develop coherent sets of experiences, patterns, and explanations—the experiences provide a valid basis for the patterns and explanations, while the patterns and explanations make the experiences meaningful.

Scientists' Practices: Inquiry and application



(Note: Sometimes arrows going to the right for inquiry and to the left for application don't show up on PC's.)

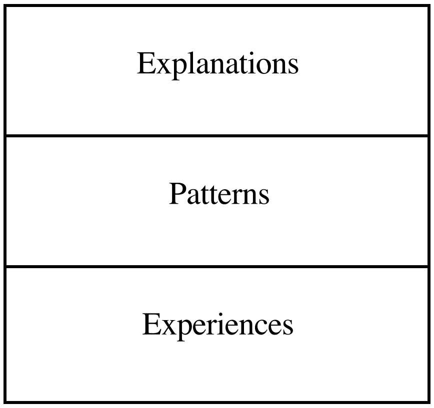
I think that Bohr's description and the comments above about the relationships among experiences, patterns, and explanations generally apply to both the pure and the applied sciences. The descriptions of practice, though, are incomplete in that they focus primarily on *scientific inquiry*—the practice of developing new scientific knowledge. Scientific inquiry is worthwhile, though, only because the knowledge it produces is valuable. Thus the practices of *application*—using scientific knowledge to describe, explain, predict, or design systems in the material world—are as important as the practices of inquiry.

Thus pure and applied scientists develop similar knowledge but differ in their practices and the purposes of their work. Scientific research uses experiences for the purpose of testing explanations and developing new ones. Applied scientists use the models and theories to accomplish practical goals. The illustration above suggests the general relationship between inquiry (typically associated with the pure sciences) and application (typically associated with the applied sciences).

Written Scientific Communication

The success of science depends on the ability of scientists to communicate with one another about their knowledge and practices. Scientific communities build bodies of knowledge and practice over generations. The scientific journal article is primary mechanism through which scientists learn from their predecessors, communicate with their colleagues, and preserve what they have learned for their successors. Journal articles are not, however, complete and accurate representations of the knowledge and practices of their authors.

Journal Knowledge: Experiences, patterns, and explanations



Parts of a typical journal article:

- --problem or question (about patterns or explanations)
- --review of relevant research (already established patterns and explanations)
- --hypotheses (tentative new patterns or explanations)
- --methods (for developing new data)
- --results (data and patterns)
- --conclusions (about patterns and explanations)

When scientists communicate about their work, their communication typically includes only those parts of their experiences that are relevant to an argument about theories and generalizations. Many of their experiences are never reported at all (e.g., methodologically suspect data, pilot tests, informal observations that were not part of the data collection effort). The data that are reported are typically displayed in ways (e.g., charts, graphs) that draw the reader's attention to patterns rather than to individual experiences (data points).

Thus experience plays a critical role in written scientific communication, but reporting of experience is embedded in arguments that alter the ratio of experiences to patterns and explanations. Written scientific communication typically devotes at least as much text to displaying patterns and discussing explanations for those patterns as to reporting data.

Journal Writing Practice: Persuasive communication

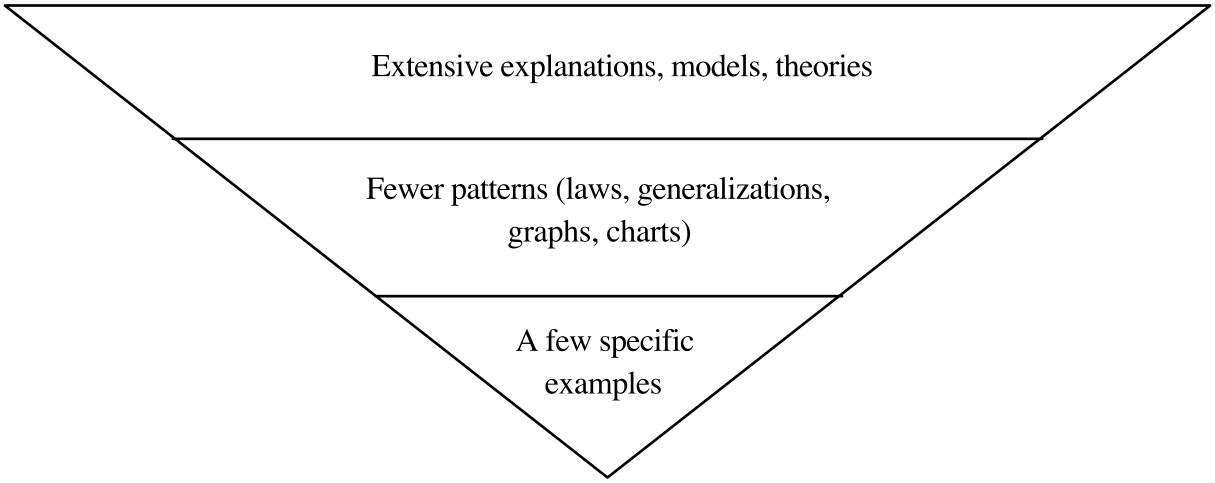
As Bazerman (ref) and other students of the rhetoric of science (e.g., Latour, Knorr-Cetina) have pointed out, the primary purpose of journal articles is not to provide accurate accounts of scientific practice. Scientists are primarily concerned with persuading their colleagues that they have achieved understanding—coherent experiences, patterns, and explanations—of some system or phenomenon. Thus they report their experiences selectively, including only valid and relevant data. They display their data in ways that reveal and emphasize patterns, and they embed their data and patterns in arguments about models and theories.

These communicative practices are efficient and effective when the readers are colleagues who share similar experiences and patterns of practice. The representations of scientific knowledge and practice that are preserved in the journals, though, are selective and incomplete—perhaps something like box scores and highlight reels as a way of preserving what happened in baseball games.

Science Textbooks

Science students at the K-12 and undergraduate levels generally neither see scientists at work nor read journal articles that scientists have written. Instead, they learn about science through textbooks whose authors are writing mostly about other scientists' work rather than their own. The representations of scientific knowledge and practice in textbooks are further altered from scientists personal experiences and their communication in journals.

Textbook knowledge: Explanations, patterns, and examples



Textbook authors typically focus on the conclusions of scientific studies rather than the details of the supporting data and arguments. They also focus on the most important theories and models in their fields when they write textbooks. This doesn't leave much room for reporting data or explaining the painstaking data collection and pattern-finding activities of scientists that have led to these conclusions. Thus textbooks are devoted mostly to explanations—models and theories—accompanied by displays that summarize patterns in data—graphs, charts, maps.

The original data are often entirely absent. A graph, for example, illustrates a relationship between variables rather than the data that convinced scientists of the validity of the relationship. There may be a few illustrative examples in boxes accompanying the text or in the problems at the end of the chapter. Sometimes there are also demonstrations or laboratory exercises designed to provide students with a few experiences with the systems they are studying.

Textbook writing practices: Summarizing authoritative conclusions

Unlike the readers of journals, the readers of textbooks are generally in no position to question the validity of scientists' evidence or arguments. Furthermore, textbook authors are faced with the task of simplifying and summarizing vast bodies of scientific knowledge—the work of thousands of scientists over many generations. Given this rhetorical challenge, the choices made by many textbook authors are understandable. They summarize the conclusions of the journal articles and present those conclusions as authoritative. They describe the supporting data and arguments only for a few illustrative examples or controversial theories.

The result, though, is that the representations of scientific knowledge and practice in textbooks diverge further from scientists' experience. In particular, the ratio of experience to explanation has been reversed. Rather than a few models and theories emerging from an extensive base in experience, textbooks use a few examples to illustrate their extensive explication of models and theories.

Students' Interpretations

Scientists generally have little trouble reading and making sense of textbooks in their fields. They can relate the theories explained in the text to their own extensive experiences. For students without the scientists' experience base, however, the problem of interpreting the text is substantially different, particularly if students are reading the text mainly for the purpose of passing tests.

Students' Knowledge: Facts, definitions, and algorithms

- Facts and definitions
- Problem-solving skills or algorithms
- Diagrams and sequences of events

For these students, the connection between the contents of the text and experiences in the material world may be almost entirely lost. For some topics (e.g., Newtonian physics) students may have extensive experiences that lead them to see different patterns and explanations from those in the texts. For other topics, (e.g., molecular biology), the texts may be about entities and relationships so far removed from students' experiences that it is almost impossible to make the connections. In these circumstances, it is not surprising that many students give up on trying to connect the contents of textbooks to their personal experiences with the material world. Students read the texts as compilations of facts, definitions, algorithms, diagrams, and sequences of events to be reproduced on demand in assignments and tests.

Students' Practices: The performance for grade exchange (procedural display)

There are advantages for science teachers and students in accepting an interpretation of science as consisting of facts, definitions, and algorithms, rather than trying to help students appreciate the importance of experience and pattern-finding in actual scientific practice. The facts-oriented approach packages the content much more neatly. Students either know the right answers or they don't. Teachers don't have to worry about ambiguities in interpretation or misconceptions arising out of students' personal experiences. Many complexities and ambiguities are removed from what Doyle (ref) has described as the "performance for grade exchange. The table below contrasts the neatly packaged facts of school science with the messier scientific knowledge on which the facts are based.

Contrasting the two conceptions of science

Facts, definitions, sequences, problem-solving procedures	***Experiences, patterns, explanations***
Linear reasoning: Question→steps in reasoning→answer	Pattern-based reasoning: Recognizing, explaining, using patterns in data
Student performances clearly right or wrong	Degrees of understanding: --extent of experience --reproducibility and precision of descriptions of experience (data) --awareness of patterns --power of explanations to account for wide ranges of experience
Can be learned as discrete bits	All interconnected
Can be learned independently of personal experience	Built on personal experience
Disconnected from students' prior knowledge	Built on students' prior knowledge
Assessment by ability to reproduce and use facts, etc.	Assessment by ability to engage in successful inquiry and application

An Alternative Approach to School Science

The responses of textbook authors, teachers, and students to the demands of school science have thus led to the development of patterns of practice that are sensible and that "get the job done." The textbooks do summarize and simplify vast amounts of scientific knowledge. The students do learn the contents of the textbooks well enough to succeed in the performance for grade exchange. What is lost, however, is critically important. The facts-oriented approach misrepresents scientific knowledge and practice fails to help students to develop meaningful and useful knowledge.

In this section I outline the key elements of an alternative approach to science teaching that recognizes the demands of school science (e.g., summarizing and simplifying scientific knowledge, clarity in the performance for grade exchange) while retaining some essential elements of scientific knowledge and practice. This approach is described in more detail in the main section of this paper.

Developing students' knowledge: Expanding experience and reducing it to order

While we cannot ask students to "reinvent the wheel," experiencing for themselves all the evidence on which scientific theories are based, we need to help students develop enough of an experience base to appreciate the power and parsimony of scientific patterns and explanations.

There are many topics in the curriculum, such as Newtonian physics, systematics, or weather, where students' personal experiences are a valuable resource. While valuable, these personal experience bases are often limited in important ways. For example, students whose experiences with moving objects are limited to motions of objects near earth that are always affected by friction and gravity are likely to see patterns (e.g., continued motion requires continued force) that do not hold for objects in general. For these students, expanding their experience may need to include personal or vicarious experiences with situations where the effects of friction and gravity are minimized. They will also need to reinterpret their previous experiences so that they can see new patterns and explanations that hold across their new, enlarged bodies of experience. This is the process of conceptual change.

Though conceptual change can be difficult, meaningful learning is still easier for topics where students have a substantial experience base to start from. For any topic, it is important to find students' personal experience bases that can be expanded and interpreted. Developing sequences of topics that enable students to learn by continually expanding their experiences and reducing them to order is a major challenge for curriculum developers. For topics where students' experiences are largely absent, such as atomic theory, molecular biology, or stellar astronomy, teachers need to make a substantial effort to help students acquire enough personal or vicarious experience to see scientific patterns as patterns, not just as "facts" disconnected from experience. A curriculum with many such topics is not likely to be meaningful to students.

Developing students' practices: Cognitive apprenticeship in inquiry and application

Collins, Brown, and Newman (1989 are among many authors who argue that we learn practices most effectively in social situations that (a) render the practices meaningful, (b) provide learners with models of successful practice, and (c) provide for coaching—situations where learners engage in the practices with support and feedback from peers and mentors. We can find many situations—parents teaching their children to talk, traditional apprenticeships, coaching in sports—where people with no special training in education function successfully as teachers. The figure below depicts this process in general terms.

Yet in many science classrooms, students' predominant practices are those associated with the performance for grade exchange—reading or listening to presentations of facts, definitions, algorithms, diagrams, or sequences of events, reproducing them on homework or tests, or following instructions for laboratory exercises. Since these are the activities that students practice, these are the activities that they get good at.

It isn't hard to understand why teachers would be hesitant to build their classroom activities around the messier and more complex practices of scientific inquiry and application, but these are the practices that make science a valued part of the curriculum. Collins, Brown, and Newman's idea of *cognitive apprenticeship* provides one possible solution to this dilemma. They suggest that with careful planning and organization, it is possible to provide students with apprenticeship-like experiences in classrooms. These ideas provide the basis for the version of the *learning cycle* that we use in our teaching.

For teachers to make learning cycles work in classrooms, they need to be quite specific about the practices that they will model and coach for their students. The Michigan Essential Goals and Objectives for Science Education are built around a detailed list of practices involved in scientific inquiry (constructing objectives), application (using objectives), and reflection (reflecting objectives). Thus standards based teaching built on learning cycles focusing on the Michigan objectives preserves some of the essential elements of scientific knowledge and practice while recognizing the importance of the Michigan Core Curriculum.

Appendix B: Introduction to Michigan Science Objectives

Introduction

Preparing students for the future is one of the principal aims of any well developed educational program. This is especially important in science education, a field that is constantly adapting to new advances in basic knowledge, including medicine, engineering, and technology. To prepare students for the twenty-first century, it is clear that an understanding of the principles and practice of science is an essential goal for all students.

To achieve scientific literacy for all students, it is more critical than ever that schools:

1. Provide quality instruction and promote integration in the three basic scientific fields of study, including life science, physical science, and earth and space science;
2. Present science in connection with its applications in technology and its implications for society;
3. Present science in connection with students' own experiences and interests, frequently using hands-on experiences that are integral to the instructional process;
4. Provide students with opportunities to construct the important ideas of science and reflect on historical and cultural perspectives that are then developed in depth, through inquiry and investigation; and
5. Provide students with fewer content topics in greater depth, as well as teach them to reason logically and evaluate critically the results and conclusions of scientific investigations.

The science curriculum program set forth in this document provides directions for an innovative approach to science education in Michigan. This document provides a philosophical foundation and curricular framework from which educators may construct comprehensive science education programs for elementary, middle, and high schools in Michigan.

Scientific Literacy for All Students

> "By all accounts, America has no more urgent priority than the reform of education in science, mathematics, and technology" (*Science For All Americans*, AAAS, 1990, p.3).

The scientific enterprise in our society is vast, complex, constantly developing, and powerful. Scientific knowledge enables us to describe and explain the natural world with a level of precision and insight that previous generations could hardly imagine. Science also contributes to our technological and economic development, giving us a capacity to change the world around us. Because science is so complex, no individual can hope to understand it all. Some knowledge of science is essential, however, for full participation in the economic, political, and cultural functions of our society. The primary purpose of K-12 science education, therefore, must be **scientific literacy**--an understanding of those aspects of science that are essential for full participation in a democratic society--for **all students**.

A commitment to the goal of scientific literacy for all students means that "covering content" is not the most important goal of science education. More important, Michigan students should come to understand science as a living, vibrant, important way of looking at the world and to use scientific knowledge successfully in their work, in their leisure time, and in fulfilling their duties as citizens. These objectives are designed to help teachers work toward this goal by describing a level of scientific literacy that should be attainable by Michigan students.

When children attempt to learn science with understanding, they are engaged in a profoundly challenging task. Scientific knowledge is often counterintuitive. Students must learn, for example, that plant food is not really food for plants, that objects set in motion do not naturally come to a stop, and that when we look out the window, we are actually detecting light coming into the window. Scientific language is often unfamiliar, precise and technical, and sometimes abstract and mathematical. Scientifically literate students have mastered complex, and sometimes difficult, problem-solving strategies.

Schools are entrusted with the task of helping students develop the complex interconnected knowledge that will enable them to participate in the community of scientifically literate people, to speak their language, and to engage in the activities that scientific knowledge makes possible. To fulfill this role, and to help their students master the objectives in this document, many Michigan schools will need a thorough reexamination of their science programs. Some of the key goals that they will need to consider are the following:

1. Emphasizing understanding over content coverage. Science teachers and curriculum developers have responded to the increasing size of the scientific knowledge base by trying to cover more and more science content in the same amount of class time. Recent research on science teaching and learning provides clear evidence that this strategy is failing; most students are memorizing facts rather than becoming scientifically literate.

The objectives have been written in a way that attempts to reduce content coverage and emphasize depth of understanding. This document contains 212 objectives, or less than one for every two weeks of teaching. Further, many facts and terms found in middle and high school science textbooks are left out. For example, terms such as *ribosome, villi, voltage, acceleration, bromine, basalt,* and *Coriolis force* are not in this document. At the same time, detail has been provided about what it means to understand the terms and ideas included in the objectives, as well as some of the qualities that make those ideas challenging for students to understand and use. As they reexamine their curricula, teachers and curriculum committees should consider whether they may be sacrificing depth of understanding for breadth of content coverage.

2. Emphasizing learning that is useful and relevant outside of school. Vocabulary-based approaches to science teaching are sometimes rationalized with the claim that "basic facts" must be learned before students can engage in the "higher order thinking" required by activities like those described above. There is now a large body of research-based knowledge that supports the experience-based beliefs of many good science teachers who believe that the "facts-first" approach to science teaching is practically and developmentally inappropriate. Even young students ask many questions about the world and have developed many strategies for finding answers to their questions. Thus, most students engage in activities requiring "higher order thinking" **before** they learn "basic scientific facts."

The objectives promote science learning that makes connections with the world outside of school by emphasizing **activities** learners engage in and **contexts** they will encounter outside of school. As they reexamine their science curricula, teachers and curriculum committees will need to consider how, and how well, they are connecting the knowledge and experience that students acquire outside of school with the classroom activities that occur in school.

3. Emphasizing scientific literacy for <u>all</u> students. The lives of all students are influenced by knowledge from the sciences and its application, and all students need to understand science if they are to fulfill their duties as citizens and their potential as individuals. The widespread evidence of scientific illiteracy among students and adults, as well as the alarming underrepresentation of minority and female students in science, indicate that many students are not well served by existing science programs.

The objectives support the development of programs that serve all students by emphasizing knowledge that is useful to all, and by providing information about how people of all races and cultures have contributed to science (see Appendix A). As they reexamine their science curricula, teachers and curriculum committees will need to actually promote strategies that serve all students.

4. Promoting interdisciplinary learning. Teaching that involves students in complex activities in real-world situations is necessarily interdisciplinary in nature. Scientifically literate people must also be literate in the traditonal sense. For instance, they must read expository text with comprehension and speak or write coherently. Some science objectives require the use of mathematical knowledge in measurement or problem solving. Others require understanding relationships among science, technology, and society. To achieve these objectives, students will have to use scientific knowledge in combination with other kinds of knowledge about the world; their success will depend on science teaching that emphasizes connections.

The objectives support interdisciplinary learning by emphasizing activities that connect science and technology with learning of other subjects, and by emphasizing conceptual and thematic connections among the objectives (see Appendix B). As they reexamine their science curricula, teachers and curriculum committees will need to consider how they will help their students see connections among the sciences and between science and other school subjects.

5. Support systems for teachers. Improving science education in Michigan transcends changing policies or developing new objectives. At a more fundamental level, teachers can become more effective only if they have access to a more extensive knowledge base about science teaching and learning, and to the tools, materials, and working conditions that will make it possible for them to use that knowledge. These objectives can play a role in giving teachers access to new knowledge, tools, and materials. In part, this has been done by incorporating research-based knowledge, including new conceptions of scientific literacy and research on the development of children's scientific ideas, into the objectives themselves.

A far more extensive and effective support system is needed, however. The objectives can contribute to improved science learning only if they stimulate teachers and administrators to think about the changes in teachers' knowledge, teaching tools and materials, and working conditions that will be necessary to support teaching for scientific understanding. Some examples include regularly scheduled inservice days, with possible support from business and industry, manageable class sizes, and resources for hands-on, minds-on learning.

Use of the Objectives to Promote Scientific Literacy

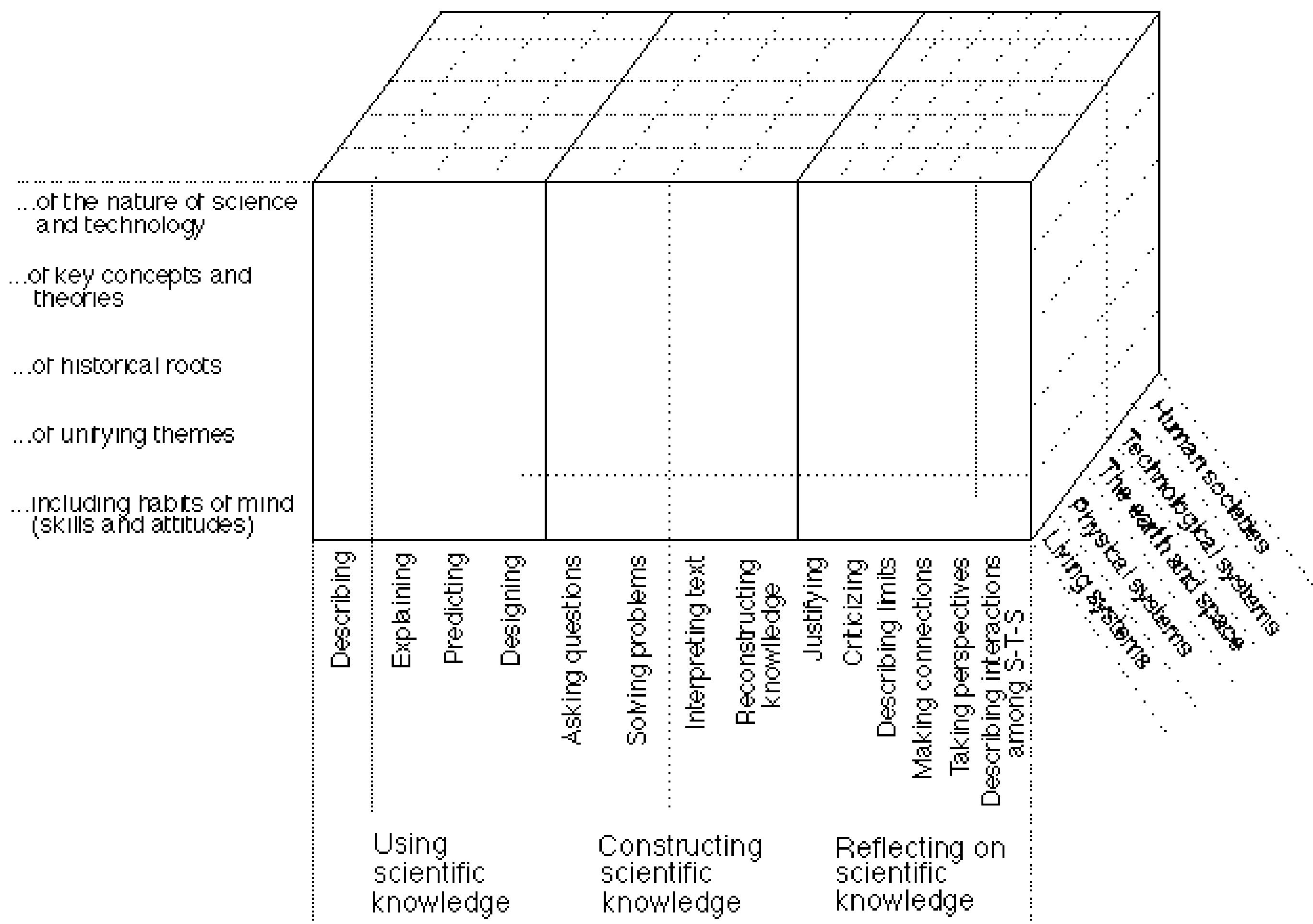
Scientifically literate students have knowledge that is **connected** and **useful**. They see connections among scientific ideas, as well as connections between what they study in science classes and their personal ideas about the world. Scientifically literate people can also use their knowledge to describe and explain the world with precision and insight, to make accurate predictions about the future, and to design strategies and systems that make our lives longer and more comfortable. The objectives describe a body of connected and useful scientific knowledge.

Dimensions of Scientific Literacy

The objectives are organized around three dimensions of scientific literacy: **knowledge, activities,** and **contexts**. All three dimensions--the activities people engage in, the knowledge they use, and the contexts in which they use their knowledge--are essential components of a description of scientific literacy.

Scientifically Literate People know how to:

Use knowledge... To engage in activities... in real-world contexts.



Knowledge: Describing Ideas, Strategies, and the Connections among them

Nothing is understood in isolation. To **understand** an idea (as opposed to, for example, memorizing a definition) is to see how it is related to and supported by many other ideas; its meaning is bound up in those relationships. The American Association for the Advancement of Science Project 2061--*Science for All Americans* report, specifies six basic characteristics of scientific literacy, each associated with a different type of knowledge:

- Being familiar with the natural world and recognizing both its diversity and its unity.
- Understanding key concepts and principles of science.
- Being aware of some of the important ways in which science, mathematics, and technology depend on one another.
- Knowing that science, mathematics, and technology are human enterprises and what that implies about their strengths and limitations.
- Having a capacity for scientific ways of thinking.
- Using scientific knowledge and ways of thinking for individual and social purposes.

Science for All Americans has been used to define the knowledge dimension of scientific literacy for the new Michigan science objectives. As a representation of the knowledge needed by scientifically literate high school graduates, *Science for All Americans* has many virtues. It was carefully constructed, with the participation of many scientists, engineers, and educators. The report emphasizes understanding rather than content coverage, consciously eliminating much of the vocabulary and specific facts

currently included in science courses. It also conveys through its language and organization, the dynamic, complex, interconnected nature of scientific literacy.

In developing these objectives, however, it was necessary to go beyond *Science for All Americans* in two critical respects. First, these objectives describe appropriate goals for younger students in elementary and middle schools as well as knowledge needed by scientifically literate high school graduates. Second, the objectives describe the activities and contexts in which Michigan students should be able to use their knowledge as well as the knowledge that they will need.

Activity: The Social Nature of Understanding

Scientifically literate people do not just **have** scientific knowledge; they **do** things with their knowledge. Usually, they do things in cooperation with other people. In spite of the popular image of "the scientist toiling alone in the laboratory," few of the ways that people use their scientific knowledge are truly individual in nature. Almost all involve communicating in speech or writing, or working collaboratively with others to solve problems. To become scientifically literate is to become a member of a **community** of scientifically literate people, and to share in the language and activities of that community.

The Michigan objectives describe three broad categories of activities that are common in scientifically literate communities: **using** scientific knowledge; **constructing** new scientific knowledge, and **reflecting** on scientific knowledge. The activities in each category are discussed below.

Using Scientific Knowledge. Scientifically literate students and adults can use their knowledge to understand the world around them and to guide their actions. Important types of activities that use scientific knowledge include **description** and **explanation** of real-world objects, systems, or events, **prediction** of future events or observations, and the **design** of systems or courses of action that enable people to adapt to and modify the world around them.

Constructing New Scientific Knowledge. Scientifically literate students are learners as well as users of knowledge. With scientific literacy comes the ability to **ask questions** about the world that can be answered by using scientific knowledge and techniques. Scientifically literate students can also **develop solutions** to problems that they encounter or questions they ask. In developing solutions, scientifically literate students may use their own knowledge and reasoning abilities, seek out additional knowledge from other sources, and engage in empirical investigations of the real world. They can learn by **interpreting** text, graphs, tables, pictures, or other representations of scientific knowledge. Finally, scientifically literate students can remember key points and use sources of information to **reconstruct** previously learned knowledge, rather than trying to remember every detail of what they study.

Reflecting on Scientific Knowledge. Scientifically literate students can also "step back" and analyze or reflect on their own knowledge. One important type of analysis is the **justification** of personal knowledge or beliefs using either theoretically or empirically based arguments. Scientifically literate students can also **show an appreciation** for scientific knowledge and the patterns that it reveals in the world; this often involves seeing **connections** among different areas of knowledge. They may be able to take a **historical and cultural perspective** on concepts and theories or to discuss institutional relationships among **science**, **technology**, and **society**. Finally, scientifically literate students can **describe the limitations** of their own knowledge and scientific knowledge in general.

Contexts: Knowing the Real World

Science is about the real world. Scientifically literate students can use their knowledge in many different real world **contexts**. In the physical sciences, the specification of contexts often focuses on **phenomena**, such as motion, electromagnetic interactions, or physical, chemical, and nuclear changes in matter. In the life sciences, earth sciences, and technology, contexts are often described in terms of **systems** and **subsystems**, such as cells, organisms, ecosystems, atmospheric systems, or technological devices. There are other contexts, such as those associated with art, history, or ethics, in which use of scientific knowledge is quite limited.

Scientific knowledge is used in both natural and human contexts. It is used to understand and influence the natural world and technological systems. Sometimes the contexts in which scientific knowledge is used are primarily social and symbolic, rather than physical. Most of us have never seen a quasar, an atom, or a volcano. Yet we know something about those systems through representations of them--descriptions, or diagrams, or pictures. Thus, the contexts in which we use scientific knowledge are symbolic, as well as natural and technological.

That someone can use a scientific idea, such as conservation of energy, appropriately in one context (e. g., a light bulb warming a room), does not necessarily mean that the concept will be used appropriately in another context (e. g., cells using food). Ideas that seem simple in one context may be more difficult to understand in another. Since understanding is often context specific, it is important to consider the contexts in which learners will be expected to use their knowledge.

Important Characteristics of the Objectives

The Michigan K-12 Science Objectives are designed to provide support for teachers and curriculum developers as they plan their science curricula. They provide suggestions about what to teach, but **not** how to teach or how to assess student learning. The Michigan Department of Education will seek to support school districts as they address these problems by other means, including professional development programs, the science component of the Michigan Educational Assessment Program, and the development of Instructional Support Materials that will provide models of teaching strategies that will help students achieve these objectives.

The knowledge, activities, and contexts described in these objectives are important for Michigan students to understand, but the lists below are **not** exhaustive. A great deal of important science content has been left out. The decision to leave out important content was deliberate, and necessary if science teaching is to emphasize science literacy for all. Nevertheless, teachers and school districts whose students are successfully mastering the objectives listed below are encouraged to extend the curriculum to include other objectives.

The three dimensions of scientific literacy--knowledge, activity, context--are described for three different grade levels: elementary (grades K-4), middle (grades 5-7) and high school (grades 8-12). At each level, descriptions are given of how students should be able to:

- use **knowledge** (simpler, prerequisite knowledge)
- engage in **activities** (constructing, reflecting on, or using scientific knowledge)
- apply concepts in real-world **contexts** (types of systems or events that one encounters in the world).

Rather than writing separate sections on topics such as "science processes," "scientific values and attitudes," "the nature of science," and "science, technology, and society," these have been integrated into the other sections. Every objective has both an **activity dimension** (process), and a **knowledge dimension** (content). Every section also includes technology-related objectives, as well as traditional scientific objectives. Scientific values, the nature of science, and science, technology, and society are discussed in the Reflecting on Scientific Knowledge section and, to a lesser extent, in other sections.

The Constructing and Reflecting on Scientific Knowledge sections are written generically (without reference to specific science content), while the Using Scientific Knowledge objectives are divided into topic-specific sections. This decision was made for editorial rather than conceptual reasons. All of the types of activities (constructing, reflecting on, and using scientific knowledge) require both general and topic-specific knowledge. For example, students can develop valuable general knowledge about the nature of scientific explanations that will help them whenever they are trying to explain something, even though objectives calling for explanation are listed separately in each topical section of the Using Scientific Knowledge objectives. Conversely, "interpreting scientific text" always requires topic-specific knowledge, even though it is listed only once as a general objective in the Constructing Scientific Knowledge section.

The organization of these objectives, including the traditional division into Life Science, Physical Science, and Earth Science, is intentionally conventional and designed for ease of access by readers. This organization is **not** a recommendation for the organization of a school curriculum. Schools are encouraged to experiment with courses that are organized in non-traditional ways, such as interdisciplinary courses or those organized around general themes or important problems. Experimenting with alternative ways of helping students to see connections between and within scientific disciplines is encouraged.

Appendix C: Example Lesson Plan on Heat Transfer

This is an introductory lesson to a learning cycle on heat transfer by conduction, convection, and radiation. It probably would not fit in a single period, but it's better to be safe by having too much planned.

Objectives

Objective	*Type*	*Stage in Learning Cycle*
1. Explain how heat is transferred through conduction, convection, and radiation.	Telling the story	Establishing the problem Modeling
2. Explain how substances change temperature through heat transfer processes..	Using	Establishing the problem Modeling
3. Qualitatively predict and compare rates of heat transfer and temperature change for substances in different environments.	Using	Establishing the problem

Materials

Presentation materials (Overhead transparencies):
- Ice melting predictions
- Reading summary table
- Criteria for a good explanation of heat transfer

Copied materials (Handouts, worksheets, tests, lab directions, etc.):
- Copies of reading summary table for each student
- Copies of Ice Melting Predictions overheads for each pair of students

Pages in textbook: Pages describing heat transfer by conduction, convection, radiation

Laboratory materials: For each laboratory station (3 students): Ice will melt in different situations:

--sitting in a cool glass beaker,
--sitting in a styrofoam cup,
--sitting inside a warm winter mitten,
--sitting in a glass beaker under a heat lamp,
--sitting in a glass beaker with a fan blowing on it.

Activities

Introduction	
5 minutes	• Journal question on board: *Think of an example of something getting hotter or colder. Describe your example and explain how it happens.* • Have some students tell about their examples and explanations • Teacher: Today we will start thinking about all sorts of situations where substances change temperature and how we can explain them.
Main Lesson Activities	
25 minutes	**Ice melting activity (establishing the problem for using objectives)** • OH, HANDOUT: ice melting predictions • Show ice cubes and different situations • Pass out copies of OH • Pairs of students discuss order of melting, write predictions and explanations • One student from each pair comes to front of room with beaker and prediction sheet. Shows prediction sheet to teacher and gets ice cubes. Teacher records predictions on board. • Students observe and record actual order of melting. Teacher records actual order of melting for each group on board. • When order is clear for most groups, compare predicted and actual orders. • Point out pattern of incorrect predictions, especially for mitten and fan. • Why were your predictions incorrect? How could we explain the actual order? • Let's read in text to figure this out. • Return lab stations to original form and get out texts.
15 minutes	**Reading from text about heat transfer (telling the story)** • OH, HANDOUT: Reading summary table. • Look at the headings in the chapter. What do you think the column headings will be? (Conduction, Convection, Radiation) • Look at the left hand column. What questions will we try to answer as we read each section? • Read text in segments. Teacher fills in columns on OH, students on their papers. • Keep these in your science folders. You will need them when you explain examples of heat transfer.
15 minutes	**Explaining an example of heat transfer by conduction (modeling for explanation using objective. May have to wait until next lesson)** • Choose example of conduction from examples suggested by students in journals (or choose ice cube in glass beaker from ice melting activity) • How can we use the ideas from the book to explain why the ice melts? • OH: A Good Explanation of Heat Transfer • Whenever we explain an example of temperature change through heat transfer, we need to include all these parts. • Teacher writes answer to question 1 on OH. Students write in journals. Heat is moving *from* table and glass *to* ice *through* glass. Make sure students have direction right. Note scientists don't talk about cold moving since it is not a form of energy. • Teacher and students write answers to question 2: Heat is being transferred through conduction. • Teacher and students write answers to question 3 based on model on OH: Faster-moving molecules in the ice and glass are colliding with slower-moving molecules and transferring energy to them.
Conclusion	
5 minutes	• What are the most important things that you have learned today? • Tomorrow we will work on explaining other examples of heat transfer and come back to why things melted in the order that you saw.

(OH) Ice Melting: Your Predictions and Explanations

Predict and explain how fast ice will melt in different situations:

--sitting in a cool glass beaker,
--sitting in a styrofoam cup,
--sitting inside a warm winter mitten,
--sitting in a glass beaker under a heat lamp,
--sitting in a glass beaker with a fan blowing on it.

Predictions: What order do you think the ice cubes will melt in?

Fastest: 1.
2.
3.
4.
Slowest: 5.

Explanations: Why do you think that they will melt in that order?

(OH) Summarizing What You Read

Summarize what you read about heat transfer by filling out the table below:

Mechanism			
Kind of substance that heat travels through			
How the heat travels (e.g., what happens to molecules)			
Examples			

(OH) A Good Explanation of Heat Transfer

In order to have a good, complete explanation, you need to draw or describe the situation, then write an explanation that includes three parts:

1. Describe *where* the heat is moving:

What substance(s) is the heat moving *from?*

What substance(s) is the heat moving *to?*

What substance(s) is the heat moving *through?*

2. Describe *how* the heat is moving: *Conduction, convection, or radiation?* (Sometimes the heat is moving more than one way.)

3. Explain what is happening to the substances as the heat moves:

Conduction: Faster-moving molecules of a solid (or sometimes liquid or gas) are colliding with slower-moving molecules and transferring kinetic energy to them.

Convection: Cooler parts of a fluid (a liquid or gas) are sinking and warmer parts are rising, creating currents that carry heat from one part of the fluid to another.

Radiation: Visible or infrared light (or other forms of radiation) is emitted by a warmer object and absorbed by a cooler object. The light can go through solids, liquids, gases, or empty space. The molecules of the warmer object slow down when they emit light; the molecules of the cooler object move faster when they absorb light.

Appendix D: Designing a Clinical Interview

Introduction

Understanding what sense students make of the content that they are taught is often a difficult problem. They can't just tell you what they know, and you often need more information than is available from your observations during classes. There are some techniques for learning about how students think about the topics that they study. One of these techniques is the *clinical interview*, in which an adult engages a student in a series of tasks, questions the student to gain a clearer understanding of his or her thinking, and probes deeply into the student's understanding. The purpose of this handout is to help you design and carry out clinical interviews.

Getting Started

Clinical interviews are more effective if they focus on a specific narrowly defined topic, rather than looking too broadly at many different topics. They can be used to help plan a unit, and/or be used after a unit to help you assess student understanding.

The process of developing a clinical interview begins with a decision about the limits of the topic that you want to investigate in terms of *organization* of academic knowledge (the terms, concepts, skills, and connections you are interested in investigating), the *uses* or activities that you expect to see students engage in when they use that knowledge, and the particular genres or schemata for *communication* that they will need to follow when they use their knowledge.

You will probably find it useful to make two lists:

- An **experiences-patterns-explanations** list: "pieces of the real world" to which the ideas on your knowledge list could be applied. These could be phenomena (such as a burning match), systems (such as a pond or a bean plant), or objects (such as a falling rock). The best "pieces of the real world" are ones that the students know well from their personal experiences. Relate these to patterns in experience that are important to scientists and to concepts, models, and theories that scientists use to explain those patterns.
- A **practices** or uses of knowledge list: meaningful activities that a child who understands the topic at his or her level should be able to engage in.

These lists can serve as the basis for the tasks that you develop for your test or clinical interview.

Developing Tasks

Interview tasks generally involve putting the student in a situation where he or she can perform some of the activities that you listed. Normally you will <u>not</u> mention the terms and concepts on your knowledge list until after the student has had a chance to bring them up on his or her own. After getting the student started on a task, your job as an interviewer is to follow where the student leads you, probing for the nature and depth of his or her understanding. Some specific ideas for tasks are listed below:

1. Free and stimulated recall. Ask the student to tell you what he or she remembers about the topic, including both main ideas and ways that they used them in class. Follow up your initial question with non-specific probes like, "Do you recall anything else?" It may help to refer to specific activities or to show pictures or assignments, asking the student to explain what he or she remembers and what he or she learned from them.
2. Tasks based on activities from your activities list. Ask the student to perform one or more of the activities on your list in a specific real-world context (e. g., ask about "this plant" or "this book," not just "plants" or "objects.". Some activities, such as those involving description or explanation, may be strictly verbal. Others may involve problem solving or the use of hands-on

materials. Encourage the student to explain how he or she is thinking about the problem, and use probing questions to clarify meaning or get more information about the student's thinking.

3. Interpreting information. Ask the student to interpret a text passage, graph, table, or picture associated with the topic. You might be interested in the student's ability to do the following:
   - summarize or state the main point
   - find unclear passages and ask for clarification
   - apply ideas discussed to other situations
   - interpret a key portion in detail
   - discuss connections with related topics
   - take a position, or discuss alternative arguments or interpretations.
4. Card sort (terms). Make up a set of index cards with key terms from your list (no more than 10 or 12 terms). Have some blank cards available so that you can add other terms mentioned by the student. Ask the student to set aside the cards with unfamiliar terms, then tell you what he or she knows about the ones that he or she recognizes. Probe for understanding of important relationships. (One way of checking for understanding of relationships is to pick out sets of two or three cards and ask the student to explain how those ideas are related.)
5. Sorting examples. The procedures here are similar to those for the card sort above, except that you use examples of things to be analyzed, such as:
   - plants and animals of different types (for an interview about classification or physiology)
   - samples of different substances (for an interview about properties of matter)
   - physics problems that differ both in appearance and in conceptual demands.

   As with the card sort of terms, the student's task is to arrange the examples and explain his or her rationale for the arrangement.
6. Critique of hypothetical responses. Ask the student to indicate which of a variety of sample responses to a task they like best and explain why. You can arrange to list of responses to assess students' sensitivity to particular issues (such as the nature of the evidence needed to support a conclusion or the existence of alternative methods for solving a chemistry problem).

How to Conduct Interviews

When doing these interviews, remember that the purpose of these interviews and tests is not to grade the students, but to find out how they think about the topic. This needs to be made clear in the introductions to any tests for understanding that you give, and it needs to be communicated in the way that you talk to students during interviews. Here are some suggestions.

Starting the Interview

1. Explain the purpose of the interview to the student. Emphasize that this is not a test, and that right or wrong answers are not what you are looking for. You might want to have them recall interviews they have seen on television, or other interviews they might have participated in to help set the context. You want to learn more about how s/he thinks about the topic.
2. If you have permission to use a tape recorder, show it to the student, explain its purpose, tell the students who might listen to the tape, and ask for permission to use it.
3. Allow time for the student to get accustomed to the setting (try to find a setting apart from the normal busy classroom) and converse a bit before beginning the actual interview.

Asking about Interests

1. Ask whether the student has ever been interested in the topic you are going to do the interview about. Ask the student to explain when and why s/he found the topic interesting.

Questioning

1. Start with general tasks or questions that would make sense to a student who has never studied the topic. You may have a list of specific ideas you are interested in, but you should start by

asking general questions, then probe about specific ideas that the student fails to mention on his or her own.

2. Give the student time to think about the task at hand; don't interrupt his or her train of thought, and minimize distractions. If you want him or her to "think aloud," make sure you indicate that in your initial directions, and try not to interrupt unless your question is crucial to clarification. It might be helpful to model the process for the student. You can raise questions later.
3. Try to get the student to talk about what he or she knows, not just about activities that took place in class, or about the task being done. Go beyond the task to explore the knowledge the student uses to complete the task.
4. Insert phrases like "do you think" or "can you remember" into questions to avoid a focus on right or wrong answers. Try to encourage detailed and thoughtful answers, but try to avoid indicating whether the answers are right or wrong. Let the student know you are interested in his or her ideas, not in their correctness.
5. Use familiar situations for application questions. The student will talk about these more freely and is much more likely to use personal knowledge as well as school knowledge.
6. Avoid vocabulary terms the student hasn't mentioned. Build on student answers and try to use student terms whenever possible. You may want to question their meaning of terms, to check that their definition of the term, matches yours. Don't assume because they use the term that they understand the term. You can ask about specific terms at the end (e.g., Have you ever heard of the word "energy"?) after you have found out more about how the student labels what he or she sees.
7. Avoid questions that can be answered with one or two words unless they precede a "why" question.

Ways of Probing for More Information

1. General non-specific probes: Do you remember anything else? Can you explain that to me? What else did you notice?
2. Direct specific probes (directed at getting information about specific phenomena): What does the battery have to do with the light bulb? What state did you say was west of Michigan? Why did you write a "3" at the top of that column?
3. Neutral probes (intended to encourage student to verbalize): I'm not sure I understand what you mean by... Can you explain that to me so I'll understand better? I'm confused about what you meant when you said...
4 . Rephrase the student's response to see if you really understand what was meant. Be careful with this approach, sometimes students view this as you giving them the "right" answer, and they will readily agree with this new answer. It may not be what they meant.
5. Follow up on wrong answers as well as right answers. You want to learn more about the student's perception of the content and its applications.

Documenting and Analyzing Your Results

If possible, you may want to tape record your interviews. In addition to tape recording, you may want to take notes about non-verbal behavior and the meaning of words like "this" or "that" whose meaning is not clear. Sometimes you can clarify a situation through the wording of your questions or comments:

"I see that you are using the meter stick now."

"Why did you put 'energy' next to 'food' when you arranged the cards?"

You will eventually need to transcribe or quote some student responses, but transcription is a lot of work, so you will want to be selective. In many cases, you will probably end up coding or categorizing student responses rather than quoting them verbatim. These responses can be useful for planning future lessons or getting a better picture of student understanding.

Questions about Students' Perceptions of the Class

If you would like to start exploring how your students think about their science class and their role in it, here are some questions that you might try.

- Of the things that you did while you were studying [name of topic], which did you like best? Why? Which did you like least? Why?
- When do you feel good about your work in this class? When do you not feel good about it?
- Tell me about a "good day" in this class. What happens? What makes it a good day?
- How has science been for you in the past?

  How did they help you learn?

  How was science easy ?

  How was science hard?
- Has this science class been like other science classes you have had in the past?

  How is it similar?

  How is it different?

Appendix E: Interviews about Plants with Joy, Jeremiah, and Ed

Contents of interviews

1. Introduction and explanation of purposes of interview. We are interested in your ideas, not just "right answers."
2. Name the parts of the plant on the table and talk about what they do (structure and function).
   --planned probe: How does this plant get its food?
3. Comparing plants and human beings.
4. Recalling what they learned from unit on plants (and ecology).
   --planned probe: What do you remember about photosynthesis?
5. Additional questions that you would like to ask about plants.

Notes on Interview with Joy (Sixth Grade)

Introduction and explanation

00:01:12

A OK You came in today so we could talk a little about plants. I want to start out with a real easy question. That I know you know the answer to and remember as we go along what ever I ask some of these will be questions you can answer on the basis of stuff you studied in school, others will be questions that you will have to think about what your own answer might be and just go ahead and tell me what it is.

Name the parts of the plant and their functions

A OK starting off with our easy question. I've got a plant right here. Tell me something about....What are some of the parts this plant has and what to they do for the plant?

J Well it's got leaves and long stems, that stores it food that it gets from the soil, the minerals. And then, leaves kind of also store the food. The stems come up to the leaves. And then, the soil helps it, it gets its minerals which it needs to make its own food -- photosynthesis. And then, the sun which it has. It needs sunlight and it needs the water and it needs air and all that makes it make its own food -- which is photosynthesis.

How do plants get their food?

00:02:38 to 00:04:33

A OK so tell me a little more about this process of photosynthesis.

J Its what we call a producer. Photosynthesis is where it gets minerals. There are four things it needs to make its own food: minerals, air, light and water. Doing this it can make its own food because it can't eat anything. So that's how it kind of stores it in it's leaves and it's stem.

A I see...So what is the food for the plant? Do you have any idea what it is?

J .... You mean what it does?

A I mean "What is food?" Like for me, if you said, What is food for people? You'd say things like: Well... it's things like steak and hamburgers. So what is food for plants? If I gave you a much of stuff...

J ...Energy ... It is just like...I don't know what you what call it...it is stuff it needs to live....if it doesn't ..then it dies. Then in order for a plant to live it has to have those four things. It is cut off from those four things....

A So what are those 4 things again?

J Air, water, light or sun, and the minerals from the soil.

A Do you think any of those are food for the plant?

J I don't know if they are food. I think they have to have all four to make it food for it. If they don't have all four then it is not food.

A OK So you think the 4? When you say "make food" I'm still not real clear what it is the plant is making...if it is food or...is it those four things in combination or is it something else.

J In combination. That gives it energy to stay alive. Then other animals can eat and they are consumers.

Remembering class unit on plants

00:04:33

A I see...OK You said you studied plants earlier in the year. What are some of the things you learned about plants, when you were studying them that you didn't know before?

J I learned photosynthesis...I didn't know how it made it's food.

We learned it was a producer and that other animals eat it and they become consumers...first order, second order, third order consumers. ... That is pretty much what we learned...We studied mostly about photosynthesis.

Comparing plants and human beings

A OK Let me ask you a question. Suppose you were going to compare us. Compare yourself and this plant. You both need food to live right? So what is the difference between the way you get food and you use food and the way the plant gets food and uses food?

J The plant pretty much -- if it is in it's environment it get exactly what it needs. It doesn't need to move or anything. We have to go to the store and buy it. The plant has it much easier. We are either... we are not a producer..so we don't make our food...it takes more to make food. How we are alike -- we both need food to live. It gives us energy and that's what helps us live.

Additional questions from Joy (does food go up or down the stem?)

00:06:13 to 00:08:01

A Do you have any questions about plants? I know you studied them but now..but you don't know everything about plants. Do you have other questions about plants that you would like to answer?

J I'm still wondering exactly how it combines the four things. I don't know how...in it's roots ...I guess it collects all the stuff and some how combines it. ...I guess it travels up the stem to the leaves where it stores the food.

A OK So if you could look inside a stem and you could see the food moving -- do you think you would see the food moving up the stem or down the stem or would you see food moving in the stem at all.

J I don't know if you could see it. Because you can't really see air. You can't see air, and sunlight you wouldn't be able to see.

A I know that but...

J But if you could see it ... it would probably be moving up the stem because leaves are what need the food.

A Where is it you said the food was made?

J ..It could be made in the leaves and travel down to the roots, or it could be made in the roots and travel up to the leaves. I think probably what it does is come from leaves.. because it can't really reach the roots and then travel down to the roots and then the roots can grow off of that and help protect the plant.

A Is that different from what you said a minute before?

J I think it was....

00:08:01 to 00:09:39

A ... I think in a way you just answered your own question. That's good. Are there other questions that you have about plants that you would be interested in knowing the answers to?

J I don't see how it can really absorb the air and the light. The water, I suppose the water goes to the roots, probably... cause it can go right to it. The sun and air.. the sun probably can't get down to the roots except through the leaves.

A ...You are right the sun can't get to the roots..that's why the plant has leaves so it can absorb the sunlight. They also have little holes in the bottom of each leaf, they are called stomata, but they are little holes that the air can get into in each leave.

J The minerals are in the soil, so they can get from the roots. All plants.. they don't have soil..they just need the minerals. So we also learned...a lot of kids thought they needed soil to live but they don't they just need the minerals.

A That right..that's interesting.

J That was interesting...I learned that.

A Any other questions that you have?

J ugh..ugh...

A OK I think we can stop then -- Thanks Joy.

Notes on Interview with Jeremiah (Sixth Grade)

Name the parts of the plant and their functions

00.31

I - OK, so I've got a plant here and here's my simple question about plants. In this plant here, it's got obviously different parts, and so what are some of the parts this plant has?

J - Roots, leaves, stem. Things like that.

I - Yeah, things like that. OK, so you mentioned three parts, you said, roots, leaves and stems. Could you tell me what those parts does for the plant?

J - The roots get the water and the minerals from the soil. The stem is like a vein in your body, it delivers it to the leaves. And the leaves keep it cool I guess.

1:24

I - OK, uh lets see.., what..., can you talk to me some about what are some of the things this plant would need to stay alive?

J - Air, water, light and minerals from the soil.

I - OK, what does each one of those things do for the plant?

J - Keeps it alive without one or the other the plant would not exist.

1:52

I - I gotcha. Do they all do the same thing, or do different things have different purposes?

J - They each have different purposes. Like the sunlight... like with a tree the sunlight shines from the east or the west it points which ever way it shines, it grows in that way.

I - Do you have any idea about why the tree would do that?

J - eh.. I don't know.

How do plants get their food?

2:26

I - That's a good question isn't it?

Let me see, another question that I had then is ... Could you explain to me how a plant survives? What kinds of things it does? Like how does it get its food?

J - It gets its food from the soil, but it doesn't necessarily need the soil because it can get the minerals it needs from the water. It doesn't need the soil. But if you have it out in open lands, and you have a flood, the soil will help it stay down in the.. stay planted there.

I - Yeah, I gotcha. You mean like the soil helps hold it in place? (yeah)

J - Yeah, sort like the roots dig in looking for a places to hold onto sort.

3:16

I - Uhm, What happens to the food when the plant gets it?

J - It, I guess just sends it to the thing. It sends it to each of these stems. Helps keep it going.

I - Do you have any idea what the leaves will do with it?

J - Use it, to stay alive.

I - Yeah that makes sense. ...

Comparing plants and human beings

3:46

I - Suppose we thought about making a comparison here. There's you and me, we're human beings, and we need food to stay alive, and we have our ways of getting food and using food and so forth, and there's the plant here which also needs food to stay alive, so it has it's way of getting food and using food. Compare the two - How would you compare with the plant in the way you get and use food?

J - We use food for.. we're like a second and third order consumer, we eat.., we either eat.. sometimes we can be a first wen we eat the plants and stuff. When we eat an animal that eats a plant we're a second order consumer, when we eat and animal that eats an animal that eats a plant than were a third order consumer. And the plants and stuff they just get their minerals from the soil. (OK) So they are really more advanced than we are.

I - They are really more what than we are?

J - Advanced

4:56

I - That's an interesting thought. They are certainly less dependent on other things. ....

Remembering class unit on plants

I - You said you studied plants earlier in the year.

J - a little bit

I - What are some of the things you learned about plants, that you didn't know before?

J - They don't really need the soil, they get the minerals they need from the water. They don't need the soil, it's just there as something to hold them in place. (yeah) Like with crab grass that we were talking about too. It has stiff leaves, like if you pull it out and leave some of the roots there it will reproduce, and it flies out everywhere it will make new plants.

Additional questions (Jeremiah’s garden)

5:58

I - Yeah, let's see. Do you have some questions about plants, even though you studied them, and I know you don't know everything. Do you have some questions about plants that you would like to ask or still have answered? Like if you had another chance to study plants or a chance to do some experiments?

J - Not really. (OK) Me and my brother, we know enough about plants. We keep our own garden and everything.

I - Can you tell me about some of the things that you learned about plants by keeping your garden?

J - You have to water it a lot. And when the harvest moon comes up that's when you pick them up and everything. Carrots and pumpkins you don't have to wait until then, and water melons and something like that. Cause Carrots, Tomatoes and Potatoes and things like that they just grow.

In California we had this little bug it was called a tomato plant, tomato bug. It had like a little horn on the top of it's head. It was an ugly thing, sort of like a caterpillar.

Planned probe about photosynthesis

I - When we were in the car one of the things we were talking about is photosynthesis.

J - I don't know a lot about photosynthesis. I don't pay attention to that part.

I - I guess that answers my question about photosynthesis. That's all the questions I got then. Thank you that was really helpful.

7:54

Notes on Excerpts from Interview with Ed (Fifth Grade)

Name the parts of the plant and their functions (leaves)

9:20

I - What about, you mentioned another part of the plant was the leaves. What is the function of the leaves?

E - Well that's what in takes in the air and sunlight and it don't mostly take in the water, but the water goes in all the stems, leaves and stuff.

I - OK so the function or job of the leave is to take in the sun, the air, and some water?

E - uh huh...to make the food.

I - To do what?

E - Make the food.

9:50

I - OK, tell me about that.

E - They need the food to stay alive, and make the cells stay alive, so they need water, air and sun to make their food.

I - OK, what are some of the things plants need, you said some of this already, but what are some of things the plant needs to stay alive?

E - Water, air, and sunlight

I - OK, and why does it need the water?

E - It helps makes the food and got parts in it and jobs it has to do.

10:32

I - OK, and why does it need the light, sunlight?

E - Helps it make the food.

I - Help it make the food, same things as the water? (uh huh) What about the air?

E - Helps make the food too.

I - What is the food for the plant?

E - Sugar

10:49

I - Sugar? And where does the sugar come from?

E - Well... they all combine together.

I - When you say they all, what do you mean?

E - The air, sun and water.

Additional questions (after Ed says that roots can't make food because they're in the dirt)

13:00

I - Could the roots do what the leaves can do?.... Make the food?

E - I .. um.. I guess, if it's not... if it's not sitting in dirt I guess.

I - If it's not sitting in dirt, OK. Explain what you're thinking.

E - Like you said, could the roots do the same things as the leaves. Well if it wasn't in dirt. The sun could not get to the roots because the roots are all piled up in the dirt, and under the dirt and can't get through the pot and stuff.

13:33

I - So you're thinking if you took the dirt away.

E - Right, and then like put it up like on top of the dirt, probably it could.

I - Probably it could make food then because it be ..

E - Getting air, sunlight.

Planned probe: Definition of photosynthesis

15:10

I - Have you ever heard of the word photosynthesis before? What's photosynthesis?

E - um.. I forgot, but I've heard of it.

Analysis: Representing students' knowledge and comparing it with your understanding

1. Make a concept map for each student and compare it with your concept map. What relationships does each student see among ideas such as *plants, leaves, roots, stem, food, sunlight, water, air, sugar,* and *photosynthesis?*
2. Make a diagram representing how each student understands the structure and function of the different parts of a plant and the movement of different substances and energy in the plant and its environment. Compare it with your flow diagram.
3. Focus on language and activities. How does each student use personal language and scientific language in doing the activities of the interview? How does each student reason about new problems (e. g., Joy and food moving up or down the stem, Jeremiah and his garden, Ed and roots making food)?

Analysis: Comparing experiences, patterns, and explanations

Make a compare and contrast table comparing the students' experiences, patterns, and explanations with your own. The table might look something like this:

Issue	*Joy*	*Jeremiah*	*Ed*	*You*
Experience: Observations of particular plants or animals				
Patterns: Parts of plant				
Patterns in plant growth or behavior				
Explanations: Functions of leaves				
Explanations: How plant gets food				
Explanations: What is food for plants?				
Explanations: Differences between plants and animals				
Explanations: Definition of photosyn-thesis				

Alternative Summaries of Jeremiah's Thinking about Plants and Photosynthesis

Summary 1

Jeremiah is a mediocre student who is not very motivated to learn science and does not always pay attention in science class. He understood about 65% of the concepts covered in the plant unit. He made a C on the unit test.

Summary 2

Jeremiah is not strongly motivated to learn science and often does not pay attention in class. He did not pay attention to the definition of photosynthesis, even though that was one of the most important points in the unit. As a result, there are many important things that he does not know about plants. He does not know that plants make their own food. He does not know the functions of plants' leaves or how plants use sunlight. He does not know how food travels inside a plant. He knows that plants are producers, but not what they produce. He does not know that sugar produced by photosynthesis is food for the plant.

There are a few things that Jeremiah knows about plants. He knows that plants need water, air, sunlight, and minerals to grow. He knows that plants get their minerals dissolved in water, so that under the proper circumstances plants can grow without soil. He knows that plants can survive with just these inputs, while animals have to eat food produced by plants. He can distinguish accurately between producers, first-order consumers, and second-order consumers.

Summary 3

Jeremiah has extensive personal experience with plants as a result of his work in his father's garden. On the basis of this experience and school science, he sees a number of important patterns in plants' needs and growth. He understands that plants need water, minerals, air, and sunlight, and that plants grow and turn their leaves toward the light. He has observed fruits and vegetables ripen and knows when they are ready to be harvested. He has observed weeds and insect pests such as the tobacco hornworm and what they can do to food plants.

Jeremiah has developed some non-scientific theories about plants that are consistent with his experience and useful for his purposes. He believes that water and minerals are food for plants, and that they get it from the soil. It travels up the stem to the leaves. He guesses that the leaves help plants to "stay cool." His theories about how plants function have no place for photosynthesis or food produced in the leaves.

Jeremiah seems to have paid selective attention to the scientific content of the plant unit. He was very interested in topics directly related to gardening such as hydroponic gardening and the propagation of crabgrass, which he described in detail. He was also interested in and understood ideas about food chains and trophic levels. He sees plants as "more advanced than we are" since they can live on air, sunlight, water, and minerals, while we need food produced by plants or lower-order consumers. He admits, though, that he didn't pay attention to the part of the unit on photosynthesis.