Remodelling Science Lessons

Introduction

The scientific approach is a very powerful way to know the world. Science provides us with two particular areas of knowledge: one is the kinds of thinking which scientists use to find answers to questions — science process; and the other is the answers themselves — science content. As science teachers, we would like to help our students develop a deep and critical understanding of both of these areas of knowledge. But what is a critical understanding of science process and content?

Rather than tackle the critical approach to science education headlong, let us begin by understanding what a critical approach is not. Too often science teaching over-emphasizes narrow mastery of the conventional explanations and techniques of established science. Sometimes this means asking students literally to memorize facts, definitions, diagrams, and so forth. At other times, students are asked to paraphrase a wide array of standard information and explanations and answer standard questions in the physical sciences, life science, or earth science. Many textbooks emphasize preparing students to answer questions like the following, all of which are paraphrased from high school science texts.

- What are the three kinds of volcanoes and how are they formed?
- What are the details of the Kreb’s Cycle?
- What are the three parts of a transformer? What kind of electricity does a transformer use?
- How are antibiotics produced? Do antibiotics cure all diseases?
- What are the bonding orbitals on the carbon atom in the methane molecule?

In addition to this kind of content knowledge, high school science teaching often stresses a certain kind of problem solving. We could call the problems to be solved “textbook problems.” Most science teachers will quickly recognize textbook problems: problems about balancing equations, calculating an equivalent resistance, figuring out the proportion of second-generation roses which will be pink. The necessary data, and no more, is given in the problem. The method for
solving the problem is given in the chapter in the textbook. Whether these problems are easy or hard for students, they represent an approach which asks students to master a standard technique by practicing on several similar problems.

There are good reasons for teaching this kind of content and textbook problem solving in high school science classes. Some of this information is interesting and helpful to students. Some textbook problems help students understand aspects of science. However, mastery of this kind of information alone does not constitute the most powerful approach to science education. Teaching for a critical understanding of science involves additional elements. Let us go on and see what these elements are.

Science education should help students understand how scientists establish their scientific beliefs. In other words, how have scientists learned the knowledge of the world which we want students to learn? Through exploration of this question, students come to a more fully informed understanding of how the very involved and beautiful explanations of professional science have developed. They begin to see that science does not arise in some impersonal way from experiments, but that human thought, in both logical and intuitive forms, plays as important a role as experimental data. In this way, they see that scientific understanding is often powerful, but also fallible. Thus, they become more critically aware “consumers” of the claims made in the name of science which we can read about in the newspapers every day. Understanding scientific thought deeply rather than superficially, they will be less inclined to take pseudo science as real science. But perhaps even more importantly, students develop an attitude of intellectual autonomy, the sense that they too can interpret their world through their own clear observation and critical thought. One attribute of critical thinkers is that they exercise independent thought and recognize that at times it is possible to come to an understanding of the world independent of authorities. Science education should combat the widespread belief that “It’s someone else who does and understands science.”

One important way to teach students how scientists establish their knowledge is to allow students to investigate actual questions in the laboratory. Many typical laboratory manuals, however, take all the initiative out of the “investigation” by presenting a detailed list of procedures to be followed, the steps to take in thinking about observations, even what the student should observe and conclude. Thus, the lab work is not true investigation, and the steps taken and results found mean little to students. To learn from a laboratory investigation, the students should understand its purpose, have some opportunity to plan the approach, and interpret data or observations. Of course, teachers play an important role in student inquiry through their guidance and structuring, but students can be given the responsibility for designing parts of investigations and interpreting their own data. Some of the remodelled lessons which follow point out ways to do this. In general, students can determine what data they need; design their own data tables; conduct experiments; think about their own interpretation of their data; and discuss their interpretations with classmates who might agree or disagree.

This is a key point in a critical approach to student inquiry: scientific thinking is not a matter of running through a set of steps called “the scientific method.” Rather, it is a kind of thinking in which we move back and forth between questions, answers to those questions, and experiments which test those answers. “What do I think about this? If that’s so, what will happen when I try ...? Why didn’t this come out the way I expected?” In this process, we engage many of the attributes and skills of critical thinking. We must not make snap judgements, we must pose questions clearly, we must see the implications of ideas clearly, we must listen as someone comes to a different interpretation from ours.
Science textbooks usually devote a few pages to a general discussion of "the scientific method." One of the problems with this approach is that there is no one method which all scientists follow. For instance, the work of a theoretical physicist who speculates about the fundamental nature of matter is different than that of the ornithologist trying to understand the behavior of birds. The physicist relies heavily on abstract mathematics, logical considerations, and even a sense of aesthetics, while ornithologists observe the natural environment very carefully and try to find a pattern in their observations. So these two scientists use a very different set of "tools" in their work. As another example, some scientists do experiments, but not all do. Chemists can go into the lab and try a reaction in a variety of conditions; in this way they can test a theory about reactions. But evolutionary biologists can not see what would have evolved if the situation had been different; they can only look at various kinds of evidence left behind by what has already happened. So these two scientists must work in different ways, with one able to perform experiments in the laboratory and the other unable to experiment but forced to rely on historical data.

Science is more than ways of thinking, however. Science includes a vast array of interlocking factual information, concepts, and theories which provide us with one particular way of understanding ourselves and the world. In this introduction, we will discuss two key features of a critical approach to teaching science content. First, that a critical understanding of science content emphasizes understanding of the fundamental ideas of science and their relationships, rather than shallow understanding of lots of material. Second, that teaching for a deep understanding must include the recognition that students come to our classes with already well-established intuitive ideas about many areas of science.

The debate about coverage versus depth is old. While there may be reasons to emphasize a brief treatment of many science subjects, advocates of the critical approach to science teaching argue that students will understand science better and become better thinkers generally, if they come to a deeper understanding of the central ideas of science. Since it takes time for students to grasp the implications of ideas and to see the connections between various scientific concepts and explanations, we must spend more time on selected material.

It is beyond the scope of this introduction to outline the most important ideas in high school science. We encourage you to review your own teaching to assure yourself that you are providing students the time and experience they need to reach a deep understanding of the ideas central to the science you teach. If we discuss one particular example, though, it will help us understand the point. In high school biology, students are introduced to the basic principles of plant growth. They are introduced to a long list of ideas like chloroplasts, photosynthesis, light reaction, dark reactions, and so forth. They learn about stomata, roots, the cambium. After all this, try asking them the following simple question. "There is a one-thousand pound oak tree outside the window. Where did that thousand pounds of stuff come from?" I have tried this question on many of my students. Several other teachers I know have also, and we all find the same thing: many students don't know that the raw materials to make a tree are basically water from the ground and carbon dioxide from the air. Though we have taught the details of photosynthesis to some degree, we have failed to help many students understand one of the most basic concepts about plants. When we try to teach for a critical understanding, we should pay more attention to the deep ideas and try not to lose the forest for the trees.

Our second point involves the preconceptions that students have concerning the science topics we teach. Science educators must recognize that students of all ages have their own ideas about the world around us. From our earliest years on, we develop ideas about the growth of plants,
the motions of pendulums, how birds can fly, and many other everyday experiences. These preconceptions play a very strong role when we teach for the deep understanding implied by a critical approach to science education. It is not enough to present the established knowledge of science. Every science teacher has experienced giving a clear and articulate explanation only to find, with a sinking feeling, that her or his students did not "get it." Reading or listening to an explanation is not enough to replace the students' original beliefs. The Proceedings of the International Seminar on Misconceptions in Science and Mathematics gives an example of a child who was presented with evidence about electrical current flow which was incompatible with the child's preconceptions. In response to a demonstration, the child replied, "Maybe that's the case here, but if you come home with me you'll see it's different there."* A critical approach to teaching science content recognizes that students must first articulate their own beliefs if they are to modify them in the light of their school experiences. Science teaching must begin by helping students to clarify and state their preconceptions so that students can go on to develop the deeper, more accurate understanding which is the goal of the critical approach to science education. Some of the remodelled lessons which follow suggest ways in which this might be accomplished.

As you think about the critical approach to science teaching, keep these things in mind. We must try to emphasize the fundamental ideas rather than a myriad of factual detail. We must try to emphasize a flexible understanding of science concepts and problem solving rather than just drill and practice to master some standard explanations and problems. And finally, we must help students understand how scientists answer questions through both experiment and thought.

Titration

Objectives of the remodelled plan
The students will:
- learn the technique of titration and some of its applications
- think independently by clarifying their results
- transfer insights and make interdisciplinary connections by discussing applications of key concepts

Standard Approach

Students will obtain samples of standard acid and base solutions of unknown concentration from the teacher and follow the procedure outlined in the laboratory manual, to determine the concentration of the base. At least three trials should be done, and reasons stated in the discussion section of the laboratory report, for variations in results among the three trials.

Critique

This lesson fails to take advantage of the information and mis-information which students already possess regarding the roles of acids and bases in the world around them and in their own bodies. The process of titration has numerous applications in pure science and industry. These applications and their importance should be brought out.

Strategies used to remodel
S-1 thinking independently
S-11 comparing analogous situations: transferring insights to new contexts
S-23 making interdisciplinary connections
S-9 developing confidence in reason

Remodelled Lesson Plan

Students will be encouraged to tell what they think the word "neutralization" means and will, after discussion of the various interpretations of this term, be presented with the process from the point of view of the chemist. Relationships between volume and molarity of acids and bases and the titration process will be explained. Students will proceed to the laboratory where the process of titrating a sample of a solution of sodium hydroxide of unknown concentration
will be demonstrated. Students will carry out the appropriate calculations to determine the concentration of the unknown solution. Class results will be presented, in the form of a table, on the chalkboard, and reasons for variations will be discussed so that the method may be clarified. S-1

Students will be asked to name substances which they are likely to encounter on a day-to-day basis which would lend themselves to the titration process. S-11 Possibilities would include household ammonia, vinegar, lemon and lime juices, etc. A discussion of a variety of indicators which might be used with these substances should be postponed, as it would only complicate matters.

Students will be asked to bring substances from home which might be titrated to determine their acid or base concentration. Care must be taken that, when these substances are titrated, they are properly diluted.

A discussion of the application of the titration process to medicine and industry will serve to relate this laboratory exercise to other branches of science. S-23

editor's note: Have students describe what happens when they are conducting their tests, explain why the procedure is as it is, and explain how they make their calculations and why. “What, exactly are you doing? Why? What effect will that have? What are these liquids doing in there during this process? Why use this? Why have that control? What would happen if we ...? How might that affect our results? Why? What does this information tell you? What do you need to know? What numbers do you need? Why? What equation are you using? Why? Which numbers go where? Why?” Etc. S-9

Teachers who can formulate and articulate what attitudes and behaviors they are trying to foster, why they are important, and how they foster them in their classrooms, are more likely to be able to create an appropriate atmosphere and to structure classroom activities that lead to good student thinking.
The Nervous System

Objectives of the remodelled plan
The students will:
- learn the parts of the nervous system and their functions
- think independently and share what they know about the parts of the nervous system
- relate this knowledge to diseases of the nervous system
- predict results of breakdown of parts of the nervous system

Standard Approach

Students will locate the terms describing the parts of the human nervous system in their text and record the terms in the proper spaces on the worksheets distributed at the beginning of class. In addition, students will be asked to write, in their own words, a description of the function of each of the parts of the nervous system which they have located.

Critique

This lesson does not attempt to relate the names and functions of the parts of the human nervous system to the health of the students. No attempt is made to incorporate information which is vital to the students regarding acute and chronic diseases of the nervous system or the effects of substances, both controlled and uncontrolled, on the nervous system.

Strategies used to remodel
S-1 thinking independently
S-23 making interdisciplinary connections
S-32 making plausible inferences, predictions, or interpretations

Remodelled Lesson Plan

Students will be asked to label as many of the parts of the nervous system as they can without making use of their textbooks. Discussion will then be carried out, with sharing of information until all of the key parts of the nervous system are labeled on the drawings with which they have been supplied. Using their texts only as much as necessary, students will, working in small groups, prepare a list of functions of each of the parts of the nervous system which they have labeled. S-1
Information will then be gathered from the group regarding diseases of the nervous system with which the students might be familiar through contact with patients. Information will be presented regarding the similarities and differences among these diseases. There will also be a brief discussion of diseases such as polio with which the students have had little or no contact.

Students will be encouraged to bring to school clippings and articles from magazines regarding diseases and injuries to the nervous system. These will be shared orally for discussion and comment. In addition, a film will be shown, at a later date, describing the effects of drugs and alcohol on the nervous system. At all times, an attempt will be made to be consistent in the use of the proper terminology for the parts of the nervous system, in order to reinforce the learning which took place on the first day. **S-23**

**Editor's note:** To allow further opportunity for independent reasoning, students could predict what would happen to someone who suffered a breakdown of each of the parts of the nervous system which they have named and labeled, before being informed of such diseases. "If this has this function, what would happen if it no longer functioned fully or at all? Why do you say so? What would that be like for the victim?" Students' predictions could then be compared with the diseases discussed. **S-32**
Scientific Reasoning: Do Snails See?

Objectives of the remodelled plan

The students will:
- develop confidence in their ability to reason scientifically
- propose experiments to provide evidence on the key question
- clarify, through discussion, that the interpretation of experiments are based on assumptions
- develop intellectual humility by examining their preconceptions

Standard Approach

Many standard biology texts devote a very large proportion of their effort to descriptive information. They tell the student how an organism is classified, how it's put together, how it all works. The standard approach to discussing the mollusks, for instance, is to talk about "mollusks with one shell" and to use the snail as a particular example. Generally, a text devotes about one page to the snail. In that page, students read about the evolution of the snail, they see a diagram of its structure and a brief description of "how the snail works." Among many other statements, there is always a statement to the effect that land snails have eyes on the tips of two tentacles.

Critique

Instruction in the life sciences emphasizes information on the processes and physiology of cells and organisms. Too often, however, we forget that science education should also include experience with the ways in which scientists establish this information. An understanding of the ways of science is important for two reasons. First, as students grow in their ability to understand how scientific ideas are established, they become more critically informed "consumers" of scientific knowledge. They learn that scientific knowledge is established by people more-or-less like themselves. They also learn that scientific knowledge does not come with an ironclad guarantee that it is "correct." Second, by learning the ways of science, students will begin to be able to transfer those same skills to experiences they encounter in their own everyday lives. They begin to develop the attitudes and skills needed to become intellectually more autonomous and to come to their own understanding of the world based on their own experience and critical thought.
Another problem with the discussions of “scientific method” found in texts is that they are often rather abstract. Students usually cannot make much sense of these kinds of discussions. They can memorize a list of steps, but they often cannot apply these steps in particular actual situations. As with all of our teaching, we must give students practice applying general, abstract ideas to particular situations. For that reason, this remodelled discussion focuses on helping students understand how scientists go about answering questions like “Can snails see?”

Strategies used to remodel
- S-9 developing confidence in reason
- S-5 developing intellectual humility and suspending judgment
- S-30 examining or evaluating assumptions
- S-33 evaluating evidence and alleged facts
- S-13 clarifying issues, conclusions, or beliefs
- S-3 exercising fairness

Remodelled Lesson Plan S-9

We could start this lesson with a discussion of snails and their behavior in order to bring out students’ preconceptions. S-5 “Do you believe snails can see? What makes you believe this? Are you certain? Why or why not?” Often, students express a range of opinions of the “sightedness” of snails. Some of the reasons for their beliefs could be called “theoretical.” For example, some students say that all animals have eyes, therefore snails must have eyes. Others say that those stalks on snails heads look like eyes so they must be eyes. Other students have reasons for their beliefs which could be called “experimental” in the sense that they are based on observational evidence. Examples of this might be the fact that snails are active at night, when it is dark, so they must be able to tell light from dark. All these reasons provide a context for students to practice many of the critical thinking skills like examining assumptions and evidence. We can help our students practice these skills by asking questions like the following? “Can you be sure they are eyes just because they look like eyes? Are you sure that all animals have eyes? S-30 Snails do come out at night, but that might be because it is cooler out. If that were so, could you still be sure that they were telling light from dark?” S-33

After questioning students about their present beliefs and reasons we turn to “experimental” ways to explore these ideas. It would be ideal if students could actually observe snails in the classroom as they test their ideas, but discussion may be the only possibility. To have students clarify this scientific conclusion, we could start by asking, “What would be the difference in the snails’ behavior if they could see or if they couldn’t see?” Perhaps a student would respond that snails would back away from a bright light. We could ask “Would shining a flashlight at a snail and observing its behavior prove that the Snail either could, or couldn’t see? Could other explanations be consistent with that evidence?” S-13 Depending on the particular responses which students made, you might suggest 1) that the light bulb also is hot, and that might be what the
snail sensed; 2) that the light might not be bright enough to affect snails; 3) that snails might like bright lights and might have moved toward the light. While some of these possibilities seem a little far-fetched, they do illustrate that experimental proof in science is complex, and that the implications of an experiment depend on assumptions.

Discussions of this sort also give students practice in listening to the arguments of others. Through this kind of discussion, we can help students to critically examine how they, and scientists in general, might establish reasons for holding their beliefs. In this way, students can come to see scientific knowledge as the result of thought and evidence working together, and they will also begin to understand that evidence is interpreted in order to arrive at knowledge. Scientific knowledge does not arise unambiguously out of experiments.

**School time is too precious to spend any sizeable portion of it on random facts. The world, after all, is filled with an infinite number of facts. No one can learn more than an infinitesimal portion of them. Though we need facts and information, there is no reason why we cannot gain facts as part of the process of learning how to think.**
Inferences and the Structure of Atoms

Objectives of the remodelled plan
The students will:
- think more precisely about thinking by developing a concept of 'inference' distinguished from evidence
- practice making and assessing inferences in everyday contexts
- practice making inferences in the specific context of the Marsden Rutherford experiment on atomic structure

Standard Approach
Texts often introduce the idea of the atom in a straightforward way. The ideas of the Greeks are discussed briefly and Dalton’s atomic theory is presented along with a brief review of the kinds of evidence which led Dalton to these ideas. The general structure of the atom is presented by making some statements about protons, neutrons, and electrons and their location in the atom. The experiments of Marsden and Rutherford in which gold foil was bombarded with a beam of alpha particles are described. The implications of this experiment are discussed through statements like the following: “To everyone’s surprise, a very small fraction of the alpha particles bounced back. Rutherford proposed that the mass of the atom and the positive charge are concentrated in a small region. He called this region the nucleus. He thought of the rest of the atom as more or less empty space.”

Critique
This standard approach is straightforward and may be appropriate as a simple introduction to the basic structure of the atom. The approach is direct and it is easy for students to master, at a simple level at least, the names of the three basic subatomic particles, their properties, and their locations inside the atom.

This chapter could, however, be expanded to teach students something about inferring as a general thinking skill. In addition, students could be exposed to the idea that our picture of the atom is not a picture in the literal sense at all, but is an inference based on experimental data like Marsden’s and Rutherford’s along with theoretical ideas like the nature of electrical forces and so forth. In the remodelling discussion, we will discuss some ways in which the material of this chapter could be used to teach about inferences.
Strategies used to remodel

**S-28** thinking precisely about thinking; using critical vocabulary

**S-32** making plausible inferences, predictions, or interpretations

**S-33** evaluating evidence and alleged facts

**S-18** analyzing or evaluating arguments, interpretations, beliefs, or theories

**S-13** clarifying issues, conclusions, or beliefs

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Remodelled Lesson Plan S-28

You might begin teaching about inferences through a class discussion, like the examples which follow, of inferences in everyday settings.

"In everyday life, we think many things are true from very simple things, like, 'my dog is standing outside the door' to very complex things like 'the world is built of very tiny things called atoms.' Have you ever stopped to think about how you know what is true?"

"We think some things are true because we believe that we have direct evidence. For instance, you might see your dog standing outside the door and so you know that he is there. You know because you can see him. But we also believe things are true even though we do not have such clear or direct evidence. Suppose you are in your house and you hear a scratching noise coming from the front door. Just as before, you might believe that it is true that your dog is standing at the door. But this time, the evidence is different; you don't actually see him, but the sound you hear makes you think he is at the front door. You might think this because you can't think of any better explanation for the noise. So you think it is your dog. We call this process 'making an inference.' An inference is something we believe to be true based on some evidence."

"We can not be sure of the truth of all of our inferences. But some inferences are better than others. In our dog example, for instance, if we hear his chain rattling and hear him barking and scratching we could be pretty sure that it is him outside the door. We could say we are pretty sure about this inference. If, on the other hand, all we heard was some scratching, we might still infer he was out there, but this time inference is less sound. It could be we are hearing some other animal, perhaps a raccoon."

"Sometimes we get so used to making a particular inference that we do not even realize that we are inferring. If every time we hear scratching at the door we find out that it is our dog, we just take for granted that scratching means our dog is out there. We get used to taking the scratching as direct evidence that our dog is there. Many of the 'facts' of science are really inferences, but we are so used to them that we do not consider them any longer to be inferences, we often just take them for truth. But it is important to remember that things like the details of atoms are really inferences from evidence and not something we have observed directly."

After this general introduction, students could review their general sense of the process of inference by answering the following questions. There are sever-
al possible answers to some of these questions. This reinforces the idea that when we make inferences, we can not be sure of the truth of our inferences, even when we have considered the evidence rationally.

1. While sitting in a sunlit room, you notice that the direct sunlight has quit coming through the window. What are the different things you might infer?

2. A few minutes after the sunlight quit coming through the window, you could observe drops of water falling from the sky. Does this provide any additional evidence for your inference? S-32

3. Can you be sure that what you have inferred is true? Why or why not? What additional evidence would support or undermine your inference? S-18

Students could then be asked to describe other everyday examples of inferring.

Now that your students understand some general ideas about inferences, you can apply this understanding to the subject of this chapter, the basic structure of the atom, and especially to the evidence of Marsden and Rutherford. The following questions are helpful:

1. We say the atom is made of a very small positively charged nucleus and negatively charged electrons which exist outside of the nucleus. Some evidence relating to the discovery of the nucleus was provided by the experiments of Marsden and Rutherford when they shot alpha particles at a gold foil. Briefly, what is that evidence?

2. After reviewing this evidence, would you say that scientists have directly observed the nucleus or have they inferred that it was there? S-33

3. Can you think of any other explanation that might account for their results? S-32

4. Explain whether or not their evidence shows that atoms of the different elements all have the same basic structure of a positive nucleus surrounded by negative electrons. S-33

5. Summing up, would you say that we know the basic structure of atoms for sure from their experiments with alpha particles and gold foil? S-13

After students have learned more about atoms, they could discuss other evidence which supports the idea.

"It does no good to know the right answer, if you don't know what it means." quote from a student
Ectothermy

by Carol R. Cottang, Mountain View High School, Mountain View, CA

Objectives of the remodelled plan
The students will:
- ask and clarify a question and propose a hypothesis
- generate and assess lab procedures to settle the question
- organize and evaluate their data
- make inferences from their results
- deeply question scientific reasoning by exploring the relative significance of various zoological classifications
- modify hypotheses, if necessary, to fit data
- examine and correct their original misconceptions

Standard Approach

Students are given a set of instructions to perform the experiment of counting breaths a goldfish takes in various temperatures. The instructions provide background information and direct the students' thinking about the problem. The procedure is provided in detail. Students are told how to graph the results. Students are called upon to make a hypothesis, collect data, and come to a conclusion.

Critique

This experiment, like most others in high school lab books, is intended to confirm a concept that has already been presented to students. Since students know this, it often leads to more confusion. High school students often have firmly-held beliefs that are based upon their own limited experience, and these ideas are not easily broadened. They tend to interpret the results of experiments in light of these limited ideas and not to look for the application of new ideas. If these students are negligent in their reading and thinking (as many students are) they will assume that the experiment is confirming their preconceived notions and will interpret data in this way. In this case, the fundamental difference between endotherms and ectotherms is the idea that may be missed unless the student is actively involved in both the design and the analysis of the experiment.
Strategies used to remodel

- S-1 thinking independently
- S-29 noting significant similarities and differences
- S-17 questioning deeply: raising and pursuing root or significant questions
- S-19 generating or assessing solutions
- S-32 making plausible inferences, predictions, or interpretations
- S-5 developing intellectual humility and suspending judgment

Remodelled Lesson Plan

Day one

In small groups, students could be asked to brainstorm what they know about fish for three minutes. This list is shared and put on the board. Next, they are asked to brainstorm what they know about cold-bloodedness versus warm-bloodedness, and this list is also put on the board. S-1

Next, each team of students is given a goldfish to observe for five minutes. The fish is in a beaker of water. Some beakers are set in larger bowls containing warm water, and some in ice chips. Students are asked to write down as many observations as possible about the fish and its surroundings. Students are asked to report their observations and “warm” teams and “cold” teams compare what they saw. One inevitable observation is that the fish in warm water were breathing faster than the fish in cold water. The teacher could focus the discussion on this fact and on the idea of metabolism. Other observations, like increased movement in warm water could be related to this. S-29

The teacher asks the class to think about a good scientific question or two that could be asked about this situation. This discussion should include discussion of what is meant in science by a good question. “Can we test this question? How? Why ask this? What value does the answer have?” S-17 Through questioning, the students can also be reminded that data involving a larger number of fish will be more reliable than data only involving one or two fish, so the entire class should follow the same procedure and combine data.

In small groups, students can decide upon a procedure to propose to the class. Each group can then present its proposal, and the class can decide upon which one to follow. “Would this procedure answer our question? Would the results be accurate? What, exactly are we looking for?” S-19

Day two

Students follow the procedure decided upon on day one, and collect data.

Day three

Data from the various teams is combined on the board, and the meaning of the data is discussed. “What did we find? What does it mean? What can we infer from these results?” S-32 This discussion should now focus upon the idea of endothermy and ectothermy, and the difference between the way
the fish responded and the way a mammal or bird would respond in a similar situation. "Are mammals affected the same way? What accounts for the difference? How? Why?" S-29

The data is likely to involve the variables of temperature and breathing rate, and the teams can be given time in groups to review graphing techniques. The remainder of the time on day three can be given to the groups to organize their notes and start work on their lab papers. The paper can be a group product.

editor's note: Students could review their original brainstormed ideas, evaluate them, and discuss possible connections between the items they mentioned and their experiments. "Does this point have any connection to our study? What? Why? How sure can we be of this? How could we find out for sure?" S-5

How important is the distinction between warm and cold-blooded animals? Why? What distinctions are more important to zoologists? Why? Less important? Why? Students can examine charts showing biological classifications, and explore possible reasons for the hierarchy of distinctions. (For example, vertebrates versus invertebrates is a more basic and therefore more important distinction than that studied in this lab.) S-17

Did any categorizations surprise you? Do zoologists group together animals that seem very different? Which? How can we find out why they are grouped this way? (For example, students may be surprised at some of the animals considered rodents. They could look the term up in a glossary, dictionary, encyclopedia, or text index, and speculate on the significance of the category.) S-17

We learn how to learn by learning, think by thinking, judge by judging, analyze by analyzing; not by reading, hearing, and reproducing principles guiding these activities, but by using those principles. There is no point in trying to think for our students.
Periodic Trends in the Elements

Objectives of the remodelled plan

The students will:
- predict trends of some important atomic characteristics
- give reasons for their predictions, engaging in dialogical discussion of them
- check the accuracy of their predictions against explanations given in their texts

Standard Approach

Many chemistry texts approach the idea of “chemical periodicity” in a similar way. They begin with a brief review of the historical work of Mendeleev. They say that he listed the elements in order of atomic number and then was able to note periodic occurrence of particular chemical properties. These texts then go on to present the modern periodic table. They explain the particular form the periodic table takes, by referring to the electron populations of the various atomic orbitals. These texts also explain several different characteristics of atoms including atomic radius, ionization energy, electron affinity, chemical reactivity, and others in terms of the electronic configuration of the atoms and their location on the periodic table.

Critique

The standard approach raises two questions. First, the content represented by this approach to the topic of chemical periodicity is complicated and abstract. Students must master several fundamental concepts in order to understand the underlying causes for the periodicity of many atomic properties. These concepts include atomic orbitals, especially the energies and spatial distributions of electrons in the various orbitals. Attentive and motivated high school students can state definitions, facts, and some standard explanations about these kinds of topics. When approached with a somewhat new situation, however, these same students often give evidence of not clearly understanding these topics. Are the broad goals of high school science education well served by teaching material which is so abstract that it may be beyond the understanding of our better students? The usual answer is that those students who go on to college chemistry will need this background. In our view, there is some basis to this. High school science teachers must weigh the question of how much of their teaching is justified only by the preparation of their students for future study. It is also our view, however, that a clear understanding of the fundamental ideas of science serves the needs of all students, regardless of their future plans by helping them understand and retain the essence of important scientific concepts. For these reasons, we caution teachers to think carefully about their emphasis on the many details which could be included under the topic “chemical periodicity.”
Our second point concerns the depth of understanding which students develop from the standard approach to chemical periodicity. Texts often cover a wide range of atomic characteristics, including atomic radius, ionization energy, electron affinity, chemical reactivity, ionic size, electronegativity and others. We must ask, however, how well students understand the fundamental concepts which explain the trends we can observe across the periodic table. Our students give us evidence of their level of real understanding when we observe how they study for this chapter. We often see their periodic tables marked up with arrows indicating that the ionization energy goes up as we go to the right on the table along with arrows indicating that the atomic radius goes down, and so forth. While these are important facts to a practicing chemist, what we really want is for our students to understand why these trends are observed. It's really more important for them to understand the why of all these trends, than to know the direction of each trend. For this reason, our remodel focuses on strategies for helping students understand the important concepts underlying chemical periodicity rather than on learning the trends in the properties themselves.

In general, we think that it is a good strategy to emphasize mastery of a few fundamental ideas rather than emphasizing knowledge of the detailed information which practicing scientists use in their work. As a basic strategy in teaching periodicity, we suggest that you emphasize understanding and applying the fundamental concepts of energies and sizes of orbitals. You can do this by using activities which require students to make predictions of the various periodic properties like atomic size, ionization energy, and so forth. In this way, you do two things. First, when students predict these trends, they pay more attention to the basic ideas themselves than to the direction of the particular trends. This helps students learn the basic ideas and it also gives them insight into how science can be seen as the sum of a relatively few basic ideas. Second, asking students to make predictions is one of the best ways for you to check their understanding of basic ideas. By listening to them explain how they arrived at their predictions, you can get an accurate sense of their understanding.

First, you should consider for yourself what the basic ideas of this chapter are. All the trends mentioned in the standard approach to chemical periodicity can be predicted on the basis of three fundamental ideas: 1) for a given principal quantum number, the energies of the electrons with that principal quantum number are lowered if the nuclear charge is increased; 2) for a given principal quantum number, the electrons are pulled closer to the nucleus as the nuclear charge is increased; and 3) as the principal quantum number is increased, both the energy and distance of the electron from the nucleus increase. This effect can overpower the opposite effect of greater nuclear charge. The first two of these ideas can be explained simply in terms of greater nuclear attraction. The third idea is more difficult to explain, since it is the result of a feature of quantum mechanics overpowering the effect of greater nuclear attraction. The point of this remodel discussion, however, is not to analyze the three fundamental ideas in detail. We are demonstrating that it is possible to list the few basic ideas of a chapter and then to review them with students so that they can practice using the basic ideas to make predictions.

**Strategies used to remodel**

- **S-25** reasoning dialogically: comparing perspectives, interpretations, or theories
- **S-32** making plausible inferences, predictions, or interpretations
Remodelled Lesson Plan  S-25

You should present your own form of the basic ideas to your students, and then present them with some challenges. "Can any of you use these ideas to predict how the size of atoms will change as we go across a row of the periodic table? Down a column? S-32 What are your reasons for this prediction?" Encourage students to argue with each other, trying to justify their positions. Through these kinds of questions, you will help your students think about the basic ideas. You will also encourage them to look at the graphs and tables in the text with more curiosity, since they will be trying to find the information to prove whether the class's predictions were accurate. "Can anyone find a graph or table in the chapter which will let us check the accuracy of these predictions?" This simple technique encourages them to be more active processors of information. Having made predictions, the correct answers and explanations will mean more to them than if they are given from the start.

In the same way you can ask them to predict some of the other trends such as ionization energy. S-32 While we do hope that their predictions will be accurate, keep in mind that it's the spirit of thoughtful prediction you are encouraging. In this way, topics like periodic trends can be used to encourage thoughtful exploration of basic ideas, rather than mastery of detailed information which remains unconnected in students' minds and is often misapplied later.
Snell’s Law: Designing Labs

Objectives of the remodeled plan
The students will:
- design a laboratory procedure for taking data to provide an answer to a question, thus developing confidence in using reasoning to solve problems
- provide an answer which is justified by reasoning from their own observations

Standard Approach
Many laboratory manuals introduce the index of refraction of a substance by defining it as "the ratio of the speed of light in a vacuum to its speed in the substance." These lab manuals might then state that "All indices of refraction are greater than one," and "The index of refraction is also obtained from Snell's Law, which states that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant for all angles of incidence." They may also state that "If a ray enters a more dense optical medium obliquely, it is bent toward the normal." A typical approach would be to give two objectives to students: 1) measure angles of incidence and refraction; and 2) calculate the index of refraction of glass using Snell's Law. Many manuals give a step-by-step procedure, a data table, directions for calculations, and several questions for interpreting the data. Students will sometimes be able to find the answers to some of these questions in the introductory paragraph for this activity.

Critique
One problem with this standard approach, from the point of view of encouraging critical thinking, is that students are directed to perform a series of measurements without first conceiving a question or planning a strategy. The point of the activity unfolds only through the questions in the "Conclusions" part of the activity, which is located at the end of the activity. The problem with this design is that students are asked to engage in a series of measurements which have no apparent relationship to any particular question. This "cookbook" approach to laboratory instruction is very common in commercial lab manuals, and this particular case gives us a good example in which to discuss an alternative approach. In addition, by asking students to copy a particular data table (for which a model is given in the text), no chance is given for the students to invent a way to organize the data they are about to take. Again, this strategy removes another opportunity for students to organize their own approach to answering a question. The remodeled
discussion will focus on this lab as an example of a general approach to lab procedures designed by the students with substantial teacher direction. We will call this process "directed student-invention" of labs.

Another problem, perhaps related to the first, is that the three questions posed by the manual are actually answered in the introductory paragraph. This reinforces the attitude that there is nothing really to be learned by actually investigating in the lab.

This activity also gives us the chance to raise the question of the appropriateness of particular science concepts for high school students. Refraction is an interesting and important characteristic of light. The quantitative, trigonometric expression of Snell's Law is one way of looking at refraction, but this quantitative expression may well mask the more fundamental qualitative understanding students should develop. For instance, what is the physical meaning of the statement that "All indices of refraction are greater than one?" Of course this means that light travels slower through any material than it does through a vacuum. But the manual does not make this clear, nor does it cause the student to think about this.

The major change needed in this lesson is to reduce the cookbook style in which directions are given by the lab manual. This can be done by asking the students to "invent" the lab without the use of the lab manual. Of course it would be foolish to ask students to invent their labs with no help; after all, many bright people have worked over a long period of time to understand the science we now teach in schools, and we certainly cannot expect our students to invent everything they are to learn or do. But students can consider certain kinds of questions and, with their teachers' guidance, design a way to find answers which are based on their own analysis of data they take in lab. It is often necessary to ask questions which are simple enough for students to really understand what the question means and design a procedure to find an answer. This necessity can be viewed as a "blessing in disguise," since it encourages us to limit the concepts to ones which students can understand and investigate in a deep and critical way.

**Strategies used to remodel**

**S-9** developing confidence in reason  
**S-19** generating or assessing solutions  
**S-11** comparing analogous situations: transferring insights to new contexts

**Remodelled Lesson Plan S-9**

The basic approach to "student-designed" labs is to pose a question in an intriguing way and then guide the class, through an interactive discussion, to a procedure for settling it. Clearly, if you ask students to invent something, you may get a wide range of inventions, or in this case, a wide range of possible laboratory procedures. While there are pros and cons to various approaches, we suggest you guide the students' thinking and discussion sufficiently that the class as a whole converges to a common procedure. Moreover, a skillful teacher can guide the class to an approach he or she knows will work. Often, this procedure could be the one that the lab manual has suggested. But the important point is that the students will become more aware of the actual question to which they are trying to find an answer, and they will have a better
understanding of the reasons for the particular procedure they will use.

One practical technique for using this approach is for you to discuss with the class possible approaches to the lab while you make a record of the class's conclusions on the overhead projector. In many cases, it is useful to have this discussion the day preceding lab day. The use of the overhead has two advantages. First, you have the ability to shape the written record. You can reject or accept ideas, reword ideas, and generally control the discussion. Second, the notes (including drawings, ideas for tables and graphs, etc.) can be projected the next day to help students remember what they are to do, what kind of table to make, and so forth. S-19 Since the record was made during class discussion, it is familiar to students and they will tend to feel a kind of psychological ownership of the procedure they are following. S-9

A variation of the Snell's Law lab discussed here is ideally suited to this technique of teacher-directed student invention. The full trigonometric expression of Snell's Law is probably too obscure for most students to investigate, but a simpler qualitative sense of the law is appropriate for student investigation without use of cookbook-like instructions. The question for investigation could be posed by having students experiment with familiar demonstrations like viewing a coin in the bottom of a cup first empty and then filled with water, or observing a straight rod inserted into a container of water. Both these demonstrations give the teacher a chance to ask how light is bent as it passes into or out of transparent media. We are not suggesting that most students could deal with this question productively without some help, and this is one of the points where you must give some information or help, but not too much. One approach is to stick two large pins or nails into a board and ask the class where you would have to put your eye along the surface of the board to make the more distant pin appear to lie behind the closer pin. Of course they will respond that you eye should go on a straight line drawn through the location of the two pins. But what does this prove? Perhaps it will not be immediately obvious to your students, but this simple observation shows that light from both pins travels in a straight line to your eye. That is why you cannot see the one pin in its location behind the other.

With some classes you could now give them their own setups and tell them to view the two pins through a rectangular piece of glass. With rather able students, it will be sufficient to tell them that they can now invent a way to answer the question generated during the demonstration. You may want to have them experiment a bit then have a whole-class discussion. In this way the class as a whole can understand how the simple setup they have can be used to answer the question. Depending on the class and your judgment of their abilities and needs, you could provide more or less direction until the class understood that they could take the data they need to answer the question. Your instructions would then be to take data, in this case, they would probably make some line drawings of a few locations of the block and glass
and the resulting "sight line" of the two pins as the light emerged, refracted, through the glass. Your instruction could include the requirement for students to provide an answer to the question with justification by using the data which they have collected. As a nice wrap-up they could try to explain why the coin became visible over the edge of the cup when water was added.  

A teacher committed to teaching for critical thinking must think beyond compartmentalized subject matter teaching to ends and objectives that transcend subject matter classification. To teach for critical thinking is, first of all, to create an environment that is conducive to critical thinking.
The Wave-Particle Theory of Light

Objectives of the remodelled plan
The students will:
- explore and clarify the nature of models and the use of model in science through discussion
- note significant similarities and differences between models and what they represent
- develop confidence in reason by proposing a model to explain a physical observation
- interpret an observation with light in terms of the wave model of light

Standard Approach—
In introducing the electromagnetic spectrum, texts will mention the wave-particle theory of light. Students are told that if they look at a distant light source through a pinhole in a card, the pattern of light they observe is larger than the actual size of the pinhole. They are told that this "strange effect can be explained if light is thought of as a series of waves." They are then told that other kinds of experiments give different results. These experiments show that light "always transfers energy in the form of small particles." The students are told that these light particles are called photons. The passage concludes by saying the wave-particle theory of light is the name of the theory that results from combining these two different kinds of experimental results.

Critique
This brief passage raises several questions: how models are used in science; why diffraction through a pinhole indicates that light acts like a wave; what "transfers energy in the form of small particles" means; what it means for light to act as a wave in some experiments and as a particle in others. Most of these issues cannot be dealt with successfully in a brief introductory passage. (In fact, such passages suggest considering whether these issues should be addressed this briefly if the result is to raise issues which students cannot understand.) It is possible, though, to help students understand the role of models in science and, for this reason, this remodelling discussion will focus on the use of models in science.

Strategies used to remodel
S-14 clarifying and analyzing the meanings of words or phrases
S-29 noting significant similarities and differences
S-9 developing confidence in reason
S-32 making plausible inferences, predictions, or interpretations
Remodelled Lesson Plan

The discussion could begin by raising the issue of models in general. The most familiar use of the word 'model' to students is probably as in 'model airplane,' a small representation of a larger object. The following questions will help students discover some features of models. "How is a model airplane like an actual airplane? How is it different? What does a model of an airplane enable you to do? What kinds of things does a real airplane do that a model cannot do?" Through these kinds of questions, we try to help students clarify their own thinking about this simple kind of model. S-14

Next, we could introduce models which are more abstract than simple model airplanes. Most students have had experience with some kind of map, and we will use this to extend the idea of a model. After reminding the students about road maps, perhaps by showing them a road map of your state as an example, you could ask them to think of the ways in which this map is a model and how this map model differs from an airplane model. "Is the map a complete picture of your state? Could you use the map to find out everything you might want to know about your state?" These kinds of questions will help students understand that a map is a useful representation of some aspects of your state in which people might be interested. The map is not a complete, accurate representation of every aspect of your state, but it does help us understand and use the road system. We would probably make a different kind of map if we wanted to understand how the hills and mountains of the state worked to form river systems, for instance. The following kinds of questions will encourage students to explore the usefulness of maps. "What does this road map tell us? What does it help us do? Is this map a miniature model of our state? Are there things in our state which aren't shown on this map? Why are these things left off?" The point of these questions, and many other possible questions, is that maps (or models in general) are not complete representations but are designed to help us understand some particular aspect of the thing we are studying. S-29

In the case of maps, we make a small model of a large object. In much of science we do the opposite — we make a large model of small things like atoms, for instance. But these models in science have many of the same features of the models and maps we have been discussing.

Sometimes in our science teaching, we can describe something or let students experience it directly and then ask students to invent some kind of model. For example, after watching a drop of ink slowly diffuse through a glass of water, students could try to invent the best model they can to explain what they saw. S-9

In the case of a model for light, we can let students observe diffraction through a pinhole, as the original lesson points out. The students can also be shown pictures of water waves bending around objects — breakwaters in a harbor, for instance. You could ask, "If light acted like these kinds of waves, what would we expect to see when light travels through pinholes and into our eyes?" S-32
Through questions like this, you can lead students to understand possible implications of the pinhole in the card activity mentioned in the original text passage. In this way we can begin to help students understand what it means to say “lights acts like a wave” or that “we can use a wave model of light.”

The text goes on to mention the particle model for light. Unfortunately, the evidence leading to this model is much more difficult to observe and interpret. We cannot present this evidence to students. In this remodelling discussion, we have, however, seen an approach which helps students understand what models are and how they are used in science. We have also taken a brief look at some of the evidence which is best interpreted thorough the wave model of light.
Newton's Second Law

Objectives of the remodelled plan
The students will:
- make plausible predictions about motions of objects
- analyze their experiences regarding motions of objects
- clarify the concepts of force, friction, and mass through discussions and questions about common experiences

Standard Approach

Texts often approach teaching Newton's Second Law of Motion by using examples of frictionless surfaces, such as a hockey puck on ice. They then state that experiments in such situations have shown that doubling the force will double the acceleration. Some texts introduce the mass of an object as the ratio between the force and acceleration, and provide a summary of Newton's Second Law: "When a force is applied to an object, the object accelerates in the direction of the applied force. The acceleration is greater when the force is greater. The acceleration is less when the mass of the object is greater."

Critique

Newton's Second Law is very difficult for students to understand, since it apparently contradicts many of our everyday experiences. For instance, frictional forces are so much a part of everyday life that students rarely have the opportunity to experience frictionless motions. The text misses an important opportunity for students to come to terms with this aspect of their experiences. Also, the definition of 'mass' as force divided by acceleration is much too abstract to be of use to students at this level.

This lesson gives us the chance to raise the question of the appropriateness of presenting particular science concepts to high school students. It is appropriate for these students to try to understand the motion of objects in terms of their own experience and in terms of the ideas of scientists who have studied motion. Newton's Laws, though, present a highly abstract and condensed way of understanding motion. Many of the important aspects of Newton's Laws are often not apparent in everyday life, and therefore, students' preconceptions about motion are often quite at odds with the abstractions of Newton's Laws. Briefly, what are some of the preconceptions students have which apparently contradict Newton's Laws?

The First Law states, "Objects move in a straight line at constant speed unless a force is acting on them." Since everyday motions are always subject to forces, especially frictional forces, children are without the kinds of experience which would enable them to have "experienced" the First Law. As a different example, many students think that if a stone whirled overhead in a cir-
cle on a string is released, the stone will follow a kind of curved path (when viewed from above). Their preconceptions on this kind of motion are entirely at odds with the prediction of the First Law that the stone will follow a straight line.

The Second Law deals with the relationship between force, mass, and acceleration. Again, this presents difficulty for students, since our everyday experience leads us to see motions in terms of force, weight, and speed. Based on everyday experience, most students believe that the harder you push something, the faster it goes. We develop these preconceptions from experiences like pushing heavy objects across the floor. While the confusion of weight for mass is not a relatively important issue for students, the spirit of the Second Law is lost when we relate forces to speeds rather than to accelerations.

Strategies used to remodel

S-12 developing one’s perspective: creating or exploring beliefs, arguments, or theories
S-11 thinking independently
S-14 clarifying and analyzing the meanings of words or phrases

Remodelled Lesson Plan S-12

We begin remodelling this lesson by changing its goal somewhat. Instead of trying to teach Newton’s Laws, we try to do two things: 1) we try to help students articulate their preconceptions about the motion of objects; and 2) we try to challenge students in a way which encourages them to modify their understanding to arrive at a more powerful, all-encompassing view of their experiences, thus developing their perspectives. If we can accomplish these goals, we will help prepare them for a critical understanding of the abstract statement of Newton’s Laws later in their education.

As an example, let us begin with the relationship between force (“pushes and pulls” to students) and motion. We could have students consider two extreme situations: pushing a car along a road and pushing an object over a very smooth, frictionless surface. (Use a situation your students might have experienced like a frozen lake, an air hockey table, sliding on a smooth or wet floor, etc.) “What happens when we stop pushing? Why?” S-11 Through questions like this, we are trying to challenge one characteristic preconception which is that something moving requires a continuing force. Our strategy is to cause students to consider the difference between high-friction and low-friction situations. Also have them consider the force required 1) to stop moving objects, and 2) to change their direction. Through this strategy, we hope that students will see changing motion (in speed or direction) as the result of external force acting on the object. This is one of the difficult points in Newton’s Laws for beginners.

Another major point in Newton’s Second Law is the mass of an object. While the texts’ definition of mass as “the ratio of force to acceleration” is technically correct, it is not an appropriate definition for students at this level. At this age, students should learn science by considering concrete ideas. While force and, to some extent, acceleration are concepts with which students have direct experi-
ence, the idea of a ratio of these quantities is too abstract for students to understand in a critical sense. It is probably better to refer to the mass of an object as "the amount of matter." Students often confuse the mass of an object with the frictional force associated with moving it. Big objects, like pianos, are difficult to move around due to friction. It is, however, surprisingly easy to move a small boat weighing about as much as a piano, since the frictional force opposing the motion of a boat in the water is very small. Through questions involving large objects and small objects, along with high- and low-friction situations, we can clarify students' understanding of mass of objects. **S-14**

Ask students, "Why is it harder to move objects on rough surfaces than smooth or slippery surfaces? Why is it harder to start an object moving on a smooth surface, than it is to keep it moving? Why is it harder to stop a bulky object than one with less matter? A faster object than a slower one?**S-1

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Macro-practice is almost always more important than micro-drill. We need to be continually vigilant against the misguided tendency to fragment, atomize, mechanize, and proceduralize thinking.
Photosynthesis: Designing Labs

by Carol R. Gontang, Mountain View High School, Mountain View, CA

Objectives of the remoulded plan
The students will:
- ask good questions about observations they make
- form hypotheses concerning these questions
- generate and assess solutions by designing controlled experiments to test their hypotheses
- interpret their results through dialectical discussion
- modify their hypotheses, if necessary, to fit the data
- discuss at length the reason hypotheses are not "proven" by experiments
- correct their original misconceptions concerning plant metabolism based upon their experiments by recognizing contradictions

Standard Approach
Students are given a complete set of instructions concerning the setup of all parts of the experiment. They use the acid indicator bromthymol blue to see if plants left in light overnight take in carbon dioxide. Questions and hypotheses are provided by the manual. Students are asked to predict the results of the experiment based upon the hypotheses provided, and to make observations.

Critique
While students are collecting and interpreting data in the original lesson, they are missing out on an important thinking exercise by not being allowed to ask good questions and to design the experiment and control for each question themselves. The original lesson does not provide a discussion of the skill of asking a good question (in the scientific sense) or the importance of a model or hypothesis.

Like many "cookbook" style labs in high school science classes, this lab is presented after the students have been given the facts about photosynthesis, so that the experiment is not a true investigation, but is a confirmation of what the students have already been told. When experiments are presented this way, students tend to see results as "proof." The fact that in real science, experiments both begin and end with questions and hypotheses is lost when labs are presented this way. The traditional presentation gives students the idea that the objective in science is to prove a preconceived notion to be correct, and that to fail to do so means a bad experiment (and a bad grade). Students should also be encouraged to add other experiments, thus broadening and enriching their study.
Strategies used to remodel
S-5 developing intellectual humility and suspending judgment
S-32 making plausible inferences, predictions, or interpretations
S-10 refining generalizations and avoiding oversimplifications
S-19 generating or assessing solutions
S-9 developing confidence in reason
S-26 reasoning dialectically: evaluating perspectives, interpretations, or theories
S-34 recognizing contradictions
S-1 thinking independently

Remodelled Lesson Plan

The experiment could serve as an introduction to a unit on photosynthesis and respiration. Students have learned in earlier classes that plants “breathe in” carbon dioxide and give off oxygen, while animals do the reverse. Typically, however, they have not understood that plants also carry out aerobic respiration at the same time that they perform photosynthesis, and that this process goes on day and night.

Day One
To begin the investigation, the students could spend ten minutes in small groups brainstorming a list of all the things they know or assume about plants and photosynthesis. These lists could then be shared and put up on the board with no correction from the teacher. At the end of the lesson, students will return to the lists to see if their original views have been supported. S-5

In a demonstration, the teacher could show the students how to add carbon dioxide to water containing the acid/base indicator bromthymol blue, by adding drops of carbonated water or by bubbling his or her breath through the water with a soda straw. (The water-bromthymol blue mixture becomes yellow with the addition of CO₂.) A length of Elodea plant is added to the water in a test tube, and the tube is left in good light overnight.

Day Two
The next day, the water around the plant will have turned green or blue. The class could then be asked to discuss what this color change might mean. “How should we interpret this result? Why? How does that interpretation fit in with what we know?” S-32 They could be asked how they can be sure that the plant caused the color change and not some other factor. This would lead to a discussion of the variables that may have played a part in the demonstration (plant, carbon dioxide, light, etc.) S-10

Students could next be given time in small groups to formulate questions about the effects of the variables, and to think of ways that they might use the demonstrated materials to try to answer their questions. “If the result might have been due to that, how could we test for it? How could we ensure that won’t affect our results? How would it enter the picture? How could we eliminate it or keep it out?” S-19 It is likely that students will ask what effect light
had on the results, and that they will decide to try a similar set-up in the dark. They might also try a control with no plant, to ascertain that it was, in fact, the plant that caused the change; or leave a plant in water to which no carbon dioxide has been added (water is green or blue); or leave a tube with blue water and no plant; or put an airtight cover over the tube with a plant. Students’ experiments are set up and left overnight. S-9

Day Three
The next day, students make observations and combine their data in a large group discussion. Through questioning, the teacher can guide the discussion to explore the results. The teacher invites hypotheses to explain the results. S-32 It is important that the teacher asks for more than one hypothesis that would be consistent with the data, and then discusses which one might fit the data and background information best. “What might this show? What else could it show, instead? ... Which seems more plausible? Why? What do we know that should make us favor one explanation over another?” Students could argue with each other for their theories and argue against competing theories. S-26

Next, the teacher brings up the question of what a plant is doing in the dark when (as an earlier experiment indicated) photosynthesis is not going on. Students again devise experiments and controls to explore whether carbon dioxide is being used or given off at this time. S-19

Day Four
The results in this last set of experiments will show carbon dioxide being given off. Students can be asked to hypothesize about what type of process might produce carbon dioxide, and they can be reminded of how their own breath turned bromthymol blue to a yellow color. This discussion leads to the idea that plants perform cellular respiration just as animals do.

Finally, students review the lists they made at the beginning of the lesson to see if the lists need to be modified or expanded. “Is this statement consistent with what we’ve found? Do our results contradict this idea? Did our experiment prove this claim? Do we have sufficient evidence to judge this?” S-34

It is important that during the design sessions and the interpretation of the results the teacher avoids shutting off further discussion by telling students a particular interpretation of data is right or wrong. Instead, the teacher should respond to a student’s proposed interpretation by inviting other students to respond to it. S-1 Interpretations should be critiqued on the basis of whether they are consistent with the data, and not on the basis of whether the student has guessed a desired response correctly. S-9
Darwin: A Socratic Approach

by Joan C. Simons, Grimsley High Schools, Greensboro, NC

Objectives of the remodelled plan
The students will:
- be introduced to the concepts of Darwinian evolution
- engage in analytical and evaluative thought in class discussion and writing

Standard Approach

I. The Darwin-Wallace Theory
   A. The planet is not static but changing
   B. Similar organisms have a similar ancestor
   C. Natural selection
      1. In every generation an enormous amount of variation occurs
      2. The individual best adapted to the environment is the one who will survive.
   D. Acquisition of traits through use and disuse, as well as adaptation
   E. The inheritance of acquired traits

II. The LaMarck Theory
   A. There exists in organisms a built-in drive toward perfection
   B. There is in nature a progression from simple and small (primitive) to large and complex (advanced) to man (perfection).
   C. There is frequent occurrence of spontaneous generation so that each organism represents a separate line of descent
   D. Organisms have the capacity to adapt to the environment, therefore they may acquire characteristics
   E. The inheritance of acquired traits

III. Using pictures of horse skulls and feet, discuss these theories as an explanation of these pictures

IV. Discuss the scientific problems of these theories in light of the students' knowledge of genetics.

V. Have the students write their own theory of evolution

Introductory note

In the fall of 1987, when my principal announced the organization of a committee to improve the teaching of critical thinking in the classroom, I made sure my name was on his list of volunteers. Finally, I thought, some administrator is interested in exciting teaching and good, lasting education for students. The result was the committee for Writing and Tacical Thinking Skills (WATTS). As direct outgrowth of my involvement with WATTS the above lesson on the introduction of Darwinian evolution was remodelled. This lesson was written and remodelled for a class of ninth and tenth grade, academically gifted students in Biology I.
Critique

This lesson plan is a basic lecture-class discussion format with the teacher acting as the primary information dispenser. This technique has the general disadvantage of encouraging student passivity rather than involvement. This format does not necessarily require thinking on the part of the students, let alone identification of thinking processes. While there is an opening for student discussion, thought-provoking questions would be a happy accident. One strength of this lesson is the attempt to urge students to tie this lesson into their knowledge of genetics. This lesson needs to identify what questions students should consider to improve their independent thinking skills as well as their content knowledge.

The Socratic lesson not only involved the students to a greater degree, but was more interesting for the teacher. The same basic information was covered as in Lesson 1, but in such a way as to require greater student investment in the process. To obtain an overall view from an observer, read the evaluation included at the end of their paper. Notice that with the Socratic lesson, fewer students remained passive, and it resulted in more time on learning tasks for the entire class.

Strategies used to remodel

| S-28 | thinking precisely about thinking: using critical vocabulary |
| S-33 | evaluating evidence and alleged facts |
| S-12 | developing one's perspective: creating or exploring beliefs, arguments, or theories |
| S-17 | questioning deeply: raising and pursuing root or significant questions |
| S-14 | clarifying and analyzing the meanings of words or phrases |

Remodelled Lesson Plan

<table>
<thead>
<tr>
<th>Activity</th>
<th>Question</th>
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<tr>
<td>I. The objectives of this lesson are three-fold:</td>
<td>1. Can you interpret these drawings?</td>
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<tr>
<td>a) To reinforce your problem solving skills</td>
<td>2. What do they appear to be?</td>
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<td>b) To help students determine what skills are used so that the process can be duplicated in the future</td>
<td>3. Can you associate these drawings with anything that you are familiar with?</td>
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<td>c) To introduce the concept of evolution</td>
<td>4. What thought processes are you using? S-28</td>
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<td>II. On the board, when the students enter, are two drawings of the skulls (profile) and foot (front view)</td>
<td>5. Are you assessing all information available to you?</td>
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<tr>
<td>1. <em>Hyracothemum</em> and</td>
<td>6. Where is that information coming from? S-33</td>
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<tr>
<td>2. <em>Merychippus</em></td>
<td>7. How would you explain the changes in these drawings? You have five minutes to write your own explanation of the evolution of this animal. S-12</td>
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<tr>
<td>III. List answers to questions on board.</td>
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V. "Now I will give you the theories of two men who have been very influential in the study of evolution" ... First, Darwin's theory.

   a) the planet is not static but changing.
   b) Similar organisms have a common ancestor
   c) Natural selection
      1. In every generation, an enormous amount of variation occurs
      2. The individual best adapted to the environment is the one that will survive.
   d) Acquisition of traits through use and disuse as well as adaptation
   e) The inheritance of acquired traits.

The second man is a Frenchman, LaMarck. He has also been a major influence on evolutionary theory. LaMarck's Theory:

   a) There exists in organisms a built-in drive toward perfection.
   b) Therefore, there is a progression in nature from simple and small (primitive) to large and complex (advanced) to man (perfection).
   c) There is a frequent occurrence of spontaneous generation so that each organism represents a separate line of descent.
   d) Organisms have the capacity to adapt to the changes in the environment, therefore they may acquire characteristics.
   e) The inheritance of acquired traits.

VI. Write the name of the theory next to the explanations on the board.

VII. The major differences between the study of genetics and evolution are the concepts of direction and time.

Now try to associate these concepts with direction.

VIII.

IX. For homework: Evaluate your theory with regard to acceptable scientific statements and rewrite it

8. From where did Darwin draw this statement?

9. On whose writings did Darwin base this statement?
10. What constitutes biological success? S-17 S-14

11. Who originated this theory?

12. Which theory is most like your own?
13. Which theory or part of a theory is most like the explanations on the board?

14. What are some different concepts of time?
15. Which direction of time is LaMarck concerned with?
16. Darwin?
17. Once again before we leave, list the critical thinking skills you have used today. S-28