REVISING GEOLOGY LABS TO EXPLICITLY USE THE SCIENTIFIC METHOD

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ABSTRACT

Many content- or skill-based labs can be revised to explicitly involve the scientific method by asking students to propose hypotheses before making observations. Labs in which this method has been successfully applied include skill-building labs such as topographic map labs, content-based labs involving experiments with models, and field labs. Because these labs force students to state their expectations before making observations, they allow students to test their own models for various processes, making the students feel more engaged in the observations. Students' self-assessment shows that they felt that they learned a great deal from this style of labs, and that they found the labs to be fun. However, students felt that they learned little about the scientific method because they believed they already understood it, although other assessment methods suggest that their understanding was incomplete. By explicitly asking students to state and test hypotheses in the course of many labs, this type of exercise reinforces other discussions of the scientific method, and gives students a better understanding of how scientists think.

Keywords: Education - undergraduate, history and philosophy of science.

INTRODUCTION

Introductory geology courses frequently serve as general education courses that fulfill natural science graduation requirements. These introductory geology courses are, in many cases, the last exposure non-science majors will ever have to the natural sciences. Thus, geologists have the last opportunity to teach many members of the general public how scientists think.

The best way to learn how scientists think is to do science. That belief underlies lab science requirements at schools that require a lab course. Many introductory courses have added group research projects to their curriculum in order to force students to apply the scientific method, to learn to deal with ambiguous data, and to work in groups (e.g. Smith, 1995; Dunnivant and others, 1999). These projects can be the most worthwhile part of a student's introductory course experience, convince students that doing science can be fun, and turn students who considered themselves non-scientists into geology majors. However, for other students, these research projects are primarily exercises in frustration, as they struggle to simultaneously figure out what question to ask, how to design a research project, and how to find mutually convenient times to meet with their research group. The logistical problems involved in a research project can become the students' primary focus, and the understanding of the scientific method may get lost beneath the details of when to meet and what to do.

The scientific method, alone, is fairly simple, however, and does not require a long, involved research project to be applied. At its most basic, the scientific method simply requires making a prediction and testing that prediction in a manner in which it can be falsified.

Most content-based geology labs (e.g., Busch, 2000; Tarbuck and others, 2000) involve students making some sort of observation, and then inferring something about more general geologic principles from their observations. This is typically the case whether in the field or indoors, and whether the lab involves using samples, maps, or experimental equipment. Scientists frequently work in this way; however, they also test the general principles they develop by making other observations. Unfortunately, in my experience, the weakest students are often confused by labs in which they are expected to infer general principles from their observations. Those students are unsure exactly what they are supposed to be observing, and they figure out the general principles they are supposed to list as answers by asking their classmates, their TA, or their instructor, or by reading their textbook.

I have begun revising many of the labs that I use to explicitly involve the scientific method in short, content-based or skill-building labs as well as in longer research projects. This format has a number of advantages. It was originally devised to reinforce discussions of the scientific method by emphasizing how often it can be applied. In addition, it focuses students' attention on the concepts that they should understand as a result of the lab and shows students the application of techniques they learn in skill-building labs. By asking students about their expectations before they make observations, this format also provides a type of pre-assessment and an insight into students' pre-existing misconceptions. It also can help students re-examine their misunderstanding of some concepts. Finally, the students enjoy these labs, perhaps because it is fun to do experiments when they have thought about what they expect to happen beforehand.

DESCRIPTION OF METHOD

Many existing labs can be revised to explicitly incorporate the scientific method. Every time the student is asked to make an observation, he or she is first asked to predict what the results of that observation might be. Depending on the background the student has in the subject before coming to lab, the student might be asked to justify his or her hypothesis before performing the test. Then, the student performs the test, in some cases following carefully prescribed steps and in others, choosing exactly which test to perform. The student records the results and then explains whether the results falsify or support the hypothesis. The student may or may not be asked to discuss the implications of the hypothesis further.

Student fears of being wrong are possibly the biggest obstacle to a thorough understanding of the scientific method. Because grading is frequently done on the basis of whether students have the correct answer or not, many students are more concerned with having the right answer than understanding the concepts. The scientific method seems particularly bizarre – "scientists design

Manual (Mechenich, 1995)	Our lab
14. Concept: Pumping wells draw water toward them from all directions. The water table gradually becomes lower around a well in an unconfined aquifer as water is withdrawn from the ground. The unsaturated zone (the zone which has been dewatered) around the well is called the cone of depression or drawdown cone. Activity: Use a syringe to withdraw water from well 2. Observe that the dye level in piezometer D, and to a lesser extent the dye levels in piezometers B and C, becomes lower as you pump well 2. Notice that dye traces from above, below, to the right and to the left all move toward the bottom of the pumping well. Discussion: Pumping the well causes a zone around it to become unsaturated. This unsaturated zone is called a cone of depression. The slope of the water table from the water level in the pumping well to the surrounding areas is much greater than the normal slope of the water table, so water can move toward the well much faster than it normally would. The cone of depression is three-dimensional, so water can be drawn toward the well from any direction, even the direction that we would normally consider to be "downstream". If you vary the pumping rate on the syringe, you can observe changes in the size and shape of the cone of depression by observing the changes in the water level in surrounding piezometers and the change in the rate at which dye traces are drawn toward the well.	Part 3: Effects of pumping wells Groundwater is a major source of drinking and irrigation water in most parts of the US. The purpose of this part of the lab is to investigate how pumping water out of wells affects groundwater flow. 1) What would you expect to happen to the groundwater table near a well that is being pumped? Would the flow direction change or stay the same? Come up with a hypothesis about how pumping water from a well should affect the flow of nearby water. • To test your hypothesis: use the large syringe to suck water out of well 2. While one member of the group is "pumping" water out of the well with the syringe, the other members of the group should measure the height of water in piezometers B, C, and D and observe the movement of the blue dye injected into the bottom of each of the piezometers. 2) Sketch the results of your pumping experiment. 3) What happened to the contaminant (red dye) supplied by the "landfill" in Part 2 when you pumped well 2? 4) Continue pumping well 2. If piezometer C were your neighbor's water well, what would happen to her water supply eventually?

Table 1. Comparison between description of well pumping exercise from the manual that came with the model and my adaptation of the exercise for the lab.

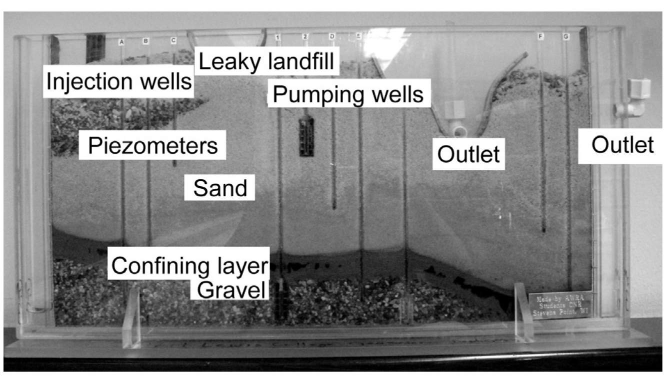

Figure 1. Groundwater model used in the groudwater lab.

experiments that should, ideally, be able to show they are wrong? No way!" We have gotten around this fear on the part of students by not grading the hypotheses in the labs, even if the hypotheses are entirely unreasonable. The hypotheses are graded solely based on whether they are present or not. (However, the reasoning behind a hypothesis can be graded, particularly if the hypothesis deals with material previously covered in other class work.) The labs are graded based on whether the students performed the tests correctly, whether they understand whether their hypothesis was falsified or supported, and the explanations and/or discussion of their results.

EXAMPLES

During winter semester 2001, I revised four out of eleven labs in an Earth Systems Science course to explicitly incorporate the use of hypotheses. The class is an introductory course taught every semester in two or three lecture sections of approximately 40 to 50 students each. Each lecture section follows the same basic syllabus, although the sections are taught by different faculty members. All students are required to take a lab, which is taught in 4 to 6 sections of 15 to 30 students each. All lab sections are taught by faculty members, occasionally with the assistance of undergraduate lab assistants.

Three of the four revised labs were indoors: a topographic maps lab, a lab on physical processes contributing to weather, and a groundwater lab using the models built by the Groundwater Model Project at the University of Wisconsin, Stevens Point. The fourth lab was an outdoor lab, observing the results of weathering in a cemetery. To illustrate how student-generated hypotheses can be incorporated into a variety of different types of labs, examples from the groundwater, topographic maps, and weathering labs are given below.

Revised topographic maps lab

Part I: Using topographic maps to test hypotheses

Before looking at the maps, go outside with your lab instructor to formulate hypotheses in response to the following questions.

1. Is it farther as the crow flies from the top of Perins Peak to the top of Smelter Mountain, or from the top of Smelter Mountain to the bench beside the chapel on campus?

[other questions omitted]

Using the map scale and topographic contours, you can test any hypothesis that deals with horizontal and vertical distances.

1. Test your hypothesis about the relative distances between the top of Perins Peak, the top of Smelter Mountain, and the chapel on campus.

- Find the top of Perins Peak, the top of Smelter Mountain, and the chapel on campus on your topographic map.
- Using your ruler, measure the distance between the top of Perins Peak and the top of Smelter Mountain and the top of Smelter Mountain and the chapel.

Map distance: Perins to Smelter
Map distance: Smelter to Chapel
Now, using whatever type of scale is available on your map, translate your map distance into the true distance.
True distance: Perins to Smelter
True distance: Smelter to Chapel
Does your answer support or falsify your hypothesis?

Part II: Using topographic maps to generate hypotheses

You can also use a topographic map to generate hypotheses that you can test directly, by making field observations or by performing another type of experiment. In this part of the lab, you will make observations on your topographic map about the Animas River. You will be testing these hypotheses later in the semester, by examining the record of flooding along the Animas River and during a field trip to look at the Animas River.

Examine two segments of the Animas River: from Baker's Bridge to Trimble Lane, and from Trimble Lane to the 32nd St. bridge in Durango.

1. Sketch the shape of the river along each segment. How do the two segments appear different from one another?

2. Determine the minimum and maximum width of the river valley in each section.

Baker's Bridge to Trimble Lane: minimum width
Baker's Bridge to Trimble Lane: maximum width
Trimble Lane to 32nd St.: minimum width
Trimble Lane to 32nd St.: maximum width

3. Determine the gradient of the river along each stretch.

Elevation at Baker's Bridge
Elevation at Trimble Lane
Elevation at 32nd St.
Elevation difference, Baker's Bridge to Trimble Lane
Elevation difference, Trimble Lane to 32nd St.
Horizontal length of river, Baker's Bridge to Trimble Lane
Horizontal length of river, Trimble Lane to 32nd St.
Gradient of river, Baker's Bridge to Trimble Lane
Gradient of river, Trimble Lane to 32nd St.

4. Generate a hypothesis: why is there a difference in the shape of the river's path upstream and downstream of Trimble Lane? In which stretch of the river do you think the water travels fastest? In which stretch of the river do you think the water carries the most sediment? In which stretch of the river do you think the river carries the largest grain sizes of sediment?

5. Suggest a way to test your hypotheses. You will have the opportunity to test them during the field trip later this semester.

Table 2. Examples of questions from the revised topographic maps lab.

Revised weathering lab

Part I: Before leaving for the cemetery.

1. Rock review: classify each of the rock types listed above as mafic igneous, felsic igneous, metamorphic, or sedimentary.

2. Mineral review: which minerals that we studied in Lab 4 might you expect to find in each of these rock types?

3. a. Propose a hypothesis that states which rock types you would expect to undergo the most rapid physical weathering. Express your hypothesis as a list, from the rocks you expect to weather fastest to those you expect to weather most slowly. (You will not be graded on your hypothesis; however, you will be graded on how well you test your hypothesis and on the reasoning on which your hypothesis is based.)

b. Why did you expect the rocks that are at the top of your list to weather the most rapidly? What processes do you expect would be most important for physical weathering in Durango?

4. a. Propose a hypothesis that states which rock types you would expect to undergo the most rapid chemical weathering. Express your hypothesis as a list, from the rocks you expect to weather fastest to those you expect to weather most slowly.

b. Why did you expect the rocks that are at the top of your list to weather the most rapidly? What processes do you expect would be most important for chemical weathering in Durango?

5. a. Which type of weathering, physical or chemical, do you expect to be most important in Durango? Why?

b. You will probably have a hard time telling the difference between physical and chemical weathering on the tombstones. Think about which weathering processes you expect to dominate. Then make a final list of the rock types from those that you expect to find most weathered to those that you expect to be least weathered.

Part II: At the cemetery.

On the table on the next page, you are given a list of tombstones. For each tombstone, 1) locate it; 2) record the date; 3) identify the rock from which the tombstone is made; 4) identify the degree of weathering of the rock (using the scale listed below), and 5) describe the weathering in more detail.

[weathering scale and directions to tombstones omitted]

6. Put the list of tombstones, their rock types, and dates into order from most weathered to least weathered.

	Name	Rock Type	Date
Most Weathered			
Least Weathered			

7. Based on your results in question 6, list the rock types from least resistant to weathering to most resistant to weathering. Consider the age of each tombstone as well as its degree of weathering.

8. Compare your list in question 6 to the lists you hypothesized at the beginning of the lab. Were your hypotheses confirmed or falsified?

Table 3. Examples from revised weathering lab.

Groundwater Lab - The manual provided with the groundwater model built by the Groundwater Model Project at the University of Wisconsin Stevens Point (Mechenich, 1995) lists a number of different demonstrations that can be used to illustrate basic groundwater concepts. Rather than using the model primarily as a demonstration device, however, we have found that having students experiment with the models themselves is both an effective way to learn groundwater flow concepts and a great deal of fun for the students.

The lab is used during the week that groundwater is discussed in lecture, so students have some background before coming to lab, but are still struggling with concepts relating to groundwater flow. It is organized with groups of two to four students working with a single groundwater model. The models are composed of a narrow plexiglass box filled with layers of sand, gravel, and a confining layer consisting of silt to fine sand mixed with 8% bentonite (Mechenich, 1995), with three wells for injecting dye, seven piezometers, two pumping wells, and two lower elevation regions with permeable bases, representing a leaky landfill and a lake or river (Figure 1).

One of the suggested demonstrations and its adaptation are shown in Table 1. The manual explains the concept to be learned (pumping wells draw water to them from all directions), then describes how to use the model to demonstrate the concept, and finally discusses how water moves in the cone of depression. Our lab's

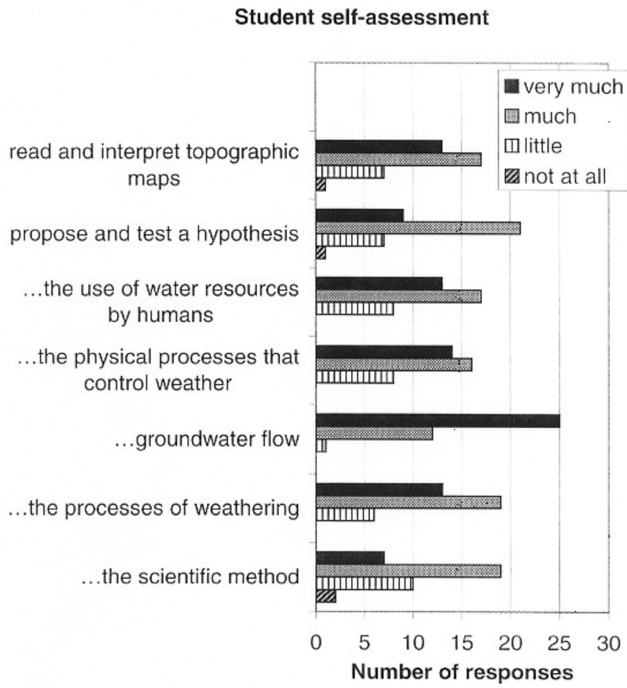

Figure 2. Student responses to assessment question "To what extend did the Earth Science Lab improve your ability to/your understanding of:" Each of these concepts and skills was emphasized in one of the revised labs.

section on pumping wells begins with a brief statement about the societal importance of wells, then asks students to predict what will happen in the model after pumping water out of one of the simulated wells. Typical predictions include statements such as "The water table will drop" (a correct prediction) or "The flow direction will stay the same" (an incorrect prediction, particularly near the pumping well). After making the prediction, students follow similar instructions to those in the groundwater manual in order to test their hypotheses. They are asked to sketch and describe their observations, and then discuss some implications for people who could live in the area. Students typically react quite vocally when their observations do not match their predictions, because one of the dye markers is supposed to represent pollution from a leaky landfill. In some of the other parts of the adapted lab, students are asked whether their prediction was supported or falsified, and asked to explain what happened if their prediction did not match the results.

Topographic Maps Lab - The ability to read and interpret topographic maps is a useful skill for any student, whether or not they plan to study more geology. In a typical introductory geology course, some students are already quite familiar with topographic maps, whereas others have a great deal of difficulty with the concept. Our topographic maps lab is the second lab of the semester. There is no discussion of topographic maps in lecture, so for some students, this is their first experience with them. The purpose of our lab is to teach basic concepts (types of horizontal scales, contour lines, determining horizontal and vertical distances on a map, calculating gradients) without boring the students who have used topographic maps before, and with the least amount of confusion for students encountering them for the first time. We used topographic maps of the area around campus during the lab, to make the connection between the map and the landscape easier, and we used the maps as a means to both test and generate hypotheses.

We incorporated student-generated predictions into the lab in two manners (Table 2). First, the students predicted horizontal and vertical distances and gradients based on landmarks they could see from campus. These predictions were generally very mundane: "Farther from Perins to Smelter," for example. Second, students made observations about the gradient and other features of two sections of a river near campus to propose hypotheses about why the river's channel has different shapes (meandering and braided) in different areas. The final hypothesis was designed to be tested during a lab later in the semester, after students had studied stream processes. The hypotheses for the differences in channel shapes were more speculative (students had no background in river behavior before the lab) than the predictions in the earlier parts of the lab: "Because there is more water upstream," for instance.

Weathering Lab - For a lab on weathering, I adapted an exercise on gravestone weathering that had been used previously in the department. Similar labs are described by Roberts (2000). The original version of the exercise asked students to locate and describe the rock type and degree of weathering of twelve tombstones in a local cemetery. After making the observations, students were asked to infer general principles about rates of weathering.

In the revised version of the lab (Table 3), students are asked to generate a hypothesis about which of several possible rock types should weather most quickly. Because the weathering lab takes place after discussions of minerals, rocks, and weathering in lecture, we expected students to come up with fairly good predictions. After locating the tombstones and describing their rock type and degree of weathering, students place the tombstones into a list from most weathered to least weathered. They compare this list with their prediction of which rocks should have weathered the most, and use their observations to test their hypothesis.

ASSESSMENT

Revising the labs had several purposes: 1) to improve student understanding of the scientific method; 2) to improve student understanding of the concepts involved in the labs by making the students think about the concepts multiple times – while formulating a hypothesis, while making observations, and while comparing their predictions to the results of the tests; and 3) to make skill-building labs (such as the topographic maps lab) more fun by adding an element of problem-solving to the lab.

I assessed the success of the labs in three different ways: 1) students completed a self-assessment survey during the last lab period, 2) one question on the final exam explicitly asked students to identify hypotheses and potential tests of hypotheses involving global warming, and 3) I evaluated presentations of the final

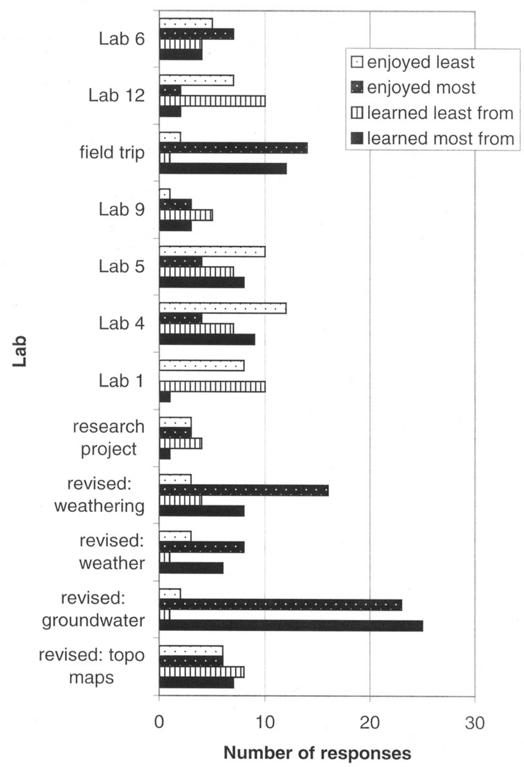

Figure 3. Responses to open-ended survey questions. Students were asked to list the three labs from which they learned most, the three labs from which they learned the least, the three labs they enjoyed most, and the three labs they enjoyed least. The four labs which were revised to explicitly incorporate the scientific method are listed at the bottom.

group projects based on whether students were able to clearly state their hypotheses and whether the tests of their hypotheses were appropriate and relevant.

The assessment methods did not directly test whether the revised labs accomplished their goals. The revised labs were not the only situations in which students encountered the scientific method – it was discussed during lecture, one lab was devoted to discussion of the scientific method itself, and students completed a self-directed group research project. Therefore, it is difficult to say exactly what affect the revision of the four labs had on student understanding of the scientific method. Furthermore, we did not assess the course in exactly the same way during the previous semester, so we can not directly compare the assessment of students who completed the course before the labs were revised with that of students after the revision. Finally, many other factors contribute to whether or not students enjoyed a lab or felt they learned a great deal in a lab. The most important factors in whether a student enjoyed a lab seemed to be whether the student perceived it as being "hands-on" and whether it involved going outside. The most important factor in whether a student felt he or she had learned a great deal from the lab was whether the student had previous experience with the skills and concepts in the lab, which varied from student to student. However, the assessment results give some insight into what the students learned or felt they learned.

Student Self-assessment - In the self-assessment survey, I asked students a) whether the labs helped improve their understanding of certain concepts or their ability to apply various skills, b) which labs they learned the most and the least from, and c) which labs they enjoyed the most and the least.

Student assessment of concepts and skills - Out of the 38 students (two lab sections) who took the survey, at least two-thirds felt that the labs had contributed much or very much to improving their understanding of all of the skills and concepts on the survey (Figure 2). The concept that the students felt they learned best in the labs had to do with groundwater flow (66% - improved very much; 97% - improved much or very much). Students rated the other concepts and skills developed during the revised labs (understanding the processes involved in weathering, understanding the physical processes governing weather, and the ability to read and interpret topographic maps) similarly to all the other skills (approximately one-third of the students felt the labs had helped them very much, and 79 to 84% of the students felt that the labs contributed much or very much to their understanding).

In contrast, students did not feel that the labs improved their ability to differentiate between facts and hypotheses, propose and test hypotheses, or understand the scientific method particularly well (Figure 2). These responses may pertain more to the success of the lab dealing specifically with the scientific method and with the group project than to the success of the revised labs (in which the role of the scientific method was subordinate to the content of the lab). One student commented that she already knew about the scientific method prior to taking the course, so the labs did not add much to her understanding; I suspect that most of the students felt similarly. However, as shown by other assessment methods and by grades on the scientific method lab (the first lab of the semester), many students did not understand the scientific method as well as they thought they did.

Student response to open-ended questions - Students were also asked to list the three labs that they learned the most from, the labs they learned the least from, and the three labs that they enjoyed the most and the least. Student response to the revised labs, when measured in this manner, was as good or better than the response to the other labs (Figure 3). For each of the revised labs, the number of students who listed the lab as one of their favorites was greater than or nearly equal to the number of students who liked the lab least. The groundwater lab was a clear favorite, with 66% of the students listing it as one of the labs from which they learned the most. The only one of the revised labs for which student opinion was mixed (as opposed to clearly positive) was the topographic maps lab; approximately equal numbers of students (15% of the class in each case) enjoyed it most and enjoyed it least. Student comments indicated that many of the students who felt they had learned less from the topographic maps lab than from the others were students who already were comfortable reading topographic maps. Given the number of experienced outdoorspeople in our student population and the skill-building nature of the lab, it is very encouraging that 15% students listed the lab as one of their favorites.

In contrast, most of the other labs had evenly divided to negative student opinions (that is, in most cases more students listed a particular lab as one of their least favorites than listed it as a favorite) (Figure 3). The only unrevised lab that students enjoyed as much or more than the revised labs was a field trip to look at the geologic history and geologic hazards in the local area – an outdoor lab on one of the first really nice days of the spring.

Assessment Based on Exam Question - One of the final exam questions was partly designed to test student understanding of the scientific method: List three facts and three hypotheses discussed in global warming debates. For each of the hypotheses, how could it be tested?" The exam question revealed that, out of 48 students, approximately two-thirds of the class had a solid understanding of hypotheses at the end of the semester, while one-third of the students had some problem identifying facts or hypotheses. Of the students who had some difficulty distinguishing facts from hypotheses, four labeled one hypothesis as a fact, five mis-identified more than one fact or hypothesis, and two listed problems and potential solutions rather than hypotheses and tests. All but two of the 48 students gave answers that implied that they had some understanding of what was meant by the term "hypothesis."

Assessment Based on Evaluation of Student Research Projects - Between my two lab sections, I had eleven different groups working on semester-long research projects. In the final written, oral, and poster presentations, only two groups had difficulty articulating their hypothesis and the tests related to that hypothesis. During the previous semester, before we revised several of the labs, at least five out of eleven groups presented projects that advocated solutions to a problem rather projects that tested a hypothesis, despite the fact that the evaluation criteria for the project stated several times that the hypothesis must be clearly stated.

DISCUSSION

The assessment suggests that, although students felt they already understood the scientific method, not all students fully understood the nature of hypotheses at the end of the semester. However, student understanding of hypotheses and the scientific method as measured by performance on the final exam and the research project seemed to be better than during the previous semester. This suggests that students need repeated exposure to the scientific method to fully grasp it. Lectures on the scientific method, labs designed to generate and test non-geologic hypotheses, and even independent research projects alone do not result in all students understanding what scientists do. It is important to work aspects of the scientific method into parts of the course that deal with course content, both in lab and during lecture, for students to really understand the way scientists think.

The tests of predictions that students make in our revised labs are only a small part of the range of activities that are part of the scientific method. These small predictions are not the same kind of sophisticated hypotheses that lead to major funded research projects. They also do not reflect the tests of multiple working hypotheses that geologists usually use (e.g. Cleland, 2001). These revised labs should not be the only way students are exposed to the scientific method. However, they do allow students to test parts of their models for the way the earth works against evidence that they can observe, and testing predictions against evidence is part of what scientists do.

On the other hand, the student self-assessment suggested that the revised labs did succeed in improving student understanding of the material in the lab. For the most part, students felt that they learned particularly well from the revised labs, although when questioned about particular skills and concepts, the only concepts from the revised labs that stood out as particularly well-learned were those in the groundwater lab.

It is not clear whether the revision of the labs affected how much fun the students had. Students generally enjoyed the revised labs more than the unrevised labs. However, their comments revealed that the primary factor that controlled how much a student enjoyed a particular lab involved how hands-on the students considered the lab, although students differed as to which labs they considered more "hands-on." The groundwater lab, one of the labs in which the hypothesis format was used, was one of the students' favorite labs, but they found it fun because they were allowed to play with a model that responded quickly to their experiments. On the other hand, some students may feel that a lab is more "hands-on" when they are testing their predictions.

CONCLUSIONS

Revising content-based and skill-building labs to incorporate student-generated predictions does not, and should not, replace projects in which students are required to come up with their own methods of answering open-ended questions. These labs can, however, add an additional element of critical thinking into labs that are primarily focused on covering particular content in an efficient manner. Asking students to commit to a hypothesis before making observations takes very little additional time in a lab, and can require fairly minor revision of existing labs. It reveals the models students used to understand the world before encountering the subject in lab, and it allows them to test and falsify those models. It focuses student attention on the problem addressed in the lab and makes clear the purpose of the observations they are asked to make. Finally, it provides models for applying the scientific method that students can consider when they try to design tests for open-ended research questions in this or other courses.

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