The Nature of Science

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Abstract:

College freshmen lack an understanding of the scientific process. Many textbooks contribute to this misunderstanding by presenting a formulaic scientific method that obscures the logical underpinnings of science and its creative, adaptive, and collaborative nature. After completing a survey of their understanding of the nature of science, students participate in activities requiring them to make observations, propose explanations, cite evidence to support their explanation and modify their explanation when presented with new or conflicting evidence. This lab stimulates student interaction with each other and the instructor as they learn the tentative nature of scientific explanations and the value of collaboration.

Introduction

College freshmen lack an understanding of the scientific process. Many textbooks contribute to this misunderstanding by presenting a formulaic scientific method that obscures the logical underpinnings of science and its creative, adaptive, and collaborative nature. We began searching for ways to improve students' understanding and appreciation of the scientific process. The laboratory seemed to be the most effective way to teach the process of science by having students do science.

What is a typical first laboratory for most introductory biology courses? Often it involves teaching a skill that will be required in subsequent laboratories, such as use of the microscope, measuring, etc. Our non-majors course followed the same approach where we taught students to use the microscope after a 20-minute introductory lecture on lab policies and procedures. For most of the lab students retreated into their shells, communicating neither with each other or the instructor. Later labs required students to observe, propose hypotheses, cite evidence, etc. producing a steadily increasing level of frustration. We decided to go a different direction. Many majors laboratories begin by giving students experience in asking questions, proposing hypotheses, making predictions and designing experiments. Why not try a similar approach with non-majors? We settled on some activities that encourage observation, proposing explanations, applying evidence from the observations to support the explanations, modifying explanations when presented with new or conflicting information, and sharing information and collaborating with other groups to reach a conclusion. We hoped that through this process and the activities that followed in the remainder of the course, students would develop an appreciation of the tentative nature of scientific knowledge, the need for evidence to support conclusions, and the potential role of prior experience and knowledge in shaping observations, conclusions, and observations.

This exercise, as delivered at our institution, lasts one hour and fifty minutes, but it can be lengthened. This lab is ideal for introductory biology courses, particularly for non-majors. Students have responded extremely well and become immediately engaged with each other and the instructor. The activities can also be separated and used as full group or small group activities in a large lecture setting. The set up is easy and the materials cost little.

Student Outline

"Science is an intellectual activity carried on by humans that is designed to discover information about the natural world in which humans live and to discover the ways in which this information can be organized into meaningful patterns. A primary aim of science is to collect facts (data). An ultimate purpose of science is to discern the order that exists between and amongst the various facts." (Gottlieb, 1997)

What do you know about the nature of science?

Because biology is one of the natural sciences, it is important that you understand the nature of science and how the scientific process works. You probably have had two or more science courses in high school, so most of you have developed ideas about science and how it works. We will begin today's lab with a brief assessment of those ideas.

Your instructor will distribute a brief True/False quiz about the nature of science. This quiz is anonymous, so respond to the questions according to what you think is true, rather than what you think your instructor wants to hear.

The Process of Science:

From the statement that begins this exercise, you can see that science is about discovery. While discoveries are sometimes made even though we are not searching for them, most discoveries result from our attempts to answer questions that we or someone else have posed. So most scientific endeavors begin with a question or perhaps several questions. The scientist's first task becomes selecting which question to answer according to whether it is answerable. Some questions cannot be answered by science because they involve non-natural phenomena or phenomena that cannot be observed or tested. Once you have chosen the question to answer, you will begin to suggest possible answers. Like questions, not all possible answers are scientific. For an answer to be scientific answer it must be testable and it must be falsifiable. A scientific answer is called a hypothesis and must be tested and supported by evidence before it is accepted. Theories are broad explanations that are supported by tested hypotheses and often generate new questions and hypotheses. Your next activity will allow you to pose and answer questions about observations that you make. Later in the semester we will begin to test answers that you propose to questions.

Proposing Explanations for Fossil Footprints

During this activity you will engage in a number of intellectual exercises routinely performed by scientists. You will:

- Answer questions by making observations
- Propose explanations and make predictions based on evidence.
- Recognize and analyze alternative explanations and predictions.
- Identify additional evidence that is required to support or falsify alternative explanations and predictions.
- Understand that scientific explanations are subject to change as new evidence becomes available.
- Understand that scientific explanations must meet certain criteria.
  - They must be consistent with experimental and observational evidence
  - They must make accurate predictions about the phenomena being studied
  - They should be logical, respect the rules of evidence, and be open to criticism
  - They should include methods and procedures
  - They should be reported to the public for evaluation and criticism
- Understand that explanations of how the natural world changes based on myths, personal beliefs, religious values, mystical inspiration, superstition, or authority may be personally useful or socially relevant, but they are not scientific

Observe the scene on the projection screen at the front of the room. These are fossilized tracks similar to those commonly found in New England and the southwestern United States. You will attempt to reconstruct happenings from the geological past by analyzing this set of tracks and form a defensible explanation of the past events associated with these tracks based only on what you can see.

1. Write your observations about the tracks.
2. Use your observations as evidence to write your explanation of the event(s).
3. What questions remain about the tracks and what do you think the answers will be to those questions?

4. What evidence do you need to support your answers to the above questions?
5. After examining a second section of fossil tracks, record your observations and use these observations to either revise your explanation or support your previous explanation.
6. Write any additional questions, proposed answers and required evidence.
7. Examine the third section of tracks, record your observations and use these observations to either revise your explanation or support your previous explanation.
8. Share your final explanation with the class. Be prepared to defend your answers/explanation. Record the lab's consensus explanation.

The Checks Lab

This activity is designed to help you experience the nature of science; that it is built on evidence that can be observed or inferred from the natural world. However, this evidence can sometimes be confusing, seemingly conflicting, and apparently random. Furthermore, each new bit of evidence often creates more questions than it answers. This activity illustrates that scientific explanations are only tentative; because new discoveries may show that previous hypotheses were incorrect.

No scientist or scientific group works alone. This activity will demonstrate the value of collaboration within each group and with other groups in order to arrive at a reasonable explanation of the problem.

There is at least one other characteristic of science that is not usually appreciated or realized by people in the non-scientific community. See if you recognize it.

Directions

1. Each group will receive an envelope containing 16 checks written by fictional characters. Do not look at any of the checks until instructed to do so. When directed and with out looking at the checks in the envelope, remove **four** of the checks from the envelope and place them on the lab table.
2. Do not allow other groups to examine your data at this time.
3. Observe the information on the checks. List the different types of information available.
4. Try to formulate a tentative explanation for, or a storyline represented by, the checks. This is your original hypothesis. Record this with your evidence or rationale for the explanation.
5. When directed, remove four more checks from the envelope. Examine the checks. Are there any new kinds of information not present on the previous 4 checks? If so record them.
6. Is your previous explanation supported by the information on these checks?
   a. If so, explain how it supports your first explanation.
   b. If not, does the new information require that you modify your first explanation or does it require that you start over? Write your modified or new explanation and include the supporting evidence.
7. When directed, remove two final checks from the envelope. Record the new kinds of information, if present.
8. Indicate below what changes need to be made in your explanation and the evidence supporting it. Write this version of your explanation.
9. Do Not remove any more checks. Scientists never have all the data they might need to reach the highest level of confidence in their explanations.

10. Choose a spokesperson to present the group's final explanation to the class. This simulates the sharing process of scientists at symposia and by publishing. Be prepared to defend your explanation by using your data (the checks) and your rationale for reaching the explanation. If you disagree with a group's explanation, you should ask them to defend their explanation, but you must be prepared to offer evidence to contradict their explanation
11. What new information did you discover from other groups?
12. After hearing the explanations from other groups, do you need to modify your explanation? If so, indicate how it is changed and why you were convinced to change it.
13. Answer the following questions

Questions

1. Did you prove your explanation (hypothesis) was correct? Explain why or why not.
2. What kinds of information were most valuable to your group in constructing your explanation?
3. What information was useless or misleading?
4. After completing this exercise and the tracks exercise, why do we say that a hypothesis in science is "tentative?"
5. Would it be possible for your hypothesis (explanation) to become a theory? Explain why or why not.
6. What characteristic(s) of science are not appreciated or realized by people in the non-scientific community.

What Did You Learn?

At this time you will repeat the survey from the beginning of the lab. After completing the survey we will discuss each of the questions and your answers.

Notes for the Instructor

At Southwestern, we have been using this exercise for the last two years as our first laboratory in Biological Concepts, our non-majors introductory course. It has been received very well both by students and instructors. It replaced a typical introduction to the microscope exercise that required almost no interaction between students and little with the instructor except to explain why the letter "e" disappeared from their field of view when they changed objectives. Since the 2009 meeting, comments I have received from individuals who have implemented this lab indicated a similar response from students. The initial set up for this lab is relatively simple and the materials are available on the Internet. Our lab periods are an hour and fifty minutes, but the activity can easily be expanded by additional discussion following each activity and repeating the survey as a post-test at the end of the lab.

The first activity is a survey of understanding and attitudes about science. We administer the survey on an electronically graded form and compile the results for all instructors. The survey can be administered a second time as a post-course assessment. Questions for this survey can be written by teaching staff or drawn from other sources. We use questions from pre- and post-tests developed by the Evolution Education Institute < http://www.evolutioneducation.org/Downloads.htm > and questions written by the author based on articles "What Science Is" and What Science Is Not" at the Evolution and the Nature of Science Institutes (ENSI) <

http://www.indiana.edu/~ensiweb/lessons/unt.n.s.html >. Another way to administer the survey is by electronic personal response systems (clickers) that can provide instantaneous feedback.

The second activity presents students with a scenario and a series of three diagrams of fossil footprints. Students are to develop explanations for the prints as they view the sequence of fossil prints. Each image reveals a little more information requiring students to modify or justify the previous explanation. We have performed this activity three ways. First, the activity can be done with all members of the class stating their observations and then developing a class consensus explanation following each image. Second, we have done the activity as a small group activity with each group developing their own explanations and then sharing their explanations with the class after viewing all three images. We then develop a class consensus explanation. Third, we have the students develop their explanations individually and share them with the class at the end for the development of a consensus explanation. We prefer the small group format. This activity is adapted and the images are from an activity in the National Academy of Sciences publication *Teaching About Evolution and the Nature of Science* (p. 89). The images are downloadable from the online version or scanned from the publication and used for educational purposes. We clipped the three sections of the image and imported them into a PowerPoint presentation for our labs.

The third activity presents each group of students with an envelope containing the same 16 cancelled checks. Each group of students randomly draws a few checks at a time from their envelope (4 the first time, 4 the second time, and 2 the last time). They do not see all of the checks nor are they allowed to see other groups' checks. After each draw they most construct a story that is supported by the checks they have drawn. Again their story may be modified as they discover additional information. After constructing their final conclusion, each group presents their story to the rest of the lab. Groups are encouraged to challenge the other stories and provide the evidence for their criticism. The original activity at ENSI < http://www.indiana.edu/~ensiweb/lessons/chec.lab.html > allows students to see other groups' checks, but we have found that it is more interesting to withhold that information and let the groups try to convince each other of the validity of their conclusion. The Checks Lab site at ENSI has several downloadable versions of the checks. The most recent versions are three different sets in a higher resolution than the older sets. There is also a set of blank checks available if instructors wish to construct their own scenarios or have students do so. I place a code on the back of each check so I can easily resort them if the checks get mixed together. I also laminated all the checks so they can be reused numerous times (we have 20-25 lab sections each semester). Because each group sees only 10 of the 16 checks it is likely they will have different stories to tell and in other cases two groups seeing exactly the same checks may come up with different explanations. Some of the checks contain names of entities with which students are unfamiliar. These results serve to illustrate the nature of scientific information gathering and analysis. A final discussion can serve to reinforce students' understanding of the tentative nature of scientific knowledge. Finally, some of the checks in all three sets may indicate traumatic life experiences for the fictitious characters involved. Some workshop participants suggested that instructors be aware that some students may have an emotional reaction to the exercise. We have not had such an occurrence in our labs so far.

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About the Author

The author is associate professor of biology and chair of the department of biological sciences at Southwestern Oklahoma State University in Weatherford, Oklahoma. He has been the coordinator of Biological Concepts and Biological Concepts Laboratories, the non-majors introductory biology course, for the last 10 years. He is the editor of the course's lab manual, *Life: A Laboratory Experience*, and the author or co-author of several lab exercises. He was the first teacher of Principles of Biology and Principles of Biology Laboratory, the majors introductory biology course, and teaches or has taught human anatomy, human physiology, vertebrate natural history, and senior seminar in biological sciences. He has a Ph.D. in Zoology from the University of Oklahoma with research interests in reptile and amphibian physiological ecology, behavior, and natural history. He is a member of the boards of Oklahomans for Excellence in Science Education and Friends of the University of Oklahoma Biological Station.

Appendix

Biology 1004L: Biological Concepts Laboratory
Nature of Science Quiz

Do not write your name on the scantron form. You will need a #2 pencil. If you do not have one, one will be provided. Answer the following questions on the provided scantron form by completely darkening the lettered space that represents your answer.

True = A
False = B

1. A scientific hypothesis is best described as “an educated guess.”
2. Untestable hypotheses fall outside the realm of scientific inquiry.
3. Science can only answer questions about things that can be seen and observed.
4. Theories are facts that have not been proven.
5. Scientific theories have strong predictive potential and explain a single natural phenomenon.
6. Evolution is a scientific theory and not a scientific fact.
7. Once validated, scientific hypotheses are elevated to scientific laws.
8. An inability to disprove a hypothesis makes the hypothesis correct.
9. Science is limited to empirical means of investigation.
10. Scientific facts are never questioned.
11. In order to be considered a scientific investigation, controlled experimentation must be employed.
12. Scientists that contribute data substantiating existing theory are held in higher regard within the scientific community than are those that cause science to re-examine established theory.
13. Science is the most powerful tool of inquiry that humanity has ever devised. Correspondingly, science is well equipped to answer all questions.
14. Science and scientists are completely objective.
15. Only women and men who have completed years of specialized education and training can practice science.