

SCIENTIFIC INQUIRY: Steps, Skills and Action

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What do you teach in biology class that students will use throughout their lives? One of the most important lessons is an understanding of scientific inquiry. This process—the steps in a scientific investigation—is a useful way of acquiring accurate information about the world in which we live. It includes the ability to build an explanation based on credible evidence and logical reasoning. These critical thinking skills require more than a passing exposure. Students need to recognize them and practice using them. Through understanding the scientific inquiry process and being able to use it, students gain a powerful capability. The National Science Education Standards emphasize the importance of scientific inquiry in the science curriculum.

Not only is experience with scientific inquiry essential for those who plan to go on into any branch of scientific or medical work, an understanding of scientific inquiry is helpful in all walks of life. When we read a newspaper, go to a doctor, or go to vote, we often are faced with scientific information we need to analyze and use. An understanding of scientific inquiry helps us evaluate the information we encounter. Further, the critical thinking skills that are an integral part of scientific inquiry are useful in our every-day problem solving.

How can you give students what they need to begin to understand this process? You must provide them with quality examples to which they can relate. Students need to go far beyond the typical list of steps so often seen in an early chapter of a science textbook. They need to understand the ideas in a meaningful context and to appreciate how powerful this approach can be. In addition, if students are to be able to put these ideas and skills to use in the future, they need practice throughout the course to build a firm foundation. In this way, students internalize the concepts of scientific investigation in a way that they can call on them for future use.

As an introduction to the topic, the video program *Scientific Inquiry: Steps, Skills and Action* provides an excellent tool for helping students acquire these important capabilities. You can use the program as a way to capture students' interest in the topic and to set up a foundation of understanding early in the course. Then you can refer back to the ideas presented in the program throughout the course, applying them to any topic you study.

After watching the program *Scientific Inquiry: Steps, Skills and Action* and participating in the class activities included in this Teacher's Resource Book, your students will be able to:

- describe the significance of scientific inquiry
- recognize reliable data collected through scientific methods
- be aware that scientific explanations are strengthened through change
- explain the criteria by which an explanation is accepted into the body of reliable scientific knowledge
- understand the meaning of the term prediction with regard to scientific inquiry
- evaluate the reliability of information within the scope of scientific knowledge
- explain examples from the program in terms of scientific inquiry
- use the principles of scientific inquiry in science and every life situations

The program *Scientific Inquiry: Steps, Skills and Action* uses strong visual images and simple, accessible scientific examples to bring the steps in scientific investigation into view. The program starts with an overview of the process. Students learn that scientific explanations must be built on reliable evidence and on sound and logical reasoning. A single observation or experiment is not sufficient as evidence to support a hypothesis. Repeated observation or experimental results are needed. In addition, most scientific explanations are built on multiple lines of evidence. The more sources exist to support data, the stronger the explanation. In other words, the confidence scientists have in a particular explanation depends in part on the volume of and quality of the evidence supporting it.

Medical practitioners (or their forerunners) once thought that infectious disease was caused by bad humors in the blood and other parts of the body. This scientific explanation changed as new evidence was obtained, evidence that microscopic organisms cause infectious disease. Examples such as these and others from basic molecular biology are used to remind students that scientific explanations change. They may be surprised to learn that that change is actually a strength rather than a weakness.

A scientific explanation is currently the most accurate description of some feature of the natural world that scientists can build given the amount of data available. But as new data is acquired, it is tested against existing explanations. If the data are reliable and repeatable but do not fit the existing explanation, the explanation must be modified. This process may surprise some students who would assume that this discrepancy would be solved by ignoring the data—but the data (if carefully obtained) are factual observations of the natural world. It is their significance that must be interpreted and modified, so explanations change to fit data, not the other way around.

The introductory section of the *Scientific Inquiry: Steps, Skills and Action* program goes on to clearly state the main steps in scientific inquiry. First scientists must **get a good idea** or become curious about a particular problem. This process happens in two ways. One is through **observation** of some aspect or event in the natural world. Scientists don't always start with a specific hypothesis: first they must gather enough information to be able to form the hypothesis. Another way to gather information is through reports of **existing scientific knowledge**. In any event, an effective scientist will “consult the literature” on a particular topic before proceeding with an investigation if the idea has come from direct observation of nature.

The next step is to **ask a good question**. This step is far, far more difficult than it may seem. Students learn that a question that is too vague or of too large a scope will not be able to direct a scientific investigation. For this reason, an investigator often needs to **refine the question** before proceeding. This refinement step should involve rethinking the question or going to the library (or online) to find out what is already known on the topic.

Next the investigator may propose a tentative explanation or **hypothesis** that can be tested. A **prediction** is made based on the hypothesis and **tested** through additional observations or experiments. Results are carefully recorded and **analyzed** before the investigator **reaches a conclusion**. If the observed events match the prediction, the hypothesis is supported by the evidence. The investigator will need to **communicate** the results in a peer-reviewed forum such as a scientific meeting or publication. The video program presents these steps in a way that they can be understood as a disciplined process and not merely memorized.

The *Scientific Inquiry: Steps, Skills and Action* program presents these steps as a process to be followed and then reinforces this knowledge through the use of several simple but intriguing examples. By using easily understood examples, students are not put off by the scientific content. Instead, the matter is very accessible, allowing students to focus attention on the key aspects of scientific inquiry itself rather than getting lost in the details of the particular topic.

The first example takes us to the beach. The program shows a simple investigation of water purity to illustrate these steps. The idea for the investigation comes from a sign posted at a beach. The sign warns of danger: ocean water may be polluted for several days immediately after a rain. This raises the question, “Why is the ocean polluted after a rain?” One possible explanation is that surface runoff water from storm drains temporarily increases bacterial contamination in the ocean water soon after a rainfall. Stated this way, the explanation becomes a testable hypothesis.

Students see a student investigator go to the beach, collect water samples before a rain (as a control experiment) and after a rain. He takes the samples to a laboratory for testing. The program shows the samples being prepared as serial dilutions prior to plating on culture dishes with growth media in a solid agar support. Once the bacteria have had the chance to grow, the colonies are counted and a calculation determines the concentration of bacteria in each of the original samples of sea water. These quantitative results can be used to support or refute the prediction and hypothesis on which it was based.

Where else can the concepts of scientific inquiry be put to use? Another application of the thinking behind scientific inquiry is shown in a medical example. A patient who presents with a sore throat is assumed to have a bacterial infection and is treated with an antibiotic. But this approach can be made more reliable if some data about the infection is collected first. Students see a doctor taking a throat swab and see a pathology laboratory technician streaking the sample on a growth plate containing antibiotic disks. The results can be clearly viewed in the program: areas where bacteria have been killed or prevented from growing by the antibiotic appear as a halo around the disk containing that drug. If the bacteria are resistant to a particular antibiotic, the opaque lawn of cells grows right up to the disk. The results are obvious at a glance: students can determine if the antibiotic the doctor planned to prescribe was a good choice. In the case illustrated in the program, it was not. Results show

that the bacteria from the patient's throat grow in the presence of that particular antibiotic. Students are able to see that careful reasoning and additional evidence improve the chances of successful treatment for this infection.

The process of scientific inquiry can be applied to a huge variety of situations, particularly in research laboratories. An example from a plant genetic engineering laboratory shows how research is structured to build up an explanation through many small steps. In addition, the role of controls in experimental design is shown. Actual research problems involve many levels of inquiry—larger questions are broken down into a series of smaller questions. The answers can be pieced together to build a scientific explanation for a significant problem. The program shows intriguing views of the stages in a project to identify genes that direct small plants called *Arabidopsis* to flower. Students see tiny plantlets being selected on a culture dish as well as the mutant and wild type fully grown plants that result from this cloning experiment. This segment of the program also illustrates the importance of communication of scientific findings in peer-reviewed scientific journals.

The most detailed and entertaining example in the program turns to a very different topic: parrots who can talk and who understand what they say. This research project is directed by Dr. Irene Pepperberg, who appears in the program along with the now-famous African grey parrot named Alex and a younger parrot named Griffin. The birds are kept in a research laboratory at Brandeis University where Dr. Pepperberg or other researchers work with them every day. Your students will enjoy seeing the antics of the parrots and hearing them as they are tested for their understanding of fairly sophisticated concepts. They understand the concepts of number, color, material and shape in addition to being able to ask for many objects by name using spoken English words. The overall purpose of the research is to determine the cognitive abilities of these birds. In other words, do they understand what they say or are they just “parroting?” This investigation expands our understanding of how brains are organized and how animals learn and use abstract ideas.

Dr. Pepperberg talks in an animated way about how she first got the idea to do this work from watching a NOVA program. This story helps the student relate to the topic and imagine that they, too, might get a clever idea for a new research approach. The program continues to reinforce the basic ideas of scientific inquiry through this fascinating example from animal behavior. The viewer learns how a large and general question (Do parrots understand what they say?) must be broken down into specific, testable questions (Does Alex understand the concept of number? Can Alex recognize colors? Can Alex use abstract labels such as spoken English to communicate these ideas?). In this way, an interesting question is refined to make it appropriate for a scientific investigation.

The next scientific inquiry concept illustrated by the parrot example is the importance of controls. Only by the use of carefully considered controls can this work be taken seriously by the scientific community. The use of controls is particularly challenging with a complex

topic like the investigation of animal behavior. Dr. Pepperberg points out a number of the controls used in this study. The person who trains the parrot to use particular words is not the same person as the one who tests the parrot's understanding of these words. Another control is for one person to ask the questions and another to sit with back turned to the bird and interpret what was said. Thus the person who "observes" and records the bird's answers does not herself know what the correct answer is. As Dr. Pepperberg says, this arrangement of the experiment helps avoid bias in the results.

The need for multiple tests and multiple lines of evidence also is emphasized in this segment. Dr. Pepperberg specifically explains how prediction is used in this work. For example, if the bird is given only two choices, the prediction is that if he actually understands a concept, he will be correct in his responses more than 50 percent of the time. Being right only 50 percent of the time is no better than guessing in this experiment where there are only two choices. Finally, Dr. Pepperberg makes connections between her observations about learning in parrots to topics in human cognition, such as work with autistic children.

The program ends with the challenge to put the concepts and skills of scientific inquiry to use both in science class and in everyday life.

The topic of scientific inquiry commands a substantial treatment in the National Science Education Standards (NSES). The combination of live-action video format and interactive text guide for the program *Scientific Inquiry: Steps, Skills and Action* can be used effectively to bring these concepts to life for your students. One of the advantages of this approach is that students see a clear presentation of the steps and ideas involved in scientific inquiry, review these concepts, and then use the knowledge in the student exercises in the teaching guide. This range of experience helps students retain this capability and put it to use throughout the course, as recommended by the NSES. For details, you may want to consult a print copy of the standards or look online at:

<http://books.nap.edu/html/nses/html/6e.html#si>

Specifically, the NSES refers to the abilities to do scientific inquiry as essential goals in a science course. Students should become able to ask a refined question about “objects, organisms and events” in the environment. Students should learn how to “plan and conduct a simple investigation.” Students also should become able to “employ simple equipment and tools to gather data and extend senses.”

The science standards also point out the importance of existing knowledge as a foundation to new investigations and new explanations. In other words, scientists do not just have a bright idea and start off cold to make discoveries. Instead, they first consult the scientific literature to find out what is already known. In fact, this step may give them new ideas. Data is useful whether it is collected in a new investigation or in an earlier one that has been published. The NSES describe this process as: “Scientists develop explanations using observations (evidence) and what they already know about the world (scientific knowledge).” Thus communication of results is also an important aspect of scientific inquiry.

Perhaps the most significant objective is to enable students to “use data to construct a reasonable explanation.” This science standard is simultaneously fundamental to the understanding of any science content and to be able to engage in any science activity as well as to reason effectively about the natural world in everyday life.

How does *Scientific Inquiry: Steps, Skills and Action* fit into your course syllabus? You can use the video program and student exercises effectively in several different points in your biology course. The video provides an excellent introduction that brings to life the basic steps in the scientific inquiry process that are often listed at the start of a biology or other science text. Instead of simply memorizing these steps, your students can use the information and examples in the program and the experience from student worksheets to get an operational understanding of scientific inquiry—an understanding that they can really use. You then can have students overtly recognize these concepts in each new part of the curriculum in addition to putting them to use in their laboratory and field exercises throughout the course. You might introduce the program by asking the following preview question:

“How do you know what you know?”

This question serves as a way to raise interest in the topic and to start students thinking about the different ways to build knowledge or form an opinion.

Please note that the program contains some examples that are dramatizations (the water purity test; the throat culture) of real investigations. The water purity investigation was inspired by a science fair project conducted by a student (Valentina Boss) although the results used in *Activity 5* are a mock-up for illustration purposes. The bacterial/ antibiotic resistance plate is a real sample from a pathology laboratory but not from the “patient” (an actor) shown in the program. In contrast, the plant genetic engineering work and the parrot learning/ animal behavior work both are actual research projects conducted at major universities. In particular, your students may have already heard of Dr. Pepperberg and Alex the parrot through many articles or a NOVA program. These research examples are more complex than the illustrative water purity testing, but the principles of scientific inquiry should be apparent in both.

Using Review Questions

After students have watched the program, you may find it useful to engage them in a short discussion as a class to reinforce the ideas that were presented. *Activity 1* provides a list of suggested review questions and potential answers. Alternatively, you may want to have students supply written responses to the questions, perhaps as homework. It is useful to discuss these ideas as soon as possible after the program, while the information is still fresh in the students’ minds in order to help them retain the concepts.

Using Student Activities

Once students have watched the program and reviewed the ideas, they can go further to actually apply the ideas in the classroom activities. This experience is extremely helpful in cementing the concepts for students. Some activities are fairly brief, while others require a combination of individual or team thinking and interactive classroom presentations. A copy master for a worksheet is provided for each activity.

Activity 1 / Review Questions

Answers to review questions are provided.

Activity 2 / Scientific Explanations**Why do scientific explanations change?**

Scientific explanations are constantly being compared to new evidence. If the evidence is sound but inconsistent with the explanation, the evidence should not be ignored. Instead, the explanation is modified to be consistent with the explanation.

Is this change a strength or weakness? Explain.

Because scientific explanations change in response to careful reasoning and new evidence, the change is a strength. It means that the explanations are being adjusted to be more and more accurate.

Give an example of a change in a scientific explanation.

Students might suggest a variety of examples. Recognition of the role of microbes in disease is one mentioned in the program.

Activity 3 / Basic Steps in Inquiry**What are the fundamental steps in scientific inquiry? List them and describe the importance of each one.**

The important aspect of this question is not just to have students list or memorize steps but to think of the parts of the process in a meaningful way. They should realize that ideas do not spring from nothing: they arise from observations and from reading existing scientific knowledge. When an interesting idea or problem is identified, the next step is to form and refine a good question, one that can be specifically tested.

A tentative explanation may be proposed at this point. The tentative explanation is an hypothesis. Not all inquiries start with hypothesis: in some cases, the scientist observes or makes tests before formulating a specific explanation.

The hypothesis is tested by making predictions and then gathering evidence (through observation or experimentation) to determine if the prediction holds true. If it does, the results support the hypothesis. Once evidence is accurately collected, recorded and analyzed, the scientist must reason carefully and draw a conclusion. Conclusions are also compared to existing knowledge.

The outcome of the investigation would then be reported. In the case of a professional research project, results are reported in a peer-reviewed journal. This step not only distributes the information to others working in the field, it also provides a check for the accuracy and logic of the work.

Activity 4 / Testing an Idea: Prediction

In scientific inquiry, what is meant by a prediction? How is a prediction used to test an idea?

The purpose of this question is to make certain that students understand the term “prediction” in the scientific context. It is not used to mean “forecast” or “fortune telling.” Prediction is a statement of logical outcomes based on a specific hypothesis. For example, a prediction might be stated in the form “If I do [a particular manipulation or experiment] and if my first hypothesis is correct, I would predict that [some specific outcome] would take place.” Predictions provide a means for comparing observed results with outcomes consistent with a particular explanation in order to see if the explanation is valid.

You have been handed a quarter and told it is equally weighted on each side—in other words, a normal coin. You want to test this hypothesis. What would you predict to be the result of one flip of the coin?

The prediction should be that the coin will come up heads or tails. Whichever the result, you cannot really draw any conclusions about the hypothesis. This single flip is not an adequate test.

What would you predict to be the result of 10 flips? Of 100 flips? If possible, do the exercise and record your results. Do your results match your prediction?

This part of the question gets at two ideas: (1) the sample size matters and (2) expected results and actual results may not be identical. For 10 flips, the prediction is that about five will be heads (or tails). You don’t expect all results to be heads or all tails. You may see results that suggest there is equal chance for the coin to be heads or tails, but 10 flips is still a very small sample size. The results with more flips is a more sensitive test, and we would expect the percentage of heads to be close to 50 percent.

Activity 5a / Testing Water Purity Part I

In the program, some students were shown investigating a claim that sea water could be dangerous for several days after a rain. What specific hypothesis were they testing?

How was the test conducted?

The hypothesis is that runoff water from storm drains soon after a rain carries bacteria into the ocean and causes the pollution. Testing was done by taking water samples before and after a rain, measuring the amount of bacteria by growing samples on culture dishes and counting the resulting colonies.

Why did they need to collect water samples before and after a rain?

The sample from before a rain serves as a baseline or to a limited extent, a control. Many factors affect the amount of bacteria in water, so if the variable being tested is storm surface runoff from rain, a measure of the amount of rain taken before is an essential part of the test.

Activity 5b-5c / Testing Water Purity Part II**What was the purpose of plating the water samples on growth media in culture dishes?**

In order to get a somewhat accurate quantitative measure of the relative amounts of bacteria, the samples were placed on culture dishes and bacterial colonies were allowed to grow. Then colonies were then counted and results for the different samples were compared.

Why were the samples diluted before plating?

In order to place an amount of bacteria on the dish that could be counted, the samples were diluted to several different concentrations.

How were the results measured?

Bacteria would reproduce and form colonies on the plates, which could be counted as a measure of the quantity of bacteria in the diluted samples. Knowing the amount of dilution allows the students to calculate the original samples.

Consider these counts for plates of samples taken one day after a rain (A) and before a rain (B) at three different sites. Colonies were counted for undiluted and diluted samples. These are the direct counts.

Dilution Factor:	Site 1: Storm drain		Site 2: Creek outlet		Site 3: Midbeach	
	(A)	(B)	(A)	(B)	(A)	(B)
Undiluted	> 50	> 50	> 50	> 50	30	27
Dilution $\frac{1}{2}$	24	22	38	21	12	14
Dilution $\frac{1}{4}$	12	13	20	11	8	7

Do these data agree with the prediction that bacterial runoff water from storm drains is the main source of pollution in water at the beaches? Explain.

No, these results do NOT support that hypothesis because the results for site 1 do not show a marked increase in bacterial contamination after the rain as compared with before the rain. (Nor do they absolutely refute it since this is a very limited test).

What do these data suggest to you as a new hypothesis for further testing?

There is a marked increase in bacterial contamination near a creek outlet after a rain. A new hypothesis is that the creek collects bacterial contamination from runoff and pollutes the ocean water near the outlet.

What additional work could make this a better investigation?

Additional tests at several storm drain sites, at this creek and at other creek outlets before and after rain more than one time would greatly improve the evidence and the ability to draw conclusions about the hypotheses.

Activity 6a / Parrot Talk Part I

In the program, what large question was being investigated through the work with speech and African grey parrots?

There really are two large questions: Do parrots use human speech in meaningful ways? How much do parrots understand?

What more specific questions were designed to direct the studies? Give examples.

These questions are too general to be directly tested. Instead many specific questions have been asked. For example, can Alex understand the concept of numbers? Can Alex recognize colors? Can Alex use English speech as labels to communicate what he understands about color (or number etc.)?

These more specific questions then generate very specific questions that define each test. For instance, one test may address the question: Can Alex tell use words to communicate recognition of objects such as a key, a piece of wood, or some paper? Can Alex recognize five objects of a particular color out of a tray of 20 objects of several colors?

If Alex is presented with 20 choices of answers, and in a 15-trial test gets correct answers 80 percent of the time, would the results support the idea that he understood the particular concepts being tested? Explain.

With just two choices, a track record of 80 percent would be impressive and far better than just random chance (that would be 50 percent). But in this case, Alex had far more choices (20) so even without a full calculation, the student can see that 80 percent correct shows a very strong correlation that is much more than random chance. The results strongly support the idea that he understands the concepts being tested.

At present Alex knows more than 100 words, but early in his training in 1977, he had a vocabulary of just four words. He was tested to see if he understood these words, or merely said them. The following results were observed:

Object label	Total # of presentations	Paper	Key	Wood	Hide
Paper	58	48	2	4	4
Key	61	3	48	5	5
Wood	60	2	2	48	8
Hide	69	12	6	3	48

After Table 3.2 page 46 of *The Alex Studies* by Irene Maxine Pepperberg, Harvard University Press, 1999.

What do these results tell you about Alex’s ability to understand the words he speaks? Give evidence to support your response.

These actual data from 1977, early in Alex’s training, show that he is using the words in a meaningful way. For example, when presented with paper, Alex correctly spoke the word “paper” in 48 of 58 trials, which is being correct 82.7 percent of the time. With four options, this is a very impressive result. Results for the other words or concepts are similar (48 of 61 for “key,” 48 of 60 for “wood” and so on.)

Activity 6b / Parrot Talk Part II

What controls did Dr. Pepperberg mention she had used in the design of the Alex studies?

Among the controls mentioned in the program are the following:

- a. The trainer is a different person from the tester to prevent unconscious cuing from one person;
- b. One person presents the test while another who has their back turned listens to responses and records them, so as to avoid over-interpreting what Alex by having the recorder not know the answer themselves.
- c. Many different questions are asked, and the questions are interspersed in different order on different testing days.

Activity 7 / Antibiotic Use

In the demonstration of testing for antibiotic resistance that was shown in the program, what is the purpose of taking a throat swab from a patient who has a sore throat?

Rather than treat the infection without specific information about the bacteria causing it, the doctor takes a throat swab to get a sample of the bacteria for testing against various antibiotics in order to see which ones are effective in killing the pathogens.

What is the significance of the clear ring seen around some of the antibiotic disks on the culture plate?

Bacteria are spread across the plate in a manner to allow them to grow up into an opaque lawn or continuous covering on the culture medium. Near effective antibiotic disks, the bacteria are killed or prevented from growing, hence a clear area near those disks. If the bacteria are resistant to a particular antibiotic, they will grow right up to the disk, so there will be no clear “halo.”

Activity 8a / A Puzzle: No Hot Water!**Part I: Starting an Inquiry**

Notes on teaching this activity: Students will work better in teams. They are presented with a basic plumbing problem: no hot water. Their task is to collect evidence and figure out what the cause of the problem is, simulating experiments and thus carrying out the process of scientific inquiry.

The goal of the activity is to allow students a chance to apply the principles of scientific inquiry to a commonplace situation. Thus, their understanding of the process at each step is as important as “getting the right answer.” Students will need to reason logically, state their reasoning and back it up with evidence. You can orchestrate this process by making certain that they are thinking and not merely guessing.

Both groups of teams will go through the initial steps in inquiry. Then, to simulate experiments, the Scientist Teams will submit one or more experiments to the Reality Teams, who will figure out what results would happen. The Scientists then reason with that information to support or eliminate various hypotheses. As time permits, you can have this exchange take place more than once to permit several experiments in sequence. Keep in mind that the reasoning at each step is what matters most.

For this part of the exercise, you will supply one set of teams (the “Reality Teams”) with additional information about the situation they represent. We provide a copy master with several copies of this information that you can cut into strips and hand out to Reality Teams. Otherwise all students get the same worksheets. The Scientist Teams will pass their worksheet to the Reality Team, who will add their notes on results and return the sheets for an open discussion.

There will be two different situations or causes of the plumbing problem, but scientist teams won’t know that. More than one team may be trying to track down the same cause. Make a copy of one situation on a slip of paper and supply it to the Reality Teams for Part II.

The two situations are:

Situation 1:**Hot water flow is turned off at the hot water heater.****Situation 2:****Hot water flow is turned off at the hot water tap.**

Here are some sample responses similar to those your students might supply:

You go to a basin and turn on the tap labeled “hot.” You let the water run for more than five minutes, but the water never gets hot. What’s wrong? Your challenge is to figure out the cause of this problem. Follow your teacher’s directions about working in teams. Apply what you have learned about scientific inquiry to this problem. All teams must fill in the following outline:

Initial observation: (students restate the problem in their own words. They must state the observation accurately and with some detail.) For instance: Tap labeled “hot” is turned on. Water runs for at least five minutes. Water does not get hot.

Question: What causes the lack of hot water?

Tentative explanations (hypotheses): Students will list a variety of ideas. The ideas below are meant to serve as examples that include the actual causes.

Sample hypotheses include:

1. Hot and cold labels are reversed.
2. Hot water flow is turned off at the tap.
3. Hot water flow is turned off at the water heater.
4. Hot water heater itself is not turned on.
5. Hot water heater is set to too low a temperature.

Predictions: List one or more experiments you could do to test all or some of these hypotheses. For each experiment, also write the predicted results based on each hypothesis. Each prediction could be a sentence similar to this: “If we do _____, and if hypothesis 1 is correct, then _____ should happen.”

To save time, you could have each team member do the predictions for one experiment on their list and then share the results as a team.

Examples:

Experiment 1. Turn off the hot water tap and turn on the tap labeled “cold.”

Predictions: For this experiment you would predict the following: If the hot and cold water labels are reversed and you do this experiment, you would observe the water getting hot. With all other hypotheses, the water would not get hot in this experiment.

Experiment 2. Turn on a hot tap elsewhere in the house.

Predictions: If tap labels were reversed at the first basin (hypothesis 1) you would now observe hot water running at another basin. This result also would be consistent with hypothesis 2, but it would eliminate hypotheses 3-5. If one of them were correct, you would observe cold water even when you turned on the hot tap at another basin.

Other potential experiments include the following:

Experiment 3: Turn the valve at the hot water tap and see if this changes the situation.

Experiment 4: Check the hot water heater and see if the heater is running.

Experiment 5: Adjust the temperature on the hot water heater.

Your students may think of other possibilities.

Activity 8b / A Puzzle: No Hot Water!

Part II: Tracking Down the Cause

Now you will perform some simulated experiments. Some teams (the Scientist Teams) will be the scientists who conduct tests to choose between the hypotheses, while other teams (the Reality Teams) will represent “the real world” for one or more situations that are the underlying cause of the lack of hot water. The Reality Teams will report the results of the simulated experiments back to the scientists so they can draw conclusions.

Scientist Teams: Select an experiment to test one or more of your hypotheses. Briefly describe the test on this form and submit it to the Reality Team assigned to their situation, leaving room for the results.

Reality Teams: Consider what would happen in the experiment based on the reality of your situation. Fill in the experimental results on this form and deliver it to the scientists.

Please supply a slip of paper to each Reality Team with one of these situations:

**Situation 1:
Hot water flow is turned off at the hot water heater.**

**Situation 2:
Hot water flow is turned off at the hot water tap.**

Thus if the experiment is to turn off the tap labeled “hot” and turn on the tap labeled “cold”, the water will still run cold for either situation, and the experiment will not indicate the cause. If the experiment is to turn on a hot tap elsewhere in the house, in situation 1 the water will still run cold, but in situation 2, the water will run hot. More information will be needed to distinguish situation 1 from a situation in which the water heater is turned off.

Scientist Teams: Analyze the results and draw your conclusions. Present your conclusions to the Reality team to find out if you have solved the puzzle.

Experiment: Provided by the Scientist Teams

Results: Provided by the Reality Teams

Conclusions: Provided by the Scientist Teams

Evaluation: Provided by the Reality Teams

Student responses will depend on which situation the team is assigned and on which experiments they select. Look for reasoning supported by evidence in the conclusions. The Reality Team will have to reason carefully to correctly interpret the results for each simulated experiment. In addition, the Reality Team will evaluate the final conclusions.

Activity 9 / Climbers Trapped!

Mountain streams often flow very strongly in the spring and summer when the snow is melting and very little in the fall when there is no more snow to melt. Two mountain climbers crossed a stream in the morning on the way to the mountain they wanted to climb and noted that it was easy to cross since they could hop from rock to rock because the water was so low. When they returned that evening, however, the stream was too high to cross in this way. How could this happen? Here are the potential explanations they thought of:

1. **A hydro-electric power plant upstream releases more water when energy demand is high, as in the afternoon.**
2. **Snow melts in the daytime when the sun is shining but not at night.**
3. **A rainstorm higher in the mountains is producing runoff water.**
4. **A dam upstream broke and is no longer impeding the flow of water.**

Why does the cause matter to the survival of these climbers?

If they guess wrongly and take the wrong action, they might die.

Explain how each potential cause would affect their situation:

Depending on the cause of the high water, the climbers may be able to wait a few hours and walk out safely. For example, if (1) is the correct hypothesis, then late at night or in the morning, the water level would be expected to be low again. If (2) is the cause, waiting until early morning also might help. However, if (3) is the correct hypothesis, the conditions may turn into flash flood and get worse, so leaving sooner even with a risk is best. If (4) is the cause, waiting may not help, but the condition may stay steady.

Is there any additional information or reasoning that could help them decide what to do? Explain.

Climbers could check the sky in the direction of upstream and see if it looks like a rainstorm is happening. If they have a radio and can get reception, they could listen for reports on the weather or news that a dam has broken. If they have cell phones and an active cell service at their location, they could call and inform someone of their predicament and also ask for information about the weather or a dam break. If they do not have service, they could experiment with changing their position slightly to see if that helps. Finally, they could mark the water level and note the time, wait an hour or two and see if the water level is changing.

Activity 10 / Confused Identity?

A woman received a phone call from a man who says that he works for a bank and that she owes the bank \$12,000. She has never heard of the bank and doesn't know what the man is talking about. She could guess what is causing this problem, but what might happen if she guesses wrong?

She might become a victim of fraud and identity theft, lose thousands of dollars or have her credit ruined.

Here is a list of possible explanations: For each one, suggest experiments or observations she could do to gather more information and figure out what is going on.

- a. **The bank has the wrong person. Someone else with the same name opened the account.**
- b. **The account was opened by an identity thief pretending to be this woman.**
- c. **The man who called her is an identity thief who is trying to get private information by pretending to be a bank.**

The woman should not give out ANY information over the phone to someone who called her. She can ask for the caller's name and phone number, hang up, look up the bank's actual number in the phone book and call them. The bank will be able to verify whether the person who called is a legitimate employee.

If not, she can call the police (situation c). If the person does work for the bank, she can indicate that they have the wrong person (a). She would also want to have the bank verify that the person is not using her social security number or other personal information or that a credit check does not show someone is using her identity (c).

STUDENT ACTIVITIES

Name: _____

1. How does scientific inquiry differ from popular opinion?

2. How has our understanding of the cause of infectious disease changed historically? What new discoveries about other diseases do you think will be made in your lifetime?

3. When do scientists need to consult the scientific literature to find out what is already known about a particular topic?

4. Why is it important to carefully refine a scientific question? What kinds of changes may improve a question? What is meant by the term “peer-reviewed literature” in scientific work? Why is this process necessary?

5. What is meant by the term “peer-reviewed literature” in scientific work? Why is this process necessary?

6. Is all scientific evidence gathered through experimentation? Explain.

This activity is continued on the next page.

Name: _____

7. What is meant by “control” in a scientific inquiry? Why are controls needed?

8. What is a hypothesis? Name one hypothesis that was presented and tested in the video program.

9. Once an investigation is complete and the data have been analyzed, what should a scientist do with her or his conclusions?

10. Can the principles of scientific inquiry be applied in a useful way to your everyday life? Explain.

Please consult the Answer Key on the next page.

Answers to Review Questions

1. How does scientific inquiry differ from popular opinion?

Popular opinion often is based on the emotional appeal of an idea, whether or not it can be tested and is supported by valid evidence. A scientific inquiry seeks information about the natural world that has been carefully collected, recorded and analyzed. An inquiry often is used to test a specific hypothesis or to make enough observations to be able to form a tentative explanation that is testable. Although the goal of an inquiry is to acquire enough valid evidence to convince most scientists of the validity of an explanation, popularity of the idea is not in itself sufficient to make an explanation be accepted unless it is backed up by substantial evidence and careful reasoning.

2. How has our understanding of the cause of infectious disease changed historically? What new discoveries about other diseases do you think will be made in your lifetime?

As described in the program, infections once were thought to be caused by evil spirits or by four mysterious humors or fluids in the body. Later, this view was discarded after pathogens such as bacteria and viruses were discovered. Evidence showed that these infectious agents caused infections.

3. When do scientists need to consult the scientific literature to find out what is already known about a particular topic?

Scientists should consult the scientific literature at the start of an inquiry in order to refine their question and to begin to inform their answer. Sometimes the initial idea for an investigation comes from the existing scientific knowledge rather than direct observation of nature.

4. Why is it important to carefully refine a scientific question? What kinds of changes may improve a question?

A question that is too broad or confusing is inappropriate for a scientific inquiry because specific tests cannot be devised.

5. What is meant by the term “peer-reviewed literature” in scientific work? Why is this process necessary?

Peer reviewed literature is the body of scientific knowledge that has been reviewed by others scientists before it is accepted for publication. Even after a report is published, it continues to be examined by scientists and if ever it is found to be inaccurate, a new report will be published to call attention to the necessary changes. Peer review is a useful part of scientific work because it serves as an ongoing test for quality and accuracy of scientific information.

The Answer Key is continued on the next page.

- 6. Is all scientific evidence gathered through experimentation? Explain.**
Experimentation is just one way to gather scientific information. Direct observation of natural occurrences also is a powerful way to gather data. Experimentation involves the manipulation of certain features of a situation in order to set up a specific test of a particular cause or process.
- 7. What is meant by “control” in a scientific inquiry? Why are controls needed?**
In scientific inquiry, control is short for “controlled experiment.” It refers to a condition or conditions held steady as a comparison. Since there are normally many factors that could affect an experimental outcome, it can be very difficult to determine which factor causes what effect. To determine this, only one or at most a few factors (variables) are allowed to vary with the rest being held constant or “controlled.” The controls are needed to clearly isolate the effects of the variable factor being tested.
- 8. What is a hypothesis? Name one hypothesis that was presented and tested in the video program.**
A hypothesis is a tentative scientific explanation. It may provide an answer to a specific question or suggest a causal relationship. To be addressable by scientific inquiry, a hypothesis must be able to be tested. The program presented several simple hypotheses. One involved water purity at the beach: The contamination after rainfall is from an increase in bacteria in the water washed in from storm drain runoff. Another hypothesis was that a particular antibiotic would kill an infection in a patient seeking treatment for sore throat. A third hypothesis explained in the program was that an African grey parrot (in this case, Alex) would understand and connect the concepts of color, texture and number.
- 9. Once an investigation is complete and the data have been analyzed, what should a scientist do with her or his conclusions?**
Conclusions should be communicated to the scientific community (and eventually to the public). This reporting needs to be reviewed and evaluated by other scientists in the field (peer review) as a way to screen out unsupported and unscientific results. Publication in a peer reviewed journal is one way to add the conclusions to the body of established scientific knowledge.
- 10. Can the principles of scientific inquiry be applied in a useful way to your everyday life? Explain.**
Yes, the principles of careful observation, accurate record keeping, building explanations based on evidence and careful reasoning are useful in every day applications. For example, if you are reading a scientific or medical report in the newspaper, you will want to carefully note what evidence supports the claims and how that evidence was gathered. This information helps you assess the reliability of the ideas being reported.

Name: _____

Part II: Experimental Results and Conclusions

What was the purpose of plating the water samples on growth media in culture dishes?

Why were the samples diluted before plating?

How were the results measured?

Consider these counts for plates of samples taken one day after a rain (A) and before a rain (B) at three different sites. Colonies were counted for undiluted and diluted samples. These are the direct counts.

Dilution Factor:	Site 1: Storm drain		Site 2: Creek outlet		Site 3: Midbeach	
	(A)	(B)	(A)	(B)	(A)	(B)
Undiluted	> 50	> 50	> 50	> 50	30	27
Dilution $\frac{1}{2}$	24	22	38	21	12	14
Dilution $\frac{1}{4}$	12	13	20	11	8	7

Do these data agree with the prediction that bacteria in runoff water from storm drains is the main source of pollution in water at the beaches? Explain.

This activity is continued on the next page.

Name: _____

Part I

In the program, what large question was being investigated concerning speech and African grey parrots?

What more specific questions were designed to direct the studies? Give examples.

If Alex is presented with 20 choices of answers, and in a 15-trial test gets correct answers 80 percent of the time, would the results support the idea that he understood the particular concepts being tested? Explain.

At present Alex knows more than 100 words, but early in his training in 1977, he had a vocabulary of just four words. He was tested to see if he understood these words, or merely said them. The following results were observed:

Object label	Total # of presentations	Paper	Key	Wood	Hide
Paper	58	48	2	4	4
Key	61	3	48	5	5
Wood	60	2	2	48	8
Hide	69	12	6	3	48

After Table 3.2 page 46 of *The Alex Studies* by Irene Maxine Pepperberg, Harvard University Press, 1999.

What do these results tell you about Alex's ability to understand the words he speaks? Give evidence to support your response.

This activity is continued on the next page.

Name: _____

Part II: Tracking Down the Cause

Now you will perform some simulated experiments. Some teams (the Scientist Teams) will be the scientists who conduct tests to choose between the hypotheses, while other teams (the Reality Teams) will represent “the real world” for one or more situations that are the underlying cause of the lack of hot water. The Reality Teams will report the results of the simulated experiments back to the scientists so they can draw conclusions.

Scientist Teams: Select an experiment to test one or more of your hypotheses. Briefly describe the test on this form and submit it to the Reality Team assigned to their situation, leaving room for the results.

Reality Teams: Consider what would happen in the experiment based on the reality of your situation. Fill in the experimental results on this form and deliver it to the scientists.

Scientist Teams: Analyze the results and draw your conclusions. Present your conclusions to the Reality team to find out if you have solved the puzzle.

Experiment:

Results:

Conclusions:

Evaluation:

Name: _____

Mountain streams often flow very strongly in the spring and summer when the snow is melting and very little in the fall when there is no more snow to melt. Two mountain climbers crossed a stream in the morning on the way to the mountain they wanted to climb and noted that it was easy to cross since they could hop from rock to rock because the water was so low. When they returned that evening, however, the stream was too high to cross in this way. How could this happen? Here are the potential explanations they thought of:

- 1.** A hydro-electric power plant upstream releases more water when energy demand is high, as in the afternoon.
- 2.** Snow melts in the daytime when the sun is shining but not at night.
- 3.** A rainstorm higher in the mountains is producing runoff water.
- 4.** A dam upstream broke and is no longer impeding the flow of water.

Why does the cause matter to the survival of these climbers?

Explain how each potential cause would affect their situation:

- 1.** _____

- 2.** _____

- 3.** _____

- 4.** _____

Is there any additional information or reasoning that could help them decide what to do? Explain. Use additional paper if necessary.

FACT SHEETS

Abstract labels: In the inquiry of animal learning and communication, abstract labels refer to human-based codes (such as speech, American Sign Language, computer symbols) that can be used to stand for particular concepts.

Analysis: In scientific inquiry, the process of carefully thinking about data. Information is collected through observations and experiments, but without careful comparison, critical thinking to build correlations and conclusions, the information would have limited value.

Antibiotic: Naturally occurring or synthetic substance used to kill a pathogen (such as bacteria) without harming the host (such as human). Drugs such as penicillin, amoxicillin, tetracycline or biaxin are anti-bacterial antibiotics used to treat bacterial infections in humans. They target some aspect of the biochemistry of a bacterial cell that is different from the eukaryotic cells of the human host.

Antibiotic resistance: Refers to the ability of some bacteria to not be killed by an antibiotic. In many cases, the antibiotic used to be effective in killing the bacteria, but through evolutionary selective pressures, mutant bacteria carrying resistance genes have come to dominate a particular population. Overuse of antibiotics has greatly increased the number of resistant strains in the last 40 years.

Bacteria: Prokaryotic organisms that are single celled. They can be harmful to humans or can be normal flora of a healthy person. Bacteria grow in almost every environment on Earth.

Cell: Unit of organization of an organism. A cell is a membrane bound compartment. Some organisms consist of a single cell (such as amoeba or bacterium). Others are multi-cellular, with different types of cells.

Cloning: Reproduction of an identical copy. This term can refer to asexual production of a new organism or to techniques for making multiple copies of a gene or other piece of genetic information through recombinant molecular genetic methods.

Control: In scientific inquiry, control is short for “controlled experiment.” It refers to a condition or conditions held steady as a comparison. Since there are normally many factors that affect an experimental outcome, it can be very difficult to determine which factor causes what effect. To determine this, only one or at most a few factors are allowed to vary with the rest being held constant or “controlled.” For example, both genetic and environmental factors affect the growth of a plant. If an experimenter wants to investigate the effect that a particular mutation has on growth, she must compare the growth of plants with and without the mutation, but with all other genetic and environmental factors controlled.

Data: Plural of datum, refers to information and in context often to scientifically acquired information. The quality or accuracy of data depends on the methods used to collect it. Scientific explanations are built on many lines of reliable data that serves as evidence for a particular idea.

Dilution: To produce a less concentrated solution of some material. Dilution of a bacterial sample suspended in a liquid medium can be helpful in producing a concentration low enough to be counted when plated on a growth medium. If the ratio of dilution is known, then the observed counts of bacterial colonies can be used to calculation the original concentration of bacteria in the solution.

DNA: Deoxyribonucleic acid, a genetic material.

Eukarya: One of three domains, a high level taxon. The Eukarya include the eukaryotic kingdoms of Animals, Plants, Protists and Fungi. Eukaryotic cells differ from the cells of prokaryotes (bacteria). This is one reason antibiotics can target bacteria without harming the eukaryotic host (human or other mammal).

Evolution: Long term, gradual heritable change in a species.

Hypothesis: In scientific inquiry, hypothesis refers to a tentative explanation. A scientist proposes an explanation or answer to a question. This is the hypothesis. It must be tested through prediction based on the hypothesis and acquisition of valid scientific evidence. This is done by experimentation or observation. If the evidence matches the prediction, it supports the hypothesis. Not every investigation begins with an hypothesis: extensive observation may occur before a very specific explanation is formed for testing. Explanations that cannot be tested do not qualify as a scientific hypothesis.

Lawn: Refers to bacterial lawn, an even layer of bacterial growth spread across a culture dish.

Observation: In scientific inquiry, observation refers to the collection of data about a natural process or organism without interference or manipulation by the investigator, as is done in experimentation.

Peer review: In scientific process, peer review refers to the review and assessment of scientific reports by other scientists in the field as a requirement for their publication or acceptance as part of the body of scientific knowledge.

Prediction: In scientific inquiry, prediction refers to making logical assumptions based on a tentative explanation as an initial step in testing that explanation. Prediction of specific events or outcomes is made based on an hypothesis. Then tests are set up to

Name: _____

find out if the prediction will match the actual events. If it does, the results support the hypothesis being tested.

Plants: One the five biological Kingdoms. The Plants are eukaryotes that can produce their own food through photosynthesis.

Prokaryotes: One of two large scale divisions of organisms. The prokaryotes have simple cells that lack a nucleus. Bacteria are prokaryotes. The Five Kingdom system collects all prokaryotes in the Kingdom Monera. The Three Domain system has two prokaryotic domains, the Archaea and the Eubacteria (sometimes called True Bacteria).

Scientific explanation: A scientific explanation is a description of the natural world, particularly of causal relationships in the natural world that is based on substantial scientific evidence and sound reasoning. Multiple lines of evidence strengthen the confidence of the scientific community in an explanation. As new data are obtained, they are compared to existing scientific explanation. If they are consistent, the new data strengthen the explanation. If they are not consistent with the explanation but are considered to be carefully collected, valid scientific evidence, then the explanation must be modified to reflect the new data. Because of this disciplined way of building scientific explanations, it is unusual for one to need to be completely discarded rather than modified to fit new data.

Sterile techniques: Refers to handling of materials such as bacterial cultures such that no new microorganisms are unintentionally introduced.

Virus: A virus is a parasite that carries its own genetic information (encoded in RNA or DNA) but requires a host cell for replication. The virus is not a cell itself. Instead, it is a genome enclosed in a protective shell made of proteins and lipids.

Name: _____

Beck, William, Karel Liem and George Gaylord Simpson. *Life, An Introduction to Biology* (3rd edition), Harper Collins, 1991.

BSCS. *Developing Biological Literacy*, BSCS, 1993.

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Creager, Joan, Jacquelyn Black, and Vee Davison. *Microbiology, Principles and Applications*, Prentice Hall, 1990.

Miller, Kenneth and Joseph Levine. *Biology* (4th edition), Prentice Hall, 1998.

Pepperberg, Irene. *The Alex Studies: Cognitive and Communicative Abilities of Grey Parrots*, Harvard University Press, 1999.

Raven, Peter H. and George B. Johnson. *Biology* (6th edition), McGraw-Hill Companies, 2002.

Shapin, Steven. *The Scientific Revolution*, University of Chicago Press, 1996.

A number of useful web addresses can be found to extend your teaching of scientific inquiry. These addresses change from time to time. If you try one of the sites we recommend and find it is not available, you might try searching using the name of the site or specific keywords. For general information, your best way to find them is to do a search using keywords such as “scientific inquiry” “scientific methods” or “nature of science.” Be careful to note the source of the materials you discover. Many sites apply the word “science” without truly meeting the criteria of scientific investigation.

Useful sites for scientific inquiry include:

1. AAAS Benchmarks
<http://www.sciencenetlinks.com/lessons.cfm?BenchmarkID=1&DocID=116>
2. United States National Academies (NAS) of Science Homepage
<http://www4.nas.edu/nas/nashome.nsf?OpenDatabase>
3. NAS links between publications and hot news topics
See publications homepage and click link or go to:
<http://www.nationalacademies.org/headlines/>
4. A publication on inquiry from National Academies of Science press
<http://books.nap.edu/books/0309064767/html/130.html#pagetop>

Background material for specific topics presented in the program:

1. Irene Pepperberg’s research and The Alex Foundation
<http://www.alexfoundation.org/>
2. Viral diseases (such as SARS) versus bacterial infections:
CDC | Severe Acute Respiratory Syndrome (SARS)
<http://www.cdc.gov/ncidod/sars/>

CDC: West Nile Virus—Fight The Bite!
http://www.cdc.gov/ncidod/dvbid/westnile/prevention_info.htm
3. Information about a collection of different diseases:
CDC Division of Vector-Borne Infectious Diseases (DVBID)
<http://www.cdc.gov/ncidod/dvbid/index.htm>

OTHER BIOLOGY PRODUCTS FOR GRADES 8-12
FROM HUMAN RELATIONS MEDIA

<i>Biodiversity: The Web of Life</i>	video/print
<i>Classification of Living Things</i>	video/print
<i>Homeostasis: The Body in Balance</i>	video/print
<i>Introduction to Cells</i>	video/print
<i>Cellular Respiration: Energy for Life</i>	video/print
<i>All Systems Go! Energy Systems of the Human Body</i>	video/print
<i>Meiosis: The Key to Genetic Diversity</i>	video/print
<i>Mitosis: Sending the Genetic Message</i>	video/print
<i>Organic Compounds in Action</i>	video/print
<i>Patterns of Inheritance: Understanding Genetics</i>	video/print
<i>Photosynthesis: Light into Life</i>	video/print
<i>The Rising Threat of Infectious Diseases</i>	video/print
<i>Translating the Code: Protein Synthesis</i>	video/print
<i>Understanding Evolution</i>	video/print
<i>Viruses: The Deadly Enemy</i>	video/print

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