Scientific Method

Introduction

Science is the study of the world around us. That world can be large, like the oceans, or very small, like genes. Scientists, like everyone, use their senses of sight, hearing, touch, smell, and taste to explore and observe things in the universe that interest them. Even astronomers who study galaxies far away use their senses; they are just amplified using technology like telescopes. Observations lead to questions, hypotheses, experiments, and usually more questions.

Everyone is a born scientist. From birth on, children are constantly exploring, observing, asking questions, and experimenting in order to understand the world around them. The process isn't as formal as what a trained scientist does, but the basics are there. Even adults use the basic scientific method on an everyday basis. Every time something goes wrong with an appliance, for example, most people try to figure out what the problem is. Example:
Observation: Toaster stops working.
Question: What is wrong with the toaster?
Hypotheses: (1) It is unplugged. (2) The unit is burned out.
Experiments: (1) Check the plug. (2) Take the toaster apart and look at the heating wires.
Results: If it was unplugged the first hypothesis is supported, if the wires inside are broken, then the second hypothesis is supported.

The Scientific Method

The scientific method is a systematic process of empirical investigation. Empirical means using the senses: science is based on what we can concretely observe with our five senses.

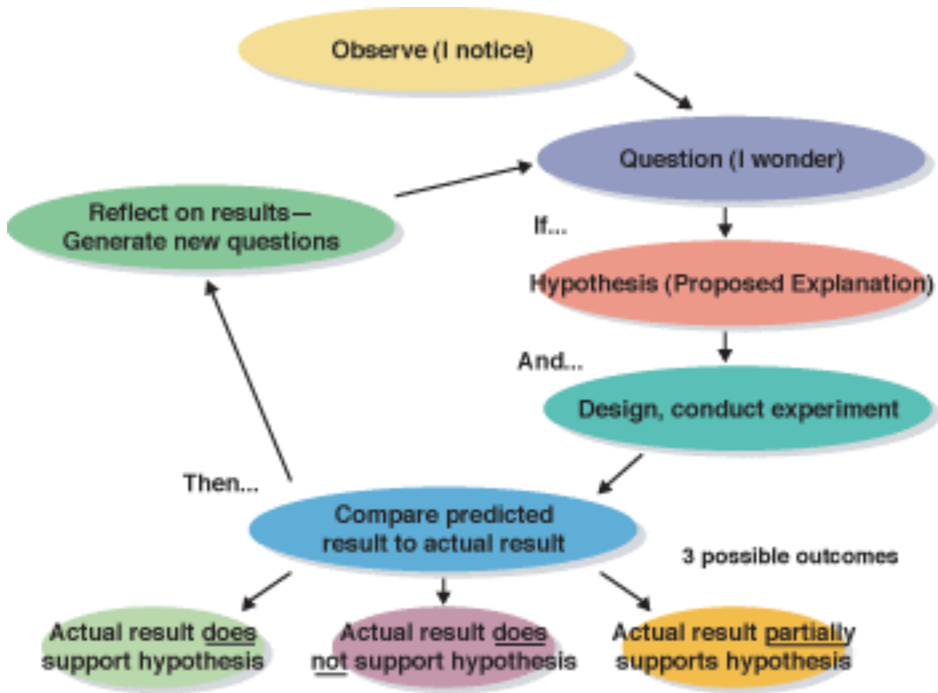

Figure 1. Scientific method.

Step One: Explore/Observe

Although today's professional scientists are highly trained and educated individuals who have specialized knowledge, they still start the process of scientific inquiry in the same way that a student does - by exploring!

When professional scientists consider questions to investigate, their explorations are focused on an area about which they have considerable prior knowledge. While this may seem to be a fundamentally different situation from that of schoolchildren, it really isn't. By the time we reach kindergarten, we all have a store of previously acquired knowledge (some of which is misinformation), and particular aspects of the world are more interesting to us than others. The nice thing about doing science with students is that their innate curiosity is flexible and can be directed to a very broad range of phenomena.

Even the most highly skilled scientist must spend time observing and exploring before s/he comes up with a question to investigate. The degree of complexity of a scientist's observations may be considerably higher than that which a student is capable of, but the process is fundamentally the same. What we notice about the world around us, whether we are looking at it in a directed or a spontaneous way, is the raw material on which our questions are based.

Step Two: Ask a Question

Every field of science has "big" questions to which the answer is not yet known. It is rarely possible for an individual scientist or a team of scientists to find the answer to a "big" question all at once. Rather, groups of scientists work together to find the answer to small questions that, when taken together, may provide an answer to a "big" question. When scientists formulate their research questions, they are usually interested in questions that, if answered, will contribute to eventually answering a "big" question.

Student scientists tend to ask "big" questions, too, although often the answers to their questions are already known ("Why is the sky blue?" for example), and can be discovered by doing research. In fact, every professional scientist who generates a potential question for investigation will do research to find out if the answer is already known before proceeding further. Although the professional scientist will not usually conduct an investigation of a question that has already been answered unless s/he believes the answer is wrong, it is perfectly valid for students to investigate questions that have already been answered. That is how they learn the process of scientific inquiry. It is up to the teacher to decide which questions should be answered with a full investigation and which should be answered by doing other kinds of research, such as reading or consulting experts. (For criteria to help determine what questions can be productively investigated in a hands-on way, see the **Inquiry Tutorial** .)

One of the nice things about investigating questions related to the ecology of your schoolyard is that, although the principles on which the answers to those questions are based will usually already be known, the ecology of your schoolyard probably hasn't already been investigated, so your students will get to experience the thrill of discovery first-hand as they proceed with their investigations.

Many questions start with the word "Why." "Why" questions tend to be "big" questions, and in this form they are usually untestable and therefore, from a scientific standpoint, unanswerable. Turn the question into one that is testable by turning it into a descriptive or causal question. There are various ways to phrase questions so that they can be tested. When we rephrase questions, usually we are breaking down a "big" question into smaller parts than can be answered, just as scientists break down their "big" questions. Here are some examples of testable question formats:

What causes ___________?
Why do Mexican poppies flower in the spring? (Their favorite time of year?)
Turns into: What causes Mexican poppies to flower in the spring?

Which ____ is best for _____?
Why do plants use nitrogen? (Very tough question!)
Turns into: Which amount of nitrogen is best for plant growth?

Is it true that______ ?
Why did I find isopods in dark places? (Who really knows?)
Turns into: Is it true that isopods prefer to be in dark places?

Which _____ is/does _____ ?
Why do animals visit desert marigold flowers? (For the bouquet?)
Turns into: Which animal visits the desert marigold flowers the most?
Why do hummingbirds eat flower nectar?
Turns into: Which sugar concentration do hummingbirds prefer?

Answerable (testable) questions usually take the form of How, What, When, Who, Which. Once a question is proposed, you can use a **question tree** to determine if it is an answerable, interesting question, whether it is comparative or non-comparative, and if it is manipulative or observational. A manipulative question is one in which the experimenter can alter or vary something in the environment for the purpose of determining if that change causes another change to happen. An observational question is one in which the researcher only observes a situation and records the results. For example, the question might be, "Which plants do butterflies prefer for laying eggs?" As long as you have at least two different plant species available for the butterflies to choose, then you watch (observe) where they lay their eggs.

Step Three: Formulate a Hypothesis

After an interesting, testable question has been proposed, one or more hypotheses are developed. A hypothesis is the potential explanation for what causes something to occur. If I asked, "Is it true that isopods prefer to be in dark places?" my hypothesis might be, "If sunlight harms isopods and isopods are put in the sunlight, then they will crawl to a dark place."

The hypothesis is not just an "educated guess," as some writers say. It is a formal statement that is designed to provide a potential explanation for something that has been observed. A hypothesis is a potential answer to a question. A hypothesis is supposed to address causes that lead to effects. The suggested cause is the hypothesis; the expected effect or result is the prediction. In the example above, the hypothesis is that "sunlight harms isopods," and "If isopods are put in the sunlight they will crawl to a dark place," is the prediction. The process of hypothesis formation is designed to produce testable predictions. The test is the experiment. The hypothesis is the statement of cause and effect that drives the design of the experiment.

"IF plants need water to grow AND we apply extra water to some plants THEN those plants should grow taller than plants not given extra water." The IF section is the hypothesis, the AND section is the basic experiment, and the THEN section is the prediction. This hypothesis doesn't attempt to address all the underlying biological processes causing the observed effect on plant growth, which is fine because, as we shall see, only one factor (or variable) should be tested at a time.

Here's a scenario: Students use the simple hypothesis above, get the predicted result, and then go on to ask more detailed questions and generate hypotheses designed to get at more of the biological processes. Here are some possible hypotheses for this next stage: Plants grow more when given water because: (1) plants use the water to make glucose, and (2) water is used in photosynthesis. It is quite common to suggest several explanations. One, both, or neither of these hypotheses may be correct. This is exactly how professional scientists work, although as often as not they don't get the predicted result, and have to review their process to figure out whether there was a flaw in their experimental design or equipment, or if the experiment was valid and their hypothesis really was contradicted by its results. In either case, they are back at the drawing board with more questions to investigate.

It is not always easy or possible to determine the actual causes of an observed effect. This could be because the experimenter does not have adequate expertise, skills, or equipment, or because we humans just don't have a way to figure it out yet. Multiple experiments with refinements are usually necessary to narrow the cause down to the true one or ones. Nature is messy, with lots of interacting causes. Some ecological situations are straightforward cases of cause and effect, but not many.

Variables

A hypothesis explicitly states the independent and dependent variables. What IS a variable? And what are independent and dependent variables?

A variable is a factor or characteristic that exists in different degrees or levels. For example, light is a variable because it exists (or can be manipulated) in different, or varying, levels, from full light to partial (shady), to none (dark). Examples of other variables you can find in your habitat area or on your school grounds are flower color, flower shape, plant height, leaf color, leaf shape, body shape, growth rate, number of eggs laid (insects or birds), levels of nitrogen in the soil, etc. The list can go on and on.

Variables in an experiment are classified as either independent or dependent. An independent variable is a factor that is being independently, deliberately set by the experimenter. It is also

called the treatment.
Examples of independent variables:
3 soil types: clay, silt, sand
3 nutrient levels: 10 ppm, 100 ppm, 1000 ppm (ppm is parts per million)
5 temperatures: 10C, 20C, 30C, 40C, 50C
3 levels of sun exposure: Direct, indirect (shade), none (dark)

A dependent variable is a factor that is being measured by the experimenter. This is the factor that the experimenter assumes will be affected by the independent variable. It is called the dependent variable because it depends on the treatment, or independent variable. Examples:
Plant growth rate
Seed production, seed size, or seed number
Leaf growth rate
Flower production
Insect offspring number, survival rate
Insect growth rate

Variables are critical to the next step in the scientific process, that of formulating hypotheses. The basic form of a hypothesis is usually similar to one of the following:

1) Dependent variable will happen BECAUSE of the independent variable. This form is best used for questions phrased as "What causes _______?" OR

2) AS independent variable is applied THEN the dependent variable will happen or be affected. OR

3) IF independent variable applied AND experiment done, THEN the dependent variable will happen. This version gives the independent variable (If...), basic experimental design (and...), and the dependent variable (then...) in one sentence.

Examples:
Question: What causes plants to grow?
Hypothesis Samples:
1) Plants grow more with nitrogen because nitrogen is a nutrient that plants need. "Plants grow more" states the dependent variable; "because nitrogen..." states the independent variable.

2) As nitrogen levels are increased the plants will grow faster. "AS nitrogen levels are increased" states the independent variable; "the plants will grow faster," states the dependent variable.

3) IF plants need nitrogen to grow AND we apply extra nitrogen to some plants, THEN those plants should grow faster/taller/more than plants not given extra nitrogen. "Plants need nitrogen" is the independent variable, "AND we apply...nitrogen," describes the experiment, and "THEN plants grow more" is the dependent variable.

Example 3 above (IF... AND... THEN) is probably the most widely used hypothesis form. It is helpful to think of the IF section as the treatment or cause, the AND section as the experiment, and the THEN section as the prediction, what you think will happen to the dependent variable. It is critical that you state the prediction before running the experiment. (See Prediction section below.)

Bar graphs of the data can help clarify the independent and dependent variables. For example, if plants are grown with different nitrogen levels and plant height is the factor being measured, the x-axis (horizontal) would have the nitrogen levels. The y-axis (vertical) would show plant height. The x-axis is the independent variable and the y-axis is the dependent variable. This process also helps check that your experimental design is a fair test, that only one variable or factor is being tested for its effect.

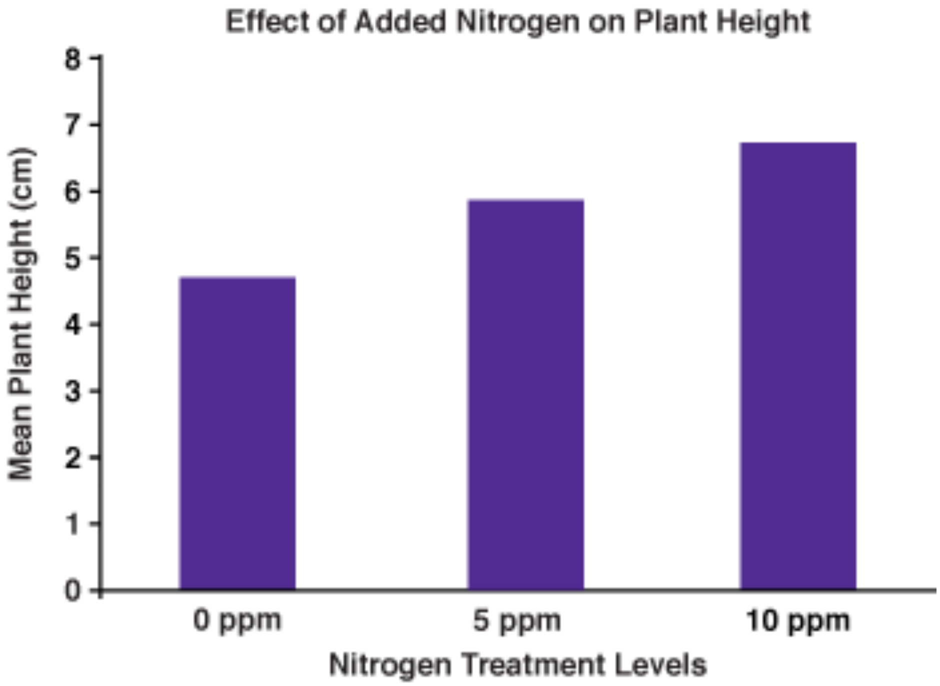

Figure 2. The independent variable of nitrogen level is on the x-axis. The dependent variable of plant height is on the y-axis.

Advanced Level Hypothesis Formation

As students become proficient with formulating questions and hypotheses, they should begin formulating multiple hypotheses for each question. Students will usually come up with more than one hypothesis in any case, and they might as well design multiple experiments or a series of experiments to test as many hypotheses as possible. Moreover, there might be more than one correct hypothesis. Different factors may interact to cause the observed result. Determining these interactions is a critical step in research.

Step Four: Design an Experiment

After a question has been proposed and a hypothesis or multiple hypotheses have been generated, an experiment is performed to test the hypothesis(es). An experiment is a set of manipulations or specific observations of nature.

To design an experiment that will genuinely test our hypothesis (answer our question), we need to know what kind of data can answer our question, and we need to set up an experiment that will yield that kind of data. And, the information (data) we are going to collect through our experiment needs to be tangible and measurable. For example, if we want to know what sugar concentration hummingbirds prefer, we need to gather data that will indicate a preference for a particular concentration over others. We might decide to collect data on the number of visits to feeders with different sugar concentrations, or the lengths of visits to the feeders. Those are two kinds of information that could indicate preference for a particular concentration. In the first case we are going to count visits, and in the second case we are going to measure the amount of time spent per feeder visit. Counting the number of hummingbirds who visit our schoolyard each day is another kind of data that we might be able to collect, but it is not data that can answer the question we have posed about feeding preference.

Fair Testing

When we have figured out what kind of data we need to answer our question and how we might be able to collect that data, we then want to make sure that we set up our experiment so that it will be a fair test. "Fair test" is a phrase describing a scientifically valid experiment. Fair testing occurs when an experiment is done changing only one factor (variable) and keeping all other conditions the same.

Investigating only one factor or variable at a time takes self-discipline. It is easy to get excited and want to test a multitude of interesting factors at once, but to really be scientific and do a fair test, only one factor at a time can be manipulated or observed. (More advanced students do study more than one factor at a time, but this requires higher-level statistics, such as analysis of variance, to analyze the data.)

In the example above, if we fill a large, round, yellow hummingbird feeder with sugar water that has one quarter cup of sugar for every cup of water, and hang it in a shady spot, and we fill a small, cylindrical, red hummingbird feeder with sugar water that has one-half cup of sugar for every cup of water, and hang it in a sunny spot, our data may not accurately reflect the feeding preferences of hummingbirds, because we are not keeping all factors except sugar concentration the same. We have used hummingbird feeders that are different sizes, different shapes, different colors, hung in different locations, AND have different concentrations of sugar water. The number of visits or lengths of visits of hummingbirds to our feeders may be influenced by several factors besides the concentration of sugar in the water.

Prediction

When designing an experiment, it is desirable to state a prediction, as well as the hypothesis. Predictions state what is expected to happen to the dependent variable in an experiment if the hypothesis is true. It is easy to confuse the hypothesis and the prediction, because often the prediction will be implied in the statement of the hypothesis. Technically, however, the prediction cannot be stated until we have decided what our experimental design will be. In the example above, our hypothesis might state: "Hummingbirds prefer food with the highest available sugar concentration because that provides them with the greatest amount of energy per unit of food consumed." Our prediction will state, "There will be more visits of hummingbirds to the feeders with high sugar concentrations than low sugar concentrations," or "Hummingbird visits to feeders with high sugar concentrations will last longer than visits to feeders with low sugar concentrations." depending on how we've set up our experiment.

Data Recording Sheets

Once we know what kind of data we need to collect and how we are going to collect it, we need to design a way to record the data before we actually begin collecting it. Students should be allowed to design their own data-recording sheet rather than have one handed to them by the teacher, although the teacher may have to provide help with the design. Designing a data recording sheet requires students to understand what they are doing and why. It also provides an extra opportunity to review the experimental idea and make sure it is doable. (See **Data Presentation** for sample data sheets.)

Data Analysis

Part of the experimental design is planning ahead how the data will be analyzed. Will we use raw numbers, averages, medians, or other statistical tests? (See**Statistics** for specifics and examples.) Planning ahead what statistics will be used to analyze the data is necessary to reduce bias. If we collect the data and then decide how to analyze it, we run the risk of trying different analyses just to see if we can find a way to show the treatment had an effect.

Data analysis is necessary because without it we cannot draw valid conclusions from our experiment. The data we collect will usually be in the form of raw numbers, and raw numbers in and of themselves are not very meaningful. They need to be placed in an appropriate context in order to yield reliable information. For example, let us say that we want to find out whether our school needs to institute a free lunch program. We collect data to find out that on Tuesday, 100 children arrived at school without a lunch. We need to know a lot more information about that number 100 in order to know whether we should have a free lunch program. Are there 250 students at our school or 2,500? Is 100 the average number of students who come without lunch each day or was there a field trip on Tuesday that included lunch, and that is why most of those 100 students showed up at school without one? How many of the 100 who didn't bring their lunch from home did bring money to buy lunch in the cafeteria? And so forth. Just as word meanings change according to their context in a sentence, the meaning of numbers is best understood in the context provided by an appropriate form of statistical analysis. See the **Statistics** section for a full discussion.

Data Presentation

Presenting data visually helps both scientists and their audiences understand it. It is an old saw that "one picture is worth a thousand words," and "pictures" of our data can go a long way towards helping us understand the results of our experiment. Pictures of data usually take the form of graphs or charts. What graphs or charts will be suited for displaying the data? A clean, clear visual presentation of the results is the best way to "see" what resulted from the experiment and to explain it to others. (For sample charts, graphs, and other presentation types, see **Data Presentation**.) Graphs, charts, and tables may be hand drawn or generated on a computer. Although decisions about how the data will be presented can be revised later as need be, it is helpful to the experimenters' thought processes to at least consider how their data might be presented before they collect it.

Step Five: Reflect on the Results

Did our prediction come true? Did the data we collected support our hypothesis or contradict it? If the hypothesis was supported, what else would we like to know about this topic and how could we find out? Let's say that the hummingbirds did make the greatest number of visits to the feeders with higher concentrations of sugar. Is there a level of concentration that is too high? How could we find out? Might hummingbirds be influenced by other factors than sugar concentration? What might those be? In nature they feed from flowers rather than feeders, so what aspects of flowers might attract them? Color? Size? Shape? Fragrance? How could we design experiments to test those different factors? The end of an experiment that yields the expected results is not the end of questioning or investigation.

What if our prediction didn't come true? What if the data did not support our hypothesis? Was it because our hypothesis was wrong, or was it because our experimental design or the way we collected our data was flawed? Was the equipment we used faulty or not sensitive enough to register the variations we expected to find? Did we analyze the data incorrectly? Do we need to redesign our experiment to correct for errors or do we need to test a different hypothesis? Or did we discover an even more interesting question in the course of our investigation that we would rather pursue?

The scientific method is not a linear process, starting at point A, arriving at point B, and stopping.

What happens in the course of getting from point A to point B may necessitate our going back to point A and starting all over again with a new plan. It is not uncommon for research scientists to spend years of their lives on an investigation that turns out to have been flawed and yields no valid results. But in science, as in most other areas of human experience, mistakes often provide the greatest opportunity for learning. If, on the other hand, we got to point B and it turned out to be pretty much what we expected, then we have both the thrill of having participated in an effective process of discovery and the opportunity to pose and investigate new questions.

The Discussion

Professional scientists present their discoveries in talks, posters, and articles published in science journals. The part of their presentation that synthesizes what they have learned is called the discussion. The discussion explains the point of the experiment, and argues whether the data support the hypothesis or not. It also explains the relevance of the experiment. Was this an experiment to advance pure knowledge? Or one that was to be applied to a particular problem to be solved? Another important part of the discussion is to suggest other experiments or further avenues of research that the current experiment has brought to light.

A discussion summarizes the extent to which the hypothesis was supported or not by the actual results of the experiment. It is important to note that a hypothesis is NEVER PROVEN. It can only be SUPPORTED by the data. The more experiments that support the hypothesis, the stronger and more accepted it becomes. But, some new experiment in the future may show the hypothesis to be wrong. This is always a possibility in science. Even in physics and chemistry, which have many hard and fast "laws," conditions that are believed to always be true may not hold in some other part of the universe. A hypothesis might be partly supported by the results, fully supported, or not supported at all.

This portion of the scientific process provides an excellent opportunity for students to hone writing skills, as well as for reflection and self-evaluation. The investigation and its results should be reviewed verbally with a full class discussion. A poster or written report that communicates results of the investigation to others can be produced by children of almost any age, with help from the teacher if necessary.

Sample Experiments

SAMPLE EXPERIMENTAL DESIGNS

Now that we have reviewed the scientific method, let's see it in action in a school setting. Here are two samples, one illustrating a manipulative experiment and the other an observational experiment that could be implemented by students.

One thing to remember is that not all experiments will show differences between treatments. This can be for different reasons: (1) there is no real difference—the result is ecologically valid; (2) there are not enough **replicates** to show a statistical difference. Try again with more replicates; or (3) errors were made in the experimental design, data collection, or analysis of data. Revise and try again.

MANIPULATIVE EXPERIMENT: Effect of Nitrogen on Plant Growth

Background: Plants are the **primary producers** of this planet. Plants take energy from the sun and convert it through **photosynthesis** into glucose, but they need more than just the sun's energy to survive, grow and reproduce. Plants need space, water, carbon dioxide and nutrients such as nitrogen and phosphorus, among others.

Step One: Explore/Observe

Form groups of two to three students. Observe (carefully!) the various types of plants in the habitat using eyes, magnifying lenses, flashlights, brushes, fingers, etc. This is open observation time. Remind students to record their observations and any ideas or questions that come to mind. They can use words, drawings, charts—whatever they think is best for record keeping. Don't be concerned if their observations and questions seem a little off the topic; that is part of the process and may well reveal important points.

Step Two: Ask a Question

Bring students back together. Either have the small groups discuss their observations and questions together first and then form one large group, or go immediately to one large group. Once in the large group, using the board or a large pad of paper, record the major points that each small group has decided are characteristics of the different types of plants.

Gather student questions. These will be all over the place at first. Keeping the focus on plant growth, guide students to ask questions about how plants grow. Sample questions: What happens if a plant does not receive any water? What do plants need to grow? What causes some plants to grow more than other plants? Do plants need other things than water and light to grow? Is it true that plants grow more when given more nitrogen?

Important aspects of guided inquiry are encouraging students to generate multiple hypotheses, and letting students make decisions about what data are important and create their own data sheets. The sample below illustrates how one of many possible investigations around this topic might develop.

Step Three: Formulate a Hypothesis

Once each group (or the whole class) has decided on which question to investigate, a hypothesis needs to be formulated. Let's use the question, "Is it true that plants grow taller when given more nitrogen?" A hypothesis could be, "If plants need nitrogen to grow and the plants are given nitrogen, then the plants will grow taller." This form of writing the hypothesis includes a short description of the experiment. Another way to write the hypothesis, which emphasizes a causal relationship, would be, "Plants grow more when they receive more nitrogen because plants need nitrogen to grow."

Step Four: Design an Experiment

Experiments are used to test the hypothesis and answer at least part of the question. Quite often, this phase consists of several experiments done in stages. The prior experiment leads to new ones that more clearly test the hypothesis and answer the question.

The important aspect to focus on is the variable of interest, or independent variable in the question and hypothesis. The experiment must be designed to test the effect of the independent variable, in this case, nitrogen. What is measured or observed is the dependent variable. What characteristic to measure to determine plant growth can be based upon observations made in the habitat. Possibilities are plant height, number of flowers produced, number of leaves, number of seeds produced, total plant weight or biomass, or another characteristic of plants that indicates growth.

Let the students conceive their own designs in small groups, then discuss those designs, concentrating on the independent variable and how to test it in such a way as to detect any difference that variable may have on plant growth.

Let's use plant height as the dependent variable. The independent variable is the amount of nitrogen added to the plants. The **control** plants will receive no nitrogen, one set of plants will receive 5 ppm (parts per million) of nitrogen, and another set will receive 10 ppm of nitrogen. The nitrogen is dissolved in 1 liter of water. The plants receiving no nitrogen will receive 1 liter of plain water. Each treatment group will consist of five plants of the same species. Fast-growing annuals, such as desert wildflowers, would be a good choice. We will use five plants per treatment so we will have **replicates**. Each plant is called an**experimental unit** or replicate.

Sample Prediction: Once the experiment is designed and before it is run, have the students write down what they think will happen. This is the prediction. It is easy to skip, but is an essential part of the process. Students should have a clear picture in mind of what they think will happen and why. If they don't, the results will be harder to interpret because they will not have anything to compare them to.

Our prediction is: The plants given 10 ppm nitrogen will grow taller than those given 5 ppm, and the plants given 5 ppm will grow taller than the control group.

Record Results: Encourage students to decide what data are relevant to record and how best to do so. Much of this will depend upon the mathematical abilities of the students. (See **Data Presentation** and **Statistics** sections of this web site for examples.) Students ideally should decide for themselves what results to record and how. This gives them the opportunity to decide what data are relevant and how best to present those data. In this example, the relevant data are amount of nitrogen received and plant height. Note that an important aspect of this experimental design is time—at what intervals treatments are administered and when plant height measurements are taken. This aspect of the design needs to be considered and written into the experimental plan, but may or may not be recorded on data sheets.

Note that when you design the experiment, in order for it to be valid you will have to control for plant height. This means that either all plants have to be the same height at the start of treatment, or that you have to measure the increase in height for each plant, rather than the overall height, if plants heights are different at the start of treatment.

Sample Analysis of Data and Presentation: Measure the heights of the plants after a set number of weeks. Make a **bar graph** with nitrogen levels listed on the horizontal axis and plant heights in cm on the vertical axis. For students who can divide, calculate the **average** plant heights for each treatment group. Graph the average number on the vertical axis.

Step Five: Reflect on the Results

Was your hypothesis supported? If yes, go on to test other hypotheses. If not, why not? What did happen? Why? This is a great opportunity to revise your hypothesis (or your experimental design!) and do another test. Discuss findings in relation to the question and hypothesis, and also in terms of what data were recorded and how it was presented.

Sample Discussion: The average plant height in treatment #3 (plants given 10 ppm of nitrogen) was greater than the plants in treatment #2 (5 ppm nitrogen), or in treatment #1 (no nitrogen). (See the bar graph in **Figure 2**.)These results support our hypothesis that nitrogen is a **limiting**, essential plant nutrient, and does improve plant growth. Questions remain, however. How much nitrogen is enough? Can a plant receive too much nitrogen? If so, how much is detrimental? Do plants require different amounts of nitrogen at different stages of development? Do different species of plants need different levels of nitrogen? These questions could be investigated with more experiments.

OBSERVATIONAL EXPERIMENT: Flowers and hummingbirds

Background: Many species of hummingbirds rely on flowers for food. Specifically, the birds drink the high sugar content nectar produced by some flower species. Hummingbirds are often territorial, with males protecting their area. Some species of hummingbirds stay in the Sonoran Desert all year, but which flowers are blooming changes with the seasons.

Other animals drink flower nectar too, so the hummingbirds may be competing with them for food. Bees, flies, moths and butterflies are some other nectar feeders. How each of these reaches the nectar is influenced by their behaviors and body shape. Some animals are not able to reach the nectar at the bottom of a deep, tubular flower.

Step One: Explore/Observe

Form groups of two to three students. Observe the flowering plants in the habitat. Record characteristics of the flowers, such as shape, size, color, scent, and any others that come to mind. Look at the flowers with a magnifying lens. Students can use words, drawings, charts—whatever they think is best for record keeping. Don't be concerned if their observations and questions seem a little off the topic; that is part of the process and may well reveal important points. What flowers are blooming will depend on the time of year.

Step Two: Ask a Question

Bring students back together. Either have the small groups discuss their observations and questions together first and then form one large group, or go immediately to one large group. Once in the large group, using the board or a large pad of paper, record the major points that each small group has decided are characteristics of the different flowers.

Gather student questions. These will be all over the place at first. Keeping the focus on flowers, guide students to ask questions about how the flowers differ and what that might mean to a hummingbird. Sample questions: Do hummingbirds prefer some flowers to others? Does flower color make a difference? What about flower shape? Can hummingbirds reach the nectar more easily in some flowers? Does the shape of the hummingbird's bill influence what flowers it uses?

Important aspects of guided inquiry are encouraging students to generate multiple hypotheses, and letting students make decisions about what data are important and create their own data sheets. The sample below illustrates how one of many possible investigations around this topic might develop.

Step Three: Formulate a Hypothesis

Once each group (or the whole class) has decided on which question to investigate, a hypothesis needs to be formulated. Let's use the question, "What flower shape do hummingbirds prefer?" A hypothesis could be, "If hummingbirds prefer tubular shaped flowers and we observe hummingbird visits to tubular and non-tubular shaped flowers, then the tubular flowers will receive more hummingbird visits." In another form, our hypothesis might state, “Hummingbirds prefer tubular flowers because their beak shape allows them to reach the nectar at the base of the flowers.”

Step Four: Design an Experiment

Experiments are used to test the hypothesis and answer at least part of the question. Quite often, this phase consists of several experiments done in stages. The prior experiment leads to new ones that more clearly test the hypothesis and answer the question.

The important aspect to focus on is the variable of interest, or independent variable in the question and hypothesis. The experiment must be designed to test the effect of the independent variable, in this case, flower shape. What is measured or observed is the dependent variable. In this experiment we do not need a**control** treatment, but we do need to attempt to **control** for other factors such as flower color. The flowers chosen need to be the same color and as close to the same size as possible. Since we are not making the flowers, but observing them in nature, it will not be possible to control all factors.

Let's use number of hummingbird visits as the dependent variable. The independent variable is the flower shape. We need to count visits of hummingbirds to tubular and non-tubular shaped flowers. In order to have replicates, we will observe multiple plants of the same species. (Ideally, there will be more than one plant of each species to observe in your habitat or school yard. But if you don't have enough plants, see "Another way of setting up the experiment . . ." below, and if you can't do that either, you can try the experiment anyway, without replicates.) For example, we might observe and record numbers of visits to three Arizona yellow bells plants (tubular yellow flowers) and three brittlebush plants (non-tubular yellow flowers). Each plant is called an **experimental unit**or replicate. Another way of setting up the experiment would be to count visits to three different species of plants with tubular flowers, of the same color, say yellow (Arizona yellow bells, aloe vera, and yellow columbine, for example), and to three different plants with non-tubular yellow flowers (brittlebush, yellow lantana, and desert marigold, for example).

Time is a factor in this experiment. We want to make our observations at the same time or times of day. Weather, time of day, and time of year are all factors which affect the feeding activity of animals. We want to observe all plants each time we record data. If we count visits to tubular flowers on sunny days at 4:00 p.m., and visits to non-tubular flowers on rainy days at noon, then factors like weather and time of day when we make our observations will interfere with the variable that we are really trying to test, which is flower shape.

Sample Prediction: Once the experiment is designed and before it is run, have the students write down what they think will happen. This is the prediction. It is easy to skip, but is an essential part of the process. Students should have a clear picture in mind of what they think will happen and why. If they don't, the results will be harder to interpret because they will not have anything to compare them to.

Our prediction is: The plants with tubular flowers will receive more visits by hummingbirds than the plants with non-tubular flowers.

Record Results: Encourage students to decide what data are relevant to record and how best to do so. Much of this will depend upon the mathematical abilities of the students. (See **Data Presentation** and **Statistics** sections of this web site for examples.) Students ideally should decide for themselves what results to record and how. This gives them the opportunity to decide what data are relevant and how best to present these data. In this case, the relevant data are flower shape and number of feeding visits by hummingbirds.

Sample Analysis of Data and Presentation: Count up the number of visits each flower type receives. Make a bar graph with flower shape on the horizontal axis and number of hummingbird visits on the vertical axis. For students who can divide, calculate the **average** number of visits for each flower shape group. Graph the average number on the vertical axis.

Step Five: Reflect on the Results

Was your hypothesis supported? If yes, go on to test other hypotheses. If not, why not? What did happen? Why? This is a great opportunity to revise your hypothesis (or your experimental design!) and do another test. Discuss findings in relation to the question and hypothesis, and also in terms of what data were recorded and how it was presented.

Sample Discussion: The average number of visits to tubular shaped flowers was greater than the average number of visits to non-tubular flowers. These results support our hypothesis that hummingbirds prefer tubular-shaped flowers. Questions remain, however. What other factors might influence which flowers hummingbirds choose for feeding? Color? Size? Aroma? Abundance of flowers? We might also want to investigate some of those factors that we tried to control for in this experiment, such as time of day at which hummingbirds feed at flowers most actively, whether weather affects their feeding activity, and so forth. Hummingbirds also feed on insects, so we might try comparing how much time is spent catching insects and how much time is spent feeding at flowers. These questions could be investigated with more experiments.

This experiment could be turned into a manipulative experiment by making flower shapes that can be fitted on a hummingbird feeder. Keep color the same while making five tubular cones and five short, non-tubular cones to fit on the feeders.