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Curiosity and research

1.1 Course goals

Science starts with curiosity about the world. It starts with questions about why the sky is blue, why dogs wag their tails, whether electric power lines cause cancer, and whether God plays dice with the universe. But while curiosity is necessary for science, it is not enough. Science also depends upon logical thought, carefully planned experiments, mathematical and computer models, specialized instruments, and many other elements. In this course, you will learn some of the research methods that turn curiosity into science. In particular, you will learn to

- Create your own experiments to answer scientific questions.
- Design experiments to reduce systematic and random errors and use statistics to interpret the results.
- Use probes and computers to gather and analyze data.
- Treat human subjects in an ethical fashion.
- Apply safe laboratory procedures.
- Find and read articles in the scientific literature.
- Create mathematical models of scientific phenomena.
- Apply scientific arguments in matters of social importance.
- Write scientific papers.
- Review scientific papers.
- Give oral presentations of scientific work.

You will not just be learning about these skills. You will be acquiring and applying them by carrying out scientific inquiries.

1.2 Kinds of questions

Testable questions Every scientific inquiry answers questions, and most scientific inquiries begin with specific questions. People often wonder about questions that are hard to address, such as

- Why is the sky blue?
- What are stars and why do they move at night?
- What is sound?
- Why are leaves green?
- How do you grow the biggest possible tomatoes?
- Why do balloons pop?
- How can you cure a cold?
- Why is lighter fluid bad to drink?

Questions that begin with "Why," "What," or "How" often ask for an explanation of something that is very complex, and give little guidance about how to begin finding an answer. *Testable questions* on the other hand suggest specific activities that may provide an answer. Some examples:

- Is the sky more blue on a clear day in summer than on a clear day in winter? [Take digital photographs of the sky at noon on many days during the summer and many days during the winter with the same camera, using the same f-stop and shutter speed, and at the same location, recording temperature, humidity, and cloud cover. Compare the numerical values of the pixels in the two sets of photographs.]
- Are there chemical solvents that remove from a leaf the substances that make it green? [Grind up leaves in solvents such as water, acetone, and alcohol and check whether the green color can be extracted.]
- How does the loudness of a balloon popping depend on how much one blows it up? [Blow up balloons to different diameters and pop them at a fixed distance from a microphone connected to a digital sound recording device.]
- Is lighter fluid poisonous for ants? [Spray a mist of lighter fluid on ants, and compare their behavior with ants not sprayed with lighter fluid.]

Most of this class will be devoted to building experiments and carrying out analyses to answer testable questions. Sometimes the answers to the questions are known and one could look them up. In fact, part of the course will deal with techniques for looking up known answers. But the point of this class is not so much to answer particular questions as to provide experience in how scientists answer questions.

Closed and open questions Another way to categorize questions is to divide them between closed and open. *Closed questions* are those with a specific answer that is already known. Some examples:

- What is the name of the third planet from the Sun?
- What is the indefinite integral of $\tan\theta$ with respect to θ?
- At what rate does a ball accelerate when dropped near the surface of the Earth?
- What is the pH of an orange?
- How many vertebrae are there in the spine of a rhesus monkey?
- How large are the largest tides observed in the Bay of Fundy?

Open questions may have multiple answers, and require much more thought and interpretation. Some examples:

- How did the third planet from the Sun get there?
- Is the unproved conjecture "Every even integer greater than 2 can be represented as the sum of two primes" provable or unprovable?
- Are the fundamental constants of physics changing over time?
- Is it possible to make a completely synthetic juice that tastes as good and is as healthy as orange juice?
- Are there mutations of the rhesus monkey that are immune to any form of common cold?
- How much will the mean sea level change over the next 100 years?

Closed questions are not very challenging if someone just gives you the answer, but they can be demanding indeed if you are the one responsible for finding it. Making progress on open questions often involves answering a series of closed questions. For example, making predictions about the mean sea level over the next 100 years should be influenced by careful measurements of the mean sea level today. Checking whether the constants of nature are changing requires measuring very carefully their current values. Learning how the Earth came to its current orbit around the Sun is aided by knowing the the mass and chemical composition of the Sun and the Earth.

So, while most scientists have open questions in the backs of their minds while they work, and are motivated by large and significant issues, they spend most of their time taking small steps, answering closed questions. You should not worry if your first steps in science address apparently simple questions. Learn the process by which scientists solve simple problems well, and you will have gained skills to begin addressing the largest questions of the day.

1.3 Research methods for science

Scientists spend their time in many ways, and using a wide variety of research methods. The following sections describe some of the most common. They are based upon practical observation of how scientists spend their time and the sorts of investigations described in published papers and in conference presentations.

1.3.1 Test a hypothesis: Hypothesis-driven research

One research method in particular is usually singled out by introductory science texts and called ***the*** *Scientific Method*. Steps in this method are

1. State a hypothesis.
2. Design an experimental procedure to test the hypothesis.

3. Construct any necessary apparatus.
4. Perform the experiments.
5. Analyze the data from the experiment to determine how likely it is the hypothesis can be disproved.
6. Refine or correct the hypothesis and continue if necessary.

Hypothesis-driven research begins (no surprise) with a hypothesis. A *hypothesis* is a statement about the world that can be true or false, and whose truth is being tested. A valid hypothesis must be *falsifiable* (Popper, 1959). This means you should imagine actually being able to show it to be false, and you should be able to imagine evidence that would make enthusiastic supporters of the hypothesis abandon it. For example, the hypothesis that people cannot cause spoons to float in the air using mental energy could be falsified by finding a single person reproducibly capable of making spoons float without the aid of wires or other supports. When a hypothesis is *valid,* it meets the rules for being a hypothesis, whether it is true or false, while if a hypothesis is invalid it breaks the rules and should not be considered. Table 1.1 provides examples of valid and invalid hypotheses.

The U.S. National Institutes of Health, which funds most of the basic medical research in the United States, divides research into two categories: hypothesis-driven research and curiosity-driven research. The National Institutes of Health almost exclusively funds hypothesis-driven research. Both hypothesis-driven and curiosity-driven research have their place, and science needs both of them to function.

Hypothesis-driven research is most appropriate when a researcher is trying to decide between a small number of mutually exclusive cases, such as finding which of two medical treatments is more effective, or whether electric power lines cause cancer. Hypothesis testing is particularly important in medical research, since nothing is more likely to cause people to invest in ineffective procedures or drugs than hopes of a cure for themselves or loved ones. Hypothesis-driven research is designed to protect researchers against subtle biases that can distort research outcomes and are particularly difficult to avoid when life and health are at stake. Biases are also hard to avoid whenever any participants in the research have preconceived notions of what the results should be. Procedures to avoid bias in hypothesis-driven research are described in more detail in Chapter 2.

Hypothesis-driven research is not appropriate when the researcher is trying to decide between a vast number of possible cases. For example, suppose one is given a rock and wants to know its density. There is nothing to stop the researcher from beginning the investigation by saying “My hypothesis is that the density of this rock is 1 gm/cm^3” and testing the hypothesis. Starting an inquiry with a rough estimate of what the answer should be expected to be is always a good idea. However, calling

Table 1.1 Various statements that could be considered as scientific hypotheses with comments on whether they are valid or not.

Statements	Comments
Briar's Aspirin cures headaches faster than RCS Aspirin.	Valid hypothesis. Can be checked by using the two forms of aspirin on randomly chosen populations of headache sufferers.
Eating two ounces of olive oil a day decreases the odds of contracting heart disease.	Valid hypothesis. Can be checked by randomly assigning large numbers of people diets that contain or do not contain two ounces of olive oil and monitoring their health over long periods of time.
The gravitational force between two masses is proportional to the products of the masses and decreases exponentially with the distance between the masses.	Valid hypothesis. Also false, since gravitational force decreases as the square of the distance, not as the exponential.
If electrons were 10% less massive, no life would exist in the universe.	Fascinating statement, but not a valid and testable hypothesis, particularly since it is impossible to anticipate all forms that life could take.
A Toyota Camry weighs exactly 1000 kg.	This is a valid hypothesis, but it is silly if left as a hypothesis. There is no reason that the weight of a car should come out to be such a neat round number.
What is the best fertilizer to use to get large and tasty tomatoes?	Not a valid hypothesis. Hypotheses have to be definite statements, and cannot be questions.
Macs are better than PCs.	Not a valid hypothesis. It is impossible to imagine evidence that could sway the enthusiastic supporters of each kind of computer to accept the other as better.

the estimate a hypothesis is not helpful, because hypotheses are supposed to be tested rigorously and rejected if they do not meet high standards of evidence. The density of a rock can have a continuous range of values. Even if the answer must lie somewhere between 0.1 gm/cm^3 and 10 gm/cm^3 there is an infinite number of possibilities. Thus by picking a single value at the outset of the investigation and testing it, the odds are overwhelming that the hypothesis will be rejected. The problem is that it is very unlikely that anyone cares particularly whether the density of the rock is exactly 1.0 gm/cm^3 or not, and if someone were to say "I have tested the hypothesis that this rock has a density of 1.0 gm/cm^3 and rejected it" the natural response would be "Please, just tell me the density of the rock." This comment leads to other modes of research.

1.3.2 *Measure a value: Experimental research (I)*

1. Identify a well-defined quantity.
2. Design a procedure to measure it.
3. Perform the experiments.
4. Analyze and report on the accuracy of the results.

Measuring a single number well is often much harder than it seems, and some of the technical issues involved are discussed in more detail in Section 2.2. Examples of measured quantities, ranging from fairly simple to very challenging, appear in Table 1.2. Some of the primary challenges in measuring values have to do with errors in the measurement process. *Random errors* reveal themselves because of continual variations in the values one obtains with repeated measurement. *Systematic errors* are more difficult to catch because the same error occurs at the same size in every measurement, and such errors can only be eliminated either by thinking through the sources of problems and removing them, or by finding completely independent ways to make the measurements and comparing them.

Measuring a few numbers underlies many of the most expensive large group projects in science. Experimental particle physics, which employs thousands of scientists at international laboratories with budgets in the hundreds of millions of dollars, is devoted to finding masses and charges of a small number of elementary particles. The Human Genome Project (GENOME, 2008) was one of the great triumphs of science in the last 50 years, yet it consisted at a primitive level in finding a long sequence composed of four letters, which one can think of as a single very large number in base 4. Government agencies like to fund projects of this type for the simple reason that the success of the project is almost guaranteed. The researchers will come up with a collection of numbers, and those numbers are a deliverable that the government agency can display to show that the money was well spent.

Measuring a single value is often the starting point for testing a hypothesis or measuring a series of related values. Therefore even when a single number is not the primary aim of a research project, being able to measure numbers is a basic skill that underlies all modes of research.

1.3.3 *Measure a function or relationship: Experimental research (II)*

1. Observe a phenomenon and develop testable questions.
2. Identify control variables and response functions.
3. Design an experimental procedure to vary the control variables, measure the response variables, and keep other factors constant.

Table 1.2 Examples of values that scientific researchers might be interested in measuring.

Value	Comments
Density of crystalline silicon at room temperature	Density cannot be obtained directly, but is defined to be the ratio of mass to volume, and so can be obtained by separately measuring mass and volume of crystalline samples and taking the ratio.
Charge of the electron	The first experimental information obtained at the end of the nineteenth century about the electron was the ratio of charge to mass. The physicist Robert Millikan won a Nobel Prize for a series of experiments between 1910 and 1920 involving oil droplets that made it possible to determine the charge separately.
Mass of the electron neutrino	The electron neutrino is one of the most plentiful particles in the universe, but it reacts very rarely with ordinary matter and is therefore almost invisible to us. All experiments to determine its mass have so far concluded that it was too small to measure, but even a very slight mass has great implications for the total amount of matter in the universe. One current experiment to measure the electron neutrino mass is being conducted at the Research Center of Karlsruhe in Germany and has a budget of 33 million euros (KATRIN, 2008).
Distance from Earth to the nearest star other than the Sun.	Proxima Centauri is 4.22 light years or 39,900,000,000,000 km from Earth (NASA, 2008).
The number of base pairs and distinct genes in the human genome	The number of base pairs is around 3 billion and the number of distinct genes is around 30,000. These values were determined as part of the Human Genome Project (GENOME, 2008), a multibillion dollar scientific effort that involved government and university scientists, as well as a corporation, and provided the first sequencing of the human genome.

4. Perform the experiments.
5. Analyze the relation between control variables and response variables, and characterize the relation mathematically.

Much of experimental physics and chemistry operates according to this research method; examples appear in Table 1.3. The starting point is to identify *control variables* and *response variables*. A control variable is a quantity that the experimenter varies at will to change the character of the experiment, while a response

Table 1.3 Examples of functions or relationships that researchers might measure.

Function or relationship	Comments
Find how the speed of sound in air at fixed pressure depends upon air temperature.	The control variable is temperature, and the response variable is sound speed. This sort of experiment is extremely common in experimental physics and chemistry, and reference volumes are full of the results. Examples are provided by the hundreds of volumes called *Numerical Data and Functional Relationships in Science and Technology* by Landolt and Börnstein, published in multiple series over many decades by Springer-Verlag, originally in German, and now in English.
Place a fluid between two cylinders, rotate the outer cylinder, and find the state of the fluid as a function of the rotation speed.	The control variable is rotation speed of the cylinder. The fluid undergoes a number of abrupt qualitative transitions, from smooth uniform motion, to rolls that look like a barber pole, to turbulence.
Measure the stiffness of a sample of rubber as a function of the amount of cross-linking agent used to process it.	The control variable is cross-linking agent (Charles Goodyear used sulfur to stiffen natural rubber) and the response variable is stiffness. This type of measurement is commonplace in engineering and industrial research.
Find the average size of a specific breed of tomatoes grown in specific soil and climate as a function of the amount of salt in the soil.	The control variable is salt concentration, and the response variable is tomato size. An experiment like this that really sought to optimize the size of tomatoes would not typically focus on a single variable. Instead a series of factors such as salt concentration, fertilizer, irrigation, and seed type would all become part of an experimental designed to improve tomatoes.
Measure how often allergy sufferers sneeze per day as a function of the dose of anti-histamine they take.	The control variable is the dose of anti-histamine. Different allergy sufferers are sensitive to different substances, all of which are likely to be varying beyond control of the experimenter.

variable is some other quantity measured as an outcome. In a good experiment, all variables other than the control variables that affect the outcome are held constant. So in measurements of the speed of sound in air with respect to temperature, the pressure and humidity of air need to be kept constant. In measuring the stiffness of rubber with respect to a cross-linking agent, the temperature needs to be held constant. An experiment on the effectiveness of an anti-histamine to prevent sneezing would raise the greatest challenges of this sort, since one person might be allergic to cats, another to mold in the air, and it would be difficult either to find lots of subjects all allergic to exactly the same thing or to control the precise amount to which they were exposed.

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More information

There are many different skills involved in actually carrying out experiments, ranging from construction of apparatus and safe laboratory practice to the safe and ethical treatment of human subjects. These and other technical issues are discussed at greater length in Chapter 2.

The mathematical analysis of a largely experimental project may involve nothing more than careful characterization of error bounds associated with each measured point. Or it may involve careful comparison with a particular mathematical theory of the experiment. Sometimes the analysis involves actual construction of a mathematical model, as in the next method of research.

1.3.4 Construct a model: Theoretical sciences and applied mathematics

1. Choose a relationship discovered through experimental investigation.
2. Construct mental pictures to explain the relationship, and develop hypotheses about origins of the phenomenon.
3. Identify basic mathematical equations from which the relation might result.
4. Using analytical or numerical techniques, determine whether the experimental relationship results from the basic mathematical equations.
5. If incorrect, find a new mathematical starting point.
6. If correct, predict new relationships to be found in future experiments.

This mode of research describes much of applied mathematics, theoretical physics, theoretical chemistry, theoretical geology, theoretical astronomy, or theoretical biology (Table 1.4). For example, the experimental observation might be intense bursts of gamma-rays. A hypothesis might be that they emerge from gravitational collapse of certain stars. A lengthy process of modeling the collapse of stars, trying to calculate the radiation that emerges from them, would be needed to check the hypothesis.

In variants of this mode of research, the modeling takes place without any experimental input, and emerges with experimental predictions. In other variants, this type of research can lead to new results in pure mathematics.

1.3.5 Observational and exploratory research

1. Create an instrument or method for making observations that have not been made before.
2. Carry out observations, recording as much detail as possible, searching for unexpected objects or relationships.
3. Present results and stimulate further research.

Laboratory experiments have control variables, but in a huge variety of scientific investigations, scientists measure quantities they cannot control. This mode

Table 1.4 Examples of models of scientific phenomena.

Model	Comments
Calculate the distance a projectile fired from a barrel near the Earth's surface at known speed will travel as a function of angle.	The calculation can be performed using Newton's laws of motion. It is fairly easy if one neglects things such as air resistance and the Earth's rotation, and more challenging if these are included.
Consider a fluid placed between two cylinders with the outer one rotating and calculate the rotation speed at which steady fluid motion becomes unstable to the formation of rolls.	This computation was first carried out by Taylor (1923) using equations for fluids called the Navier–Stokes equations, and constituted the first nontrivial comparison of theory and experiment for fluid motion.
Find the arrangement of atoms in deoxyribonucleic acid (DNA).	Watson and Crick (1953) determined the structure of DNA. Although their article contains a few numerical values, the paper mainly contains the concept of DNA as a double helix with a schematic diagram, no complicated calculations.
Find the weather in the United States two days from now.	Weather prediction is one of the most computer-intensive activities in the world. The process of prediction begins with a vast collection of data from weather monitoring stations around the globe and continues with computations based upon equations for the motion of air including temperature, pressure, and humidity.
Find how the populations of animals change from year to year in an environment of fixed size and limited resources.	Simple iterative equations written down in the 1970s to describe the time development of populations led to the mathematical theory of chaos.

of research covers an enormous range of possibilities. It describes the expeditions that revealed the different continents to European explorers and mapped the globe. It describes first investigations when new scientific tools are developed. It describes the increasingly accurate maps of the night sky created by new generations of telescopes, or unexpected new particles discovered in particle accelerators. It describes much geological and biological field work. More examples are in Table 1.5.

Many research projects contain an exploratory phase, which produces something of interest that then becomes the subject of other research methods. For example, the first observation of gamma-ray bursts by Klebesedal *et al*. (1973) simply reported observations of enormously powerful far-away explosions made over several years, ruled out the possibility that they were due to known sorts of