Introduction: Experimental Techniques

The Scientific Method

What is science? How does it differ from the other ways we learn the things we believe? Unlike religious dogma or our parent's opinions regarding the "best" political party or pickup truck, science deals only with those things that can be measured.

Scientists employ an efficient and systematic approach called the *scientific method*. The scientific method can be summarized in five basic steps:

1. Observations or controlled measurements are made of some aspect of the phenomenon.

2. A hypothesis is formed on the basis of the observations or measurements.

3. A prediction regarding some unobserved aspect of the phenomenon is made on the basis of the hypothesis.

4. The prediction is tested experimentally.   If the prediction fails the experimental test, the hypothesis is modified or a new hypothesis formed, and the process is repeated.

5. The results are published so that other scientists can test them.

All of us occasionally use the scientific method. Suppose you come home from classes and flip the light switch on the back porch. The light doesn't come on. You form a hypothesis that the electricity is off. If your hypothesis is true, then the digital clock on the kitchen range should be out, too. You check and see that it is on. Therefore, your original hypothesis is incorrect. You hypothesize that the bulb is burned out. You remove the bulb and check it with an ohmmeter, and it shows infinite resistance. Your second hypothesis was supported by experiment.

The Fundamental Axiom of Science

A keystone of the scientific approach is the assumption that the universe is "orderly," and that the same basic rules govern natural processes everywhere. For example, astronomers assume that the principles governing gravity and electromagnetism are independent of space and time. This may seem like a big assumption, but it really underlies all human activity. Every time you take some medicine, you are working on the assumption that the rules of biochemistry have not changed. Every time you get on an airplane, you are gambling that the principles of aerodynamics still hold. Without the assumption of an orderly universe, the results of any study would only apply to the very specific time and place when and where the study was conducted.

Formulating Scientific Hypotheses

A hypothesis is an educated guess generated to explain a given phenomenon. Consider these hypotheses:

- Gravity causes objects to fall at the same acceleration regardless of their mass.

- White light is a mixture of multiple colors.
- Babies are delivered by a stork.

These are all *testable* hypotheses. In other words, one can think of observations and/or experiments that would provide evidence to support or refute the hypothesis.

In contrast, the hypothesis “Glenn Miller's music was better than any of this crap they play today.” is not testable, since there is no universally accepted standard to determine what is “better” in music.

The creation vs. evolution debate is a perfect example of misunderstanding of what constitutes science. It is certainly possible that the Biblical account of the origin of life is literally true. However, it is untestable by scientific methods. On the other hand, evolution by natural selection is a process that is observable, and many observations have been made that support it. It is in the realm of science. Questions about the meaning of life, the existence of God, and the number of angels that can dance on the head of a pin, cannot be answered scientifically. They are in the realm of philosophy and religion.

A scientific hypothesis with *universal* application (i.e., “All groundhogs hibernate in the winter.”) can never be absolutely proved (*verified*) because we can’t watch every one of them. Even if we could watch all the ones living now, we couldn’t watch all the ones in the past or future. However, finding just one active groundhog in January would disprove (*falsify)* this hypothesis. An *existential* hypothesis (i.e. "Some extraterrestrial planets support life.") can be verified with an example. It can't be falsified by example, however, because its negative is a universal statement ("No extraterrestrial planets support life.")

What is A Theory?

The scientific use of the word "theory" is very different from its common use meaning an opinion (i.e. "Joe has a theory about why the Royals lost their last 20 games.”). A scientific theory refers to a hypothesis based upon observation or measurement. Examples include atomic theory (matter is composed of atoms) and gravitational theory (objects attract each other with a force that varies directly with the product of their masses and inversely with the square of their distance apart). An accepted theory has withstood years of rigorous scientific testing. Scientists are actually more likely to be wrong about a "fact" than about a theory. For example, it is far more likely that a measurement is in error (a pressure gauge may malfunction) than for a well-established theory (air pressure is directly proportional to the number of air molecules in a given volume provided temperature is constant) to be overturned.

Science depends not only on the forming and testing of hypotheses, but also on the accurate reporting of results. New scientific research builds on work done in the past. Whenever scientists report their results, they must include a detailed description of how they carried out the study. This information allows anyone else—either now or 100 years in the future—to examine, and if they wish, repeat the study to see if they get the same results. Peer review of research is all-important. Thus, in contrast to the stereotype of the scientist working alone in the laboratory, scientific advancements involve the interconnected work of many people.

Exercise – Testable Hypotheses

Read the following statements. Circle "yes" if the statement is a sound scientific hypothesis or "no" if the statement is not a sound scientific hypothesis (whether or not you think it is *true*). Explain your answer.

The cuckoo is a pretty bird.	YES	NO
I will learn a lot in this class.	YES	NO
My mother-in-law weighs a ton	YES	NO
John Elway was the greatest quarterback ever.	YES	NO
The boiling point of water is lower at higher altitude.	YES	NO
Aspirin reduces the risk of heart attacks.	YES	NO
Gremlins are responsible for traffic accidents.	YES	NO

Testing Scientific Hypotheses

Scientists test hypotheses in various ways. One way, an *observational study***,** requires us to study a phenomenon in its "natural" environment. Another, the *experimental study***,** allows us to manipulate the environment. Physicists usually use experimental studies while astronomers – of necessity -- usually use observational studies.

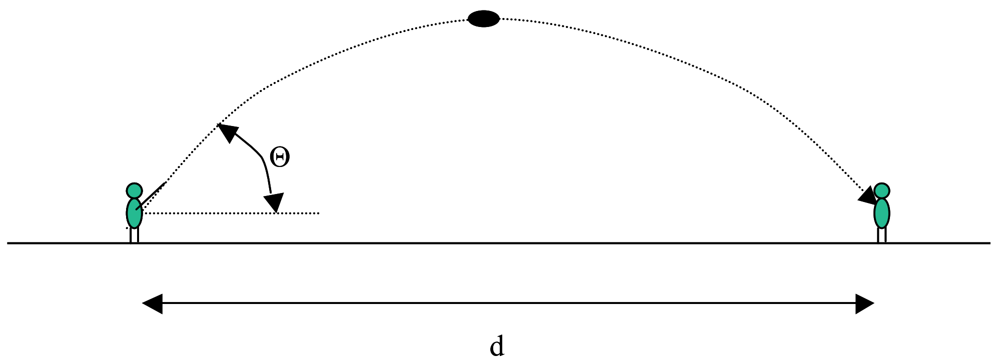
The advantage of the experimental study is that one can control the situation more precisely, which makes results easier to interpret. But, since this is an artificial environment the results sometimes have limited applicability in the "real world." More than one medicine that has killed a virus in a test tube has proven ineffective or dangerous when given to people.

As stated before, we test hypotheses every day, but this testing is usually not as orderly and planned out as testing of scientific hypotheses. Many scientific experiments and observational studies are designed to test how one variable affects another variable. When scientists design an experiment or an observational study, they must pay attention to these factors:

- *Independent variables*
- *Dependent variables*
- *Constants*
- *Confounding variables, artifacts, and bias*
- *Replication*
- *Randomization*
- *Control experiments*

Variables are things that vary within the experiment, like distance, time, force, voltage, etc. The term *independent variable* refers to a quantity controlled or chosen by the scientist. The *dependent variable* changes in response to the independent variable. A well-designed experiment will have only one independent variable. If more than one independent variable is allowed, we have no way of knowing which one produced the observed effect.

For example, let's say we wanted to know the optimum angle Θ to throw a football so that it travels furthest down the field to a receiver (and let's assume the quarterback throws it at the same release speed for any angle).



Here the independent variable is the angle Θ, which could vary from 0 to 90˚. The dependent variable—in this case d—will change as we manipulate values for the independent variable (in the above experiment, other dependent variables could include the time of travel or maximum height of the ball). So, we would throw the football at varying angles Θ, say 10°, 20°, 30°...90˚, and measure the d for each Θ.

Anything kept the same in the experiment we call a *constant*. To really know the effect of the release angle, Θ, on distance traveled, we would have to keep everything constant: speed of throw, wind speed and direction, type of football, amount of spin the football has, etc. If any of these conditions varied while we were varying Θ, then we wouldn't know if the resulting changes in distance were due to Θ or to that other *confounding variable* (also called simply, a "*confound*") When a confounding variable causes an effect on the experiment, we call that effect an *artifact***.** Confounding variables are often troublesome and are usually the main hindrance to getting meaningful results. Remember the big news when some scientists "discovered" cold fusion? They were measuring an artifact and didn't know it. But if we know a variable is confounding our experiment, then we can try to account for it. Since we can never account for all confounds in an experiment, we use three techniques to try to eliminate their effects: *replication, randomization, and controls*.

Replication is a way of double-checking an individual result. Let's say that when we threw the football at 90˚(straight up) a huge gust of wind above us carried the football 100 yards down the field. You would probably not believe it, and throw it again to check. Since we never know all the confounds, we generally always replicate trials. Normally, a minimum of 3 to 5 trials is advisable.

Randomization prevents "order effects." Now let's say the quarterback got more and more tired as he kept throwing, and ball speed dropped steadily throughout the day. If the throws were in the order Θ = 0, 10, 20, 30, 40, 50, 60, 70, 80, 90°, then the ball would travel less far than it should for all those higher angles. One thing to help prevent this artifact is to randomize the order: 40, 80, 0, 30, 10, 70, 50, 20... Then on top of this we replicate it, but in a different random order: 50, 20, 40, 70... The confounding variable of fatigue is still there and will increase the random error in the results, but at least it won't *bias* the results since the effect is spread out instead of concentrated at one end or the other.

A *control* is a special subset of the experiment, identical to the rest, but with one of the constants set at a different value. In this football example we might repeat the experiment with a different thrower throwing at a different speed.

Reporting Results

Professional scientists report their results to the scientific community in a more or less standard format. For example, scientists commonly record data or results in tables or graphs as a means of summarizing a large amount of information.

Tables

Tables are usually a rearranged form of the original data. A table always has a title, and appropriately labeled rows and columns. Below are some hypothetical data from the football throwing experiment. A good table is clear in its presentation, and shows units for each column. The "Average" is one common example of *data reduction*, where the data is condensed to a more usable form. Averaging the data helps eliminate "noise"—random variations in the measurements. However it won't necessarily eliminate the effects of confounds (artifacts and bias).

Table 1: Distance of football throw as a function of throw angle, 3 trials and averages.

	Distance Traveled (meters)			
theta (deg)	trial 1	trial 2	trial 3	Average
0	7.0	9.0	5.0	7.0
10	12.0	20.0	22.0	18.0
20	39.0	37.0	22.0	32.7
30	51.0	45.0	36.0	44.0
40	39.0	51.0	59.0	49.7
50	49.0	48.0	44.0	47.0
60	32.0	33.0	45.0	36.7
70	24.0	33.0	24.0	27.0
80	10.0	18.0	19.0	15.7
90	-3.0	-5.0	5.0	-1.0

Graphs

Graphs are another way of displaying data, and communicate trends better than tables. Here are the rules for a good graph:

- Always plot the independent variable (the one you manipulate) on the horizontal or x-axis, and the dependent variable (the effect you measure) on the vertical or y-axis. This arrangement is referred to as “y *versus* x.”

- Give each figure a descriptive title, centered over the figure.

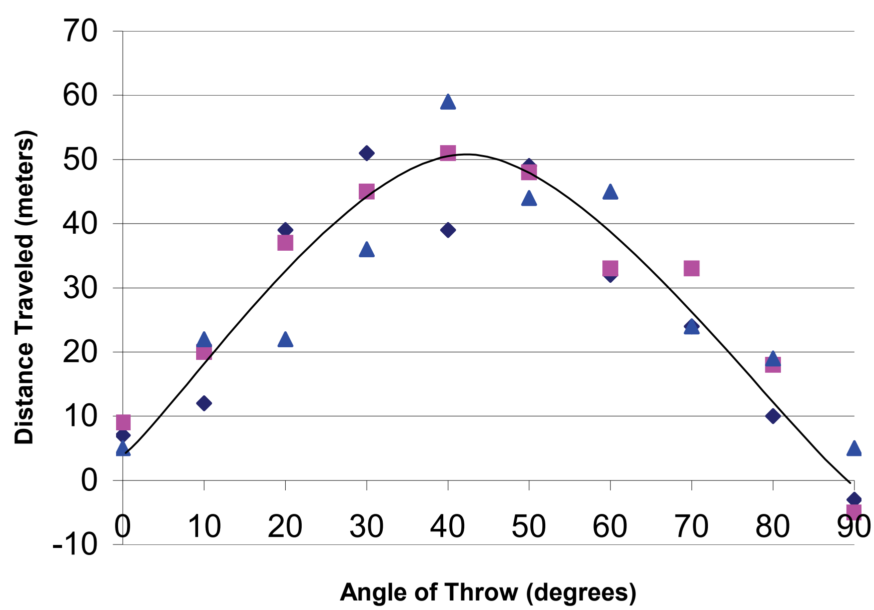
- The x and y axes should have descriptive labels (e.g., "Distance") and units (e.g., "meters").

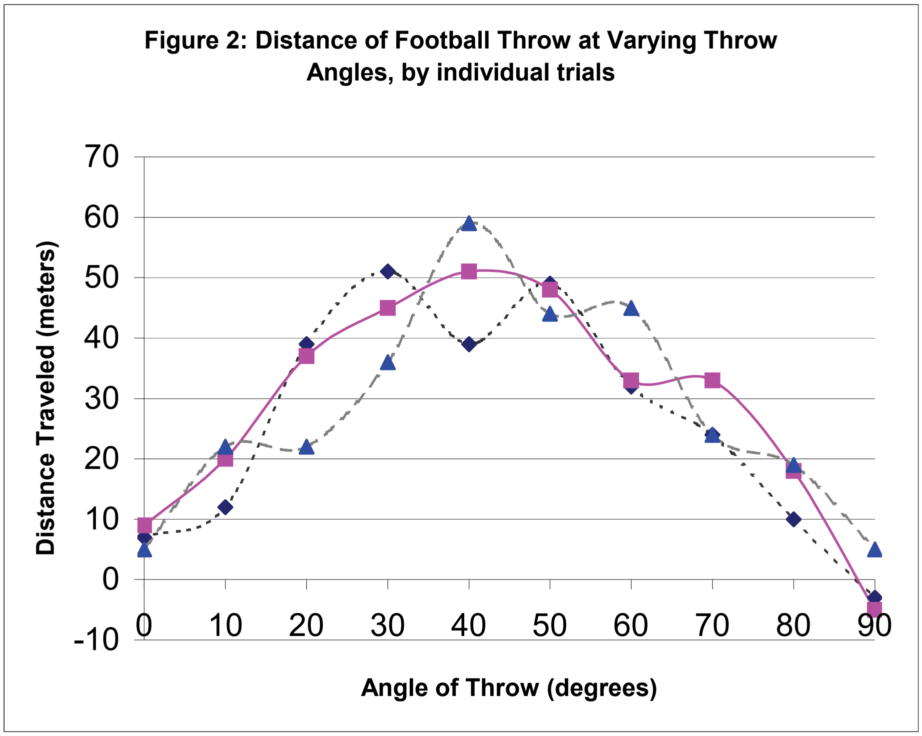
- Spread the data across most/all of the available graph area (not crammed into 1 corner)

- Plot the raw data (or the averages with *error bars* showing the variation) and draw a *simple, smooth curve* through the points. This curve need not pass through all the points themselves (and might not pass through *any* of them); rather, it should capture the *trend* of the data.

In Figure 1, below, the raw data is shown and a curve is drawn through to best represent the trend. Notice the curve doesn't necessarily go through any particular data point and that it isn't overly complex— straight lines or simple curves like parabolas are predictive of most phenomena, so it is best not to over-interpret the shape. Showing the raw data points allows the reader to see how consistent the data is—i.e., how much random error is occurring and thus how confident we can be in the results. In this case there is quite a bit of random error: see Figure 2 for the line-plots of each individual trial. Figure 2 also shows why it is good to take more than one reading, and why we wouldn't want to draw the lines through each individual data point.

Figure 1: Distance of Football Throw at Varying Throw Angles

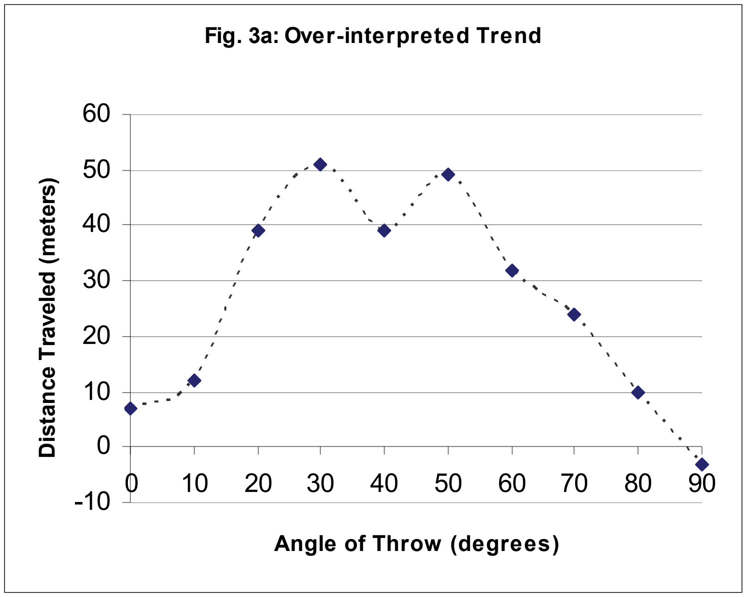




Because in this lab we won't always have time to replicate every data point, remember the following:

- Most physical phenomena are best described by straight lines or simple curves.
- All of our measurements are going to have error in them -- hopefully small and random but potentially large and biasing.
- Because of inevitable errors, we wouldn't want to rely on each individual data point for the shape of the curve.

Thus, if we only have 1 trial to work with, we should use a shape that captures the trend but doesn't over-interpret. For examples see Figures 3a (over-interpreted) and 3b (appropriate).



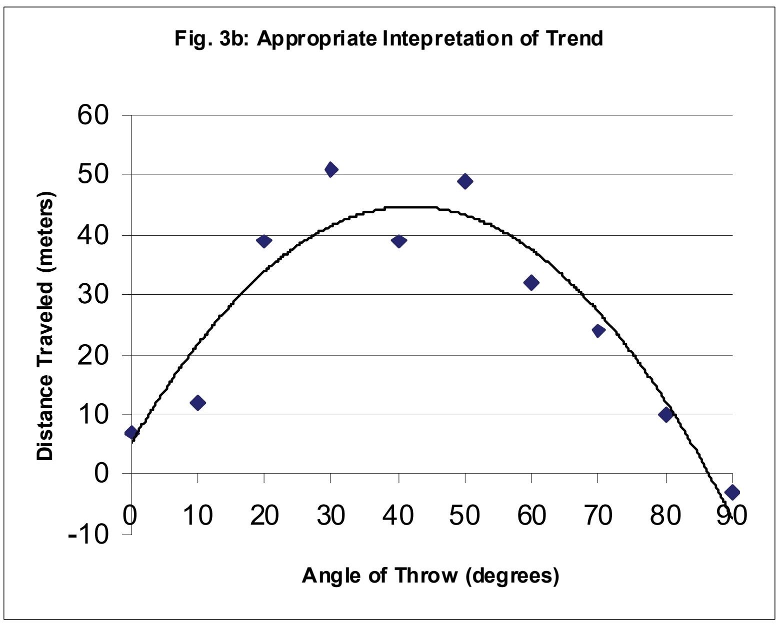


Figure 1 shows the optimum throw angle is between 40˚ and 50˚. It can be shown theoretically that the optimum angle is indeed 45˚— assuming no air resistance. With normal air resistance it is less than 45˚, although this depends greatly on the mass, size, shape, and speed of the object. For a shot-put, the optimum is only slightly less than 45°, while for a high-powered rifle bullet it is about 30°. To make matters even more interesting, the German army in World War I found that very powerful artillery pieces could fire farther at angles somewhat greater than 45° because the projectiles could be gotten above most of the earth's atmosphere that way. The so-called "Paris gun" was able to shell the French capitol from 75 miles away.