The History & Nature of Science

The quiet was like the stillness hours before a hurricane reaches the shore. A jittery, excited anticipation rippled through the ranks of the heavenly host – waiting, watching, and wondering when he would lay down his pride and submit to the King. Wait! There he goes. Head bowed. Lips moving. Tears forming. Heart opening. (Al…..most……….there.) ALIVE! And at that moment -- an explosion of sight and sound of the spirit of exhilaration and exaltation as the heavenly host celebrated in joyful tumult. The word was already spreading -- He got saved! Hallelujah! His life has been redeemed! Praise the King! He's born again! Hallelujah! He's a son of the righteous One – who was, and is, and is to come! Hallelujah! Hallelujah! Hallelujah!

Meanwhile, despite the celebratory din of the thousand thousands there was no sense of any of that back on earth. It was quiet. The young man, 24 years old, lifted his head, stood up, and silently left the sanctuary where that heavenly transaction took place. He didn't know what to do. Should he be feeling different? Joyful? Should he tell someone? Hug someone? Cry? Pray? Shout, "Hallelujah!" His mind was a whirlwind. What about my family? Are people looking at me? What about my fiancé? Do these people somehow know what I just did? What about my professor? How could they know? Does it show? Should I tell them? Should I tell him? I mean, its religion. That's science. He won't care, will he? Creation. Evolution. Christian. Will he? God. Atheist. Science. Research. Ph.D. Genesis. Science. Will he? University. Jesus Christ.

That was me in January 1996. I had just moved to Miami, Florida, to begin working on a Ph.D. at Florida International University in nearshore marine ecology. At the time, I was the prototypical science graduate student – I ate and breathed science; I slept in the lab; designed experiments at two in the morning on the inside of pizza boxes (in the areas where the cheese was not sticking to the box top); knew dozens of literary citations by heart; was already published and not afraid to present my ideas to my peers at science conferences; had a sick infatuation with statistics; and loved to be in the field. What more could a professor ask for? Oh, and now, I could add one more characteristic to my personal resume -- "a Bible-believing Christian." Yippie! Just what every scientific, atheist professor wants from Santa Claus! On the other hand, it's what every young Christian wants to deal with: "And please Lord Jesus, place me into a contentious, sin-filled, heathen atmosphere so I can be a bright light in the dark world of atheistic science while I am trying to earn my Ph.D. from those who think I look at them as sinners condemned to hell because they believe in and do science."

Well, with that kind of introduction you would expect me to follow-up this narrative with horror stories of me being academically persecuted for my beliefs, emotionally drained for having to take a daily stand, and physically worn out from having to be a lone ranger because nobody would want to work with the Christian. Well, you would be wrong. It would be easy for me to say that it took me eight years to complete my Ph.D. work because of all of these things and more, but that wasn't the case. Instead, I encountered the greatest resistance and bewilderment from other Christians. "How can you do science, you're a Christian now?" Or, "Isn't it a compromise to be a Christian and be a scientist?" And even, "You may want to reconsider being a scientist." What? Quit?! Reconsider my dream to be a scientist? Are you kidding me? Are you crazy? I love doing science. Why can't I do science? Why can't a Christian do science?

That last question hurts because you get bitten from both sides. There are Christians who fear the scientific establishments and believe that all science is out to prove that God does not exist. And there are atheistic scientists who believe that all Christians are flat-earthers who run up and down the church aisles attempting to cast out demons from the ghost of Charles Darwin. Wait a minute! Haven't people heard of Galileo Galilei? Robert Boyle? Johannes Gutenberg? Sir Isaac Newton? Blaise Pascal? Michael Faraday? René Descartes? Sir Francis Bacon? Johannes Kepler? All great scientists, and all great men of faith. These men were most certainly not ignorant flat-earthers, and they were not afraid of delving in and discovering the intricacies of God's creation. They were not afraid of science, and we shouldn't be either.

We have to first understand that science is not against God. Yes, there are scientists who use naturalistic evolution in an attempt to explain how life happened without the intervention or existence of God. But, evolution and science are not one. They are not married. Please don't elevate evolution to something it is not. Yes, in the mind of many scientists, evolution is one of the great ideas of science; but don't make the mistake of sounding foolish just because one overly-advertised idea comes into direct conflict with our beliefs and convictions. In other words, we can do science without ever debating, discussing, or dialoguing about evolution. Technically, science is a whole lot bigger than evolution, and science doesn't need evolution to be science. We, as Christians, need to understand this. Too often the word science and the word evolution are treated synonymously. This is wrong. Plain wrong. Ever hear of the expression, "Don't throw out the baby with the bathwater?" Well, in this case, science is the baby and evolution is the bathwater. We can reject naturalistic evolution and still have science. We can even do science!

I know for some of you the idea of solid Christians doing solid science may seem like a foreign concept or a strange revelation. But it is true. So, instead of convincing ourselves that the mixture of science and faith is unreasonable, and instead of listening to the popular media tell us that science and faith is a bad marriage, we should be asking ourselves why this mixture sounds so unnatural. Why do Bible-believing Christians have a difficult time swallowing this concept that not all science is evil? Perhaps it has everything to do with one of the great historical misconceptions or mistranslations of a verse in the Bible. Reading from the King James Version, the Apostle Paul instructs young Timothy of the following:

> *O Timothy, keep that which is committed to thy trust, avoiding profane [and] vain babblings, and oppositions of science falsely so called.* (I Timothy 6:20-21, KJV)

The common reading of this verse suggests that we are to stay committed to the Bible and to sound doctrine, while avoiding the oppositions of science. So, when Charles Darwin shared with the world his ideas about the evolution of humans and the origins of life the church retreated and avoided these oppositions of science falsely so called. The problem is that the Apostle Paul was not talking about the scientific establishment, the process of science, or even scientific ideas. Science, as a dedicated academic field of study, did not fully emerge until the Renaissance – more than 1,000 years after the Apostle Paul's epistles were written. So, what was the Apostle Paul talking about? Let's read a parallel verse from another epistle:

> *Beware lest anyone cheat you through philosophy and empty deceit, according to the basic principles of the world, and not according to Christ. (Colossians 2:8, NKJV)*

In other words, we are being warned that there are manmade philosophies and ideas about the world in which we live that do not glorify God nor lead us to Christ. Stay away from those! Don't compromise our faith with empty deceit! In I Timothy 6, the same warning is given using the word "science," which comes from the Greek word "gnosis" and means knowledge. He was warning Timothy, the church, and us to be careful of those who say they have a hidden mystery or a higher knowledge with regards to spiritual things. (At that time there was a group called the Gnostics that were influencing people within the church.) Now, if issues of science do fall under these categories, then yes, we are to be careful of them – but to automatically and immediately assume all science is wrong and evil is a gross misinterpretation of the Scriptures. Thus, the historical church was just as responsible for the rift between science and faith as was the naturalistic evolutionists who paraded Darwinian evolution as the be-all-end-all answer atheists were looking for. This rift quickly evolved (pun intended!) into the war we see today. Think about it this way. If there are two armies facing off against one another, there might be negotiations between the leaders of the two armies or there may even be hesitation to commence the attacks because of the uncertainty of victory and the certainty of casualties. Well, what if one army began to retreat? Wouldn't the leaders of the opposing army feel confident about the outcome of the conflict and then proceed to attack? And as the retreating army continued to retreat that would give the opposition even more confidence. Without a stand-off there is no possibility for negotiations, and without talks, there would definitely be no possibility for reconciliation or a truce.

Suppose that one day the retreating army decided that they had run away for long enough, and then turned and began to engage the opposition. Their enemy would laugh in derision at the feeble attempts of the once retreating forces. They would chide: "Why fight now? You knew in the past you could not win this battle, so what makes you think you are a worthy opponent today? Go back! Do what you have been doing and stay as irrelevant as you have been. Because if you choose to fight this battle, you'll lose, and then the whole world will see that we were right all along." Despite the ridicule the fight ensues. And this describes the state of affairs today between the established science community and biblical Christianity.

A Brief History of Science

Science and faith used to not be enemies. In fact, it was the influence of Christianity that provided the fertile environment for science to develop. Unfortunately, in the minds of many, Charles Darwin's ideas of our origins also included the origin of science—which couldn't be further from the truth. Science did not begin with Charles Darwin, and Charles Darwin most definitely did not define science.

The history of science is long and rich as it transcends culture, world empires, and individual contributions. It's bigger than any one man and no one man can ever be given credit for its advancement. Those who study the history of science suggest that the label of being the first scientist should go to an Egyptian named Imhotep, who lived sometime around 2,650 BC. Imhotep was the architect of the 200' step pyramid at Ṣaqqārah in the city of Memphis, and has also been credited for being the first to document the workings and failings of cures for particular ailments – though credit for his medicinal abilities remains somewhat speculative.

As time marched on so did world empires—from the Egyptians to the Babylonians to the Persians, as well as the great Chinese dynasties—where discoveries and inventions like the potter's wheel, standardized masses for weigh scales, tooth filling, and sundials helped to advance civilization. However, science in of itself did not make any real great strides until the rise of the Grecian Empire because of the way cultures viewed the world. Those who lived outside of the Judean religion and society worshipped a plethora of false gods. These civilizations also "used" these gods to explain the (at the time) unexplainable. For example, if there was a period of drought and famine then the "god of rain" was not happy with the people. Or, if a river flooded it was because of their "god of the waters." This mentality (or some might call ignorance) of pointing to the supernatural to always explain the natural world inhibited the advancement of science. Why bother coming up with a testable explanation for a natural event when you had a pocket full of gods and a purse jam-packed with mythologies to choose from. There was no incentive to discover how things worked or why events occurred. Unfortunately, these societal traits from ancient cultures are applied to contemporary Christianity by the scientific and educational organizations as they erroneously believe that people of faith have no interest in either the advancement of science or the unearthing of new discoveries.

The Greeks, on the other hand, were interested in how the world around them worked and how life and matter were organized. They began to study and construct explanations of natural events; albeit, many of them incorrect. Aristotle was given the label as the Father of Biology because of his initial work in animal and plant classification. Aristotle's student, Ptolemy, promoted the geocentric (earth-centered) theory of the universe. Democritus proposed that all matter was made up of indivisible small particles called atoms. Hippocrates believed that to treat an illness you had to treat the whole patient. Another medical doctor, Galen, suggested that a person's health was tied to a balance of internal environmental conditions and fluids he called humors. Archimedes. Euclid. Thales of Miletus. Diogenes. Aristarchus. Pythagoras. All were Greek scientists and mathematicians who first looked for a natural explanation to explain a natural phenomenon, and were willing to discuss and debate their ideas with one another. Now, while it is true that the Greeks still worshipped their gaggle of mythological deities, they only attributed natural phenomenon to their gods when a natural explanation could not be otherwise found.

The Grecian Empire was eventually overrun by the Romans, who were not necessarily known for their scientific advancements inasmuch as their improvements to culture and societal structure—like plumbing and spas, roads, the arts, architecture, and public entertainment. Yet, it was the fall of the Roman Empire and the entry of Europe into what is commonly known as the Dark or Medieval Ages that stymied the momentum for scientific learning. Numerous feudal wars, famines, wide-spread poverty, disease, and political instability created an environment that was not conducive for the arts, education, and science. Who can think about learning when your own survival is questionable? However, let us not totally condemn scientific learning to the basement during this era. The church believed that during these difficult days they needed to provide medicinal services for the sick and food for the hungry. The only way to beat the conditions in which they lived was to learn new ways to live. So the churches built schools and strongly supported the *universitas magistrorum et scholarium* (community of teachers and scholars), now commonly known as universities. Church involvement in the advancement of academia in Europe tends to one of the less-mentioned truths about the emergence of the Renaissance.

The Renaissance, starting sometime in the mid 1300's in northern Italy and continuing through the mid-1700's and encompassing all of Europe, is considered a rebirth in culture and society. European society as a whole emerged from a disquieted slumber to once again enjoy the arts, literature, exploration, and education. We know the names, we've seen the works of art, and we're a product of their travels. Michelangelo. William Shakespeare. Raphael. Marco Polo. Niccolò Machiavelli. Christopher Columbus. Leonardo da Vinci. Ferdinand Magellan. Miguel de Cervantes. Donatello. And this list can be greatly expanded because in the midst of this rebirth came two movements with their own multitude of heroes: the Scientific Revolution and the Reformation. Most scholars set the date of the beginning of the Scientific Revolution at 1543, the year that two great scientists, Nicholas Copernicus and Andreas Vesalius, published their books *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Heavenly Spheres) and *De Humani Corporis Fabrica* (On the Fabric of the Human Body), respectively.

We have to ask ourselves: What was so special about the publication of these books that has prompted historians to declare their publication date the beginning of the Scientific Revolution? Some suggest that the contributions of these two scientists should be overshadowed by the invention of the printing press by Johannes Gutenberg in the 1440's because without the printing press, there would be no mass production of any books. And besides, the argument continues, what significance does a book on the rotation and revolution of the planet earth and a book on the anatomy of the human body have on the overall world of science and society? Aren't they just two books in two totally different fields with good presentations of fairly accurate scientific findings? Weren't there other publications by other notable scientists with other significant results that were just as, or even more so, relevant to both science and society? Why these two books in 1543? There has to be a greater explanation than just the fact that 1543 is a convenient date because it was during that year <u>two</u> notable books were published. There has to be a better explanation! And, there is. But, to understand the reason, we must understand what was really behind the Revolution.

The Scientific Revolution was more than just a conglomerate of discoveries and inventions, it was a drastic change in the way scientists dealt with knowledge—the accuracy of past knowledge, the presentation of current knowledge, and the promotion of searching for future knowledge. These scientists, superbly represented by Nicholas Copernicus and Andreas Vesalius, were challenging orthodoxy and tradition. Just because someone hundreds of years ago said something to be true, no longer meant that it was always to be accepted as truth. Every idea was to be taken off the bookshelf, dusted off, and then reexamined in light of new observations and testable experimentation. Aristotle who? Ptolemy who? Galen who? They were scientists who were also philosophers. That means they were men who made observations colored by opinions, and thus the objectivity of their results should be questioned. The men of the Scientific Revolution did just that. Nicholas Copernicus presented a model of the solar system that contradicted the teachings of both the scientific community and the church—the earth rotated on an axis and revolved around the sun. How did he know this? He presented mathematical proofs of data collected from years of observations, which was one of the first books to present mathematical proofs as testable evidence for a conceptual model. And Andreas Vesalius presented his findings on the anatomy of the human body with artistic drawings so that others could see what he was describing, and if they wanted to, they then could verify or challenge his results by comparing their observations to his drawings. That is what made these books so special in the eyes of historians.

The glory given to these two books and the date 1543 cannot be trumpeted over the fact that science underwent an incredible revolution in how it was to be accomplished. Galileo Galilei continued in the spirit of this revolution, and then further stretched the boundaries of the extent of this revolution, when he published his results on the existence and characteristics of sunspots. You have to remember that the sun, stars, and celestial objects beyond the moon were considered perfect creations from a perfect God (or gods, as in the case of the Greeks and other cultures). This explains why astronomers originally determined that the orbits of the planets around the sun were circular in shape because the circle was viewed as a perfect and pure shape, and thus should correctly be attributed to the celestial objects in the heavens. Galileo's findings of imperfections on the sun contradicted both scientific and religious orthodoxies. The sun wasn't perfect. The heavens may not be perfect. And it would be okay. Life could continue. Science could go on. God was still perfect. The church could still sufficiently represent Him. But the battle against tradition and orthodoxy would not be an easy one, as many of these earlier scientists found out.

It is at this point that skeptics point out that there were already clashes between science and faith, of which provided fertile ground for the rise of naturalism and eventually Darwin's theory of evolution. However, their premise could not be farther from the truth. The scientists of the Scientific Revolution, who supposedly were at odds with faith, were men of faith! They were not at odds with believing in the God of the Bible nor were they at odds with the Bible itself. Instead, their conflict was with the established institutions which were holding onto Aristotelian orthodoxy and tradition as though it were truth. The established church forgot that when they supported the development of the universities several hundred years prior, the universities were designed to be breeding grounds for individuals to challenge authority and orthodoxy. The universities were to lead the charge into new ways of thinking, and the only way to accomplish that is to determine if the old ways of thinking are valid. The established church and academic communities unnecessarily felt threatened by the rise of a system of thought with a core belief that ideas were to be systematically tested and experimentally proven before being accepted as fact. The year 1543 is identified as the beginning of the Scientific Revolution, but it symbolically represents the beginning of something much more important than a movement or a period of time. The year 1543 represents a true revolution, not just in knowledge or facts or discoveries, but in the methodology of how science is to be conducted.

The Scientific Method

If the Scientific Revolution is considered victorious because of how it has influenced and changed the way science is conducted, then the scientific method is the flagship representing that change. Such imagery for change was what was implied on the cover of Sir Francis Bacon's *Instauratio magna* ("The Great Instauration") written in 1620. The ship portrays learning sailing beyond the Straits of Gibraltar, representing the limits of present human knowledge, and venturing into the unknown. Bacon's opinion of the current state of affairs with regards to science and learning are best summed up in the opening lines of his preface:

That the [current] state of knowledge is not prosperous nor greatly advancing, and that a way must be opened for the human understanding entirely different from any hitherto known, and other helps provided, in order that the mind may exercise over the nature of things the authority which properly belongs to it.

This "way," as described and prescribed by Bacon, later became known as the scientific method—a systemized approach to learning and gaining knowledge that has been specifically applied to how science is conducted. The scientific method was to be an objective procedure that followed the progression of an idea to a valid fact. Scientific knowledge, whether presented as fact, principle, theory, or law, would no longer be accepted as truth unless it was published with proof of validation via experimental testing. Good ideas were just that—good ideas—until proven to be true. Even great and logical ideas were to be questioned, and even rejected, until evidence was presented showing that the scientist conducted experimental tests and discovered by experience that his ideas were true. The concept of validating your ideas with experimental testing and data did not quickly receive acceptance by all in the scientific community as many scientists reported that experimental *would* validate their ideas. However, this trend did not last for long and eventually experimental science became the norm.

So, what exactly is the scientific method? Let's start off with what it is not. It is not an exact recipe calling for a specific three-, five-, seven-, or ten-step procedure. There are different versions of the scientific method that vary with respect to the exact number of steps and the specified detail of each step. However, the scientific method, regardless of the number of steps, is based on three foundational principles:

(1) Science is supposed to be objective and free from personal bias.

Recognizing that personal and cultural beliefs influence both our perceptions and our interpretations of natural phenomena, we aim through the use of standard procedures and criteria to minimize those influences when developing a theory. As a famous scientist once said, 'Smart people (like smart lawyers) can come up with very good explanations for mistaken points of view.' In summary, the scientific method attempts to minimize the influence of bias or prejudice in the experimenter when testing a hypothesis or a theory.

Wolfs, F. 1996. Introduction to the scientific method. Physics Laboratory Experiments, Appendix E, Department of Physics and Astronomy, University of Rochester.)

(2) Science is supposed to be empirical and derived from direct observations.

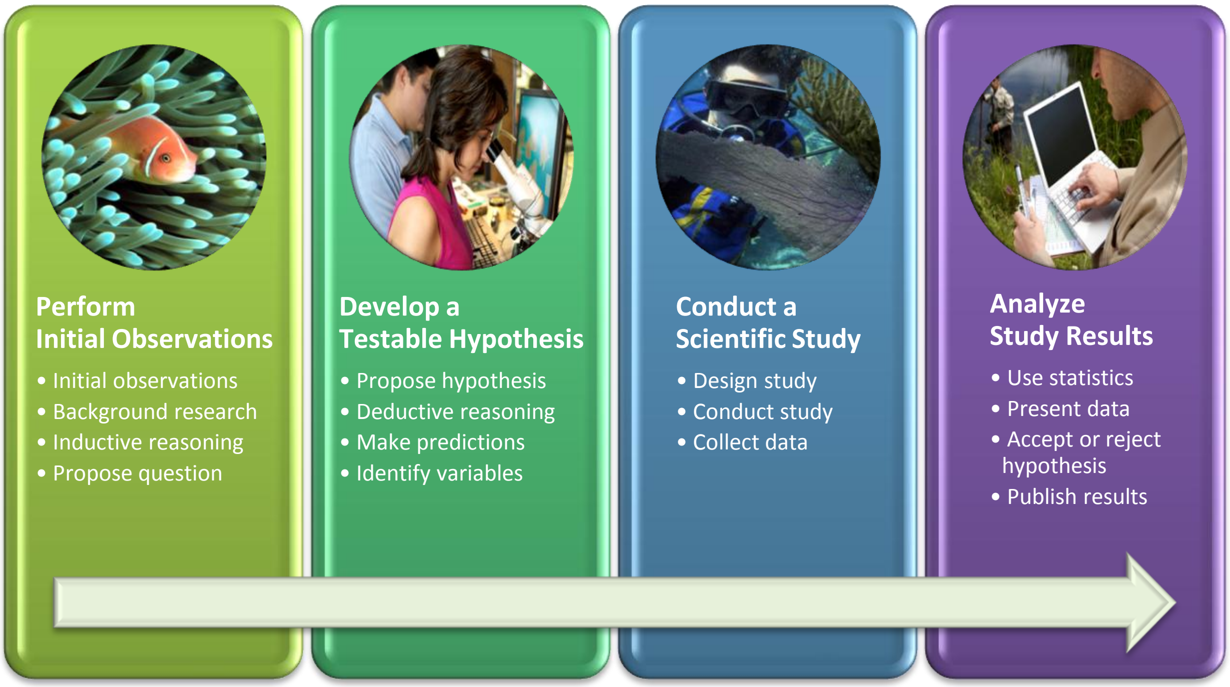
For, quite apart from the importance of the discoveries he made, Galileo's key contribution to the birth of science lay precisely in emphasizing the need for accurate, repeated experiments to test hypotheses, and not to rely on the old 'philosophical' approach of trying to understand the workings of the world by pure logic and reason… (John Gribbin. 2002. The Scientists: a History of Science Told through the Lives of Its Greatest Inventors. Random House, pg 72)

(3) Science is supposed to be rational and free from over-imaginative, just-so stories.

Much of people's behavior in elevators is not the result of rational thinking. It's an automatic, instinctive response to the situation. The threat of aggression is not real, yet our mind responds as if it is, and produces behaviors meant to protect ourselves. Elevators are relatively recent inventions, but the social challenges they pose are nothing new. Close proximity to other people in restricted spaces is a situation that has occurred millions of times in the history of humankind. Imagine two Paleolithic cavemen who follow the tracks of a large bear into the same small, dark cave. There is no bear in there, only the other hungry caveman ominously waving his club: clearly an awkward situation that requires an exit strategy. In those Paleolithic days, murder was an acceptable way to get out of socially awkward situations, much in the way we use an early morning doctor's appointment as an excuse to leave a dinner party early. In the cave, one of the cavemen whacks the other over the head with his club and the party is over. (Dario Maestripieri. May 27, 2009. "Why the Elevator Floor Is So Interesting." Internet article on the Wired Science web site: http://www.wired.com/wiredscience/2009/05/ftf-mastripieri/)

It was during the Scientific Revolution, via primarily Bacon's contributions, where these three principles emerged. If science was going to be the discipline via which knowledge would be increased, and if the scientific method was going to be the flagship under which this banner flew, then strict adherence of these principles would provide scientists an ethical code of conduct with which they were to follow. In other words, by introducing a set of standards with which science was to be done, then peer-review of scientific work would enable true science and valid knowledge to sail forth out of the confused seas of what was being called science or what was being done in the name of science. These principles were to be a help to the scientists and not a hindrance; and they were to be a stumbling block for those who were interested in only promoting themselves rather than truth. And as a Christian, Bacon was focused on the advancement of truth and knowledge—and not man's personal agenda.

Today, the scientific method can be divided into four main sections, and within each section, there is a checklist of tasks that needs to be accomplished if our scientific studies are going to be considered valid.



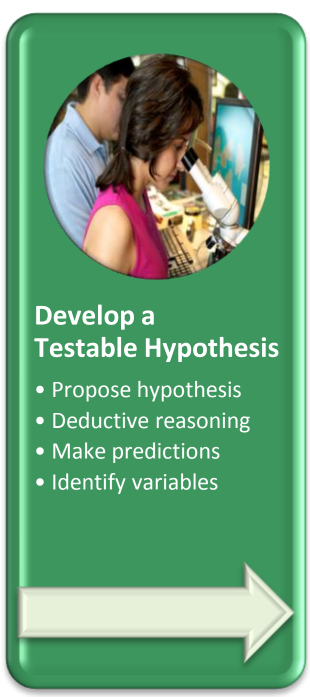
The application of the scientific method and its use in the furtherance of science can be summarized by the following quote from the National Academy of Sciences:

> *Scientific knowledge and understanding accumulate from the interplay of observation and explanation. Scientists gather information by observing the natural world and conducting experiments. They then propose how the systems being studied behave in general, basing their explanations on the data provided through their experiments and other observations. They test their explanations by conducting additional observations and experiments under different conditions. Other scientists confirm the observations independently and carry out additional studies that may lead to more sophisticated explanations and predictions about future observations and experiments. In these ways, scientists continually arrive at more accurate and more comprehensive explanations of particular aspects of nature. Because observations and explanations build on each other, science is a cumulative activity. Repeatable observations and experiments generate explanations that describe nature more accurately and comprehensively, and these explanations in turn suggest new observations and experiments that can be used to test and extend the explanation. In this way, the sophistication and scope of scientific explanations improve over time, as subsequent generations of scientists, often using technological innovations, work to correct, refine, and extend the work done by their predecessors.* (National Academy of Sciences. 2008. Science, Evolution, & Creationism, pg 10)

Perform Initial Observations. The scientific method begins with making observations. Observations include information you receive through your five senses: sight, hearing, touch, taste, and smell. These observations can come from a purposed intent to learn something new about on event, object, or phenomenon in which you are interested, or can come about accidentally. The initial observation that sparked our curiosity is usually followed by additional observations as we attempt to learn more about this object or phenomenon of interest. What we cannot learn from our observations will come from conducting background research to learn what others have discovered. It is here, at this step, where the scientific process takes root. Our observations, coupled with our learning of what's already known, are filtered through a process called inductive reasoning. Inductive reasoning is when we develop a solitary idea from all of our accumulated observations and information. This synthesis leads us to ask a new question about the topic. We know it is a new question, or at least an unanswered question, because of our background research. Failing to do adequate background research can lead to a redundancy of work that, while at least confirms what was already known, often fails to advance the ship of knowledge from its previous location. This is similar to the 2004 sci-fi action thriller movie *iRobot*, where the detective was forced to continuously question a holographic image about a past event until a specific question was asked, and then the character in the image told him, "That detective, is the right question." The image then disappeared leaving the detective to follow any leads to answer that specific question. The premise for those scenes in the movie is analogous to the task of a scientist because asking the right question is paramount to conducting a worthwhile and successful study. The key to asking the right question is based on the researcher's ability to answer that question—taking into consideration time constraints, financial limitations, the accessibility of necessary equipment, and other logistics (e.g., the number of people it will take to set-up and run the scientific study). This is often the primary reason why many students struggle to complete their science fair projects (other than waiting until the last minute!). Both the student and the teacher are responsible for determining the feasibility of a study before the study is to begin. These same sentiments were echoed by our Lord Jesus Christ in considering the cost of becoming a disciple:

> *For which of you, intending to build a tower, does not sit down first and count the cost, whether he has enough to finish it—lest, after he has laid the foundation, and is not able to finish, all who see it begin to mock him, saying, 'This man began to build and was not able to finish'?* (Luke 14:28-30, NKJV)

The history of science is replete with disastrous beginnings because too many scientists fall in love with their own questions and fail to recognize the inherent dangers in asking the wrong question. I had fallen into this trap as a graduate student. For my undergraduate thesis project I conducted a study on the effects of red and far-red light on the growth of seagrasses. As an obvious next step when I was in graduate school I decided to isolate the plant pigment phytochrome from seagrasses because of its significance with respect to responding to red and far-red light changes. It had never been done before in seagrasses. In fact, its presence and significance in marine plants was skeptically questioned in the scientific literature. But I knew that because I had correctly shown the effects of the working of this pigment in seagrasses, it was there, and its extraction would be an extremely valuable scientific contribution. Well, be that as it may, after eighteen months of no results I called and spoke with a leading researcher in this field. After he stopped laughing (and I am not kidding about that part!), he told me quite frankly that he agreed with my premise and even agreed that my study would be scientifically valuable, but he also advised me that he would not ask his best doctoral student with ten years of funding to undergo such a project. Though I was crushed, I learned a valuable lesson about being thoughtful to understand the limitations that sometimes surround the best of questions.



Develop a Testable Hypothesis. Once we have a reasonable question about a specific topic in mind, we then propose a hypothesis. The idea of a hypothesis is perhaps the most well-known trademark of the scientific method. Since elementary school every student has practically been taught that a hypothesis is an educated guess. But what exactly is an educated guess? Imagine with me one of those metal coffee cans with a plastic lid sitting on a table. A student tells you that they placed an item in the coffee can. Your job is to guess what is in the can. You can't look inside the can, you can't handle the can, and you can't ask any questions about the object inside. This is what we would call a blind guess. You, as a scientist, are totally blind. However, if you were able to handle the can and ask questions about the object without opening the can, then you would be taking a reasonable or an educated guess about the identity of the object in the can. Do you see the difference?

Defining a hypothesis as an educated guess is an oversimplification of the idea. A hypothesis is really a testable statement that is derived from your scientific question. For example, if your question is: Does temperature affect the rate of breathing in fish? Then your hypothesis might be: An increase in temperature increases the rate of breathing in fish. Your question is derived from a combination of previous experiences and background research, from which you propose a statement that helps to explain your observations. But you are going to need to eliminate other possible hypotheses or prove that there is only one explanation for the observed pattern. This is done through deductive reasoning. Deductive reasoning is the process by which we take a general idea and apply it to more specific cases or scenarios. This logic-based approach is considered to be the reverse of inductive reasoning. Remember, inductive reasoning was used to develop our solitary idea from an accumulation of observations and information. Here, with deductive reasoning, we are making specific predictions that stem from our hypothesis statement. In the sciences, a prediction is an "if, then" statement that attempts to forecast a specific outcome of a test of our hypothesis. From our previous example our hypothesis stated: An increase in temperature increases the rate of breathing in fish. We can now make predictions that put our hypothesis statement to the test and that will help answer our original question. For instance: If we increase the water temperature by 5 °C, then the rate of breathing will increase. Or: If we decrease the water temperature by 5 °C, then the rate of breathing will decrease. If my predictions are correct, then my hypothesis is supported--and I have an answer to my question. On the other hand, if my predictions are proven incorrect, then I need to reexamine my hypothesis statement.

Remember, a hypothesis is a testable statement that attempts to both explain and identify possible relationships between variables. With our example, both the water temperature and the rate of fish breathing are variables. Variables are simply defined as factors that may influence the outcome of a scientific study, or are factors that are changed during the scientific study. There are three types of variables: independent, dependent, and control. Independent variables, also called experimental variables, are the factors in the scientific study that are manipulated or changed. The dependent variables, also called the response variables, are the factors in a scientific study that are affected by the changes in the independent variable. If this sounds confusing, then you can look at it this way:

the dependent variable is dependent upon what happens with the independent variable; or, the response variable is what is responding to the changes in the experimental variable.

You have the independent/experimental variable being changed and the dependent/response variables being measured as a result of the change. In our fish breathing and temperature study, the scientist is changing the temperature of the water in order to see a response in the rate of breathing in fish. Therefore, the water temperature is the independent/experimental variable and the rate of breathing is the dependent/response variable.

There are other factors or variables that can affect the outcome of the scientific study by their influence on the dependent/response variable. These other variables are called controlled variables because they are "controlled for" or kept constant so that they do not have any influence on the outcome of the study. Obviously, a scientific study conducted in a laboratory situation has a much better chance of standardizing and controlling for all the influential variables compared to a study conducted *in situ* (meaning, in the field or natural environment). In our study, the pH, salinity, and depth of the water were controlled variables and thus were kept constant. The species, sex, age, and size of the fish used in the study should also be controlled for as these could very easily cause variability.

There are two final considerations with regard to the different types of variables in a scientific study. First, though it is common to think about the independent/experimental variable as the one we manipulate and the dependent/response variable as the one we measure, we have to remember that we are also taking measurements of the independent/experimental variable. Some studies require changes to occur with the independent/experimental variable over time, and these adjustments have to be recorded. Other studies require that the independent/experimental variable be constant throughout the course of a study (such as keeping a fish aquarium 5 °C warmer than ambient temperature), and thus making measurements and recording them is essential for the publication of the results of your study.

The second consideration regarding variables in a scientific study is that in order for a study to be successful there should only be one independent/experimental variable manipulated at a time. Having concurrent or simultaneously changing variables will only cause confusion as you cannot discern the effects of each variable independently. If we had increased the water temperature by 5 °C and the salinity by 5 ‰ at the same time we would not be able to determine which one of these variables caused a change in the rate of breathing in the fish. On the other hand, we can measure several dependent/response variables at one time as the object, organism, or phenomenon can be affected in a multitude of ways by the change in the independent/experimental variable. This rule of thumb can, however, be broken when more complex experimental designs are employed to be able to account for the individual and combined effects of manipulating two independent/experimental variables. Special statistics are also used in these scenarios.

Conduct a Scientific Study. At this point in the process we have our scientific question, hypothesis, predictions, and a list of important variables that will be manipulated, measured, or controlled. Now, all we need is the scientific study!

One misnomer about science is that everyone thinks that everything we do involves an experiment. When in fact there are two types of scientific studies: observational and experimental. Observational studies examine scientific questions and test hypotheses without manipulating the independent/experimental variables. For instance, let's say we are interested in the diameter of oak trees along a 200-mile, north-south transect across the state of Arkansas. We then hypothesize that there will be a positive correlation (or relationship) between going south along the transect and the diameter of oak trees. In other words, as we go south the diameter of oak trees increases. The independent/experimental variable is the location along the transect while the dependent/response variable will be tree diameter. This would be considered an observational study because we are not making any manipulations to any of the variables within the study. While it is true that we are studying how one variable responds to concurrent changes in another variable, these changes are occurring naturally within a natural habitat. In this type of study it is not uncommon to measure other variables that we would normally control for in a laboratory situation. For instance, we may collect climate, precipitation, and soil chemistry data along the same north-south transect to examine the possibility of other important or interacting relationships that may have an effect on the growth of oak trees.

Experimental studies, simply known as experiments, are more complicated because we are attempting to manipulate the independent/experimental variable in ways that are not naturally occurring. Although our manipulations of the variables should <u>simulate natural variations</u> so that our project has realistic applications, and these can be done in either the laboratory or *in situ*. We'd all love to do experiments *in situ* because they will most resemble naturally-occurring conditions. However, logistical limitations often direct our studies towards the laboratory where we have greater control of the variables and an easier time conducting the study; albeit, at the cost of losing some "realness" with our work.

In setting up an experiment we must first decide how to vary the independent/experimental variable. Hopefully, we've researched our subject well enough to know the naturally-occurring range of our variables. Then, we need to decide how many different variations of the independent/experimental variable we will need. Each variation or increment of the independent/experimental variable that we use in our experiment is called a treatment or treatment group. In our fish breathing experiment we are interested in the fish breathing rates of tetras, which like their ambient (i.e., natural or regular) aquarium water to be set around 25 °C. We decide that we want to test the breathing rates across the range of 19 to 31 °C because pet owners are sometimes not careful about controlling the water temperature, and we were interested in measuring the stress levels of the tetras across this range. Why did we pick this temperature range of 19-31 °C? Well, maybe during the background research stage of the scientific method we surveyed friends, neighbors, pet stores, and students who owned fish as pets, and discovered that the temperatures in their tanks occurred within this range. Then, within this temperature range we established five water temperatures for our tetras: 19, 22, 25, 28, and 31 °C. Thus, our experiment included four treatments: 19, 22, 28, and 31 °C. The 25 °C water temperature is not considered a treatment group because it is the natural/regular/ambient water temperature for the fish. We call this the control group. Our data analysis will focus on the comparison between fish-breathing rates in the treatment groups relative to the fish-breathing rates under controlled/ambient conditions (i.e, the 25 °C water temperature).

Now, we come to another misnomer about doing science. Scientists would like everyone to think that when it comes to conducting a scientific study that everything is done perfectly and with all the best available techniques. Most scientists aren't hypocritically or maliciously putting on a façade; it's just that we are trying our best to do what is best for our study. There are statistical procedures that we can use to determine how many treatments to set-up, how many test subjects we should use, and how many times we should sample these test subjects. This is referred to as sampling strategy. And as good as these statistical procedures may be, practicality often becomes the rule of thumb because we can only do what we can do, and we cannot do what we cannot do. Meaning this: if I am a marine biologist studying coral and my fancy statistical procedures and background research tell me to establish ten treatments consisting of 20 separate coral colonies over a 5 km^2 area and that I need to examine them once a week for 30 straight weeks, then I either hire five teams of graduate students to conduct the research for me (probably unrealistic because of the lack of funds and the lack of graduate students) or buy a house boat and live offshore for eight months (which is probably even more unrealistic, especially if I am married). Thus, the moral of the story is this: we design our scientific studies with the most optimal sampling strategy and work backwards towards the realm of practicality. And, in truth, most scientific studies are conducted by balancing statistical appropriateness with logistical ability.

Let's take a more detailed look at what it means to have a sampling strategy. The main purpose of conducting a systematic study is to separate the behavior of an organism or a system from background noise, which is often caused by temporary environmental changes or inherent variability in the test subjects. If a few of my tetras are younger than the rest of the ones I am using in my experimental study, then their breathing rates may slightly vary. This is why it is dangerous to base any scientific conclusions from what is called a snapshot observation, or a one-time sampling, because we do not know if the data we collected are representative of the system we are studying or if we just happened to observe an infrequent anomaly. The same is true foe only sampling one test subject. For example, maybe my tetra previously lived in tanks that were slightly colder and thus has acclimated to a water temperature slightly colder than most fish within that species. My results would once again be skewed by an anomaly.

Our sampling strategies are generally designed around statistics, which are used to differentiate random events from real-world patterns. The science of statistics is defined as the mathematical science by which inferences regarding entire populations are made from studying samples of the populations under study. A statistical population is the target group we are interested in studying. For example, if we were interested in the average weight of adult male bears, our statistical population would include all adult male bears; and the results from our study would apply to all adult male bears. Is this a feasible question? Can we weigh every adult male bear? Probably not. Statistical populations are generally large, unobtainable, and hypothetical, and thus we must develop another strategy to attempt to determine the average weight of all adult male bears. A common strategy involves measuring a sample, or subset, of the entire population, and inferring the results of our sample onto the entire population. For this example, we can go to various woodland regions throughout the world and measure the weights of 20 bears at each site, and then use the data to estimate the average weight of all adult male bears – without weighing each and every adult male bear.

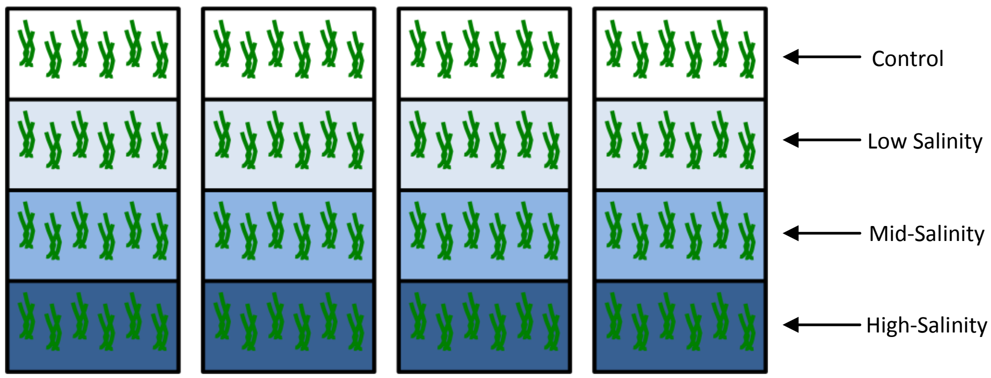
What happens if we can only sample bears in four separate wildlife parks in the state of Colorado? Can we still provide a valid answer for the question? Or, are we trying to infer too much from a limited study? The latter is probably true. It would be invalid if we stated that we provided the average weight of all adult male bears strictly from bears living only in four wildlife parks in Colorado. So, what can we do if we cannot properly answer the question? Simple: change the question; which means changing the target group or population. In this case, the new population could be all adult male bears in Colorado, or narrowing the definition, we can define our target population as all adult male bears in only the four separate wildlife parks in Colorado. Neither answer is incorrect; although the latter perspective is probably more valid because the samples are a better representation of adult male bears living in the four wildlife parks than all adult male bears in Colorado. However, this may be contested if an expert on bears suggests that any variation or differences in the weights of bears is minimal throughout Colorado—thus, either of the new statistical populations could be used.

After defining your target group or population, your next step is to develop a strategy of how you are going to sample your population. How many samples would provide a good estimate of the population? How would these samples be collected? And, how do you determine which samples to collect? Though we are not going to delve too deeply into statistics you should be aware of some of the assumptions that need to be satisfied in order to correctly analyze your data. One key assumption is random sampling. Random sampling means that each observation that you record is totally independent of previous observations. For instance, if you shot and tranquilized a bear in one of the state parks in Colorado and then shot a bear you found nearby, this would not be considered random sampling because the second bear's selection was based on and related to the first bear's location. Examples of random sampling include using a random number generator on a computer or calculator, a random number table in a statistical book, or rolling dice (you can purchase 4-, 6-, 8- 10-, 12-, 20- and 30-sided dice from any online vendor who specializes in role-playing games like the old Dungeons and Dragons series). Each of these methods gives you a number that has been randomly chosen. To use these numbers, you can devise some type of grid system where your numbers correspond to points within your grid. For example, if you need to collect sediment cores from a field that is 100 m x 100 m, you can think of the field as an x,y coordinate plane--which is divided into 100 rows (x) and 100 column (y) at 1 m intervals. You can then select pairs of randomly chosen numbers from 0-100, and correspond them to an x,y coordinate. This can be repeated for as many samples as you need to take.

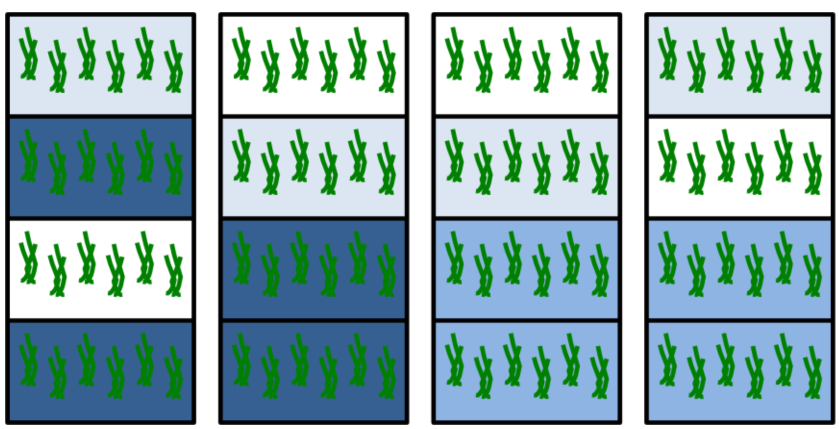
In the case of attempting to find bears in Colorado you can identify five parks where bears have been spotted and divide each park into six sections. If you want to take measurements of 20 total bears, then you roll your pair of dice 20 times. The first die tells you which park to go to (with the numbers 1-5 corresponding to parks numbered 1-5) and the second die informs you which of your six sections to go sample (with the numbers 1-6 corresponding to each of the six sections). One of the drawbacks of random sampling is the amount of time dedicated to each sample. For instance, let's revert back to our 100 m x 100 m field. If we had to collect 50 random samples from this field, it would take us all day to locate our 50 points. Also, in the case of looking for bears, you may have rolled a "1" and a "4" – telling you to go into the first park and in the fourth section. Well, what if there are no bears in that section? Or, even worse, what if that section is submerged underwater because of recent flooding? What do we do now?

There are several ways that we can overcome this problem. We can (1) establish a smaller area within the field from which our sampling will occur; (2) collect our data haphazardly, which is similar to random sampling, but our observations are not independent of one another (because if you walk away from one sampling point and then decide just to take another sample wherever you are at, it is not random because that second point is related to the first point); or (3) collect our data systematically--that is, in a predesigned pattern (for example, collecting a sample every 3 m). Collecting data haphazardly or systematically does not necessarily bias your study. On the other hand, if you can avoid putting a question of doubt over your study, your results will be more widely accepted.

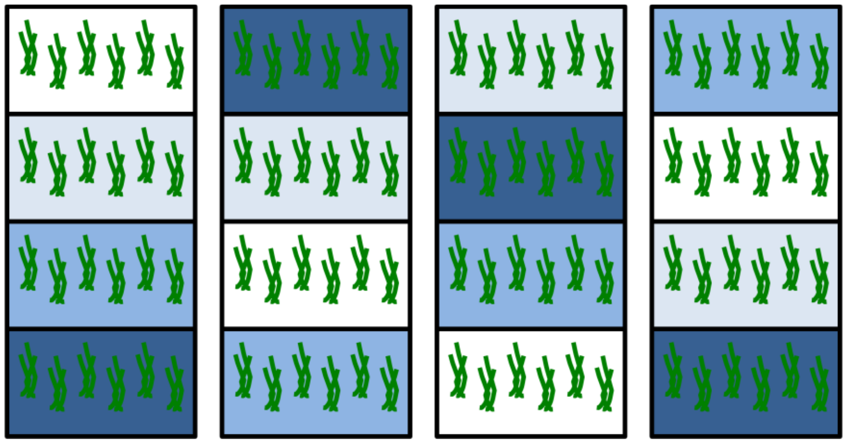
Regardless of the sampling strategy the researcher must be cautious with how the replicates are distributed in space (i.e., spatially) and in time (i.e., temporally). Let's present this idea using a new scenario. We're going to grow seagrasses in saltwater aquaria to determine the effects of salinity of the growth rates of the plants. Salinity is the independent/experimental variable and the leaf growth rates is the response/dependent variable. There will be one control group and three treatment groups (low, mid, and high salinity values); of which there will be four aquaria for the control and each of the three treatments for a total of sixteen aquaria. The following schematic is an example of setting up the tanks of seagrasses in a systematic design.



Logistically, this is the easiest to do and to remember because the same treatments are located in the same areas. However, this presents problems because what if there are some inherent differences in the design of the system and the tanks on the top all get more sunlight – then we would be introducing a variable into our system that was not controlled. So, we then attempt to control for any inherent variable and randomize the pattern of aquaria.



Randomization can also create a problem. Do you see it in the above example? You can actually get the same problem because all of your mid-salinity treatments are bunched together on the lower right-side. This is not acceptable. Some would suggest randomizing the tank placement again, but then it is really not random if I continue to randomize the tanks until I get a pattern I like. There is another solution presented below.



This is called a randomized block design. The randomness is within each of the individual blocks; with a block being defined as a row or column of aquaria. This design helps keep things random while preventing any kind of spatial patterns or bias.

Temporal patterns or biases are also important and must be accounted for when conducting scientific studies. For instance, if you sampled the original systematic pattern of tanks, it is possible that in the morning hours you sampled all of one treatment group and then you finished sampling another treatment group in the afternoon hours. This could cause a difference in the results, especially if you were measuring instant (i.e., on the spot) rates of photosynthetic production). Your results could be skewed. More often than not, temporal bias or patterns is not that significant of an issue; but it can occur, and thus should be controlled.

Once we have decided how the data are going to be collected (i.e., random vs. haphazard vs. systematic sampling), then we need to determine how many observations should be collected and how many times the study will be conducted. The number of observations in each experiment is called an experiment's sample size, and is represented by the letter n. The number of experiments, or trials, is referred to as replication. It is easy to land in the pitfall and assume that the more replications and the greater your sample size, the stronger your results become–and there are times that this statement holds true. Generally, the strength of your results will not significantly increase with an increase in sample sizes and an increase in your sample size and number of experimental trials; if you first began the study with reasonable parameters. Thus, we ask how do we determine how much work needs to be done? This question is usually and unfortunately answered by our time and financial budgets. For instance, SCUBA divers are limited by air supply, scientists using boats are limited by weather and seasonal patterns, and forest rangers are limited by daylight (who wants to go bear hunting at night?!).

On the other hand, the statistical answer involves looking at the variation in our observations. Variation is a statistical term used to describe the range of measurements around an average number. For example, earthworm widths of 1 mm, 2 mm, 1 mm, 1 mm, 1 mm, and 2 mm, have less variation than the earthworm lengths: 220 mm, 140 mm, 370 mm, 700 mm, and 675 mm. The general-rule-of-thumb states that the greater your sample size the lower your variation. However, you will eventually come to a point where increasing your sample size does not significantly change your variation. There are several methods that you can use to determine the statistically valid sample size and replication number, but are beyond the purposes of this text. Rather, the take-home messages are: (1) if you notice that your variation is relatively high, increase your sample size in an attempt to reduce it; (2) the idea behind an increased sample size and replication number is to eliminate background noise and the chance effects of an anomaly; (3) if you are trying to show differences between two groups of test subjects and the amount of difference between these test groups is small, then an increased sample size will help you determine if that difference is really a difference; and, (4) there will be times when increasing your sample size 100-fold will not lower your variation–in other words, you need to know your subject.

Finally, after all that work, you cannot forget to actually take and record your measurements. Warning! This is where most young students err—especially on weekend blitzes to complete those dreaded science fair projects. Data are technically your measurements or information collected from your study. Most students (and many top notch researchers) lazily record their information of whatever piece of paper is handy, without consideration for that paper's safety and security. I've witnessed far too many graduate students who have had to redo work because of a lost piece of "scrap" paper. Please make sure that students use a science log book, a classroom data binder, and pre-designed data sheets for their studies; and that there is a back-up system in place (both for papers and computer files). Students can sometimes do the impossible things without thinking about what or why they are doing it—like deleting entire spreadsheets, saving the file, and then asking for the location of the undo button.

In all seriousness, there are a few basic principles scientists and students should follow when recording their data during scientific studies.

(1) Use the metric system, use the metric system, and use the metric system!

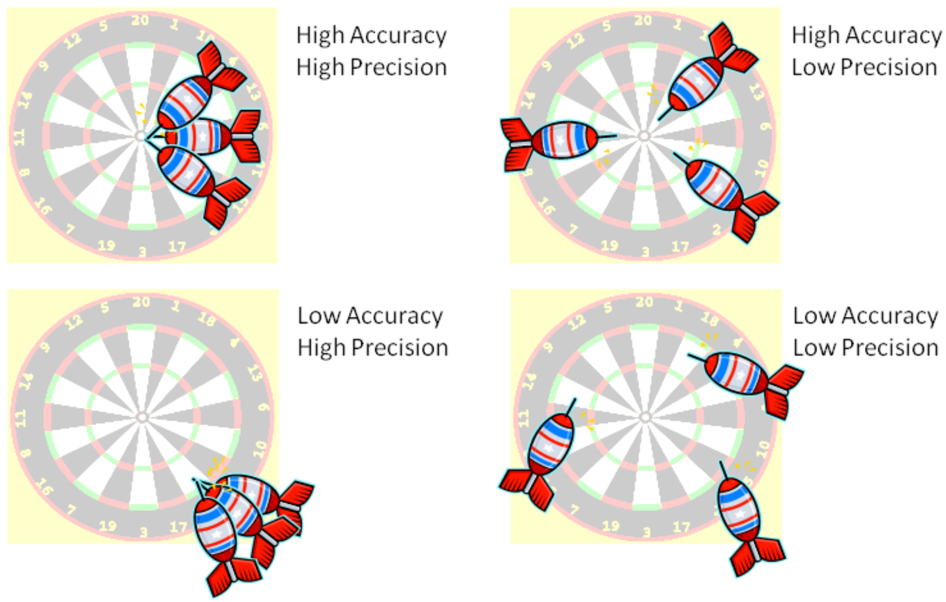
I know that we all know that the United States has not converted to the metric system. However, as we also know, the rest of the world is using the metric system and so is the scientific community. In actuality, scientists use the SI, also known as the Système International d'Unités, or the International System of Units; which is, for the most part, the metric system. That being said, please introduce the metric system early and often in your lessons and ban those dreaded inches, feet, pounds, and ounces from our elementary classrooms! You'll make everyone's life a lot easier and your upper level science teachers will be grateful that their students know that a meter is not just the place you put quarters when you park your car on the street! Furthermore, our students need to learn the basics of unit conversion—within the metric system (like centimeters to meters) and between the two systems of measurement (like inches to meters). And, there may also be times we take measurements without using a standardized tool or instrument. For instance, let's say you take the class on a field trip and were planning on measuring the circumference of trees. To your dismay and chagrin, the one student you entrusted with the tape measure, left it in the classroom. Now, what do you do? Do you scratch the whole trip? Do you forget about that aspect of the project? Do you put that student in timeout? No, no, and no! I have participated in too many boat trips where we envision our equipment sitting back at the lab, in the car, or even on the dock—rather than being with us two miles offshore in the Gulf of Mexico. Students need to learn to be flexible and to improvise. In the case of our missing tape measure we can use a shoestring to obtain "a measurement" of the circumference of the trees. We can then mark on a piece of paper the length of our measurement, and accurately measure the length of those marks when we return to the lab. Please hear me on this one because these lessons go far beyond the four walls of our classrooms. Our culture, and as a result our students too, have progressively lost that ability to think independently. As a whole we may be smarter. We may have more resources at our disposal. But, generally speaking, if it is not through a fast-food window, available as an icon on a computer screen, or presented as a blog on Facebook, then many of our students have not the desire or training to think outside the box. We, as educators and especially as science teachers, have the privilege and responsibility to teach these skills to our students. If not, who will? English teachers? Ha! (Just joking!) Seriously, as science teachers with hands-on lab exercises, we have the responsibility to train our students how to think, discuss, and solve problems.

(2) Data should be presented using the most appropriate units.

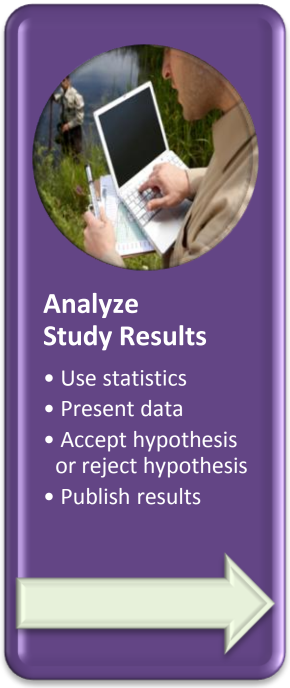
This is more than just using the SI system of measurement. Think about it this way. If we were measuring the speed of car driving on a highway, would we use miles per hour (mph), meters per second (m/s), kilometers per hour (km/h), or centimeters per minute (cm/min)? Not only do we have to have the correct abbreviations, but students also need to think about the appropriateness of using a specific unit of measurement in a specific situation. The distance a car traveled may be measured in kilometers, while the distance a marble rolled may be measured in meters, and the distance a caterpillar crawled may be measured in centimeters.

(3) Data need to be both accurate and precise.

There is a scientific difference in the definitions of the words accuracy and precision. Accuracy is a description of how close a measurement is to the true value, whereas precision is the exactness of a measurement; referring to how close several measurements agree with one another. The diagram below should clarify these definitions:



As scientists, we want all of our data to be both accurate and precise. However, in the real world, our measurements can take on a life of their own. Our responsibility as teachers is to be on the look-out for erroneous or troublesome data, and at the upper grades, we need to teach students to think about the range and consistency their data sets should have. Students need to realize that poor data collection has the chance to ruin their hard work and best efforts. Minor corrections or changes in the use of equipment are sometimes all that is needed to prevent disaster.



Analyze Study Results. Now we are at the fourth and final stage of the scientific method. Yeah! We finally get to analyze and interpret the results of our scientific study. Interpretation of the results of scientific studies uses statistics. Students should be able to examine what are commonly referred to as summary statistics (aka measures of central tendency), and determine if there are any differences in the response/dependent variables between treatments and controls (in an experimental study), or differences between test subjects (in an observational study). Summary statistics are fairly easy to understand and calculate, and include the following: the mean (i.e., the average), the median (i.e., the middle number), the mode (i.e., the number that shows up the most in a data set), and the range (including the minimum and maximum values within a data set). Depending on student ability and the availability of resources, students should be able to calculate these statistics by hand, with the use of calculators, or in a computer-based spreadsheet. Regardless of the method of calculation, the data should be presented using the appropriate number of significant digits. Without getting into too much detail, students should be using the appropriate number of significant digits in their answers. Most high school textbooks in physical science, chemistry, and physics, cover this topic in great detail. For younger grade levels, it would be appropriate to show students that if their mass balance gives readings with an accuracy of 0.1 grams, then the students cannot have data or averages with an accuracy reported to two decimal places. For example, if the mass of similar objects is 2.3 g and 2.4 g, and the student needs to report the average of these measurements, they cannot report a value of 2.35 g. Yes, this value is mathematically correct, but you cannot have an average with greater accuracy than its measurements. Thus, the correct average would be 2.4 g.

Upon completion of the summary statistics the students should be taught how to present their data in an easy, readable, and neat manner. Depending on the nature of the data, students should present the data using tables, figures, and graphs (collectively known as charts). The use of computers to complete these tasks is not necessary; but, is an added bonus. The main idea behind data presentation is that every table or graph should be able to tell the story of the scientific study without having to read any additional text. That means the graph axes, columns/rows, and legends all need to be sufficiently labeled, and the titles/descriptions of these charts need to be descriptive and complete. Well done charts will help the students to better analyze their results and present their findings to their peers.

Once the students know what their results say, they then can interpret their results in light of their original hypothesis and predictions. If their results agree with their hypothesis statement, then their hypothesis is accepted. On the other hand, if their study resulted in findings that disagreed with their hypothesis and their predictions did not come true, then the students would reject their hypothesis statement.

It is very important that at this time the students realize that a negative result is still a result, and if an appropriate question is asked, then their findings are still valid and helpful. Either way, the student has now come to what many scientists agree is the most important step of the scientific method: examining alternative hypotheses. It is at this point in time the student scientist must be correctly led down the path of knowledge to humbly ponder the following questions: What does it mean to have accepted or rejected my hypothesis? What have I learned? What have I not learned? What went wrong (if anything)? What should I do differently (if I need to repeat the study)? What new questions can be asked? What else may explain the patterns that I see? These last two questions are important because it teaches the student that even though I believed in an idea, and even though the data from my study supported my idea, it does not mean that my idea is correct or that my idea is the only answer to my original question. It may be the one and only answer, or it may just be one answer. The point is that even after our study, we need to be thinking, pondering, and playing with the possibility that other answers exist and we should be the FIRST to suggest the other possibilities. Unfortunately, this idea, as noble as it sounds, does not occur very often in the world of science. Why? Because too many scientists are too insecure when it comes to presenting their ideas to the public and peers. We're supposed to be more interested in the advancement of science than the advancement and reputation of ourselves. Please don't let your students walk away from science class with the fear of failure. Much of the world focuses on being the lead scorer without considering that the one who receives the credit would not be there if it were not for his/her teammates. That is the same thing for science. Every Nobel Prize winner has built their ideas on the backs of his/her predecessors. And even though one person may have received the prize, all have contributed are all are necessary if science is going to continue to advance.

The Scientific Method or the Method of Science?

What you are reading at the conclusion of the previous section is actually one of the real issues with doing science. How should science be done? Scientists, historians, and philosophers have debated this question, have put forth plenty of suggestions, and have even tried to define and redefine the methods of science. A philosopher by the name of Karl Popper pondered the influence of human nature on the outcomes of science. Would it be possible for scientists to follow one of the main tenets of the scientific method?

(1) Science is supposed to be objective and free from personal bias.

When scientists forget about this tenet and focus on their pet ideas, reputations, and research funding, the heart gets ripped out of the scientific method. So, Popper presented an approach to doing science, not replacing the scientific method, but hoping that it would help promote what the scientific method was initially intended to do. His ideas have since been termed the Popperian Method and are as follows:

(1) Start off with a theory (and it doesn't matter how true/false it is)
(2) Clearly state your initial theory (so that everyone is on the same page and understands exactly what you are postulating)
(3) Actively search for <u>falsifying evidence</u> that would reveal the need to modify or improve your initial theory.

Wow! What a difference! You mean, as scientists, we should suggest an idea and then look to prove it wrong?! But why? Because if I am actively looking to prove myself wrong, then I am open to change and criticism, which would be helpful in promoting science and not myself. Furthermore, as an expert in my field and especially with my particular study, I have the greatest opportunity to be my own self-critic and point out the flaws, weaknesses, and or mistakes that I was not able to overcome—in the hopes that someone else will. That means, as Popper also suggested, a scientist needs to have the following heart:

(1) Scientists are not supposed to be afraid to make mistakes
(2) Scientists are not supposed to cover up their mistakes
(3) Scientists are not supposed to take refuge in a theory that explains too much too easily.
(4) Scientists are not supposed to elevate the subject matter's importance over the attitude of the scientist.

Can you imagine with me what science would be like today if Popper's ideas were able to take root? There would be not intense debate between creation scientists and naturalistic evolutionists. There would be dialogue, discussion, and perhaps the advancement of science as both sides learned to communicate and respect one another. Unfortunately, Popper's ideas are more utopian than practical because man, without God, will follow the ways of the world and will obey the lusts of the flesh (I John 2:16).

Attitudes of Science

So, as a science teacher the question arises: How can we correctly teach students about the heart of doing science? They are not going to understand the Popperian Method or the intricacies of the debate surrounding the scientific method. Well, we can go back to the Word of God and lay a foundation of character that can only come from knowing Jesus as Lord and Savior. Listed below are seven attitudes that should be in the heart of every scientist regardless of age, grade, and intelligence. If our students would display these godly attitudes, then we just might influence the next generation of scientists.

(1) Integrity (uprightness, honesty, having sound biblical morals)
He who walks with integrity walks securely, but he who perverts his ways will become known.
(Proverbs 10:9, NKJV)

(2) Cooperation (the desire, patience, and humility to work well with another person)
Two are better than one, because they have a good reward for their labor. For if they fall, one will lift up his companion. But woe to him who is alone when he falls. (Ecclesiastes 4:9-10)

(3) Humility (being modest, not drawing attention to yourself, being others-centered)
Woe to those who are wise in their own eyes, and prudent in their own sight! (Isaiah 5:21)
The way of a fool is right in his own eyes, but he who heeds counsel is wise. (Proverbs 12:15)
When pride comes, then comes shame; but with the humble is wisdom. (Proverbs 11:2)

(4) Perseverance (to persist, to continue steadily despite the weight of the task at hand)
Whoever loves instruction loves knowledge, but he who hates correction is stupid. (Proverbs 12:1)
I can do all things through Christ who strengthens me. (Philippians 4:13)

(5) Diligence (careful attention, focused on sufficiently completing a task)
Be diligent to present yourself approved to God, a worker who does not need to be ashamed, rightly dividing the word of truth. (2 Timothy 2:15)
In all labor there is profit, but idle chatter leads only to poverty. (Proverbs 14:23)
The end of a thing is better than its beginning; the patient in spirit is better than the proud in spirit.
(Ecclesiastes 7:8)

(6) Healthy Skepticism (not believing until being proven true or until being directly observed; respectfully questioning authority or doctrine)
As iron sharpens iron, so a man sharpens the countenance of his friend. (Proverbs 27:17)
These were more fair-minded than those In Thessalonica, in that they received the word with all readiness, and searched the Scriptures daily to find out whether these things were so. (Acts 17:11)

(7) Inquisitiveness / Curiosity (eager for knowledge, the act of asking questions, showing interest, desiring to learn)
Counsel in the heart of man is like deep water, but a man of understanding will draw it out.
(Proverbs 20:5)
Apply your heart to instruction, and your ears to words of knowledge. (Proverbs 23:12)
It is the glory of God to conceal a matter, but the glory of kings is to search out a matter. (Proverbs 25:2)

Scientific Inquiry

This last attribute--inquisitiveness and curiosity--leads us to the main direction in which science is moving today, and that is scientific inquiry. In fact, the idea of inquiry is considered to be so important to the nature of science today that in the National Science Education Standards (NSES) for teaching science, inquiry shows up in two different ways:

> *First, it refers to the abilities students should develop to be able to design and conduct scientific investigations and to the understandings they should gain about the nature of scientific inquiry. Second, it refers to the teaching and learning strategies that enable scientific concepts to be mastered through investigations. In this way, the Standards draw connections between learning science, learning to do science, and learning about science.* (National Research Council. 2000. Inquiry and the National Science Education Standards: a Guide for Teaching and Learning. National Academy Press, pg xv).

The heart of scientific inquiry is this:

> *Inquiry is a multifaceted activity that involves making observations; posing questions; examining books and other sources of information to see what is already known; planning investigations; reviewing what is already known in light of experimental evidence; using tools to gather, analyze, and interpret data; proposing answers, explanations, and predictions; and communicating the results. Inquiry requires identification of assumptions, use of critical and logical thinking, and considering alternative explanations.* (National Research Council. 1996. National Science Education Standard. National Academy Press, pg 23).

Did you catch all that? Scientific inquiry sounds like, looks like, and is a lot like the scientific method, but with a Popperian heart, and the acceptance of the fact that you may have to use an eraser. Do you see the key difference? Look at the very last words of the quote from the NSES…*and considering alternative explanations*… Ahhh! Scientific inquiry has returned science to its roots because inquiry stresses that the journey, the process, the methodology, the heart, and the attitude of science is of greater importance and value than the actual outcome. Interesting indeed!

Closing Thoughts

Scientific inquiry is the world's answer to help kids love science. But here is one thing I have learned: Kids already love science! What they do not love is to sit in a classroom and listen to a teacher run through a laundry list of fancy definitions and study how someone else got to do something cool. They want to be cool too! They want to do the real science. They want to imagine, pretend, draw, create, experiment, model, and solve. They want to do science! Remember what science is all about: it is both the knowledge and the journey to discovering that knowledge. As Christians we should be teaching our kids and students to be thinkers, to be like the Bereans of the New Testament, who listened to the Apostle Paul and then tested his words against Scripture. If our children are going to have a chance to stand on their own when they encounter the worldly philosophies, then they need to be able to think—logically, practically, and spiritually. Science is a wonderful gift from God. He gave us this world to enjoy, and then He gave us this ability to examine and explore it for our use and His glory. Remember my testimony that I shared at the opening of this text. I didn't know what I was going to do with my new-found faith, and despite the questions, criticisms, and doubts, I completed my doctorate in Marine Biology and then went on to be a science teacher at a Christian school and a pastor of a young church plant in Texas. God allowed me the privilege of earning a degree in a field that I love. And now I have the even greater blessing of being able to share about true science with my students, parents, congregation, and other teachers. In fact, we all have that responsibility and opportunity. If there is one thing I can share in closing that you will remember forever, it would be this: Don't be afraid of science! It can't bite or bark! It has no power to keep a soul separated from God. Enjoy science! Teach the children to use science to explore the outermost reaches and to examine the innermost depths of His creation. To see His world that He made for us. To use His abilities that He gave to us. To know His love that covers over us. *I have no greater joy than to hear that my children walk in truth.* (3 John 4)