Chapter 2

Concepts in Science and Hints on Experimental Design

Scientists perform five basic kinds of investigations

The above sections indicate that the scientific pursuit of understanding is more than the methodical making of observations and performing experiments. But, investigations remain at the heart of scientific learning. Aristotle and Hippocrates of ancient Greece first established the pattern of methodical observation. About 1600 years later, Sir Francis Bacon proposed a formalized method of experimentation. Today, scientists perform five basic kinds of investigations. They are:

1) Observational/descriptive investigation "What have we here?"
2) Controlled what-if experiment "I wonder what will happen if I push this button?"
3) Explanation-seeking experiment "What caused it to do that?"
4) Modeling what-if experiment "If I understand things correctly, I can predict how this thing will handle under different circumstances."
5) Problem-solving what-if experiment "I don't care how you do it, just FIX IT!

The point is that scientific endeavors are not confined to the classical mode of operations defined above as the "scientific method". Scientists are explorers and there simply are many different ways to go exploring. It just depends on what your goal is.

Each kind of scientific investigation is useful in different stages of exploration

Imagine that you have just stumbled upon some kind of odd-looking object while hiking in the desert. It is as big as a house. It is shiny and sleek. It looks like an airplane of some kind, but what is it? I will give you a hint. It is a spacecraft. This discovery has aroused your curiosity, and you have decided to investigate. As we will see, your investigation will start out very simply, then progress to more sophisticated stages. This often is how science works. Panel 2.1 shows how the different kinds of scientific investigations can be applied to seven different situations.

"What have we here?" Observation/descriptive investigations cast the scientist as a somewhat passive spectator

The first step in your encounter with this spacecraft is to check it out. At this stage of your investigation, you know almost nothing about it. So, you first begin by walking around it at a safe distance making careful observations. A scientist would be making sketches and jotting down notes of her observations. Once you have seen all that you can from a distance, you decide to move in for a closer look. You observe a fine texture in the spacecraft's skin — something you couldn't see before. You feel its jagged surface, still warm. You smell a chemical odor and follow your nose to a purple fluid leaking out of the craft. There is strange lettering next to what looks like a big orange button. There is nothing else that you think is worth looking at.

System you are studying	Investigation	Observation / descriptive investigation	Controlled what-if experiment	Explanation-seeking experiment	Modeling what-if experiment	Problem-solving what-if experiment
Corn and acid rain	stimulating comment	What have we here?	I wonder how corn plants will react to acid rain?	What causes corn plants to grow slower when subjected to acid rain?	How might increases in acid rain affect corn production in the US?	Future increases in acid rain could cause major losses in farm production. I don't care how you do it, just prevent it.
	Action	You note that acid rain has been on the rise. You observed that it has damaged lakes and forests	Subject some corn plants to acid rain and others to normal rain and see what happens.	You test multiple hypotheses including damage to leaves, damage to roots, leaching of cell contents.	Based upon what you have learned, you develop a computer model that predicts the effect of acid rain on corn. This allows you to predict what might happen in the future as acid rain continues to increase.	Not so fast again! This problem cannot be easily solved because it involves complex public policy decisions. The measures for reducing acid rain are expensive and may hurt the economy. Try to find the cheapest, easiest solutions first and see if they help.
	Result	You become curious about the effects of acid rain on crops.	The more acidic the rain, the slower corn plants grow. You are curious why.	You find evidence to support all of your hypotheses.	Your model predicts that corn production will drop as acid rain increases.	Monitor efforts to reduce acid rain. If there is no improvement, consider more aggressive measures.
Blind date	stimulating comment	What have we here?	I wonder what would happen if I went out on a blind date.	What caused your blind date to like you?	You learned nothing that would help you model your experience. Love is blind.	Your lover left you. I don't care how you do it just fix it!
	Action	You are offered an opportunity to go out on a blind date.	Go out on the date and see what happens.	You test multiple hypotheses by asking your blind date why they like you. Is it because of your looks, the way you dress, your personality, your body?		Good luck!
	Result	You become curious about how the blind date might go.	Your blind date tells you that they really like you. You are curious why.	Your blind date isn't sure, they just like you. Science is no help.		
Music CD	stimulating comment	What have we here?	I wonder if I will like this music.	What caused you to like this music so much?	What would be the chances of commercial success for a band that avoids these musical pitfalls?	We were once a very popular band. Now the public ignores us. I don't care how you do it, just fix it!
	Action	You observe a CD by a group you have never heard of.	Listen to the CD and see if you like it.	You perform a survey with 100 of your friends in which you compare this music to music you all hate. You test multiple hypotheses including beat, kinds of instruments, lyrics, musicianship, hooks and singing styles.	Based upon what you have learned, you develop a model that predicts the market acceptance of different bands.	The model that catapulted you to success is out of date. Better do a new study and develop an updated model. And do something about that hair!
	Result	You become curious about it.	It sounds like a mix between Hootie and the Blowfish and Led Zeppelin. You love it and you wonder why.	You discover you and your 100 friends don't like music with a wimpy beat, brass instruments, trite lyrics, no musical hook, and polished singing.	Your model helps many new bands modify their styles to better satisfy the musical tastes of young music-buyers.	Your new model predicts that your band's time has come and gone, and there is no future for you. Las Vegas, here I come!
Mud	stimulating comment	What have we here?	I wonder if there are any medically interesting microorganisms in this mud.	What caused the bacteria to die?	You have learned nothing from which to develop a model. More mud, please.	
	Action	You observe some mud puddles in a forest you have never been to.	Collect the mud, grow its organisms under varying conditions and see what happens.	You test multiple hypotheses including bad growing medium in the dish, contamination, activity of the fungus, you forgot to put in the bacteria.		
	Result	You become curious about the kinds of microorganisms in the mud.	Bacteria that cause body odor don't grow in the same dish as a new fungus from the mud. You begin to wonder why.	You rule out all hypotheses except one. You must have forgotten to place the bacteria in the original dish.		

Panel 2.1. Different stages of scientific exploration.

You have just completed a survey of the spacecraft. This is a type of observation / descriptive investigation, probably the most basic scientific investigation. This is where the scientist is simply surveying, hoping to see new things. Aristotle was a prime example of such an explorer. Observation / description investigations cast the scientist in a somewhat passive role. He is busy trying to observe and describe all the many components that make up a system.

For example, field botany often is purely descriptive. A botanist sets out to collect and describe all the different kinds of plants on a mountain. Here is another example. A boat load of oceanographers criss-crossed the world's oceans collecting data on ocean depth and water chemistry. Based upon the information they collected, these explorers were able to create a detailed map of the ocean floor. Cataloging information in this way is essential in clearing the path for science's other powerful tools —experimental investigations.

Experiments are different from observation / descriptive investigations. They do more than simply observe and describe. They interrogate the system by either introducing changes or by making carefully controlled observations. The goal of experimentation is to probe below the observable surface and reveal what makes things tick.

Experimental investigations are by far the most efficient ways of finding things out. Basically, they formalize the process of trial-and-error — a process strangely unacceptable to ancient philosophers but so natural to children in the time of Empedocles of ancient Greece. Experimentation builds on the notion of trial-and-error and make it more efficient. The use of experiments represents a major advance in human scientific technique. Below, I discuss the different kinds of experiments.

"I wonder what will happen if I push this button." Controlled what-if experiments increase the opportunity for observation but seek neither explanations nor predictions

Having thoroughly explored the spacecraft exterior, your curiosity remains unquenched. Just in case you have missed something important, you make one more pass around the craft. You are satisfied that there is nothing important left to learn by simply surveying the craft's exterior. You are ready to move to the next level. It is time to intrude.

At this point, you begin to wonder what might happen if you push the big orange button on the side of the ship. Since you know nothing about how the craft works, you have no way of predicting what will happen when you push the button. Nonetheless, you believe that if you push the button, the craft might respond, and if you observe carefully, you might learn something interesting. So, you do it, and a door opens. You have just completed a controlled what-if experiment.

Controlled what-if experiments are different from observation / descriptive investigations because they represent an intrusion into the studied system. The scientist introduces some kind of change, then sits back to see what happens. Hopefully, the consequences of his intrusion will yield some new opportunities to make interesting observations — observations that were not possible while performing the passive, observation / descriptive investigation. In your case, you intruded by pushing the orange button. The consequence of that intrusion was that the door opened on the spacecraft, presenting you with an abundance of new observational opportunities.

Controlled what-if experiments can be played out in all areas of our lives not just in the accepted fields of science. When cooks "experiment" with a splash of this and a pinch of that, they are hoping for an unusual new taste. Artists of all kinds are constantly trying new techniques or variations to create newness in their work. Musicians come up with new rifs by trying new rhythms and chord combinations. Controlled what-if experiments are an important part of examining the full range of possibilities of a system. See Panel 2.4 for more examples of controlled what-if experiments.

If scientists are lucky, their controlled what-if experiments will result in new and interesting observations. Given enough time with your spacecraft, you may achieve a full working knowledge of how to operate the craft. But you may not know the theory behind it. You may not be able to explain how its propulsion systems work, or its navigation. In order to find explanations, a different kind of experiment must be done.

"What causes it to do that?" Explanation-seeking experimentation is a hypothetico-deductive process

In order to explain what causes this interesting spacecraft to behave the way it does, you have to become more sophisticated in your experimental approach. Right now, you are at "technician" level. You know what buttons to push and levers to pull. But you do not understand the basis for the operation of the ship. You cannot explain it.

Explanation-seeking experimentation is the kind of experimental work you normally would associate with "the scientific method". This flavor of experiment seeks explanations to account for interesting things the scientist has observed. It is a hypothetico-deductive process. The term "hypothetico-deductive" refers to the use of *hypotheses* (possible explanations) in order to deduce an explanation. Simply stated, *deduction* is a logical process in that attempts to reach an understanding by using reason. Explanation-seeking experiments are composed of the following main components:

1) *Observation* of an unexplained phenomenon
2) Formulation of a *causal question*
3) Development of multiple *hypotheses*
4) Preparation of *predictions* with which to evaluate hypotheses in light of experimental results
5) performance of *experiments* or other controlled observations
6) *Assessment* of results by comparing them to predictions
7) Making a *final determination* of the one most likely hypothesis, or rejecting all hypotheses

Observations of unexplained phenomena get the scientist thinking

Not all unexplained phenomena are appealing to scientists. They choose only the most interesting mysteries. Here is an example for you. You have become proficient at flying the strange spacecraft. You have observed that you can fly to Mars and back during your lunch hour. No doubt about it, this is a fast ship. It is amazingly fast. This unexplained phenomenon definitely has your attention. So you begin to think about it.

Causal questions address the nature of your interest in the observation

Having noted the super speed of the spacecraft, you could do a couple of things. One thing you could do is simply be very passive about it and accept things, just fly it without a worry. This would not be a scientific approach. Or you could begin to ask all kinds of questions, like, "How fast am I going? What will happen if I break down in space and miss my final exam? Why doesn't this thing have a CD player?" All important questions of course, but they don't address the *cause* of your interesting observation. Instead you become engaged in a process which seeks an explanation about the craft's speed. You do this by asking the simple question, "What causes the spacecraft to go so fast?" This is an example of a *causal question* in which you seek to understand what caused the phenomenon you observed. For the purpose of this example, answering this question becomes the central purpose of your soon-to-follow scientific efforts.

Causal questions may have many possible answers — many possible hypotheses

The purpose of determining the cause of the spacecraft's speed is simply that you want to understand it. As we will see later, this knowledge can have important benefits. Now, this spacecraft is a complex thing. But you already have studied the spacecraft (by performing numerous descriptive observations and controlled what-if experiments) and have a pretty good idea about the location of different systems and how to operate them. The act of studying the available information and formulating possible explanations is a creative logical process called *abduction*. Based upon the your previous work, you have learned that there are several possible explanations for the craft's propulsion. Each possible explanation is called an *hypothesis*.

Scientists exploring nature develop multiple hypotheses when they try to figure things out. Once you have formulated many hypotheses, you need to determine which ones are false, and which one (or ones) is (are) the best. But before you proceed with your experiment, you need to develop some predictions upon which to judge your hypotheses.

Predictions and experiments are used to evaluate hypotheses.

During the experimental phase of your investigation, each hypothesis should have a predictable result. Therefore, the next step is to formulate a predicted outcome for each hypothesis — in the context of a planned experiment. Each hypothesis is tested one-at-a-time by experimentation. The results of each round of experimentation are compared to the predictions made for each hypothesis. When the results of experimentation don't match the prediction, then you reject the hypothesis.

"If... and... then... and/but... therefore" statements organize the logic of experimental investigations

Hypotheses, experiments and predictions are logically tied together using *"if... and... then... and/ but...therefore"* reasoning. For example, let's organize two hypotheses as follows:

Hypothesis No. 1:	*If* the spacecraft goes so fast because it is powered by anti-gravity engines,
Experiment:	*and* after running out of fuel, I put in more anti-gravity fuel
Prediction:	*then* the spacecraft will fly again.
Result:	*and* after doing this, I observed that the craft flew once again
	(but *after doing this, I observed that the ship could not move again.)*
Conclusion:	*therefore*, if my results match my prediction, my hypothesis is supported. If my results do not match my prediction, my hypothesis is not supported.
Hypothesis No. 2:	*If* the spacecraft is powered by nuclear engines,
Experiment:	*and* after running out of fuel, I put in more nuclear fuel
Prediction:	*then* the spacecraft will fly again.
Result:	*and* after doing this, I observed that the craft flew once again
	(but *after doing this, I observed that the ship could not move again.)*
Conclusion:	*therefore*, if my results match my prediction, my hypothesis is supported. If my results do not match my prediction, my hypothesis is not supported.

Explanation-seeking experiments test one factor at a time

I hope you noticed in the above examples I did not test both hypotheses simultaneously. Why not? Let's say I test two hypotheses at the same time. For example, when the spacecraft runs out of fuel, imagine that I put in both anti-gravity fuel and nuclear fuel and the ship moves again. No doubt about it, my problem would be solved, but what have I learned? What caused it to move? Anti-gravity engines or nuclear engines?

“If I understand things correctly, I can make reliable predictions” Modeling what-if experiments use understandings to arrive at reliable predictions

Modeling what-if experiments take the understandings gathered from explanation-seeking experiments and develop a theoretical model of the whole system. The point of developing models is to be able to make reliable predictions. We can use the model to make predictions about how a system will respond to different and unusual kinds of conditions. Modeling is very useful when it is very expensive or risky to perform a full-size experiment.

Unlike explanation-seeking experiments, modelers develop no hypotheses. Models do not try to find explanations outright. However, they may point to interesting phenomena not anticipated by scientists. In which case, the results of simulations may lead to new rounds of explanation-seeking experiments.

For example, engineers will simulate the stresses that a large dam might encounter during heavy floods. They evaluate different designs and identify weak spots. They modify the design accordingly and model it again. They repeat this process until they have a satisfying design. Then when they actually build the dam, they have much greater confidence in it. Without some kind of modeling ahead of time, it would be too expensive, risky and time-consuming to build full-scale trial dams.

Sometimes models are used to simulate phenomena that take many years to run their course. For instance, scientists who study the global climate (climatologists) develop models that can predict how the global climate will respond to human pollution. Since global climate undergoes very slow change, climatologists use models to make speedy predictions. That way if the predictions are really bad, we can start doing things now to prevent them from coming true.

Let’s get back to your spacecraft. You have performed many explanation-seeking experiments and know pretty well how and why the ship handles the way it does. It is very impressive. It is so impressive that you have it in your head that you can fly through a star with it. This is too risky to try in real life, so you decide to develop a model in order to safely simulate it.

You base your model on understandings you achieved by performing numerous explanation-seeking experiments. Developing a model tests whether you really understand how things work. Simulation models would not be possible without strict adherence to scientific principles. The benefit of modeling what-if experiments is that our knowledge can advance faster, with less expense and less risk to lives.

Finally, simulation models have no desired outcome, which sets this kind of experiment apart from problem-solving what-if experiments.

“I don’t care how you do it, just fix it!” Problem-solving what-if experiments often test more than one variable at a time

Problem-solving what-if experimenters try to reach a specific desired outcome as quickly and efficiently as possible. The goal of problem-solving is to solve a problem, regardless of the cause.

Let’s imagine you have mechanical trouble with the spacecraft. Confronted with a problem like this, you probably are going to be operating not in *explanation-seeking mode* but in *problem-solving mode*. There is a subtle difference. When your ship starts to run roughly, it could be because of lots of minor things. So, you take your spacecraft in for a tune-up. Tune-ups are perfect examples of problem-solving activities in which it is more efficient to install multiple solutions simultaneously. Tune-ups replace several pieces of equipment including spark plugs, plug wires, points, condensers, fuel filters. Then your spacecraft’s timing and fuel systems are adjusted. Would it be cheaper for the garage to test each component one-at-a-time and see if your spacecraft runs better after they try out each one? When you get your ship back after a tune-up, it runs great. Why? Was it the new spark plugs? Was it the new fuel filter? You will never be able to know. But who cares? Your goal was to have a well-running spacecraft. The tune-up helped you achieve that goal. It helped you solve your problem.

This is just an example of how the process of problem-solving often can be achieved more efficiently by performing multiple experiments at the same time. You can see that problem-solving uses some elements of explanation-seeking experimentation, but its goal is not to understand. Its goal is to solve problems, however that is most efficiently achieved. Explanation-seeking experiments and problem-solving what-if experiments often are practiced differently. When your goal is to understand, then use explanation-seeking experiments.

EXPERIMENTAL DESIGN

Good experiments should include the following main concepts:

1. Establish your "control group". Set up several (or many) copies of the same experiment. Establish at least one group as your control group. This group should reflect normal conditions, and you should not manipulate any variables in the control group. You will use this group as your "normal" reference, and you will compare all "experimental groups" to it.
2. "Experimental groups". Unlike your control group, you may (and should) "fiddle" with your experimental groups. You may have many different experimental groups, all of which share the same conditions as your control group — except for one variable. You can change only one variable per experimental group, and must hold all other variables constant. In any experiment, there are bound to be numerous factors that can be changed in unusual ways by the experimenter. If the experimenter manipulates only one variable, it is much easier to relate the experiment's results to that single, changed factor. However, if you get impatient and start tweaking more than one factor at a time, you won't be able to tell which of the changed variables caused differences in the experiment's outcome.
3. Data collection and analysis. Determine the type of data your experiment will yield. Set up your experiment to take best advantage of the information as it unfolds. Establish how you are going to collect the data, and the type of analyses you are going to perform on it.
4. Eliminate Error and Artifact. Despite our best intentions, we humans have an infinite number of ways to screw up any experiment. Murphy's Law and all that. Designing and performing an experiment is very difficult, and requires lots of practice.

Error. Wrong assumptions, faulty equipment, and poor analytical techniques are typical sources of error that can invalidate experimental results. Unfortunately, identifying the many potential sources of error frequently cannot be done until initial attempts are made (i.e., you have to try it first, then learn from your mistakes).

Artifact. Artifact is defined as 'anything made by humans'. Experimenters can unwittingly introduce artifacts that can influence and confuse the outcome of their experiment. Examples of artifacts include:

- The experimenter damages part of the experimental system while making observations and taking measurements.
- The experimenter fails to secure the experimental system. Intruders come in and change things around without the experimenter's knowledge.
- In human studies, the experimenter can make certain statements to the human test subjects that can influence how these subjects respond to the experiment.

5. Honor your results — even if they are totally unexpected. It is unavoidable. When we start an experiment, we all have some notion of how it will probably turn out (pre-conceived notion). Danger. Pre-conceived notions can severely contaminate our observational powers. If we don't see what we expect to see, we may ignore it, and that would be a shame. Just remember, the whole point of doing an experiment is to look for something totally unexpected. The old adage goes, "believe what you see, don't see what you believe". Still, if you do see something unexpected, you have to make sure it isn't the result of some error or artifact. So, you may have to do a separate experiment to test the validity of your unusual observations. If it's unusual, don't automatically discard it. Check it out. You may learn something.
6. Err on the side of ignorance. Resist the temptation to conclude too much, especially if your experiment has significant errors. In the beginning stages, honest attempts at scientific experimentation often yield worthless results, because of unforeseen mistakes made along the way. Ignoring these mistakes does not advance your understanding, and is not practical scientific procedure. Rather, communicate your misadventures so that others can learn to avoid them.
7. Be open to valid criticism. The wonderful thing about scientific pursuits is that they are totally open to study and criticism by others. Try to keep your ego out of your work. Let others critique your efforts, and use their different points of view to gain new insights into your problem. If you want to be "right" all the time (even if you're clearly not), then run for public office, or study law.