

CHAPTER 2: A TEMPLATE FOR SCIENTIFIC INQUIRY



Despite the complexities of studies conducted in different scientific fields, there is an underlying structure common to all. This structure involves 5 basic elements: goals, models, data, evaluation, and revision.

SECTION 1

Five Elements

Five elements are found in most applications of the scientific method. Understanding these elements will enable you to understand both how to use the scientific method and its limitations. In template form, these 5 elements are:

Scientific Method Template

GOAL	the objective of doing the study
MODEL	any and all abstractions of what is being studied or manipulated
DATA	observations made to represent "nature" for testing the model
EVALUATION	comparing the model to the data, to decide if the model is okay
REVISION	changing the model if it is not okay



Nuclear Power Plants

Epidemiologists in Britain noted that the rates of certain types of cancers were more common in people who lived near nuclear power plants than in the population at large. The obvious conclusion from such a finding was that the power plant actually caused the increase in cancer (because of radiation). However, epidemiologists kept looking at more data and eventually noted an unexpected pattern that changed their view: higher cancer rates also existed in sites that had been selected for nuclear power plants but in which the plants had not been built. Thus, it was likely that the higher cancer rates surrounding the nuclear power plants had existed before the plant was built and so were not caused by the plant.



This simple example contains all five elements of our template:

Goal: The goal is to identify (and ultimately reduce) environmental causes of cancer.

Models: The most conspicuous model - and the one of greatest concern -is that a nuclear plant is the cause of increased cancer rates. It is a model because it is a description of what might be occurring in and around the nuclear power plants.

Data: The data are merely the cancer rates in people living in different locations. Data were analyzed in two sets, however. Set 1: cancer rates in people living near power plants and cancer rates in the population at large. Set 2: cancer rates in people living at sites selected for construction but where the plant was not yet built.

Evaluation: The model is fairly specific about which groups of people should show elevated cancer rates, so the evaluation can be performed without any sophisticated analysis: the model can only explain higher cancer rates around existing power plants. The first set of data is consistent with the model, whereas set 2 is not consistent with the model.

Revision: We reject the model because it is not consistent with both data sets. In the next round of applying the scientific method, we would consider an alternative model such as: increased cancer rates are caused by something associated with the sites chosen for nuclear power plants.

Using our template:

SCIENTIFIC METHOD TEMPLATE	
GOAL	identify environmental causes of cancer
MODEL	power plants cause cancer
DATA (1st set)	higher cancer rates near power plants
DATA (2nd set)	higher cancer rates at proposed sites
EVALUATION	the model is consistent with data set 1 but inconsistent with data set 2
REVISION	reject the model and choose an alternative

Fetal Alcohol Syndrome

As little as 30 years ago, excessive alcohol was known to be a health risk to the drinker, but there was no public awareness of its possible impact on the fetus developing in a pregnant woman. In short, no one worried about it, and people were willing to assume that alcohol consumption by the mother was not a problem for the fetus. In the language of science, we would say that this public indifference was in fact an implicit model: alcohol consumption had no lasting effect on the fetus.

The first scientific studies on this topic were published in the early 1970s and demonstrated that women who drink a lot of alcohol during pregnancy have a much higher-than-average chance of producing an offspring suffering from mental retardation and various facial deformations. These data thus rejected that original model in favor of a model in which excessive alcohol consumption caused birth defects.

Later, in the 1980s, it was discovered that drinking even modest amounts of alcohol could cause the child to suffer learning disabilities and to be comparatively inept at certain physical tasks. At this point, the data supported a model in which consumption of moderate as well as excessive doses of alcohol could cause birth defects, with the dose corresponding to the degree of consumption.

Even with this progress, questions remain unanswered today, including whether drinking less than two drinks per day has any effect, and whether drinking in the first month of the pregnancy has a different effect than does drinking in the second and third months. That is, we aren't able to discriminate between models in which sporadic, light consumption of alcohol has slight, lasting effects on the fetus versus models in which such consumption has no effect.

Using our template:

SCIENTIFIC METHOD TEMPLATE	
GOAL	determine the impact of maternal alcohol drinking on the fetus
MODEL	alcohol has no effect on birth defects
DATA (1970s)	obvious birth defects are associated with excessive maternal consumption
EVALUATION	the model is inconsistent with the data
REVISION	the model is rejected, and a new one is adopted in which maternal drinking causes birth defects

The Wright Brothers

An example of historical interest to Americans is the invention of powered, flying aircraft carrying a passenger. This invention is widely credited to Wilber and Orville Wright, on December 17, 1903. In today's culture of world travel by jet, it is virtually incomprehensible that, only 101 years ago, flight had not been achieved. It is even more stunning that such an important "first" in human invention was accomplished by a pair of bicycle shop owners with no formal training in science or engineering. Yet, a careful investigation of the steps leading to this invention reveals that the Wright brothers relied heavily on the scientific method (as described, for example, in the 1990 book, *Visions of a flying machine* by P.L. Jakab, Smithsonian Institution Press, Washington DC, USA). Engineers of the day had made little attempt to create flying machines, and there was little supporting scientific work.

The Wright brothers assault on this problem so closely fits the scientific method at many steps of the process that it is one of the clearest examples we can offer:

GOAL	To make a powered aircraft that will carry a passenger. The 1990 Jakab book makes the point that the Wright brothers never deviated from this goal. They made many critical advancements to the science of flight, but they were never sidetracked into purely academic pursuits as they advanced the field. Each time they accomplished what they needed, they moved on toward the goal of a flying machine. It is sobering that it took them less than 5 years to achieve this goal from the time they started – about the length of time you will be an undergrad.
MODELS	They used lots of models. At first they worked with kites shaped like miniature airplanes. They then spent 3-4 years working with gliders – aircraft that could carry a person but had no propulsion system. These kites and gliders were tested at Kitty Hawk, on the North Carolina coast (lots of wind; long, flat stretches of sand, suited for a glider). At home, they worked with other types of models: small wind tunnels, devices to measure the lift and drag of wing shapes in those wind tunnels, mathematical models, and even a cardboard box – which gave Orville the idea of using wing-warping to control the direction of the airplane. Strange as it may seem, their understanding of bicycles was important to some of their steps, which means that the bicycle was used as a model of an airplane.
DATA, EVALUATION & REVISION	The Wright brothers' method involved continual testing, evaluation, and revision – we would call it trial and error. With each implementation of a new model into their glider, they would test it (= data), decide whether it worked well enough to move on (= evaluation), and modify it if needed (revision). Because the testing was done at Kitty Hawk, which they visited only once a year, they could not make improvements as fast as was desirable, although much of this trial and error was performed at Kitty Hawk as they were testing the glider (and powered craft in 1903). The modifications that they added over the years included changes in wing shape (to achieve a better lift/drag ratio), adding rudders to the rear of the glider, increasing wing length, and modifying the axels for the propellers.

A Continual Process of Improvement

Science is a process, and our ideas keep changing. These changes may be merely refinements of earlier ideas, or they may be complete overhauls in our understanding. Probably the most important single feature to remember about the scientific method is that it is a means by which we can achieve progress. The scientific method is used when we are trying to improve something, whether it be to cure cancer, design a new vaccine, increase profits or build a better airplane. Each success breeds new expectations, so that there is rarely any point at which we stop the process. Improvement and progress is measured by the turnover of models: better models allow us to better achieve our goals. The following figure helps to illustrate the dynamics that underlie this progress.

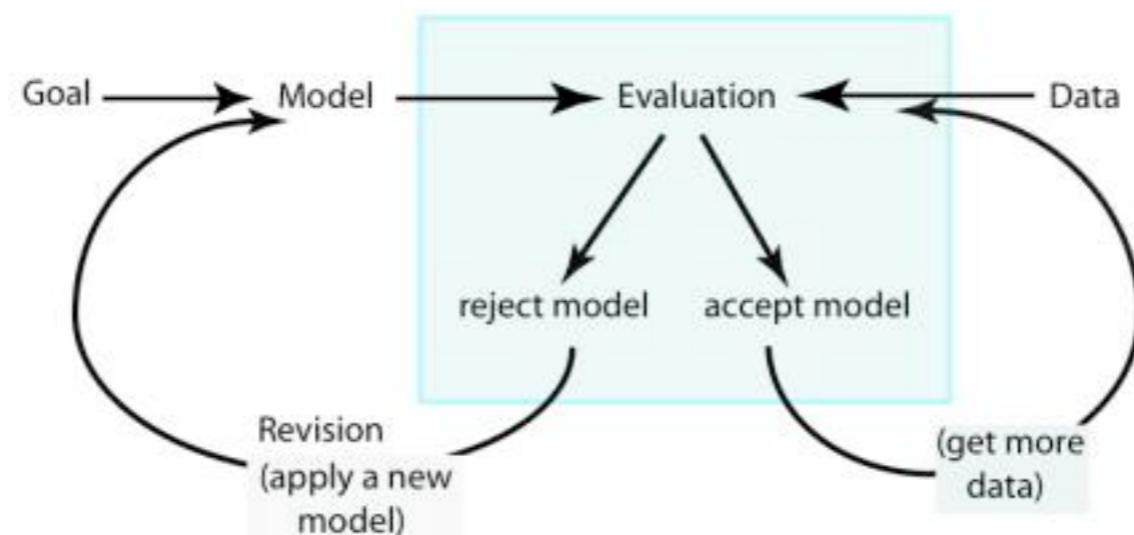


Figure. Pictorial view of the scientific method, showing the dynamics involving the different elements. Starting point in any inquiry is a goal. Then one develops a model of the process that will be studied or the phenomenon that will be manipulated. From there data are gathered (or one uses data that have already been gathered). The data and model are compared in a process of evaluation, which is simply a process of deciding if the model can make sense of the data. If the model does not perform well, it is revised -- either discarded completely or modified, and the process is repeated.

Except for the goal, each element in the scientific template is subject to change, so it is best to think of the scientific method as a cyclic process, repeated over and over. (For any given goal, the other 4 elements will be changing as progress is made toward that goal.) Thus, we start with one or more models of how we think nature works. These models are compared to data (the evaluation stage), and if the model is obviously at odds with the data, it is modified or replaced by a completely new one (revision). Whether the old model is retained or rejected, the process is continued with further refinements of data and evaluation.

Although we have formally dissected only two examples according to our template, there are many examples of progress achieved this century using the scientific method. Some of these are feats of engineering, as in larger buildings, bridges, and airplanes, or better electronic appliances such as stereos, televisions, and microwave ovens. Michael Shermer (1997, *Why people believe weird things*, W.H. Freeman and Co., NY) offers an example of advances in the speed of man-made vehicles:

VEHICLE	MPH
1784 Stagecoach	10
1825 Steam Locomotive	13
1870 Bicycle	17
1880 Steam Train	100
1906 Steam Auto	127
1919 Early Aircraft	164
1938 Airplane	400
1945 Combat Plane	606
1947 X-1 Jet (Chuck Yeager)	750 (mach 1)
1960 Rocket	4,000
1985 Space Shuttle	18,000
2000 TAU Deep-space Probe	225,000

In biology, perhaps the greatest progress has been in genetics:

1900	Rediscovery of Mendel's Laws
1916	first proof of the chromosome theory of heredity
1944	demonstration that DNA was the material basis of heredity
1953	structure of DNA solved
1977	first entire sequence of a DNA genome (a bacteriophage)
1980s	genes identified for several inherited diseases
1990s	first gene therapy trials to correct genetic defects in humans
2001 - 3	completion of the human genome sequence

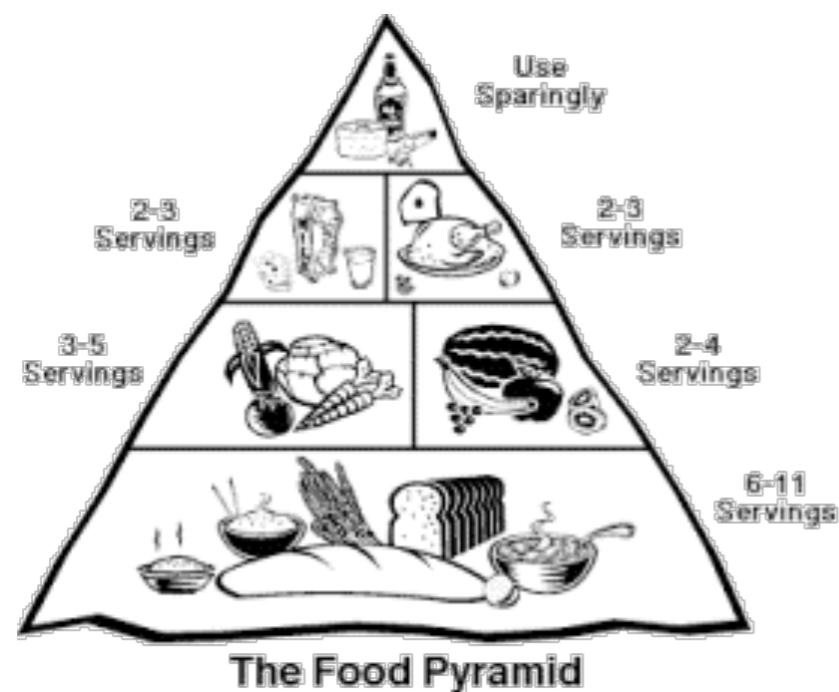
These events are only some of the more important advances; the science of genetics is filled with countless improvements of a lesser magnitude as well as many ideas overturned.

Progress (or at least change) is also evident in our understanding of the relationship between diet and health:

- 1916 The first USDA food guide was published. Other guides were published in subsequent years.
- 1956: USDA issued a diet recommendation consisting of four food groups that most of today's adults remember:
 1. meats, poultry, fish, dry beans and peas, eggs, and nuts;
 2. dairy products, such as milk, cheese, and yogurt;
 3. grains, and;
 4. fruits and vegetables

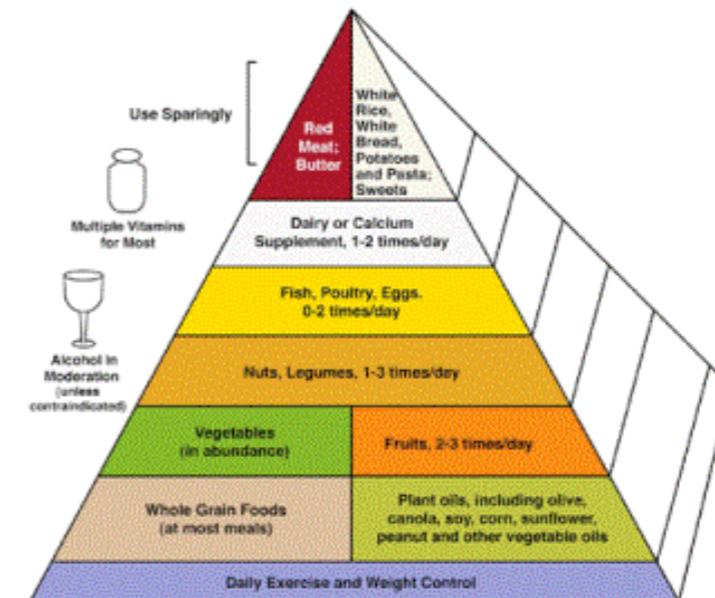
Recommendations for a balanced diet included foods from each of the four groups daily.

1992: In the decades following the release of the 1956 recommendations, it became increasingly clear that heart disease and some cancers were caused by certain types of fats found in dairy products and meats. In 1991, the USDA was about to release a new recommendation of four food groups that virtually omitted animal products and emphasized grains, vegetables, and fruits. After considerable politics in that year, the USDA issued a food “pyramid.” In contrast to the 1956 recommendation, this pyramid increased the emphasis on certain foods (grains, vegetables) and decreased the emphasis on others (fats, meats).



2003: In response to their disagreements with the USDA food pyramid, some members of the Harvard School of Public Health issued their own food pyramid, based on numerous studies (and perhaps less influenced by politics). Some of their main objections to the USDA food pyramid were (i) that many oils were known to benefit health, and (ii) simple carbohydrates (white flour, pasta) were not especially healthy and may have been contributing to an epidemic of obesity in the US. Their new food pyramid retained some elements of the 1992 food pyramid, but recommended reduced simple carbohydrates and increased vegetable oils.

Healthy Eating Pyramid



This will not be the final advice on diets that you receive in your lives. Indeed, it is relatively common now to read commentary about the conflicting dietary advice we get. The latest craze is the Atkins diet, which in its extreme reduces carbohydrate intake to the point that the body goes into a metabolic state of ketosis, and obtains glucose from protein. No doubt you will see studies in the future that identify health complications of the Atkins diet. We also get lots of advice about supposed “magic bullet” foods – items that are minor components in any diet that may perform a special function, such as reduce heart disease or cancer and about commonly-eaten foods that may be exceptionally harmful (in the past, salt and eggs were given this distinction). One can merely hope that what we have learned to the present is an improvement over the past.

One of the difficulties in dealing with science and health is that diets are so complex and varied, that it is difficult to identify specific components of diets that are good or bad for you. Furthermore, a person’s genetic makeup and exercise habits also influence health, and those factors are not easily separated from diet. (This is an equally important problem in medicine – it is estimated that 100,000 Americans die each year because of complications with drugs they take. The problem is that not everyone responds to a medicine the same way.) So with diet, we have witnessed “progress” in the sense that new recommendations have replaced old ones, but we don’t yet know how much of an improvement is to be gained by adopting the new guidelines.

It might seem that improvement stops when the scientific method has achieved perfection. That is, we should be done once we have proved a model to be true, right? No. Science does not prove models to be true and does not achieve perfection. For example, we will never know all possible health risks to the fetus of maternal alcohol consumption or know all the environmental effects of a nuclear power plant. And computers continue to improve, as do airplanes.

The point of this book is to relate the scientific method to examples in everyday life - problems not traditionally regarded as science, and problems that will affect you regardless of your chosen career. The next chapter initiates that objec-