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# Doing Science

Design, Analysis, and Communication of Scientific Research



$$y = \sum Y_i / n$$

Ivan Valiela

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*Doing Science* offers useful, practical advice based on how working scientists practice their craft. It covers each stage of research, from formulating questions and gathering data to developing experiments and analyzing results and finally to the many ways for presenting results. Drawing on his extensive experience both as a researcher and a research mentor, Ivan Valiela has written a lively and concise survey of everything a beginning scientist needs to know to succeed in the field. He includes chapters on scientific data, statistical methods, and experimental designs, and much of the book is devoted to presenting final results. He gives valuable suggestions for improving scientific writing, for preparing scientific talks, and devotes three chapters to hands-on advice for presenting data in charts, tables, and graphs. Anyone beginning a scientific career, or anyone who advises students in research, will find *Doing Science* an invaluable source of information.

#### ABOUT THE AUTHOR

Ivan Valiela is a professor in the Boston University Marine Program at the Marine Biological Laboratory, Woods Hole, Massachusetts.

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## 1

## Obtaining Scientific Information

## 1.1 Introduction

We make scientific progress in unpredictable and multifaceted ways. The first impetus is the contribution by individuals of genius and talent. An observation, previous information, accumulated experience, or older theories could spark a new explanation or hypothesis. For Newton, it was the apocryphal falling apple. Galileo is said to have been inspired to develop the laws of mechanical motion after observing an incense-filled censer swinging in the Cathedral at Pisa.<sup>1</sup> Distracted from the Mass being celebrated, Galileo used his pulse to time the oscillations and found that, regardless of the amplitude of the swing, the period was the same. He then experimentally confirmed the observation and developed equations that mirrored the laws governing the motion. Galileo's process included three steps. First, he asked the feasible question of *how fast* objects moved, rather than trying the then-unfeasible task of explaining *why* they moved. Second, Galileo made connections between the detailed, specific observations he made and general laws that could account for the way objects moved. Third, Galileo insisted on synthesizing the newly gained knowledge by devising a mathematical expression for the laws.

Not all inspirational cues will be as memorable as falling apples or swinging censers, nor do we all have the genius to deduce the link between a falling apple, the rise and fall of tides, and the motion of planets. The mark of scientific inspiration can be thought to be the ability to see "a reflection of the universe in the glint on a drop of dew." Scientific genius is unlikely to be merely the result of training, but, whatever the level of one's scientific prowess, it is possible to learn to be a better, more critical and effective practitioner of science, to discriminate among more and less effective ways to do science, and to communicate one's results to others in more transparent fashion.

A second impetus to scientific progress is that people require solutions to a plethora of problems. These solutions more often than not can bene-

fitenius, as previously the saint, has direct access to truth by an unexplained route, while the person of talent must use regular and repeatable methods to find his way step by step, rather than by the singular flash of insight.

Stuart Hampshire,  
paraphrasing  
Kant's concept of genius

1. Galileo did not do, or at least was not the first to have done, the better known experiment of dropping wooden and iron balls off the Leaning Tower of Pisa, which is in actuality the campanile to the Cathedral. A Dutchman, Simon Stevin, did a similar experiment elsewhere a few years before Galileo's work on the subject.

Galileo's conviction that science and mathematics were twin pillars of his approach to understanding nature is literally depicted in the title page of *The Assayer* (see figure on p. 2), one of his key books. We see Science on the left, mind illuminated (by the light of reason!), holding a book in which are stored the facts about the Universe, the sphere held in Science's left hand. On the right is Mathematics, the crowned queen of disciplines, holding in

her left hand a compass used to draw the trajectories of celestial bodies, embodied in the armillary sphere in her right hand. Below Mathematics are telescopes, and below Science a detailed description of a plant, perhaps the iris that is Florence's symbol. These icons tell us, in a continuation of Medieval artistic tradition, about the ideas, tools, and information used by Galileo in his search for understanding nature.

fit from scientific know-how. It has been said that scientific research of a basic nature is concerned primarily with description and explanation, while applied research focuses on prediction and control. A marine ecologist does basic work to define nutrient and phytoplankton relationships in an estuary, while the applications of the results involve using the relationships to assess water quality, and perhaps control nutrient inputs so as to keep phytoplankton growth below a threshold.

There is still a remnant prejudice, at least in some academic circles, that the basic aspects are more demanding, or somehow more meritorious, than those of applied science; comparisons of the relative merits seem to be to the disadvantage of applied work. To many academics, the image of applied research is often of second-rate, uninspiring activities, such as a chemist testing for biological activity of an endless series of compounds extracted from tropical plants or marine invertebrates, or an agronomist testing multiple combinations of fertilizers until perhaps coming upon the one mix that doubles yield.

Such attitudes ignore the history of science. Many scientific disciplines and areas originated as attempts to solve applied problems. These efforts yielded not only technical progress, but also insights into the fundamental workings of nature. In its turn, the basic knowledge acquired made it possible to explore new ways of achieving material progress.

Distinctions between basic and applied science are therefore more blurred and more damaging than we might think. Creative applied science dovetails with, and stimulates, basic science, since it both applies general principles and provides new questions and tests of basic principles. Moreover, if science is to maintain the public support essential for sustaining institutions that in turn support science—research labs, universities, funding agencies—it needs to make evident how it helps solve important applied problems. Deprecation of the applied facets flies in the face of a major reason for public support of science, and displays little awareness of the history of science.

## 1.2 Empirical Science

Galileo was a proponent of empirical observations to obtain factual information, and of deductive work to synthesize the observations into laws. Clearly, he did not separate these two major components of doing science.

### Basic and Applied Aspects of Science Are Seldom Separate

Examples of the give and take between applied needs and scientific progress are historically plentiful. The need for water pumps for water supplies to cities, the construction of navigable canals, and the desire to increase ship speeds stimulated the understanding of fluid mechanics during the age of European exploration. The problem of determining a ship's position at sea led to advances in astronomy, geography, and the measurement of time. A dispute between the Grand Duchy of Tuscany and the Papal States about whether the waters of the Chiana Valley should flow into the Arno or the Tiber resulted in a commission to the *Accademia del Cimento* in Florence in the 1660s; that work advanced hydrological knowledge by finding empirical evidence that contradicted existing theories of water motion. Antonie van Leeuwenhoek needed to take a closer look at satin and wool fibers in his family's textile factory, so he invented an optical device that opened new windows for science. It is not recorded whether the microscope also made sales of textiles more profitable.

Closer to our time, in the late 1800s there were powerful agricultural market pressures to over-

come crop damage by insect pests. Entomologists thus became the largest and best-funded group of zoologists in the country. In return, entomologists developed a problem-based way to do science, and their work not only reduced crop losses to insects, but also strongly influenced the way science in general is currently done, published, taught, and funded in the United States (Sorenson 1995).

Since the 1930s, fundamentals for the newly developing discipline of ecology have come from such sources as insights obtained while searching for information with which to control sheep blowflies in Australia, attempts to understand the eutrophication of midwestern U.S. lakes or the growth of fish in ponds in Europe, and efforts to manage overpopulated deer herds and improve fishery harvests in many places in the world. Such links between basic and applied research continue to be forged. For example, fundamental research has recently led to the discovery of fullerenes, a new form of carbon in which the atoms are arranged as on the surface of a soccer ball. This chemical structure has remarkable properties that likely will revolutionize materials science.

We treat these separately here, but only as a way to sort out some important features. It should be understood that the two complement each other.

### Some Principles of Empirical Science

A few principles set empirical science apart from other kinds of study: testability (empirical verification), operational definition, and controlled observations.

#### Empirical Verification

Empirical science characteristically begins with some observation, which prompts the observer to ask a question. The new question is then subjected to some kind of verification. If the ideas survive the tests, they become part of the body of scientific knowledge, and may give rise to further new ideas; at least until more stringent tests challenge the ideas.

The "empirical" part of this process is of major importance. There is no place in science for revealed truth: we require that the actual facts be reported, that we be told how the facts were obtained, and that the reasoning used to reach a conclusion from the facts shown be explicit. Nothing can be accepted from oracular authority.

The unity of all science consists alone in its method, not its material. . . . It is not the facts themselves which form science, but the method they are dealt with. . . .

*Karl Pearson*

## Operational Definition

Any thing or idea that is not operationally definable is not accessible to study by empirical science. All terms used in descriptions or explanations must be specifically and realistically defined. This makes it possible for someone else to understand explicitly what the facts are, and perhaps carry out further tests of the facts or explanations. Operational definitions make ideas testable.

Some examples of nonoperational concepts are well known. It is a waste of time, of course, to worry about the density of angels on any surface, let alone the head of a pin, unless we have a working seraphometer available. Another example is the "world ether," a hypothetical, homogeneous, all-pervading substance that was presumed to occupy all empty space. The concept was recognized as nonoperational after

## Not a New Concept: Observe and Test

The emphasis on operational observation and empirical testing has a venerable history. Francis Bacon (1561–1626), an English philosopher, refused to accept dogma from the writings of Aristotle and others, or from revealed truth as given by religious texts. Bacon insisted on devising ways to make empirical observations. Truth would become manifest if we saw things as they are, but, Bacon contended, why not create conditions to answer our questions? One example of a Baconian "experiment" might be, instead of accepting Aristotle's value for the number of teeth in a horse's mouth, to actually determine the number by counting. In the 1600s a critical extension of the notion of "experiment" was achieved by Galileo Galilei, one of the early intellectual giants of science. Galileo not only insisted on Bacon's empirical verification, but added the idea that an experiment ought also to be an "ordeal" of *cimento*, which later became the name of the major Florentine Accademia of science) for the question being asked. Thus, Galileo held, we could do a critical experiment and decide on the truth or falsity of the question. This rational way to learn eventually led Galileo into direct conflict with the Church, whose revealed truths were contradicted by Galileo's work.

Further separation with any connection to revealed truth became a necessity for philosophers in Northern Italian universities and academies, who, partly as an effort to escape the fate of Galileo,

decided on a policy of complete separation of actual observations about the world and explanations that might be construed as bordering on the theological by the Holy Office of the Inquisition. The Florentine *Accademia*, and many others elsewhere in Europe, steadfastly declined to explore immanent truth, forcing themselves to deal only with the facts before them, and explicitly avoided attempts at metaphysical explanations.

This attitude had both bad and good consequences. On the one hand, it made for a piecemeal way to study science; many academics became more collectors of curious and unrelated facts than scientists trying to understand the way the world worked. In one essay, van Leeuwenhoek discussed the properties of pepper, then digressed to bring up tea (with a subdigression explaining that he would refrain from advocating his view that he favored the salubrious use of the beverage), only to segue to a short passage on Spanish flies (beetles that cause blisters) before returning to a few more observations on pepper. No synthetic, organizing theory there! On the other hand, separation of empirical from metaphysical opened the way for making science operational, focusing on the possible and practical.

After the late 1600s, scientific progress largely became the purview of Northern Europeans, who were uninhibited by the constraints placed on Catholic scientists by the Council of Trent. Inexorably, science expanded through the following centuries, at the expense of revealed belief, invad-

(continued)

ing many topics forbidden to the *Accademici*. Religious dogma on themes such as the central position of Earth and humans in the universe was replaced by newer empirical views.

The principle that only operational ideas are accessible to empirical scientific study eventually won out, but not easily or uniformly. In the seventeenth century, for example, many reputable scholars who would not dream of studies of the Creation still managed to argue for the existence of phlogiston, a colorless, tasteless, odorless, weightless substance that was conceived as present in flammable materials and given off during burning. In 1799, J. Woodhouse, an upstart professor from the University of Pennsylvania, could remonstrate with the eminent Englishman Joseph Priestley that “Dr. Priestley . . . adheres to the doctrine of phlogiston, [even though] chemists

reject phlogiston [as] a mere creature of the imagination, whose existence has never been proved.”<sup>1</sup> Phlogiston, lacking measurable properties, was a nonoperational concept and so, in fact, could not be tested. Lavoisier’s demonstration of a more plausible, and operational, explanation of combustion as a chemical oxidative reaction<sup>2</sup> spelled the end of phlogiston and moved scientists to face the need to expand the idea of operational definition to all scientific topics.

1. Woodhouse, J. 1799. An answer to Dr. Joseph Priestley’s confutation of the doctrine of phlogiston, and the decomposition of water; founded upon demonstrative experiments. *Trans. Am. Philos. Soc.* 4:452–475.

2. *Reflexions sur le phlogistique*. 1862. *Œuvres de Lavoisier*. Tome II. *Mémoires de Chimie et de Physique*, pp. 623–655. Imprimerie Impériale, Paris.

it was realized that detecting motion in this homogeneous substance was impossible, since we can detect motion only by tracing paths of irregularities.

Concepts such as angels, souls, or Xibalba—the Maya underworld—are inaccessible to scientific inquiry, because they are not operationally definable. What was politically expedient for scientists of the 1600s serendipitously set scientific inquiry on a path essential to future advances: from then on, science made progress when addressing operationally well-defined issues. Ever since, we have advanced when we kept the domains of empirical science and revealed belief separate. Where we have not kept belief systems separate from science, we have seen little scientific progress and, in worst cases, unfortunate consequences. Examples of the latter include the melding of ideology and genetics that led to Lysenkoism in the Soviet Union, and of eugenics and belief in inherent racial superiority in Nazi Germany.

#### Controlled Observations

If change in a presumed independent variable leads to change in a dependent variable, we suspect a causal relationship. A convincing test of the effect of a variable on another requires a further result: that we observe the response in the presumed dependent variable when the independent variable does not change. This idea appears at various stages in the history of science; perhaps it was first suggested by Roger Bacon (1214–1294?), a Franciscan monk who taught at Oxford, but clearly by Galileo. Now it is a key concept of empirical science.

There are different ways to control the effect of certain variables. The most unambiguous is to run the test in conditions that do indeed omit or

### Why Do We Need Controls?

Lack of appropriate controls<sup>1</sup> is a common flaw in reasoning. For instance, it has been demonstrated on innumerable occasions that the beating of tom-toms brings an end to eclipses. We too often neglect to ask what happens when no one beats the drums.

The issues involved are made evident in the following example. Consider a weather forecaster who in 100 days of forecasts, correctly predicts that there will be rain 81% of the time (81 out of 100 days of predictions). That is a rather good track record, isn't it? (Especially if we assume that being correct on 50 of 100 days would constitute "breaking even.") But suppose we wish to learn how good our weatherman is at predicting weather during specific days. What happened when he predicted rain? On days in which the forecaster predicted rain, it rained 81 times and it did not rain 9 times. That is still pretty good: it rained 90% of the time when our forecaster said it would rain. But what was his record of correct predictions for, say, 100 days? The forecaster was correct on 82 out of the 100 days (81 rainy days, plus one nonrainy day), and 82% seems a fair record for weather forecasting.

We are left with the need for one more bit of information, one that at first glance might appear uninteresting, but happens to be all-important: what happened when the forecaster predicted no

rain? We can diagram the facts before us in a two-by-two table:

		Predicted Weather	
		Rain	No Rain
Actual Weather	Rain	81	9
	No Rain	9	1

It turns out that regardless of the prediction by the weatherman, it rains 90% of the time. Our earlier "tests" of the forecaster's ability were based on one cell (81% success), one row (90% correct), or on diagonal evidence (82% correct). When we consider the breakdown of the data into all four cells in the table, it suddenly becomes apparent that in this case, forecast accuracy comes largely from the fact that the weather in the area happens to be rather rainy, not from meteorological expertise.

Although in retrospect the above considerations may appear simplistic, such "one-cell," "one-line," or "diagonal" arguments are by no means rare. Anderson (1971) cites as instances from everyday experience the popular faith in astrological horoscopes, the many commercial testimonials from "satisfied users," the advice from well-off relatives that "if you work hard like me you will succeed," and the conviction from stay-at-home folks that one's country provides the best life in the world. Lack of "four-cell" reasoning is also not rare in scientific thought.

1. See chapter 4, especially sections 4.2 and 4.3, for further discussion of controls.

hold the variable constant. A second is to randomize (see below for explanation) the units of study so as to ensure that the action of the variable does not appear in a systematic way in the measurements. A third way is to estimate the effect of the variable and subtract it from the measurement obtained. I give examples of these procedures below.

The hallmarks of empirical science therefore include the concepts of *testability of specific questions*, *operational definitions*, and *controlled observations*. To test questions we need to obtain information guided by these principles. As we will discuss below, it is not always possible to achieve all the desirable criteria.

### Ways to Garner Empirical Information

Not all approaches in science research are equally likely to specify and define causes and effects, and to provide the most effective ways to fal-