Chapter 1: Introduction

Overview

Consider the dance of science -- the dance that obsesses us so.

> It's said that in viewing the night sky, the present is illusion. The stars are so distant that I see them as they were millions or billions of years ago, when their light rays began the voyage to my eye. It's said that I am infinitesimally small and transient; the stars will not miss the light my eyes have stolen. They will not notice that they have joined me in the dance.

Technique and style are the framework of dance. Techniques of science are generally the easy part; many are deliberately and systematically taught. For example, throughout our many years of schooling we refine skills such as fact gathering and mathematical analysis. We learn other scientific techniques -- such as statistics, deductive logic, and inductive logic -- in classes that lack the perspective of scientists' needs.

Some techniques are more intangible: critical thinking and analysis, pattern recognition, and troubleshooting of experimental technique. Scientists are not merely technicians; an equally crucial part of the dance is style: how do scientists combine rationality and insight, or skepticism and innovation; how do scientists interact, and what motivates their obsession? These skills seldom are taught explicitly. Instead, they are implicit in the scientific apprenticeship, an excellent but often incomplete educational process.

Who of us has mastered all of the techniques of science? I certainly have not; researching and writing this book have shown me that. Of course, when I recognize that an aspect of my scientific methods is deficient, I am enough of a professional to seek a remedy. More often, I, like Konrad Lorenz's [1962] water-shrew, am not even aware of what is missing:

> The water shrew dashes through its territory at incredible speed, by following the familiar path. "To them, the shortest line is always the accustomed path." Lorenz decided to explore the extent of this habit by removing a stone from a water-shrew's path. When it came racing along, it jumped over the nonexistent stone. It paused in bafflement, backed up and jumped 'over' it again, then finally reconnoitered the anomaly.

How often do we leap missing stones?

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Consider the *science* of science. Let's turn our gaze on our lives, looking beyond the surface interplay of experiment and theory. What are we scientists doing, and what tools are we using?

We've left such introspection to philosophers, but their goals differ from ours. They deal in abstracts: what rules do scientists follow, and how should the process of science change? We scientists generally prefer the more pragmatic approach of just doing, not talking about doing. Are we too busy, or too confident in our established routines, to analyze what we are doing? Why are virtually all of the books on scientific methods written by philosophers of science, rather than by scientists?

> "It is inevitable that, in seeking for its greatest unification, science will make itself an object of scientific investigation." [Morris, 1938]

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This book was originally intended as 'How to do science', or 'How to be a scientist', providing guidance for the new scientist, as well as some reminders and tips for experienced researchers. Such a book does not need to be written by the most expert or most famous scientist, but by one who likes to see the rules of play laid out concisely. It does need to be written by a working scientist, not by a philosopher of science. The first half of the book, called 'Scientist's Toolbox', retains this original focus on what Jerome Brumer called the structure of science -- its methodologies and logic.

This objective is still present in the second half of the book, 'Living Science'. In researching that section, however, I was fascinated by the perspectives of fellow scientists on 'What it is like to be a scientist.' Encountering their insights into the humanity of science, I found resonance with my already intense enjoyment of the process of science. Gaither and Cavazon-Gaither [2000] provide many additional scientific quotations on the experience of science.

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Consider the *process* of science.

Knowledge is the goal of science: basic research seeks reliable knowledge, and applied research seeks useful knowledge. But if knowledge were our primary goal *as scientists*, we would spend much of our available time in reading the literature rather than in slowly gathering new data. Science is not static knowledge; it is a dynamic process of exploring the world and seeking to obtain a trustworthy understanding of it. Everyone practices this process, to some extent. Science is not the opposite of intuition, but a way of employing reality testing to harness intuition effectively and productively.

As we explore the scientific process in this book, we will attempt to answer some of the following questions.

- History: What are the *essential* elements of scientific method?
- Variables: How can I extract the most information from my data?
- Induction and pattern recognition: If I cannot think of an experiment to solve my problem, how can I transpose the problem into one more amenable to experimental test? How can I enhance my ability to detect patterns? Where is the boundary between correlation and causality?
- Deduction: How large a role does deduction really play in science? What are some of the more frequent deductive fallacies committed unknowingly by 'logical' scientists?
- Experimental techniques: What seemingly trivial steps can make the difference between an inconclusive experiment and a diagnostic experiment? What troubleshooting procedures have proven effective in all branches of science?
- Objectivity: How much do expectations influence observations? In what ways is objectivity a myth? How can we achieve objective knowledge, in spite of the inescapable subjectivity of individuals?
- Evaluation of evidence: When I think I am weighing evidence rationally, what unconscious values do I employ? How much leverage does prevailing theory exert in the evaluation of new ideas?

- <u>Insight</u>: What are the major obstacles to scientific insight, and how can I avoid them?
- <u>The scientist's world</u>: What issues affect the scientist's interactions with fellow scientists and with society?
- <u>The scientist</u>: What are the *essential* characteristics of successful scientists?

* * *

Thumbnail History of Scientific Methods


[Harris, 1970]

What are the essential elements of scientific method, and what are the incidentals? Let's ask history. We can use the Method of Difference (described in Chapter 3): examine changes in the vitality of science as scientific methods evolved. We need to avoid a pitfall: mistaking coincidence for causality (see Chapters 3 and 4).

To many scientists, the field of history offers little interest. A gap separates the 'two cultures', scientific and literary, and prevents each from appreciating the contributions of the other [Snow, 1964]. Yet even a brief history of the development of scientific methods demonstrates compellingly that:

- communication, particularly access to previous writings, is critical for vitality of science;
- an individual can have a remarkable impact on science -- as an actor or as a mentor;
- we exaggerate our links to the Greeks and to the Italian Renaissance; and
- our 20th century intellectual chauvinism is not justified.

This narrative, like history itself, seems at times to be a string of related, adjacent events rather than an upward evolution toward some objective. Over the past 2500 years, many ingredients of the scientific method ebbed or flowed. More than once, almost all of these elements came together, but they failed to transform because some catalyst was missing.

Fowler [1962] provides a more comprehensive but still concise history of these developments.

* * *

In 399 B.C., a jury of 500 Athenians sentenced Socrates to death. The charges: religious heresy and corrupting the morals of the youth. His crimes: asserting that there is only one God and that people should personally evaluate the meaning of virtue. Perhaps he could have recanted and lived, but the seventy-year-old man chose drinking hemlock over refuting his life's teachings.

His student, Aristocles (Plato), must have been devastated. Plato left Athens and traveled extensively for twelve years. His anguish over the trial ripened into a contempt for democracy and for democratic man:

> "He lives from day to day indulging the appetite of the hour;...His life has neither law nor order; and this distracted existence he terms joy and bliss and freedom; and so he goes on." [Plato, ~427-347 B.C., a]

Finally (and fortunately for the future of Western science) Plato did return to Athens. He taught philosophy just as his mentor had done. One of his students, Euclid, wrote Elements of Geometry, the foundation of geometry for the next twenty-two centuries. Another student, Aristotle, taught Alexander the Great, who fostered the spread of Hellenic science throughout his new empire. The seeds sown by Alexander in Asia flowered throughout Europe more than a thousand years later, catalyzing the 'birth' of the modern scientific method.

Why do I begin this brief history of scientific methods with the death of Socrates and with Plato's response? From Pythagoras to Ptolemy, many individuals built Hellenic science. Yet the heart of this development may be the remarkable mentor-student chain of Socrates-Plato-Aristotle-Alexander. The focal point was not a panorama of historic events, but the response of an individual, Plato, when faced with a choice: should I follow the example of Socrates or should I react against the injustice of society?

Science and the scientific method were not born in Greece. Two criteria for the existence of science -- scientific observation and the collection of facts -- thrived in several pre-Hellenic cultures. Ancient astronomy is the most obvious example: the Mesopotamians in about 3500 B.C., as well as other agricultural cultures at other times, gradually evolved from star-gazing to using the stars and sun for predicting the seasons and eclipses. If technology implies science, should we trace science back to the first use of fire or the first use of tools?

A remarkable number of the key ingredients of scientific methodology were discovered during the Hellenic period:

- Pythagoras, and later Plato, advocated what has become the fundamental axiom of science: the universe is intrinsically ordered and can be understood through the use of reason. Socrates stressed that human intelligence and reason can discover the logical patterns and causal relationships underlying this order. This axiom cannot be proved; we accept it because it is so successful (Killeffer, 1969). Previously, most cultures had interpreted order and law as human concepts that were largely inapplicable to nature.

- Pythagoras identified the relationship between musical notes and mathematics. The Pythagoreans educed that mathematical laws could describe the functioning of nature and the cosmos. Although they did invent geometry, they were unable to develop the mathematical techniques needed to exploit this insight.

- The Hellenic culture, founded on intellectual freedom and love of nature, created a science both contemplative and freer from religious dogma than the preceding and following millennia. The systematic Hellenic investigation of nature, as seen in their geometry, mathematics, astronomy, geography, medicine, and art, may be responsible for our modern Western perception that science had its roots in ancient Greek civilization (Goldstein, 1988). Then, as now, science tested the limits of intellectual freedom. The death of Socrates is proof.

- Aristotle firmly steered Greek science towards rational thought and classification. He honed the blunt tool of deductive logic into the incisive instrument of syllogism. Aristotle also attempted to classify and systematize biological samples that Alexander sent back to him.

- Aristotle also fostered the development of induction, the inference of generalizations from observation: "Now art arises when from many notions gained by experience one universal judgement about a class of objects is produced." [Aristotle, 384-322 B.C.]

Greek science in general, and Aristotle in particular, developed many of the elements of modern scientific method. Yet they neglected verification. Aristotle often succumbed to the rational pitfall of hasty generalization; for example, he claimed that all arguments could be reduced to syllogisms. Greek forays into experimentation and verification, though rare, were sometimes spectacular. In about 240 B.C., for example, Eratosthenes estimated the diameter of the earth, with an error of less than 4%, by measuring the angle of a shadow at Alexandria, when the sun was vertical at Syene. More frequently, however, Greek science ignored experiment and focused instead on the ‘higher’ skill of contemplative theorizing. Almost two millennia passed before European cultures discarded this bias and thereby embarked on the scientific revolution. Although Aristotle swung the pendulum too far, imparting rigidity to Greek science (Goldstein, 1988), he revealed the potential of deduction and induction.

Science is the Greek word for knowledge. Yet the gift of the Greeks to future science was more a gift of techniques than of facts. Science survived the transition from Greek to Roman culture and the move to Alexandria. But what more can be said of Roman science beyond the observation that its greatest discoveries were the arch, concrete, and improved maps?

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Repeated incursions by nomadic tribes into the boundaries of the Roman Empire eventually overwhelmed the urban Roman civilization. At the same time the appeal of Christian teachings, which provided explanation and solace in the face of increasingly difficult conditions, eventually caused much of the population to embrace the idea that the world of the senses is essentially unreal. Truth lay in the inscrutable plan of God, not in the workings of mathematics. The accompanying eclipse of scientific knowledge and methods went virtually unnoticed. This world-view excluded science, because science requires love of nature and confidence in the world of the senses.

> “The Gothic arms were less fatal to the schools of Athens than the establishment of a new religion, whose ministers superseded the exercise of reason, resolved to treat every question by an article of faith, and condemned the infidel or skeptic to eternal flame.” [Gibbon, 1787]
>
> The scientific nadir came in about 389 A.D.: “In this wide and various prospect of devastation, the spectator may distinguish the ruins of the temple of Serapis, at Alexandria. The valuable library of Alexandria was pillaged, and near twenty years afterwards the appearance of the empty shelves excited the regret and indignation of every spectator whose mind was not totally darkened by religious prejudice. The compositions of ancient genius, so many of which have irretrievably perished, might surely have been excepted from the wreck of idolatry, for the amusement and instruction of succeeding ages.” [Gibbon, 1787]

Augustine (354-430 A.D.) was the most eloquent and influential proponent of the new attitude toward science:

> “It is not necessary to probe into the nature of things, as was done by those whom the Greeks call *physici*; nor need we be in alarm lest the Christian should be ignorant of the force and number of the elements - the motion, and order, and eclipses of the heavenly bodies; the form of the heavens; the species and the natures of animals, plants, stones, fountains, rivers, mountains; about chronology and distances; the signs of coming storms; and a thousand other things which those philosophers either have found out or think they have found out...It is enough for the Christian to believe that the only cause of all created things, whether heavenly or earthly, whether visible or in-

> visible, is the goodness of the Creator, the one true God." [St. Augustine, 354-430 A.D., a]

Augustine was probably the major influence on European thought for the next seven centuries. Like other religious mystics before and after him, he turned attention away from rationalism and the senses and toward concern for religion. If the three pillars of wisdom are empiricism, rationalism, and faith (or intuition), then Augustine turned the focus of intellectual thought to the third and previously most neglected of these pillars: intuition, the direct realization of truth by inspiration (Chambliss, 1954). Augustine achieved his insights with the aid of purgation, expecting 'less-disciplined' individuals to accept these insights as dogma. Scientific insights, in contrast, are tested before acceptance. Yet even today scientific insights, once accepted by scientists, are presented to the public as dogma.

In 529 A.D. the Emperor Justinian closed the School of Athens; European science had begun to wane long before. During the long European medieval period of the next six hundred years, technological change virtually ceased. Because technology is an inevitable outgrowth of science, the lack of medieval technological change implies an absence of science.

Augustine had distinguished two types of reason (*ratio*): *sapientia*, the knowledge of eternal things, is the *ratio superior*, while *scientia*, the knowledge of temporal things, is the *ratio inferior* [Fairweather, 1956]. Almost all records from the European medieval period are from the Church, an institution that still followed Augustine's anti-scientific lead. For example, Isidore of Seville's book Etymologies, an early 7th century compilation of knowledge, was influential for 500 years, yet Brehaut [1912] comments on Isidore's 'knowledge':

> "The attitude of Isidore and his time is exactly opposite to ours. To him the supernatural world was the demonstrable one. Its phenomena, or what were supposed to be such, were accepted as valid, while no importance was attached to evidence offered by the senses as to the material."

* * *

Arabs, not Europeans, promoted science throughout the first millennium A.D. Alexander had begun the eastward spread of Greek science. When intellectual freedom waned in the Mediterranean, some scientists and scholars moved to Persia, where it was still encouraged. In the 7th and 8th centuries, the Bedouin tribes of the Arabian Peninsula promulgated Islam throughout the region from Spain to India; they also spread a culture that was remarkably fertile for science.

The Muslim armies were religiously single-minded. They were also tolerant of cultural variations and willing to absorb the heterogeneous cultures that they encountered and conquered. Among the knowledge assimilated were Indian and Babylonian mathematics and the Greek manuscripts. At a time when medieval Europe was turning away from the harshness of worldly affairs, the Muslim were embracing nature's diversity and surpassing the Greeks in applied knowledge. The Arabs adopted Greek scientific methods and knowledge, then added their own observations and came to fresh conclusions. The Arabs were the first to counter the Greek emphasis on contemplation and logic with an insistence on observation.

By the 12th century, Arab science included inexpensive writing paper, medical care (including hospitals), major advances in optics, significant advances in observational astronomy, a highly simplified numeric system, and the equation. The latter two were crucial scientific building blocks. Al-Khwarizmi and other Muslim mathematicians had taken the Babylonian sexagesimal (60-based, e.g. seconds and minutes) and Indian decimal systems and further simplified them into a powerful mathematical system. This ‘Arabic system’ included the mathematical use of zero and positional numbers indicating units. Al-Khwarizmi's ‘al-jebr’ (literally the reducing and recombining of parts), with the simple procedure of changing both sides of the equation by the same amount, allowed complex relationships to be quantified and unknown variables (‘x’) to be determined in terms of other variables. At last, Pythagoras’ dream of a mathematical description of nature was realizable.

These cumulative accomplishments marked the zenith of Arab science. In the 12th century, Muslim science was smothered by the growing consensus that all worthwhile knowledge can be found in the Koran. Science survived through serendipity: after nourishing the flame of science throughout the millennium of anti-science ‘Dark Ages’ in Europe, the Muslim passed it back to Europe just when a cultural revival there was beginning to crave it.

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The medieval cultural revival of the 12th century began a rediscovery of the most basic scientific foundations. The Catholic Church, sole source of schools and learning, was the epicenter. For example, Peter Abelard used religious reasoning to rediscover the connection between nature and human logic: the universe is logical and ordered because God made it that way; humans were created in God’s image so they can decipher the universe’s logic. In his book Sic et Non [1122 A.D.], he argued against religious dogmatism and for personal critical evaluation:

> “All writings belonging to this class [of scriptural analysis] are to be read with full freedom to criticize, and with no obligation to accept unquestioningly . . . These questions ought to serve to excite tender readers to a zealous inquiry into truth and so sharpen their wits. The master key of knowledge is, indeed, a persistent and frequent questioning. . . By doubting we come to examine, and by examining we reach the truth.”

The scientific renaissance began in the 12th-century cathedral schools, particularly the School of Chartres [Goldstein, 1988]. By the early 13th century, the surge of knowledge had moved to the first universities, such as those in Paris, Oxford, and Salerno. Yet, in the brief period surrounding the construction of the cathedral of Chartres, its school made several impressive innovations:

- establishment of the natural sciences as areas of study at least as important as liberal arts;
- creation of the first substantial library of science since Roman times, with a particular emphasis on collecting ancient scientific writings;
- reintroduction of the Pythagorean idea of a mathematically ordered structure of the universe; and
- search for causality throughout nature, based on the idea that “nature is intelligible for the human mind precisely because both proceed according to the same inherent rational law” [Goldstein, 1988].

The architects of the new science at the School of Chartres were Thierry of Chartres and his student William of Conches. Thierry laid the groundwork by establishing religious justifications for the study of nature. He asked, “Given God, how do we prove it?” and he encouraged scientific contribution to this goal. William of Conches [~1150 A.D.] was less cautious:

> “To seek the ‘reason’ of things and the laws governing their production is the great task of the believer and one which we should discharge together, bound by our curiosities into a fraternal enterprise.”

Inevitably, this fundamental modification of perception aroused the fear and anger of conservatives. Inevitably, conservatives attempted to use the Church to prevent the change, by arguing that this altered perception violated fundamental principles of the Church. The battle that began then -- as a conflict between two religious views of nature -- continues even today, couched as a conflict between science and religion.

> "Science and religion, religion and science, put it as I may they are two sides of the same glass, through which we see darkly until these two, focusing together, reveal the truth." [Buck, 1962]

The enemy of science then and today is not religion, any more than the enemy of science during Plato's day was democracy. Both the Christian religion and democratic laws had seemed threatening when they were introduced. Later, each became the weapon wielded by conservatives to protect themselves from the fear engendered by scientific change. Unlike the conservatives and religious zealots, scientists greet claims of 'absolute truth' with skepticism. Revelation is eventually seen as naïveté, for all understandings evolve and improve.

The *status quo* will always be used to challenge scientific change.

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At about the same time that the School of Chartres was rediscovering Greek knowledge with their own pitifully small library, Europeans encountered the entirety of Greek and Arab scientific knowledge on several fronts. In Spain the long civil war between Christians and Muslims led to capture of Muslim cities, and the Christian king Alfonso VII established a center in Toledo for the study of Islamic science. The Crusaders also found libraries rich in Greek manuscripts, particularly during the capture of Constantinople in 1204. When the emerging European spirit of scientific enquiry encountered potential answers in the form of Greek and Arab scientific writings, translators were kept busy for more than a century.

Eight hundred years later as I write this, war between Western Christians and Arab Muslims has flared again, and the Arab gift to the west of practical applied science is returning to Iraq in the form of high-technology weapons.

Much of the Arab science was not fully absorbed by the Europeans for centuries. Scientific knowledge was only a part of the Islamic gift to the Europeans. The Islamic pleasure and curiosity in observing nature's diversity spearheaded a 12th-century cultural and scientific renaissance of intellectual and sensual liberation [Goldstein, 1988]. This renaissance was exemplified by Robert Grossteste (1175-1253), once chancellor of Oxford, and his student Roger Bacon (1214-1294 A.D.). Grossteste gave the first relatively complete description of modern scientific method, including induction, experimentation, and mathematics [Crombie, 1953]. Bacon argued that it is necessary to combine mathematical analysis with empirical observation and that experiments should be controlled. More than two centuries before the technological insights of Leonardo da Vinci, Roger Bacon [~1270 A.D.] foresaw the potential technological results of scientific method:

> "Great ships and sea-going vessels shall be made which can be guided by one man and will move with greater swiftness than if they were full of oarsmen. It is possible that a car shall be made which will move with inestimable speed, and the motion will be without the help of any living creature. . . A device for flying shall be made such that a man sitting in the middle of it and turning a crank shall cause artificial wings to beat the air after the manner of a flying bird. Similarly, it is possible to construct a small-sized instrument for elevating and depressing great weights . . . It is possible also that devices can be made whereby, without bodily danger, a man may walk on the bottom of the sea or of a river."

Grosseteste and Bacon were prophets, not flag-bearers, of the coming new science. Their emphasis on observational, empirical science was overshadowed by a prevailing respect for authority that fostered acceptance of the ancient writings [Haskins, 1927]. The scholastic Albertus Magnus [~1250 A.D.] responded with the still-familiar rebuttal: “experience is the best teacher in all such things.” Their contemporary Thomas Aquinas was more persuasive; he created a mainstream scholastic attitude that empiricism and rationalism should have the more limited scope of serving religion.

The scholastic approach of combining reason and faith was more scientifically effective than the Islamic approach of accepting diverse perspectives without requiring intellectual consistency among them. By the beginning of the 14th century, the young European science had already surpassed its Greek and Arab parents, partly because earlier Christian theological arguments had fostered a rationalist, logical style of evaluating abstract concepts. Yet a strong tradition of mysticism was able to exist side-by-side with the rationalist school of the Scholastics. The mystic tradition was less scientifically efficient than more rational science, because it encompassed research on invisible powers. Yet the centuries of alchemical research encouraged creativity and patient observation and eventually gave birth to modern chemistry.

"Frankly, I'd be satisfied now if I could even turn gold into lead."

[Harris, 1970]

In the 15th and 16th centuries, an Italian Renaissance gained momentum and the pace of change increased. Begun as a revival of interest in Greek and Roman literature, it rejected the otherworldly traditions of the previous millennium and embraced the love of nature and study of nature, at first through art and later also through science. Leonardo da Vinci (1452-1519) exemplifies the intimate relationship of art to science in this period, as well as the age’s spirit of curiosity. The synergy of curiosity about nature, medieval rationalism, and empiricism led to an age of exploration and to the scientific revolution.

> “The scientific revolution began in curiosity, gained momentum through free inquiry, [and] produced its first fruits in knowledge of the material universe.” [Chambliss, 1954]

> “The condition most favorable to the growth of science in the sixteenth and seventeenth centuries was the increasing number of men who were drawn into intellectual pursuits. Genius is like a fire; a single burning log will smolder or go out; a heap of logs piled loosely together will flame fiercely. . . But the establishment of strong governments, insuring at least domestic peace, the accumulation of wealth followed by the growth of a leisure class, the development of a secular, sanguine culture more eager to improve this world than anxious about the next, and above all, the invention of printing, making easier the storing, communication, and dissemination of knowledge, led naturally to the cultivation and hence to the advancement of science.” [Smith, 1930]

There were scientific setbacks in these centuries, but the acceleration of science could not be stopped. In 1543, European science took a quantum leap forward into the scientific revolution, as the result of publication of three remarkable books:

- Archimedes' book on mathematics and physics was translated from the Greek and became widely read for the first time;

- The Structure of the Human Body, a book of Andreas Vesalius' anatomical drawings, provided the first accurate look at human anatomy;

- The Revolution of the Heavenly Spheres, by Nicolaus Copernicus, presented the concept of a heliocentric cosmology and set the scientific revolution in motion, as its author lay on his deathbed.

Giordano Bruno (1473-1543) advocated this Copernican universe and was burned at the stake. A century later Galileo strongly argued for a Copernican universe. He was tried by the church and threatened with excommunication, he was forced to recant, and he spent the rest of his life under house arrest. Later scientists, particularly Kepler and Newton, concluded the battle with less adverse personal impact. Bronowski [1973] calls Galileo the "creator of the modern scientific method" because in 1609-1610 he designed and built a 30-power telescope, used it for astronomical observations, and published the result. I see Galileo not as the creator but as one who exemplifies an important phase in the evolution of modern scientific method.

Galileo valued experimental verification of ideas. In the 17th century, Francis Bacon, René Descartes, and others succeeded in steering science away from mysticism and confining scientific research to topics that are verifiable, by either the senses or deduction. Indeed, even the 17th-century scientific genius Isaac Newton devoted part of his life to alchemy. When researchers adopted the pragmatic attitude of giving priority to what is observable with the senses, they took one of the final steps in development of modern scientific method.

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The early 17th century saw a watershed collision of two philosophies of scientific method: deduction and experimentation. René Descartes' [1637] book Discourse on Method emphasized mathematical deduction and laid out the following four principles of his scientific method:

- "never accept anything as true if I had not evident knowledge of its being so. . .
- divide each problem I examined into as many parts as was feasible. . .
- direct my thoughts in an orderly way; beginning with the simplest objects. . .
- make throughout such complete enumerations that I might be sure of leaving nothing out."

In contrast, Francis Bacon's [1620] book Novum Organum sought to establish a new empirical type of science. He argued compellingly that science cannot be confined to either deduction or observation; one must use a combination of experiment and hypothesis, testing hypotheses empirically.

> "All true and fruitful natural philosophy hath a double scale or ladder, ascendent and descendent, ascending from experiments to the invention of causes, and descending from causes to the invention of new experiments." [Bacon, 1561-1626]

Both approaches had strengths and weaknesses, and both contributed to modern scientific method. Bacon, who was not a working scientist, failed to realize the importance of intuition in creating hypotheses and of judgment in rejecting most hypotheses so that only a subset need be tested. Descartes sought to confine science to those areas in which mathematics could yield 'certainty':

> "Science in its entirety is true and evident cognition. He is no more learned who has doubts on many matters than the man who has never thought of them; nay he appears to be less learned if he has formed wrong opinions on any particulars. Hence it

> were better not to study at all than to occupy one's self with objects of such difficulty, that, owing to our inability to distinguish true from false, we are forced to regard the doubtful as certain; for in those matters any hope of augmenting our knowledge is exceeded by the risk of diminishing it. Thus . . . we reject all such merely probable knowledge and make it a rule to trust only what is completely known and incapable of being doubted." [Descartes, ~1629]

This deductive dogmatism is incompatible with almost all of modern science; even theoretical deductive physics begins with unproven premises. In the 17th century, however, the outcome of the battle over the future direction of science could not be predicted.

Antoine Arnauld [1662], in an influential book on logic, presented a pragmatic approach to scientific and other judgment: rational action, like gambling, is based not on Cartesian certainty but on consideration of the probabilities of the potential outcomes. Isaac Newton [1687] reinforced the Cartesian perspective on science with his book Principia Mathematica. Considered by some to be the most important scientific book in history, Principia established a new paradigm of the physics of motion, drawing together a very wide suite of observations into a rigorous mathematical system. Newton was primarily a theoretician, not an empiricist, but he eagerly used data collected by others.

Eventually, the conflict was resolved: with the edges of the road defined, a middle way could be trod. John Locke argued persuasively that experimental science is at least as important as Cartesian deduction. Locke became known as the 'father of British empiricism.' 'Champion of empiricism' is probably a more appropriate epithet, however, for Locke made no important scientific discoveries. Locke provided the needed scientific compromise: certainty is possible in mathematics, but most scientific judgments are based on probable knowledge rooted in controlled experiments. Each person must evaluate open-mindedly the evidence and make a personal judgment.

> "The mechanical world view is a testimonial to three men: Francis Bacon, René Descartes, and Isaac Newton. After 300 years we are still living off their ideas." [Rifkin, 1980]

> Isaac Newton [1676] wrote to Robert Hooke, "If I have seen a little further it is by standing on the shoulders of Giants."

> Bernard of Chartres [~1150] wrote, "We are like dwarfs sitting on the shoulders of giants; we see more things, and things that are further off, than they did -- not because our sight is better, or because we are taller than they were, but because they raise us up and add to our stature by their gigantic height."

* * *

Remarkably, scientific method has changed very little in the last three centuries.

Archimedes [~287-212 B.C.], emphasizing the power of the lever, boasted, "Give me a place to stand on and I can move the earth." Of course, no lever is that strong. Even the 300-ton blocks of Egyptian and Middle American pyramids were beyond the strength of individual, rigid levers; recent research suggests the possibility that many flexible bamboo levers could have shared and distributed each load [Cunningham, 1988].

Three hundred years ago, the suite of scientific levers was completed. The world began to move in response.

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Myth of a Scientific Method

> “The unity of science, which is sometimes lost to view through immersion in specialist problems, is essentially a unity of method.” [Russell, 1938]

> “But on one point I believe almost all modern historians of the natural sciences would agree. . .There is no such thing as *the* scientific method.” [Conant, 1947]

Our brief examination of the history of science suggests that trial and error have refined the following elements of modern, successful scientific method:

> Facts are collected by carefully controlled experiments. Based on these facts, verifiable hypotheses are proposed, objectively tested by further experiments, and thereby proven or discarded.

This view of scientific method was universally embraced in the 19th century, and it is still popular. Most scientists would probably comment that this two-sentence description is necessarily a bit simplistic but is about right. They would replace the word ‘facts’, however, by ‘observations’, because they recognize that science is too dynamic for any data or ideas to be considered as immortal facts.

Philosophers of science universally reject this view of scientific method. They emphasize that objectivity is a myth, that experimental observations are inseparable from theories, and that hypothesis tests seldom cause rejection of a hypothesis and cannot prove a hypothesis. Furthermore, it is impossible to define a single scientific method shared by all scientists; the sciences and scientists are far too heterogeneous. Most philosophers of science conclude that the term ‘scientific method’ should be abandoned.

> “Scientists are people of very dissimilar temperaments doing different things in very different ways. Among scientists are collectors, classifiers, and compulsive tidiers-up; many are detectives by temperament and many are explorers; some are artists and others artisans.” [Medawer, 1967]

Both scientists and philosophers seek universal concepts, but scientists often settle for less: an idea may still be considered useful even if it does not fit all relevant data. We scientists can abandon the idea of ‘*the* scientific method’ but still embrace the concept of ‘scientific methods’ -- a suite of logical techniques, experimental techniques, principles, evaluation standards, and even ethical standards. Unlike Francis Bacon and Renè Descartes, modern scientists can select from this suite without rejecting the constructs of those who choose to use different methods. We must, however, know the limitations of both our methods and theirs.

* * *

Scientific Methods

Two of the most fundamental tools in the scientific toolbox are data and concepts. So basic is the distinction between the two, that nearly all publications confine data and interpretations to separate sections. Clearly, interpretations depend on data; less obviously, all data collection involves concept-based assumptions (Chapter 6).

Explanatory concepts can be given different labels, depending on our confidence in their reliability. A **law** is an explanation in which we have the greatest confidence, based on a long track record of confirmations. A **theory**, for most scientists, denotes an explanation that has been confirmed sufficiently to be generally accepted, but which is less firmly established than a law. An **axiom** is a concept that is accepted without proof, perhaps because it is obvious or universally accepted (e.g., time, causality) or perhaps to investigate its implications. A **hypothesis** is an idea that is still in the process of active testing; it may or may not be correct. **Models** are mathematical or conceptual hypotheses that provide useful perspectives in spite of recognized oversimplification. Whereas laws and theories are relatively static, hypothesis formation, testing, and evaluation are the dynamic life of science.

Laws, theories, and hypotheses also differ in generality and scope. Theories tend to be broadest in scope (e.g., the theories of relativity and of natural selection); most provide a unified perspective or logical framework for a variety of more specific and more limited laws and hypotheses. All three are generalizations; rarely do they claim to predict the behavior of every particular case, because they cannot encompass all variables that could be relevant. Most laws are expected to be universal in their applicability to a specified subset of variables, but some are permitted exceptions. For example, the geological law of original horizontality states that *nearly* all sediments are initially deposited *almost* horizontally. Hypotheses have not fully bridged the gap between the particular and the universal; most are allied closely with the observations that they attempt to explain.

Researchers do not take these terms too seriously, however. The boundaries between these three categories are flexible, and the terms may be used interchangeably.

Hypotheses, theories, and laws are explanations of nature, and explanations can be qualitative or quantitative, descriptive or causal (Chapter 3). Most explanations involve variables -- characteristics that exhibit detectable and quantifiable changes (Chapter 2) -- and many explanations attempt to identify relationships among variables (Chapter 3).

All scientific concepts must be testable -- capable of confirmation or refutation by systematic reality checking. Uncertainty is inherent not only to explanatory concepts, but also in the terms describing concept testing: confirmation, verification, validity, reliability, and significance. Scientific confirmation does not establish that an idea must be correct, or even that it is probably correct. Confirmation is merely the demonstration that a hypothesis is consistent with observations, thereby increasing confidence that the hypothesis is correct.

Some concepts can be tested directly against other, more established concepts by simple logical deduction (Chapter 4). More often, we need to investigate the hypothesis more indirectly, by identifying and empirically testing predictions made by the concept. **Data** are the experimental observations, or measurements, that provide these tests.

The interplay between hypothesis and data, between speculation and reality checking, is the heart of scientific method. Philosophers of science have devoted much analysis to the question of how hypothesis and data interact to create scientific progress. In the latter half of the twentieth century, the leading conceptualization of the scientific process has been the hypothetico-deductive method. Popper [1959, 1963], Medawer [1969], Achinstein [1985], and many others have provided perspectives on what this method is and what it should be. Most suggest that the gist of this **method of hypothesis** is the following:

> Scientific progress is achieved by interplay between imagination and criticism. Hypotheses are the key, and hypothesis formation is a creative act, not a compelling product of observations. After developing a hypothesis, the scientist temporarily as-

> sumes that it is correct, then determines its logical consequences. This inference may be deductive, a necessary consequence of the hypothesis, or inductive, a probable implication of the hypothesis. To be fruitful, this inference must generate a testable prediction of the hypothesis. An experiment is then undertaken to confirm or refute that prediction. The outcome affects whether the hypothesis is retained, modified, or refuted.

This method of hypothesis is the crux of scientific method, but scientific progress need not be quite as linear as shown. Hypotheses can be generated at any stage. Most die virtually immediately, because they are incompatible with some well-established observations or hypotheses. A single hypothesis may yield multiple predictions: some useless, many testable by a brief search of published experiments, some requiring an experiment that is infeasible, and few leading to actual experiments.

The insistence on verifiability, or its converse -- falsifiability, limits the scope of science to the pursuit of verifiably **reliable knowledge**. Reliability is, however, subjective (see Chapters 6 and 7), and hypothesis tests are seldom as conclusive as we wish. Though a hypothesis test cannot prove a hypothesis, some scientists (especially physicists) and many philosophers claim that it can at least disprove one. This argument, however, holds only for deductive predictions. More often, the test is not completely diagnostic, because assumptions buffer the hypothesis from refutation. Many hypotheses are abandoned without being refuted. Others are accepted as reliable without proof, if they have survived many tests; we cannot work effectively if we constantly doubt everything.

* * *

Is there a scientific method? The answer depends on whether one is a lumper or a splitter. Certainly the method of hypothesis is central to nearly all science, but scientific techniques and style depend both on the problem investigated and on individual taste.

For some, like Francis Bacon or Thomas Edison, experimentation is exploration; interpretations will inevitably follow. Trial and error, with *many* trials, is the method used by Edison, the medieval alchemists, and modern seekers of high-temperature superconductors. Others, like Aristotle, employ the opposite approach: develop an idea, then experimentally demonstrate its validity. A few, like René Descartes or Immanuel Kant, deduce the implications of premises. Many more, like Galileo, make predictions based on a hypothesis and empirically test those predictions. For most, each of these approaches is sometimes useful.

Research style is also fluid. At one extreme is Leonardo da Vinci, fascinated by everything he saw. Mohammad Ali, in describing himself, also described this research style: “Dance like a butterfly; sting like a bee.” At the other extreme is the Great Pyramid style -- systematically and possibly laboriously undertake multiple experiments in the same field, until the final foundation is unshakeable. Charles Darwin used this strategy for establishing his theory of evolution, except that he compiled evidence rather than experiments.

The scientific method is both very liberal and very conservative: any hypothesis is worthy of consideration, but only those that survive rigorous testing are incorporated into the framework of reliable knowledge. The scientific method is incredibly versatile, both in the range of knowledge amenable to its investigation and in the variety of personal scientific styles that it fosters and embraces. Invariably, however, it demands an intriguing and challenging combination: creativity plus skepticism.