Science as a Human Endeavor

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And I gave my heart to seek and search out by wisdom
concerning all things that are done under Heaven:
this sore travail hath God given to the sons of man
to be exercised therewith.

Ecclesiastes I:13

Preface

Science has always been controversial. It has been welcomed by some for its commitment to the rational solution of problems and to the advance of testable knowledge. It has been rejected by others for its opposition to traditional thought and its attack on mysticism. Today it is defended by those who prize the high standard of living that science makes possible. It is criticized by others who claim that it is misdirected by the interests of its clients, or that it is a self-moving force indifferent to human concerns.

Why does science give rise to such conflicting views? As a human undertaking, science is fallible; it can degenerate or it can respond to men's highest aspirations. As a part of society, science also is open to outside influences; like any social enterprise, it can be used or misused. Thus different aspects of science arouse different responses. In this book, however, I seek to correct these partial responses by portraying science in its entirety. I inquire into its powers and limitations, into the threats it poses and the promises it holds. Throughout I seek to show that science is a human endeavor and not an impersonal juggernaut.

This work is intended for scientists and humanists alike. It should help scientists to see the relevance and interdependence of their specialties, and humanists to understand what scientists are trying to do. It presupposes no more scientific knowledge than what is contained in a good basic course in general science. Although I have had the lay reader in mind throughout, I have made no attempt to popularize my subject matter. I have clarified terms, simplified concepts, and provided many illustrations, but I have not tried to make science appear either entertaining or easy. Science is an enormously complex enterprise that brings the intellect to its peak, and the lay reader must be willing to pause and reflect on his reading. If he does so, he will be richly rewarded, for science is as fascinating and challenging as any human quest.

No one realizes more keenly than I the risk I have run in seeking to cover so much so briefly. Specialists in every topic I treat will know more about it than I do. Yet if books of any scope are to be written, depth in the specialty must be sacrificed to the coherence of the whole. Some experts will maintain that a work on this subject should be entrusted to a number of specialists, each treating an aspect. Yet that approach does not exclude mine. For no set of contributors can form a single point of view, and only the single point of view can recreate for the reader the unity of the scientific enterprise in all its spheres.

This does not mean that the single writer must do his work alone. I have profited immensely from the criticisms of the many specialists who have read individual chapters, as well as from appraisals of the work as a whole by Professor Robert M. Westman and the Columbia University Press reviewers. Without the help of John M. Harrison the book might never have appeared. I am grateful to all these persons for their valuable advice. Nevertheless, what appears here is the product of a single mind aware of its limitations. If I have done less than justice to any topic I have treated, I hope that this will be balanced against my attempt to do justice to the whole.

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Chapter 1

Science in History

Simply put, science is knowledge of nature and the pursuit of that knowledge. Yet this pursuit involves a great deal. It involves, among other things, a history, a method of inquiry, and a community of inquirers. Today especially, science is a cultural force of overwhelming importance and a source of information indispensable to technology. My aim in this book is to explain these aspects of science and show how they are interrelated.

SCIENCE AND THE ORDER OF NATURE

Glancing through history, we find that nature has been studied for a variety of reasons. In Aristotle's Lyceum [1] it was studied to enlighten and improve the seeker of knowledge; in Renaissance Europe, to display God's design in His creation; in modern times, to advance knowledge both for its own sake and for its social and technical uses. But these grand purposes seem to have inspired scientists less than two primal emotions—wonder and fear. Early man was largely at the mercy of nature. Perhaps his strongest motive for natural inquiry was to attain peace of mind through having some plausible explanation of natural disasters. He wanted to find out what caused earthquakes, floods, fire, and disease. In China the Taoist natural philosophers, in ancient Europe the Stoics, the Epicureans, and the followers of the atomist Democritus, all practiced science from this motive.[2] Epicurus wrote that "if we were not troubled at all by apprehensions about phenomena in the sky and concerning death, lest it somehow concern us, and again by our failure to perceive the limits of pains and desires, we should have no need of the study of nature."[3]

Fear is allayed by the recognition that nature is orderly and intelligible. Wonder begins with this recognition. As science grew and men began to master the world, wonder became the driving force behind the greatest scientific achievements. Einstein made this point eloquently:

> the cosmic religious feeling is the strongest and oldest motive for scientific research. Only those who realize the immense efforts and, above all, the devotion without which pioneer work in theoretical science cannot be achieved are able to grasp the strength of the emotion out of which alone such work, remote as it is from the immediate realities of life, can issue. What a deep conviction of the rationality of the universe and what a yearning to understand it . . . Kepler and Newton must have had to enable them to spend years of solitary labor in disentangling the principles of celestial mechanics![4]

What, then, is the "order of nature"? For many people it is the laws of the heavens, admired by the philosopher Kant, who compared them to the "laws in our breasts," and celebrated by George Meredith in his poem "Lucifer in Starlight":

> He reached a middle height, and at the stars,
> Which are the brain of heaven, he looked, and sank.
> Around the ancient track marched, rank on rank,
> The army of unalterable law.[5]

To the scientist, however, all of nature is interrelated and, as such, orderly. Instead of being a chaos, the universe is a single grand nexus of things and processes. No event, he holds, is utterly unconnected with others and hence inexplicable. Whatever seems unconnected will, with continuing inquiry, be found to occur only in conjunction with other events. So-called freak events—hurricanes, plagues, explosions of galaxies—are as orderly in this sense as the wheeling of the planets and the ripening of corn.

Thus the order of nature is whatever remains invariant among the changes of things and is the cause of those changes. These invariant features of nature are fixed patterns in events at all levels from atoms to galaxies. The fall of the apple on Newton's head in his family's garden at Woolsthorpe could not in practice have been predicted. Yet it was orderly, for it obeyed the same gravitational force that keeps the stars in their courses and the tides to their ebb and flow.

The aim of science is to reach an exact and comprehensive understanding of the order of nature. Because the constituents of nature are almost infinitely diverse, this quest has taken many centuries and will take many more. Hence science is intrinsically historical. Not only scientific knowledge but the techniques by which it is produced, the research traditions that produce it, and the institutions that support them all change in response to developments among themselves and in the social and cultural world to which they belong. If we are to understand what science really is, we must regard it first and foremost as a succession of movements within the greater historical movement of civilization itself.

OTHER CIVILIZATIONS, OTHER SCIENCES

I say a "succession of movements" because history reveals not one science but several. In every civilization certain men have thought systematically about the natural world and have sought the causes of phenomenal change in nature itself rather than in human or suprahuman volition. But until the Arabs inherited Greek natural philosophy and Chinese alchemy and transmitted them to the West, there was no single body of natural knowledge that passed from one civilization to another. On the contrary, in every civilization the study of nature took its own path. Greek and Chinese natural philosophers explained much the same physical world very differently. The Greeks proposed the theory of the four elements (earth, air, fire, water) and the theory that everything in the universe has its natural place. The Chinese used the theory of opposing natural forces, yin and yang, and the theory of the five phases through which all things pass in cycles. We call these different cultural traditions "science" not because they form a single historically evolving entity, but because they are different historical entities of the same general kind.

But this judgment depends on hindsight. In China, classical Greece, Islam, and medieval Europe there was no term equivalent to our "science" and there was no scientific community. The activities we group together as Greek or Chinese science were carried out by philosophers, mathematicians, astronomers, physicians, and others holding quite different views about the kind of inquiry they were pursuing. It is we who see in their work the characteristics of a science that they themselves could not recognize.

The latest of these scientific traditions, the Western or European, has proved astonishingly successful and (we think) has come closest to representing what nature is really like. Whereas previous sciences were culture bound, expressed in the language of a particular people, European science has become international and universal, for it is expressed in the supracultural language of mathematics and is practiced the world over.[6] Nevertheless, this science was not created by Europeans alone. Through a range of contacts—conquest, trade, diplomacy, travel—Europeans drew on the scientific and technological achievements of other civilizations. From the Greeks they inherited Ptolemaic astronomy, Euclidean geometry, Galenic medicine, the mathematical tradition of Plato and Pythagoras, and the more empirical tradition of Aristotle. From China came magnetic physics, explosives chemistry, astronomical coordinates, the idea of infinite space, quantitative cartography, and a stream of technological inventions such as gunpowder, paper, horse harnesses, the driving belt, the chain drive, and the sternpost rudder.[7] From India there came numerals, zero, algebra, a theory of atomism, and a rich pharmacology of herbs and minerals.

Most of these achievements were first absorbed by Islam, which from 750 A.D. to the late Middle Ages stretched from Spain to Turkestan. The Arabs unified this vast body of knowledge and added to it. They improved algebra, invented trigonometry, and built astronomical observatories. They invented the lens and founded the study of optics, maintaining that light rays issue from the object seen rather than from the eye. In the tenth century Alhazen discovered a number of optical laws, for example, that a light ray takes the quickest and easiest path, a forerunner of Fermat's "least action" principle.[8] The Arabs also extended alchemy, improving and inventing a wealth of techniques and instruments, such as the alembic, used to distill perfumes. In the eighth century the physician al-Razi laid the foundations of chemistry by organizing alchemical knowledge and denying its arcane significance. Inventor of the animal-vegetable-mineral classification, he categorized a host of substances and chemical operations, some of which, such as distillation and crystallization, are used today. When Arabic science declined, of the three great civilizations on the borders of Islam—China, India, and Europe—the last inherited its great synthesis.

In 1000 A.D. Europe was so backward that it had to borrow the Islamic sciences wholesale, translating Arabic writings into Latin. By 1600 European science had no superior. What caused this dramatic transformation? Why did modern science begin its exponential rise among the warring states of crowded Europe rather than in some older, more harmonious civilization? Why not in China, for instance?[9]

Chinese Science. As Joseph Needham has shown,[10] during the first fifteen centuries of the Christian era Chinese science was the equal of any and Chinese technology was probably superior to all. Certain sciences—astronomy, mathematics, hydraulic engineering—were supported by the state bureaucracy, which was imbued with the teachings of Confucianism. This philosophy studies man as a social being and proposes principles for the wise management of society. Other sciences—alchemy, biology, medicine (to some extent), physics (except for harmonics), and geology—remained unorthodox and were practiced largely by the Taoists, who studied man's inner life and his relation to nature. (Man, they said, should renounce ambition and live in accord with the order, or tao, of natural events.) Taoists inspired most of Chinese science, but they distrusted reason and speculation, while the Confucians were interested in science only for its social uses. As a result Chinese science tended to avoid theory and remained largely empirical.

Nevertheless, this empiricism was anything but crude. The Chinese observed and recorded accurately and persistently. Their astronomers noted the positions of stars and other celestial phenomena in measured degrees. Indeed, their lists of novae,[11] comets, and meteors are used by radio astronomers today. In the first century B.C.

their hydraulic engineers were recording the silt content of rivers precisely. To improve observation, the Chinese invented instruments such as the seismograph, the mechanical clock, and the magnetic compass. They classified many phenomena, such as stars, diseases, and medicinal herbs and minerals. They also carried out experiments; for instance, they tested the acoustical properties of bells and strings, and the strengths of different materials.[12]

What sciences developed with these methods? The Chinese had algebra but little geometry. Hence their theoretical astronomy remained weak. Unlike Greek geometry, which represented the movements of the heavenly bodies in three-dimensional space, Chinese algebraic techniques implied no particular physical hypothesis. Hence despite voluminous records they lacked an adequate theory of the heavens. In physics they had little mechanics and no dynamics, but they pioneered the science of magnetism and made an exhaustive study of their own music. During the Middle Ages their maps were much more accurate than European ones. In medicine they developed a comprehensive account of relations between body, mind, and environment. Their alchemy, the oldest in the world, sought the health-giving elixir of eternal life, an idea which did not appear in Europe until the twelfth century by way of Islam.

The Chinese had theories, too, but these were general and qualitative. According to the "two-force" theory, the fundamental forces in the universe are yin (expressed, for instance, in rain and femaleness) and yang (expressed in heat and maleness). The "five-phases" theory sought to classify the basic processes at work in nature, naming them water, fire, wood, metal, and earth. The phases supersede one another in cycles: wood supersedes earth; metal, wood; fire, metal; water, fire; earth, water; and then the cycle begins again. With these phases they correlated everything in the universe that could be classified in fives—tastes, smells, seasons, cardinal points, musical notes, planets, weathers, and so on. The fivefold correlations display the mutual affinities between things. All things in the same class (e.g., east, wood, green, wind, wheat) resonate with one another, exchanging energies. In the words of the philosopher Tung Chung-Shu, writing in the second century B.C., "If water is poured on level ground it will avoid the parts which are dry and move towards those that are wet. If [two] identical pieces of firewood are exposed to fire, the latter will avoid the damp and ignite the dry one. All things reject what is different [from themselves], and follow what is akin."[13]

But, distrusting reason as they did, the Taoists neither developed these theories nor welded them into a systematic account of nature comparable with that of Aristotle. As a result Chinese science remained intellectually fragmented, capable of steady empirical accumulation in many fields but incapable of further theoretical growth. For example, none of the theories we have mentioned stimulated a development like that of the "impetus" tradition in dynamics. Aristotle had maintained that a body in forced motion continues to move only so long as it is in contact with the original mover. If so, he was asked, why does an arrow continue to fly for some time after it has been released? The answer, he replied, is that the air displaced by the arrow as soon as it is fired rushes behind it and thrusts it forward. But, as John Philoponus of Alexandria objected in the sixth century A.D., there is no reason why the air should move behind the arrow rather than in some other direction. "How is it," he wrote,

> that the air, pushed by the arrow, does not move in the direction of the impressed impulse, but instead, turning about, as by some command, retraces its course? Furthermore, how is this air, in so turning about, not scattered into space, but instead impinges precisely on the notched end of the arrow and again pushes the arrow on and adheres to it? Such a view is completely implausible and is more like fiction.[14]

The arrow, he concluded, continues in flight because a force—later called "impetus"—is imparted to it by the archer and remains with it after it has left the bow. This theory of projectile motion was further developed by a succession of Islamic and medieval philosophers. Chinese science has no parallel.

Backward European science began its meteoric career with Galileo's discovery that mathematical hypotheses, tested by experiments, can give precise knowledge of the workings of nature. This approach, together with the philosophy of mechanism (the doctrine that all natural phenomena can be explained in terms of the motions of particles under the influence of forces), soon put European science far ahead. For it turned out that, contrary to the Taoists, the order of nature is not after all inscrutable. What remains to be explained is why the Chinese themselves, in more than a millennium of inquiry, failed to hit upon the mathematical-experimental method and the mechanist philosophy.

A number of answers have been proposed. It has been suggested that the enormous Chinese bureaucracy with its Confucian ethos frustrated scientific innovation. The civil service examination was open to all and offered good careers to those who survived the intense competition. But it required a mastery only of the Confucian classics and literary works and so provided no incentive to study science and technology. Nevertheless, although the bureaucracy undoubtedly acted as a brake on theoretical inquiry, it did stimulate applied science and, in astronomy at least, systematic observation. It was responsible for the invention of the seismograph, the erection of rain- and snow-gauges, and the mounting of great expeditions to survey a meridian arc for 1,500 miles from Indochina to Mongolia and to map the stars of the southern hemisphere from Java. The Astronomical Bureau lasted 2,000 years without radical change. Its main functions were to record all celestial events and to forecast the fates of rulers and states from astrological omens. This arrangement insured a continuous flow of accurate data but discouraged original thinking and an interest in new problems.

A related suggestion is that the Chinese bureaucracy minimized the influence of the merchants. For over 2,000 years the civil service attracted the best brains in the country. Such was its prestige that even the sons of wealthy merchants struggled to get into it. Yet a flourishing mercantile class was essential, it has been argued, to the rise of modern science in Europe. The merchants had a financial interest in technological invention; they believed in the freedom necessary for scientific debate; and, being ready to work with their hands, they recognized the importance of experimentation. This argument is persuasive, but it should not be pressed too far. It has not been shown, for example, that scientific advance depends on whether or not a merchant class has won political power.[15] In Italy, for instance, republican systems of government, supported by the merchants, had widely given way to one-man rule before Galileo was born (1564). In