WHAT IS SCIENCE?*

Isaac Asimov

ALMOST in the beginning was curiosity.

Curiosity, the overwhelming desire to know, is not characteristic of dead matter. Nor does it seem to be characteristic of some forms of living organism, which, for that very reason, we can scarcely bring ourselves to consider alive.

A tree does not display curiosity about its environment in any way we can recognize; nor does a sponge or an oyster. The wind, the rain, the ocean currents bring them what is needful, and from it they take what they can. If the chance of events is such as to bring them fire, poison, predators, or parasites, they die as stoically and as undemonstratively as they lived.

Early in the scheme of life, however, independent motion was developed by some organisms. It meant a tremendous advance in their control of the environment. A moving organism no longer had to wait in stolid rigidity for food to come its way, but went out after it.

Thus, adventure entered the world – and curiosity. The individual that hesitated in the competitive hunt for food, that was overly conservative in its investigation, starved. Early on, curiosity concerning the environment was enforced as the price of survival.

The one-celled paramecium, moving about in a searching way, cannot have conscious volitions and desires in the sense that we do, but it has a drive, even if only a 'simple' physical-chemical one, which causes it to behave as if it were investigating its surroundings for food or safety, or both. And this 'act of curiosity' is what we most easily recognize as being inseparable from the kind of life that is most akin to ours.

As organisms grew more intricate, their sense organs multiplied and became both more complex and more delicate. More messages of greater variety were received from and about the external environment. At the same time, there developed (whether as cause or effect we cannot tell), an increasing complexity of the nervous system, the living instrument that interprets and stores the data collected by the sense organs.

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The Desire to Know

There comes a point where the capacity to receive, store, and interpret messages from the outside world may outrun sheer necessity. An organism may be sated with food, and there may, at the moment, be no danger in sight. What does it do then?

It might lapse into an oysterlike stupor. But the higher organisms at least still show a strong instinct to explore the environment. Idle curiosity, we may call it. Yet, though we may sneer at it, we judge intelligence by it. The dog, in moments of leisure, will sniff idly here and there, pricking up its ears at sounds we cannot hear; and so we judge it to be more intelligent than the cat, which in its moments of leisure grooms itself or quietly and luxuriously stretches out and falls asleep. The more advanced the brain, the greater the drive to explore, the greater the 'curiosity surplus'. The monkey is a byword for curiosity. Its busy little brain must and will be kept going on whatever is handy. And in this respect, as in many others, man is a supermonkey.

The human brain is the most magnificently organized lump of matter in the known universe, and its capacity to receive, organize, and store data is far in excess of the ordinary requirements of life. It has been estimated that, in a lifetime, a human being can learn up to 15 trillion items of information.

It is to this excess that we owe our ability to be afflicted by that supremely painful disease, boredom. A human being, forced into a situation where one has no opportunity to utilize one's brain except for minimal survival, will gradually experience a variety of unpleasant symptoms, up to and including serious mental disorganization. The fact is that the normal human being has an intense and overwhelming curiosity. If one lacks the opportunity to satisfy it in immediately useful ways, one will satisfy it in other ways – even regrettable ways to which we have attached admonitions such as 'Curiosity killed the cat', and 'Mind your own business'.

The overriding power of curiosity, even with harm as the penalty, is reflected in the myths and legends of the human race. The Greeks had the tale of Pandora and her box. Pandora, the first woman, was given a box that she was forbidden to open. Quickly and naturally enough she opened it and found it full of the spirits of disease, famine, hate, and all kinds of evil – which escaped and have plagued the world ever since.

In the Biblical story of the temptation of Eve, it seems fairly certain (to me, at any rate) that the serpent had the world's easiest job and might have saved his words: Eve's curiosity would have driven her to taste the forbidden fruit even without external temptation. If you are of a mind to interpret the Bible allegorically, you may think of the serpent as simply the representation of this inner compulsion. In the conventional cartoon picturing Eve standing under the tree with the forbidden fruit in her hand, the serpent coiled around the branch might be labeled 'Curiosity'.

If curiosity can, like any other human drive, be put to ignoble use – the prying invasion of privacy that has given the word its cheap and unpleasant connotation – it nevertheless remains one of the noblest properties of the human mind. For its simplest definition is 'the desire to know'.

This desire finds its first expression in answers to the practical needs of human life: how best to plant and cultivate crops, how best to fashion bows and arrows, how best to weave clothing – in short, the 'applied arts'. But after these comparatively limited skills have been mastered, or the practical needs fulfilled, what then? Inevitably the desire to know leads on to less limited and more complex activities.

It seems clear that the 'fine arts' (designed to satisfy inchoate and boundless and spiritual needs) were born in the agony of boredom. To be sure, one can easily find more mundane uses and excuses for the fine arts. Paintings and statuettes were used as fertility charms and as religious symbols, for instance. But one cannot help suspecting that the objects existed first and the use second.

To say that the fine arts arose out of a sense of the beautiful may also be putting the cart before the horse. Once the fine arts were developed, their extension and refinement in the direction of beauty would have followed inevitably, but even if this had not happened, the fine arts would have developed nevertheless. Surely the fine arts antedate any possible need or use for them, other than the elementary need to occupy the mind as fully as possible.

Not only does the production of a work of fine art occupy the mind satisfactorily; the contemplation or appreciation of the work supplies a similar service to the audience. A great work of art is great precisely because it offers a stimulation that cannot readily be found elsewhere. It contains enough data of sufficient complexity to cajole the brain into exerting itself past the usual needs; and, unless a person is hopelessly ruined by routine or stultification, that exertion is pleasant.

But if the practice of the fine arts is a satisfactory solution to the problem of leisure, it has this disadvantage: it requires, in addition to an active and creative mind, physical dexterity. It is just as interesting to pursue mental activities that involve only the mind, without the supplement of manual skill. And, of course, such activity is available. It is the pursuit of knowledge itself, not in order to do something with it but for its own sake.

Thus, the desire to know seems to lead into successive realms of greater etherealization and more efficient occupation of the mind – from knowledge of accomplishing the useful, to knowledge of accomplishing the esthetic, to 'pure' knowledge.

Knowledge for itself alone seeks answers to such questions as How high is the sky? or, Why does a stone fall? This is sheer curiosity – curiosity at its idlest and therefore perhaps at its most peremptory. After all, it serves no apparent purpose to know how high the sky is or why the stone falls. The lofty sky does not interfere with the ordinary business of life; and, as for the stone, knowing why it falls does not help us to dodge it more skillfully or soften the blow if it happens to hit us. Yet there have always been people who ask such apparently useless questions and try to answer them out of the sheer desire to know – out of the absolute necessity of keeping the brain working.

The obvious method of dealing with such questions is to make up an esthetically satisfying answer: one that has sufficient analogies to what is already known to be comprehensible and plausible. The expression 'to make up' is rather bald and unromantic. The ancients liked to think of the process of discovery as the inspiration of the muses or as a revelation from heaven. In any case, whether it was inspiration, revelation, or the kind of creative thinking that goes into storytelling, the explanations depended heavily on analogy. The lightning bolt is destructive and terrifying but appears, after all, to be hurled like a weapon and does the damage of a hurled weapon – a fantastically violent one. Such a weapon must have a wielder similarly enlarged in scale, and so the thunderbolt becomes the hammer of Thor or the flashing spear of Zeus. The more-than-normal weapons is wielded by a more-than-normal man.

Thus a myth is born. The forces of nature are personified and become gods. The myths react on one another, are built up and improved by generations of mythtellers until the original point may be obscured. Some myths may degenerate into pretty stories (or ribald ones), whereas others may gain an ethical content important enough to make them meaningful within the framework of a major religion.

Just as art may be fine or applied, so may mythology. Myths may be maintained for their esthetic charm or bent to the physical uses of human beings. For instance, the earliest farmers were intensely concerned with the phenomenon of rain and why it fell capriciously. The fertilizing rain falling from the heavens on the earth presented an obvious analogy to the sex act; and, by personifying both heaven and earth, human beings found an easy explanation of the release or the withholding of the rains. The earth goddess, or the sky god, was either pleased or offended, as the case might be. Once this myth was accepted, farmers had a plausible basis for the art of bringing rain – namely, appeasing the god by appropriate rites. These rites might well be orgiastic in nature – an attempt to influence heaven and earth by example.

The Greeks

The Greek myths are among the prettiest and most sophisticated in our Western literary and cultural heritage. But it was the Greeks also who, in due course, introduced the opposite way of looking at the universe – that is, as something impersonal and inanimate. To the mythmakers, every aspect of nature was essentially human in its unpredictability. However mighty and majestic the personification, however superhuman the powers of Zeus, or Ishtar or Isis or Marduk or Odin, they were also – like mere humans – frivolous, whimsical, emotional, capable of outrageous behaviour for petty reasons, susceptible to childish bribes. As long as the universe was in the control of such arbitrary and unpredictable deities, there was no hope of understanding it, only the shallow hope of appeasing it. But in the new view of the later Greek thinkers, the universe was a machine governed by inflexible laws. The Greek philosophers now devoted themselves to the exciting intellectual exercise of trying to discover just what the laws of nature might be.

The first to do so, according to Greek tradition, was Thales of Miletus, about 600 B.C. He was saddled with an almost impossible number of discoveries by later Greek writers, and it may be that he first brought the gathered Babylonian knowledge to the Greek world. His most spectacular achievement is supposed to have been predicting an eclipse for 585 B.C. – which actually occurred.

In engaging in this intellectual exercise, the Greeks assumed, of course, that nature would play fair; that, if attacked in the proper manner, it would yield its secrets and would not change position or attitude in midplay. (Over two thousand years later, Albert Einstein expressed this feeling when he said, 'God may be subtle, but He is not malicious.') There was also the feeling that the natural laws, when found, would be comprehensible. This Greek optimism has never entirely left the human race.

With confidence in the fair play of nature, human beings needed to work out an orderly system for learning how to determine the underlying laws from the observed data. To progress from one point to another by established rules of argument is to use 'reason'. A reasoner may use 'intuition' to guide the search for answers, but must rely on sound logic to test particular theories. To take a simple example: if brandy and water, whiskey and water, vodka and water, and rum and water are all intoxicating beverages, one may jump to the conclusion that the intoxicating factor must be the ingredient these drinks hold in common – namely, water. There is something wrong with this reasoning, but the fault in the logic is not immediately obvious; and in more subtle cases, the error may be hard indeed to discover.

The tracking down of errors or fallacies in reasoning has amused thinkers from Greek times to the present. And we owe the earliest foundations of systematic logic to Aristotle of Stagira who in the fourth century B.C. first summarized the rules of rigorous reasoning.

The essentials of the intellectual game of man-against-nature are three. First, you must collect observations about some facet of nature. Second, you must organize these observations into an orderly array. (The organization does not alter them but merely makes them easier to handle. This is plain in the game of bridge, for instance, where arranging the hand in suits and order of value does not change the cards or show the best course of play, but makes it easier to arrive at the logical plays.) Third, you must derive from your orderly array of observations some principle that summarizes the observations.

For instance, we may observe that marble sinks in water, wood floats, iron sinks, a feather floats, mercury sinks, olive oil floats, and so on. If we put all the sinkable objects in one list and all the floatable ones in another and look for a characteristic that differentiates all the objects in one group from all in the other, we will conclude: Objects denser than water sink in water, and objects less dense than water, float.

The Greeks named their new manner of studying the universe *philosophia* ('philosophy') meaning 'love of knowledge' or, in free translation, 'the desire to know'.

Geometry and Mathematics

The Greeks achieved their most brilliant successes in geometry. These successes can be attributed mainly to the development of two techniques: abstraction and generalization.

Here is an example. Egyptian land surveyors had found a practical way to form a right angle: they divided a rope into twelve equal parts and made a triangle in which three parts formed one side, four parts another, and five parts the third side – the right angle lay where the three-unit side joined the four-unit side. There is no record of how the Egyptians discovered this method, and apparently their interest went no further than to make use of it. But the curious Greeks went on to investigate why such a triangle should contain a right angle. In the course of their analysis, they grasped the point that the physical construction itself was only incidental; it did not matter whether the triangle was made of rope or linen or wooden slats. It was simply a property of 'straight lines' meeting at angles. In conceiving of ideal straight lines, which are independent of any physical visualization and can exist only in imagination, the Greeks originated the method called abstraction – stripping away nonessentials and considering only those properties necessary to the solution of the problem.

The Greek geometers made another advance by seeking general solutions for classes of problems, instead of treating individual problems separately. For instance, one might have discovered by trial that a right angle appeared in triangles, not only with sides 3, 4, and 5 feet long, but also in triangles of 5, 12, and 13 feet and 7, 24, and 25 feet. But these were merely numbers without meaning. Could some common property be found that would describe all right triangles? By careful reasoning, the Greeks showed that a triangle is a right triangle if, and only if, the lengths of the sides have the relation $x^2 + y^2 = z^2$, z being the length of the longest side. The right angle lies where the sides of length x and y meet. Thus for the triangle with sides of 3, 4, and 5 feet, squaring the sides gives $9 + 16 = 25$; similarly, squaring the sides of 5, 12, and 13 gives $25 + 144 = 169$; and squaring 7, 24, and 25 gives $49 + 576 = 625$. These are only three cases out of an infinity of possible ones and, as such, trivial. What intrigued the Greeks was the discovery of a proof that the relation must hold in all cases. And they pursued geometry as an elegant means of discovering and formulating such generalizations.

Various Greek mathematicians contributed proofs of relationships existing among the lines and points of geometric figures. The one involving the right triangle was reputedly worked out by Pythagoras of Samos about 525 B.C. and is still called the Pythagorean theorem in his honour.

About 300 B.C., Euclid gathered the mathematical theorems known in his time and arranged them in a reasonable order, such that each theorem could be proved through the use of theorems proved previously. Naturally, this system eventually worked back to something unprovable: if each theorem had to be proved with the help of one already proved, how could one prove theorem no. 1? The solution was to begin with a statement of truths so obvious and acceptable to all as to need no proof. Such a statement is called an 'axiom'. Euclid managed to reduce the accepted axioms of the day to a few simple statements. From these axioms alone, he built an intricate and majestic system of 'Euclidean geometry'. Never before was so much constructed so well from so little, and Euclid's reward is that his textbook has remained in use, with but minor modification, for more than 2,000 years.

The Deductive Process

Working out a body of knowledge as the inevitable consequence of a set of axioms ('deduction') is an attractive game. The Greeks fell in love with it, thanks to the success of their geometry – sufficiently in love with it to commit two serious errors.

First, they came to consider deduction as the only respectable means of attaining knowledge. They were well aware that, for some kinds of knowledge, deduction was inadequate; for instance, the distance from Corinth to Athens could not be deduced from abstract principles but had to be measured. The Greeks were willing to look at nature when necessary; however, they were always ashamed of the necessity and considered that the highest type of knowledge was that arrived at by cerebration. They tended to undervalue knowledge directly involved with everyday life. There is a story that a student of Plato, receiving mathematical instruction from the master, finally asked impatiently, 'But what is the use of all this?' Plato, deeply offended, called a slave and, ordering him to give the student a coin, said, 'Now you need not feel your instruction has been entirely to no purpose.' With that, the student was expelled.

There is a well-worn belief that this lofty view arose from the Greek's slave-based culture, in which all practical matters were relegated to the slaves. Perhaps so, but I incline to the view that the Greeks felt that philosophy was a sport, an intellectual game. Many people regard the amateur in sports as a gentleman socially superior to the professional who makes his living at it. In line with this concept of purity, we take almost ridiculous precautions to make sure that the contestants in the Olympic games are free of any taint of professionalism. The Greek rationalization for the 'cult of uselessness' may similarly have been based on a feeling that to allow mundane knowledge (such as the distance from Athens to Corinth) to intrude on abstract thought was to allow imperfection to enter the Eden of true philosophy. Whatever the rationalization, the Greek thinkers were severely limited by their attitude. Greece was not barren of practical contributions to civilization, but even its great engineer, Archimedes of Syracuse, refused to write about his practical inventions and discoveries; to maintain his amateur status, he broadcast only his achievements in pure mathematics. And lack of interest in earthly things – in invention, in experiment, in the study of nature – was but one of the factors that put bounds on Greek thought. The Greeks' emphasis on purely abstract and formal study – indeed, their very success in geometry – led them into a second great error and, eventually, to a dead end.

Seduced by the success of the axioms in developing a system of geometry, the Greeks came to think of the axioms as 'absolute truths' and to suppose that other branches of knowledge could be developed from similar 'absolute truths'. Thus in astronomy they eventually took as self-evident axioms the notions that (1) the earth was motionless and the centre of the universe, and (2) whereas the earth was corrupt and imperfect, the heavens were eternal, changeless, and perfect. Since the Greeks considered the circle the perfect curve, and since the heavens were perfect, it followed that all the heavenly bodies must move in circles around the earth. In time, their observations (arising from navigation and calendar making) showed that the planets do not move in perfectly simple circles, and so the Greeks were forced to allow planets to move in ever more complicated combinations of circles, which, about 150 A.D., were formulated as an uncomfortably complex system by Claudius Ptolemaeus (Ptolemy) at Alexandria. Similarly, Aristotle worked up fanciful theories of motion from 'self-evident' axioms, such as the proposition that the speed of an object's fall was proportional to its weight. (Anyone could see that a stone fell faster than a feather.)

Now this worship of deduction from self-evident axioms was bound to wind up at the edge of a precipice, with no place to go. After the Greeks had worked out all the implications of the axioms, further important discoveries in mathematics or astronomy seemed out of the question. Philosophic knowledge appeared complete and perfect; and for nearly 2,000 years after the Golden Age of Greece, when questions involving the material universe arose, there was a tendency to settle matters to the satisfaction of all by saying, 'Aristotle says . . . ,' or, 'Euclid says. . . .'

The Renaissance and Copernicus

Having solved the problems of mathematics and astronomy, the Greeks turned to more subtle and challenging fields of knowledge. One was the human soul.

Plato was far more interested in such questions as What is justice? or, What is virtue? than in why rain falls or how the planets move. As the supreme moral philosopher of Greece, he superseded Aristotle, the supreme natural philosopher. The Greek thinkers of the Roman period found themselves drawn more and more to the subtle delights of moral philosophy and away from the apparent sterility of natural philosophy. The last development in ancient philosophy was an exceedingly mystical 'neo-Platonism' formulated by Plotinus about 250 A.D.

Christianity, with its emphasis on the nature of God and His relation to man, introduced an entirely new dimension into the subject matter of moral philosophy that increased its apparent superiority as an intellectual pursuit over natural philosophy. From 200 A.D. to 1200 A.D., Europeans concerned themselves almost exclusively with moral philosophy, in particular with theology. Natural philosophy was nearly forgotten.

The Arabs, however, managed to preserve Aristotle and Ptolemy through the Middle Ages; and, from them, Greek natural philosophy eventually filtered back to Western Europe. By 1200, Aristotle had been rediscovered. Further infusions came from the dying Byzantine empire, which was the last area in Europe to maintain a continuous cultural tradition from the great days of Greece.

The first and most natural consequence of the rediscovery of Aristotle was the application of his system of logic and reason to theology. About 1250, the Italian theologian Thomas Aquinas established the system called 'Thomism', based on Aristotelian principles, which still represents the basic theology of the Roman Catholic Church. But Europeans soon began to apply the revival of Greek thought to secular fields as well.

Because the leaders of the Renaissance shifted emphasis from matters concerning God to the works of humanity, they were called 'humanists', and the study of literature, art, and history is still referred to as the 'humanities'.

To the Greek natural philosophy, the Renaissance thinkers brought a fresh outlook, for the old views no longer entirely satisfied. In 1543, the Polish astronomer Nicolaus Copernicus published a book that went so far as the reject a basic axiom of astronomy: he proposed that the sun, not the earth, be considered the centre of the universe. (He retained the notion of circular orbits for the earth and other planets, however.) This new axiom allowed a much simpler explanation of the observed motions of heavenly bodies. Yet the Copernican axiom of a moving earth was far less 'self-evident' than the Greek axiom of a motionless earth, and so it is not surprising that it took more than half a century for the Copernican theory to be accepted.

In a sense, the Copernican system itself was not a crucial change. Copernicus had merely switched axioms; and Aristarchus of Samos had already anticipated this switch to the sun as the centre 2,000 years earlier. I do not mean to say that the changing of an axiom is a minor matter. When mathematicians of the nineteenth century challenged Euclid's axioms and developed 'non-Euclidean geometries' based on other assumptions, they influenced thought on many matters in a most profound way: today the very history and form of the universe are thought to conform to a non-Euclidean geometry rather than the 'commonsense' geometry of Euclid. But the revolution initiated by Copernicus entailed not just a shift in axioms but eventually involved a whole new approach to nature. This revolution was carried through in the person of the Italian Galileo Galilei toward the end of the sixteenth century.

Experimentation and Induction

The Greeks, by and large, had been satisfied to accept the 'obvious' facts of nature as starting points for their reasoning. It is not on record that Aristotle ever dropped two stones of different weight to test his assumption that the speed of fall is proportional to an object's weight. To the Greeks, experimentation seemed irrelevant. It interfered with and detracted from the beauty of pure deduction. Besides, if an experiment disagreed with a deduction, could one be certain that the experiment was correct? Was it likely that the imperfect world of reality would agree completely with the perfect world of abstract ideas; and if it did not, ought one to adjust the perfect to the demands of the imperfect? To test a perfect theory with imperfect instruments did not impress the Greek philosophers as a valid way to gain knowledge.

Experimentation began to become philosophically respectable in Europe with the support of such philosophers as Roger Bacon (a contemporary of Thomas Aquinas) and his later namesake Francis Bacon. But it was Galileo who overthrew the Greek view and affected the revolution. He was a convincing logician and a genius as a publicist. He described his experiments and his point of view so clearly and so dramatically that he won over the European learned community. And they accepted his methods along with his results.

According to the best-known story about him Galileo tested Aristotle's theories of falling bodies by asking the question of nature in such a way that all Europe could hear the answer. He is supposed to have climbed to the top of the Leaning Tower of Pisa and dropped a 10-pound sphere and a 1-pound sphere simultaneously; the thump of the two balls hitting the ground in the same split second killed Aristotelian physics.

Actually Galileo probably did not perform this particular experiment, but the story is so typical of his dramatic methods that it is no wonder it has been widely believed through the centuries.

Galileo undeniably did roll balls down inclined planes and measured the distance that they travelled in given times. He was the first to conduct time experiments and to use measurements in a systematic way.

His revolution consisted in elevating 'induction' above deduction as the logical method of science. Instead of building conclusions on an assumed set of generalizations, the inductive method starts with observations and derives generalizations (axioms, if you will) from them. Of course, even the Greeks obtained their axioms from observation; Euclid's axiom that a straight line is the shortest distance between two points was an intuitive judgement based on experience. But whereas the Greek philosopher minimized the role played by induction, the modern scientist looks on induction as the essential process of gaining knowledge, the only way of justifying generalizations. Moreover, the scientist realizes that no generalization can be allowed to stand unless it is repeatedly tested by newer and still newer experiments – the continuing test of further induction.

The present general viewpoint is just the reverse of the Greeks. Far from considering the real world an imperfect representation of ideal truth, we consider generalizations to be only imperfect representatives of the real world. No amount of inductive testing can render a generalization completely and absolutely valid. Even though billions of observations tend to bear out a generalization, a single observation that contradicts or is inconsistent with it must force its modification. And no matter how many times a theory meets its tests successfully, there can be no certainty that it will not be overthrown by the next observation.

This, then, is a cornerstone of modern natural philosophy. It makes no claim of attaining ultimate truth. In fact, the phrase 'ultimate truth' becomes meaningless, because there is no way in which enough observations can be made to make truth certain and, therefore, 'ultimate'. The Greek philosophers recognized no such limitation. Moreover, they saw no difficulty in applying exactly the same method of reasoning to the question What is justice? as to the question What is matter? Modern science, on the other hand, makes a sharp distinction between the two types of question. The inductive method cannot make generalizations about what it cannot observe; and, since the nature of the human soul, for example, is not observable by any direct means yet known, this subject lies outside the realm of the inductive method.

The victory of modern science did not become complete until it established one more essential principle – namely, free and cooperative communication among all scientists. Although this necessity seems obvious now, it was not obvious to the philosophers of ancient and medieval times. The Pythagoreans of ancient Greece were a secret society who kept their mathematical discoveries to themselves. The alchemists of the Middle Ages deliberately obscured their writings to keep their so-called findings within as small an inner circle as possible. In the sixteenth century, the Italian mathematician Niccolò Tartaglia, who discovered a method of solving cubic equations, saw nothing wrong in attempting to keep it a secret. When Geronimo Cardano, a fellow mathematician, wormed the secret out of Tartaglia on the promise of confidentiality and published it, Tartaglia naturally was outraged; but aside from Cardano's trickery in breaking his promise, he was certainly correct in his reply that such a discovery had to be published.

Nowadays no scientific discovery is reckoned a discovery if it is kept secret. The English chemist Robert Boyle, a century after Tartaglia and Cardano, stressed the importance of publishing all scientific observations in full detail. A new observation or discovery, moreover, is no longer considered valid, even after publication, until at least one other investigator has repeated the observation and 'confirmed' it. Science is the product not of individuals but of a 'scientific community'.

One of the first groups (and certainly the most famous) to represent such a scientific community was the Royal Society of London for Improving Natural Knowledge, usually called simply the 'Royal Society'. It grew out of informal meetings, beginning about 1645, of a group of gentlemen interested in the new scientific methods originated by Galileo. In 1660, the society was formally chartered by King Charles II.

The members of the Royal Society met and discussed their findings openly, wrote letters describing them in English rather than Latin, and pursued their experiments with vigour and vivacity. Nevertheless, through most of the seventeenth century, they remained in a defensive position. The attitude of many of their learned contemporaries might be expressed by a cartoon, after the modern fashion, showing the lofty shades of Pythagoras, Euclid, and Aristotle staring down haughtily at children playing with marbles and labelled 'Royal Society'.

All this was changed by the work of Isaac Newton, who became a member of the society. From the observations and conclusions of Galileo, of the Danish astronomer Tycho Brahe, and of the German astronomer Johannes Kepler, who figured out the elliptical nature of the orbits of the planets, Newton arrived by induction at his three simple laws of motion and his great fundamental generalization – the law of universal gravitation. (Nevertheless, when he published his findings, he used geometry and the Greek method of deductive explanation.) The educated world was so impressed with this discovery that Newton was idolized, almost deified, in his own lifetime. This majestic new universe, built upon a few simple assumptions derived from inductive processes, now made the Greek philosophers look like boys playing with marbles. The revolution that Galileo had initiated at the beginning of the seventeenth century was triumphantly completed by Newton at the century's end.

Modern Science

It would be pleasant to be able to say that science and human beings have lived happily ever since. But the truth is that the real difficulties of both were only beginning. As long as science remained deductive, natural philosophy could be part of the general culture of all educated men (women, alas, being rarely educated until recent times). But inductive science became an immense labour – of observation, learning, and analysis. It was no longer a game for amateurs. And the complexity of science grew with each decade. During the century after Newton, it was still possible for a man of unusual attainments to master all fields of scientific knowledge. But, by 1800, this had become entirely impracticable. As time went on, it was increasingly necessary for a scientist to limit himself to a portion of the field with which he was intensively concerned. Specialization was forced on science by its own inexorable growth. And with each generation of scientists, specialization has grown more and more intense.

The publications of scientists concerning their individual work have never been so copious – and so unreadable for anyone but their fellow specialists. This has been a great handicap to science itself, for basic advances in scientific knowledge often spring from the cross-fertilization of knowledge from different specialities. Even more ominous, science has increasingly lost touch with nonscientists. Under such circumstances, scientists come to be regarded almost as magicians – feared rather than admired. And the impression that science is incomprehensible magic, to be understood only by a chosen few who are suspiciously different from ordinary mankind, is bound to turn many youngsters away from science.

Since the Second World War, strong feelings of outright hostility toward science were to be found among the young – even among the educated young in the colleges. Our industrialized society is based on the scientific discoveries of the last two centuries, and our society finds it is plagued by undesirable side effects of its very success.

Improved medical techniques have brought about a runaway increase in population; chemical industries and the internal-combustion engine are fouling our water and our air; the demand for materials and for energy is depleting and destroying the earth's crust. And this is all too easily blamed on 'science' and 'scientists' by those who do not quite understand that while knowledge can create problems, it is not through ignorance that we can solve them.

Yet modern science need not be so complete a mystery to nonscientists. Much could be accomplished toward bridging the gap if scientists accepted the responsibility of communication – explaining their own fields of work as simply and to as many as possible – and if nonscientists, for their part, accepted the responsibility of listening. To gain a satisfactory appreciation of the developments in a field of science, it is not essential to have a total understanding of the science. After all, no one feels that one must be capable of writing a great work of literature in order to appreciate Shakespeare. To listen to a Beethoven symphony with pleasure does not require the listener to be capable of composing an equivalent symphony. By the same token, one can appreciate and take pleasure in the achievements of science even though one does not oneself have a bent for creative work in science.

But what, you may ask, would be accomplished? The first answer is that no one can really feel at home in the modern world and judge the nature of its problems – and the possible solutions to those problems – unless one has some intelligent notion of what science is up to. Furthermore, initiation into the magnificent world of science brings great esthetic satisfaction, inspiration to youth, fulfilment of the desire to know, and a deeper appreciation of the wonderful potentialities and achievements of the human mind.

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