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HISTORY OF SCIENCE

What Is Science?

Essential Characteristics of Science

Everyone has some notion about what "science" is, and we all have at least a passing familiarity with the world of science. Rarely does a week go by without a new scientific study or discovery being reported in the media. "Astronomers confirm space structure that's mind-boggling in its immensity" and "Scientists identify gene tied to alcoholism" are the headlines from two recent stories in my daily newspaper.

In what follows here, the word science will not be used in the way the headlines use it [Note 1]. Neither will science be understood to be abstract theories such as found in astrophysics or elementary particle physics that are practically beyond understanding by anyone outside the few specialists working at the frontiers of these specializations. We cannot divorce the nature of science from its daily practice. Science is both practical and theoretical.

Can science be defined by its subject matter? Science investigates natural phenomena of every conceivable sort -- from the physical to the biological to the social. Scientists study everything from events occurring at the time of the formation of the universe to the stages of human intellectual and emotional development to the migratory patterns of butterflies. Judging by its subject matter, then, science is the study of very nearly everything.

Then can science be defined by looking at the range of activities "scientists do." Many of us would be hard-pressed to say much more about the nature of science than that science is whatever it is scientists do for a living. In fact, some learned authorities try to do just that.

A descriptive definition was said to be that science is what is "accepted by the scientific community" and is "what scientists do." The obvious implication of this description is that, in a free society, knowledge does not require the imprimatur of legislation in order to become science. More precisely, the *essential characteristics of science* are: [Note 2].

1. It is guided by natural law;
2. It has to be explanatory by reference to natural law;
3. It is testable against the empirical world;
4. Its conclusions are tentative, i.e., are not necessarily the final word; and
5. It is falsifiable.

Scientists theorize about things, organize vast research projects, build equipment, dig up relics, take polls, run experiments on everything from people to protons to plants; the list is almost endless. A description of science in terms of the sorts of things "scientists do," then, does not reveal much about the nature of science, for there does not seem to be anything scientists typically do. Said another way, there is little that scientists do not do.

Thus, to understand just what science is, a different perspective is required. Instead one must explore why scientists study what they do. Secondly, one must understand the way in which scientific inquiry is conducted, no matter what its subject.

Body of Knowledge

The failure of simplistic descriptions of the nature of science forces us to look deeper. When pressed, we might reply that science must surely be "a body of knowledge." And it is true that science provides an interpretation of the world. Scientist attempt to provide a credible insight to see into nature. What is this insight? Can it indeed be called either imaginative or creative?

To the literary person the question may seem merely silly. The humanist is taught that science is a large collection of facts; and if this is true, then the only scientists need do is to see the facts. Such a person then pictures colorless professionals of science going off to work in the morning into the universe in a neutral, unexposed state. They then expose themselves like a photographic plate. And then in the darkroom or laboratory they develop the image, so that suddenly and startlingly it appears, printed in capital letters, as a new formula for atomic energy.

The danger in this view is in thinking that all that science provides is a rusty file cabinet full of dusty old ideas to which we turn when we run out of creativity or when we have forgotten some needed fact or other. As J. Bronowski recounts:

> I have had of all people a historian tell me that science is a collection of facts, and his voice had not even the ironic rasp of one filing cabinet reproving another. [Note 3].

Far more than the facts of science is the process of science, which, we will see, has proved useful in a variety of ways. We'll come back to this point. It should be obvious, however, that this is so. After all, the greatest scientists of all time, Isaac Newton, Antoine Lavoisier, Dmitri Mendeleev, and others, often did not get it quite right. We honor them nonetheless because they pointed the way, and their creative work made the more complete (and more nearly right) understanding that much more apprehendable.

Perhaps the most important contribution of the knowledge science provides is the opportunity it offers humanity to gain control over nature. Let us turn now to that aspect of science.

Science and Nature

As concluded above, to me the best way to define science is to accept J. Bronowski's definition of science which is appropriate, complete, and useful:

> I define science as the organization of our knowledge in such a way that it commands more of the hidden potential in nature. [Note 4].

This definition is appropriate because it is just as valid for the first stirrings of scientific thought as it is for the cutting-edge theories of today. In order to enhance one's chances for survival early humans had to find ways to "command more of the hidden potential in nature."

Without inventiveness the human species would not have survived. Primitive humans stood naked, subject to the vagaries of nature, without a body protection against cold, heat, scrapes and sunlight. Primitive humans also were ill equipped to protect themselves, lacking the body parts with which to fight back, and able to run among the slowest of the predators. The capacity to invent gave humans the wherewithal to deal with their deficiencies.

This inventiveness was not limited to mere protection or obtaining food; he also possessed imagination and finger-skills. Along with developing means of coping with the environment, predators, enemies, finding shelter and food, we also developed the ability to plan ahead. Other animals inherited experience - we call it instinct. Homo sapien learned to understand his environment and to use that understanding to gain mastery over it. [Note 5].

The needs for survival have not vanished. Today heart diseas, cancer and AIDS are major threats to life on the planet. Finding ways to protect against such diseases and curing them when they occurs can be achieved only when the disease is well understood. That means scientific inquiry. Nuclear weapons, although diminishing somewhat in the threat they offer to the world, still present serious problems to civilization. No matter how committed the community of nations may become, control of the weapons requires credible means of control, and these means will be based on scientific knowledge.

Of course, what I've done here is remove the boundary between knowledge and use. There are of course people who like to draw a line between pure and applied science. To them, the word useful is a final arbiter, either for or against a work; and they use this word as if it can mean only what makes a man feel heavier after meals.

An approcaphal story is told of Plato (which I cannot attest to being factual) that one of his students approched him and inquired to what use he could put the knowledge he was gaining. According to the story, Plato called a slave and had him give the student a coin and dismissed him, noting that if what he wanted was something useful he now had it and should leave.

Hephastus, the Greek god of the technical arts, was noted as being handicapped -- he limped. Thus, to the Greeks, apparently, the "utility of science" was a lesser and baser occupation than the "purity" or whatever of intellectual pursuit. But such a division is artificial, and is based on intent of the individual doing the work. There is no sanction for confining the practice of science in this or another way, and certainly no benefit. True, science is full of useful inventions. And its theories have often been made by men whose imagination was directed by the uses to which their age looked. Isaac Newton turned naturally to astronomy because it was the subject of his day, and it was so because finding one’s way at sea had long been a practical preoccupation of the society into which he was born. It should be added, mischievously, that astronomy also had some standing because it was used very practically to cast horoscopes. Kepler used it for this purpose. In the Thirty Years’ War he cast the horoscope of Albrecht von Wallenstein which wonderfully told his character, and he predicted a universal disaster for 1634 which proved to be the assassination of Wallenstein. [Note 7]., spent their time in a scramble for patents.

What a scientist does is compounded of two interests: the interest of his time and his own interest. In this a scientist’s behavior is no different from any other person’s. The need of the age gives its shape to scientific progress as a whole. But it is not the need of the age which gives the individual scientist a sense of pleasure and of adventure, and that excitement which keeps one working late into the night when all the support staff have long since gone home. The scientist is personally involved in, and taken by the work, as the poet is in poetry, and as the artist is in painting. Paints and painting too must have been made for useful ends; and language was developed, from whatever beginnings, for practical communication. Yet you cannot have a person handle paints or language or the symbolic concepts of physics, you cannot even have that person stain a microscope slide, without instantly waking a pleasure in the very language, a sense of exploring his own activity. This sense lies at the heart of creation.

The sense of personal exploration is as urgent, and as delightful, to the practical scientist as to the theoretical. Those who think otherwise are confusing what is practical with what is humdrum. Good humdrum work without originality is done every day by everyone, theoretical scientists as well as practical, and writers and painters too, as well as truck drivers and bank clerks. Of course the unoriginal work keeps the world going; but it is not therefore the monopoly of practical men. And neither need the practical man be unoriginal. If he is to break out of what has been done before, he must bring to his own tools the same sense of pride and discovery which the poet brings to words. He cannot afford to be less radical in conceiving and less creative in designing a new turbine than a new world system.

And this is why in turn practical discoveries are not made only by practical people. As the world’s interest has shifted, since the Industrial Revolution, to the tapping of new springs of power, the interest of the theoretical scientist has too. Speculations about energy have become as abstract as once they were about astronomy; and they have been profound now as they were then, because the individual loved to think. The Carnot cycle [Note 8] and the dynamo grew equally from this love, and so did nuclear physics and the German V weapons and Lord Kelvin’s interest in low temperatures. People do not invent by following either use or tradition; they do not invent even a new form of communication by calling a conference of communication engineers. Who invented the television set? In any deep sense, it was James Clerk Maxwell whose formulation of what was known about electricity and magnetism foresaw the existence of radio waves, and Heinrich Hertz who proved they were there, and J. J. Thomson who discovered the electron. This is not said in order to rob any practical man of the invention, but from a sad sense of justice; for most likely neither Maxwell nor Hertz nor J. J. Thomson would take pride in television just now.

Nature is mastered not by force but by understanding. This is why science has succeeded where magic failed: because it has looked for no spell to cast over nature. The alchemist and the magician in the Middle Ages thought, and the addict of "science fiction" is still encouraged to think, that nature must be mastered by a device which outrages her laws. But in four hundred years since the Scientific Revolution we have learned that we gain our ends only with the laws of nature; we control her only by understanding her laws. We cannot even bully nature by any insistence that our work shall be designed to give power over her. We must be content that power is the byproduct of understanding. So the Greeks said that Orpheus played the lyre with such sympathy that wild beasts were tamed by the hand on the strings. They did not suggest that he got this gift by setting out to be a lion tamer.

People who have read Balzac and Zola are not deceived by the claims of these writers that they do no more than record the facts. The readers of Christopher Isherwood do not take him literally when he wrote "I am a camera." [Note 9] Yet the same readers solemnly carry with them from their schooldays this foolish picture of the scientist fixing by some mechanical process the facts of nature.

It seems impossible that the historian mentioned above who felt that science was a file of dusty facts had ever studied the beginnings of a scientific discovery. The Scientific Revolution can be held to begin in the year 1543 when there was brought to Copernicus, perhaps on his deathbed, the first printed copy of the book he had finished about a dozen years earlier. The thesis of this book is that Earth moves around the sun. When did Copernicus go out and record this fact with his camera? What appearance in nature prompted his outrageous guess? And in what odd sense is this guess to be called a neutral record of fact?

Less than a hundred years after Copernicus, Kepler published (between 1609 and 1619) the three laws which describe the paths of the planets. The work of Newton and with it most of our mechanics spring from these laws. They have a solid, matter of fact sound. For example, Kepler’s second law states that the square of the time of revolution of a planet divided by the cube of its mean distance from the Sun gives a number that is the same for all the planets. Kepler certainly did not propose this law by taking enough readings and then squaring and cubing everything in sight. To try that approach would doom any would-be scientists to a wasted life with not more prospect for making a scientific discovery than the PC sitting on his desk.

It was not this way that Copernicus and Kepler thought, or that scientists think today. Copernicus found that the orbits of the planets would look simpler if they were looked at from the sun and not from Earth. But he did not in the first place find this by routine calculation. His first step was a leap of imagination -- to lift himself from Earth, and put himself wildly, speculatively into the Sun. "Earth conceives from the Sun," he wrote; and "the Sun rules the family of stars." We catch in his mind an image, the gesture of the virile man standing in the sun, with arms outstretched, overlooking the planets. Perhaps Copernicus took the picture from the drawings of the youth with outstretched arms which the Renaissance teachers put into their books on the proportions of the body. Perhaps he had seen Leonardo’s drawings of his loved pupil Salai. Regardless, the gesture of Copernicus, the shining youth looking outward from the Sun, is still vivid in a drawing which William Blake in 1780 based on all these: the drawing which is usually called Glad Day.

Kepler’s mind, we know, was filled with just such fanciful analogies; and we know what they were. Kepler wanted to relate the speeds of the planets to the musical intervals. He tried to fit the five regular solids into their orbits. None of these likenesses worked, and they have been forgotten; yet they have been and they remain the stepping stones of every creative mind. Kepler felt for his laws by way of metaphors, he searched mystically for likenesses with what he knew in every strange corner of nature. And when among these guesses he hit upon his laws, he did not think of their numbers as the balancing of a cosmic bank account, but as a revelation of the unity in all nature. To us, the analogies by which Kepler listened for the movement of the planets in the music of the spheres are farfetched. Yet are they more so than the wild leap by which Lord Rutherford and Niels Bohr in our own century found a model for the atom in, of all places, the planetary system.

No scientific theory is a collection of facts. It will not even do to call a theory true or false in the simple sense in which every fact is either so or not so. The Epicureans held that matter is made of atoms two thousand years ago and we are now tempted to say that their theory was true. But if we do so we confuse their notion of matter with our own. John Dalton in 1808 first saw the structure of matter as we do today, and what he took from the ancients was not their theory but something richer, their image: the atom. Much of what was in Dalton’s mind was as vague as the Greek notion, and quite as mistaken. But he suddenly gave life to the new facts of chemistry and the ancient theory together, by fusing them to give what neither had: a coherent picture of how matter is linked and built up from different kinds of atoms. The act of fusion is the creative act. [Note 10].

> All science is the search for unity in hidden likenesses. Let me illustrate. Western mountain climbers, at home with compass and map projection, can match a view of an some inaccessible and rarely seen mountain with another view that they have seen years ago. But to the native climbers with them, each face is a separate picture and puzzle. The natives may know another face of the mountain, and this face too, better than the strangers; and yet they have no way of fitting the two faces together. Here is Shipton moving up to a view of Everest from the south, which is new to him, but which his leading Sherpa, Angtarkay, had known in childhood:
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> > On the morning of the 27th we turned into the Lobujya Khola, the valley which

> > contains the Khombu Glacier (which flows from the south and south-west side of Everest). As we climbed into the valley we saw at its head the line of the main watershed. I recognized immediately the peaks and saddles so familiar to us from the Rongbuk (the north) side: Pumori, Lingtren, the Lho La, the North Peak and the west shoulder of Everest. It is curious that Angtarkay, who knew these features as well as I did from the other side and had spent many years of his boyhood grazing yaks in this valley, had never recognized them as the same; nor did he do so now until I pointed them out to him.

> The leading Sherpa knew the features of Everest from the north as well as Shipton did. And unlike Shipton, he also knew them from the south, for he spent years in this valley. Yet he had never put the two together in his head. It is the inquisitive stranger who points out the mountains which flank Everest. The Sherpa then recognizes the shape of a peak here and of another there. The parts begin to fit together; the puzzled man’s mind begins to build a map; and suddenly the pieces are snug, the map will turn around, and the two faces of the mountain are both Everest. Other expeditions in other places have told of the delight of the native climbers at such a recognition.

The search for hidden likenesses may be on a grand scale, as in the modern theories which try to link the fields of gravitation and electromagnetism. But we do not need to be overwhelmed by the scale of science. There are discoveries to be made by snatching a small likeness from the air too, if it is bold enough. In 1935 the Japanese physicist Hideki Yukawa wrote a paper which can still give heart to a young scientist. He took as his starting point the known fact that waves of light can sometimes behave as if they were separate pellets. From this he reasoned that the forces which hold the nucleus of an atom together might sometimes also be observed as if they were solid pellets. A schoolboy can see how thin Yukawa’s analogy is, and his teacher would be severe with it. Yet Yukawa without a blush calculated the mass of the pellet he expected to see, and waited. He was right; his meson was found, and a range of other mesons, neither the existence nor the nature of which had been suspected before. The likeness had borne fruit.

The scientist looks for order in the appearances of nature by exploring such likenesses. For order does not display itself of itself; if it can be said to be there at all, it is not there for the mere looking. There is no way of pointing a finger or a camera at it; order must be discovered and, in a deep sense, it must be created. What we see, as we see it, is mere disorder.

This point has been put effectively in a fable by Karl Popper.

> Suppose that someone wished to give his whole life to science. Suppose that he therefore sat down, pencil in hand, and for the next twenty, thirty, forty years recorded in notebook after notebook everything that he could observe. He may be supposed to leave out nothing: today’s humidity, the racing results, the level of cosmic radiation and the stockmarket prices and the look of Mars, all would be there. He would have compiled the most careful record of nature that has ever been made; and, dying in the calm certainty of a life well spent, he would of course leave his notebooks to the Royal Society. Would the Royal Society thank him for the treasure of a lifetime of observation? It would not. The Royal Society would treat his notebooks exactly as the English bishops have treated Joanna Southcott’s box. [Note 11]. It would refuse to open them at all, because it would know without looking that the notebooks contain only a jumble of disorderly and meaningless items. [Note 12].

Science finds order and meaning in our experience, and sets about this in quite a different way. It sets about it as Newton did in the story which he himself told in his old age, and of which the schoolbooks give only a caricature. In the year 1665, when Newton was twenty-two, the plague broke out in southern England, and the University of Cambridge was closed. Newton therefore spent the next eighteen months at home, removed from traditional learning, at a time when he was impatient for knowledge and, in his own phrase, "I was in the prime of my age for invention." In this eager, boyish mood, sitting one day in the garden of his widowed mother, he saw an apple fall. So far the books have the story right; we think we even know the kind of apple; tradition has it that it was a Flower of Kent.

But now they miss the crux of the story. For what struck the young Newton at the sight was not the thought that the apple must be drawn to Earth by gravity; that conception was older than Newton. What struck him was the conjecture that the same force of gravity, which reaches to the top of the tree, might go on reaching out beyond Earth and its air, endlessly into space. Gravity might reach the moon: this was Newton’s new thought; and it might be gravity which holds the moon in her orbit. There and then he calculated what force from Earth (falling off as the square of the distance) would hold the moon, and compared it with the known force of gravity at tree height. The forces agreed; Newton says tersely, "I found them answer pretty nearly." Yet they agreed only nearly: the likeness and the approximation go together, for no likeness is exact. In Newton's sentence modern science is full grown.

It grows from a comparison. It has seized a likeness between two-unlike appearances; for the apple in the summer garden and the grave moon overhead are surely as unlike in their movements as two things can be. Newton traced in them two expressions of a single concept, gravitation: and the concept (and the unity) are in that sense his free creation. The progress of science is the discovery at each step of a new order which gives unity to what had long seemed unlike. Faraday did this when he closed the link between electricity and magnetism. Clerk Maxwell did it when he linked both with light. Einstein linked time with space, mass with energy, and the path of light past the sun with the flight of a bullet; and spent his dying years in trying to add to these likenesses another which would find a single imaginative order between the equations of Clerk Maxwell and his own geometry of gravitation.

When Coleridge tried to define beauty, he returned always to one deep thought: beauty, he said, is "unity in variety." [Note 13].

The discoveries of science, are explorations of a hidden likeness. The discoverer presents in them two aspects of nature and fuses them into one. This is the act of creation, in which an original thought is born, and it is the same act in original science and original art. But it is not therefore the monopoly of the individual who wrote the poem or who made the discovery. On the contrary, the discovery exists in two moments of vision: the moment of appreciation as much as that of creation. The appreciator must see the movement, wake to the echo which was started in the creation of the work. In the moment of appreciation we live again the moment when the creator saw and held the hidden likeness. When a theory is at once fresh and convincing, we do not merely nod over someone else's work. We re-enact the creative act, and we ourselves make the discovery again. At bottom, there is no unifying likeness there until we too have seized it, we too have made it for ourselves.

How slipshod by comparison is the notion that either art or Science sets out to copy nature. If the task of the painter were to copy for men what they see, the critic could make only a single judgment: either that the copy is right or that it is wrong. And if science were a copy of fact, then every theory would be either right or wrong, and would be so for ever. There would be nothing left for us to say but this is so, or is not so. No one who has read a page by a good critic or a speculative scientist can ever again think that this barren choice of yes or no is all that the mind offers.

Reality is not an exhibit for man's inspection, labeled "Do not touch." There are no appearances to be photographed, no experienced to be copied, in which we do not take part. Science, like art, is not a copy of nature but a re-creation of her. We re-make by the act of discovery, in the poem on in the theorem. And the great poem and the deep theorem are new to every reader, and yet are his own experiences, because he himself re-creates them. They are the marks of unity in variety; and in he instant when the mind seizes this for itself, in art or in science, the heart misses a beat.

We have seen what science is not -- not a mere body of facts, certainly not a collection of facts; not what "scientists do," for reasons of vagueness; not a specified subject matter for its interest is too broad. We have concluded that science is the search that leads to discovery of hidden likenesses in nature and the organizaition of what is learned in such a way that it commands more of the hidden potential of nature.

We can explore further, though, what it is that scientists do. Once we have a clearer picture of what scientists do, we may be able to say something more general about the process of science, that is, specifically what distinguishes science from, say, art, philosophy, or religion. To this end we note that scientists are characterized by asking why, offering explanations, and testing explanations. Let us look at each of these activities and then draw some conclusions about the scientific method.

Asking Why

Of course, we cannot hope to give a simple, ubiquitous reason why each and every scientist studies the natural world. There are bound to be as many reasons as there are practicing scientists. Nevertheless, there is a single "why" underlying all scientific research. In general, scientists study the natural world to figure out why things happen as they do. We all know, for example, that the moon is riddled with craters. From a scientific point of view, what is of interest is precisely why this should be so. What natural processes have led to the formation of the craters? Thus, in part, science is an activity aimed at furthering our understanding of why things happen as they do in the world in which we live.

To see what it is that scientists actually do in attempting to "make sense" of nature, let’s take a look at an historical instance that, as it turns out, played an important role in the development of modern medicine.

Up until the middle of the 19th century, little was known about the nature of infectious diseases and the ways in which they are transmitted. In the mid-1800s, however, an important clue emerged from the work of the Hungarian physician, Ignaz Semmelweiss . At the time, many pregnant women who entered Vienna General Hospital died shortly after giving birth. Their deaths were attributed to something called "childbed fever."

Semmelweiss interested himself at once with childbed fever. It was a puzzling disease, since women bearing children in Vienna hospitals with the help of superbly educated doctors died of the vever very commonly, while women bearing children at home with the help of ignorant midwives usually survived. Equally curious was the fact that the death rate from childbed fever in the hospital ward where the patients were treated by physicians was five times higher than in another ward where women were seen only by midwives. Physicians were at a loss to explain why this should be so. But then something remarkable occurred. One of Semmelweiss’ colleagues cut his finger on a scalpel that had been used during an autopsy. Within days, the colleague exhibited symptoms remarkably like those associated with childbed fever, and subsequently he died. Semmelweiss knew that physicians often spent time with students in the autopsy room prior to visiting their patients in the maternity ward.

Now, the phenomenon that Semmelweiss wanted to understand is clear: the remarkable difference in the death rates from childbed fever owing to manner of treatment - doctors and midwives. Relying largely on the clue provided by the death of his colleague, Semmelweiss speculated that the doctors themselves were somehow carrying the disease from the dissecting rooms via what he termed "cadaveric matter." In 1847 Semmelweiss began to force doctors under him to wash their hands in stroing chemicals before touching any patients. This was unpleasant for the doctors, especially to those who were proud of the "hospital odor" of their hands and who resented being told they were causing disease.

Offering Explanations

Semmelweiss , in arriving at a solution to the childbed fever problem, was certainly asking why. Let us note that in seeking answers he made careful, painstaking observations with his senses. He gave names to the things he observed and attempted to correlate observations. He drew a general conclusion (i.e., that the fever was transmitted by doctor’s hands) and set out a procedure to prove his contention (forcing doctors to wash their hands.) In all this there were, in fact, several generalizations - that there was a cause within the hospital for childbed fever, that their was something in the autopsy room that could be the cause for the fever, and that "cadaveric matter" he believed responsible could be transmitted from cadever, to doctor to patient.

Semmelweiss’ observations presented him with facts that puzzled him - notably, the marked difference in rates of death by childbed fever in the two wards and the fact that physicians attended patients only in the ward where the death rate was higher. His generalization to explain the puzzle was a conjectural but, if true, it would account for those puzzling facts.

Semmelweiss’ generalization is all the more interesting because it introduced what were, at the time, some very new and controversial ideas about the way in which disease is transmitted. Many of Semmelweiss’ contemporaries believed that childbed fever was the result of an epidemic, like the black plague, that somehow infected only pregnant women. Others suspected that dietary problems or difficulties in the general care of the women were to blame. In making his generalization, Semmelweiss hinted at the existence of a new set of explanatory factors that challenged the best explanations of the day and had the potential to advance dramatically current views about how diseases are spread.

Generalizations do not have to involve such controversial new notions, however. Indeed, in our daily lives we often work with generalizations of a more mundane sort. Imagine, for example, the following case. For the past few nights, you haven’t been sleeping well. You’ve had a hard time getting to sleep and have begun waking up frequently during the night. It is unusual, for you are normally a sound sleeper. What could be causing problem? Well, next week is final exam week, and you’ve been staying up late every evening, studying. Could concern about your upcoming exams be causing the problem? This seems unlikely, since you’ve been through exam week several times before and haven’t had any problems sleeping. Is there anything else unusual about your behavior the past few nights? It has been quite warm, so you have been consuming large quantities of your favorite drink, iced tea. This could explain the problem. You are well aware that most teas, like coffee, contain a stimulant, caffeine, though tea usually contains much less than coffee. It may well be the caffeine in the ice tea that is disturbing your sleep.

Though nothing of any great scientific consequence turns on the solution of this little puzzle, the way in which we have undertaken its solution nonetheless involves precisely the elements we identified in Semmelweiss' work on childbed fever. The puzzling fact here is your recent inability to sleep soundly. The key factors in the generalization - in this case that the stimulant in iced tea is apt to keep you from sleeping - are your increased iced tea consumption and the fact that iced tea contains a stimulant. Thus, to a large extent, thinking about things from a scientific perspective - thinking about the "hows" and "whys" of things - involves thinking in ways with which you are already familiar.

These two cases - the scientific and the mundane - have something else in common. Both provide us with explanations of something puzzling, yet in neither case do we have any tangible evidence that the explanation offered is correct. No doubt, if there is something in cadaveric matter that can cause childbed fever, then Semmelweiss' explanation might be on the right track. Similarly, it may be the iced tea that is causing your sleeplessness. But then again, it may be something else, something we have not yet considered; it may even be a combination of the iced tea and other factors. Earlier, we observed that science aims at explaining natural phenomena. Now we need to look at the way in which proposed explanations are put to the test. Not coincidentally, the second part of the answer to our question "What is science?" involves the way in which explanatory stories are tested, both in the world of official science and in our daily lives.

Testing Explanations

Consider once again the problem of sleeplessness. You have a hunch that your recent inability to sleep is a result of your increased consumption of caffeine. But is this the right explanation? In this instance, a relatively quick, easy, and effective test can be performed. You might, for example, try drinking ice water instead of iced tea in the evening. If you were to do this, and if you began sleeping normally again, you would have good reason to think that this explanation is correct: It must be the caffeine in the iced tea. Conversely, if you did not begin sleeping normally, you would have some reason to suspect that you had not yet found the right explanation: eliminating the caffeine didn't seem to do the trick.

At the heart of the proposed test lies the following strategy: first, looking for a consequence of the generalization - something that ought to occur if circumstances are properly arranged and if your generalization is on the right track. If caffeine is causing your sleeplessness, and if we arrange for you to stop consuming caffeine, we would expect your sleeplessness to stop. Next, we took pains to arrange these circumstances: you stopped your caffeine consumption. Finally, you waited to see what would happen - whether or not the predicted result would actually occur.

Something very much like this same strategy was employed by Semmelweiss in testing his generalization. Semmelweiss reasoned as follows: if childbed fever is caused by cadaveric matter transmitted from physician to patient, and if something were done to eradicate all traces of cadaveric matter from the physicians prior to their visiting patients in the maternity ward, then the incidence of childbed fever should diminish. As stated, Semmelweiss arranged for physicians to wash their hands and arms in chlorinated lime water - a powerful cleansing agent - prior to their rounds in the maternity ward. Within two years, the death rate from childbed fever in the ward attended by physicians approached that of the ward attended by midwives. By 1848, Semmelweiss was losing not a single woman to childbed fever! [Note 14].

It is this experimental strategy that provides the final part of the answer to the question "What is science?" Science is characterized by its underlying interest in making sense of things. It does so, first, by proposing explanations for natural phenomena and, second, by devising experimental conditions under which explanations can be tested. And as we have seen the experimental strategy on which scientists rely is not all that different from the kind of commonsense strategy we ourselves follow in answering the "hows" and "whys" of our daily lives.

Scientific Method

Everyone has a notion that there is something called the "scientific method" which characterizes all science. If by scientific method one means something like a step-by-step recipe generally followed by scientists in their research, then there is no single scientific method. Scientific interests and activities are far too broad for there to be anying of the sort. A common thread, however, does run through all good scientific research and we have begun indicating just that in the examples above. Thescientific method is a rigorous process whereby new ideas about how some part of the natural world works are put to the test..

The essentials of the intellectual game of man-against-nature are four.

1. First, you must collect observations about some facet of nature (*observation*).
2. Second, you must organize these observations into an orderly array (*correlation*). 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.
3. Third, you must derive from your orderly array of observations some principle that summarizes the observations (*generalization*).
4. And finally, the principle must be put to the test along with a set of basic standards for judging the merits of experiments designed (experimentation).

It is this four-step process that we can roughly but accurately describe as the basic method of the sciences.

The discovery of things is made in steps. At the first step there are only the separate data of the senses: we may observe that marble sinks in water, wood floats, iron sinks, a feather floats, mercury sinks, olive oil floats, and so on. It would be mere pomp to use words as profound as true and false at this simple step. What we see is either so or is not so. Where no other judgment can be made, no more subtle words are in place.

At the second step we put the data together. We see that it makes sense to treat them as one thing. And the thing is the coherence of its parts in our experience. So, 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, and we give a symbol or a name for what we observe; we may refer to the property of specific gravity, or density.

And finally we generalize: we will conclude: objects denser than water sink in water, and objects less dense than water, float.

The scientific method is not all that straightforward nor, for that matter, easy to apply. Generalizations are not always as readily tested as our initial examples might suggest, nor are test results always as decisive as we might like them to be. We will also find that, with some minor variations, scientific method can be used to test things other than explanations. But when all is said and done, when we have followed the rather intricate twists and turns involved in applying scientific method, we will have at our disposal an accurate picture of the basic methodology underlying scientific research.

Before moving on, an important caveat is in order. In focusing on the preoccupation of science with making sense of nature by providing and testing explanations, we have ignored what is surely an equally compelling interest of the sciences - namely, making the world a better place to live through technological innovation. Indeed, when we think of science, we often think of it in terms of some of its more spectacular applications: computers, high-speed trains and jets, nuclear reactors, microwave ovens, new vaccines, and so on. Yet our account of what is involved in science is principally an account of science at the theoretical level, not at the level of application to technological problems.

Don’t be misled by our use of the term theoretical. Theories are often thought of as little more than guesses or hunches about things. In this everyday sense, if we have a theory about something, we have at most a kind of baseless conjecture about it. In science, however, theory has a related but different meaning. Scientific theories may be tentative and, at a certain point in their development, will involve a fair amount of guesswork. But what makes a scientific theory a theory is its ability to explain - not the fact that at some point in its development it may contain some rather questionable notions. Just as there will be tentative, even imprecise, explanations in science, so also will there be secure, well-established explanations. Thus, when we distinguish between theory and application in science, we are contrasting two essential concerns of science: concern with understanding nature, and concern with exploiting that theoretical understanding as a means of solving more practical, technological problems.

It is primarily at the level where new ideas about nature are proposed and tested that science and scientific method neatly fit our description. Yet there is an important, if by now obvious, connection between the worlds of theoretical and applied science. With very few exceptions, technical innovation springs from theoretical understanding. The scientists who designed, built, and tested the first nuclear reactors, for example, depended heavily on a great deal of prior theoretical and experimental work on the structure of the atom and the ways in which atoms of various sorts interact. Similarly, as one of our examples should serve to remind us, simple but effective new procedures for preventing the spread of disease were possible only after the theoretical work of Semmelweiss and others began to yield some basic insight into the nature of germs and the ways in which diseases are spread.

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 diffficulties 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 labor - 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 specialties. 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 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, fulfillment of the desire to know, and a deeper appreciation of the wonderful potentialities and achievements of the human mind.

Notes

1. Some of these questions are raised in Stephen S. Carey, *A Beginner’s Guide to Scientific Method*, Belmont, CA: 1994, pp. 1-7.

2. Judge William R. Overton. "Creationism in Schools: The Decision in McLean versus the Arkansas Board of Education," The judgment, injunction, and opinion were reprinted in *Science*, Vol. 215 (January 19, 1982), pp. 934-943.

3. J. Brownowski. *Science and Human Values*. New York: Harper & Row, Publishers, 1965, p. 11.

4. Brownoski, 1965, p. 7

5. Lord Ritchie-Calder. "Knowing How and Knowing Why," introduction to Part Seven, "Technology," in the *Propaedia, Encyclopaedia Britanica*, 15th edition, 1976, pp. 434-436.

6. Albrecht von Wallenstein, (1583-1634), was an Austrian general who fought for the Habsburgs as a mercenary during the Thirty Years' War (1618-48). A convert to Catholicism, he remained loyal to Holy Roman Emperor Ferdinand II during the Bohemian rebellion (1618-23). In 1625, Wallenstein raised an army at his own expense for the emperor and was appointed imperial generalissimo. He treated his command as a business operation; profits were to come from levies imposed on conquered territories. A skillful military leader, he was rewarded (1629) with the imperial duchy of Mecklenburg, but his enemies at court and among the German princes, fearing the emperor's new power based on Wallenstein's 70,000-man army, persuaded Ferdinand to dismiss him in 1630. The fortunes of war forced Ferdinand to recall Wallenstein in 1631, who received additional lands and money. Wallenstein, pursuing an independent policy, began negotiating for peace, apparently hoping for terms that would make him a major European leader. Ferdinand feared that Wallenstein was plotting against him and ordered the general's capture -- dead or alive. Wallenstein was assassinated at the fortress of Eger in Bohemia. See Golo Mann. *Wallenstein, His Life Narrated*, Charles Kessler (trans.) London: Deutsch, 1976. Translation of *Wallenstein, sein Leben erzahlt.*.

7. Norbert Wiener (1894-1964) coined the term "cybernetics" in his 1948 book. *Cybernetics; or, Control and Communication in The Animal and The Machine*. New York: J. Wiley, 1948, wherein he worked out the mathematical basis of the communication of information, and of control of a system in light of such communication.

8. The French physicist Nicolas L&eacu;onard Sadi Carnot (17906-1832) was interested in the amount of work that could be obtained from a heat engine. The steam engine invented by James Watt, although far better than any previous model, was quite efficient. Carnot was interested in improving the efficiency.

9. Christopher Isherwood (1904-1986), was a novelist and a writer of nonfiction. His work is largely autobiographical or quasi-autobiographical. In 1928 he began to study medicine but soon left the University of London to go to Germany. Living there off and on until 1933, Isherwood described the social and political climate of pre-Hitler Germany. The drama *I Am a Camera , A Play in Three Acts*, by John Van Druten, New York: Random House, 1952, was adapted from the Berlin Stories (1951) of Christopher Isherwood, and the musical Cabaret (1966) also came from his writings on Germany.

10. J. Brownowski, *Science and Human Values*, p. 30

11. See Richard Reece, *A correct statement of the circumstances that attended the last illness and death of Mrs. Southcott : with an account of the appearances exhibited on dissection : and the artifices that were employed to deceive her medical attendants*. London: Printed for the author; published by Sherwood, Neely, and Jones, 1815.

12. Bronowski, 1965, p. 14.

13. In one of the places in which Coleridge put forth this definition, the essays *On the Principles of Genial Criticism* which Coleridge thought "the best things he had ever written," he traced it back to Pythagoras: "The safest definition, then, of beauty, as well as the oldest, is that of Pythagoras: the reduction of many to one."

14. When Hungary revolted (unsuccessfully) against Austria in 1849, the Viennese doctors were able to call patriotism to the aid of folly and forced Semmelweiss out. The incidence of childbed fever climbed to record heights as soon as handwashing was stopped but the Viennese doctors didn't mind as long as they could keep their pride.

[HOS Calendar Page]

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