The Scientific Enterprise

6. The Methods in Science

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If there are specific methods that are particularly characteristic of the scientific enterprise, what are they? Before we examine this question we must be clear about what we mean by the scientific method. By this phrase we do not mean a set of well-defined procedures which, when carefully followed, will lead to scientific discoveries. Clearly if such procedures existed, a few years of training in this should make every student of science a discoverer, great or modest. This certainly does not happen. This fact is most dramatically illustrated in the accomplishments of Francis Bacon who wrote extensively and eloquently on the scientific method, but made hardly a single discovery of note in science himself. Bacon was also a strong anti-Copernican (Jerzy Dobrzyckip, *The Reception of Copernicus' Heliocentric Theory*, p. 325). And there are countless other examples.

Great discoveries come about in unexpected ways, and seldom by following clear-cut rules. As James Bryant Conant pointed out (*Science and Common Sense*, 1951): "The stumbling way in which even the ablest of the scientists in every generation have had to fight through thickets of erroneous observations, misleading generalizations, inadequate formulations, and unconscious prejudice is rarely appreciated by those who obtain their scientific knowledge from textbooks."

Let us therefore be clear about two meanings that might be attached to scientific method. First, we may consider it as a set of rules to be followed to make progress in the scientific understanding of the world. It is prescriptive in nature for a student of science. The other is to look upon it as a description of what scientists do in their investigation of nature. Aspects of the scientific method may change from period to period, since our knowledge, resources, and insights may change over the centuries, and scientists may be adopting different procedures at different times. For example, the use of optical telescopes was part of the scientific method in astronomy for three centuries. Now, not many astronomers look through telescopes in their investigations.

We may therefore use the term scientific method as a system of procedures for the scientific community in its efforts to explain natural phenomena; and more importantly to confirm or reject discoveries and theories. It embraces a set of operations and values within which the scientific community functions. The adoption of the method does not ensure the correctness of the interpretations, and it does not necessarily lead to new discoveries. These procedures include criteria for determining whether or not a proclaimed proposition deserves to be accepted as such by the scientific community. They spell out ways by which a novice in science may understand, appreciate, and convince for oneself the validity of scientific truths.

In other words, if we regard the scientific enterprise as a game in which scientists are engaged, the scientific method refers, in the phrase of Karl Popper (*The Logic of Scientific Discovery*, 1968), to "the rules of the game". But it is a serious game.

Careful Observation

If our goal is to understand phenomena, we must first divide the world of experience into specific domains which can be studied piece by piece; if not, we will be confronted with a staggering immensity far beyond any single individual's grasp. Once a field of study is chosen, every phenomenon related to it must be carefully observed. In ancient science, reflection and speculation, more than systematic observation, often played the dominant role.

We become aware of the physical world through our channels of perception. This awareness can occur in two ways: It could be an unconscious registering of external stimuli, or it could be associated with a deliberate act of the will. When a conscious effort is combined with the process of sense perception we say that we are *observing*: the mind takes part in observations. Observation is not the same as simply seeing. Everyone has seen the moon, but few have observed it. One who has not observed it will not be able to say how the rising hour of the moon changes from day to day. As an ancient Latin poet Publilius Syrus pithily said, "Observation, not old age, brings wisdom." (*Sententiae: Sensus, non aetas, invenit sapientiam.*) Many astrologers who write and predict on the basis of horoscopes have not even seen the planets or the constellations themselves, let alone observed them.

Our sense perceptions include sight, hearing, smell, taste, and touch, made possible through our eyes, ears, nose, tongue, and sensitive skin. Associated with these are nociception (experience of pain), equilibrioception (ability to maintain balance), proprioception (ability to move in unison), kinesthesia (ability to accelerate), sense of time, sense of temperature difference, and magnetoception (sense of direction). (James J Gibson, *The Senses Considered as Perceptual Systems*, Boston 1966.) These are undoubtedly the most remarkable faculties that have evolved in the universe, processing billions of bits of information each second. But they are not perfect. We recognize their imperfection on at least three different levels.

First, the sensitivity of our senses is limited. The normal ear cannot hear very faint sound vibrations. The eye is unable to detect stars that are present in the day sky. A tiny thread landing on our neck may go unrecognized. Science overcomes these limitations by devising instruments that amplify the effects for the senses. A combination of lenses may be used to construct a telescope through which very faint or distant objects may be detected. Another combination forms the microscope through which very minute entities may be rendered visible. In like manner, there are sound magnifying instruments also.

Next, the range of sense-perception is also limited. The eye is sensitive to only one small region of the electromagnetic spectrum. Electromagnetic waves whose wavelengths lie beyond the interval of the visible spectrum cannot be detected by the human eye. The place where you are reading these lines at this moment is bathed in radio waves and microwaves of all wavelengths coming from the most distant parts of the world and beyond. Your physiological mechanisms are inadequate to register or recognize these effectively. We need special instruments, such as a radio receiver which responds in some observable way to ranges of the waves to which the human body is insensitive.

The revelations of the senses can sometimes be misleading. Two perfectly parallel lines may be made to appear to converge or to diverge by appropriately inserting sets of slanting lines between them. Or again, consider the impression we get of the sun and the stars rising and setting. To all appearances these celestial objects are moving across the sky, but we know that this is not quite so. Similarly, if one were to taste sweetened coffee after eating some halva, the coffee will not taste sweet. There are a number of other instances where our senses turn out to be misleading. The way to handle such problems is by careful analysis.

Conceptual Framework

We just noted that observation is a conscious and sustained mode of recording our sense impressions of the external world. But this is not enough. In scientific observations one tries to relate what is observed to its several parts or to other observed phenomena. In other words, one makes an effort to discern connections and patterns: to discover systematic relationships.

For this, we need a framework of concepts and terminology in which observations may be properly recorded. Only then can we even attempt to find relationships. Thus, when the moon is observed, we must have the concepts of time, position, and phase, for example. Without these, there cannot be any observation of the moon. When we observe rainfall we must have the concept of quantity per a given time, the period of the year, etc.

All scientific observations and theorizing rest on concepts, some of which have direct correspondence with what we perceive; and others have only an indirect link to the perceived reality. Thus, for example, volume and electric charge can be directly perceived while entropy and magnetic flux only indirectly.

Experiments

When one is interested in a very specific aspect of a phenomenon one tries to separate it from other concurrent events. For example, sunlight heats the air, winds blow, birds fly in the atmosphere, leaves rustle in it, and a hundred other things happen in air. Suppose we wish to find out about the effect of heat on air. For this we may fill a jar with a quantity of air and study its behavior when heated. When we do this, we are performing an experiment.

Again, in order to do an experiment we need a conceptual framework. Thus, when we say we wish to determine the effect of heat on air, there must be ways of stating what kinds of effects we have in mind, and how we will measure that heat. Here, the concepts of volume, pressure, and density are useful, as also that of temperature.

An experiment is like a personal interview that the investigator conducts with some aspect of nature. We are posing specific questions to nature regarding its behavior under well-defined conditions. The results of the interview constitute the data of the experiment. These may consist of verbal descriptions, columns of numbers, graphs, etc.

In one of the Upanishads (*Chhandogya Upanishad*) we read about a personage by the name of Uddalaka Aruni. He shows by direct experimentation with his own body that life (*prânâ*) arises from the finest essence of water, that food goes to make the mind, that "everything in nature originates from heat, water and food": in modern terms, energy, elements, and complex molecules. Debiprasad Chattopadhyaya (*History of Science and Technology in Ancient India: Formation of the Theoretical Fundamentals of Natural Science*, 1991) pointed out that Uddalaka should be "recognized as the first conscious nature scientist in global history". However, in the long run supernatural science and metaphysics took over in the Hindu intellectual quest. They continue to be powerful elements in the Indian worldview. Though insightful and enriching, they are not helpful in the scientific exploration of the world.

Experiments can be simple or extremely complex. They may take hours, or days or even months. Consider Charles Darwin's thorough experiments with certain orchids. As F W Westaway (*Scientific Method*, 1931) reminded us long ago: "For twenty-three consecutive days he (Darwin) examined flowers in all states of weather, at all hours, in various localities. Flowers of different ages were subjected to irritating vapours, to moisture, and to every condition likely to bring on the secretion" before he concluded these orchids do not secrete any nectar.

Categories of Experiments

Countless experiments are performed every day in the laboratories of the world. These may be put under three broad categories in terms of their goals. These are as follows:

(a) *Mere Measurement*: An experiment may be performed solely for the purpose of measuring a physical quantity. Thus, one may wish to determine the density of a newly found substance, the distance of a star, the heartbeat of an animal, the intensity of cosmic radiation, etc. Although one rarely refers to experiments with this epithet, these are among the most common and valuable types of experiments in the scientific enterprise. Measurement experiments are fundamental in physics: there can be little physics without measurements.

(b) *Verification/Confirmation*: The aim of an experiment of this type is to verify or confirm a result that follows from theoretical considerations. This was already mentioned in the article on 'Goals and Assumptions' (*Resonance*, September 2008). For example, we may be told that a feather and a lead ball will both fall to the ground at the same rate. To see if this true, one can do an experiment. That is the only way to determine the correctness or otherwise of the proposition. Experiments of this kind are essential at the research level in the continual interactions between theoretical and empirical science. Sometimes a theory may predict an aspect of the world that is unknown, and the actual verification might come years or even decades later. For example, in 1930 Wolfgang Pauli postulated the existence of a new fundamental particle – later called the neutrino by Enrico Fermi – while interpreting the data of beta decay. Twenty-six years later Frederick Reines and Clyde Rowan experimentally put into evidence the existence of neutrinos, confirming the theoretical prediction. (Isaac Asimov, *Neutrino: Ghost Particle of the Atom*, 1966). Once again, in 1924 Satyendra Nath Bose's paper on the statistics for photons appeared. The following year Einstein deduced from this statistics (Lev P Pitaevskii and S Stringari, *Bose–Einstein Condensation*, 2003) "a phase transition in a gas of non-interacting atoms". This led to the possibility of an entirely new state of matter, now called *Bose–Einstein condensate*, for certain substances. Seventy years later, in 1995, after many other theoretical refinements and experimental techniques, the predicted state was actually observed.

(c) *Discovery of Relationship*: Finally, we have experiments whose purpose is to discover an unknown relationship. In the transformations occurring in the universe innumerable physical quantities are involved. One of the interests of the scientist is to discover relationships between these variables. For example, we may wish to know in what specific manner the current in a wire depends on the voltage difference between its terminals, or whether there is any relationship between the amount of food one eats and the number of hours spent in sleep. Relationships of this kind are at the basis of the general laws of nature.

This categorization of experiments is by no means watertight. They refer only to the initial purpose of the experimenter. And the goals of the experiments may overlap. Some aspects of an experiment of the second or third kind may be mere measurement. Sometimes while performing an experiment of one kind, i.e., with one of the three goals mentioned above in mind, the investigator may change it into an experiment of a different kind. Thus, in trying to measure the rate of fall of different bodies – a mere measurement type – one may discover that this rate depends on the medium through which the fall occurs. The experiment then becomes one of the third kind. Or again, in trying to verify that the current through a conductor is proportional to the potential difference between its ends, the experimenter may discover that this is not quite true at very high temperatures. Thus an experiment of the second kind is transformed into one of the third.

Reproducibility

One important characteristic of all scientific experiments is reproducibility. A result following from an experiment is valid only if the experiment, when done again, yields the same result, especially when performed by someone else in another location. Many alleged facts turn out to be non-reproducible. Much controversy between science and non-science arises from the importance that science attaches to reproducibility.

Chemists Stanley Pons and Martin Fleischman claimed in 1989 to have discovered nuclear reactions at low temperatures: cold fusion. (Frank Close, *Too Hot to Handle*: *The Race for Cold Fusion*, 1991.) But their claim could not be reproduced, and their reputation suffered.

However, not every phenomenon and process or even experiment in science need be capable of being reproduced in practice. Rather, if repeated, the results must be the same. Indeed, science also attaches significance to certain non-reproducible conceptual experiments. Theories pertaining to geology, astronomy, astrophysics, archeology, and evolutionary biology belong to this category. In these fields it is physically impossible to reproduce the conditions that are implicit in the theories. What is required here is that if the experiments were re-done, the (long range) results would be as stated (or observed). What one actually means by reproducibility is consistency of results when the experiment is repeated.

Classification of Data

The results of an experiment are known as experimental data. These must be carefully arranged and classified if we wish to obtain some useful insights or information from them.

Classification is the first step in many sciences. In astronomy one begins by classifying the celestial bodies as stars and planets. Stars are classified as single and double, variable and non-variable; planets are classified according to their orbits with respect to the earth's orbit (inner and outer planets), etc. In botany and zoology classification is extremely important and forms the basis of taxonomy. Likewise, in geology, rocks and minerals are classified, in chemistry, substances are classified, and so on.

In the matter of categorization ancient Hindu thinkers were unsurpassed. They classified substances into *maharasas, uparasas, ratnas*, and *vishas.* They categorized plants and animals, foods and innate qualities, feelings, society, diseases, philosophical systems, knowledge, and more. (D M Bose et al., *A Concise History of Science in India*, 1971.)

Many insights and discoveries have resulted from systematic classification of experimental data. It is by carefully arranging and studying the observational data amassed by Tycho Brahe pertaining to the motion of Mars that Kepler was able to discover his laws of planetary motion. (John North, *The Fontana History of Astronomy and Cosmology,* 1994.) Similarly, by a detailed study of A J Angstrom's spectroscopic data relating to the wavelengths emitted by hydrogen, J J Balmer was able to discover an important relationship between the spectral lines of hydrogen. (B H Bransden and C J Joachain, *Physics of Atoms and Molecules*, 1983.)

Scientific Explanation

A goal of science is to explain. But what does one mean by *explanation*? This question has been discussed by philosophies in great detail. (D Ruben, ed., *Explanation*, 1993.) But we shall consider it from a simple point of view. For this, let us consider the case of a child in front of a TV. If too little, she will be indifferent to it. If she is a little older, she may watch it happily, and the question may not even arise in her mind as to how people are talking, cars are moving, music is playing, etc., all on a screen. The question does not bother even some adults. At this stage there can be no science at all, since a need for explanation has not been felt.

At a more advanced stage the child may wonder about these matters. Suppose the child is old enough to ask how it is possible to see people playing music on the screen. An adult may reply that there are in fact live singers inside of the box, and many other things also which show up every time we turn on the TV. The child might simply say, “Oh!” and be satisfied. As far as she is concerned, the matter has been explained.

Next consider the fact that an object hurled into the air always falls back to the ground. Suppose we are told that everything in the neighborhood of the earth belongs to the earth, like children belonging to their parents. Just as a child which moves away from home eventually returns, so too objects moving away from the earth return to the ground. This explanation is known to have satisfied many.

Finally, consider the phenomenon of water becoming steam when sufficiently heated. How does this happen? We may be told that the effect of heat on any substance is to change its state from solid to liquid, and from liquid to vapor. This explanation may be satisfactory to many.

A scientifically literate individual will characterize the first explanation as ridiculous, the second as unscientific, and the third as being only partly acceptable, if at all. But what is important in any given instance is whether or not the person seeking the explanation is satisfied by the answer. If this happens, then as far as the person is concerned, an explanation has been found. Indeed, one often refers to explanations as being satisfactory or not. Thus, explanation is creating the impression that one understands.

The question that now arises is: How can one be sure that the impression of having understood a phenomenon is not just an illusion? We may gain some insight into the problem by analyzing the types of explanations one encounters.

To begin with, let us go back to the adult’s answer to the child concerning the TV. We may not find that explanation satisfactory at all, but the child does. This is because, to begin with, the child is not mature enough. Her mind is as yet not developed enough to recognize the impossibility, not to say the absurdity, of the explanation offered. This is because she is not sufficiently acquainted with the world. Two important conditions are necessary for giving or evaluating an explanation: intellectual maturity, and a fair degree of familiarity with the world.

Now let us take up the explanation for why bodies fall to the ground. This type of explanation is rejected by science because it assumes that inanimate nature behaves like animate organisms. This view was quite common in ancient science, and was successful (in the sense of being satisfactory) for many centuries. Explanations based on the idea that nature behaves in a goal-directed manner are known as *teleological*. Teleological explanations are not taken seriously in the physics of our own times, although they may still have some relevance in biology.

Why did physics give up teleological explanations? Modern science chooses to follow those paths that lead to tangible results, and abandon those that seem fruitless, especially in quantitative contexts. Even granting that bodies do fall back to the ground because of a natural affinity for mother earth, we cannot go much farther with this perhaps interesting idea. Many other facts pertaining to bodies thrown up in the air cannot be explained on this basis. For example the parabolic path of projectiles cannot be understood in terms of the parent-child analogy. The quantitative features of falling bodies, such as the rate of fall, the time taken, or the velocity at various instants, cannot be explained by teleological explanations. This is why certain types of explanations are ignored by modern science.

Cause and Effect

In scientific explanations one often tries to establish causal connections. In other words, one seeks to explain observed phenomena in terms of causes and effects. The notion of cause itself is very complicated, one on which again philosophers do not agree. (Judea Pearl, *Causality*: *Models of Reasoning and Inference*, 2000.) One can go into an analysis of whether a supposed cause is necessary or sufficient, whether the effect is implicitly contained in the cause, whether the effect is always necessary or may only occur with a certain degree of probability, etc.

From a common sense point of view, when two events A and B always occur in conjunction, A (generally, but not necessarily) preceding B even by a minute fraction of a second, we say that A is the cause and B is the effect. As an example of the simultaneity of cause and effect, the motion of the automobile may be regarded as the cause of the motion of the passengers in it. Yet both occur at the same time. This simplistic view can be logically challenged on a philosophical basis. Nevertheless the search for causes continues in science where one makes an attempt to find interrelations between various phenomena. Once we grant that natural phenomena do not occur sporadically, that there is an order governing the behavior of nature, we also assume that the observed events bear mutual relationships, direct or indirect, and often sequential. These relationships are described in terms of cause and effect.

If we view cause and effect as a long and all embracing chain, serious problems can arise at the metaphysical level. For if we say that we are trying to find the cause of everything, one has to find the causes of the various causes also, and the puzzle can go on indefinitely. If we say that gravitation is one of the causes of the elliptic orbits of planets, one may ask what causes gravitation. We will have to admit at some point that certain things are the properties of certain aspects of nature. Thus one may say that gravitation is an intrinsic property or essence of all material bodies. It is futile to ask what gives it that property. We may define matter itself in terms of the property. Or again, if one tries to explain the inverse square law as resulting from the three dimensionality of space, the question may be asked as to what caused our physical space to be three dimensional. Similarly, if we were to say that Newton's Second Law of Motion is what causes the variety of motions we observe, one may ask what causes the Second Law of Motion to operate.

This problem is handled by describing the last (or first) step in a causal explanatory chain as a Law of Nature.

There is one type of so-called scientific explanation which is, in fact, a pseudo-explanation. This consists in the free use of technical terms to create the impression that something has been explained. John Ruskin gave a good example of this. (*The Queen of the Air*, 1869.) Why are leaves green? Because they contain chlorophyll. And the uninitiated will imagine that science has explained why leaves are green. Now any good dictionary will tell us that in Greek *chloros* means green, and *phylon* is leaf. So, put in plain English, all we are saying is that leaves are green because they contain a substance that makes them green. Likewise, in answer to the question why a metal rod expands when heated one may say that it is because metals have a positive coefficient of expansion. Why are DNA molecules so long? Because they are polymers. Why is milk good and onion bad? Because one is *sattvik* and the other is *rajasik*. And so on. Unfortunately this type of pseudo-explanation is practiced as much by innocent science-oriented people as by clever advertisers whose object is to sell something on the basis of its scientific-sounding support.

Let us then summarize what we have said about explanations:

(a) An explanation is the creation of the impression that we understand something.

(b) Explanations in terms of final causes, i.e., teleological explanations, although quite common and generally accepted in pre-modern science, have been practically banished from modern physical sciences.

(c) Science tries to explain phenomena in terms of causes and effects, as also through laws of nature, but these are not without philosophical difficulties.

(d) In looking at scientific explanations we should be careful not to be duped by technical sounding terms which may be merely covering up one's ignorance through the use of words from Latin, Greek, or Sanskrit.

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[*] Part 1. Science: Some Definitions and Views, *Resonance*, Vol.13, No.6, pp.596–605, 2008.
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