The Scientific Enterprise

8. Theories and Hypotheses in Science

V V Raman

Introduction

The word 'theory' is derived from the Greek *theoria*: a speculation or a view. It is used in both technical and ordinary language in a variety of meanings. Thus one speaks of Plato's theory of ideas, of Kant's theory of knowledge, of Cantor's theory of sets, of Hobbes' political theory, of the impressionist theory of art, and of music theory. In each of these instances the word has a different meaning; the only common feature in all of them is the conceptual framework involved. Similarly, in common parlance, simple beliefs are sometimes referred to as theories. Thus, a detective might say, "My theory is that it is Mrs. Deshpande's ex-husband who ate all the jilebis from the refrigerator." Likewise, the belief, once propagated by Rumley Dawson (*The secret of Sex: The discovery of a new law of nature, How sex is caused*, Cochrane Publishing Co., Rapid City, SD, 1909), that the right ovary produced male children, and the left ovary female ones, is sometimes called a theory, though the author imagined it to be a law of nature. According to the Aristotelian theory, writes one author, heavier bodies fall faster than lighter ones.

In scientific literature, and especially in physics, theory has a very clear meaning and function. It is certainly not a simple belief, nor just another way of looking at things. It serves the principal explanatory goal of science. Efforts to explain physical phenomena and their generalizations (laws of nature) lead to the formulation of theories. A theory in science is the conceptual development of a set of basic ideas and inter-relationships concerning the physical world in terms of which observationally noted phenomena and empirically derived laws may be understood.

Thus, for example, if we consider Kepler's First Law of planetary motion according to which planets move in elliptical orbits, we may ask why planets follow such orbits rather than, say, circular or square ones. In the context of these results Isaac Newton made certain fundamental assumptions about the physical world (gravitation and laws of motion). A whole body of mathematical development based on these assumptions adequately explains the empirically derived laws of planetary motions. Similarly, Bohr's theory of the hydrogen atom is based on certain basic assumptions, and its function is to account for the empirically observed results pertaining to the spectral lines of hydrogen. In physics, a theory must *explain*, not simply *describe*, something.

Hypothesis in science

We noted above that a theory in science is always based on certain fundamental assumptions. These assumptions constitute the hypotheses of the theory. Thus Newton's theory of gravitation to explain the observed planetary motions (Kepler's laws) was based on the hypotheses of the inverse square law of attraction and the laws of motion. Einstein's theory of the photoelectric effect was based on Planck's hypothesis of the quantum of radiation. The whole of wave mechanics was based on De Broglie's hypothesis of the wave-particle duality. A hypothesis is thus the starting point of a theory in science. The term is derived from the Greek, *hypo*: under, and *tithenia*: to put; thus meaning that which is put under. (Latin words for under: *sub*, and to put: *ponere*, have given rise to the words, *supposition* and *suppository*.) A Sanskrit equivalent might be *upanyâsa*.

A hypothesis is usually succinct in expression, concise as a formula, and quite general as a statement. In physics, it has invariably a mathematical component. By itself, a hypothesis is of no interest in science. It is only when one explores its consequences that its significance, if any, will become apparent. The exploration of the consequences of a hypothesis often constitutes a theory in science.

Usually, though not always, a hypothesis in science will refer to some aspect of the physical world that is not amenable to direct observations. Thus the wave theory of light is based on the hypothesis that light consists of undulatory disturbances that propagate through space. This is not a property of light that can be directly perceived, but its consequences can be observed. Similarly, the kinetic theory of gases rests on the hypothesis that a gas is made up of extremely small billiard-ball-like entities (molecules) that move and collide at random. It may be impossible to observe molecules and their motions directly, but the theory brings out several observable consequences of such a state of affairs. These have been amply verified. Hence the hypothesis has been accepted as true. The validity of a hypothesis depends on the verifiability of its consequences as brought out by the theory that is based on it.

The Hypothetico-Theoretic Method

The central problem of science is to explain phenomena. Explanation, we recall, is creating the impression that we understand why a particular thing happens. That understanding is effected in the world of science in two ways: (a) By noting that what is observed is only a special case of a general pattern of behavior of the physical world; i.e., it is an instance of a law of nature. (b) Through the development of a theory which includes some not-directly-observable features of the world, in such a way that the observed phenomena are shown to be logical (natural) consequences of those features.

The logical conclusions from a set of hypotheses are deduced by reasoning and by mathematical derivation. This process is therefore referred to as the hypothetico-deductive method. Since it invariably involves a theory, it could also be called the hypothetico-theoretic method.

Some of the consequences logically flowing from the hypotheses may correspond to actually observed phenomena. Yet others may not have been observed at all. In such a circumstance the scientific community undertakes a search for these new (theoretically predicted) effects. If such an effect is actually observed, then the theory and its hypotheses take on a greater degree of validity. The hypothetico-theoretic methodology, which is perhaps the most fruitful mode through which human beings have interacted with the world around at the intellectual level, has not only served to explain a whole variety of phenomena, and given new insights into the nature of the unseen world, but also led to many discoveries in science through its predictive powers.

Crucial Experiment

Sometimes two rival hypotheses with their corresponding theories may be able to explain the same set of phenomena. In such situations it is hard to decide which one to accept. A classic case of this occurred during the 18th century when two competing views as to the ultimate nature of light – the corpuscular and the wave theories – were current. Each one could successfully explain practically all the then known optical phenomena. However, it follows from the corpuscular theory that light should travel faster in water than in air, whereas according to the wave theory it should be the other way around. The experimental resources of the 18th century were not sufficient to test out which of these two consequences is actually the case. When, in the course of the l9th century, on the suggestion of François Arago, Léon Foucault and Fizeau succeeded in doing the experiment that determined these velocities, it was found that light travels faster in air than in water (Comptes Rendus de l'Académie des Sciences, Paris p.551, 1850). The corpuscular hypothesis of light had to be abandoned. An experiment of this kind which decides between two competing, till then equally valid hypotheses, is known as a *crucial experiment*. But Pierre Duhem argued (*The Structure of Scientific Theories,* Atheneum New York, 1962) that the crucial experiment did not close the debate once for all. With the rise of the quantum (photon) hypothesis, the corpuscular idea was back again. This just shows how the fundamental worldviews of science are never etched in stone. We may note in passing that the Latin phrase *experimentum crucis* was first used by Newton in 1672 in the context of his own theory of light and colors.

From Data to Hypothesis and Theory: An Imaginary Example

The hypothetico-theoretic method of science may be illustrated through an imaginary problem in which a hypothesis will be considered on the basis of certain observed facts.

Suppose that we observe someone writing the letters of the alphabet in two rows. First she writes five letters, and takes a pause. The letters are written out as below:

A E
B C D

Let this correspond to the first set of observed phenomena. On studying this, what can we say about the rule by which a given letter is put in one or the other row? One hypothesis would be that vowels are put on the upper row and consonants on the lower. This certainly explains the observed phenomena. Moreover, according to this hypothesis, F, G, and H will next appear on the lower row. Suppose now that the person resumes the writing and stops at J as shown below:

A E F H I
B C D G J

This clearly contradicts the predictions of the hypothesis. It must therefore be abandoned. Now someone comes up with another hypothesis: The letters are put according to how their sounds are spelled out. Thus, in a, bee, cee, dee, ee, eff, etc., if the beginning letter is a vowel, it is put in the upper row. If the beginning letter is a consonant, it is put in the lower row. It follows from this theory K that should appear in the lower row, whereas L, M, and N should be in the upper row. Actual observation reveals the following:

A E F H I K L M N
B C D G J

We now see that L, M, and N turn out to be as predicated, but K contradicts the theory. As the theory is quite successful in everything except for K, we are not willing to give up this theory. We will simply call K an 'anomalous' or 'strange' letter.' Now we will look for the position of O which, according to our theory, must be in the upper row. Further observations now show the following to be the case:

A E F H I K L M N T V
B C D G J O P Q R S U

Obviously our theory has to be abandoned on the basis of these observations. Now someone comes up with another idea: All those letters which are made up of only straight lines are put in the upper row, and those that involve curved lines are in the lower row. Further observations reveal that **W, X, Y**, and **Z** are indeed in the upper row, as predicted by this theory. Thus, at last, one has found a theory which explains satisfactorily all the facts pertaining to this phenomenon.

Now it could well be the author himself had something quite different in his mind: something that even the most perceptive observer could not have fathomed. For example, it may be that the author had come across the statement: "Summers Can Be Dull Unless One Quickly Gets Reasonable Jobs Or Projects," and decided to put the beginning letters of the words in this sentence in the lower row, and all other letters in the upper row. The point is that whatever our theories, and however satisfactory they may seem from our perspective, one can never be absolutely certain that they are the only (or even, ultimately the correct) explanations for what is observed. But then, correctness is not the goal in science: it is consistency.

The So-What Criterion and Dogma

One is allowed to make any hypothesis in science. But if the hypothesis is to be of any interest to the scientific community, it must come out successfully when subjected to the 'so-what criterion'. According to this, when a hypothesis is formulated, it must answer the question, "So what?" It is the answer or answers to this question that will determine the importance, usefulness, relevance, and consequent acceptability of the hypothesis. This criterion is almost self-evident to the working scientist. But it is often lost sight of in debates between science and other fields of human endeavor.

Consider the following statements, in both of which the idea of light has been introduced:

> And God said: Let there be light, and there was light.
>
> *devam devatra sûryam aganma jyotiruttamam*: God among gods, to sûrya we have come: the most supreme of all light.

Light is made up of electromagnetic vibrations propagated through space with a finite velocity. All these say something about light. From the third statement we can draw a number of conclusions whose correctness or otherwise may be checked by direct observations, and through well-defined experimental procedures. Thus, if one asked, 'So what?' when this statement is made, a number of answers may be given.

On the other hand, hardly any consequence of empirical interest follows from the first two statements. This does not necessarily imply that they are false or incorrect. Indeed it may well be that in some deeper sense they are fundamentally truer than the third statement. For, our views as to the ultimate nature of light may still change drastically in the course of the next few centuries, while a Supreme Being could well have created the universe, imposing light in it by a mere command, and the sun is surely the brightest of all sources of light in out planetary region. But the point is that unless a statement about an aspect of perceived reality leads to observable consequences, it is of little value to the scientific enterprise. It is in this sense that the first two statements are not scientific while the third is.

When a hypothesis is introduced, and even more so, when it is accepted without any consideration of or regard to its consequences, it becomes a dogma. In Christian theology the word has taken on special technical connotations, referring primarily to belief in God on the basis of the Scriptures. In the Hindu world the origin of the Vedas as being not of human authorship (*apaursheya*) is a dogma. In the context of our discussion, however, we may make the distinction between a dogma and a hypothesis on the basis of the so-what criterion. The validity of a dogma is based on its intrinsic, *á priori* truth-value, not on the consequences it may lead to; whereas in the case of a hypothesis, quite the opposite is the case.

The Doctrines of Science

The world of science has occasionally been condemned for 'dogmatically' refusing to incorporate supra-physical, psychic, spiritual, and similar factors as possible components of the universe. There is an element of truth in this characterization of science. But it must be remembered that for over three thousand years thinkers in all civilizations did imagine such possibilities; but hardly any tangible effect (in terms of positive knowledge) seems to have arisen from such beliefs. Even after the rise of modern science a number of serious and competent scientists have accepted such entities in the universe, and have even spent years trying to establish scientifically their existence; but thus far, with little success.

It must also be noted that the upholders of the supernatural, which includes such items as psychic communication and numerology, have more followers than scientists do. Unfortunately, most of the willing believers in these matters don't have the scientific stature to which the advocates of such views would themselves attach much weight. Also, many of the thinkers who argue that science is too narrow-minded in rejecting the possibility of supra-physical phenomena have not furnished by their own endeavors any concrete evidence to their contentions. Their inclination to accept these matters is based on the statement that anything and everything is possible in this universe.

This last contention cannot be denied. There is no logically valid reason for rejecting as untrue even the most fantastic speculations about what may be happening beyond our ranges of perceptions. But until there is some justification for accepting them as such, it would be unreasonable – and futile – to condemn the scientific community as being close-minded on this score. To have an open mind does not mean that one will permit anything and everything into it, but rather that the mind will not be closed to the careful consideration of any new idea.

Sources of Theories

We noted that a theory is developed in order to explain some observed phenomena. How does a scientist come up with a theory? There are no hard and fast rules for the construction of a theory in science. Many different factors and circumstances could give rise to a theory. We must bear in mind that the development of a theory is a supremely creative act on the part of the scientist, like the composition of a great piece of music or a great work of art. The only constraint here is that its ultimate results be in accordance with observed facts. Let us consider some of the factors giving rise to theories, along with specific examples:

(a) ***Analogy***: In trying to understand something that is new, a parallel with something with which we are already familiar helps a great deal. Hence the role of analogies in scientific explanations. The distinction between heat content and temperature, for example, can be better grasped if an analogy between water content and water level is pointed out. Some scientists have regarded analogy not merely as an aid to understanding, but as an indispensable part of any theory. This attitude arose in the l9th century when Newtonian mechanics had proven itself to be remarkably successful. As a result, explanations often meant expressing situations in terms of a mechanical model.

The 'billiard ball' analogy helped in the development of the kinetic theory of gases. The Rutherford model for the hydrogen atom was based on an analogy with planetary orbits around the sun. But analogies have also sometimes misguided scientists. Thus the caloric theory of heat (which was current in the 18th century, but has now been discarded) was developed in analogy with hydrodynamics, and hence it regarded heat as a fluid. The analogy of vortices from smoke rings led Lord Kelvin to attempt electrical theories on a vortex model. What is more, this great physicist of the l9th century had difficulty in accepting Maxwell's elegant mathematical theory of electromagnetism on the ground that it could not be pictured in terms of a mechanical analogy. He famously said, “”I am never content until I have constructed a mechanical model of the subject I am studying. If I succeed in making one, I understand; otherwise I do not.” (*Baltimore Lectures*, MT, Kessinger Publishing Whitefish, 2007.)

(b) ***Guess work***: Occasionally, no more than an intelligent guess could originate a physical theory. This is especially the case when order is to be discovered in a maze of observed data. The recognition of specific relationships between the wavelengths of radiation (the so-called Balmer series) in the hydrogen spectrum was the result of intelligent guess work (*Magie, William Francis* (*A Source Book in Physics*, Harvard University Press, Cambridge, MA, 1969).

(c) ***Flash of insight***: When the guessing process reveals some intrinsic feature of the world which goes beyond merely telling us about what could have been gathered by intelligent guessing, we have a case of a flash of insight. Many theory builders have reported how they arrived at the germinal idea in a moment of inspiration or insight. Most scientists will also admit that a good deal of preliminary work, i.e., a study of the problem in depth, struggles to clarify the situation; considerable hours of reflection, etc., are needed before the flash occurs.

The discovery of the ring structure of the benzene molecule by Kekulé is a classic example. Kekulé is said to have had a first insight into the question while on a bus ride in London. Suddenly it occurred to him that some organic compounds must have their various carbon atoms connected to each other in chain-like links. Some years later, in 1865, he had a dream in which the carbon atom chains moved about serpent-like until finally the mouth of the serpent grabbed the tail and formed a closed ring structure. (A J Rocke, Hypothesis and Experiment in the Early Development of Kekulé's Benzene Theory. *Annals of Science,* Vol.42, pp.355–81,1985)

The story of Newton discovering gravitation when an apple fell on his head does not rest on any historical event, but it does illustrate the role of flashes of insight in the formulation of theories. (V V Raman, A Background to Newtonian Gravitation, *The Physics Teacher,* 10, 8, pp.439–442, Nov 72.)

(d) ***Mathematical puzzle***: Sometimes, especially since the rise of sophisticated mathematical physics, the mathematical aspects of physical theories have given rise to altogether new theories. Thus, for example, in trying to express the then known laws of electromagnetism in a systematic mathematical form, Maxwell was obliged to introduce the concept of the displacement current. This had a major impact in our understanding of electromagnetism. (Edmund Whittaker, *A History of the Theories of Aether & Electricity,* Vol.I, p.251, Harper Torchbooks, New York, 1951) Again, it attempting to find an acceptable mathematical function whose graph would correspond to the observed curves of black body radiation, Max Planck hit upon the quantum theory of radiation. (Armin Hermann, *The Genesis of Quantum Theory* (1899–1913), The MIT Press, Cambridge, MA, 1971.)

(e) ***Conceptual dilemma***: There arise occasions when it becomes difficult to accept or interpret a physically observed situation on the basis of well-known and long-accepted ideas. The physicist is then at a loss to find out what has gone wrong. Under such circumstances, a clarification of the paradox could result from some new and major scientific discovery. A classic example of this is related to the problem of the ether-drift. In the late l9th century, physicists had accepted the notion of an all-pervading ether in which the celestial bodies moved (somewhat like ships on an ocean), and through which light and other forms of radiation propagated between celestial bodies. Extremely delicate experiments designed my Michelson and Morley to put into evidence such an ether failed to reveal any such thing. This was incompatible with the ideas of an absolute space and absolute time. Almost twenty years later, in 1904, Einstein formulated the Theory of Special Relativity, quite independently of the Michelson–Morley experiment and solved the paradox, rejecting in the process some of the basic assumptions of classical Newtonian physics (Abraham Pais: *Subtle is the Lord…*, Oxford University Press, New York, p.172, 1982).

Stages in the Theoretical Interpretation of Nature

The physicist tries to understand and interpret the physical world. This is accomplished in various stages, although the same individual physicist may not be engaged in all of them, and the various stages may not always occur in a chronological order. It is nevertheless helpful to look into the different stages which are involved in the physicist's interpretation of the world.

(a) ***Observation****:* It goes without saying that the phenomenon to be explored must first be studied very carefully. It must be realized that in the sophisticated laboratories of our own times observation itself may be a very complex enterprise. The apparatuses and instruments that are brought into play could cost enormous sums of money, and may be totally bewildering to the uninitiated.

(b) ***Concept-making****:* The scientific description of the physical world would be very limited if one does not bring in conceptual entities in that description. Such simple phenomena as a falling body, boiling water, or reflection of light from a mirror, cannot be brought under scientific study unless and until one introduces certain conceptual ideas, such as: speed, temperature, angle of reflection, etc. The introduction of abstract concepts is a major step in the intellectual grasp of nature: in the world of science.

(c) ***Generalization****:* Using concepts in the description, the scientist tries to formulate broad generalizations about particular facets of nature. These generalizations constitute the physical laws or laws of nature in terms of which the world is understood. When based on experiments alone, these are known as empirical laws.

(d) ***Mathematization****:* An important stage in the scientist's interpretation of the physical world consists in the description of observed phenomena in quantitative terms, and in the expression of physical laws in a formal mathematical language. This becomes especially possible and indispensable in physics, and to a lesser degree in other branches of science.

(e) ***Extraction of further information****:* The mathematical formulation of a physical situation or law is perhaps the most powerful achievement of the human mind. By this we mean that the physicist can describe accurately innumerable situations, as well as their evolution, without having to look directly into the phenomena in question. The physicist thus accomplishes, in a metaphorical sense, the mind-reading of nature. She knows exactly what nature will do next.

She can predict its behavior. This is only possible by playing with the mathematical aspects of a situation. By the same process, the physicist may sometimes become aware of entirely unsuspected aspects of the physical world. In other words, one will be able to discover entirely new entities in nature by simply using paper, pencil, and the techniques required in the analysis of the mathematical formulation of the situation in question. Electromagnetic waves, the photon aspect of radiation, the planets Neptune and Pluto, as well as some elementary particles such as the positron, the pion and others were discovered this way.

It is important to understand this aspect of the physicist's way of interpreting the world, because it is sometimes stated, even by physicists, that science merely describes the world in its own way, even as art does. This is no doubt true, but science's description has an entirely different dimension to it, namely, its power of prediction. No art or poetry describing the moon can foretell where the moon will be three nights or ten years hence. But science can.

(f) ***Development of theories****:* Once a law has been stated in precise mathematical form, the task of the theoretical scientist is to account for it, i.e., to derive it as a consequence of some fundamental principles which are assumed to be operating in the world. The role of the theoretical physicist is somewhat like that of the psychoanalyst in that he endeavors to delve deeper into the unseen realm by studying the behavior at the level of observation.

It must be noted that this is a very complex program of activity. The stages we have referred to are by no means clear cut, nor assigned to specific scientists at specific times. People may move from one stage into another, communicate with others in the same or in different stages, debate, discuss, exchange information, and correct the efforts of one another. The dynamics of scientific research is extremely involved. Many factors besides time, talent, a spirit of disinterested inquiry, and rational thinking come into play in the actual process of scientific creativity and growth.

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V V Raman is Emeritus Professor of Physics and Humanities at the Rochester Institute of Technology, Rochester, New York.
Email : vvrsps@rit.edu