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THE VALUE OF SCIENTIFIC UNDERSTANDING

Wesley C. Salmon

In a synoptic overview of the vicissitudes of scientific explanation during the course of the twentieth century, one fact stands out above all others. In the early decades the dominant view among philosophers and scientists was that science does not provide explanations at all, whereas in the closing decades it is widely held that science is capable of furnishing explanations of many aspects of the world. This change results, not so much from the dramatic successes achieved in various scientific domains during the century, but rather from a difference in philosophical orientation. In the earlier parts of the century it was often said that the business of science is to describe the phenomena, to predict future facts, and to organize and systematize our knowledge of the world; if one wanted explanations it was necessary to leave the domain of science and seek understanding in metaphysics or theology. Rudolf Carnap (1966, 1974) provides an illuminating discussion of this attitude toward explanation in the early decades. Roughly speaking, it was held that science can tell us *what* but not *why*. Present scientists seem not at all reluctant to offer explanations of the phenomena with which they are concerned and philosophers of science, by and large, do not deplore this situation. Quite the contrary, a number of philosophers maintain that the achievement of explanatory truth (or approximate truth, or well-supported explanatory theories) is one of the major aims of scientific investigation, if not *the* principal goal. As always, there are, of course, some philosophers who disagree.

The transition from the early attitude to the view that is generally held today was greatly facilitated in the middle decades by the works of several major philosophers. The first of these was Karl Popper's *Logik der Forschung* (1935) which, because it appeared in German, had little influence in the English-speaking world. At that time, we should recall, Europe was in a state of turmoil because of Hitler's recent rise to power, and many of the most important philosophers of science fled to other places. Chaos reigned in the German-speaking world. Popper's influence increased dramatically when the subsequent English edition, *The Logic of Scientific Discovery* (1959), including a great deal of new material, was published. In the meantime, the classic Hempel-Oppenheim (1948) article, "Studies in the Logic of Explanation" appeared, but it had little influence for about a decade. Richard B. Braithwaite's *Scientific Explanation* (1953), which made no mention of Hempel-Oppenheim (1948), also appeared. During the late 1950s and early to middle 1960s there was a burst of interest in the topic of scientific explanation. Two extremely influential books came out, namely, Ernest Nagel's magnum opus, *The Structure of Science: Problems in the Logic of Scientific Explanation* (1961), and Hempel's *Aspects of Scientific Explanation and Other Essays in the Philosophy of Science* (1965), containing the magisterial essay "Aspects of Scientific Explanation" along with a reprinting of Hempel-Oppenheim (1948). By this time the notion that the sciences can provide explanations was strongly consolidated.

Another clear indication of the situation lies in the fact that the late 1950s saw the beginning of a rash of critical articles. The criticisms were *not* based on a conviction that scientific explanation does not exist, instead, they attacked specific features of the conceptions of scientific explanation advocated by one or another of the above-mentioned authors — for example, the thesis that every legitimate scientific explanation must contain, either explicitly or implicitly, a law of nature (or a statement thereof).

It is not my purpose in this paper to give a detailed account of the developments to which I have referred; that can be found in Salmon (1990). It is worth noting, however, that in the above-mentioned discussions surprisingly little attention was devoted to what Carnap later called "clarification of the explicandum" — that is, to a preliminary informal discussion of the concept to be explicated. Often a few examples were expected to furnish the reader with an adequate idea. Notably lacking, for the most part, was any discussion of the value of scientific explanations or of the reasons for seeking them. In retrospect this point is brought out forcefully by the view, currently held in some quarters, that science is actually concerned, not with providing explanations, but rather with the solving of problems or puzzles. One is led to wonder why we should devote such enormous human and material resources to the solving of scientific problems and puzzles unless success in that endeavor contributes to our understanding of nature. I realize, of course, that problem-solving can have great practical value in many cases; obviously we are rightly concerned to solve puzzles concerning the causes of airplane crashes in order to try to prevent future accidents. My interest in this paper is, however, mainly in pure rather than applied science; the aim is to characterize the kind of intellectual understanding we can achieve, for example, from knowledge of basic aerodynamic principles.

In the foregoing paragraphs I have used the term "understanding" several times without trying to clarify its meaning. This is, I believe, the key concept. Unfortunately, it is extremely ambiguous. As of this writing, for example, *You Just Don't Understand* by Deborah Tannen (1991), a book whose main thesis is that women and men speak different languages, has been on the *New York Times* best-seller list for 80 weeks. The highly publicized "generation gap", which appears to be a permanent feature of relationships between parents and children, consists of a lack of understanding between them. In both cases the situation is deplored. "My wife just doesn't understand me" is the eternal complaint of husbands, and is the standard line for those who are wayward — or would like to be. Obviously, to understand and be understood is a deep desire for an enormous number of people.

The kind of understanding involved in these situations is empathy — the sharing of feelings and emotions. People have often sought a similar kind of understanding with nonhuman parts of the world, leading to various forms of theism, pantheism, and the view, as Thales is reputed to have said, that all things are full of gods. Such conceptions often provide great psychological satisfaction, but their theological and/or metaphysical character led many scientists and scientific philosophers to spurn scientific explanation (understanding) altogether.

One manifestation of the desire for understanding of the world found in many (if not all) cultures is the construction of cosmological theories or world-pictures. In the Judeo-Christian tradition we have the Biblical story of creation as given in *Genesis*.[1] Readers of Tony Hillerman's highly successful novels can learn a great deal about Navajo cosmology. In his popular account of modern cosmology, *The First Three Minutes* (1977), Nobel laureate Steven Weinberg briefly recounts the Norse myth of creation found in the *Younger Edda* (compiled circa 1220). There is an important sense in which we desire to comprehend the overall character of our universe and our place within it. Creation myths seem to fulfill this function. So-called "creation science" is one such influential myth to which an unfortunately large number of Americans adhere, much to the detriment of education in the United States. A striking feature of these myths is their blatant anthropomorphism.

During the ages, however, philosophers and scientists have sought what can now be identified as a scientific world-picture — a scientific *Weltanschauung*. The cosmology of Aristotle and Ptolemy, though also anthropomorphic (especially in the hands of medieval Christians), involved serious efforts to construct a conception based on a significant body of empirical evidence. The conception developed by Copernicus, Kepler, and Galileo — as well as the variation proposed by Tycho Brahe — provided significant improvements, culminating in "the Newtonian synthesis". The great power of the Newtonian synthesis lay in three aspects: (1) it provided a coherent and comprehensive world-picture; (2) it was highly unified because of the small number of fundamental principles on which it was based; and (3) it was supported by an extraordinary amount of empirical evidence. Its inability to account for the darkness of the sky at night (Olbers' paradox, which was actually articulated by Edmund Halley in 1720) was an unfortunate fundamental defect.

The fact that classical physics broke down at the turn of the twentieth century does not detract from its achievement in providing a comprehensive and unified *scientific* world-picture. Our present world-picture — involving quantum mechanics, relativity, the expansion of the universe, and the "big bang" — departs radically from that of classical physics. With twentieth century scientific developments we have good reason to believe that we have a high degree of understanding of the universe and our place within it. We obviously have much more to learn, including answers to such problems as the origin of life and the nature of consciousness in humans, other animals, and possibly machines. The Copernican revolution and Darwinian evolution may have been psychologically disappointing to many, but they are supported by substantial scientific evidence, which tends to enhance our confidence in their accuracy, even if we might prefer that the world were otherwise. In any case, we can say that we have *scientific* understanding of phenomena when we can fit them into the general scheme of things, that is, into the *scientific* world-picture.

There is another kind of understanding that appeals to a large number of people, especially children. We want to know *how things work* (and, perhaps it should be added, *what they are made of*). This obviously applies to contrivances devised by humans, for example, watches and automobile engines. By opening them up, taking them apart, and putting them back together again we can often learn something about how they work. Further study can enhance such understanding. Certainly there is great practical value in knowing how things work, for example, to fix them when they are broken or to improve on their design. As I indicated above, however, the main focus of this paper is on pure science, so these practical considerations will be put aside for now in order to turn our attention to intellectual curiosity as such.

Suppose we have a plain black box with a red and a green light on it. At times the red light flashes briefly; at other times the green light flashes briefly. Our curiosity is aroused. We want to open the black box and find out how it works — why the green light goes on, why the red light goes on, etc. We examine the interior of the black box in the hope of satisfying this curiosity. I will return to this example, which turns out to be extraordinarily difficult.

In nature, of course, it often happens that the contents of the "black box" are entities too small to be observed with the naked eye, or with the aid of a magnifying glass or simple optical microscope. In these cases we are seeking the hidden or underlying mechanisms, and the mechanisms are often causal. A well-known historical example illustrates the point. Early in the nineteenth century, Robert Brown noticed the apparently random movement of microscopic particles suspended in fluids — the phenomenon known as Brownian motion. Although this phenomenon was extensively investigated during the nineteenth century, no satisfactory explanation was forthcoming until the early years of the present century, when Einstein and Smoluchowski offered a theoretical account in terms of the collisions between the Brownian particles and the molecules of the fluid in which they are suspended. Extremely delicate and precise experiments conducted by Jean Perrin at about the same time provided striking confirmation of the theoretical explanation. The thoroughly causal and mechanical nature of the explanation is obvious; a scientific understanding of the phenomenon of Brownian motion was achieved by precisely characterizing the mechanisms that produce it. The ultimate upshot of Perrin's investigations was the establishment, to the satisfaction of the vast majority of knowledgeable physical scientists, of the reality of such entities as molecules and atoms — an issue on which there was no firm scientific consensus at the turn of the twentieth century. The details of these developments are discussed in a highly illuminating manner in Mary Jo Nye's *Molecular Reality* (1972) and in Perrin's own *Les Atomes* (1913). As Perrin himself points out, his work provides mechanical explanations of a huge variety of phenomena, including even the blueness of the daytime sky (when it is not obscured by clouds).[2]

One can hardly deny the enormous explanatory power of the atomic/molecular theory of the constitution of matter, for example in chemistry and molecular biology. Knowledge of the mechanisms of chemical bonding and of the molecular mechanisms of heredity enables us to understand an immense range of physical and biological phenomena. Knowledge of the mechanisms of disease transmission in terms of germs and viruses provides understanding of epidemics and pandemics. It would be an insult to the intelligence of the reader to continue the list of phenomena so various and so obvious that can be explained in terms of underlying mechanisms.

Up to this point I have said nothing about quantum mechanics, a field that presents us with some of the most difficult problems of explanation. On the one hand, no theory has had more powerful explanatory success; on the other hand, it presents us with mysteries that presently seem to defy explanation. Let us return to the black box, mentioned above, with the red and green lights. Suppose there is another just like it, located some distance away, with no physical connections to the first. On each of these boxes is a dial with a hand that points randomly to one of the three numerals, "1," "2," or "3." The two black boxes are detectors. Halfway between the two black boxes is a "source" — i.e., a device with a button on top. When this button is pressed, either the red or the green light flashes on each of the black boxes. Aside from the fact that the source emits particles that activate the detectors, here are no physical connections among the three objects. We conduct an experiment by pressing the button on the source a large number of times, and recording the results on the two detectors, noting in each case which numeral was indicated on the dial and which light had flashed on the detector. The result of one event might be recorded as 21RG, signifying that for the first detector the pointer indicated the numeral "2" and the red light flashed and that for the second detector the pointer indicated the numeral "1" and the green light flashed. After an experiment involving a great number of such events we find two results:

(1) Whenever the pointers on the dials of the two detectors indicate the same numeral the same color lights flash on the two detectors, and

(2) Ignoring the indications on the dials of the detectors, we find that R and G occur randomly, each with probability 1/2, and independently of the colour that occurs on the other detector.

Notice that the phenomena described (the results on the detectors) are macroscopic.

The example just sketched is one offered by N. David Mermin (1985) to demonstrate vividly the difficulty posed by Bell's inequality and its violation in certain quantum mechanical situations. When we open up the two black boxes, the detectors, we find that each of them contains a set of Stern-Gerlach magnets that can assume any of three different spatial orientations. As Mermin shows, when we try to give a mechanical account of the working of the entire apparatus, extraordinarily difficult problems arise. Mermin's own assessment of the problem is that those who are not worried about it have rocks in their heads.

In this paper I have tried to show that there are at least two intellectual benefits that scientific explanations can confer upon us, namely, (1) a unified world-picture and insight into how various phenomena fit into that overall scheme, and (2) knowledge of how things in the world work, that is, of the mechanisms (often hidden) that produce the phenomena we want to understand. The first of these benefits is associated with the unification view of scientific explanation; Philip Kitcher (1989) is its present principal proponent. The second is associated with the causal/mechanical view of scientific explanation that I have advocated (Salmon, 1984). My current view is that the two accounts are by no means incompatible. In the process of searching out the hidden mechanisms of nature we often find that superficially different phenomena are produced by the same basic mechanisms. To the extent that we find extremely pervasive basic mechanisms we are also revealing the unifying principles of nature. Sometimes a certain fact can be explained in either of two equally legitimate ways, that is, by subsumption under highly general principles or by exposure of underlying causal mechanisms.[3] I find no ground for claiming that one is legitimate and the other illegitimate. They complement rather than conflict with one another.

The quantum mechanical case is especially interesting. Here we have an extremely well-confirmed theory that enables us to predict the observed outcomes of experiments. Some philosophers accordingly say that we have adequate explanations because we have a unifying theory. At the same time, to the best of my knowledge, we do not have an adequate grasp of the underlying mechanisms involved. They seem utterly mysterious, so we lack a causal/mechanical explanation. The moral of the story, I think, is that there are various explanatory virtues, two of which I have discussed above. It would not surprise me to find that there are others that I have failed to mention.

In a kind and generous review of Salmon (1990) for which I am extremely grateful, Andrew Lugg raises the following provocative question regarding scientific explanation: "... one can be forgiven for wondering whether the exercise still has a clear purpose ... it is difficult to shake the impression that the debate has become amorphous, some would even say aimless. ... It is not so easy to see the need for a general philosophical account of explanation. ... In particular if the aim is — as it now seems to be — one of understanding scientific practice, why can't we get by with a perspicuous account of the multitude of ways in which scientists proceed?" (Lugg, 1991, p. 69). My answer is that the aim is not one of understanding scientific *practice* — it is the aim of understanding scientific *understanding*. Although it is obviously important to take note of the ways in which scientists proceed, we need a great deal more. Scientific explanation of what transpires in our world is a complex matter, partly because we live in a complicated world. The philosophical problem is to clarify what is meant by *scientific understanding of the world*.

Not long ago a friend who is biologist kindly gave me a copy of A.G. Cairns-Smith's *Seven Clues to the Origin of Life* (1985). The author urges consideration of the hypothesis that life actually originated from clay, and he gives a mechanistic account of how it might have happened. He does not claim it is the correct hypothesis, only that it be given serious consideration. Given my meager knowledge of biology I cannot make any judgment about the adequacy of this explanatory hypothesis. But suppose it is correct. Then I believe we would have genuine understanding of the origin of life on earth, and by virtue of evolutionary biology, an understanding of how we humans came to be. According to *Genesis*, "God the Eternal moulded man from the dust of the ground, breathing into his nostrils the breath of life; this was how man became a living thing". There are many people who derive spiritual inspiration from the *Genesis* account, and with this I have no quarrel. But for an understanding of the fact of life on earth, it seems to me that the scientific account is intellectually far more satisfactory because of its mechanical detail and because of the objective basis on which it rests. At the beginning of the present century it was thought that the search for explanation and understanding would necessarily take one outside of the domain of science, into the domain of metaphysics or theology. At the end of this century we can seriously argue that, although metaphysics and theology may serve as sources of inspiration or consolation, intellectually illuminating explanations are to be found within the realms of natural science.

University of Pittsburgh

NOTES

1. According to an old joke, one philosopher asks another, "Which is more important, the sun or the moon?" After some thought the second answers, "The moon, because it shines at night when we really need the light". According to the first chapter of *Genesis*, on the first day "God said, 'Let there be light', and there was light. God saw that the light was good, and he separated the light from the darkness; God called the light Day and the darkness he called Night... Then [on the fourth day] God said, 'Let there be great lights in the Vault of heaven to separate day from night',... God made the two great lights, the greater light to rule the day, the lesser light together with the stars to rule the night". The second philosopher can claim Biblical support for the answer.
2. Perrin does not characterize these as cases of explanation, but I see no obstacle to our regarding them as such.
3. I have offered what is to me a compelling example, it concerns the behavior of a helium-filled balloon on an airplane; see Salmon (1990, pp. 183-84).

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