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Contents

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Introduction

Science, like Janus, has two distinct aspects: an historical side and a logical or epistemological structure. It involves both a dynamic process of knowledge acquisition and the product of that process; viz., organized knowledge. The present study aims at achieving a deeper understanding of both the process and the product. It is a study in the history and philosophy of physical science.

On the historical side, we shall attempt to document one key phase in the development of the modern quantum theory. Chapter 6, a detailed account of events leading to the discovery of the meson, is entirely devoted to this subject. But earlier portions of the book (notably Chapter 1) are both logically and chronologically linked to it as well. Of necessity, the historical treatment is episodic. The history of optics, mechanics and electromagnetism since Newton is obviously beyond the scope of one slender volume. The episodes we shall emphasize, however, are deliberately chosen for their capacity to illuminate both the history *and* logic of modern physical theory. Newton's work on colors and light, Einstein's hypotheses on photoelectricity and the quantum of energy, and other subjects to be discussed all stand historically and logically behind the 20th century's conception of what physical explanation is and ought to be. We offer, then, not a comprehensive history of the quantum theory and its antecedents but, instead, a brief survey of some of the explanatory techniques of quantum and pre-quantum physics as evidenced in the actual history of these branches of science.

On the logical side, we shall attempt to evaluate critically some of the central and most widely accepted philosophical accounts of the nature of physical laws, explanations and theories. Chapter 2 (and Chapter 1, in part) emphasize and underline certain serious omissions in the well-known Deductive-Nomological model of scientific explanation. While accepting the main outlines of this model we shall try to show that it is radically incomplete and insufficient as a logical analysis of actual physical explanations.

In Chapter 3, the Hypothetico-Deductive account of scientific theories will be considered and, like the Deductive-Nomological account of explanation, found wanting. A modified and amended version of the H–D model will be sketched out—a version closer in spirit to the practice of working scientists and at the same time more faithful to the inferential patterns between theory and observation which actually obtain in quantum and pre-quantum mechanics.

Chapters 4 and 5, respectively, focus on the questions of how statistical laws function in theories like quantum mechanics and how the limits of explanation of a physical theory are to be determined. Both issues, of course, have been in the forefront of philosophical discussion of the quantum theory in recent years. They are moreover essential to a true historical understanding of the way in which the quantum theory has developed.

The central theme throughout will be the concept of "anomaly"—the concept of a fact or event which requires or demands explanation. *Our thesis, briefly put, is that both the logical structure of scientific theories and their historical evolution are organized around the identification, clarification and explanation of anomalies.* As an historical thesis this can only be defended by copious reference to the facts. As a logical thesis, however, several of its implications can be drawn out immediately by way of anticipation. For example:

(1) The conception of explanation as deriving its logical force from mere deduction of a description of the facts at hand from general laws is a drastic oversimplification. A physical explanation, we shall argue, depends implicitly on a context of assumptions against which the given fact is seen to require explanation. Contrary to the "deductivist thesis," therefore, it is not the deductive linkage which carries explanatory illumination but the *contrast* between the background context and the proffered explanatory statements. Even where the deductive connection is present it can fail to provide explanation unless the proper *logical* relations obtain between the contextual background, the description of the anomaly and the laws cited. This is not, we shall claim, a mere psychological or pragmatic point but one going to the very heart of the logic of explanation.

(2) Theories in the physical sciences, while having features in common with axiom systems of pure mathematics, will be shown to have special logical and semantic properties setting them apart. These properties arise as a result of the dual role played by theories in both *identifying* and *explaining* anomalies. To the extent that a theory is capable of locating a fact discordant with itself and then explaining that fact away the theory must not be a purely axiomatic system. If a purely axiomatic theory implies that a phenomenon p should not occur and p indeed does occur there will be no chance of explaining p via that theory. If anything, p must be counted as evidence against the theory. But as we shall subsequently show physical theories typi-

cally accomplish the task of identifying and explaining one and the same anomaly without being disconfirmed in any way.

In what follows, these points will be developed at greater length as the historical role played by anomalies in the shaping of physical theory comes under scrutiny.

1

Natural Anomalies

What makes a good scientific explanation?

The simplest answer to this question—though surely not the best—is that explaining an event consists in pointing out its cause. The word 'cause,' of course, is so ambiguous and vague that this is hardly very illuminating. But typically something fairly definite is meant when one speaks of causes in the context of scientific explanation. The idea is that some event or occurrence, antecedent to (or contemporary with) the one being explained, is to be singled out as the causal factor. Presumably, this event is singled out because of its "decisive" or "special" importance for the occurrence of the event we wish to explain. Thus, the cause of a match bursting into flames is generation of heat through friction in the striking of the flame. And the cause of an object rising on a block and tackle is the application of force at the other end of the chain.

It is extremely difficult to say what gives these particular antecedent events their "decisive" importance in the production of the effect events. In some sense, however, they are essential to the occurrence of the effect. As a first approximation we might say that they are "non-eliminable conditions within a total set of conditions jointly sufficient for producing the event."[1] For there surely are a host of other relevant factors besides the heat which ignites the match and the force which raises the weight. Provisionally, therefore, we shall assume that a cause is simply a single condition selected from a longer list of conditions because of its special relevance in producing the effect. Its elimination from the list will result in the failure of the effect to follow.

The condition identified among all relevant conditions as "the cause" of the anomalous occurrence is not uniquely determined, of course. Many factors included in a full list of the jointly sufficient set of conditions may be "essential" in the indicated sense. Thus,

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[1] Some writers regard the cause of an event as a *sufficient condition* for its production. Thus, Cohen and Nagel say: "By the *cause* of some *effect* we shall understand, therefore, some appropriate factor invariably related to the effect. If *A has diphtheria at time t* is an effect, we shall understand by its cause a certain change *C*, such that the following holds. If *C* takes place, then *A* will have diphtheria at time *t*; and this is true for all values of *A*, *C*, and *t*, where *A* is an individual of a certain type, *C* an event of a certain type, and *t* the time." Morris R. Cohen and Ernest Nagel, *An Introduction to Logic and Scientific Method* (New York: Harcourt, Brace and Co., 1934), p. 248. The only real difference between this account of causality and the one we have discussed is that it ignores the contextual conditions accompanying *C* or assumes that mention of them has been included in *C*. See also, John Hospers, *An Introduction to Philosophical Analysis* (New York: Prentice-Hall, Inc., 1953), pp. 242–45.