Imagery in Scientific Thought
Creating 20th-Century Physics

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A *Pro Scientia Viva* Title

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Preface

Throughout my research in the history of science I have been struck by the interest of many key scientists in the origins of scientific concepts and the process of creative thinking, particularly its intuitive dimension. These scientists saw apparently disparate subjects as being related because the depth of their research had led them to consider the process of thinking itself. This book explores the connection of creative scientific thinking with the origins of scientific concepts and the ways in which this connection may provide a better understanding of scientific progress. Thus my concern here is with individuals, with the detailed structure of scientific change, and not with its macrostructure.

I have chosen to study Niels Bohr, Ludwig Boltzmann, Albert Einstein, Werner Heisenberg, and Henri Poincaré. Through their work, the period 1900–1950 was one in which our customary notions of space, time, causality, and substance were transformed as never before. These philosopher-scientists were chiefly responsible for setting the intellectual milieu of the twentieth century.

I have developed the history, philosophy, psychology, and science contained herein with the goal of reaching the widest possible audience. Every effort has been made to render this book self-contained. Parts I and II contain historical case studies of Bohr, Boltzmann, Einstein, Heisenberg, and Poincaré from which emerge the philosophical-scientific currents of their times. The analyses strive to elucidate their styles of thinking, particularly their modes of mental imagery. These results are input for the cognitive psychological analyses in Part III that explore creative scientific thinking. Thus, in Part III, the history of science is used as a laboratory for cognitive psychology.

My recent book, *Albert Einstein's Special Theory of Relativity: Emergence (1905) and Early Interpretation (1905–1911)*, probed the problem of creativity for a particular case, with emphasis on scientific and philosophical aspects. I concluded that book by suggesting the need for further investigation into the imagery in Albert Einstein's thought experiments. This is among the topics developed here. Like that book, this one concludes with problems for further work. That is the manner in which my essays often end, and that is the way it should be when the history of science is defined broadly enough to be considered part of the history of ideas.

It is my hope that this book will serve as a catalyst for increasing interaction between cognitive psychologists and historians of science, so that we may amplify each other's intellectual strengths for a multidisciplinary approach to a fascinating problem in the history of ideas: creative scientific thinking.

ARTHUR I. MILLER

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Chapter 3 benefitted from Gerald Holton's perceptive comments.

For Chapter 4 I acknowledge conversations particularly with Felix Bloch, Stephen G. Brush, Abner Shimony, and Victor Weisskopf. For Chapter 5 I thank Michael Wertheimer, Lise Wertheimer Wallach, Rand Evans, S. E. Asch, Gerald Holton, Joseph Phelan, and Mrs. John Hornbostel (formerly Mrs. Max Wertheimer) for informative conversations and assistance. I gratefully acknowledge Rudolf Arnheim's insightful comments on an early version. I am particularly indebted to Mr. Valentine Wertheimer for guiding me through the Wertheimer papers on deposit at the New York Public Library.

It is a pleasure to acknowledge comments on Chapter 6 from Robert E. Innis, Jon Madian, Donald A. Norman, Herbert A. Simon, and particularly Martha Farah and Stephen M. Kosslyn for their insightful guidance through the whys and wherefores of cognitive science.

I was fortunate to have the comments of Susan Bloch and Kurt Fischer on very early drafts of Chapter 7. Through the criticisms of Howard E. Gruber, based on his deep knowledge of Jean Piaget's genetic epistemology, I was able to bring Chapter 7 into its current form.

For Gerald Holton's encouragement to extend my research into cognitive psychology I am deeply grateful. Our interactions over the years have been an inspiration to me.

This book was written in Harvard University's Department of Physics, whose hospitality I gratefully acknowledge.

For permission to quote from their archives, I thank the Jewish National and University Library, Hebrew University of Jerusalem, the Estates of Henri Poincaré and Max Wertheimer, and the Center for History of Physics of the American Institute of Physics.

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For editorial assistance I thank Mrs. Geraldine Stevens.

Author's Notes to the Reader

So as to avoid unnecessary nestings of footnotes that contain no information other than a page number, I use abbreviations of the sort "Poincaré (1903)," which means the paper listed in the Bibliography (pp. 315–338) under Poincaré and dated 1903. In Chapters 4, 6, and 7 the abbreviation AHQP appears. Quotations from *AHQP* (*Archive for History of Quantum Physics*) are taken from the interviews of Werner Heisenberg by Thomas S. Kuhn. AHQP materials are on deposit at the American Institute of Physics in New York City, the American Philosophical Society in Philadelphia, the University of California, Berkeley, and at the Niels Bohr Institute in Copenhagen.

Contents

Introduction

Laws of thought have evolved according to the same laws of evolution as the optical apparatus of the eye, the acoustic machinery of the ear and the pumping device of the heart . . . . We must not aspire to derive nature from our concepts, but must adapt the latter to the former.

L. Boltzmann (1904)

Mr. Russell will tell me no doubt that it is not a question of psychology, but of logic and epistemology; and I shall be led to answer that there is no logic and epistemology independent of psychology.

H. Poincaré (1909)

Scientific thought is a development of pre-scientific thought.

A. Einstein (1934a)

Indeed, we find ourselves here on the very path taken by Einstein of adapting our modes of perception borrowed from the sensations to the gradually deepening knowledge of the laws of Nature. The hindrances met on this path originate above all in the fact that, so to say, every word in the language refers to our ordinary perception.

N. Bohr (1928)

According to our customary intuition [we attributed to electrons the] same sort of reality as the objects of our daily world . . . . In the course of time this representation has proved to be false [because the] electron and the atom possess not any degree of direct physical reality as the objects of daily experience.

W. Heisenberg (1926b)

WHAT ARE THE ORIGINS of scientific concepts? How are scientific concepts transformed as science progresses? What is the role of mental imagery in scientific research? How do scientists invent or discover theories? Because these problems go right to the heart of the age-old inquiry of how we construct knowledge through interacting with the world we live in, they have long occupied scientists and philosophers and, more recently, historians of science and cognitive psychologists.

Here I propose a fresh approach. First the relation between creative scientific thinking and the construction of scientific concepts from prescientific knowledge is explored through historical case studies in nineteenth- and twentieth-century mathematics and physics. Then the scenarios that emerge from these analyses are examined by means of contemporary cognitive psychology so that both the role of mental imagery in the research of twentieth-century science and the dynamics of creative scientific thinking may be assessed.

Scientists whose work set the foundations of twentieth-century science have emphasized the importance that considerations of the origins of scientific concepts have had in their research. The epigraphs to this introduction indicate that this was a guiding theme for

Ludwig Boltzmann, Henri Poincaré, Albert Einstein, Niels Bohr, and Werner Heisenberg. How it came about and how it affected their scientific work is developed here.

The problem of whether scientists invent or discover theories concerns the extent of the influence of empirical data on their thinking. Einstein eloquently stated this problem in a letter of 6 January 1948 to his old friend and confidant, Michele Besso (Einstein, 1972):

> Mach's weakness, as I see it, lies in the fact that he believed more or less strongly, that science consists merely of putting experimental results in order; that is, he did not recognize the free constructive element in the creation of a concept. He thought that somehow theories arise by means of *discovery* [durch Entdeckung] and not by means of *invention* [nicht durch Erfindung]. (italics in original)

By invention Einstein meant the mind's ability to leap across what he took to be the essential abyss between perceptions and data on the one side and the creation of concepts and axioms on the other. I shall be less abrupt than Einstein by defining discovery as "putting experimental results in order" according to already existing models or mental images. This is the distinction between invention and discovery that I use in this book. Although Einstein sometimes interchanged the terms invention and discovery, he deemed invention to be the route to creative scientific thinking.

BACKGROUND

The suggestion that cognitive psychology might shed further light on the history of science has been made most notably by Jacques Hadamard (1954), Gerald Holton (1973), Thomas S. Kuhn (1962), Peter Medawar (1969), Jean Piaget (1970a), and Max Wertheimer (1959). In this book the application is actually made.

An early example of modern investigations by historians of science into the psychology of scientific discovery is Gerald Holton's article, "On Trying to Understand Scientific Genius" (1973g), in which he explores Einstein's style of thinking. Holton's assessment of most studies of scientific creativity by psychologists still holds true (see also Holton, 1978):

> What is meant by genius in science? What are its characteristics? Can one understand it, or is that a contradiction in terms? I am not speaking merely of "creative" people, nor of men of "high attainment." I am aware of the large amount of literature on creativity, and of some fine studies of men of genius in the arts or in political affairs. But I do not

> find them very helpful for understanding the life or the work of a Fermi or an Einstein, and even less for discerning how his personality and his scientific achievements interact.

For example, studies by Mahoney (1976) and Mansfield (1981) comprise results of various intelligence tests administered to scientists and students, and then of interviews and surveys concerning race, marital status, politics, education, frequency of publication, refereed reports on their work, and discussions of how and whether these results fit into scenarios proposed by Robert K. Merton, Imre Lakatos, Thomas S. Kuhn, and Sir Karl Popper. The most informative investigation based on surveys of scientists remains Roe's (1952).[1] A model for psychobiography is Manuel's (1968) work on Newton.[2] In Arieti's otherwise interesting book (1976), the discussion of scientific creativity is brief and mostly second-hand. For example, for Einstein he depends on Wertheimer's book *Productive Thinking* (1959), in which the scenarios turn out to have been reconstructed according to the Gestalt psychological theory of thinking; before I brought to light the relevant archival documents in 1974, this facet of Wertheimer's analysis was unknown (as discussed in Chapter 5). Beveridge's survey of methods of scientific research is aptly entitled *The Art of Scientific Investigation*. Although useful, the historical narrative is mostly anecdotal, there is no discussion of current theories of psychology, and no new conclusions are drawn.[3] There are serious and well-intentioned efforts to form a new discipline called the psychology of science (see Tweney, 1981), whose goal is to "investigate the cognitive mechanisms that underlie scientific thinking." In my opinion a new name is not necessary for history of science properly defined as the history of ideas. The 1945 book by the mathematician Jacques Hadamard is an informative survey of creative scientific thinking that focuses on mathematicians, particularly on Hadamard's teacher, Poincaré. Among the psychologists today who have entered seriously into the examination of scientific thinking by immersing themselves in a science is Howard E. Gruber, whose book on Darwin (1974) is a landmark study.

METHODS OF ANALYSIS

Part I is a comparative study of the origin and development of philosophical views of science that affected the direction of research in the twentieth century. Chapters 1 and 2 explore the extent of the reciprocal interactions between science and philosophy in the thinking of

Boltzmann, Einstein, and Poincaré. Besides setting straight the differences and similarities in the philosophical and scientific views of Poincaré and Einstein, Part I delineates the central role played by the style of visual thinking that was characteristic of currents in German philosophy dating back at least to Kant. From Part I we learn that Poincaré's philosophy of science affected his scientific research with little inverse reaction, for Boltzmann, that the converse was the case; and how Einstein realized the necessity for mutual interaction between philosophy and science in order to formulate a consistent physics.

The theme of visual thinking is developed further in Part II through case studies of major developments in twentieth-century physics. Chapter 3 presents a scenario of Einstein's invention of the special theory of relativity that is consistent with available archival data and both primary and secondary sources. This scenario places Einstein within the currents of philosophy, science, and electrical engineering in 1905 and shows how he drew from these disciplines a new view of physical theory. It is essential to bear in mind that Einstein's first paper on electrodynamics was initially appreciated largely for the wrong reasons, if at all. In other words, in 1905 there was no scientific revolution. Einstein worked in the Patent Office in Bern, Switzerland until 1909, when he received his first academic appointment on the basis of his research on the quantum theory of solids—not on relativity.

From Chapter 4 emerges the transformation of mental imagery required by research into a realm beyond visualization, the world of the atom. Chapter 4 traces the rise and fall of Bohr's atomic theory from 1913 to 1925, Heisenberg's invention of the quantum mechanics in 1925, the struggles of Bohr and Heisenberg during 1926 and 1927 to understand what constitutes physical reality in submicroscopic physics, and then Heisenberg's further dazzling research in the period 1926–1943, that resulted in the exchange force, the beginnings of modern nuclear physics, and quantum electrodynamics. This research of Heisenberg is conjectured to have been among the antecedents of modern-day elementary particle physics. Whereas Bohr ultimately arrived at a hybrid form of positivism—the so-called Copenhagen interpretation—Heisenberg's predilection for mathematics led him to a Platonic idealism. All these startling developments between 1913 and 1943 are related to transformations in, and abstractions of, mental imagery. Bohr and Heisenberg offer examples of how a scientist's philosophical view could be determined