HENK W. DE REGT

UNDERSTANDING SCIENTIFIC UNDERSTANDING

Understanding Scientific Understanding

OXFORD STUDIES IN PHILOSOPHY OF SCIENCE

The Book of Evidence
Peter Achinstein

Science, Truth, and Democracy
Philip Kitcher

Inconsistency, Asymmetry, and Non-Locality: A Philosophical Investigation of Classical Electrodynamics
Mathias Frisch

The Devil in the Details: Asymptotic Reasoning in Explanation, Reduction, and Emergence
Robert W. Batterman

Science and Partial Truth: A Unitary Approach to Models and Scientific Reasoning
Newton C. A. da Costa and Steven French

Inventing Temperature: Measurement and Scientific Progress
Hasok Chang

The Reign of Relativity: Philosophy in Physics 1915–1925
Thomas Ryckman

Making Things Happen: A Theory of Causal Explanation
James Woodward

Mathematics and Scientific Representation
Christopher Pincock

Simulation and Similarity: Using Models to Understand the World
Michael Weisberg

Systematicity: The Nature of Science
Paul Hoyningen-Huene

Causation and its Basis in Fundamental Physics
Douglas Kutach

Reconstructing Reality: Models, Mathematics, and Simulations
Margaret Morrison

Understanding Scientific Understanding
Henk W. de Regt

Understanding Scientific Understanding

HENK W. DE REGT

OXFORD
UNIVERSITY PRESS

OXFORD
UNIVERSITY PRESS

Oxford University Press is a department of the University of Oxford. It furthers the University's objective of excellence in research, scholarship, and education by publishing worldwide. Oxford is a registered trade mark of Oxford University Press in the UK and certain other countries.

Published in the United States of America by Oxford University Press
198 Madison Avenue, New York, NY 10016, United States of America.

CIP data is on file at the Library of Congress
ISBN 978–0–19–065291–3

9 8 7 6 5 4 3 2 1
Printed by Sheridan Books, Inc., United States of America

For Pieter and Daan

Contents

Preface

THIS BOOK HAS been long in the making. I started writing in the academic year 2009–2010, when I had the privilege to spend a year as a Lorentz Fellow at the Netherlands Institute for Advanced Study (NIAS) in Wassenaar. But it incorporates results that have been achieved over an even longer period of time. In fact, I started thinking about scientific understanding already during my PhD research at the Vrije Universiteit Amsterdam in the early 1990s, when I studied the work of Erwin Schrödinger, especially his views on visualizability as a condition for scientific theories. A few years later, after having completed my PhD thesis, Dennis Dieks encouraged me to generalize my previous work on Schrödinger and to make it the starting point of a research project on the intelligibility of theories in modern physics. This research was carried out at Utrecht University, during a three-year postdoctoral project funded by the Netherlands Organization for Scientific Research (NWO). Subsequently, I broadened the scope of my research even more in the five-year research program "Understanding Scientific Understanding," also funded by NWO and carried out at the Vrije Universiteit Amsterdam in the years 2001–2006. The aim of this program was to develop a theory of scientific understanding, a topic that had been neglected by philosophers of science. The two PhD students in this research program, Sabina Leonelli and Kai Eigner, helped to broaden the perspective by including projects on understanding in biology and psychology. This book presents my share in that program, and its case studies focus on physics. As a result of a research program that started in 2001, it is the fruit of at least fifteen years of research in philosophy of science.

The book presents the philosophical theory of scientific understanding that I have developed in the course of these years, plus some detailed historical case studies in support of this theory. My motivation for constructing it was that no such theory existed in philosophy of science. Of course, I was not the first philosopher who observed that understanding is a central aim of science, but earlier discussions of understanding turned out to be rather superficial, in the sense that they did not really address the notion of understanding itself but focused on the related notion of explanation. For example, in the preface to his seminal 1984 book *Scientific Explanation and the Causal Structure of the World*, Wesley Salmon writes that the purpose of his book is to get clear on what scientific understanding is: "Our aim is to understand scientific understanding" (p. ix). However, he immediately adds: "We secure scientific understanding by providing scientific explanations; thus our main concern will be with the nature of explanation." This is typical of the way in which scientific understanding has been treated in philosophy of science until recently. The importance of understanding was acknowledged, but its nature and structure remained unanalyzed. It has been my main goal over the last fifteen years to rectify this situation by developing a philosophical theory of scientific understanding on the basis of a thorough investigation of its role in scientific practice. I am glad to have discovered that I am not on my own but part of a more general trend, as the situation has changed in recent years, with understanding having become a focus of attention both in philosophy of science and in epistemology.

Acknowledgments

MANY PEOPLE HAVE helped and supported me over the years. First and foremost, I would like to thank my mentors and former supervisors Dennis Dieks, Hans Radder, and Peter Kirschenmann, from whom I have learned so much and who have encouraged and inspired me during various stages of my career and my research on understanding. The 2005 paper "A Contextual Theory of Scientific Understanding," in which an earlier version of my theory of understanding is presented and which forms the basis of chapter 4 of this book, was co-authored with Dennis. I owe him a great debt of gratitude for his part in the development of the contextual theory of understanding. Ever since they supervised my PhD research, Hans and Peter have had a strong influence on my thinking about science. Our countless discussions on a great variety issues in philosophy of science, and their feedback on my papers and draft chapters, have been very useful to me and I am enormously grateful to them for this. Thanks are also due to my PhD students Sabina Leonelli and Kai Eigner, who participated in my research program and have contributed to its success in important ways. Over the years, versions of chapters have been presented and discussed in our departmental research group Philosophy of Science and Technology. I thank its members—in particular Edwin Koster, Huib Looren de Jong, David Ludwig, Gerben Meynen, and Jeroen de Ridder—for their continuous interest in and feedback on my work.

I am grateful to the many colleagues with whom I have exchanged ideas about scientific understanding and related philosophical topics. I cannot mention them all but they include (in alphabetical order): Christoph Baumberger, Hein van den Berg, Soazig le Bihan, Mieke Boon, Marcel Boumans, Jeremy Butterfield, Hasok Chang, Heather Douglas, Igor Douven, Steffen Ducheyne, Dingmar van Eck, Kate Elgin, Jan Faye, Victor Gijsbers, Stephen Grimm, Sebastian de Haro, Frank Hindriks, Kareem Khalifa, Maarten Kleinhans, Theo Kuipers, Janneke van Lith, Frans van Lunteren, Caterina Marchionni, James McAllister, F. A. Muller, Wendy Parker, Arthur Petersen, Sabine Roeser, Samuel Schindler, Michael Strevens, Mauricio Suárez, Paul Teller, Jos Uffink, Erik Weber, Daniel Wilkenfeld, and René van Woudenberg.

The actual realization of the book manuscript has been made possible through the support of a number of institutions and individuals, to whom I am very grateful. First of all, the Netherlands Institute for Advanced Study (NIAS) provided an ideal environment for scholars who want to devote their time to researching and writing a book. I thank the NIAS staff and fellows of the academic year 2009–2010, and in particular Kees Ruys, who has since then become a dear friend. I am also indebted to the Netherlands Organization for Scientific Research (NWO), which provided the financial support for a large part of the research on which this book is based, and to Paul Humphreys and Peter Ohlin, Oxford University Press, for their encouragement to submit my manuscript to OUP and for their continuing support over the years. With the support of a grant from the Varieties of Understanding Project at Fordham University and the John Templeton Foundation, I was able to complete the manuscript. I thank Bas Jongeling for correcting my English, Joost van Ommen for his help with the illustrations, Paul van Acker for supplying the cover image, Andrew Ward for his assistance during the production process, Lynn Childress for editing the manuscript, and two anonymous reviewers for comments on previous versions of the text.

Finally, my warmest thanks go to those who are closest and most important to me, and who encouraged and supported me unfailingly in the long process of writing this book: my sons Pieter and Daan, and above all my wife and companion in life Martien Rienstra.

THIS BOOK DRAWS in part on material that has been published in the following journal articles: "Visualization as a tool for understanding," *Perspectives on Science* 22 (2014): 377–396; "The epistemic value of understanding," *Philosophy of Science* 76 (2009): 585–597; "Wesley Salmon's complementarity thesis: Causalism and unificationism reconciled?" *International Studies in the Philosophy of Science* 20 (2006): 129–147; "A contextual approach to scientific understanding," *Synthese* 144 (2005): 137–170 (with Dennis Dieks); "Discussion note: Making sense of understanding," *Philosophy of Science* 71 (2004): 98–109; "Space-time visualisation and the intelligibility of physical theories," *Studies in History and Philosophy of Modern Physics* 32B (2001): 243–265; "Ludwig Boltzmann's *Bildtheorie* and scientific understanding," *Synthese* 119 (1999): 113–134; "Erwin Schrödinger, *Anschaulichkeit*, and quantum theory," *Studies in History and Philosophy of Modern Physics* 28B (1997): 461–481; "Philosophy and the kinetic theory of gases," *British Journal for the Philosophy of Science* 47 (1996): 31–62.

Understanding Scientific Understanding

1

Introduction

THE DESIRE TO UNDERSTAND

The act of understanding is at the heart of all scientific activity; without it any ostensibly scientific activity is as sterile as that of a high school student substituting numbers into a formula.

—P. W. BRIDGMAN, *Reflections of a Physicist* (1950, 72)

IT MIGHT SEEM a commonplace to say that the aim of science is to provide understanding of the world around us. Scientists and laypeople alike will typically regard understanding as one of the most important and highly valued products of scientific research and teaching. Indeed, science appears to be quite successful in achieving this aim: Who would doubt that science has given us understanding of such diverse phenomena as the motions of the heavenly bodies, the tides, the weather, earthquakes, the formation of rocks and fossils, electricity and magnetism, and the evolution of species? Climate scientists, who strive to understand the process of global warming and other climate changes, provide a contemporary example of the centrality of understanding as an aim of science. The main task of the Intergovernmental Panel on Climate Change (IPCC) is to assess progress in scientific understanding of the climate system and climate change, as can be gleaned from its 2007 report. In the one-page introduction of the technical summary of *Climate Change 2007: The Physical Science Basis* (IPCC 2012), the terms "understand" or "understanding" are used nine times. Here is a typical passage:

> While this report provides new and important policy-relevant information on the *scientific understanding* of climate change, the complexity of the climate system and the multiple interactions that determine its behaviour impose limitations on our ability to *understand* fully the

> future course of Earth's global climate. There is still an incomplete *physical understanding* of many components of the climate system and their role in climate change. (IPCC 2012; italics added)

But what does it mean to seek or to achieve such understanding? What exactly is scientific understanding? This is the question that this book aspires to answer. It is first and foremost a philosophical question, and one that has indeed been addressed by philosophers of science in the context of the long-standing debate about scientific explanation. Wesley Salmon, one of the key figures in this debate, spent the greater part of his career developing a philosophical account of scientific explanation. As he emphasized in his essay "The importance of scientific understanding" (1998, 79–91), the principal goal of scientific explanation is the production of understanding of events and phenomena. Salmon's own theory, which will be discussed in detail in chapter 3, focuses on causal explanations, highlighting the fact that understanding is often achieved by uncovering the causes of phenomena. While there are alternative philosophical views of how scientific understanding is attained through scientific explanations, most philosophers agree on the idea that understanding—whatever its precise nature—is a central aim of science.[1]

The question of the nature of scientific understanding is also a historical question: to answer it we can do no better than look at how scientific research has actually produced understanding in the course of its historical development. Indeed, science as a historical phenomenon may be defined with reference to the notion of understanding: it is traditionally presumed that science was born in ancient Greece, when Ionian philosophers of nature—in particular Thales of Miletus and his school—first adopted what may be called a naturalistic approach to explaining natural phenomena: they abandoned the idea that nature is subject to the capricious will of supernatural gods and thereby beyond human comprehension, and instead assumed that observed phenomena can be understood in terms of natural causes and laws. This important change in the attitude toward nature has been emphasized, for instance, by the physicist Erwin Schrödinger. In his 1948 Shearman Lectures, delivered at University College, London, which were later published under the title *Nature and the Greeks*, he stated:

1. Note that the term "understanding" can be used in various ways, both in and outside science. I am specifically concerned with *explanatory understanding*: the understanding of why a phenomenon occurs that results from a scientific explanation of that phenomenon. Other types of understanding, such as objectual understanding, understanding-how and understanding-that, will not be discussed in this book. See Baumberger et al. (2017) for an overview of notions of understanding in epistemology and philosophy of science.

> The grand idea that informed these men was that the world around them was something *that could* be *understood*, if one only took the trouble to observe it properly. . . . They saw the world as a rather complicated mechanism, acting according to eternal innate laws, which they were curious to find out. This is, of course, the fundamental attitude of science up to this day. (Schrödinger [1954] 1996, 57)

The prospect of understanding forms the basis of most—if not all—Greek natural philosophy since Thales. It is, for example, fundamental to Aristotle's philosophical work. "All men by nature desire to know," reads the famous opening sentence of his *Metaphysics* in the well-known translation by W. D. Ross. In his introduction to Aristotle's philosophy, however, Jonathan Lear argues that Aristotle's words are better interpreted as referring to a desire to understand: "To have *epistēmē* one must not only know a thing, one must also grasp its cause or explanation. This is to understand it: to know in a deep sense what it is and how it has come to be" (Lear 1988, 6). It was therefore the idea that humans can understand nature that sparked the development of science.

1.1 Scientific understanding: diversity and disagreement

My aim in this book is to investigate and explicate the nature of the understanding that science can provide. A first question that may be asked in this context is: Are there universal, timeless criteria for scientific understanding? Even a cursory look at the history of science suggests that the answer is: no. As a first illustration, I will sketch an episode from the history of physics in which discussions about understanding played a crucial role: the genesis of quantum mechanics in the 1920s, which involved heated debates about the intelligibility of this theory and the related question of whether it can provide understanding of the phenomena in the domain of atomic physics. This case shows that scientists' standards of intelligibility and understanding vary strongly—not only diachronically but also synchronically. (The episode will be analyzed in detail in chapter 7; more historical evidence for the thesis that criteria for understanding vary will be given in chapters 5 and 6).

The first quantum theory of atomic structure was developed by Niels Bohr, who presented it in his famous papers of 1913 and 1918. It included an atomic model that was problematic in various respects—both empirically and conceptually—and in the early 1920s many physicists attempted to improve Bohr's theory. After a number of years when not much progress was made, two new, rival quantum theories of the atom appeared on the scene: in July 1925 Werner Heisenberg submitted a paper which contained the foundations of matrix mechanics, and in early 1926 Erwin Schrödinger published a series of papers in which he presented wave mechanics as an alternative to matrix mechanics. Heisenberg's theory was intended to describe only relations between observable quantities, such as the frequencies and intensities of spectral lines emitted by atoms; it did not provide a concrete picture or model of the internal structure of atoms. Thus, it was a highly abstract theory which, moreover, was based on a type of mathematics—matrix theory—that most physicists were unfamiliar with at the time. Schrödinger's wave mechanics, by contrast, suggested the possibility of a visualizing atomic structure: his theory described the atom in terms of wave phenomena. Also, the mathematics of his theory was simpler and more familiar to physicists than that of matrix mechanics: it was based on wave equations, which were part and parcel of university physics teaching.

Immediately, proponents of the two theories engaged in intense, sometimes even emotional discussions on the question of which theory was superior. It was Schrödinger who brought the notions of understanding and intelligibility to the center of the debate, claiming that his wave mechanics was much better in providing true understanding of the phenomena, over and above mere description and prediction. Schrödinger expressed a strong commitment to the view that visualization is a necessary condition for scientific understanding: "We cannot really alter our manner of thinking in space and time, and what we cannot comprehend within it we cannot understand at all" (Schrödinger 1928, 27). Accordingly, he argued, only theories that are visualizable in space and time are intelligible and can give us understanding of phenomena. Schrödinger was not alone in this respect: many physicists supported the idea that understanding requires visualization and space-time description. Therefore, according to Schrödinger, visualizability is a necessary condition for the intelligibility of a scientific theory. Wave mechanics is visualizable (or so Schrödinger suggested) and thereby intelligible; matrix mechanics, by contrast, is not visualizable, and accordingly unintelligible. This was not merely a philosophical point: Schrödinger also argued that visualizable, intelligible theories are more fruitful. Because of its visualizability and its mathematical structure, wave mechanics was more easily applicable to a great variety of physical problem situations. It was therefore more favorably received and—at least initially—empirically more successful than matrix mechanics.

The advocates of matrix mechanics maintained, however, that their theory could yield understanding as well, and they tried to refute Schrödinger's line of reasoning by arguing that intelligibility is not necessarily associated with visualizability. Wolfgang Pauli, who like Heisenberg was a member of Bohr's group, admitted that matrix mechanics was an unusual theory that might indeed appear less intelligible than wave mechanics. However, he claimed that understanding it was a question of becoming familiar with the new conceptual system of the theory. Pauli admitted that the demand for intelligibility is legitimate, but he stated: "It should never count in physics as an argument for the retention of fixed conceptual systems. Once the new conceptual systems are settled, they will also be intelligible" (Pauli 1979, 188). In other words, when future generations of physicists are used to quantum mechanics, they will find it intelligible even though it is not visualizable.

The competition between the two theories ultimately led to their synthesis. On the one hand, Schrödinger's hope for a visualizable interpretation of quantum mechanics was not fulfilled: his atomic model turned out not to be completely visualizable due to specific technical problems (see section 7.3). Heisenberg, on the other hand, abandoned his radically abstract approach and reintroduced visualizable notions, such as position and momentum of electrons, at the atomic level. The combination of matrix and wave mechanics led to quantum mechanics as it is accepted and taught today. With hindsight, it is clear that Schrödinger's thesis that visualizability is a necessary condition for intelligibility must be rejected—there is no a priori relation between understanding and visualization. Still, it does not follow that his ideas were completely misguided and worthless. History only shows that standards of intelligibility and understanding may vary and change. Moreover, as will be argued in more detail in chapter 7, the history of quantum mechanics shows that debates about understanding and intelligibility often stimulate scientific development.

Almost every physicist will agree that understanding is a key aim of science, but there appears to be strong variation in views about what is required for such understanding. The case of quantum theory illustrates this nicely. Even today physicists and philosophers debate the question of whether—and if so, how—quantum mechanics can provide understanding (the many different interpretations of the theory can be seen in this light). Of course, one might think that quantum theory is an exceptional case, being an esoteric, counterintuitive theory that applies to a remote domain of reality. Thus, Richard Feynman famously stated that nobody understands quantum mechanics. Of atomic behavior he said: "Even the experts do not understand it the way they would like to, and it is perfectly reasonable that they should not, because all of direct, human experience and of human intuition applies to large objects" (Feynman et al. 1963–1965, 3:1–1). While quantum theory surely is a strange theory, the fact that scientists disagree about its intelligibility is not exceptional: as the other case studies in this book will show, the history of physics abounds with debates about the intelligibility of theories and criteria for scientific understanding.

1.2 Integrating history and philosophy of scientific understanding

It was the observation of historical controversies such as the one sketched in section 1.1, and the failure of existing philosophical theories of explanation and understanding to deal with them, that inspired the study that has resulted in this book. The problem appears to be that traditional philosophical accounts of explanation are typically uninformed by historical and empirical studies of science. The debate about explanation in the philosophy of science is—notwithstanding the rejection of Carl Hempel's covering law model—still very much in line with the logical empiricist tradition, with the consequence that (1) philosophical analyses of scientific explanation ignore the variation among (past and present) scientists' views of how explanatory understanding is achieved; and (2) while paying lip service to the idea that good scientific explanations produce understanding, they regard the notions of understanding and intelligibility as philosophically irrelevant and accordingly neglect debates about understanding in actual scientific practice (see chapters 2 and 3).

This book presents a philosophical theory of scientific understanding that sheds light on episodes like the one I have sketched. It is a philosophical study but it also contains detailed historical case studies of scientific practice. In contrast to existing philosophical studies of the topic, it takes into account scientists' own views about explanation and understanding and analyzes their role in scientific debate and development. The aim of the book is to develop and defend a theory of understanding that describes criteria for understanding actually employed in scientific practice and explains their function and historical variation.

The way in which this study approaches its subject differs fundamentally from mainstream philosophical discussions of explanatory understanding (which are scarcely informed by historical and empirical studies of science). Combining systematic philosophical analysis with historical case studies, the book stands in the tradition of history and philosophy of science (HPS). The HPS tradition has its roots in the early 1960s, when scholars like Norwood Russell Hanson, Stephen Toulmin, Paul Feyerabend, and Thomas Kuhn based their philosophical analyses of science on serious study of the history of science. Despite the enormous impact of Kuhn's work, the idea of combining historical and philosophical study of science into a single discipline, HPS, was not without difficulties, and from the 1980s onward it appeared that historians and philosophers were parting ways again. In recent years, however, the ideal of HPS has been revived and currently new attempts are being made to flesh it out and develop it into truly integrated history and philosophy of science.[2]

A serious problem for the HPS approach was, and still is, the question of how historical studies of science can be used to bolster a philosophical claim about science. This problem has been pinpointed by Joseph Pitt as "the dilemma of case studies":

> What do appeals to case studies accomplish? Consider the dilemma: On the one hand, if the case is selected because it exemplifies the philosophical point, then it is not clear that the historical data hasn't been manipulated to fit the point. On the other hand, if one starts with a case study, it is not clear where to go from there—for it is unreasonable to generalize from one case or even two or three. (Pitt 2001, 373)

In other words, the philosopher who uses case studies is either guilty of "cherry-picking" or of overgeneralization. A skeptical reader might think that my study of scientific understanding cannot but fall prey to this dilemma, since this book presents a philosophical theory of scientific understanding plus a number of historical case studies, suggesting that the theory has been developed on the basis of the historical material and that the case studies exemplify the theory.

This worry is unfounded, however, because Pitt's dilemma rests on a misguided view of the relation between philosophy and history of science. It assumes what Jutta Schickore (2011) calls the "confrontational model of HPS," on which philosophical theories of science have to be confronted with historical data. Much scholarly work in the HPS tradition (such as that of Imre Lakatos and his followers, and that of Larry Laudan) was based on this model, and this is understandable, because a key motivation for starting HPS was the idea that at the time philosophy of science (in particular, logical empiricism) was out of touch with real science. The idea was to "test" philosophical theories of science against the historical record. While there is nothing wrong

---

2. Since 2007 international conferences on integrated history and philosophy of science are being organized under the acronym & *HPS*. See Schickore (2011) and Mauskopf and Schmaltz (2012) for reviews of the long-standing debate about integrating history and philosophy of science, and for assessments of the current state of the art in HPS.

with this motivation—indeed, I believe that philosophy of science should take account of the actual practices of past and present science—there are serious difficulties with the simple confrontational model. The main source of problems is that the model conceives the relation between philosophy and history of science in terms of the relation between theory and data, comparable to the theory-data relation in the sciences themselves. It assumes that philosophers want to/can/should make general claims about the nature of science, while historians merely want to/can/should describe specific historical episodes.

This simple view of philosophical and historical study of science is untenable because, on the one hand, universal philosophical theories of science are bound to fail, and, on the other hand, purely theory-neutral descriptions of historical episodes are impossible.[3] The former point follows from the fact that science, as a historical entity, is subject to change: not only is our current scientific knowledge different from that of, say, one or two centuries ago, our idea of what science is, what its methods are, and so on has also altered in the course of the centuries. Thus, a universal (static) philosophical account of the nature of science for all times is a chimera.[4] The latter point follows from the fact that it is impossible to write history of science without at least some philosophical conceptions about the nature of science. Any historical study of an episode in the history of science must assume, first of all, some idea of what science is in order to select relevant historical data, and furthermore, employ more specific philosophical notions (e.g., regarding the nature of scientific theory, observation, experiment, explanation, etc.) in order to interpret the data and construct a coherent narrative out of them.

These observations suggest that a different model of HPS is needed, one that truly integrates history and philosophy instead of merely confronting them. If it is acknowledged that philosophical analysis and historical study of science have to be inextricably intertwined, an integrated HPS will emerge that results in the dissolution of Pitt's dilemma. This study of scientific understanding aspires to exemplify such an integrated approach.

Several scholars have attempted to formulate an integrated HPS approach that transcends the confrontational model. Schickore argues that the study of

---

3. These problems echo problems at the level of science itself, in particular, problems of induction and theory-ladenness of observation. But they are even more troublesome at the meta-level because every historical case is unique and historical study always involves interpretation.

4. This would also apply to a universal philosophical theory of science that ignores differences between scientific disciplines. Just as the nature of science varies throughout history, it varies across disciplines.

science (for which she uses the term "metascientific analysis") should adopt a hermeneutic approach: "Initial case judgments—judgments that identify portions of the historical record as noteworthy—and provisional analytic concepts are gradually reconciled until they are brought into equilibrium" (Schickore 2011, 471). Thus, philosophical analysis and historical research should continuously and mutually interact. Applied to the topic of this book, this approach implies starting with a particular historical episode selected on the basis of our initial view of scientific understanding, and then investigating this case using our preliminary philosophical conceptions of understanding, explanation, intelligibility, etc., as tools for analysis and interpretation. The attempt to construct a coherent narrative may require articulation or modification of the employed philosophical concepts, which can subsequently be applied in other historical case studies. While it is not to be expected that this process converges on a universally valid philosophical conception of scientific understanding, it will most likely generate conceptual tools that are useful for analyzing and interpreting a range of cases of (past and present) scientific practice.

Although he does not use the term "hermeneutic," a comparable approach is defended by Chang (2012), who proposes the following "mode of history-philosophy interaction" as a possible method for integrated HPS:

Existing philosophical framework

- Historiographical puzzle: an episode that is difficult to understand
- Search for a new philosophical framework
- Better understanding of the episode, in the new philosophical framework
- Further development of the new philosophical framework
- Application of the new framework to other episodes

(Chang 2012, 121)[5]

Note that where Schickore designates philosophical concepts as "tools," Chang uses the term "framework," which suggests that philosophy is more than just a resource for writing history of science. I agree with the latter view: philosophy of science can make substantive claims about science that transcend the particular, without immediately lapsing into universalism. This important aim of philosophy has been aptly characterized by Hans Radder (1997, 649) as "exposing and examining structural features that *explain or make sense of non-local patterns* in the development of science." The philosophical theory

5. Alternatively, one may start from existing historiography and a philosophical puzzle; see Chang (2012, 122).

of scientific understanding presented in this book should be regarded as a framework that elucidates such non-local patterns.

The research on which my theory is based has roughly followed Chang's procedure, and accordingly also exemplifies the hermeneutic approach advocated by Schickore. I started with the historical episode summarized section 1.1: the genesis of quantum mechanics in the 1920s (in which I had become interested for different reasons). The observation that physicists like Schrödinger, Pauli, and Heisenberg debated whether the various proposed quantum theories were intelligible, what the criteria for intelligibility were, and in what sense, if any, quantum mechanics could provide understanding of the phenomena, was hard to interpret in terms of the framework of traditional philosophy of science, which deemed these issues uninteresting and even irrelevant from an epistemological perspective. Standard philosophical models of scientific explanation largely ignore historical studies of science. But a look at the history of quantum mechanics reveals a "historiographical puzzle for the existing philosophical framework": philosophical questions about explanatory understanding that the historical actors considered highly important and that affected the development of atomic physics in the 1920s, were invisible from the perspective of the traditional philosophy of scientific explanation.

A detailed analysis of the historical episode inspired me to develop a new interpretation of the concept of "intelligibility," which helped me to better understand the historical case (for my first attempt at analyzing the case with the notion of intelligibility, see De Regt 2001). Through an iterative process of further developing the philosophical tools, and applying them to other examples from the practice and history of science, I have developed—in collaboration with Dennis Dieks—a contextual theory of understanding (De Regt and Dieks 2005). Additional historical case studies and systematic inquiry led to further articulation and refinement, but also to substantial modifications, of this theory. This book is the end result of this process, presenting a philosophical framework for the analysis of scientific understanding and a number of case studies using this framework. For the sake of clarity, the philosophical theory is presented first (in chapters 2–4) and the historical case studies are described next (in chapters 5–7). Obviously, this order does not follow the way the study was carried out, and neither does it reflect the justificatory relation between the historical and philosophical aspects. Moreover, chapters 2–4 do present historical examples as well, and chapters 5–7 contain further discussion and articulation of the philosophical framework.

My theory of scientific understanding is a contextual theory because historical studies show that there are no universally valid, timeless standards of explanatory understanding. Nonetheless, the theory does specify a general characterization and criteria for achieving scientific understanding, so that one might ask whether this is consistent with the thesis that conceptions of understanding vary throughout history (and across disciplines). However, there is no contradiction. As long as the general characterization and criteria for understanding include elements that allow for historical and disciplinary variation, it is perfectly well possible to formulate an account that transcends the purely local context (see chapter 4 for further elucidation of the contextuality). It is plausible that, in addition to historical variation, there is also disciplinary variation in concepts and criteria of understanding. The present study focuses on the physical sciences, and the case studies in chapters 5–7 deal with the history of physics only. I submit, however, that the proposed account of understanding may be applicable to the natural sciences more generally, and I present some examples from other sciences to illustrate this claim. But further research should reveal to what extent the theory possesses a wider validity.

Although the empirical evidence on which my philosophical theory is based is first and foremost historical, I will also refer to results from cognitive science and psychology in support of my arguments. Thus, my approach may be regarded as "naturalistic" in the sense that it is based on the idea that philosophy of science should take into account results of empirical studies of science, of which history of science is but one example: sociology and psychology of science may be relevant as well.[6] While I consider empirical findings like these highly relevant for developing a sound philosophical account of explanation, I do not endorse a thoroughly naturalistic position in the spirit of Quine, who championed a complete reduction of philosophy to empirical science. In my view, there should be room for conceptual analysis. Moreover, if the naturalistic approach is conceived as the idea that "the study of science must itself be a science" (Giere 1999, 173), I agree only if it is kept in mind that it is a human science, not a natural science. Accordingly, its methods may differ from those of natural science, as the hermeneutic approach for HPS outlined by Schickore (2011) illustrates.[7]

6. For instance, a recent experimental study into the way in which scientists and laypeople classify various cases of explanations confirms the central thesis of this book: intelligibility is crucial for scientific explanation (Waskan et al. 2014).

7. Cf. Radder (1997), who acknowledges that historical study is an important resource for the philosophy of science, but criticizes fully naturalistic approaches and instead promotes the idea that philosophy cannot do without interpretation, normative assessment, and reflexivity.

1.3 Overview

The book begins with an argument against the traditional view—due to Hempel—that understanding is merely a psychological and subjective by-product of explanation, and therefore irrelevant for philosophical analyses of science. In chapter 2, I argue that, by contrast, achieving understanding of phenomena is a central epistemic aim of science. I introduce the notion of intelligibility, defined as the value that scientists attribute to the cluster of qualities that facilitate the use of the theory, and show that it is essential for achieving understanding. Note that on this definition the epithet "intelligible" applies to theories, not to phenomena.[8] Intelligibility is a pragmatic value, but I argue that this does not undermine the objectivity of scientific explanation and understanding. Chapter 3 investigates what existing theories of explanation—such as causal and unificationist models—assert or imply about the nature of understanding. On the basis of a discussion of the merits and problems of these models, I conclude that we have to accept a plurality of types of explanation, and that an overarching theory is needed that explains how each type generates understanding. Wesley Salmon has suggested that causal and unificationist models can be reconciled as complementary ways of achieving understanding, but a critical analysis of his proposal shows that this attempt fails. Instead, a more radically pluralist approach is required. In chapter 4, a contextual theory of scientific understanding is presented, which answers this demand: it accommodates the diversity of types of explanation by showing how various explanatory strategies function as alternative tools to achieve the goal of understanding. It is based on the idea that understanding of phenomena requires intelligible theories, and that scientists need conceptual tools and associated skills to use a particular theory in order to achieve understanding of the phenomena. The availability and acceptability of conceptual tools can change with the historical, social, or disciplinary context. The chapter closes with a discussion of the implications of the theory for the issues of reductionism and scientific realism.

The second half of the book offers historical case studies that highlight various aspects of the issue of understanding. Chapter 5 focuses on the relation

8. Accordingly, to avoid confusion, I will use the terms "intelligibility" and "intelligible" only in connection with the understanding of theories (in quotations, however, these terms sometimes apply to phenomena). The relation between understanding theories and understanding phenomena is crucial to my account of scientific understanding (see section 2.1).

between metaphysical worldviews and scientific understanding. It examines the seventeenth-century debate about the intelligibility of Newton's theory of universal gravitation, and the subsequent development of physicists' views on contact action versus action at a distance in the eighteenth and nineteenth centuries. This case nicely illustrates how criteria for understanding may change in time. Initially, Newton's theory was criticized because it failed to conform to the Cartesian intelligibility ideal of contact action; the idea of forces acting at a distance was unacceptable to most seventeenth-century physicists. But between 1700 and 1850 action at a distance rather than contact action and causal chains dominated the scientific scene, and attempts to formulate theories of gravitation based on contact action were ignored. Only in the second half of the nineteenth century did contact action again become an acceptable explanatory resource. I analyze this episode with the help of a distinction between metaphysical and scientific intelligibility. Chapter 6 examines how mechanical models can provide understanding, by means of a detailed study of the period when mechanical modeling was most prominent in physical science: the nineteenth century. I survey the work and ideas of key representatives of the mechanical approach in physics: William Thomson (Lord Kelvin), James Clerk Maxwell, and Ludwig Boltzmann. These physicists advanced explicit views of the function and status of mechanical models, in particular of their role in providing understanding. Thus, Kelvin famously wrote: "I never satisfy myself until I can make a mechanical model of a thing. If I can make a mechanical model I can understand it" (Kargon and Achinstein 1987, 206). I investigate how such views affected scientific practice, in particular, via a case study of attempts to explain the so-called specific heat anomaly with the help of the kinetic theory of gases. Finally, I examine Boltzmann's mature views on the status and value of mechanical models, specifically his "picture theory" (*Bildtheorie*), which involves a pragmatic conception of understanding that accords with the contextual theory of scientific understanding defended in this book. Chapter 7 discusses the relation between visualizability and intelligibility by means of an in-depth study of the episode that I have briefly discussed: the transition from classical physics to quantum physics in the first quarter of the twentieth century. Focusing on the views and contributions of Niels Bohr, Wolfgang Pauli, Werner Heisenberg, and Erwin Schrödinger, I analyze the debate on the intelligibility of matrix mechanics and wave mechanics. The relation between visualization and understanding is further illustrated by an account of the discovery of electron spin in 1926, and by an exploration of the role of visualization in postwar quantum physics, focusing on the introduction of Feynman diagrams. I conclude that visualizability is but one out of many possible tools for understanding, albeit one that has proved to be very effective in science. Chapter 8 concludes the book with a discussion of the scope of my contextual theory and a reflection on the issues of relativism and normativity.

2

Understanding and the Aims of Science

IN *NATURE AND THE GREEKS,* Schrödinger argues that science is "something special": it is a Greek invention, based on the Greek way of thinking, and it is accordingly, "not the only possible way of thinking about Nature." Subsequently, he asks himself: "What are the peculiar, special traits of our scientific world-picture?" and immediately answers this question as follows:

> About one of these fundamental features there can be no doubt. It is the hypothesis that *the display of Nature can be understood.* . . . It is the non-spiritistic, the non-superstitious, the non-magical outlook. A lot more could be said about it. One would in this context have to discuss the questions: what does comprehensibility really mean, and in what sense, if any, does science give explanations? (Schrödinger [1954] 1996, 90–91)

Schrödinger then observes that philosophers from Hume to Mach to the logical positivists failed to give positive answers to these questions. On the contrary, they argued that scientific theories are merely economical descriptions of observable facts, which do not supply explanations. This view, which was endorsed by most of Schrödinger's physicist colleagues, seems to lead to a strange tension: the basic hypothesis of science, that Nature is understandable, does not seem to have any positive content—it consists merely in a denial of supernatural, nonscientific worldviews.

However, this situation would change very soon: with hindsight, one can say that the year when Schrödinger presented his ideas in his lectures at University College, London, was a turning point in the philosophical attitude toward explanation in science. For it was in 1948 that Carl Hempel and

Paul Oppenheim put the topic of explanation on the philosophical agenda, with their pioneering paper "Studies in the Logic of Scientific Explanation" (reprinted in Hempel 1965). But Hempel, whose covering law model of explanation was to dominate the debate for the next two decades, was still reluctant to talk about understanding. The reason was, as he explained in his 1965 essay "Aspects of Scientific Explanation," that "such expressions as 'realm of understanding' and 'comprehensible' do not belong to the vocabulary of logic, for they refer to the psychological and pragmatic aspects of explanation" (Hempel 1965, 413). In Hempel's logical-empiricist view, the aim of philosophy of science is to give an account of the objective nature of science by means of logical analysis of its concepts. Its psychological and pragmatic aspects may be of interest to historians, sociologists, and psychologists of science (in short, to those who study the phenomenon of science empirically) but should be ignored by philosophers. Since Hempel, philosophers of science have gradually become more willing to discuss the topic of scientific understanding, but it has remained outside the focus of philosophical attention until quite recently.

In this chapter, I will argue—against the traditional view of Hempel and others—that understanding is not merely a psychological byproduct of explanation but in itself a central epistemic aim of science. First, in section 2.1, I investigate in more detail why the notion of understanding has long been neglected by philosophers of science, and I discuss philosophical views that deny an epistemic role to understanding in science. Subsequently, in section 2.2, I challenge these views by arguing that understanding is indeed pragmatic but nonetheless crucial for achieving the epistemic aim of scientific explanation. This thesis is further elaborated in section 2.3, where I analyze pragmatic understanding in terms of the notion of intelligibility and examine the implications for the objectivity of scientific explanation and understanding. Finally, in section 2.4, I argue that understanding is both a means to, and an end of, explanation.

2.1 The neglect of understanding

Why was the theme of scientific understanding ignored by philosophers of science, while the period since World War II witnessed ample discussion of scientific explanation? The debate about explanation started in the logical empiricist tradition, which regarded logical analysis and reconstruction of the finished products of scientific activity as the chief task of philosophy of science. The aim of such reconstructions was to assess the validity of scientific claims to knowledge, and the central logical-empiricist thesis was that only empirical evidence and logic are relevant to the justification of knowledge. Logical empiricism came under serious attack in the early 1960s, but whereas it lost the battle in the domain of scientific methodology (under the influence of Popper and Kuhn and their followers) it has remained dominant in the area of scientific explanation. Although many philosophers of explanation criticized Hempel's covering law model in the 1960s and 1970s, most analyses did not depart radically from the logical-empiricist viewpoint but continued in the same spirit. One aspect of the logical-empiricist philosophy of explanation, voiced explicitly by Hempel, is that understanding and related notions such as intelligibility and comprehensibility lie outside its domain. To be sure, Hempel recognized that there is a relation between explanation and understanding, but he argued that philosophers may—or rather should—ignore the latter because these notions are not logical but psychological and pragmatic. Hempel (1965, 425–433) claimed that understanding belongs to the pragmatic dimension of science, which is irrelevant to the philosophical analysis of science. To begin with, he observed that there exists a pragmatic interpretation of explanation, which surfaces if one conceives of explanation as an activity that has understanding as its goal:

> Very broadly speaking, to explain something to a person is to make it plain and intelligible to him, to make him understand it. Thus construed, the word "explanation" and its cognates are pragmatic terms: their use requires reference to the persons involved in the process of explaining. In a pragmatic context we might say, for example, that a given account *A* explains fact X to person P_1. We will then have to bear in mind that the same account may well not constitute an explanation of X for another person P_2, who might not even regard X as requiring an explanation, or who might find the account A unintelligible or unilluminating, or irrelevant to what puzzles him about X. Explanation in this pragmatic sense is thus a relative notion: something can be significantly said to constitute an explanation in this sense only for this or that individual. (Hempel 1965, 425–426)

The notions of understanding and intelligibility are pragmatic because they refer to human subjects: the persons (e.g., scientists) who offer or receive the explanatory account. According to Hempel, a pragmatic conception of explanation which includes these notions may perhaps be of interest to empirical scientists, such as psychologists or historians of science, but it is irrelevant to the philosophy of science. In line with logical-empiricist tenets, he held that philosophers of science should occupy themselves only with analysis and assessment of scientific statements (e.g., theories) and their relation to the empirical evidence. The hallmark of scientific knowledge is, in Hempel's view, its objectivity: "proper scientific inquiry and its results may be said to be objective in the sense of being independent of idiosyncratic beliefs and attitudes on the part of the scientific investigators" (Hempel [1983] 2001, 374). Accordingly, philosophical analyses and evaluations of science—for example, of scientific explanation—should uncover the objective relations between theory and evidence, and should therefore abstract from pragmatic issues:

> For scientific research seeks to account for empirical phenomena by means of laws and theories which are objective in the sense that their empirical implications and their evidential support are independent of what particular individuals happen to test or to apply them; and the explanations, as well as the predictions, based upon such laws and theories are meant to be objective in an analogous sense. This ideal intent suggests the problem of constructing a non-pragmatic concept of scientific explanation. (Hempel 1965, 426)

An objectivist account of scientific explanation should avoid pragmatic aspects, such as understanding and intelligibility because these are relative and subjective: whether or not a proposed explanation is intelligible and provides understanding may vary from person to person and has no implications for its objective validity, or so Hempel argues.[1] It should be noted that sometimes Hempel refers to understanding in a positive way, but then he gives a very different interpretation of the term. When he refers to "scientific understanding" or "theoretical understanding," he means an objective feature associated with scientific explanation in the nomological sense. For example, Hempel (1965, 488) writes that the understanding conveyed by scientific explanation "lies rather in the insight that the explanandum fits into, or can be subsumed under, a system of uniformities represented by empirical laws or theoretical principles," and that "all scientific explanation . . . seeks to provide a systematic understanding of empirical phenomena by showing that they fit into a nomic nexus" (see section 3.1 for further discussion). In sum, Hempel's insistence on excluding pragmatic aspects—among which are considerations regarding understanding and intelligibility—from a philosophical theory of scientific explanation was motivated by his fear that they would

1. Cf. Hempel's (1966, 41) insistence on an objective criterion of simplicity, which does not refer to "intuitive appeal or ease with which a hypothesis or theory can be understood or remembered."