# REPRESENTING ELECTRONS

## A Biographical Approach to Theoretical Entities

**Theodore Arabatzis**

The University of Chicago Press
Chicago and London

# Contents

# Introduction

This book reconstructs some aspects of the historical development of the representation of the electron from the late nineteenth century till the mid-1920s, addressing explicitly the historiographical and philosophical issues involved in such a project. The aim of the book indicates the need for an interaction between the history and philosophy of science. The very idea of structuring a historical narrative around the representation of the electron spawns pressing philosophical questions. In the philosophical literature the electron is usually portrayed as the paradigm of an unobservable entity. For those who disbelieve in the existence of unobservable entities, and ipso facto of the electron, a historical project devoted to its representation might seem vacuous, an attempt to write the history of a theoretical entity which has no real counterpart in nature.[1] Furthermore, in telling the story of the electron's representation one has to tackle the issue of the electron's identity over time. The representation in question was an evolving entity, and it could be argued that the scientists who used the term "electron" in, say, 1900 and those who used it in, say, 1925 were not talking about the same thing. If that were the case, the representation of the electron could not be the subject of a coherent historical narrative. Finally, the evolution of that representation has implications for the issue of scientific realism, since it might be interpreted as throwing doubt on the existence of the electron.

1. The possibility of this antirealist reaction was pointed out to me by Ernan McMullin.

In engaging with this historical project, besides its "intrinsic" interest the possibility of a fruitful exchange between the history and the philosophy of science provided my main motivation. The significance of the philosophy of science for understanding historically scientific practice has been underrated. Even though the relationship between the history of science and the philosophy of science has been discussed extensively, the focus of the discussion has been on the importance of history of science for the philosophical understanding of science.[2] To the best of my knowledge, there has been very little discussion of the ways in which the philosophy of science can enrich historiographical practice.[3] Some authors have even denied that the philosophy of science has anything to offer to the history of science. Thomas Kuhn's words are characteristic: "I do not think current philosophy of science has much relevance for the historian of science."[4] Kuhn made that statement in the 1970s, but it captures the attitude of many historians ever since. The historians' skepticism toward the value of the philosophy of science may have been justified, in view of some crude attempts to "apply" philosophical theories of scientific change to historical case studies. As I will try to show in this book, however, the philosophy of science has two historiographically significant functions: first, to provide a metahistorical analysis of conceptual issues in the history of science, and second, to examine the philosophical presuppositions of historiographical categories (e.g., of the notion of scientific discovery) and choices (e.g., of the subject of a historical narrative).

While my research was well under way, I came across some features of the electron's representation that had not been previously apparent to me. I had tacitly assumed that the representation in question was a plastic resource that physicists and chemists could manipulate at will, in order to solve the conceptual and empirical problems they faced. While attempting to understand how

2. See, e.g., A. Donovan, L. Laudan, and R. Laudan (eds.), *Scrutinizing Science: Empirical Studies of Scientific Change* (Baltimore: Johns Hopkins Univ. Press, 1992). This collection "addresses diverse and frequently conflicting claims about how science changes. *It seeks to test these claims against well-researched historical cases*" (p. xii; my emphasis).

3. This is confirmed by recent literature on the relationship between the history and philosophy of science. See T. Nickles, "Philosophy of Science and History of Science," in A. Thackray (ed.), *Constructing Knowledge in the History of Science, Osiris,* 10 (1995): 139–163; C. Pinnick and G. Gale, "Philosophy of Science and History of Science: A Troubling Interaction," *Journal for General Philosophy of Science,* 31 (2000): 109–125; and H. Radder, "Philosophy and History of Science: Beyond the Kuhnian Paradigm," *Studies in History and Philosophy of Science,* 28 (1997): 633–655. The historiography of experimentation provides, perhaps, the only notable case where philosophical questions and issues have motivated and guided historical work. See, e.g., F. Steinle, "Experiments in History and Philosophy of Science," *Perspectives on Science,* 10 (2002): 408–432.

4. T. S. Kuhn, *The Essential Tension* (Chicago: Univ. of Chicago Press, 1977), p. 12.

a new property, spin, was attributed to the electron, however, I realized that the electron's representation did not tolerate the newly suggested property. In particular, the attempt to incorporate spin within a classical representation of the electron's structure resulted in a violation of the special theory of relativity—a theory that was also supposed to govern the electron's behavior. Thus, the physicists' attempt to portray the electron as a tiny spinning ball resulted in an incoherent representation of its behavior. The physicists were forced, in turn, to restore the coherence in the electron's representation, which had not conformed to their expectations and desires.[5] In other words, the representation in question turned out to have a life of its own.

The autonomy of the electron's representation suggested to me that theoretical entities are active agents that participate in the development of scientific knowledge.[6] Since I was familiar with Karl Popper's suggestion that the world of representations has some independence from (and interacts with) the world of humans, my "discovery" fell on prepared ground. From that point on, I started to develop the historiographical implications of this idea and attempted to read my historical materials in that light. It occurred to me that certain episodes in the history of science, which involved the electron qua theoretical entity as an active participant, could be told from its point of view. The emphasis in a narrative of that kind would be on the heuristic resources embodied in the electron's representation and on the resistance that it exhibited to manipulation. Such a narrative would have the structure of a biography, with the electron's representation as the main actor.

This approach will be fully spelled out in chapter 2. Here a clarification is necessary, to avoid a confusion that the term "theoretical entity" may give rise to. In the philosophical literature the expressions "theoretical entity" and "unobservable entity" are used interchangeably to denote entities that are postulated within a certain theoretical context and are not accessible to observation. Bas van Fraassen has argued that "[s]uch expressions as 'theoretical entity' and 'observable-theoretical dichotomy' are, on the face of it, examples of category mistakes. Terms or concepts are theoretical (introduced or adapted for the purposes of theory construction); entities are observable or unobserv-

5. This episode is reconstructed in detail in chapter 8.

6. Here I assume that "a life of its own" implies "autonomy." This assumption is not idiosyncratic. For example, Ian Hacking's famous slogan that experimentation has a life of its own was meant to emphasize its independence from theory. Furthermore, the term "agent" should not be interpreted as implying intentional action. In fact, in current English usage there is no necessary link between "agency" and "intentionality." According to my *Pocket Oxford Dictionary*, an "agent" is just "one who or *that which* exerts power or produces effect" (my emphasis). See also chapter 2, p. 46.

able."[7] Even though his observation is correct, strictly speaking, one might still retain the term "theoretical entity" as a shorthand expression of more cumbersome phrases like "the representation associated with an unobservable entity." In what follows, I use that term in the sense specified. Thus, by "writing the history of theoretical entities" I mean "writing the history of the corresponding representations." The unobservable entities that the representations stand for, on the other hand, are, in most cases, supposed to be invariant and, therefore, do not have a history.

The ambiguity between the electron and its representation is quite common in the historical and philosophical literature. For instance, a recent collection of essays is titled *Histories of the Electron,* whereas it clearly concerns representations of the electron. Furthermore, one sees repeatedly expressions like "Lorentz's electron" or "Bohr's electron." As I will argue in chapters 2 and 9, these expressions do not stand for different entities (different kinds of electrons), but for different representations of the same entity. Thus, "Bohr's electron" should be interpreted as a shorthand expression of "Bohr's representation of the electron."

Historical investigation can be daunting. As Fernand Braudel has aptly remarked, "There is a whole past to be reconstructed. Endless tasks rear up and demand our attention, if we are to deal with even the simplest realities."[8] The more my research progressed the more aware I became of the immense complexity of the life of the electron's representation. I would not exaggerate if I said that its story from the late nineteenth century to the mid-1920s is the story of physics and chemistry during that period. It is hard to think of developments that did not somehow implicate the electron. A historical narrative adequate to the task of telling the life of its representation would require a much longer and significantly more detailed treatment than the one I have been able to provide. I came around this problem by focusing on some historical developments that were directly relevant to my historiographical and philosophical concerns. Thus, the story that I tell is highly selective and told with an eye toward the methodological issues raised in chapters 1 and 2. Furthermore, in choosing the topics of the historical chapters I attempted, first, to focus on historical developments that altered significantly the representation of the electron and, second, to complement existing historical scholarship on the electron.

So this book does not aim at comprehensive coverage of the history of the electron's representation. Rather, its primary objective is metahistorical—

7. B. C. van Fraassen, *The Scientific Image* (New York: Oxford Univ. Press, 1980), p. 14.

8. F. Braudel, *On History* (Chicago: Univ. of Chicago Press, 1980), p. 13.

namely, to understand the process of scientific discovery in microphysics, how theoretical entities are constructed, and how they function in scientific practice. Each of the historical chapters addresses a particular metahistorical issue: chapter 4 the "discovery" of unobservable entities, chapters 5, 6, and 8 the agency and recalcitrance of theoretical entities, and chapter 7 the identity of theoretical entities across disciplines and over time. However, the case studies I present do not have the character of "illustrations" of preestablished philosophical positions. Rather, my philosophical approach to the above issues has evolved in an attempt to come to grips with the historical material. The following chapters can be seen as an extended argument that these issues are not artificially imposed on the early history of the electron's representation, but are raised by the attempt to come to terms with that history.

The episodes I have chosen to reconstruct took place in the period from 1891, when the term "electron" was introduced, to 1925, when the notion of spin was put forward. That was a turning point in the history of the electron's representation. The proposal of spin was the last step in the development of the old quantum theory before the creation of quantum mechanics by Werner Heisenberg, Max Born, Pascual Jordan, and Paul Dirac. The new mechanics constituted a radical break with the older theory and was accompanied by severe interpretative difficulties, to a large extent absent from pre-1925 electron physics, whose repercussions are still debated by physicists and philosophers.

Within that period (1891–1925), the development of the representation of the electron can be construed as the outcome of two distinct (even though partially interacting) research programs. The first aimed at an increasingly precise measurement of certain electronic parameters (initially the charge-to-mass ratio and subsequently the charge of the electron). The other research program concerned the nature and behavior of electrons: the origin of their mass (mechanical or electromagnetic?) and its dependence on velocity, their size (do they occupy a finite space or are they point particles?), their self-energy, the laws that they obey, their degrees of freedom, their distribution within the atom, and their wave properties. With the exception of Pieter Zeeman's and J. J. Thomson's experiments, which initiated the former research program and which I discuss, I have focused on some aspects of the latter research program. Most of those episodes are familiar to specialists. The originality of the book, as I see it, consists in presenting a synthesis of primary sources and secondary scholarship on some important aspects of the development of the electron's representation, in light of the pertinent historiographical and philosophical issues.

## The Structure of the Book

Chapter 1 provides an overview of these issues. First, it starts with an explication of the notion of the problem situation, a notion that pervades the historical chapters to follow. Second, it gives a critical presentation of the issue of scientific discovery, with an emphasis on the "discovery" of unobservable entities. This part aims, among other things, to show the interdependence of the historiographical category of scientific discovery and the philosophical issue of scientific realism. The final section sketches the debate on the implications of meaning change for scientific realism and gives a historical twist to that debate, a twist that is fully developed in chapter 9.

Chapter 2 develops my biographical approach to writing the history of theoretical entities, an approach that, I hope, dispels the antirealist's skepticism toward the significance of such historical projects. I suggest a view of theoretical entities as constructions from experimental data. Viewing theoretical entities in this way enables us to understand their agency and to tackle successfully the problem of their identity over time. Furthermore, I point out the advantages of biography as a means of tracing the historical development of theoretical entities. Finally, I contrast this biographical perspective with recent approaches that also employ the notion of biography to reconstruct the history of "scientific objects."

Chapter 3 is an attempt to reconceptualize the "discovery of the electron." I provide a critical appraisal of the received view of that discovery, with an eye to the methodological issues about discovery that were raised in chapter 1. I attempt to show that the question Who discovered the electron? is not merely factual, but requires conceptual analysis and is entangled with the problem of scientific realism. I discuss some realist accounts of the discovery of the electron and find them wanting. Furthermore, I present evidence from early-twentieth-century sources which supports the view that the establishment of the electron as a new and fundamental constituent of matter was not an event, but a gradual process that was intertwined with the parallel debate over the existence of atoms.

Chapter 4 attempts to situate the principal historical actors within the wider process that led to the acceptance of the electron as an element of the ontology of physics. This chapter could very well expand into a book. I have not aimed at completeness; rather, I take up only those theories and experiments that were crucial for convincing the scientific community of the existence of the electron. Zeeman's and Thomson's measurements of the charge-to-mass ratio of the electron ($e/m$) are presented as the first steps in the construction of the quantitative aspects of the electron's representation. Unlike traditional narratives of the "discovery of the electron," mine puts special emphasis on the discovery of the Zeeman effect, the magnetic splitting of spectral lines. That discovery not only led to a determination of $e/m$ before Thomson's classic experiments on cathode rays, but also played a very important role in establishing the reality of the electron. Furthermore, it turned out to be crucial for the subsequent development of the representation of the electron. Key aspects of that development (e.g., the exclusion principle and spin) were the direct outcome of successive attempts to account for the "anomalous" Zeeman effect. These attempts are examined in chapter 8.

Chapters 5, 6, and 8 provide a reading of the development of the old quantum theory of the atom, which aimed at understanding the behavior and distribution of electrons bound within the atom, from the perspective of the electron. A defining characteristic of biographical studies as well as their main historiographical asset is that they offer a unique perspective on the historical developments in which their subject participated. Read in this way, the evolution of the old quantum theory can be construed as an extended episode from the life of the electron qua theoretical entity.

In particular, chapter 5 examines the birth of a quantum representation of the electron. It reads Niels Bohr's papers, the locus of that birth, from the point of view of the electron and highlights the active role of its representation in both guiding and constraining Bohr's thought. Bohr's revolutionary proposal transformed the electron's representation into that of a nonclassical particle, that is, a particle that did not fully obey the laws of classical mechanics and electromagnetic theory. Chapters 6 and 8 explore the further metamorphosis of the representation of the electron after that initial "quantum leap." They focus on some aspects of the history of quantum numbers, selection rules, the correspondence principle, transition probabilities, the exclusion principle, and spin. Each of these developments has a history that I have not attempted to follow. The emphasis of my narrative is on the introduction of these important innovations rather than on their subsequent elaboration and application. Again, I portray the electron qua theoretical entity as an active agent and highlight its role in the development of the old quantum theory of the atom.

I should point out that chapters 5, 6, and 8 are not put forward as a novel interpretation of the historical development of quantum theory. They are too selective and schematic to fulfill that purpose. Moreover, with few exceptions, my interpretation of the developments that I reconstruct is in agreement with the results of the considerable and solid historical scholarship of the past three decades. The aim of these chapters is, rather, to read some aspects of that history from the perspective of the electron, as opposed to the atom and, more important, to introduce the electron's representation as an autonomous actor who participated in the construction of that theory.

Chapter 7 discusses the chemists' representation of the electron and contrasts it with its physical counterpart. Here we see that the notion of the problem situation is crucial for explaining the diverging outlooks of chemists and physicists. I sketch the first indications of the nature of the reconciliation that was eventually achieved with the advent of quantum mechanics. Furthermore, I discuss the transdisciplinary character of the electron qua theoretical entity and its significance for bringing chemistry and physics closer.

Chapter 9 provides an analysis of the philosophical debate concerning the meaning variance of scientific terms and its implications for scientific realism. I argue against the widespread view that meaning change is incompatible with scientific realism and, thus, provide a way out for the aspiring realist, without, however, committing myself to a realist position. Furthermore, I indicate the importance of a historicist approach to the ontological status of unobservable entities. I suggest that the historical reconstruction of the concept associated with an unobservable entity and, more important, of its putative referent are indispensable for an adequate realist construal of that entity's ontological status. Thus, realism can make sense only locally (i.e., with respect to particular entities). In concluding the book I discuss the compatibility of the evolution of the concept of the electron with a realist interpretation of its ontological status and argue that certain aspects of that evolution allow, but not require, a realist attitude toward the electron.